BIOGEOMORPHOLOGY OF COASTAL STRUCTURES:

Understanding interactions between hard substrata and colonising organisms as a tool for ecological enhancement

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

Signature: **M. A. Coombes**

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ABSTRACT

Urbanisation is increasingly recognised as a major ecological pressure at the coast. By 2035, the Department for Environment, Food and Rural Affairs will have to spend £1 billion each year on flood defence and erosion control infrastructure if current levels of protection are to be sustained in England and Wales; this represents a substantial commitment to building new hard structures. Ecological research has shown that structures like seawalls, breakwaters, and harbour and port infrastructure are poor surrogates for undisturbed rocky shores. This, alongside substantial international policy drivers, has led to an interest in the ways in which structures might be enhanced for ecological gain. Virtually all of this research has been undertaken by ecologists, while the contribution of geomorphological understanding has not been fully recognised.

This thesis presents an assessment of the two-way interactions between colonising organisms and the materials used to build hard coastal structures under a framework of biogeomorphology. The influence of material type and small-scale surface texture on early colonisation is assessed alongside detailed observations of the ways in which biota are involved in the alteration of substratum properties and behaviours through weathering and erosion in the intertidal zone. The research demonstrates that biotic (organisms) and abiotic (material substrata) components of coastal structures are inherently linked at various spatial and temporal scales through complex biogeomorphic interactions and feedbacks. Importantly, these interactions have consequences for the subsequent operation of ecological and geomorphological processes that are of relevance to urban marine ecology, weathering and rock coast geomorphology, and engineering.

This thesis demonstrates the considerable potential to manipulate substratum-biota interactions on artificial structures for ecological gain, both directly and indirectly. More broadly, the explicitly interdisciplinary methodological approach adopted shows the value and necessity of integrated research for achieving useful, applied outcomes.

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Personally, I owe so much to my partner, Adam, for his unwavering support from the very beginning – through thick and thin. I can honestly say I could not have done this without you – thank you so much.

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ABBREVIATIONS

ANOVA	Analysis of Variance
BEI	Backscattered Electron Imaging
BRE	Building Research Establishment
CIRIA	Construction Industry Research and Information Association
DCLG	Department for Communities and Local Government
Defra	Department for Environment, Food and Rural Affairs
DELOS	Environmental Design of Low Crested Coastal Defence Structures
EA	Environment Agency
EC	European Commission
EDS	Energy Dispersive X-ray Spectroscopy
EEA	European Environment Agency
EIA	Environmental Impact Assessment
EPS	Extracellular Polymeric Substances
HMWB	Heavily Modified Waterbody
ICE	Institute of Civil Engineers
ICZM	Integrated Coastal Zone Management
IPCC	Intergovernmental Panel on Climate Change
LA	Local Authority
MHWN	Mean High Water Neap
MID	Microbially Induced Deterioration
MLW	Mean Low Water
MRM	Micro-Roughness Meter
MSW	Making Space for Water Programme
MTL	Mean Tide Level
NFCDD	National Flood and Coastal Defence Database
OSPAR	Oslo and Paris Conventions for the Protection of the Marine Environment
PPG	Planning Policy Guidance Note
PPS	Planning Policy Statement
PSS	Potential Settlement Sites
SEA	Strategic Environmental Assessment
SEM	Scanning Electron Microscopy
SMP	Shoreline Management Plan
SNK	Student-Newman-Keuls test
SST	Sea Surface Temperature
TEEB	Economics of Ecosystems and Biodiversity
UKTAG	United Kingdom Technical Advisory Group (for WFD)
UKTS	United Kingdom Tourism Survey
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
WAC	Water Absorption Capacity
WFD	Water Framework Directive

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CHAPTER 1

INTRODUCTION AND THESIS AIMS

A Biogeomorphological Approach to Understanding Coastal Structures as Habitats

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CHAPTER 1. INTRODUCTION AND THESIS AIMS

A Biogeomorphological Approach to Understanding Coastal Structures as Habitats

1.1 Coastal Structures and Biodiversity

Coastal environments are an extremely important component of global biodiversity. Estuaries, coral reefs, cold-water reefs, rocky shores, mangroves, salt marshes and seagrass beds are all recognised as valuable habitats (Ray 1988). At the same time, coasts are vital economic and social assets (French 1997; Ramanathan et al. 2010) supporting more than 60 % of the current global population, a figure expected to exceed 75 % by 2025 (EEA 1999). Economic activities associated with ports and harbours and tourism have driven rapid and often intensive transformations of coastal regions from natural to artificial shorelines, particularly in Europe (Turner et al. 1998; Airoldi and Beck 2007).

This concentration of assets at the coast means there is a continued need to protect people, homes and businesses and habitats from flooding from the sea and coastal erosion, the risks of which are expected to increase in the future as a result of climate change (IPCC 2007a). By 2035, the Department for Environment, Food and Rural Affairs (Defra) will have to spend £1 billion each year on new defence infrastructure and maintaining existing defence assets in the UK if current levels of protection are to be sustained (Defra 2010); this represents a substantial commitment to building new structures. Despite the move towards Integrated Coastal Zone Management (ICZM) which places emphasis on soft defence solutions and environmental appraisal (EC 2002; Defra 2006), it is unavoidable that new structures will have to be built where risks to valuable assets are currently unacceptable, or where they will become unacceptable in the future.

Hard artificial coastal structures, such as port and harbour infrastructure, seawalls, breakwaters and jetties, are readily colonised by marine organisms (Bulleri 2006). However, they do not typically support the abundance and diversity of species that are found on natural rocky shores (Chapman 2003). Indeed, many ecologists recognise that a continued need to defend and develop the coast will be a major driver of habitat alteration, disturbance and loss in the future (Thompson et al. 2002; Airoldi and Beck 2007; Hawkins et al. 2008). Observing biological responses to different design features of structures at a range of spatial scales (e.g. Moschella et al. 2005), and understanding the operation of specific ecological processes at their surface (e.g. Bulleri 2005b), has therefore gained considerable research attention in the ecological community (see Bulleri and Chapman 2010 for a recent review). Ways to manipulate engineering designs specifically for ecological enhancement are also beginning to be explored (e.g. Chapman and Blockley 2009; Martins et al. 2010).

> "While there is increasing demand to defend coastlines worldwide, integrated coastal management requires that this must be done in ways that promote the sustainability of natural marine systems…basic knowledge derived from simple studies such as the description of patterns of species distribution in combination with experimental marine ecology can provide information of applied interest that can inform ecologists and fishery and coastal managers."
>
> **Martins et al. 2010 p. 208.**

In addition to environmental concerns, statutory requirements to minimise the impact of new structures where they have to be built are further driving urban marine ecology research. In Europe, this includes the implementation of the Environmental Impact Assessment Directive (85/337/EEC, as amended by Directives 97/11/EC and 2003/35/EC), the Water Framework Directive (2000/60/EC) and various conservation regulations including that Habitats Directive (1992/43/EC). In the UK, additional national level requirements and controls include Planning Policy Statement 9 (Biodiversity and Geological Conservation) and the Marine and Coastal Access Act (2009). Knowledge of interactions between hard structures and the organisms that colonise them is therefore of considerable value as a means of identifying ways to meet these requirements, and is necessarily high on the research agenda of applied ecology (Bulleri and Chapman 2010).

A further challenge is a lack of understanding of the implications of colonisation for durability and the performance of coastal structures, which remains somewhat of an ambiguity in marine engineering science (e.g. CIRIA 2010). Improving understanding of substrate – biota interactions in an engineering context is of importance, therefore, if practitioners (coastal managers and engineers) are to be expected to uptake measures designed to facilitate colonisation for purely ecological gains.

1.2 A Biogeomorphological Approach

Despite calls for close collaboration between ecologists, engineers and coastal managers to develop and implement ways of improving the ecological value of hard structures (Burcharth et al. 2007; Bulleri and Chapman 2010), the value of geomorphological understanding in these discussions has seldom been recognised. This is surprising because the physical properties of rocky shore substrata, particularly surface 'complexity' (i.e. texture, see later), is known to influence key ecological processes such as settlement and recruitment in the intertidal zone, at a range of spatial and temporal scales (e.g. Crisp 1974; Archambault and Bourget 1996; Hills et al. 1998). Furthermore, substratum thermal properties (e.g. Raimondi 1988a) and weathering behaviour (e.g. Herbert and Hawkins 2006) are also thought to exert some control on mortality and competition of early colonists.

Natural environments may be viewed within a framework of 'biogeomorphology', which considers the two-way interactions between biotic components (the living biology) and abiotic components (the non-living, physical environment) at multiple scales (Viles 1988a, see Chapter 3 for detailed discussions). Biogeomorphology is, therefore, inherently an interdisciplinary science (Viles 2000b). In rocky coastal environments, biogeomorphological research has focused on the involvement of organisms in the destruction ('bioerosion') and, to a lesser extent, protection ('bioprotection') of rocks at a range of spatial scales (< µm – m; see Chapter 7). However, the operation of these processes on materials introduced into the tidal zone through coastal engineering has rarely been considered, particularly on artificial materials like concrete. 'Ecosystem engineering' is a parallel concept in ecology which has recently been applied to intertidal environments (Harley 2006). The concept recognises the role of animals and plants in the creation, modification and destruction of physical habitat niches (Jones et al. 1994, 1997b) but has not typically considered the consequences of biogeomorphic interactions and feedbacks for ecology and *vice versa* (see Chapter 3). This is particularly true at a micro-scale (< mm) where technical and theoretical challenges arise (Viles 2001; Naylor et al. 2002).

> "Essentially, biogeomorphology involves cooperation between ecology and geomorphology… [it] could foster the sharing of theories, the development of novel models and the creation of new and mutually useful data collection techniques between geomorphologists and ecologists."
>
> **Naylor et al. 2002 p. 4.**

Understanding the ways in which construction materials, their physical properties and geomorphic behaviours both influence and respond to colonisation in the intertidal zone is a facet of coastal urban ecology that is worthy of specific attention. Understanding these processes is challenging, as it is necessarily highly interdisciplinary, but offers the opportunity for significant theoretical development (both for ecology and geomorphology, and for biogeomorphology as an integrated discipline) as well as making valuable applied contributions to current understanding of artificial structures as habitats, and ultimately how they may be manipulated for ecological gains.

1.3 Research Aims and Thesis Structure

Broadly speaking, the work presented in this thesis aims to further theoretical understanding of substrate-biota interactions in the intertidal zone within both ecology and geomorphology disciplines, under a framework of biogeomorphology. The overall aims of the research are shown in Table 1-1.

Table 1-1 Overall thesis aims

A1. To improve understanding of biological responses (at a < cm scale) to different material types and textures used in coastal engineering.

A2. To improve understanding of the geomorphological responses of different construction materials (at a < cm scale) during exposure in the intertidal zone, with particular attention on the role of biology in geomorphological change and implications for engineering durability.

A3. To improve understanding of interactions and feedbacks between geomorphological and ecological processes on different materials exposed in the intertidal zone, within a framework of biogeomorphology.

A4. To apply biogeomorphic understanding of hard coastal structures in identifying opportunities for ecological enhancement.

Ecologically, the influence of materials used in coastal engineering and their physical characteristics (i.e. texture) on marine colonisation was of interest at a currently understudied scale (< cm; **Aim 1**). Geomorphologically, the physical response of materials to intertidal exposure and colonisation was explored, both with respect to weathering and erosion, and engineering durability (**Aim 2**). Specific attention was given to the role of biota in substratum alteration and subsequent geomorphological and ecological consequences of these interactions (**Aim 3**). Finally, the overarching aim of the research was the application of biogeomorphological understanding in the ecological enhancement of hard structures built in the intertidal zone (**Aim 4**). Fundamentally, the thesis advocates an integrated, interdisciplinary approach to understanding natural systems as a means of advancing scientific knowledge, testing and developing new methods and models, and achieving applied outcomes.

This thesis is divided in to five main Parts, as shown in Table 1-2. ***Part 1*** (this Chapter) provides a short overview of the research area, overall research aims and motivation (above). More detailed background information is presented in ***Part 2*** by reviewing current literature on coastal urbanisation and marine urban ecology, identifying limitations to existing understanding, and highlighting opportunities for the integration of geomorphological knowledge in these discussions (Chapter 2). Further information of more disciplinary relevance is reserved for the respective chapters of each piece of experimental work described below. Chapter 3 outlines the broad philosophical and methodological approach to the research, using a conceptual framework of 'biogeomorphology' and related ecological concepts of 'physical ecosystem engineering'. Specific objectives, research questions and hypotheses are also presented in Chapter 3.

Part 3 details four main areas of experimental work, with a preliminary chapter (Chapter 4) describing the materials used throughout. Field block exposure trials used to examine the response of a common intertidal organism (barnacles) to different material types and textures used in coastal engineering are described in Chapters 5 and 6, respectively. These two chapters are primarily focussed on 'biotic responses' to introduced hard substrata. The 'abiotic response' (i.e. alteration) of materials is examined in Chapters 7 and 8. In Chapter 7, colonisation and weathering of the materials by microorganisms was explored using microscopy (Strand 1), alongside assessments of changes in bulk material properties of more relevance to engineering durability (Strand 2), and morphological (i.e. textural) responses at a scale of particular relevance for barnacle colonisation (mm-scale) (Strand 3). A discussion of this work is also presented in Stand 4, which explores linkages between the difference scales of enquiry. In Chapter 8, a new method for measuring the wetting-drying and warming-cooling behaviour of materials under simulated intertidal conditions is described; the implications of these behaviours for geomorphological and ecological processes both before and after a period of exposure in the intertidal zone are discussed.

Table 1-2 Thesis structure.

Part 1	**Introduction and Thesis Aims**	**Chapter 1**
Part 2	**Background and Methodology**	
	Background (contextual literature review)	**Chapter 2**
	Research Framework and Methodology	**Chapter 3**
Part 3	**Experimental Work**	
	Materials: Baseline characterisation	**Chapter 4**
	Ecological Response (A): Material type	**Chapter 5**
	Ecological Response (B): Material texture	**Chapter 6**
	Geomorphological Response (A): Weathering and erosion	**Chapter 7**
	Strand 1 – Micro-scale (<mm) response	
	Strand 2 – Bulk-scale (>mm) response	
	Strand 3 – Morphological response (mm-scale)	
	Strand 4 – Discussion	
	Geomorphological Response (B): Substratum warming-drying behaviour	**Chapter 8**
Part 4	**Synthesis: Biogeomorphology as a tool for ecological enhancement**	**Chapter 9**
Part 5	**Conclusions and Recommendations**	**Chapter 10**
	Appendices	
	SEM Pilot study	**Appendix 1**
	SEM Spatial Variability	**Appendix 2**
	Existing Coastal Structures SEM	**Appendix 3**
	Plymouth Breakwater Case Study	**Appendix 4**
	Reference list	

Part 4 presents a synthesis of the experimental work (Chapter 9) using the biogeomorphological framework outlined in Chapter 3. Interactions and feedbacks between biotic and abiotic components are explored using a series of conceptual models, with particular reference to material type, textural development and spatio-temporal variability. The relevance and application of the research findings for the ecological enhancement of hard coastal structures is then specifically considered; Plymouth Breakwater is used here as an illustrative case study.

Finally, the main conclusions of the work for ecological, geomorphological and biogeomorphological theory and understanding, and ecological enhancement are presented in **Part 5** (Chapter 10), along with recommendations for future research. Appendices containing supplementary work are included at the end of the thesis, which are referenced throughout the main text were appropriate. A separate copy of the thesis outline (Table 1-2) is attached as supplementary material to aid navigation through the document.

CHAPTER 2

BACKGROUND

Coastal Structures as Habitats: Current understanding, limitations and the geomorphological contribution

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CHAPTER 2. BACKGROUND

Coastal Structures as Habitats: Current understanding, limitations and the geomorphological contribution

2.1 Introduction

This chapter provides a background to the broad-scale themes of the thesis by reviewing existing literature. Discussions are structured to provide a rationale for the work and to inform the specific experimental aims, objectives and hypotheses, and the research framework presented in the following chapter (Chapter 3).

Due to the highly interdisciplinary nature of the project (see Chapter 3), this chapter does not aim to give a detailed background of each individual disciplinary component of experimental work presented in *Part 3* (Chapters 4 – 8); this is reserved for the respective introduction and discussion sections of each chapter. Instead, the review presented here outlines the motivation for the overall thesis by discussing the following themes (Table 2-1): (i) the need for coastal structures now and in the future; (ii) structures as habitats; (iii) policy drivers for ecological enhancement; (iv) progress and limitations of existing research on ecological enhancement of coastal structures, and; (v) the potential geomorphological contribution to these discussions.

Table 2-1 Background themes reviewed in Chapter 2.

	Theme	Relevant thesis question	Pages
Section 2.1	**Introduction to Chapter 2**	n/a	**p. 43**
Section 2.2	**Coastal assets and the need for defence**		
	The current need for coastal armouring, and future commitments to build hard structures in the coastal zone.	How common are hard coastal structures now and in the future?	**p. 45**
Section 2.3	**Urban Marine Ecology: structures as habitats**		
	Current understanding of artificial structures as an ecological pressure	Why should we be concerned about coastal urbanisation?	**p. 55**
	Current understanding of the influence of substrata and various design features on the ecology of coastal structures	How and why are hard artificial coastal structures different from natural rocky shores, and what does this tell us about opportunities for enhancement?	**p. 61**
Section 2.4	**Policy drivers for ecological enhancement**		
	Policy drivers for the enhancement of hard coastal structures.	Beyond conservation, what statutory requirements are there to enhance the ecological potential of artificial coastal structures? Why is this research important in a policy framework?	**p. 70**
Section 2.5	**Maximising ecological potential: Current understanding and testing**		
	Options for enhancing artificial coastal structures for ecology; progress to date.	What ecological enhancement trials are currently being done around the world?	**p. 76**
Section 2.6	**Geomorphology and coastal structures**		
	Geomorphological understanding of intertidal rocks and contributions to discussions of ecological enhancement of artificial structures.	Why is geomorphology relevant to hard coastal structures and how can geomorphological knowledge contribute to our understanding of ecological enhancement?	**p. 85**
Section 2.7	**Limitations to Marine Urban Ecology: The geomorphological contribution**		**p. 93**
	The limitations of current understanding and applied testing of ecological enhancements.	What are the main limitations of current research on ecological enhancement, what experiments are needed and how can geomorphology contribute?	
Section 2.8	**Summary and conclusions**	n/a	**p. 97**

2.2 Environmental, Economic and Social Assets and the Need for Coastal Defence

In the UK, ecologically valuable coastal landscapes, habitats and species are protected by a suite of environmental designations implemented at a National, European and Global level (Table 2-2). Coastal habitats and species feature heavily on priority lists for protection as set out in the UK Biodiversity Action Plan (2008), including coastal cliff and foreshore, rocky reefs and saltmarsh habitats. More than 120 of England's Natura 2000 sites (Special Protection Areas [SPAs] and Special Areas of Conservation [SACs]) and 19 different Areas of Outstanding Natural Beauty (AONBs) are coastal or tidally influenced. In addition, 47 National Nature Reserves (NNRs), 31 Heritage Coasts and more than 320 Sites of Special Scientific Interest (SSSIs) are categorised as coastal or tidally influenced.

More than 75 % of the European population is expected to live within 100 km of the coast by 2025 (EEA 2006). Along with Italy, Spain and the Netherlands, UK coastlines are classified as being intensively occupied (EEA 2006). Such rapid population increases at the coast have been associated with intensive economic development, with tourism being particularly important in Europe. Mediterranean coastlines are expected to attract up to 350 million seasonal tourists each year by 2025 (Hinrichsen 1998). In the UK, revenue from domestic coastal tourism alone amounted to more than £5 billion in 2007 (UKTS 2007). All coastal economic activates, including tourism, import and export industries, and private and commercial fishing, are estimated to generate more than £50 billion in turnover each year in the UK (Turner et al. 1998).

Table 2-2 UK and European legislation and policy for the designation and conservation of coastal environments.

	Associated designations	UK examples (emphasis on South West England)
UK Legislation and Policy		
Convention on Biological Diversity (1992)	Priority Habitat (UKBAP)[1]	Coastal saltmarsh
		Coastal sand dunes
		Cold-water reefs
		Estuarine rocky habitats
		Intertidal underboulder communities
	Priority Species (UKBAP)[1]	Bearded Red Seaweed (*Anotrichium barbatum*)
		Fan Mussel (*Atrina fragilis*)
		Coral Maërl (*Lithothamnion corallioides*)
		Gooseneck Barnacle (*Mitella pollicipes*)
Countryside and Rights of Way Act (2000)	Sites of Special Scientific Interest (SSSIs)[2]	Porthleven Cliffs (Cornwall)
		Lower Fal & Helford Intertidal (Cornwall)
		Meneage Coastal Section (Cornwall)
		Barricane Beach (Devon)
	National Nature Reserves (NNRs)[2]	The Lizard (Cornwall)
		Axmouth to Lyme Regis Undercliffs (Devon)
		Slapton Ley (Devon)
	Area of Outstanding Natural Beauty (AONB)[3]	378 km of coast in Cornwall
	Heritage Coast[3]	317 km of coast in Cornwall
The Marine and Coastal Access Act (2009)	Marine Conservation Zones (MCZ)[2]	Currently undergoing selection

European Legislation and Policy		
Ramsar Convention (1971)	Ramsar Sites[2]	Poole Harbour (Dorset) Isles of Scilly (Cornwall) Severn Estuary (England/Wales)
Birds Directive (79/409/EEC)	Special Protection Areas (SPAs)[2]	Poole Harbour (Dorset) Isles of Scilly (Cornwall) Severn Estuary (England/Wales)
Habitats Directive (92/43/EEC)	Special Areas of Conservation (SACs)[2]	Plymouth Sound and Estuaries (Devon and Cornwall) Isles of Scilly Complex (Cornwall) Godrevy Head to St Angnes (Cornwall) Fal and Helford (Cornwall) Braunton Burrows (Devon) Dawlish Warren (Devon)
Global Designations		
World Heritage Convention (1972)	World Heritage Sites[4]	Dorset and East Devon Coast
	Biosphere Reserves[4]	Braunton Burrows (Devon)

[1]Maddock (2008)
[2]Natural England (http://www.english-nature.org.uk/, accessed May 2010)
[3]Planning Policy Guidance 20: Coastal Planning (http://www.communities.gov.uk/planningandbuilding/, accessed May 2010)
[4]UNESCO (www.unesco.org, accessed May 2010)

2.2.1 Coastal Flood and Erosion Risk Management in the UK

More than 5 million people and 2.4 million properties are at risk from river and coastal flooding in England (Environment Agency 2009b), with a further 220,000 people at risk in Wales (Environment Agency 2009c). In addition, coastal erosion is a significant problem in the UK, with more than 28 % of the coastline eroding at a rate of 10 cm per year or more (Defra 2009a).

Flood and erosion risk management in England and Wales is governed by the Department for Environment, Food and Rural Affairs (Defra) and implemented by the Environment Agency (EA). Local Authorities (LAs) and Internal Drainage Boards (IDBs) have additional responsibilities for flood risk, particularly relating to planning and development control. Currently, the Government's 'Making Space for Water Programme' (MSW) guides all flood and erosion risk management activities in England and Wales (Defra 2005). This strategy reflects a fundamental, strategic-level shift in approaches to coastal management in the last 20 years, towards one based on Integrated Coastal Zone Management (ICZM, Viles and Spencer 1995; EC 2002; McInnes 2003; Defra 2006, 2008a; Townend 2008). This is a holistic approach to management that aims to balance social needs (flood and erosion risk, recreation and access), economic needs (industrial activities and tourism) and environmental needs (habitats and biodiversity) in a sustainable way (Figure 2-1).

With respect to coastal risk, a key component of the MSW Programme continues to be Shoreline Management Plans (SMPs), which complement the Catchment Flood Management Plans (CFMPs) developed for assessing fluvial (river) risks. The second round of SMPs are currently being published by the EA (SMP2s), which aim to identify the most sustainable approaches to coastal management in the short term (0-20 years), medium term (20-50 years) and long term (50-100 years; Defra 2010). These plans are the primary tool for guiding future investment works, including new defence schemes, monitoring programmes and further research.

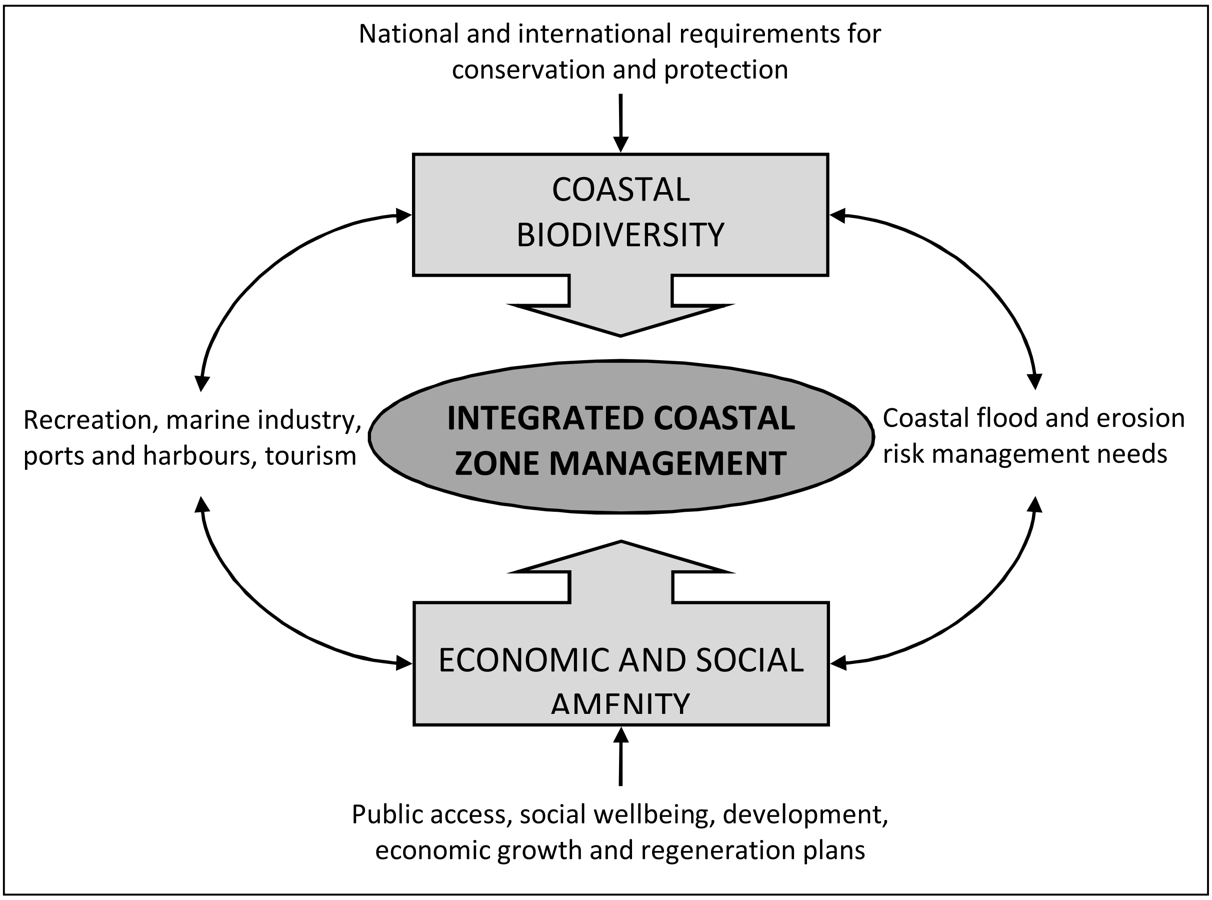


Figure 2-1 Environmental, social and economic aspects of Integrated Coastal Zone Management related to ecological enhancement of coastal structures.

2.2.2 Current and future commitments to hard defence in the UK

2.2.2.1 Existing structures

A significant proportion of the European coastline is artificial (Airoldi and Beck 2007). This has resulted from shoreline urbanisation for infrastructure purposes, such as port and harbour facilities, as well as structures built primarily for flood and erosion control. The EA records UK flood defence assets in the National Flood and Coastal Defence Database (NFCDD). This database is still being populated with asset information, however data of coastal structures in Devon is presented here, with permission from the EA, to illustrate the extent of coastal armouring and the pressure it places on coastal habitats in one area of the UK.

The locations of artificial hard coastal structures on north and south Devon coasts compared to 'natural' stretches of coast (i.e. cliffs and beaches) or areas which have soft defences (such as earth banks, dune systems and maintained channels) are shown in Figure 2-2. In total, around 30 % of the Devon coastline is armoured, equivalent to 124 km of hard structures. Interrogation of the NFCDD indicates that of these stretches of coast, concrete and masonry walls (incorporating mortared concrete or stone) account for 59 % (73 km), while rock structures such as rubble breakwaters and groynes account for 6 % (8 km; Figure 2-3). A further 43 km of the coastline has defences which are not currently specified in the database. As well as being vital for flood and erosion risk management, these structures represent a substantial economic commitment in Devon, with estimated replacement costs of more than £500 million (NFCDD, accessed June 2010).

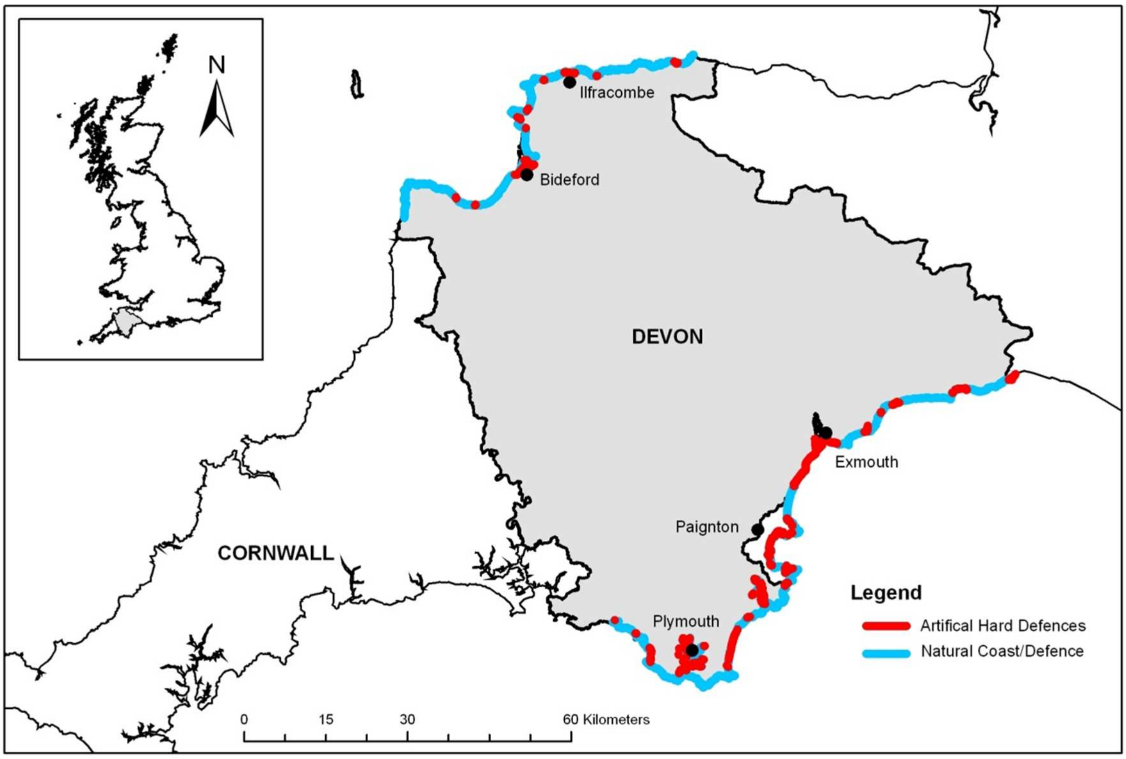


Figure 2-2 Natural coastline and hard artificial defence structures in Devon, UK (source data: NFCDD).

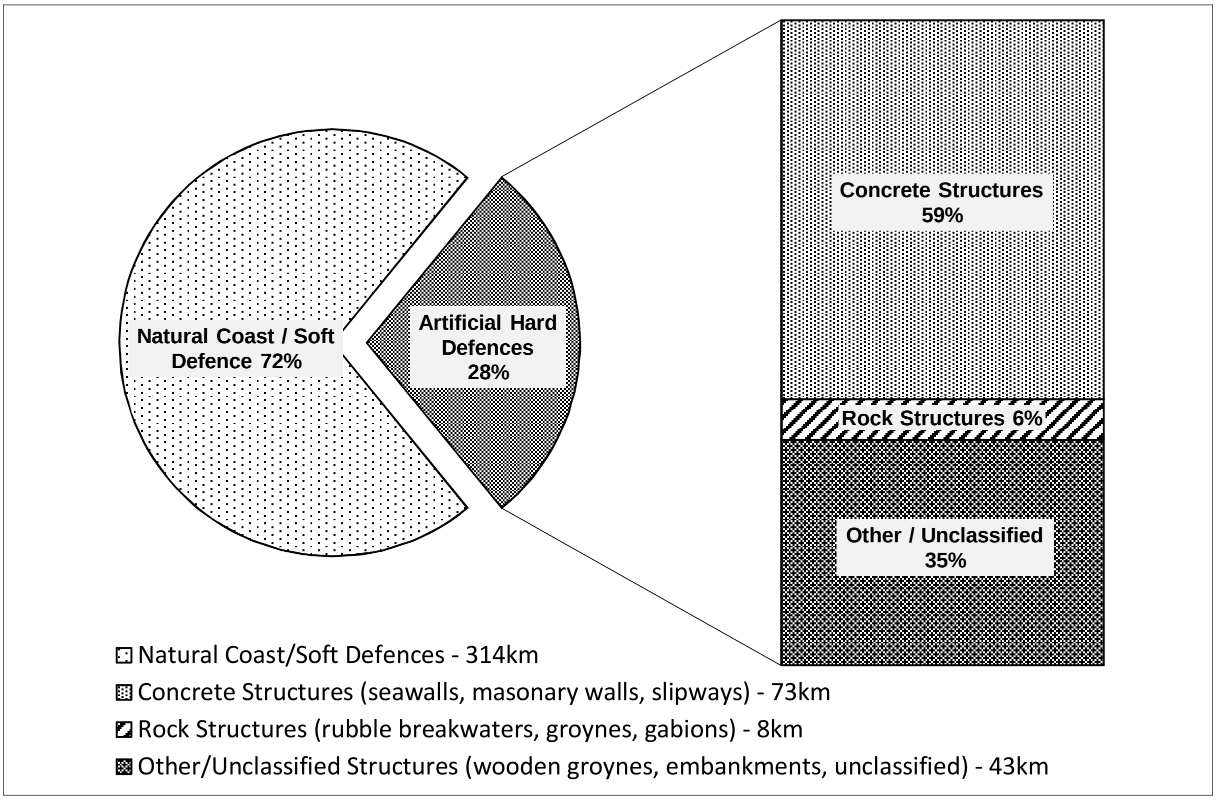


Figure 2-3 Coastal structures in Devon (north and south coasts), UK (source data: NFCDD).

As an example, Devon highlights several important points. First, it is clear that the conversion of natural shorelines to hard, armoured coasts is changing the habitat type of a significant proportion of the UK coastline. Furthermore, given that some 259 km (59 %) of the Devon coast is naturally protected by hard cliffs, the pressure to build new defences in other low-lying and soft sediment-dominated areas of the country (such as the Wash and East Anglia, e.g. Environment Agency 2010b), is significantly higher, particularly in the face of sea level rise and regional-scale land movements (Holman et al. 2002).

Second, there is obvious spatial variability in the current extent of coastal urbanisation. While in total 28 % of Devon's coast is armoured, this figure is 55 % for the south coast alone. The association of hard structures with major population centres (i.e. Plymouth, Paignton and Exmouth in the case of south Devon) means that future commitments to maintain, upgrade and build new structures must necessarily be focussed in these locations. Armouring a high proportion of the shoreline in major population centres means that the potential ecological impacts in these locations are of particular concern (Wilby and Perry 2006). In Europe, the association between coastal urban centres and shoreline hardening is clear, with an estimated 280 coastal cities having a population of 50,000 or more (Airoldi and Beck 2007). At this scale, ecological pressure from coastal urbanisation is most significant in Mediterranean countries, where the population doubled in the 20 years between 1980 and 2000 (UNEP 2001).

Thirdly, the range of structures built at the coast, and hence the types and characteristics of the materials they are made of, is highly variable (e.g. Table 2-3). Concrete and masonry structures constitute a significant proportion of the defences in Devon (Figure 2-3). Concrete structures also constitute 15 % of the annual construction expenditure for coastal defence nationally (CIRIA 2010). Rock rubble armouring is a more common defence strategy in other areas of the country, including Dorset for example (Clarke 1988; Pinn et al. 2005a), while the combined use of concrete walls and rock armouring is also a common, such as the major defence scheme at Clacton-on-Sea in Essex (EA 2010a). Granite and limestone are the most common rock types used for armourstone, while pre-cast concrete armour units are also widely used as they are typically more cost effective (CIRIA 2007; 2010, see Chapter 4). In a European context, it is estimated that 22,000 km^2 of the coastal zone is concrete or asphalt (EEA 2005).

The range of materials available for coastal engineering means that developing generic models of ecological (see Section 2.3) and geomorphological (see Section 2.6) processes on them is difficult without much more experimental testing. This type of research is necessary if simple, cheap and widely applicable recommendations for enhancing the ecological potential of hard structures are to be developed (Bulleri and Chapman 2010).

Table 2-3 Example types of hard coastal infrastructure used to manage flood and erosion risk.

Structure type	Description / function	Construction materials	Example
Seawalls / Bulkheads / Masonry walls	Vertical structures built either as part of port and harbour infrastructure, or specifically for erosion control. Designed to reduce/deflect wave impact on the shore.	Concrete (pre-cast units or cast *in situ*). Natural stone (typically 'block and mortar' arrangement). Metal sheet piling is also common in harbours and ports.	**Penzance seawall, Cornwall** Construction: vertical wall with rubble toe armouring. Material: granite facing and granite rubble.
Breakwaters	Solid structures either attached to the shore (such as an 'arm' of a harbour) or positioned offshore. Designed to dissipate wave energy. Offshore breakwaters are typically overtopped at high tide (termed 'low crested').	Typically built with a 'core' of rock or concrete rubble, with concrete facing or stone / mortar cladding. Rubble breakwaters (offshore) may be built from large (> 1 ton) boulders of natural rock (e.g. granite, limestone, sandstone).	**Plymouth Breakwater, Devon** Construction: low-crested, flat-topped, offshore breakwater. Material: limestone rubble core faced with limestone and granite paving. Additional concrete armour units (see Section 9.8.1.3).
Groynes	Structures built perpendicular to the shore to restrict long-shore transport of sediment. Typically used in association with other seawalls and rock breakwaters.	Traditionally wooden in the UK. Rock rubble groynes increasingly common, built of granite (e.g. larvikite), limestone or sandstone.	**West Bay, Dorset** Construction: rock rubble groyne. Material: limestone.
Revetments / Armourstone / Riprap	Structures built parallel to the shore, similar in purpose to seawalls but typically with an angled sloping face. Armourstone usually placed in front of a primary defence such as a seawall.	Rubble constructions often pre-cast concrete armour units, or rock boulders. Older examples may be constructed in wood. Hard (durable) rock favoured (e.g. granite), but limestone and sandstone also common.	**Overstrand, Norfolk** Construction: A-frame revetment built on the upper shore in front of natural cliffs. Material: wood
Pilings	Vertical structures built primarily for supporting other infrastructure e.g. piers and bridges.	Concrete, wood, fibreglass, metal are all common.	**Newlyn Harbour, Cornwall** Construction: support pilings for administrative buildings, walkways and moorings. Material: concrete, metal.

2.2.2.2 Future structures

A key facet of the holistic approach advocated by ICZM and implemented by the MSW Programme in the UK is an acceptance that it will neither be technically feasible or economically sustainable to defend all parts of the coast from flooding and erosion in the future (Defra 2010). Despite this, hard defence of UK shorelines will be unavoidable where there is unacceptable flood risk, or where there would be significant economic and social gains from doing so (EA 2009b).

This year (2010/11) the EA plans to spend £800 million on flood and coastal erosion risk management (EA 2009a, Figure 2-6). Of this, 20 % (£161 million) will be used to maintain existing assets and 34 % (£270 million) to build new defence structures. A further 6 % (£52 million) is reserved for construction by LAs and IBDs. As of February 2011, the Environment Agency had more than 300 flood defence schemes in development or under construction, which are expected to reduce risk to more than 320,000 homes (www.environment-agency.gov.uk/research/planning/116703.aspx, accessed February 2011).

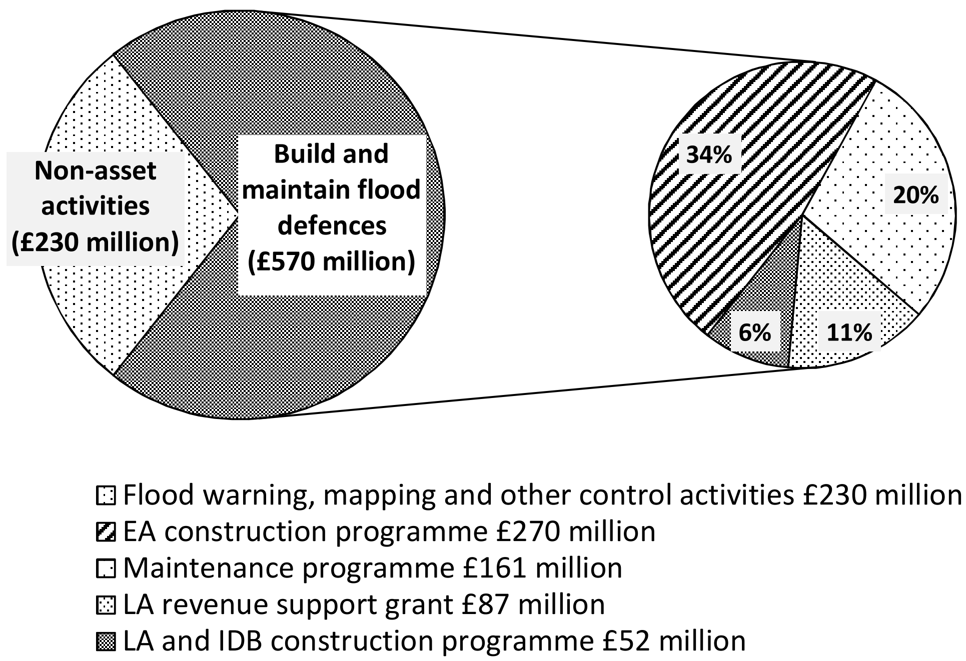


Figure 2-4 EA expenditure commitments for flood and coastal risk management 2010-2011 (adapted from Environment Agency 2009b).

In the future, climate change will be a major driver of coastal change in the short- and long-term, with flood and erosion risk expected to increase as a result of sea level rise and increased storminess (Hulme et al. 2002; Bindoff et al. 2007). The Intergovernmental Panel on Climate Change (IPCC) predicts that global sea level will increase by 15-95 cm by 2100 (IPCC 2007b), while greater regional increases are predicted in some areas of the UK associated with isostatic land movements (http://ukclimateprojections.defra.gov.uk, accessed June 2010). The EA recognises that river and coastal defence remains a primary tool for responding to the risks of flooding and erosion posed by climate change, and that investment for building and maintaining defences will need to double to more than £1 billion per year by 2035 to maintain current levels of protection (EA 2009a, b). This investment represents an increase of 80 % on 2010/11 spending.

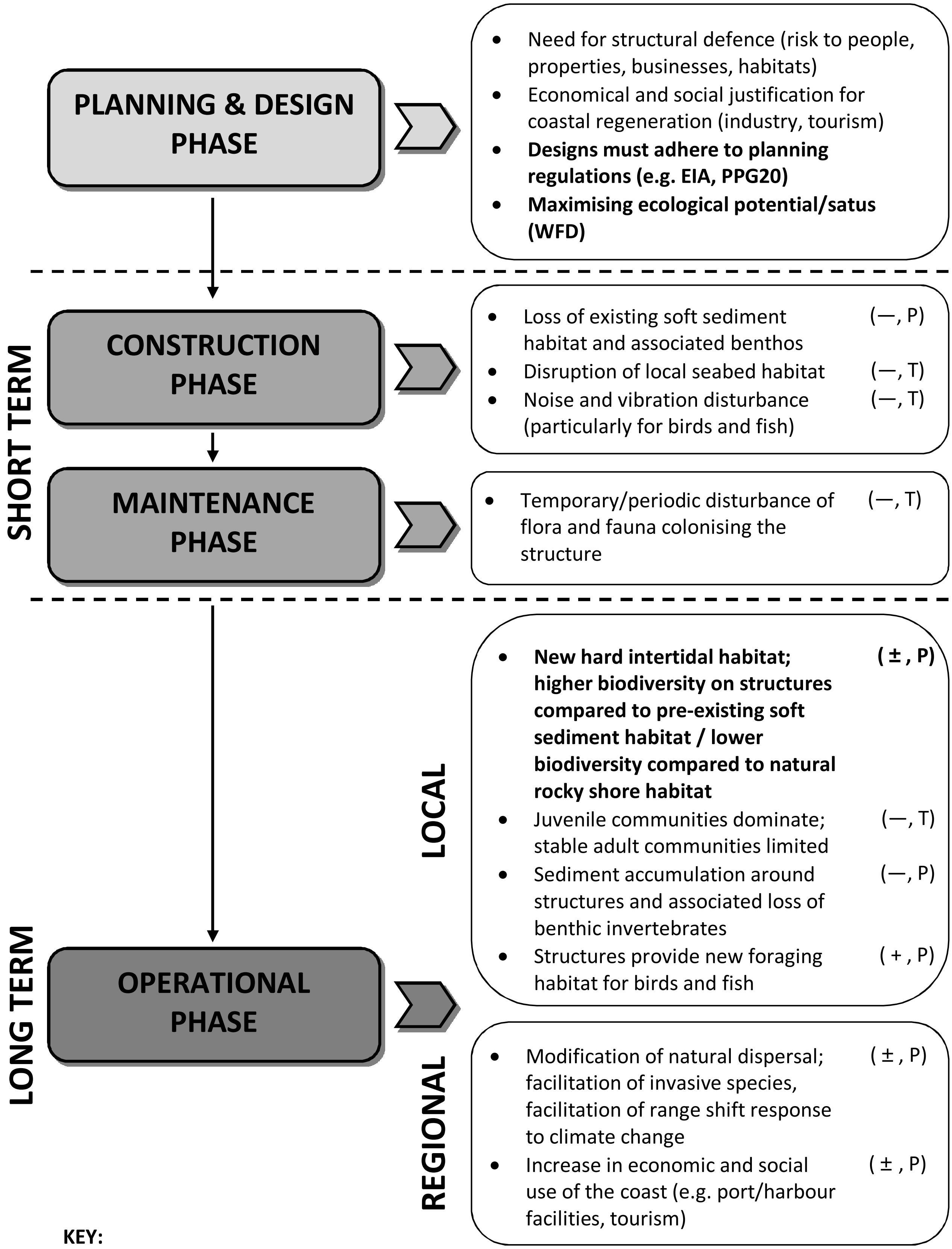
Over a longer time-scale, the Foresight Future Flooding report (Evans et al. 2004a, b; Evans et al. 2008) suggested that **between £22 billion and £75 billion of new engineering commitments will be needed by 2080 in England and Wales to manage increasing flood risk resulting from climate change**. These commitments represent a substantial increase in the extent of hard structures along UK coastlines in the future, which will come hand-in-hand with significant ecological pressures (Section 2.3).

2.3 Urban Marine Ecology: Structures as habitats

Population growth and related economic activities are associated with the physical disturbance and homogenisation of natural habitats (McKinney and Lockwood 1999). Urbanisation can lead to changes in ecological functioning, proliferation of invasive and 'weedier' species, loss of diversity and localised extinctions (Lockwood and McKinney 2001; Sax and Gaines 2003; McKinney 2006). These processes are widely recognised in terrestrial environments (e.g. Murphy 1988; McKinney 2002) yet coastal areas have received only recent attention in this context. Halpern et al. (2008), for example, do not include artificial structures in their review of human impacts on marine environments. Bulleri (2006) suggests that there is segregation between marine and urban ecology, and that a redistribution of research effort is needed towards understanding urban ecology at the coast. This concern is shared by others who recognise that existing ecological understanding and models developed for 'pristine' environments cannot necessarily be applied in significantly altered habitats, which may offer novel conditions for colonising organisms (Glasby and Connell 1999; DeLuca et al. 2008; Bulleri and Chapman 2010; Ivesa et al. 2010).

In response to these concerns, there has been a recent shift towards the study of urbanised coasts as ecological systems in their own right. This research is reviewed in the following two sections as a rationale for needing to improve understanding of biological interactions with hard structures and how to develop ways to improve ecological potential where they have to be built. Importantly, the environmental impacts of a structure will vary both in time and space, as conceptualised in Figure 2-5. Each phase of planning and design, construction, maintenance and operation of a structure has ecological consequences associated with it. These impacts may be positive (e.g. creation of new hard habitat) or negative (e.g. loss of existing habitat), and may be temporary effects (e.g. noise disturbance during construction) or permanent effects (e.g. change of substratum type, Figure 2-5).

All of these impacts may be considered as either 'direct' or 'indirect' consequences of the structure (Morris and Gibson 2007; OSPAR 2009; Marzinelli et al. 2009, Figure 2-5). Direct impacts are those which involve the structure itself, and therefore tend to occur at the local scale. For example, structures act as habitats in their own right, with organisms colonising their surfaces (a potentially positive impact, e.g. Chapman and Bulleri 2003); this is a direct ecological effect of the physical structure being there (see Section 2.3.1). Indirect impacts may be considered those which occur as a result of the structure being built, but which operate away from the immediate structure itself (see Section 2.3.2). For example, organisms that colonise structures may provide a food source for species living in adjacent waters (a positive effect, e.g. Boaventura et al. 2006; Clarke et al. 2008) or may alter water flow for other habitats in the lee of the structure (a potentially negative effect, e.g. Shalovenkov 2000).



KEY:
Direction of impact: negative (—), positive (+), both negative and positive (±)
Persistence of impact: temporary (T), prolonged (P)

Figure 2-5 Ecological considerations and impacts of coastal structures (aspects specifically related this thesis shown in bold), developed from OSPAR 2009.

2.3.1 Direct impacts of hard structures on coastal ecology

Hard structures built in the intertidal zone present novel substrata for colonising marine organisms (Glasby and Connell 1999). As these structures have become more common, ecologists in different parts of the world have begun to examine the communities that develop on them (see Table 2-4 for examples). Much of this work has involved the description of the organisms present, their abundance and the diversity of the community that the structure supports. A significant amount of this research has been done by dedicated departments within research institutions, particularly the Centre for Research on Ecological Impacts of Coastal Cities (EICC) at the University of Sydney (e.g. Connell and Glasby 1999; Glasby 2000; Connell 2001; Glasby and Connell 2001; Chapman 2003; Chapman and Bulleri 2003; Bulleri 2005a; Bulleri 2005b; Bulleri et al. 2005; Blockley and Chapman 2006; Chapman 2006; Moreira et al. 2007; Glasby et al. 2007; Clarke et al. 2008; Bulleri and Chapman 2010; Iveša et al. 2010). Urban marine ecology is also becoming a well established area of interest in Europe and the UK (e.g. Defra 2001; Bacchiocchi and Airoldi 2003; Bulleri and Chapman 2004; Bulleri and Airoldi 2005; Li et al. 2005; Martin et al. 2005; Moschella et al. 2005; Pinn et al. 2005a; Burcharth et al. 2007; Garcia et al. 2007; DeLuca et al. 2008; Vaselli et al. 2008; OSPAR 2009) and in other parts of the world (e.g. Davis et al. 2002; Hsing-Juh and Kwang-Tsao 2002; Pister 2009).

A review of this research shows that there is a general acceptance that hard structures built in the tidal zone for infrastructure and for flood and erosion control purposes do not act as surrogates for natural rocky shores, typically supporting lower diversity and abundance of species (Moschella et al. 2005; Bulleri and Chapman 2010). Although Chapman and Bulleri (2003) found that the same suite of species were present on vertical sandstone seawalls in Sydney Harbour compared to nearby sandstone reefs, the relative abundance of these species was different between the habitat types. Connell (2001) also found differences in colonising organisms on pilings and pontoon structures in Sydney compared to natural reefs, and suggested that floating pontoons should be regarded as a unique habitat type.

Table 2-4 Ecological studies of hard artificial coastal structures.

Type of structure	Location	Material type	Nature of study	Reference
Breakwater	Plymouth, Devon UK	Limestone / granite	Study examining influence of wave exposure on epibenthic communities	Southward and Orton 1954
Breakwaters and groynes	Emilia Romagna, Italy	Limestone	Examination of ecological communities at different positions of the structures, and colonisation after maintenance disturbance	Bacchiocchi and Airoldi 2003
Seawalls	Sydney Harbour, Australia	Sandstone	Development of epibiotic assemblages on seawalls and role of recruitment processes in generating differences compared to rocky shores	Bulleri 2005a 2005b
Breakwaters and seawalls (in marinas)	North-west coast, Italy	Marble / calcareous boulders	Comparison of community development and dynamics on structures compared to natural rocky shores	Bulleri and Chapman 2004
Low-crested structures	Various, Europe	Granite / limestone / concrete	Influence of broad-scale engineering design features and habitat complexity on epibenthic communities	Moschella et al. 2005
Seawalls	Sydney Harbour, Australia	Sandstone	Seawalls as novel habitats, and limitations to ecological value	Chapman 2003, 2006
Seawalls and wharves	Sydney Harbour, Australia	Sandstone	Effect of shading on seawall assemblages	Blockley and Chapman 2006; Blockley 2007
Riprap (rock rubble)	California, USA	Granite / sandstone	Influence of rock type on intertidal assemblages and community dynamics	Pister 2007
Groynes	Dorset, UK	Limestone	Influence of structure age and microhabitat (pools and open rock) on assemblage diversity	Pinn et al. 2005

In Europe, hard artificial structures are also regarded as relatively poor surrogates for unaltered rocky shores, with assemblages typically showing lower abundance and diversity (Moschella et al. 2005). In Italy, Bulleri and Chapman (2004) found different assemblages and abundance of organisms on seawalls and breakwaters compared to rocky shores. These differences were mainly due to variations in the amount of uncolonised bare space, with seawalls and 'natural' shores being most dissimilar. In a different study in Italy, Bacchiocchi and Airoldi (2003) found that the assemblages on rock groynes and breakwaters showed 'remarkably low diversity', which in this instance was attributed (in part) to the distance of the structures from potential source areas of new colonists (i.e. other rocky habitat). This suggests that structures built in areas without nearby rocky habitat will become dominated by a few species with large dispersal ranges (Airoldi et al. 2005). In Spain, Garcia et al. (2007), for example, found that the difference in species diversity between rocky shores and rock breakwaters was greater for structures located furthest away from unmodified shores.

2.3.2 Indirect impacts of hard structures on coastal ecology

While this study is specifically concerned with direct impacts of structures – that is to say the interactions (ecological and geomorphological) between the materials used to build the structures themselves and the organisms that colonise their surfaces (Section 2.3.1 above) – indirect impacts are given some attention here as they are important for contextualising the wider significance of the work.

Hard structures may act as physical barriers to natural ecological processes in several ways. Structures can alter water currents and movement of larvae along the coast for example (Burcharth et al. 2007). This may have negative implications by changing the source and sink dynamics of populations at a regional scale (Bulleri and Chapman 2010). On the other hand, colonisation of anthropogenic structures has been suggested to facilitate the spatial adaptation of species in response to climate change in a positive way, termed 'assisted colonization' by Hoegh-Guldberg et al. (2008). Assisted colonisation on coastal defence structures has been suggested as a mechanism by which barnacles may respond to increasing sea surface temperatures in the English Channel, for example (Herbert et al. 2007). Understanding how structures can be designed to facilitate colonisation may, therefore, offer some potential for enabling the adaptation and ultimately survival of epibiotic species in response to climate change and sea level rise (see detailed discussions in Chapter 8). This becomes particularly important where no other suitable habitat is available (e.g. Herbert et al. 2007). A limitation of this argument is that the natural adaptation of some coastal habitats to sea level rise, such as the rollback of gravel barriers or the landward migration of salt marshes, is prevented in many parts of the UK by the presence of hard defence structures. This itself will result in the loss of intertidal habitat through coastal squeeze (Rupp-Armstrong and Nicholls 2007; Hadley 2009).

Similar to the assisted colonisation concept, Glasby and Connell (1999) suggest a 'stepping-stone' mechanism may be important for connecting fragmented coastal populations. There is also, however, increasing recognition that artificial structures may facilitate the spread of invasive species in this way (Bulleri and Airoldi 2005; Glasby et al. 2007). Invasives are probably able to colonise structures efficiently due to the poorer environmental conditions offered compared to rocky shore habitats. This may allow invasive species to survive where local species cannot (Bulleri and Chapman 2010). Vaselli et al. (2008), for example, found that rock breakwaters along the coast of Italy have allowed the spread of the non-native algae *Caulerpa racemosa*, and Dafforn et al. (2009) found that floating pontoons promote the establishment of invasive invertebrates in Australia. Bulleri and Chapman (2010) also suggest that weaker competitive interactions on artificial structures – where species diversity is typically lower (Section 2.3.1 above) – may allow invaders to establish viable populations more easily.

2.3.3 Factors affecting ecological processes on artificial structures

Understanding the reasons why artificial structures and natural shores are ecologically different is a key aim of marine urban ecology (Bulleri 2006). This is necessary if effective ecological enhancement options are to be developed (Moschella et al. 2005; Burcharth et al. 2007; Bulleri and Chapman 2010). Some of these reasons are discussed in the following sections, at different spatial scales.

2.3.3.1 Large-scale design features (> m): structure type and position

Large-scale design features (> m) of coastal structures are important for ecology. Structure height, length and position within the tidal frame (Moschella et al. 2005), and the orientation of a structure (Glasby 2000; Glasby and Connell 2001) can influence the nature of the community that develops on it. Structures built lower on the shore, for example, are typically colonised by a greater range of organisms because more species are naturally found there (Hawkins and Jones 1992; CIRIA 2007; Burcharth et al. 2007). Orientation is linked to the influence of light and shading on epibenthic (surface) communities (Wethey 1984; Blockley and Chapman 2006) as well as wave and water flow dynamics around the structure (Moschella et al. 2005). Blockley (2007), for example, found that species assemblages were significantly different on vertical seawalls that were shaded by wharves compared to unshaded walls, and Vaselli et al. (2008) found that differences in species richness and abundance on inner and outer sides of rock breakwaters could be attributed, in part, to reduced water flow behind the structures.

For vertical structures (i.e. walls), an implicit factor in their design is that they are free-draining, holding much less water at low tide compared to horizontal surfaces. Water retention in pools is clearly linked to biodiversity on rocky shores (e.g. Martins et al. 2007) associated with physical stress amelioration (e.g. Therriault and Kolasa 2000, also see Chapter 8). The absence of these features on artificial structures will, therefore, place limitations on ecological potential (Chapman 2003, Chapter 9). The tidal range on vertical structures is also much less compared to horizontal and sloping shores. As well as offering less space for colonisation, this may also lead to crowding of species within a narrow intertidal band on vertical walls, leading to intensified competitive interactions between species and within populations (Bulleri and Chapman 2010).

2.3.3.2 Meso-large scale design features (> cm scale): habitat heterogeneity

Habitat heterogeneity is a foundation concept in ecology that predicts highly diverse communities in physically complex environments through the provision of habitat niches at a range of spatial scales (e.g. Gaston 2000; Tews et al. 2004). On rocky shores, these interactions are extremely important factors controlling the distribution of species and the operation of ecological processes (Dayton 1971; Menge and Olson 1990; Archambault and Bourget 1996; Johnson et al. 2003). The importance of environmental stresses (heat and desiccation) in rocky intertidal environments means that the cooler and wetter conditions offered by complexity elements (such as pools, overhangs and crevices) leads to a strong spatial association between these features and biological abundance (Menge and Sutherland 1987). On natural shores, geological and geomorphological processes operate to create habitat heterogeneity and structural complexity (see Section 2.6).

Associations between physical habitat complexity and reduced physiological stress can operate actively, through the behavioural response of mobile species (e.g. Helmuth and Hofmann 2001, see Chapter 8 for further discussions), or passively, as a result of enhanced survivorship of sessile species in favourable locations (e.g. Walters and Wethey 1996). Topographic features also provide refuge from waves on very exposed shores (Denny 1985; Todgham et al. 1997; Harley and Helmuth 2003) and from predation (Paine 1974; Johnson et al. 1998).

At the scale of whole structures (i.e. several metres), those which offer 3-dimensional complexity are likely to be more similar to rocky shores, which are typically more physically complex (Moschella et al. 2005). A rock rubble breakwater, for example, will provide more crevices, shaded areas, overhangs and pools for a greater range of species compared to a flat vertical seawall (Bulleri and Chapman 2004). The relative absence of these meso- to large-scale (cm – m) physical habitat features on artificial structures is suggested as a primary factor leading to differences in assemblages compared to rocky shores (Davis et al. 2002; Chapman 2003; Lam et al. 2009).

This was well demonstrated by Moreira et al. (2007), who found that crevices between sandstone blocks in seawalls were important for maintaining populations of chitons, while the flat surfaces of the blocks supported far fewer organisms. Barnacles, whelks and limpets were also shown to have similar spatial preferences for crevices (Moreira et al. 2007), although interestingly they were not effective for sustaining viable populations of limpets on the same walls (Moreira et al. 2006). Importantly, this suggests that refuge requirements may be species specific, having important implications for designing ecological enhancement features on artificial structures (see Section 2.5 below and Chapter 9); species that require particular scales of physical refuge for settlement, survival and/or reproduction must be expected to occur less frequently on artificial structures that lack physical complexity.

2.3.3.3 Small-scale design features (< cm): substratum texture and material type

At a finer scale (< cm), physical complexity equates to substratum surface morphology or roughness in geomorphic terms, and is an equally important control on intertidal ecology. Substratum roughness is widely known to influence initial settlement of marine invertebrate larvae (e.g. Pomerat and Weiss 1946; Barnes and Powell 1950; Crisp 1974) and the subsequent development of epibenthic communities (e.g. Anderson and Underwood 1994; Jacobi and Langevin 1996; Lapointe and Bourget 1999). A significant amount of experimental work has been done on common organisms, such as barnacles, which demonstrates the importance of substratum texture (e.g. Crisp and Barnes 1954; Hills and Thomason 1998; Berntsson et al. 2000; Skinner and Coutinho 2005, also see Chapter 5). Settlement and recruitment of barnacles is typically greater on rougher surfaces (e.g. Lapointe and Bourget 1999, but see below), and, for algae, both settlement of spores (Fletcher and Callow 1992; Johnson 1994) and removal by hydrodynamic forces varies with substratum roughness (Granhag et al. 2004). The grazing efficiency of molluscs is also affected by surface roughness (Wahl and Hoppe 2002). Walters and Wethey (1986) further suggest that subordinate species may gain competitive advantage over more dominant species on topographically complex substrata.

An important consideration of substratum heterogeneity is scale. Experiments using artificial materials (such as plastic tiles) with precisely manufactured textures at varying scales (µm – cm) have shown that the influences of texture on settlement and recruitment are complex (e.g. Bourget et al. 1994). Importantly, behavioural preferences for particular scales of texture may vary not only between different organisms, but between different species. Berntsson et al. (2000), for example, found that the barnacle *Balanus improvisus* actively rejected materials with micro-heterogeneity (with a topographic range of 30–45 µm), observing a 92 % reduction in settlement and recruitment compared to completely smooth surfaces. Lapointe and Bourget (1999) found that the presence or absence of 1 mm grooves had the greatest influence on developing epibenthic communities in North Carolina, USA. While influences of texture at this scale have received a lot of attention in experimental marine ecology, much more work is needed to test the effects of small-scale surface texture using the types of materials used in coastal engineering (Section 2.5).

Closely related to substratum heterogeneity is rock type. The development of benthic marine communities on different substrata has been given specific attention by ecologists, with some conflicting results (Table 2-5, also see Chapter 5 for further discussion of these studies). Moore and Kitching (1939) suggest that rock type has a strong influence on the distribution of barnacles (*Chthamalus stellatus*) on UK shores, while Caffey (1982) found no consistent effect of rock type on the recruitment and mortality of a different species (*Tessoropra rosea*) in Australia. Holmes et al. (1997) tested the response of another species of barnacle (*Semibalanus balanoides*) on 15 different rock types exposed on Scottish shores. They found differences between some rocks, but similarities between others. Raimondi (1988b) used a manipulative experiment to show that the settlement, recruitment and survival of *C. anisopoma* was different on basalt and granite shores in California, USA. Herbert and Hawkins (2006) also found differences in the settlement, recruitment and mortality of *C. montagui* on four different calcareous rocks in South East England.

Table 2-5 Example ecological studies examining the influence of substratum type on marine epibenthic communities.

Study reference	Substratum type	Location	Study species	Conclusion (influence attributed to rock type)
Caffey 1982	Shale / Sandstone / Mudstone / Gabbro	Southeast Australia	*Tessoropra rosea*	No differences in recruitment or mortality.
Raimondi 1988a, 1988b	Basalt / Granite	California, USA	*Chthamalus anisopoma*	Significant differences in settlement and recruitment.
McGuinness 1989	Coral limestone / Siltstone / Wood / Perspex / Concrete	Panama, Central America	Various (algae)	Significant differences in sessile assemblages (mainly algae).
Osborn 2005	Basalt / Sandstone / Granite / Slate	California, USA	*Chthamalus fissus* *Chthamalus dalli*	Significant differences between substrata, but variation between species and sites.
Anderson and Underwood 1994	Concrete / Plywood / Aluminium / Fibreglass	New South Wales, Australia	Various	Significant differences for both initial settlement of invertebrates, and species composition over longer time-scales.
Holmes et al. 1997	Slate / Quartz / Marble / Millstone grit sandstone / Granitic gneiss	Millport, Scotland	*Semibalanus balanoides*	Significant differences in settlement between substrata.
Herbert and Hawkins 2006	Limestone (Bembridge and Blue Lias) /Chalk / Kimmeridge cementstone /	South West England, UK	*Chthamalus montagui*	Significant differences in recruitment and mortality.
Pister 2007	Sandstone Granite	California, USA	Various	No effect on community diversity or composition. No difference in recruitment of barnacles.
Savoya and Schwindt 2010	Commercial tiles (‘hard’) / sandstone (‘soft’)	Patagonia, Argentina	*Balanus glandula*	Differences in recruitment and survival.

Differences in the communities found on materials used in coastal engineering have been specifically examined, although much less often. Osborn (2005), for example, found differences in the responses of barnacles (*C. fissus* and *C. dalli*) to materials used for coastal armouring in California, USA (basalt, sandstone, granite and slate), but there was little consistency between species. Interestingly, Osborn (2005) observed lowest settlement on slate, while Holmes et al. (1997) found this to be the most attractive substratum for *S. balanoides*. In contrast, Pister (2007, 2009) found no difference in communities on granite and sandstone rock rubble (riprap) in California (but see Section 2.3.3.4 below).

Because surface texture is particularly difficult to control for on natural rocks, differences attributed to 'rock type' include any differences which may have occurred as a function of surface texture alone (e.g. Herbert and Hawkins 2006). The distinction between rock *composition* (i.e. lithology) and surface texture (with 'rock type' often used as an all-encompassing term) is an important one (Chapter 5 and 6); while the two are inherently linked (Section 2.6.2), in a geomorphological sense 'rock type' distinguishes geological (mineralogical/chemical) properties, while 'surface texture' is a different, morphological parameter (see Chapter 4). Inherent geological properties of substrata (such as grain size) and weathering (geomorphic) behaviour will give rise to natural variations in texture between material 'types' (Section 2.6). McGuinness and Underwood (1986), for example, suggest that the coarser mineral grains of sandstone (0.1 – 2 mm) and finer grain sizes of shale (< 0.01 mm) may have influenced settlement of marine larvae on rocky shores and boulders in Sydney.

In reality, a combination of geological and textural properties probably influence colonisation of natural (i.e. rock) substrata in complex ways, even where it is stated that texture is controlled for in experiments (e.g. Savoya and Schwindt 2010). As McGuinness and Underwood (1986) suggest, it is probably impossible to attribute differences in ecological assemblages between rock types to composition independently from texture. Furthermore, substratum geology and surface texture may exert independent controls on the survival of epibiota by influencing warming and drying behaviour, which has consequences for heat and desiccation stress (see Section 2.6.2 and Chapter 8).

2.3.3.4 Time: structure age

The age of artificial structures, which have invariably been exposed to colonisation for less time than most undisturbed rocky shores, is probably a key factor contributing to the ecological differences between them. Although very few studies have specifically considered age in their experiments, Connell and Glasby (1999) attributed a high proportion of ecological variation between natural sandstone reefs and a range of harbour structures in Sydney to their age (including fibreglass pontoons, concrete pontoons, wooden pilings, concrete pilings and sandstone seawalls). Pinn et al. (2005a) examined assemblages on 10 limestone rock rubble groynes on Sandbanks Peninsular, Dorset, UK, ranging in age from 1 to 7 years. They found significant differences between groynes of different age, with a general increase in numbers of species on older structures. Butler and Connolly (1999) also found that assemblages on pilings in south Australia were still changing after 13 years.

Theoretically, older structures may become more ecologically similar to rocky shores through natural succession (Odum 1969; Osman 1977, see Section 9.4.2). Palmer-Zwahlen and Aseltine (1994), for example, observed the development of an algal turf community on a quarry rock structure (type unspecified) in California, USA, over a 5 year period. The community became more similar to mature reefs (again, unspecified material type) with time. Pister (2009) also attributed similarities in assemblages on riprap structures, built before 1950, and 'natural' shores in California to the length of time succession has been able to operate. In Europe, the DELOS Project (see Section 2.5.1) found some contrasting results of the effect of structure age on epibiota. Assemblages on structures less than 5 years old were significantly different from those on 5 – 10 year old and > 20 year old structures, while there was no difference between the younger structures and those aged 10 and 20 years (http://www.delos.unibo.it/, Deliverable 46, accessed March 2008).

The potential importance of natural weathering and erosion processes for generating ecologically favourable physical habitat complexity over time is specifically discussed in Section 2.6.2 below, and further explored in Chapter 9 based on experimental observations made during this project.

2.3.4 Artificial structures as habitats: conclusions

The alteration, fragmentation and loss of intertidal habitat specifically through the construction of hard sea defences is now widely recognised as a global-scale ecological problem, particularly given likely management responses to future climate change and increasing coastal risk (Thompson et al. 2002; Moschella et al. 2005; Bulleri 2006; Helmuth et al. 2006; Airoldi and Beck 2007; Burcharth et al. 2007; Hawkins et al. 2008; Hawkins et al. 2009; Coombes et al. 2009; Bulleri and Chapman 2010). The challenge, therefore, is to identify ways in which the environmental impacts of structures can be minimised wherever they have to be built (Burcharth et al. 2007). Correspondingly, considerable effort has been made recently to examine epibiotic communities on a range of artificial structures compared to undeveloped shores. This increasing body of work is demonstrating clear ecological differences, including the abundance and diversity of species which structures support as habitats in themselves (Section 2.3.1). Building hard structures can also have wider implications for local and regional ecology (Section 2.3.2).

Ecological differences between artificial structures and rocky shores have largely been attributed to large-scale design features (i.e. greater than a metre) like shore position, orientation and exposure, and meso-scale design features (i.e. cemtimetres to metres) like the presence/absence of pools, crevices and holes. These factors relate to the provision of refuge from environmental (heat and desiccation) and ecological (competition and predation) stresses which are known to drive ecological dynamics in the intertidal zone (Section 2.3.3.2). The heterogeneity of rocky substrata at a smaller scale (i.e. less than a centimetre) is also known to influence ecology, including the settlement and recruitment of larvae, but this scale of interaction has received much less attention in the context of artificial structures (see Section 2.5). Even less attention has been given to the influence of geomorphological behaviours and responses of hard substrata on epibiota. This is surprising given suggestions that substratum weathering and thermal properties may be important in the creation of favourable habitat (see Section 2.6).

2.4 Policy Drivers for Ecological Enhancement

Bulleri and Chapman (2010) suggest that one reason why urban structures have received less attention by ecologists is because they are not primarily designed to enhance or conserve biodiversity, unlike artificial reefs for example (Jensen 1997; Jensen et al. 2000), and that globally there is no general requirement to do so. In Europe however, there is a significant amount of policy concerned with the conservation of coastal landscapes, habitats and species (Coombes et al. 2009; Naylor et al. in preparation). These requirements mean that there is increasingly a need for engineers, coastal managers and regulatory authorities to consider the environmental impacts of coastal structures (e.g. Jensen et al. 1998; Fowler et al. 2001, 2002).

In the UK, there are various national and international (European) regulations and controls which have given specific attention to ecological considerations in coastal development. The European Water Framework Directive 2000/60/EC (WFD) specifically targets water bodies (including coasts) as a statutory conservation goal, and requirements implemented through the Government's planning system (Section 2.4.3) are outlined below in the context of artificial hard coastal structures.

2.4.1 The Water Framework Directive (WFD)

The WFD was established in 2000 as a strategy for sustainable planning, management, protection and improvement of European water resources (EU 2000). This legislation is particularly influential in a coastal defence context as it outlines specific requirements for modified water bodies, which includes defended coastlines (see below). As transposed into UK law, the Directive covers all inland waters (surface and groundwater) as well as transitional and coastal waters defined by a seaward line one nautical mile from low water (2000/60/EC). All estuaries, ports and harbours, nearshore, intertidal and some offshore waters are therefore included under the Directive.

An initial step for implementing the WFD was for the current ecological state of water bodies to be classified into one of five categories (high, good, moderate, poor and bad). This classification is being used to determine Programmes of Measures needed to achieve the target status, which for all UK water bodies is ‘good ecological status’ by 2015.

In significantly altered environments the system of classification is slightly different. Where the measures deemed necessary to achieve the target status would have significant negative impacts on the functioning of an altered water body, it may be designated under the Directive as ‘heavily modified’ or ‘artificial’. Importantly, Heavily Modified Water Bodies (HMWBs) include many ports, harbours and defended coastlines with respect to their navigation, flood protection and erosion control functions (2000/60/EC Article 4/3). Rather than ‘ecological status’, HMWBs are classified according to their ‘ecological potential’ (2000/60/EC Article 4/1). The target for UK HMWBs is for sufficient protection and enhancement measures to be in place to satisfy the requirements for ‘good ecological potential’ (UKTAG 2008a).

The first results of classification for England and Wales are currently being published by the EA in River Basin Management Plans (RBMPs, www.environment-agency.gov.uk/wfd, accessed June 2010). The Directive specifies a broad range of physical, chemical and biological indicators (‘assessment elements’) which are used in these classifications. Assessment elements specified for coastal HMWBs (2000/60/EC Annex V) which have the greatest potential for enhancement through engineering design (in a coastal context) include:

- The structure and substrate of the coastal bed and intertidal zone;
- Morphological conditions including depth variation and wave exposure;
- Water conditions (e.g. transparency, thermal and oxygenation conditions);
- Composition, abundance and biomass of phytoplankton, benthic invertebrates and other aquatic flora.

The UK Technical Advisory Group (UKTAG) for the implementation of the WFD has published additional guidance on what constitutes 'good ecological potential' for HMWBs (UKTAG 2008b). This includes a range of perceived environment pressures and suggested mitigation measures. Example pressures and mitigation measures relevant to existing hard coastal structures are listed in Table 2-6. More detailed guidelines on mitigation are being developed by the EA in a 'Mitigation Measures Manual' (http://evidence.environment-agency.gov.uk/FCERM/en/SC06006.aspx, accessed July 2010), within which 'modifying or enhancing' structures for ecological gain is specified – but currently limited. Importantly, this guidance recognises that certain mitigation measures will not be appropriate where they are too costly, offer only relatively minor ecological gains, or when such measures would compromise the primary function of the modified water body. For coastal defences, which cannot be compromised in function, ecological enhancement measures that can be incorporated at a design stage while having negligible impacts on performance are therefore of particular interest.

Where it can be demonstrated that all feasible measures have been taken to enhance the relevant assessment indicators (above) and mitigate adverse environmental pressures (Table 2-6), coastal defence structures should achieve the required standards of 'good ecological potential' (2000/60/EC Article 4/5; NIEA 2008; UKTAG 2008a, b; Defra 2008b). Requirements set by the WFD mean that both existing coastal structures, and those which will need to be built in the future (see Section 2.2.2.2), must be designed to maximise ecological potential and equally importantly must not lead to degradation of the existing habitat. The need to improve understanding of structure-ecology interactions as a tool for developing ways to achieve these targets should be seen as a significant driver of urban marine ecology research in the UK and the rest of Europe (Bolton et al. 2009; Coombes et al. 2009; Naylor et al. in preparation).

Table 2-6 Example environmental pressures and mitigation measures for HMWBs relevant to existing artificial coastal structures.

Pressure	Impact	Suggested Mitigation
Ports and Harbours (structures, reclamation, dredging)	• Changes in flows • Changes in sediment transport • Changes in wave energy and direction • Changes in water quality • Habitat loss and disruption of habitat continuity or connectivity	• Remove obsolete structures • Modify structure (e.g. reduce wave reflection, increase wave absorption, replace with 'environmentally friendly' materials or design) • Flow manipulation (e.g. structures to normalise flow, realign frontage) • Sediment management (e.g. trickle recharge, sediment bypass, water column recharge, beneficial placement)
Inland Navigation (hard bank protection e.g. vertical walls)	• Loss of riparian zone and marginal habitat • Loss of connectivity (sediment and flow) • Wave energy absorption.	• Remove hard bank, or replacement with soft engineering solution • Preserve and where possible enhance ecological value of marginal aquatic habitat, banks and riparian zone • Preserve/restore historic aquatic habitats
Flood Risk Management (shoreline reinforcement/ elevation)	• Coastal squeeze • Disruption of estuarine and sediment dynamics and habitats • Loss of faunal refuge and feeding areas.	• Modify existing structures • Replace with soft engineering solutions • Bank reprofiling • Managed realignment • Restore/create/enhance habitats • Indirect/offsite mitigation (offsetting)

Source: Modified from UKTAG 2008a, Annex IV

2.4.2 Other environmental legislation

Alongside the WFD, sites designated under the Habitats Directive (1992/43/EC) and Birds Directive (1979/409/EC, see Table 2-2) have additional protection requirements (see review by Fowler et al. 2002) which have implications for coastal defence (Lee 2001). The WFD classification framework of 'ecological status' and 'ecological potential' (for HMWBs) should equate to favourable conservation status specified under these other directives, as well as targets set for other nationally designated sites such as SSSIs. Where there is a mismatch between different pieces of legislation, a lower WFD classification status may be set with sufficient justification (UKTAG 2008a).

The soon to be implemented Marine and Coastal Access Bill (www.defra.gov.uk/marine/legislation, accessed June 2010) also aims to strengthen the UK's commitment to various other national, European and international maritime legislation. Aims of the 'Marine Bill' include promoting sustainable development of ports and the protection and enhancement of marine-based businesses and communities. With this will come additional requirements for nature conservation and biological diversity, and is therefore an additional driver for research of ecological enhancement options for coastal structures.

2.4.3 Planning regulations

2.4.3.1 UK guidance

Within the UK planning system, there are several tools and regulations that stipulate ecological considerations in new developments, including at the coast (Defra 2009b; Naylor et al. in preparation). These must be met if the necessary planning permissions and licences are to be obtained for any defence scheme (Burcharth et al. 2007). The Department of Communities and Local Government (DCLG) provides guidance on statutory planning provisions for LAs through Planning Policy Statements (PPSs) and the former Planning Policy Guidance Notes (PPGs). Key documents include 'PPS25: Development and Flood Risk' (DCLG 2010), along with the Supplement on coastal change, which advocate minimising risk in flood and erosion prone areas. Ecological considerations are specifically addressed in 'PPS9: Biodiversity and Geological Conservation' (DCLG 2005), which states that any new development should be refused permissions where significant environmental harm cannot be prevented, adequately mitigated against, or compensated for. Biodiversity enhancement in new developments is also required under PPS9 wherever possible, and is considered on a case-by-case basis. 'PPG20: Coastal Planning' also provides additional impetus for ecological consideration in the coastal zone.

2.4.3.2 European guidance

At a European level, the Strategic Environmental Assessment (SEA) Directive (2001/42/EC) and Environmental Impact Assessment (EIA) Directive (85/337/EEC and 97/11/EEC) outline a tiered process of impact assessment for new developments, including in coastal areas. SEAs and EIAs are undertaken to predict all environmental consequences of developments before any construction commences, as a preventative strategy based on alternative approaches (Wood 2003). SEAs are required in addition to EIAs where the potential environmental impact of a development is deemed to be significant. As part of this process, developers are required to outline measures to prevent or reduce adverse environmental effects (Article 5-3). Mitigation measures could include limiting or reducing the degree, extent, magnitude or duration of adverse impacts (Sheate et al. 2005; Defra 2009b). SMPs, Water Level Management Plans (WLMPs) and Coastal Habitat Management Plans (CHaMPs) will also typically need to be fully considered within EIAs and SEAs. Sustainability Appraisals (SAs) are similar assessments of impact, having a stronger focus on social and economic appraisal (Burcharth et al. 2007).

A further, and considerable, impetus for fully incorporating environmental considerations in planning is the Environmental Liability Directive (ELD, 2004/35/EC). This Directive is primarily concerned with limiting damage to those habitats and species protected under EU legislation (see Table 2-2). The ELD specifies that mitigation must be taken against any effects which adversely affect these designations reaching or maintaining favourable conservation status (Article 2-1), and places financial liability on operators where this is not undertaken.

From this review it is clear that research aiming to understand and develop options for maximising the ecological potential of coastal structures (Section 2.5 below) is of interest not only for biodiversity conservation, but also as a tool for developers, Local Authorities and engineers to meet stringent legal requirements that must be adhered to through the planning process, at both a National and European level.

2.5 Maximising Ecological Potential: Current understandsing and testing

2.5.1 Existing guidance and applied testing

Encouragingly, the work discussed in Section 2.3 and additional policy drivers outlined in Section 2.4 has led to dedicated research projects on the topic of ecological enhancement of coastal structures. In 2001, a feasibility study on options for enhancing marine habitats within coastal structures was produced by Defra in association with Halcrow Maritime (Defra 2001). The focus of this research was on enhancements for macrobiota, and followed a similar vein to existing research on offshore artificial reefs (e.g. Jensen et al. 2000). This work was later followed up in a publication in Marine Engineering (Li et al. 2005) which suggested maximising habitat heterogeneity of rock rubble structures by introducing spaces between boulders primarily for enhancing lobster populations. Maximising habitat complexity is also the main recommendation of a study by the Construction Industry Research and Information Association (CIRIA) on the design of multi-function artificial reefs and offshore breakwaters (CIRIA 2008). The 'Manual on the Use of Rock in Hydraulic Engineering', also produced by CIRIA (2007), provides more detailed considerations of design enhancements for ecology (Table 2-7), although the discussion is limited to 1 page in the 1267 page guide.

In 2002, the Canadian Wildlife Service published guidance on the environmental design of shoreline structures, with specific focus on estuaries and large rivers (Adams 2002). Again, this guidance suggests larger-scale (and largely indirect, Section 2.3.2) features of structures which could be used to improve ecological potential and reduce environmental impact. Recommendations include minimising the footprint of structures, designing structures to limit impact on water flow and sediment movement, and using a mix of material sizes in rubble structures to create interstitial spaces for organisms.

Table 2-7 Opportunities for environmental enhancements as specified in 'The Rock Manual'.

Consideration	Enhancement opportunity
Location	Aim to reproduce the structure where rocky habitat is already present. Structures lower in the tidal frame will increase opportunities for fisheries enhancement.
Crevices	Include crevices; increasing heterogeneity will enhance biodiversity.
Materials	Use a mix of rock types.
Roughness	Create a structure that has rough surfaces rather than smooth and symmetrical.
Consult end-users	Conservation groups, academics, ecologists, fisheries organisations and the public should be consulted if enhancement is considered.
Promote	Taking care to design a structure that will blend into the landscape as this will be more popular than one that visually conflicts.
Be realistic	No project will be able to do everything. Take a long-term view to enhancement.
Monitor	Demonstrating the benefits of enhancement requires monitoring. This may require professional surveys, or get local conservation groups/schools involved.

Source: CIRIA 2007 p55, based on Jensen et al. 1998

The most substantial piece of work on ecological enhancement of structures in Europe was the 'Environmental Design of Low-Crested Coastal Defence Structures' (DELOS) project, which ran as an international collaboration between 1998 and 2002 (http://www.delos.unibo.it/, accessed June 2010). Alongside wider considerations such as impacts during construction, DELOS assessed the ecological influence of broad-scale design features on existing defence structures, including structure height, length, shore position and material type (Burcharth et al. 2007, see Section 2.3.3.1).

DELOS recommendations for maintaining biodiversity on breakwaters (Deliverable D46) are shown in Table 2-8. Key factors noted are the importance of habitat heterogeneity (from the scale of whole structures to the scale of material surface texture), the ability of water to pond at low tide and the influence of the age of the structure on assemblages (Moschella et al. 2005, see Section 2.3.3.4). Importantly, the DELOS study concluded that there is 'very high' potential for influencing ecological communities by manipulating the surface complexity of construction materials; the role of geomorphological processes in the generation of habitat complexity, however, was given only passing consideration (Burcharth et al. 2007).

Table 2-8 Design features to maintain epibiota on low-crested defence structures: DELOS Deliverable 46.

1	Building structures lower on the shore will increase biodiversity, and more species can colonise below MTL.
2	Building material has no effect on epibiota on British shores, but assemblages are more variable on limestone, and little effect on other European shores (Italy), with the main differences occurring in early colonisation of biofilm.
3	Diversity is greater on complex surfaces compared to smooth, this having a greater influence on horizontal surfaces.
4	'Maturation' of structures takes at least 5 years, so maintenance should be minimised. Younger structures (<3 years) were significantly different from older (>8 years) structures.
5	The presence of rock pools significantly increases the biodiversity value at the coast.

Source: http://www.delos.unibo.it/, accessed June 2010.

Perhaps more important than these initial reports and guidance, which are largely limited to broad-scale recommendations for enhancement, are attempts to experimentally test enhancement measures *in situ*. Known examples of this are summarised in Table 2-9. An experiment undertaken at Elmer, Sussex, UK, as part of DELOS involved the use of concrete panels to asses the effect of artificial meso-scale (< 10 cm) habitat complexity (Moschella et al. 2005). This is one of very few experiments that have examined colonisation on manipulated concrete. In the experiment, smooth panels (representing surfaces of 'plain-cast' concrete armour units, see Chapter 4) and panels with holes cast in the surface (15 mm and 30 mm diameter, 20 mm depth) were fixed at Mean Tide Level (MTL) to the surfaces of rock rubble breakwaters for one year. At the end of the experiment, the panels with holes had more than twice the number of species than the smooth panels (Moschella et al. 2005). The same workers also found that, on average, twice the number of species were associated with pools (> 10 cm) which formed within rubble structures compared to free-draining areas of rock. The potential to manipulate surface complexity at smaller scales (< cm) was not tested.

Table 2-9 Global examples of applied testing of ecological enhancement measures for hard coastal structures.

Study	Year	Location	Type of structure	Nature of enhancement	Outcomes	Reference
Environmental Design of Low Crested Structures (DELOS)	2005	Elmer, Sussex, UK	Rock rubble breakwater	Concrete panels with smooth surfaces and with holes (15 mm and 30 mm diameter, 20 mm depth) attached to rock rubble and monitored for 1 year. The effect of pools forming within the structure was also examined.	Holes increased diversity of species two-fold compared to smooth panels. Species diversity was on average twice as high in pools compared to free-draining areas of the structure.	**Moschella et al. 2005** **Project website:** www.delos.unibo.it/
Integrating intertidal habitat into seawalls	2008 – current	Seattle, Washington, USA	Vertical concrete walls.	Large (7' x 5') pre-cast concrete 'habitat panels' with smooth and rough ('false cobbled') surface bolted to existing seawall. Panels attached (i) vertically (ii) horizontal as shelves and (iii) finned (i.e. sloping shelves). Troughs (i.e. pools) containing sediment attached to promote salmon spawning.	Different organisms showed different responses after in Year 1 e.g. mussels prefer cobbled compared to smooth. Panels do not yet support as many species as reference (control) areas of the old seawall. Monitoring is on-going.	**Simenstad 2009** **M. Goff**, personal communication, February 2010 **Project website:** https://sites.google.com/a/uw.edu/seattle-seawall-project/design
Colonisation of wave energy foundations	2009	Lysekil, Sweden	Concrete foundations for wave energy devices	Rectangular holes (12 cm width x 15 cm height x 30 cm depth) cast in subtidal concrete test units.	Fish and crab abundance was significantly higher in association with units with holes compared to those without holes.	**Langhamer and Wilhelmsson 2009**

Urban Research on Biodiversity of on Artificial and Natural Coastal Environments	2008 / on-going	Various, United Kingdom	Rock rubble structures, disused docks	Three-year research project aiming to better understand the ecology of artificial urban coastal habitats so as to promote biodiversity and minimise impacts.	Use of 'BIOBLOCS' to increase meso-scale (cm-m) habitat complexity in rock rubble defence structures. Monitoring is on-going.	**Project website:** http://urbaneproject.org/
Engineering novel habitats on urban infrastructure	2009 / on-going	Sydney Harbour, Australia	Vertical concrete seawall with sandstone block façade	Creation of cavities (60 cm x 30 cm x 30 cm) and artificial pools in stone facing. Water retained at low tide by way of a stone lip at the front of the recess, thereby offering cooler and wetter microhabitat.	Invertebrate species richness was increased after one year. Barnacles, tube worms, ascidians, bryozoans and sponges were greater in numbers, particularly in pools higher on the walls. Pools do not yet support the full suite of species present on natural rocky habitats, particularly larger mobile species; recruitment of these species is likely to take longer.	**Chapman and Blockley 2009** **Project website:** http://eicc.bio.usyd.edu.au/research/anthropogenic_disturbances/urban_structures/index.shtml
Enhancing stocks of exploited limpets by modifying seawalls	2010	Azores, Portugal	Vertical basalt seawall	Small (12 mm) and medium (24 mm) holes drilled into the seawall to test potential for enhancing numbers of an exploited limpet (*Patella candei*). Holes were designed to mimic naturally occurring refuge sites commonly found on adjacent basaltic rocky shores.	Numbers of limpets were significantly higher in association with holes compared to control areas of the wall. The holes enhanced migration of adults and recruitment of juveniles to the wall.	**Martins et al. 2010**

In a similar vein, Martins et al. (2010) drilled small (12 mm diameter) and large (24 mm diameter) pits (both 10 mm depth) into a smooth basalt seawall in the Azores, Portugal, after observing that the exploited limpet *Patella candei* was commonly associated with similar features on adjacent, volcanic rocky shores. Limpets aggregated where pits were introduced with, on average, a five-fold increase in abundance compared to control areas of the wall. Results were attributed to immigration of adult limpets and enhanced recruitment of juveniles in association with the pits. Adding holes to engineered structures at this scale has also been shown to create ecological benefits sub-tidally, increasing fish and crab abundance and diversity associated with concrete foundations of wave energy devices (Langhamer and Wilhelmsson 2009).

In Seattle, Washington, USA, an experiment is being undertaken to examine the potential for enhancing the ecological value of vertical seawalls using artificial habitat (Simenstad 2009; Goff 2010). This study has involved the deployment of large (7 feet x 5 feet) concrete panels with smooth and rough ('false cobble' texture) surfaces on seawalls along Seattle waterfront. Both vertical (flat against the wall), horizontal (jutting out of the wall like shelves) and finned panels (sloping shelves) have been attached. Preliminary results showed that panels did not support the same diversity of species present on the existing seawall (after one year), that there were differences in epibiota between the treatment types, and that responses were largely species specific. Crevices on the cobbled panels, for example, attracted more mussels, while sloping (finned) surfaces facilitated the recruitment of species known to be important for the availability of food for juvenile Pacific Salmon (Goff 2010).

Most of the above studies have involved retrospective modification of structures, such as drilling holes or attaching artificial habitat to existing structures once built. The advantage of this approach is that sections of original, unmodified structure provide a direct control against which the influence of the enhancement can be compared; this is essential if the value of these types of enhancements is to be clearly demonstrated (also see Chapter 9). Retrospective modifications are also more common because an initial period of observation of the original structure typically precedes any notion that it is having adverse effects on ecology in the first place (e.g. Chapman 2003).

The alternative approach, which involves designing structures with ecological enhancements from the outset, is more challenging as it requires considerable collaboration with engineers and coastal managers, and is a relatively expensive/labour intensive way of testing possible enhancement options (Naylor et al. in preparation). Such an approach follows the concept of 'ecological engineering' (different from 'ecosystem engineering', see Chapter 3), which involves the design of infrastructure to mimic natural habitat and/or minimise environmental impact as far as is technically possible (e.g. Mitsch 1996; Bergen et al. 2001).

The extensive amount of background research in Sydney Harbour undertaken by the EICC group has allowed an ecological engineering approach to be adopted during the replacement a section of vertical seawall (Chapman and Blockley 2009). Artificial tide pools were incorporated into the structure by leaving out sandstone blocks used to face a concrete foundation wall, and inserting a stone 'lip' to retain water at low tide. This created 60 cm x 30 cm x 30 cm cavities designed to provide refuge from heat and desiccation on walls previously shown to lack the diversity of species present on nearby rocky substrata (Chapman 2003; Chapman and Bulleri 2003). After one year, the artificial pools had increased the number of algae and animal species. The artificial pools had the greatest effect on sessile organisms (including barnacles, tube worms, ascidians, bryozoans and sponges) where they were placed higher on the wall, probably attributable to the relative importance of stress (desiccation and heat) amelioration here compared to lower on the walls (Chapman and Blockley 2009).

What all of these applied studies clearly demonstrate is that there is significant potential to influence epibenthic marine ecology through manipulation of engineered structures at a meso-scale (cm's and above). In comparison, the possibilities of smaller-scale manipulation (< cm) remain largely unexplored (Section 2.6 and 2.7 below).

2.5.2 Ecological enhancement and engineering durability

Since the late 1990s, coastal engineers and developers have been required to include environmental considerations in the design of coastal structures (e.g. Jensen et al. 1998; Morris and Gibson 2007, see Section 2.4). The implications of environmental conservation policy for marine engineering have been discussed by Fowler et al. (2002), and specifically in the context of the WFD by Bolton et al. (2009). Although limited, progress in this area is demonstrated by the inclusion of discussions of broad-scale opportunities for ecological enhancement in key pieces of engineering guidance (e.g. CIRIA 2007). There has also been increasing collaboration between engineers and ecologists in the design of structures (see Section 2.5.1 above).

There are, however, two main uncertainties surrounding environmental enhancement within applied engineering science. First, Morris (2011) suggests that there is a general concern in industry that restrictions placed on construction to meet the EU Habitats Directive, for example, are too stringent and have placed the UK at a disadvantage to the rest of Europe. Morris suggests, however, that this has largely been a product of the UK implementing European policy more quickly than other countries, and because of the form in which it has been transposed into UK law. As well as meeting policy requirements, other advantages to engineers of giving full environmental consideration in new schemes include increasing the likelihood that a scheme will be accepted by regulatory authorities such the EA and hence the speed construction can begin, and for gaining public bye-in (CIRIA 2007, see Section 9.8.5).

Secondly, biological activity is generally regarded in coastal engineering as a deteriorative agent, having negative implications for 'durability'. Durability is defined in engineering as the ability of a material to continue to perform adequately in a specific environment, as a function of the intrinsic resistance of the material and the aggressiveness of the forces acting upon it whilst in service (CIRIA 2007). In geomorphology, the durability of rock and stone is typically discussed in relation to weathering behaviour, where the importance of the conditions in which the material is exposed is also a key consideration (Inkpen et al. 2000, Chapter 7: Strand 2). Engineers recognise the importance of rock weathering in durability (Fookes et al. 1988; Fookes et al. 2005), although this is only expected to be a concern after 50 – 100 years of service life in marine environments (CIRIA 2007). Weathering behaviours of rock aggregates have also been given specific attention in relation to concrete durability (Fookes 1980).

The involvement of biology in weathering and changes in the durability of construction materials is somewhat ambiguous, at least in the marine environment. 'Biological attack', 'biofouling', and 'biodeterioration' are terms that can be found in marine engineering books and guidelines (e.g. Bijen 2003). This has mainly been in the context of macro-organism colonisation of wooden structures (e.g. Cragg et al. 1999; Oevering et al. 2001) and metal components (i.e. 'biocorrosion', e.g. Chambers et al. 2006) but also in reference to concrete and mortar (e.g. Illston and Domone 2001; CIRIA 2010) and rock (e.g. Scott et al. 1988). The involvement of marine microorganisms in the breakdown of rock and stone used in engineering has been specifically termed 'microbiologically induced deterioration' (MID, Ortega-Morales et al. 2010). While biological attack is not assumed to be a major concern for most hard marine structures, actively encouraging colonisation may be somewhat counterintuitive for engineers (W. Allsop personal communication, December 2007).

The importance of weathering in the tidal zone for engineering durability has more recently been suggested in the context of climate change, particularly with respect to concrete (e.g. Australian Government 2009). Increases in temperature, humidity, atmospheric CO_2 concentrations and seawater splash have been shown to accelerate the degradation of concrete. Peng and Stewart (2008), for example, recorded a 720 % increase in the probably of concrete corrosion under a 'worst case' climate scenario. Whilst this emerging research suggests that the importance of weathering processes in civil engineering may increase with climate change, the biological contributions in this context have not been evaluated.

In the context of terrestrial building stone, Viles (2002), Smith et al. (2004) and more recently Smith et al (in press-a) have suggested that the involvement of biota in weathering may increase under warmer and wetter climatic conditions. These concepts are difficult to apply to engineered structures in the intertidal zone, however, because of the presence of seawater and the relative (current) aggressiveness (in durability terms) of tidal environments irrespective of any significant future changes in climate (see detailed discussion in Chapter 8). Given these uncertainties, there is a requirement to consider engineering (durability) consequences of growth on structures, if only to demonstrate that this will have limited or no influence on durability. These kinds of assessments need to be done at scale relevant to engineers (a 'bulk' scale), using familiar parameters like material strength and hardness.

2.6 Geomorphology and Coastal Structures

2.6.1 The current role of geomorphology in the design of coastal structures

Geomorphology has, necessarily, become engrained in the principles of coastal management over the last 20 years or so (Evans 1992; Hooke 1999). The involvement of geomorphologists in current management responses to coasts has become commonplace, as advocated at a national level (such as in the production of SMPs) and international level (e.g. EC 2002). Geomorphic knowledge of sediment supply, transport and deposition, beach erosion, coastal hazards and vulnerability, and shoreline evolution have all proved valuable tools in ICZM (e.g. Hooke et al. 1996; Pethick and Crooks 2000; Pethick 2001; Crooks 2004).

The application of geomorphological understanding in coastal engineering has also been widely advocated, particularly with respect to hazards (Brunsden 2002; Fookes et al. 2005; Trenhaile 2009; Naylor et al. 2010). For the design of coastal structures, geomorphological understanding has been applied to large- and meso-scale problems (> m). This includes the influence of structures on water flow, alongshore movement of sediment and the effects this has on sediment supply further down the coast (e.g. Clayton 1989). Scour and beach lowering in front of structures such as seawalls has also been given significant attention as a particular engineering problem (e.g. Miles et al. 2001; Pearce et al. 2007).

In contrast, the value of applying geomorphic knowledge to understand interactions between hard substrata and colonising organisms remains largely unexplored. Section 2.6.2 below outlines two areas of geomorphology (rock coast geomorphology and weathering science) that are focussed on the inherent properties and behaviours of hard materials. Within these sub-disciples, specific attention has been given to the interactions between rocks and the organisms that colonise them (i.e. 'biogeomorphology', see Chapter 3). The value of considering artificial coastal structures in this way for (a) advancing geomorphic and ecological theory and understanding, and (b) contributing to discussions of enhancement of marine urban structures is outlined as the over-arching aim of this thesis.

2.6.2 Rock coast geomorphology and weathering science in urban marine ecology

The majority of work examining the influence of coastal urban structures on colonising epibiota has necessarily been ecologically focussed. This research (reviewed above) has shown that there are differences in early colonisation processes (settlement and recruitment) on various natural and artificial material types used in construction, and that the abundance and diversity of the assemblages that they support as biological substrata can also be different. The role of intrinsic material properties in causing these differences has, however, largely been inferred rather than explored in detail. The exception to this is surface texture (see Section 2.3.3.3), although focus here has been on the initial texture of materials rather than the mechanisms involved in development of texture through time.

In geomorphology, the physical properties of rock are of primary importance (Yatsu 1966). Rock coasts are predominantly erosional landforms (Trenhaile 1987), so that rock coast geomorphology is concerned with the processes acting to shape coastal landforms at all scales, their rates and their operation over evolutionary time (Naylor et al. 2010). Correspondingly, the influence of geology and rock type has been examined in a rock coast context because they are important controls on the susceptibility of materials to change through weathering and erosion (e.g. Moses 2001; Thornton and Stephenson 2006). Rock control theory, for example, which is concerned with the influences of rock composition and structure in geomorphology (Yatsu 1966; Sunamura 1992, 1994), has been increasingly applied to rock coasts (Naylor and Stephenson 2010; Kennedy 2010). The role of biology in modifying the process that rock coast geomorphologists are interested in has also been increasingly recognised (e.g. Spencer 1988a; Stephenson and Kirk 2000b; Naylor 2001).

Weathering science is also concerned with the processes, dynamics and controls of material breakdown (predominantly rock and stone) in a range of environmental settings (e.g. Yatsu 1988; Robinson and Williams 1994). In the intertidal zone, salt weathering (e.g. Robinson and Jerwood 1986; Tingstad 2008), wetting and drying (or 'slaking', e.g. Kanyaya and Trenhaile 2005; Trenhaile 2006) and thermal expansion and contraction (e.g. Gómez-Pujol et al. 2007) have been given specific attention as mechanical weathering processes. The importance of rock type and geomechanical properties (such as hardness, porosity and thermal capacity) are also therefore of interest to weathering scientists because they determine wetting-drying, warming-cooling behaviour and hence their susceptibility to these processes (e.g. McGreevy 1985b; Goudie 1999; Begonha and Sequeira Brago 2002; Aoki and Matsukura 2007a, see Chapter 8). Biological weathering is further recognised as a highly important process in the intertidal zone, where growth may be relatively abundant (see Chapter 7: Strand 1 for specific discussions of biological contributions to coastal geomorphology).

Figure 2-6 shows some preliminary conceptual links between lithology (mineral composition), geomorphology (morphology and physical behaviour) and the ecological study of hard materials as biological substrata in the coastal zone. Two main interactions and feedbacks are identified: (1) associations between morphology occurring as a result of weathering and erosion of the substratum, and the consequential generation of physical habitat complexity, and; (2) the potential influence of substratum physical properties (warming-drying behaviour) on environmental stress (heat and desiccation). Each of these interactions is introduced in turn below. In addition, the consequences of these interactions for geomorphology and engineering durability are also considered within a framework of biogeomorphology (see Chapter 3).

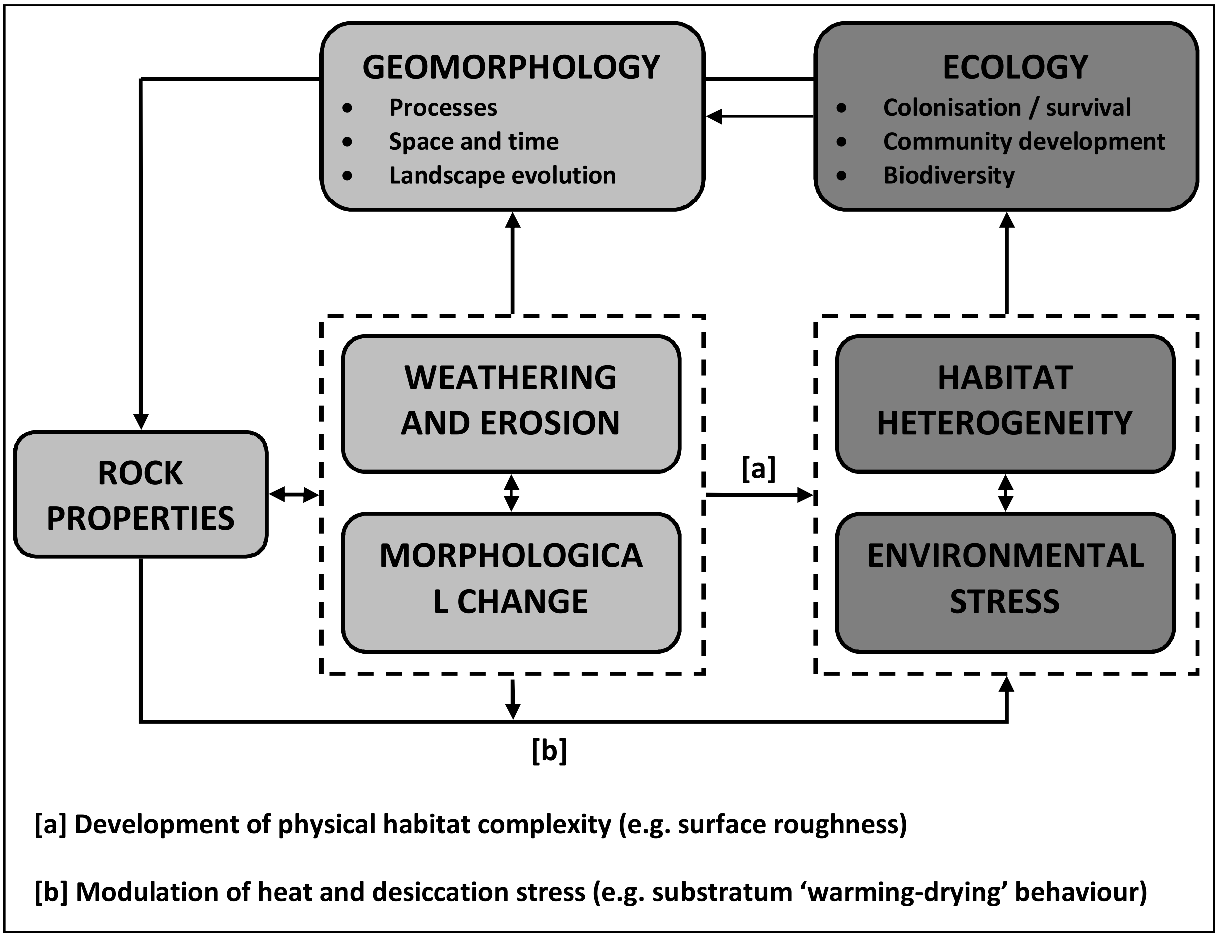


Figure 2-6 Substratum-geomorphic influences on intertidal benthic ecology given specific attention in this thesis.

2.6.2.1 Weathering and erosion and habitat complexity

Weathering and erosion of rocky shores has bearing on ecology through the creation of habitat heterogeneity, at a range of spatial and temporal scales (Archambault and Bourget 1996). Physical, chemical and biological weathering and erosion process (see below) act to modify hard coasts through time; the potential importance of these processes will depend largely on material type (lithology) and the conditions under which they are exposed (Trenhaile 2002; Anthony 2008).

Alongside large-scale events (> m) like block removal, which are probably geologically controlled (e.g. Naylor and Stephenson 2010), weathering produces physical (i.e. geomorphic) complexity at a micro-small scale (< µm – cm) at the surface of rocks (e.g. Stephenson and Kirk 2000b). Changes in surface texture and morphology at this scale have been studied in geomorphology as a proxy for weathering state (e.g. McCarroll 1992; McCarroll and Nesje 1996, see Chapter 4). In an ecological sense, these kinds of morphological alterations equate to changes in the physical complexity of the substratum (Figure 2-6, connection [a]) at scales known to influence colonisation on rocky shores and artificial structures (e.g. Lapointe and Bourget 1999; Gómez-Pujol et al. 2006).

Table 2-10 lists ecological studies in which reference has been made to the potential importance of weathering for intertidal epibiota. From these examples it is clear that weathering is recognised as a mechanism for the development of habitat heterogeneity, but that the processes involved and, in particular, their relative importance on different substrata used in engineering has not been examined. Furthermore, the involvement of organisms themselves in the generation of texture has rarely been considered in marine urban ecology, but is of interest as an example of 'ecosystem engineering' (see Chapter 3).

2.6.2.2 Substratum warming-drying behaviour and environmental stress

The second link between rock coast geomorphology, weathering science and intertidal ecology examined this thesis is related to environmental stress. Heat and desiccation are primary factors controlling the development and persistence of marine epibiotic assemblages, both on rocky shores and artificial hard substrata (see Section 2.3.3). In ecology, the potential importance of substratum type in mediating these relationships has been suggested (Figure 2-6, connection [b]); examples are listed in Table 2-11. Most studies have referred to these relationships in passing, or in a non-quantitative way, and they have not been explored in the context of marine urban ecology.

Table 2-10 Examples of references made to the potential importance of substratum weathering behaviour for intertidal ecology.

Reference	Study context	Reference to weathering control	Level of consideration
Bulleri 2005	Comparison of early colonisation of seawalls and natural shores	"…differential weathering between rocky shores and seawalls may have produced differences in important attributes of the substratum, such as roughness, porosity and/or altered chemical composition." (p357)	Suggested as a control on surface texture and colonisation; not quantified.
Moschella et al. 2005	Effect of broad-scale engineering design features for ecological enhancement of low-crested structures	"Carbonate rocks such as limestone weather faster than igneous rocks, becoming rougher after few years, with crevices, pits and deep fractures forming. Surface complexity on carbonate rocks can further increase due to bioerosion by grazers and rock boring organisms such as *Lithophaga lithophaga* that make deep holes and galleries" (p1061)	Suggested to generate important habitat features in limestone rocks; some illustrations and examples given.
Herbert and Hawkins 2007	Influence of rock type on barnacle settlement, recruitment and early mortality	"The mineral composition of the substrate determines its hardness and resistance to weathering, and can therefore influence surface topography and heterogeneity…Friable and soft limestones, chalk and sandstones may however be unsuitable for barnacles and large algae compared to harder granite, while pitted limestones could be more beneficial for small littorinids." (p97) "The hardness of the rock substrate is known to influence bio-erosion, rock boring fauna and algal species…but must also be important in enabling the persistence of sessile faunal species and algae." (p107)	Suggested to influence substratum roughness, and stability; rock hardness and roughness measured and correlated to barnacle colonisation.
Bulleri and Chapman 2010	Review of ecological implications of deploying hard coastal structures, and enhancement options	"Assemblages on artificial structures that have been in place for several decades may be more similar to those on adjacent rocky shores…perhaps as a result of increased heterogeneity of the substratum because of weathering" (p28-29)	Passing reference in a review context.

Table 2-11 Examples of references made to the potential importance of substratum warming-drying behaviour in intertidal ecology.

Reference	Study context	Reference to geomorphic control	Level of consideration
Caffey 1982	Settlement and survival of barnacles	"Differences probably exist among types of rock in water retention, heating in sunlight, algal colonization and possibly other characterises." (p121)	Suggested as mechanism for findings. No quantification.
McGuinness and Underwood 1986	Colonisation of intertidal boulders	"Boulders of sandstone are usually lighter in colour…this might influence the rates of gain and retention of heat." (p100) "The algae *Ulva* and *Ralfsia* were also more abundant on concrete than on natural boulders, probably because the porous concrete reduced stresses associated with emersion…" (p120)	Passing reference/ inferred importance of substratum porosity/ thermal properties. No quantification.
Raimondi 1988	Factors affecting barnacle zonation	"The mechanism responsible for the difference in survivorship between barnacles on granite vs. basalt appears to be related to the thermal properties of the two types of rock…basalt gets much hotter than granite which may lead to greater heat or desiccation stress." (p263)	Measurements of surface temperature on granite and basalt shores were made, but on separate days.
McGuinness 1989	Substratum type and intertidal assemblages	"The latter [Perspex] plates dried out very quickly and this may be the reason that they often had least [algal] cover." (p206)	Drying suggested as an influence on ecology. No quantification.
Moschella 2003	Substratum influences on marine epilithic biofilms	"Porous rocks retain more water, keeping the surface damp during low tide. This is likely to reduce desiccation stresses experienced by intertidal microbial communities." (p.200)	Inferred importance of water retention properties in relation to thermal stress and desiccation.
		"Thermal stresses will be influenced by the colour of the rock substratum…surface temperatures recorded on white chalk were a few degrees lower than the dark dolomite in July. This small difference could be of major importance for diatoms, which are very sensitive to high insolation and thermal stresses occurring during summer." (p200)	No quantification.
Pister 2007	Colonisation of rock rubble structures	"Sandstone is more porous that granite which makes it more likely to retain water at low tide, thus reducing desiccation." (p65)	Passing reference. No quantification.

Iveša et al. 2010	Colonisation of seawall construction materials by microorganisms as a food source for limpets.	"The concrete plates may have retained more water during low tide than did the sandstone plates, remaining damp like low-shore areas." (p66)	Passing reference as a possible factor influencing differences in microbial biomass and limpet survival. No quantification.
Savoya and Schwindt 2010	Substratum influences on recruitment and survival of an invasive barnacle	"…rock characteristics like hardness, texture, mineralogical composition, colour, and the presence of crevices may modulate the intensity of the desiccation and temperature stress, and therefore the performance of the many marine organisms settling on them…" (p125-126) "Rock attributes such as colour, thermal capacity and roughness directly affect the surface temperature, and they may indirectly regulate the density of organisms by affecting recruitment and survival…" (p128)	Suggestion that rock properties may explain colonisation differences observed. No quantification.

2.6.3 Potential contributions to theory

From a geomorphological perspective, hard materials used to build coastal structures in the intertidal zone are subject to the same geomorphic agents as natural rocks. Structures conveniently provide rock (or artificial material such as concrete) on which to study the types and rates of intertidal weathering and erosion processes that are of interest for understanding natural rock platforms (e.g. Takahashi et al. 1994; Mottershead 1997; 2000, see Chapter 7). Examining the geomorphological processes occurring on construction materials and the physical changes that result are therefore of mutual interest to geomorphologists – in the context of rock coast geomorphology and weathering – and ecologists – who are interested in the influence of these processes on colonisation. The involvement of organisms in the alteration of the materials they colonise (e.g. morphology and strength) is of interest to geomorphologists in a biogeomorphological context, and to ecologists as a potential example of physical ecosystem engineering; geomorphology-ecology linkages are specifically discussed in Chapter 3, and further explored in Chapter 9 in relation to the project findings. Colonisation may also have implications for material durability in an engineering context (see discussions in Chapter 7: Strand 3 and Chapter 9).

2.7 Limitations of Marine Urban Ecology: The geomorphological contribution

There has been increasing attention given to understanding urban marine environments as ecological systems in the last 10 years (see review above). It is noticeable, however, that the number of studies recording the abundance and diversity of species on structures far outweigh those that have examined the operation of ecological processes on their surfaces. Settlement, recruitment, morality and reproduction of species, and the interactions between species colonising artificial structures (i.e. competition, predation and facilitation) have been studied much less. Bulleri and Chapman (2010) suggest that this is a general short-fall of current urban marine ecology research, and that understanding how these processes operate on structures is vital if differences observed between structures and rocky shores are to be explained. Recruitment, for example, has been shown to be the key process leading to differences in species assemblages between seawalls and rocky shores (Bulleri 2005b), and between shaded and unshaded walls in Sydney Harbour (Blockley and Chapman 2006). These kinds of studies are needed to understand the factors which are most important for colonising epibiota, to guide future development and testing of the sorts of design features that could be manipulated to enhance the ecological potential of structures.

This thesis is concerned with the direct interactions and feedbacks between substratum (i.e. materials used in engineering) and colonising biota in the intertidal zone. Based on the review of current ecological understanding of these interactions above (Section 2.3) and the examples of applied testing of ecological enhancement options (Section 2.5.1), three main limitations and opportunities have been identified, discussed in turn below, which form the rationale for the specific research objectives and hypotheses presented in the following chapter (Chapter 3):

1. The limited use of materials which adequately reflect those ‘as-used’ in engineering in experiments (i.e. materials types used in engineering with representative surface textures);
2. The need to test the potential for ecological manipulation using texture at a small-scale (< cm);
3. The influence of substratum physical properties (geomechanical properties and geomorphological behaviours) on ecological outcomes.

2.7.1 Representative materials

The influence of naturally occurring rock types on intertidal biota has received steady attention by ecologists (Section 2.3.3.3). Artificial materials have also been used to experimentally test specific hypotheses relating to substratum heterogeneity as they can be more easily manipulated and replicated (e.g. McGuinness and Underwood 1986; Bourget et al. 1994), and because some natural rocks may be too hard or too friable to cut into experimental blocks or panels (e.g. Savoya and Schwindt 2010). McGuinness (1989) suggests that experiments examining substratum influences using materials such as plastic and metal may be extremely misleading when applied in the real world. Although they can be used to gain useful theoretical understanding of the ecological processes involved in early stages of colonisation (e.g. Turner and Todd 1993), these kinds of materials have limited relevance for understanding processes occurring on structures built from natural rock and concrete. Indeed, there have been only a handful of studies examining ecological responses to the range of engineering materials available for coastal defence, particularly concrete (e.g. Table 2-4).

Importantly, where concrete has been used in ecological experiments, the type of concrete has not reflected that used in marine engineering. Marine concrete is specifically designed for aggressive marine environments, and as such may differ greatly in composition from terrestrial concrete (Allen 1998; Neville 2004; Newy 2008; CIRIA 2010, see Chapter 4). Experimental studies examining ecological responses to concrete have either not specified the type of concrete used (e.g. Iveša et al. 2010) or have used mixes designed for terrestrial use, which are more easily obtainable (e.g. McGuinness 1989). It is also notable that while some limited recommendations for the ecological enhancement of rock structures are available to engineers (CIRIA 2007, 2008a), reference to enhancement of concrete structures is notably stark in the most recent guidance (CIRIA 2010). The influences and responses of *marine concrete*, specifically, to colonisation was therefore of great interest in the context of urban marine ecology, geomorphology and engineering.

Perhaps most importantly, where materials such as granite and concrete have been used in experiments, they do not necessarily reflect these materials 'as-used' in structures. Granite rock armour, for example, is invariably rough in texture yet many experimental studies have used smoothed or polished rocks (e.g. Holmes et al. 1997). Although this approach is necessary to control for texture (as an attempt to isolate the effects of lithology alone, see Chapter 6), most studies suggest that the roughness of the substratum is probably more important than its chemical composition for ecology – although the two are clearly linked (see discussions in Chapter 5 and 6). If relevant conclusions are to be made about the influence of construction materials on the ecological potential of urban coastal structures, not only are more experiments needed using the same *types* of materials used in engineering, but the *surface characteristics* (i.e. texture) of experimental materials must also adequately reflect those as found *in situ*.

2.7.2 Manipulation of small-scale habitat heterogeneity

Despite a substantial research base demonstrating the importance of habitat heterogeneity on coastal ecology, and the suggestion that the absence of physical complexity on artificial structures is an important factor limiting ecological potential (Section 2.3), there have only been a few studies testing these principals in an urban marine context (Section 2.5.1). Those experiments which have been done clearly show there is great potential for manipulating ecology through broad-scale design (> m) and by introducing complexity at a meso-scale (cm – m). Positioning structures lower in the tidal frame and minimising their (indirect) impacts on adjacent habitats are examples of broad-scale considerations. Introducing artificial habitat complexity in structures, including holes and pools, has also proved effective for manipulating species abundance and diversity (Section 2.5.1).

What has not been explored, is the potential to influence ecology on construction materials by manipulating small-scale habitat heterogeneity (< cm). There is considerable experimental and theoretical research to suggest that the surface texture of materials at this scale is extremely important for the colonisation of bare substrata by early colonists such as barnacles, as well as in the development of communities over longer timescales (Section 2.3.3.3, also see discussions in Chapter 9). More applied testing of these principles is needed to contribute to discussions of ways to increase the ecological potential of hard engineered structures in the tidal zone.

2.7.3 Substratum geomorphological properties and behaviours

The influence of substratum properties on epibiota has largely been restricted to experiments examining surface heterogeneity and 'rock type' (see Section 2.3.3.3 for limitations of these comparisons in ecological research). The importance of geological properties on colonisation, such as lithology and hardness has received much less attention (but see Ista et al. 2004 for example). Furthermore, while the potential importance of weathering and erosion processes, and warming-drying behaviours of substrata has been noted in ecological studies (see Section 2.6.2), there has been very little quantitative assessment of how these properties might differ between common materials used in coastal engineering and how they may change through time, particularly in an intertidal setting where field conditions make study challenging (Chapter 8).

2.8 Summary and Conclusions

Coasts are extremely important environmental, economic and social assets. Rapid population growth and associated urban development has led to significant hardening of the shoreline in the UK and across the rest of Europe, particularly through the use of rock armouring and concrete structures (Airoldi and Beck 2007). In the UK, the approach to coastal management is necessarily integrated, and there is recognition that not all areas can be protected from flooding and erosion in the future. However, it is clear that Defra and the EA must commit substantial financial resources for defence where risks to valuable assets (whether environmental, social or economic) are threatened, particularly in the face of climate change; this commitment will necessarily involve the construction of new hard structures and the maintenance, repair and upgrading of existing structures (Section 2.2).

While hard coastal structures provide novel habitat for marine organisms, they are not expected to function as surrogates for unmodified rocky shores (Moschella et al. 2005; Bulleri and Chapman 2010). This presents an issue of significant conservation concern and has led to considerable efforts by ecologists to understand coastal structures as habitats in their own right. Currently, marine ecologists have made the greatest contribution to understanding structures in this context (Section 2.3) given the need to establish a solid understanding of ecological responses to structures that must underpin any attempts for enhancement. The key outcomes of this existing work have been:

- Evidence that hard artificial coastal structures are generally poor ecological surrogates for rocky shores;

- Evidence that broad-scale design features (such as shore position and orientation) are important for overall ecological value of artificial structures;
- Recognition that meso-scale habitat heterogeneity (i.e. pools, crevices and holes) is of high importance for overall ecological potential of artificial structures, and;
- Applied testing of artificial meso-scale (cm – m) features (e.g. artificial pools and holes) as a way of manipulating target species and for increasing overall ecological value of structures.

In addition to conservation concerns, national and international policy and legislation provides an additional and significant driver for consideration of enhancement options where artificial structures have to be built. Currently, planning regulations and the WFD, which requires all HMWBs to achieve 'good ecological potential', are the primary policy drivers for research in this area (Section 2.4). Furthermore, ecological enhancement provides considerable opportunities for meeting the requirements of many end-users and practitioners (e.g. Figure 2-1 p. 49).

Despite significant advances in marine urban ecology, three main limitations to current approaches have been identified (points 1-3 below), and the opportunity for geomorphological considerations is emphasised in the context of this thesis (point 4 below):

1. **Focus** has been on recording the occurrence, abundance and diversity of species on structures rather than observing fundamental ecological processes, such as settlement and recruitment, which are vital for establishing viable populations.
2. Studies examining the influence of substratum type have rarely compared materials commonly used in marine engineering, particularly with surface textures representative of those made available to colonising organisms during construction (i.e. materials 'as-used' in coastal engineering).
3. There has been limited applied testing of opportunities for ecological manipulation at a small-scale (< cm), despite clear experimental evidence that habitat heterogeneity at this scale is important for organisms on rocky shores.

4. The role of geomorphological processes in generating habitat heterogeneity (through weathering and erosion of the substratum, at small spatial scale) and in modulating potential environmental stresses (as a function of substratum warming-drying behaviour) has not been explored despite suggestions within the ecological literature that these processes may be important.

It is clear that there is considerable scope for experimental and theoretical advancement of understanding substratum-biota interactions in the tidal zone; this work is of interest to geomorphology (weathering, biological contributions and 'biogeomorphology' more broadly), ecology (colonisation processes, epibenthic communities on structures and 'ecosystem engineering'), and engineering (potential biological influences on durability). Exploring these interactions offers the opportunity to contribute to discussions on the ecological enhancement of artificial coastal structures, by identifying how different properties of the materials used in construction may influence their potential as ecological habitats.

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CHAPTER 3

CONCEPTUAL OVERVIEW AND RESEARCH FRAMEWORK

Biogeomorphology: An integrated approach to understanding natural systems

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CHAPTER 3. CONCEPTUAL OVERVIEW AND FRAMEWORK

Biogeomorphology: An integrated approach to understanding natural systems

3.1 Integrating Geomorphology and Ecology

> "Predicting future states of the ecosystems on Earth, and developing effective management and restoration practices, necessitates developing a coupled understanding of how these two aspects of the environment influence each other, and how the processes feedback into each other."
>
> **Renschler et al. 2007 p. 1.**

Traditionally, geomorphology is a discipline focussed on the physical landscape and the processes that act to shape landforms over time and space (Schumm and Lichty 1965; Rhodes and Thorn 1996). Ecology on the other hand is typically more concerned with the processes that shape the distribution of species and populations, and their interactions with the physical environment (Weiner 1995; Begon et al. 2005). While these traditional disciplinary approaches to study have proved successful, challenges arise when problems being addressed require holistic thinking. This is increasingly the case in the context of environmental management, conservation and restoration where combined input from the physical and ecological sciences is often required in ways that complement each other (e.g. Sear 1994; Margerum 1995, 1999; Apitz et al. 2006).

Pickett et al. (1994) suggest that there are three primary limitations to disciplinary-based research. First, gaps appear (in knowledge) at the interface of disciplines while, second, the focus of research is often restricted to specific scales and levels of organisation. Thirdly, view points, perspectives and assumptions become more specific as sub-disciplines emerge. The latter point is consistent with the concepts of a reductionist approach to science, in which smaller and smaller levels of organisation are studied to elucidate useful information (Gallagher and Appenzeller 1999). The limitations of reductionism have been argued in the context of geomorphology by Harrison (2001), who suggests that landscapes are essentially emergent phenomena. Ideas about complexity, self-organisation and non-linearity are also becoming increasingly developed and discussed within the geomorphological community (e.g. Phillips 1992; Phillips 2003, 2006a, b; Murray et al. 2009, see discussions in Chapter 9). Reductionism has also been recognised as a limitation in modern ecological research (e.g. Bergandi and Blandin 1998; Ponge 2005).

Renschler et al. (2007) suggests that there are several areas of environmental science where integration of geomorphological and ecological thought is necessary, particularly in the context of global environmental change. At the coast, for example, understanding and predicting the responses of natural systems to sea level rise requires knowledge of coupled physical and ecological processes, as does the study of biogeochemical cycling, biodiversity and anthropogenic impacts on the environment (Viles and Spencer 1995; Goudie 2006b; Renschler et al. 2007; Anthony 2008).

There is now considerable steer at a European level to manage coasts in a way that takes full account of both biological and physical components (see Section 2.4). Integration in this way is increasingly practiced in contemporary river science and management, within which concepts of ‘holistic’, ‘ecosystem’ and ‘integrated’ approaches have become well established (Vaughan et al. 2009; Rice et al. 2010). Alongside the applied need, both geomorphology and ecology have much to gain from integration as disciplines, necessarily involving the cross-fertilisation of ideas, methods and theories in ways that can aid academic advancement (Naylor et al. 2002; Molau 2006; Darby 2010).

3.1.1 Challenges to integration

Research at the interface of disciplines is difficult because each may be concerned with fundamentally different underlying questions and philosophical approaches, typically focusing sampling and monitoring at particular time and space scales, and because research tends to remain dominated by the paradigms familiar to the component disciplines (Renschler et al. 2007). Broadly speaking, geomorphologists want to know about the non-living, physical aspects of the environment (the 'abiotic'), while ecologists want to know about the living, biological aspects (the 'biotic'). This means that the methods and research designs they commonly adopt are not always complementary – their experiments may be designed to look at different things.

Contemporary ecological study is very much based on the classical scientific method of hypothesis testing and statistical significance, requiring sufficient replication for consideration of generality in space and time (Beck 1997). This is certainly the case with respect to benthic marine ecology where experiments are typically designed with a particular statistical procedure in mind (e.g. Underwood 1997; Quinn and Keough 2002). In contrast, geomorphology is often based on multi-parameter data collection with less replication, having a traditional steer more towards theoretical reasoning (Stallins 2006; Urban and Daniels 2006; Church 2010). This is not to say that either approach is inadequate (but see Yatsu 1992; Molau 2006; Cox 2007; Tooth 2009), or that the underlying theories are not compatible, but that challenges will undoubtedly arise when aiming to develop integrated studies that meet the specific requirements of multiple disciplines (Benda et al. 2002; Cash et al. 2003; Boulton et al. 2008). A further consequence is that studies which do explicitly examine interactions between living (biotic) and non-living (abiotic) components of the environment do not necessarily fit neatly within the traditional themes of ecology or geomorphology (Viles and Naylor 2002).

As opposed to 'multi-disciplinary' and 'trans-disciplinary' research which is largely 'additive' (*sensu* Renschler et al. 2007), true 'interdisciplinary' science requires the merging of two or more separate areas of understanding into a one conceptual-empirical structure (Pickett et al. 1994). This requires researchers to be aware and accommodating of the approaches commonly used in each component discipline. For geomorphology and ecology, it has been suggested only recently that true integrative studies are still largely lacking (Haussmann 2011). For researchers aiming to understand the environment as a complex physical-biological system, and to develop applied management solutions to environmental problems, the goal should be to integrate knowledge, theory and experimental design practice from the start of a project to ensure that the research can fit the requirements of both disciplines; this is inherently challenging (Benda et al. 2002).

In the intertidal zone, geomorphologists and ecologists have crafted their own specific areas of research (e.g. Trenhaile 1987; Raffaelli and Hawkins 1996). While both groups recognise that biological and physical components interact at the coast (see Chapters 2 and 7 for reviews), the true integration of knowledge needed to tackle management problems in a holistic way remains lacking. It was suggested in Chapter 2 that better (geomorphological) understanding of the properties and behaviours of the physical habitat created through urban activities, alongside (ecological) understanding of the responses of marine organisms to such activities, would be of value for management and conservation in coastal environments. Importantly, how these two sets of processes interact with each other requires much more attention (Renschler et al. 2007; Bulleri and Chapman 2010).

3.2 A Biogeomorphological Approach to Understanding Natural Systems

3.2.1 Biogeomorphology

'Biogeomorphology' has been established as an area of geomorphology that explicitly considers the ways in which biological (organic) and geomorphological (inorganic) processes interact. In the first formalisation of the concept, Viles (1988a) identified two core aspects of biogeomorphology (Figure 3-1): firstly, the influence of geomorphology on the distribution and development of organisms (connection [1]) and, secondly, the influence of organisms on Earth surface processes and landforms (connection [2]). In the strictest sense, the influence of geomorphology on the ways in which organisms interact (i.e. the influence of landforms and land-forming processes on ecological interactions such as competition) should also be included under point [1].

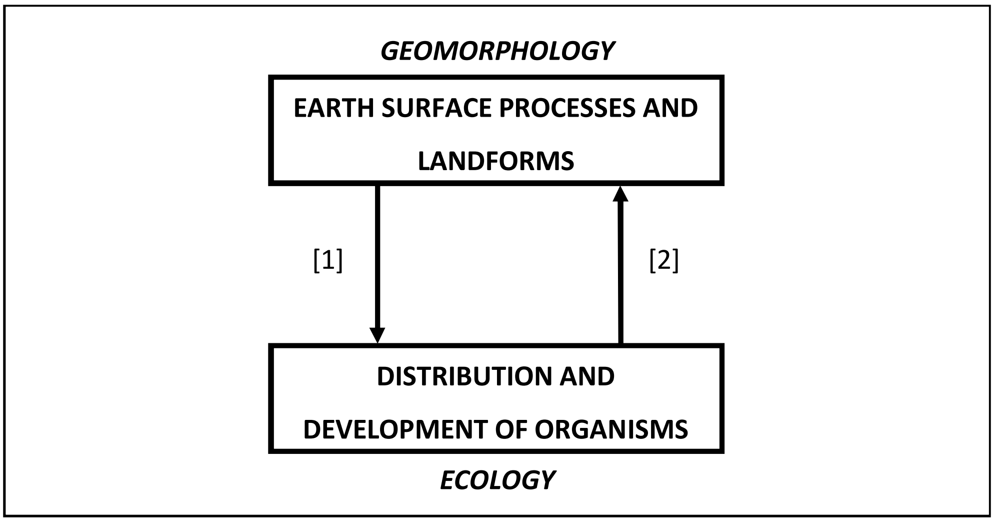

Figure 3-1 Simple conceptual framework of traditional biogeomorphology, based on Viles 1988 (see text for details).

Whilst Viles notes that the two aspects are interlinked, the first ([1] in Figure 3-1) has received most attention by biogeographers and landscape ecologists, for whom the general spatial and temporal scale of enquiry is typically broad (MacArthur 1972; Cox and Moore 2010). The second aspect on the other hand ([2] in Figure 3-1) is more in-line with the paradigm of process-based geomorphological study (Anderson and Burt 1990; Rhodes and Thorn 1996). Correspondingly, the vast majority of biogeomorphological research over the last 20 years has focussed on this second aspect – the study of the geomorphic impacts of organisms, at a range of scales (see Howard and Mitchell 1985; Viles 1988a; Butler 1995 for some specific examples).

Broadly speaking, biogeomorphology may be thought of as comprising of three distinct but interacting bioprocesses (Naylor et al. 2002). 'Bioerosion' is the direct or indirect involvement of organisms in the breakdown, mobilisation and/or redistribution of material. In the coastal zone, examples of bioerosion include rock weathering by microorganisms (e.g. Trudgill 1987a; Moses and Smith 1994), sediment mobilisation by burrowing crabs (Wang et al. 2010) and rock boring by bivalve molluscs (Pinn et al. 2005b, 2008). In contrast, 'bioprotection' involves the direct or indirect prevention or reduction of other Earth surface processes by organisms, such as the reduction in salt weathering efficiency on rocks by the presence of microbial biofilms (Mottershead et al. 2003) and encrusting species (Mustoe 2010), and wave energy dissipation by saltmarsh vegetation (Möller 2006). Lastly, 'bioconstruction' is the direct or indirect production of sedimentary deposits and structures by organic means. Examples of coastal bioconstructions include worm reefs (Naylor and Viles 2000), stromatolites (Duane et al. 2003) and coral reefs (Spencer and Viles 2002). These classifications are by no means isolated, and one may lead to the occurrence of another, or may operate simultaneously in the same area (Naylor et al. 2002). Bioerosion has been given most attention by coastal biogeomorphologists, mainly in the context of limestone shores (see Chapter 7 for a review), while coastal bioconstruction and bioprotection remain generally understudied (Naylor et al. 2002; Carter and Viles 2005).

> In essence, biogeomorphology is only one part of a broadly defined earth systems science which links biological, geochemical, sedimentological and geomorphological processes and outcomes.
>
> **Naylor et al. 2002 p. 6.**

It is important here to make the distinction between the study of particular biogeomorphological *processes*, such as bioerosion (e.g. Donn and Boardman 1988), bioturbation (e.g. Wilkinson et al. 2009), sediment stabilisation (e.g. Stal 2010) etc., and a *biogeomorphological approach* to research. In this context, bioerosion, bioprotection and bioconstruction essentially constitute specific processes leading to geomorphic change, in which organisms are involved. These areas of biogeomorphic research consequently all fall under point [2] in Figure 3-1, where the process, its rates and spatial-temporal variability are the primary focus of the study. In contrast, the concept of a 'biogeomorphological approach' is used here to describe a much broader philosophical framework to understanding natural systems which considers both biotic and abiotic components of environments, their interactions and feedbacks in time and space (see Section 3.2.5). The general lack of attention given by geomorphologists to the implications of biogeomorphic processes for the functioning of subsequent ecological processes (which necessarily requires ecological knowledge) is highlighted here as a limitation of contemporary biogeomorphology (see Section 3.2.2 below).

3.2.2 Limitations, challenges and opportunities for biogeomorphology

> "Biogeomorphology needs to move beyond list bound descriptions of unidirectional interactions of geomorphic and ecological components."
>
> **Stallins 2006 p. 214.**

In a discussion of geomorphology-ecology integration, Stallins (2006) concludes that more effort is needed to move beyond descriptions of one-way interactions of how ecological and geomorphological landscape components interact. Most biogeomorphology studies, for example, have tended to examine either the influence of organisms on geomorphology, or (more rarely) the influence of geomorphology on organisms (i.e. Figure 3-1). Biogeomorphologists have also tended to focus on how specific species affect specific forms, and *vice versa*, rather than interactions occurring at an ecosystem and landscape level (but see Reinhardt et al. 2010). Considerations of multiple causality and feedbacks are also lacking (Stallins 2006). Haussmann (2011) further suggests that where biogeomorphological studies have been undertaken, the majority remain essentially geomorphological in focus, with a 'bio' component bolted on (the 'additive integration' defined by Renschler et al. 2007). In contrast to such an approach, true integrative studies, which must involve ecological expertise in the design of experiments and interpretation of results, remain rare. There is, however, increasing recognition and discussion of complexity more widely in geomorphology (e.g. Phillips 2003, 2006a, b), and specifically in the context of biogeomorphology (Phillips 1995a).

Viles et al. (2008), for example, have recently discussed linked geomorphic and ecological systems in the context of disturbance regimes, both natural and human. In this respect, the introduction of a hard structure into the coastal zone can be thought of as a biogeomorphological disturbance, eliciting both physical and biological responses which may be linked in complex ways. Viles et al. (2008) conclude that studying the environment as linked geomorphic – ecological systems should provide opportunities for biogeomorphology to contribute to environmental management, including biodiversity conservation.

> "Biogeomorphological research as it is practiced at the moment is often from the start biased towards either one of the fields and approaches, simply as a result of the background training of those involved. To facilitate unbiased, integrative research, increased collaboration (i.e. biogeomorphology teams consisting of both geomorphologists and ecologists) is necessary."
>
> **Haussmann 2011 p. 138.**

In ecological studies, most researchers have treated geomorphic forms as static (Renschler et al. 2007; Stine and Butler 2010). Despite this, if the operation of an ecological process is dependent on a particular landscape feature (such as rocky substrata in the intertidal zone), geomorphological understanding should be able to provide information on how that process operates and varies in space and time (Renschler et al. 2007). While the nature of the substratum (i.e. the rock) has been widely acknowledged as important for rocky shore ecology, its physical properties and behaviours, how these change with time (i.e. geomorphology), and the influence of these properties and behaviours on ecology have only been considered in passing (Chapter 2). Furthermore, whilst patterns and biotic interactions are widely observed and quantified in ecology, Haussmann (2011) argues that less is done to understand the underlying mechanisms. In marine urban environments, the need to understand the mechanisms behind patterns of species found on artificial structures has been highlighted (Bulleri and Chapman 2010). What the structure is made out of, and how its properties and behaviours influence ecology in time and space and *vice versa*, should be an integral component of this work.

Scale is a critical consideration in all environmental disciplines (Church 2010). Scale dictates experimental design and data collection, and is a necessary consideration for contextualising findings more widely (Schumm and Lichty 1965; Wiens 1989; Levin 1992; Lane and Richards 1997). Importantly, the strength of interactions between geomorphological and biological components of a system is expected to vary at different scales, because each component may be operating over different timescales for example (Naylor et al. 2002). Hierarchy theory is an allied concept in ecology, which recognises that coupling among processes can vary from strong to weak at different scales (Allen and Starr 1982; Stallins 2006). In a biogeomorphological context, Viles and Naylor (2002) note that most studies have focussed on fine-scale and short-term interactions between individual species and geomorphology. A key challenge in biogeomorphology, therefore, is assessing the relevance of organic activity for landform and landscape evolution (Phillips 1995a; Viles 2001; Reinhardt et al. 2010). A further challenge related to scale is that geomorphologists and ecologists do not necessarily use the same terminology to describe different scales, which can hinder communication of ideas (e.g. Figure 3-2 as scaled to rocky shore communities).

Throughout the thesis, the terms ‘spatial scale’ and ‘temporal scale’ are used to discuss the operation and observation of phenomena at a particular order of magnitude in spatial extent (whether micrometres, millimetres, centimetres etc., Figure 3-2) and over particular time periods (days, weeks, months etc.). This style of scale distinction is denoted in the text using abbreviations such as ‘<mm’ (i.e. features that are micrometres in size) and ‘µm – mm’ (i.e. denoting features or processes occurring or measured across micrometre and millimetre spatial extents); this follows standard notation adopted in process-based geomorphological studies and, in particular, discussions of weathering phenomena (cf. Viles 2001). It is, however, acknowledged that further distinction between scale terms is critical in cognate areas of research including landscape ecology, statistical analysis, and geospatial analysis in particular; in this respect, the area of sampling (whether in field plots or fields of view under the microscope) equates to spatial ‘extent’, while the size/area of

phenomena being sampled, and their spatial arrangement, equates to the distinction of 'grain' and 'resolution' in scale terms (e.g. Dungan et al. 2002).

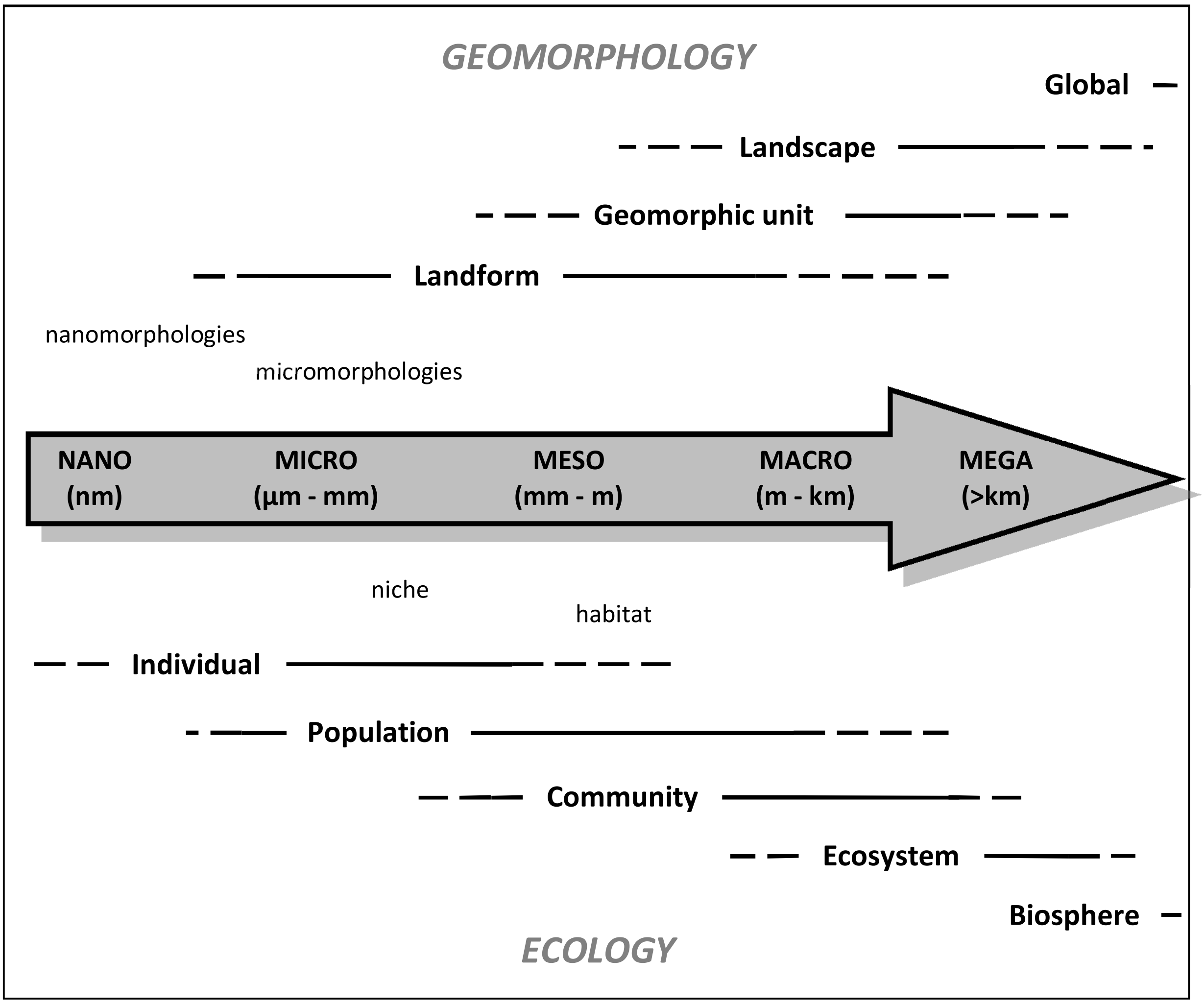

Figure 3-2 Indicative scales of enquiry in geomorphology and ecology scaled to rocky shore environments and epibenthic communities.

The above discussions demonstrate a recognition that more needs to be done in biogeomorphology as an *approach* to understanding natural systems, rather than purely studying particular biogeomorphic *processes*. This is not to say that 'traditional' biogeomorphological studies are obsolete – on the contrary, knowledge of process and rates are vital to enable broader considerations to take place. A 'biogeomorphological approach' should, however, be based on informed understanding of both the physical and biological components of a system, and more importantly, their interactions and feedbacks in time and space (Section 3.2.5).

3.2.3 Applied biogeomorphology

The need to further establish geomorphology as an applied science has been well advocated (Slaymaker 2008; Goudie 2009; Slaymaker et al. 2009; Church 2010). In the applied world, biogeomorphology as it is currently practiced has proved most useful where the feature of applied interest is the physical component of the system being studied. For example, geomorphologists have made a considerable contribution to understanding the role of organisms in stone deterioration (see Scheerer et al. 2009 for a recent review). In this instance, biogeomorphological knowledge has direct bearing on the conservation of the physical aspect of the system – the stone. Another example is the study of plant-sediment interactions in the development of intertidal saltmarshes, in which biogeomorphic understanding provides insight into the function of these systems as physical flood protection assets (e.g. Möller 2006; Möller et al. 2009).

While Naylor et al. (2002) and Naylor (2005) suggest the potential application of biogeomorphology in the fields of environmental reconstruction and environmental engineering, among others, where current biogeomorphic research falls short is in demonstrating its value in a wider ecological context - that is to say the relevance of biogeomorphic processes and outcomes for ecological management and conservation. These kinds of considerations may typically fall within the bounds of applied ecology, yet biogeomorphic knowledge should be of value where the habitat or ecosystem of interest is heavily dependent on the 'physical' component of the system, including benthic marine environments.

Currently, there is a considerable amount of applied value (social and economic) in conservation research (Sala et al. 2000; Ehrlich and Pringle 2008; TEEB 2010). This is certainly the case in coastal environments, for which their ecological, social and economic value is well recognised (e.g. Martínez et al. 2007, see Chapter 2). The role of applied ecologists in tackling environmental conservation problems and informing conservation policy is clear (Memmott et al. 2010), while the role of geomorphologists in this context is not so immediately obvious. This is reflected in a current emphasis on restoring ecological function in wetland restoration schemes for example (Wolters et al. 2005), rather than on achieving biogeomorphic function (Viles et al. 2008), and in the use of ecological parameters in the design and practice of environmental assessments associated with development, including EIAs (Section 2.4.3). Despite enormous potential to do so, biogeomorphology is yet to be fully established as an applied science.

3.2.4 Ecosystem engineering as an allied discipline

Given that biogeomorphology is a relatively new area of study bridging well established disciplines of geomorphology and ecology, defining what exactly constitutes 'biogeomorphic research' has proved challenging (Viles 2000b; Naylor et al. 2002). Despite this, the somewhat disparate and uncoordinated nature of biogeomorphological research has been suggested as one of its strengths rather than one of its weaknesses (Viles and Naylor 2002). In order for biogeomorphologists to successfully engage with ecologists in addressing the kinds of applied problems discussed above, however, contextualising biogeomorphology within current paradigms of ecological thought would be particularly advantageous (e.g. Beers 2009). This should not only help identify where biogeomorphological understanding fits within contemporary ecological research (which is generally more widely applied in environmental management), but is also necessary to highlight the potential value of integration between geomorphologists and ecologists more broadly.

> "While positive correlations between geomorphic heterogeneity and species diversity has been recognised, the degree to which heterogeneity is the cause and an effect of its relationships with biota, has not been well investigated."
>
> **Stallins 2006, p. 210.**

'Ecosystem engineering' is a concept in ecology that has received a considerable amount of interest and debate since its introduction in the mid 1990s by Jones et al. (1994). Whilst is it beyond the scope of this thesis to provide a detailed assessment of ecosystem engineering as a sub-discipline (see the recent volume by Cuddington et al. 2007 and Chapter 9 for some further discussions), it is outlined here as a concept closely related to biogeomorphology that may provide considerable opportunities for geomorphology-ecology integration. The concept also provides a framework within which biogeomorphological discussions of substratum-organism interactions can be aligned with ecological ideas, in the context of hard coastal structures.

As originally defined, ecosystem engineering constitutes the direct or indirect modulation of the availability of resources by one species to other species, by causing a physical state change in biotic or abiotic materials (Jones et al. 1994 p374). Ecosystem engineering is classified as 'autogenic' when it is the physical structures of the 'engineering' organism itself that alters conditions for other organisms. For example, seaweed clumps are autogenic engineers in the sense that they facilitate the establishment and persistence of other species on rocky shores by providing shade and moist refuges (e.g. Thompson et al. 1996). Ecosystem engineering where the 'engineer' alters the physical (abiotic) environment (e.g. the rock or soil substratum, or water flow etc.) is classified as 'allogenic' engineering. The creation of holes in rock by rock boring piddocks, which provide physical habitat for other species, is therefore an example of allogenic engineering in the intertidal zone (e.g. Pinn et al. 2008).

A related concept in ecology is that of 'niche construction', whereby organisms modify their own and/or each other's habitat niches (Odling-Smee et al. 2003). While ecosystem engineering and niche construction have been used synonymously (Laland and Boogert 2010), the latter is typically preferred by evolutionary biologists, who are more concerned with the consequences of ecosystem engineering for selection pressures. 'Facilitation' – where the presence of one organism benefits another – is another related concept that has been particularly well applied in the intertidal zone (see Bulleri 2009; Thomsen et al. 2010). The distinction between facilitation and ecosystem engineering is not immediately clear, but Buchman et al. (2007) indicate that the latter can be regarded as an all-encompassing framework within which specific examples may constitute facilitation, niche construction and other such ecological concepts (see discussion in Chapter 9).

Where explicitly applied in a rocky shore context (Gutiérrez et al. 2003; Crain and Bertness 2006; Harley 2006), most examples of ecosystem engineering constitute 'autogenic engineering', which need not involve any modification of the physical environment *per se*. For example, the shells of molluscs provide 'secondary substrata' (i.e. biogenic habitat) on which other species can colonise (Sousa et al. 2009) as well as refuge from waves and desiccation where grouped together (Gutiérrez et al. 2003). On seawalls, the (autogenic) ecosystem engineering role of oysters has been suggested in Australia (Jackson et al. 2008), as these organisms provide biogenic habitat for whelks. This kind of ecosystem engineering may be particularly important in 'stressed' environments like rocky shores where the provision of refuge is an important community regulator (see Chapter 2). It is worth noting that such examples of ecosystem engineering could fit equally well under the definition of 'facilitation' (Bulleri 2009).

After its introduction, the ecosystem engineering concept received some criticism because it was interpreted as being too broad, and a new 'buzzword' that re-defined already established concepts in ecology (such as those outlined above; Power 1997; Jones et al. 1997a; Reichman and Seabloom 2002; Wilby 2002). Whilst most biogeomorphological studies have largely been concerned with providing examples of a particular organism's effects on geomorphic processes (Section 3.2.2), ecosystem engineering was likewise accused of 'merely' providing examples of 'just-so' stories, with little effort to address the broader issues raised by the ecosystem engineering conceptual framework (Berkenbusch and Rowden 2003). Importantly, the concept must not be interpreted to infer 'intent' from the 'engineer' (Jones and Gutiérrez 2007).

These criticisms have led to some re-definition and development of the concept, largely for clarification purposes. In their later discussions, Jones and co-workers place more emphasis on the *physical* alteration of the environment as part of the ecosystem engineering process, preferring the term '*physical ecosystem engineering*' (Jones et al. 1997b; Wright and Jones 2006; Gutiérrez and Jones 2006; Jones and Gutiérrez 2007; Jones et al. 2010; Gutiérrez et al. in press). They also state that ecosystem engineering defines relationships between organisms beyond purely trophic interactions (i.e. predation, competition, food webs, nutrient cycling etc.; Jones and Gutiérrez 2007). Efforts to identify those 'engineers' which have a disproportionately large influence on the environment is needed to avoid the concept becoming trivialised (Reichman and Seabloom 2002; Wright and Jones 2006).

Most recently, Berke (2010) proposed a process-based classification of four functional classes of ecosystem engineering. '**Structural engineers**' are those organisms which modify structural elements of the habitat (e.g. reef builders and dam building beavers); '**bioturbators**' are those which excavate and redistribute sediment (including badgers, gophers, burrowing crabs and lugworms); '**light engineers**' are organisms that alter the intensity, penetration and scatter of light in both air (shading) and water (i.e. turbidity; which includes zooplankton, canopy forming plants and filter-feeders); and the activities of '**chemical engineers**' create biogeochemical gradients (including gaseous changes through respiration and biomantle development; Gutiérrez and Jones 2006; Berke 2010). A limitation of this approach is that many organisms fall under two or more of these classes; burrowing and boring organisms, for example, excavate and redistribute sediment (i.e. 'bioturbators'), create structural forms (i.e. 'structural engineers') and alter the distribution of moisture and gasses within the 'burrowing' media (whether in silt, soil or rock; i.e. 'chemical engineers'; e.g. Meadows and Meadows 1991).

It was noted above that while geomorphologists have necessarily begun to incorporate biological considerations in their studies, the application of biogeomorphological knowledge in ecological studies is altogether more rare (Haussmann 2011). It is argued here, however, that any such study would invariably fall under the 'ecosystem engineering' or 'facilitation' umbrella. Indeed, ecosystem engineering studies are very much biogeomorphic in nature, even if they do not explicitly say so, because they typically involve the identification and quantification of biotic involvement in physical modifications to the environment. Using Berke's (2010) recent classification, 'structural engineers' equate to those organisms of geomorphic interest that directly create or modify landforms (e.g. Goudie 1988; Cox and Hunt 1990; Butler 1995), while 'bioturbators' are relevant for sediment flux and erosion rates (e.g. Voslamber and Veen 1985; Black and Montgomery 1991; Coombes 2005). Allogenic ecosystem engineering essentially involves the direct creation of structures and the modification of physical habitat – these kinds of process fall under aspect [2] of Viles' (1988) biogeomorphic framework (Figure 3-1 p.75). Similarly, the physical structures of autogenic and allogenic engineers can alter the distribution of geomorphic agents such as wind, water and thermal energy, and hence the efficiency of weathering and erosion in time and space (e.g. Gurnell 1998). Such changes in the operation of *subsequent* geomorphic processes (as a knock-on effect of initial biogeomorphic processes) may have important feedbacks ecology (i.e. connection [1] in Figure 3-1); these kinds of complexities have typically not been identified or discussed by biogeomorphologists nor ecosystem ecologists.

The most recent clarifications of the concept by Jones and Gutiérrez (2007), Jones et al. (2010) and Gutiérrez et al. (in press) further aligns ecosystem engineering with biogeomorphology. They define two distinct components of physical ecosystem engineering, the '***engineering process***' and the '***engineering consequence***'. The engineering process involves 'organismally caused, structurally mediated changes in the distribution, abundance, and composition of energy and materials in the abiotic environment' (Jones and Gutiérrez 2007, p. 7). Such a definition inherently overlaps with biogeomorphological research frameworks. Indeed, Jones and Gutiérrez (2007) themselves imply that the 'structural changes' resulting from the ecosystem engineering process can be thought of as analogous to geomorphic processes – the key difference being that the factors needed to predict when and where such processes might occur (i.e. whether biological or geomorphological) will be different. Engineering consequences refer to the outcomes of engineering processes (above), which in ecology is specifically focussed on the distribution, abundance and interaction of organisms (see below).

Recognising these conceptual overlaps between ecosystem engineering and biogeomorphology provides a significant opportunity for integration. In the case of boring bivalves, for example, the boring activity is an example of a biogeomorphic process (i.e. bioerosion) for which geomorphologists can provide expertise on rates of operation and the modification of structural form, and ecologists can provide expertise on the consequences of this process for other organisms. The fact that the environments and the organisms of interest to geomorphologists and ecologists in these contexts very often overlap (e.g. Table 3-1) itself indicates a common interest. Biogeomorphologists are also increasingly referencing ecological studies, and adopting terminology originally developed in discussions of the ecosystem engineering concept (e.g. Francis 2006; Viles 2008; Viles et al. 2008; Francis et al. 2009; Reinhardt et al. 2010; Coombes et al. 2011). Furthermore, key workers in the field of ecosystem engineering have recently alluded to the opportunities for incorporating geomorphological (and even specifically biogeomorphological) understanding in their research (Jones et al. 2010 p. 1868), while current attempts to do so are limited.

The distinction between what constitutes biogeomorphology and ecosystem engineering largely depends on where the focus of the outcome of these studies is ultimately placed. The schematic presented in Figure 3-3 suggests that modification of the physical environment by organisms is the core interest in both areas of research, but that ecosystem engineering necessarily involves the creation, modification or maintenance of *habitat* - thereby placing emphasis on the ecological consequences of such interactions (Jones et al. 1994, 1997b; Jones et al. 2010). Biogeomorphology, on the other hand, places most emphasis on the geomorphic consequences of the interaction – whether this is the direct creation/modification of landforms, or the alteration of other geomorphic processes (Figure 3-3).

For biogeomorphology to begin to be recognised more as being able to contribute to applied environmental management problems, the philosophical approaches, methods and findings of biogeomorphologists need to be discussed within a framework that ecologists are familiar with. Biogeomorphology would gain much from placing more emphasis on how the processes being studied are relevant for ecology – or at least engage ecologists in studies where these kinds of feedbacks are expected to be significant. At the same time, integrating ecological understanding into biogeomorphological process studies is necessary for predicting where and when organisms will be most important for landform and landscape evolution (Naylor et al. 2002; Stallins 2006; Viles et al. 2008), and where biogeomorphic processes will have greatest consequences for ecology (Jones and Gutiérrez 2007; Jones et al. 2010; Gutiérrez et al. in press, see discussions in Chapter 9).

Table 3-1 Examples of biogeomorphology and physical ecosystem engineering oriented studies of some common intertidal organisms.

Organism	Example biogeomorphology study	Example ecosystem engineering study
Molluscs	*Trudgill 1987a*	*Pinn et al. 2008*
	Bioerosion of limestone	Burrows increase habitat complexity
Microorganisms	*Naylor and Viles 2002*	*Gerbersdorf et al. 2009*
	Bioerosion and bioprotection of limestone rock	Biostabilisation of intertidal and marine sediments
Limpets	*Andrews and Williams 2000*	*Gutiérrez et al. 2003*
	Bioerosion of chalk	Secondary substrata and refuge provision
Barnacles	*Mustoe 2010*	*Harley 2006*
	Bioprotection and formation of honeycomb weathering morphologies	Creation of habitat complexity and facilitation of other species
Coral	*Spencer and Viles 2002*	*Buhl-Mortensen et al. 2010*
	Bioconstruction and bioerosion rates and processes	Secondary substrata and refuge provision
Polychaete worms	*Naylor and Viles 2000*	*Volkenborn et al. 2009*
	Worm reefs as bioconstructions, growth and morphology	Tube structures provide habitat complexity and facilitate other species
Macro-algae	*Løvås and Tørum 2001*	*Schmidt and Scheibling 2006*
	Wave dissipation and effects on sand dune erosion	Secondary substrata and refuge provision

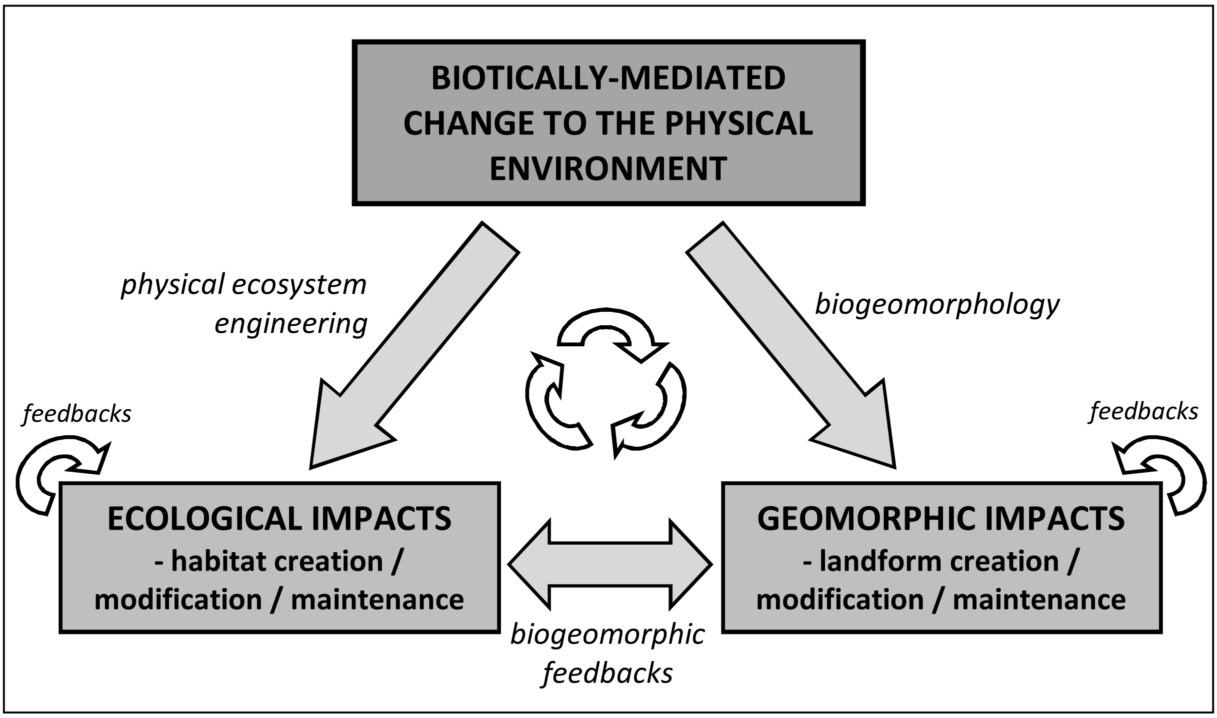

Figure 3-3 Ecological and geomorphological perspectives on organism – environment interactions.

At the same time, it is important that the fundamental distinction between biogeomorphology and ecosystem engineering approaches (Figure 3-3) is emphasised, not as a hindrance, but as being necessary for both biotic and abiotic components of natural systems to be fully understood. True integration comes where knowledge of both of these components is used to develop new theory and understanding that is able to explain and predict their interaction, feedbacks and dynamics at different scales (so called 'extractive integration' by Renschler et al. 2007).

3.2.4.1 Some common ground

There is a considerable amount of common ground between biogeomorphology and ecosystem engineering that should aid their integration and mutual development. First, it has already been suggested that they are essentially interested in the same underlying process of biotically-mediated change to the physical environment (Figure 3-3). Second, there is a mutual interest in measuring the outcome of this interaction, whether it be classified as 'rates' or 'morphology' by geomorphologists, or 'habitat heterogeneity' or 'biodiversity' by ecologists. Sharing and mutual development of measurement techniques and data would be beneficial here. Third, identifying organisms which have the greatest physical impacts in the landscape is a key goal for both groups of researchers (Jones et al. 1997b; Stallins 2006). Consequently, the organisms of interest to biogeomorphologists and ecosystem engineering ecologists will very often overlap (e.g. Table 3-1). Fourthly, predicting where (in space) and when (in time) organismally-mediated physical change will be most important, and how dynamic these interactions are, are fundamental questions that both ecologists and biogeomorphologists share (e.g. Jones et al. 1994; Jones et al. 1997b; Naylor et al. 2002; Wright and Jones 2006; Hastings et al. 2007; Viles et al. 2008; Jones et al. 2010).

3.2.5 Summary: Linking biogeomorphology and ecosystem engineering for environmental management

Biogeomorphology places most emphasis on the *process* of biotically-mediated physical change, while ecosystem engineering places more emphasis on the ecological *consequences* of these interactions. Biogeomorphologists will gain much from involving ecologists in their studies, as they can offer insights into the consequences of biogeomorphic processes for other species and the wider ecosystem (Figure 3-4). Broadening current approaches to biogeomorphology in this way would not only enable geomorphologists to engage in – and contribute to – highly informative concepts in ecology, but also make the discipline more relevant to environmental management and conservation. Conversely, geomorphologists can provide insight into the 'ecosystem engineering process' (*sensu* Jones and Gutiérrez 2007), including the means and rate of its operation, its significance relative to other abiotic processes also altering the habitat and its response to environmental change. All of these processes can have feedbacks on ecology (Figure 3-4).

Adopting such an integrated approach offers considerable potential for understanding and predicting where and when the physical actions of organisms will be most important for environmental functioning and stability. This has considerable applied value, and moves beyond the study of unidirectional organism-environment interactions that has been a limitation of much previous biogeomorphological and ecosystem engineering research.

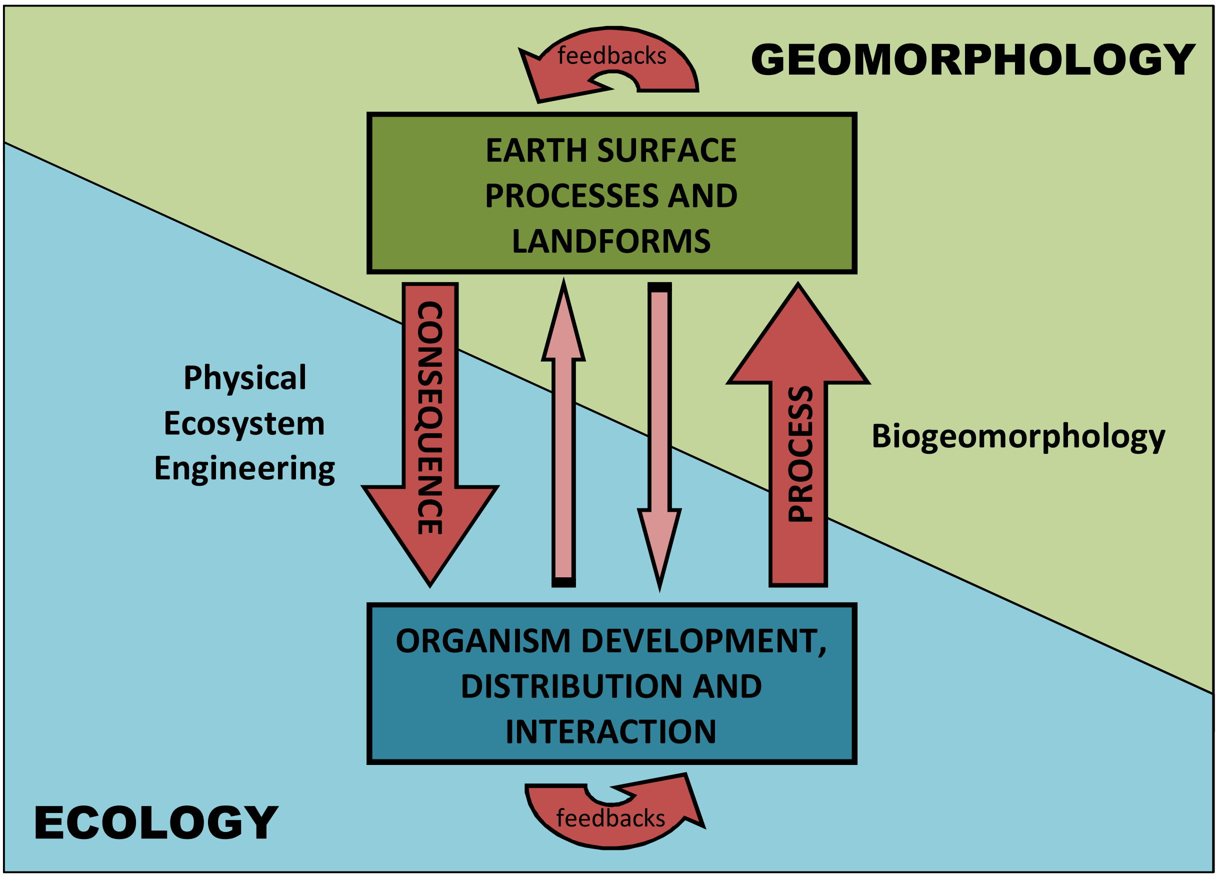

Figure 3-4 A framework for holistic understanding of biotically-mediated change to the physical environment (size of arrows indicates traditional disciplinary research emphasis and current knowledge base).

3.3 Thesis Conceptual Framework and Specific Research Objectives

In this interdisciplinary study, every effort has been made to incorporate both geomorphological and ecological approaches in a way that allowed advancement of both disciplines, while ultimately informing the core thesis questions surrounding ecological enhancement of hard artificial coastal structures. To do this, the work was structured using the biogeomorphological conceptual framework shown in Figure 3-5. The framework was developed from a review of the exiting literature (Chapter 2) and methodological approaches to geomorphology-ecology integration discussed in this Chapter.

The framework is based on the notion that any fresh (previously unexposed) material placed in the intertidal zone (whether through building of an engineered structure, or through natural disturbance on a rocky shore) will elicit two types of response: (i) a biotic response, involving the colonisation of the new surface, and (ii) an abiotic response, involving the physical modification of the surface through the operation of geomorphological processes upon it. These two broad categories of response (biotic and abiotic) may be regarded as the core interests of ecology and geomorphology disciplines in the context of this study, respectively. Correspondingly, the work was structured to inform questions and hypotheses of specific disciplinary interest (i.e. additive research), whilst ensuring that the design and data collected was relevant for both sets of questions. This knowledge structure is illustrated in Figure 3-6. For the field-based trials, for example, levels of replication were raised beyond that typically used in geomorphological experiments in order to ensure an ecologically robust design (see Chapters 5 and 6).

Specific research questions and experimental hypotheses tested under each of the main thesis aims (see Table 1-1 p. 37) are listed in Table 3-2; this table is also included as supplementary material to aid navigation through subsequent chapters. Specific background information for each set of hypotheses is given in their respective chapters, as indicated. Directional hypotheses were used in instances where there is sufficient evidence to suggest a particular relationships between measured variables; this was based on the comprehensive review of current understanding in both intertidal ecology and weathering geomorphology given in Chapter 2 and the repective experimental chapters.

Importantly, knowledge and understanding gained through each experimental component was used to develop theoretical understanding of hard artificial coastal structures as biogeomorphic systems, involving interactions and feedbacks between biotic and abiotic components (i.e. extractive integration, Figure 3-4 and Figure 3-6). Whilst an emphasis is placed on biotic-abiotic interactions throughout, consequences of biogeomorphic interactions and feedbacks are explored in a later, dedicated synthesis chapter (Chapter 9). This work is used to inform applied questions surrounding the ecological potential and enhancement of artificial hard coastal structures, including any implications of material responses for engineering durability (Figure 3-6 and Figure 3-5).

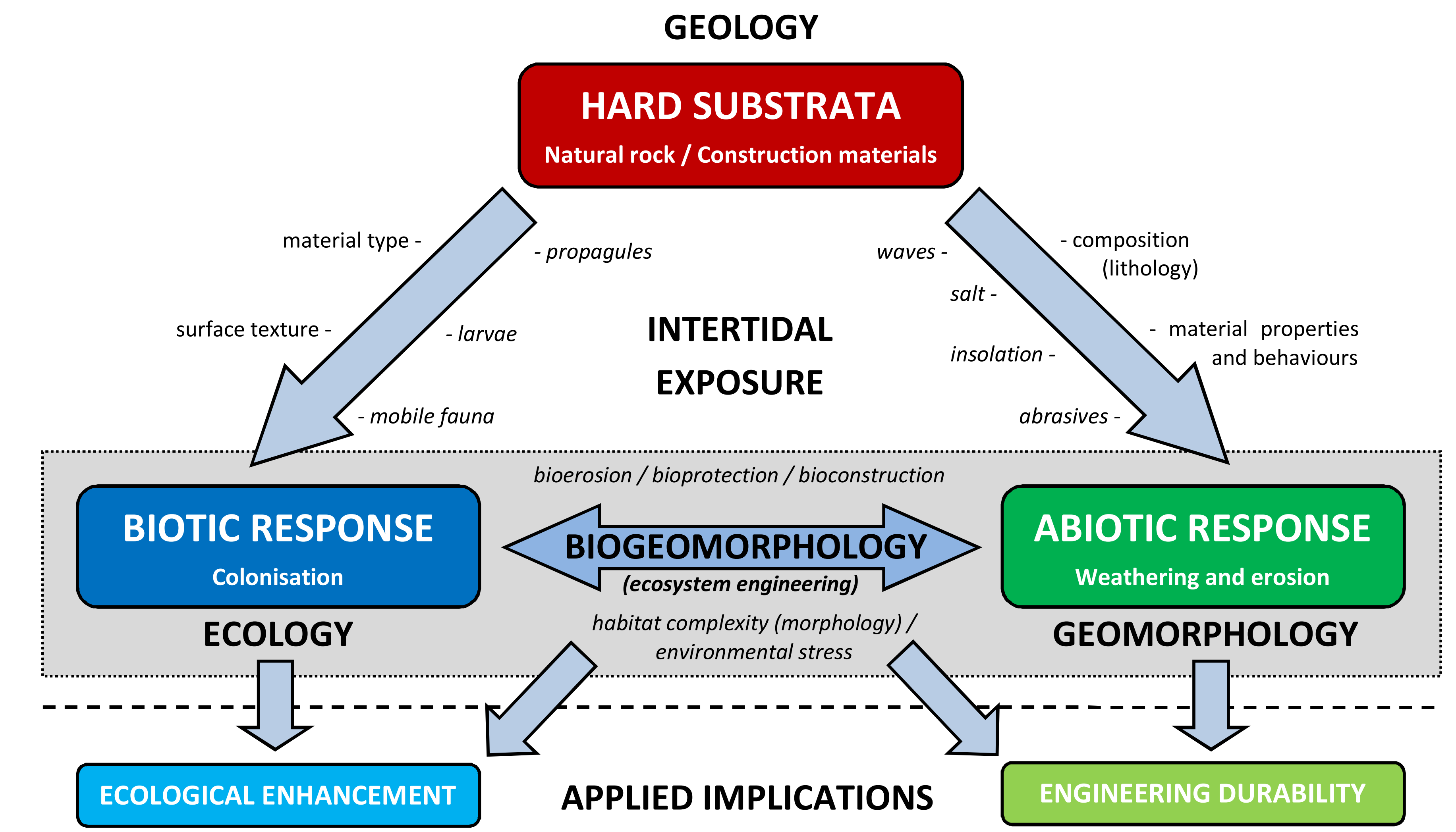

Figure 3-5 Thesis conceptual framework of biotic and abiotic responses of hard substrata during exposure in the intertidal zone.

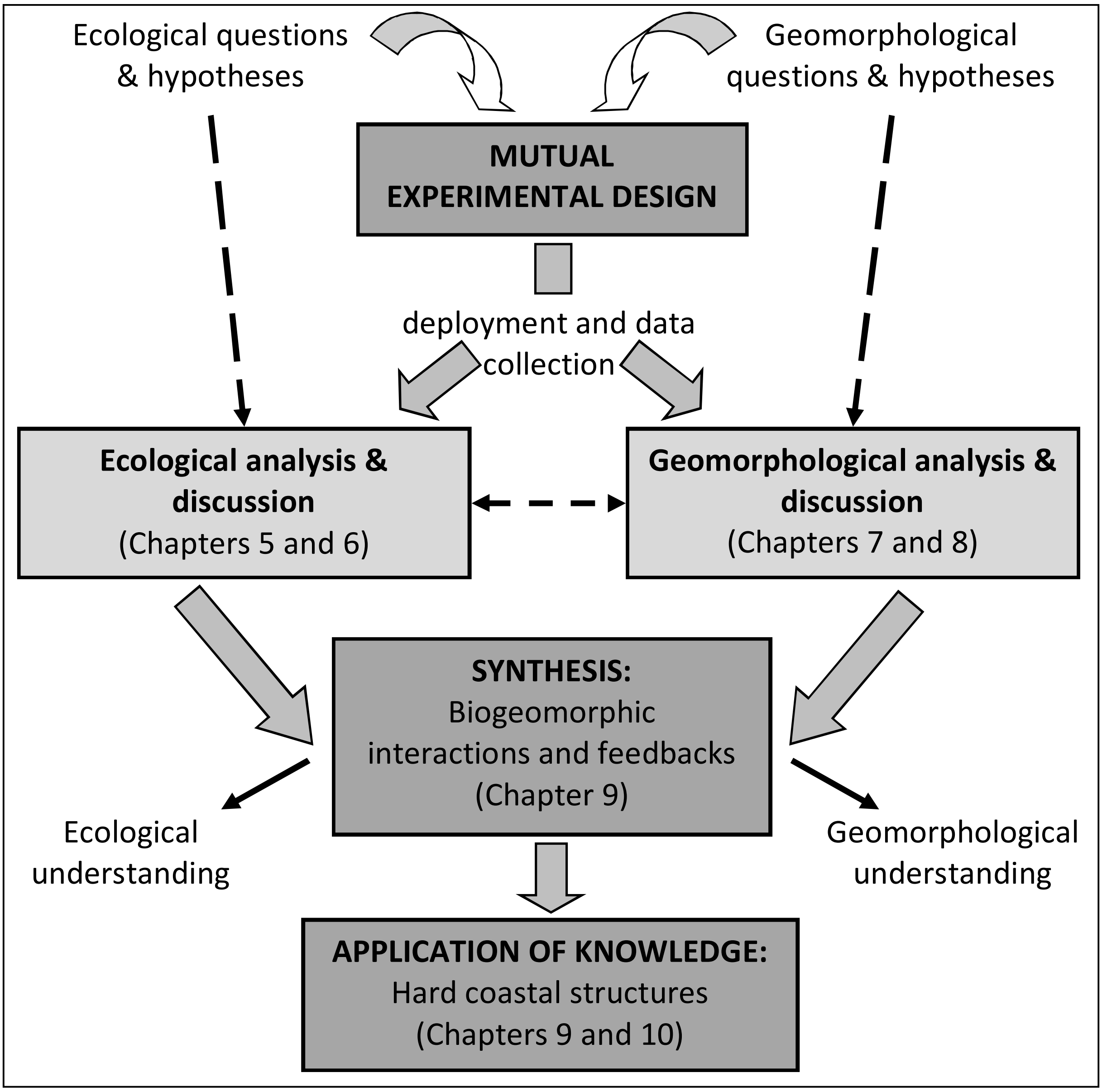

Figure 3-6 Schematic of the interdisciplinary knowledge structure used in this thesis.

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Table 3-2 Thesis aims, specific research questions and experimental hypotheses.

THESIS AIMS (see Table 1-1**)**	**#**	**SPECIFIC RESEARCH QUESTIONS**	**EXPERIMENTAL HYPOTHESES**	**RELEVANT THESIS CHAPTER**
AIM 1. **To improve understanding of biological responses (at a < cm scale) to different material types and textures used in coastal engineering.**	**1.**	How does colonisation compare between natural rocky shore substrata and introduced construction materials?	(1a) Settlement of barnacle cyprids is lower on introduced construction materials compared to natural platform rock.	**CHAPTER 5** **ECOLOGICAL RESPONSE (A):** MATERIAL TYPE p. 161
			(1b) Recruitment of adult metamorphs is lower on introduced construction materials compared to natural platform rock.	
	2.	How does colonisation compare between different types of construction material 'as-used' in coastal defence?	(2a) Settlement of barnacle cyprids is not the same between different materials representative of those 'as-used' in construction.	
			(2b) Recruitment of adult metamorphs is not the same between different materials representative of those 'as-used' in construction.	
	3.	How does mortality compare between natural rocky shore substrata and introduced construction materials?	(3) Morality of barnacle recruits is higher on representative construction materials compared to natural platform rock.	
	4.	How does mortality compare between different types of construction material 'as-used' in coastal defence?	(4) Mortality of barnacle recruits is different between material types representative of those 'as-used' in construction.	

Table 3-2 continued

THESIS AIMS (see Table 1-1)	#	SPECIFIC RESEARCH QUESTIONS	EXPERIMENTAL HYPOTHESES	THESIS CHAPTER
AIM 1. Continued…	**5.**	How does colonisation compare between smooth and rough versions of the same material type?	(5a) Settlement of barnacle cyprids is greater on roughened construction materials compared to smooth replicates.	**CHAPTER 6** **ECOLOGICAL RESPONSE (B):** MATERIAL TEXTURE p. 203
			(5b) Recruitment of adult metamorphs is greater on roughened construction materials compared to smooth replicates.	
	6.	Is the type of texture (at a mm-scale) important for colonisation of marine concrete – are some textures better than others?	(6a) Settlement of barnacle cyprids is not the same on concrete with different types of mm-scale surface texture.	
			(6b) Recruitment of adult metamorphs is not the same on concrete with different types of mm-scale surface texture.	
	7.	Can artificial texturing of construction materials be used to replicate early colonisation of a dominant organism occurring on natural rocky shore substrata?	(7a) Settlement of barnacle cyprids is no different (or higher) on construction materials with certain textures compared to natural platform rock.	
			(7b) Recruitment of adult metamorphs is no different (or higher) on construction materials with certain textures compared to natural platform rock.	
	8.	Does the presence of bio-chemical cues influence colonisation of rock substrata in this environment?	(8a) Settlement of barnacle cyprids is lower on sterilised clearings on platform rock compared to unsterilised clearings.	
			(8b) Recruitment of adult metamorphs is lower on sterilised clearings on platform rock compared to unsterilised clearings.	

Table 3-2 continued

THESIS AIMS (see Table 1-1**)**	**#**	**SPECIFIC RESEARCH QUESTIONS**	**EXPERIMENTAL HYPOTHESES**	**THESIS CHAPTER**
AIM 2. **To improve understanding of the geomorphological responses of different construction materials (at a < cm scale) during exposure in the intertidal zone, with particular attention on the role of biology in geomorphological change and implications for engineering durability.**	**9.**	How do microorganisms respond to different material types used in coastal engineering?	(9a) The occurrence of microbiological growth features varies between materials representative of those used in construction after a period of exposure in the intertidal zone.	**CHAPTER 7** **GEOMORPHOLOGICAL RESPONSE (A):** STRAND 1 p. 245
			(9b) The occurrence of microbiological growth features on different materials varies after different periods of exposure.	
	10.	How does **surface** weathering and erosion (at a micro-scale) compare between material types used in coastal engineering?	(10a) The occurrence of surface micro-weathering and erosion features varies between materials representative of those used in construction after exposure in the intertidal zone.	
			(10b) The occurrence of surface micro-weathering and erosion features on different materials varies after different periods of exposure.	
	11.	How does **subsurface** weathering and erosion (at a micro-scale) compare between materials types used in coastal engineering?	(11a) The vertical extent (depth) of weathering and erosion varies between materials used in construction after a period of exposure in the intertidal zone.	
			(11b) The vertical extent (depth) of weathering and erosion varies with exposure time.	

Table 3-2 continued

THESIS AIMS (see Table 1-1**)**	**#**	**SPECIFIC RESEARCH QUESTIONS**	**EXPERIMENTAL HYPOTHESES**	**THESIS CHAPTER**
AIM 2. Continued…	**12.**	How do bulk geomechanical properties of different construction materials compare (relative to each other) after exposure in the intertidal zone?	(12) Geomechanical properties of limestone, granite and marine concrete are different after initial exposure (< 2 years) in the intertidal zone.	**CHAPTER 7** **GEOMORPHOLOGICAL RESPONSE (A):** STRAND 2 p. 283
	13.	How do bulk geomechanical properties of construction materials vary after different amounts of time in the intertidal zone?	(13a) Geomechanical properties of materials exposed for different amounts of time (8 and 20 months) are not the same. (13b) The degree (statistical significance) and direction of change in geomechanical properties after exposure is not the same between material types.	
	14.	How do construction materials change morphologically (at an ecologically relevant scale) during intertidal exposure?	(14a) Surface roughness (at a mm-scale) is higher after exposure in the intertidal zone. (14b) Different materials types respond differently (morphologically, at a mm-scale) during exposure in the intertidal zone.	**CHAPTER 7** **GEOMORPHOLOGICAL RESPONSE (A):** STRAND 3 p. 295
	15.	How do morphological responses vary across the shore?	(15) Morphological development (surface roughness) varies between shore levels.	
	16.	How does the warming-drying behaviour of construction materials vary under intertidal conditions?	(16a) Warming-drying behaviours vary between material types under simulated and field intertidal conditions. (16b) Warming-drying behaviours are altered after a period of colonisation and weathering in the field.	**CHAPTER 8** **GEOMORPHOLOGICAL RESPONSE (B):** WARMING-DRYING BEHAVIOUR p. 333
	17.	What are the implications of substratum warming-drying behaviour for weathering and erosion, and colonisation?	N/A [Discussion]	

Table 3-2 continued

THESIS AIMS (see Table 1-1**)**	**#**	**SPECIFIC RESEARCH QUESTIONS**	**EXPERIMENTAL HYPOTHESES**	**THESIS CHAPTER**
AIM 3. **To improve understanding of interactions and feedbacks between geomorphological and ecological processes on different materials exposed in the intertidal zone, within a framework of biogeomorphology. [Discussion]**				**CHAPTERS 5 - 8**
AIM 4. **To apply biogeomorphological understanding as a tool for identifying opportunities for the ecological enhancement of hard coastal structures. [Discussion]**				**CHAPTER 9: SYNTHESIS** p. 395 **CHAPTER 10: CONCLUSIONS AND RECOMMENDATIONS** p. 435

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CHAPTER 4

EXPERIMENTAL MATERIALS

Selection, Procurement and Baseline Characterisation

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CHAPTER 4. EXPERIMENTAL MATERIALS

Selection, Procurement and Baseline Characterisation

4.1 Introduction and Aims

The same material types were used for all experimental work presented in *Part 3* of this thesis (Chapters 5 - 8). Materials were chosen to represent the broad range of types available for coastal engineering in the UK, with particular focus on sea defences (Allsop et al. 1985; BS 6349 2000; CIRIA 2007). Portland limestone and Cornish granite were chosen to represent relatively soft and hard geo-materials, respectively, and a standard marine concrete was also selected (Allen 1998). This allowed observation and comparison of ecological and geomorphological processes acting on two rock types with very different physical properties, alongside a standard artificial material widely used for shoreline armouring (see Section 2.2.2). Comparisons were also made between these materials and naturally occurring *in situ* substrata, as described in the following chapters.

The aim of this first chapter of *Part 3* is to present baseline information for the materials used throughout. Presenting this information separately avoids unnecessary repetition in each experimental chapter. Rationale for selection of each material (including previous use in coastal defence) is presented first (Section 4.2). Bulk geomechanical properties are then discussed (Section 4.3) as an assessment of the experimental materials in an engineering context with respect to their durability, and as a baseline characterisation for the work presented in Chapter 7: Strand 2 after a period of exposure in the intertidal zone. Finally, the surface morphology of the materials with textures used in field trials was characterised at the millimetre – centimetre scale using a simple profile gauge method (Section 4.4). Data collected are presented in Section 4.5 along with some general discussion in Section 4.6.

For field experiments (see following chapters), the selected materials were cut into blocks. The use of experimental blocks in intertidal ecology is well established as a way of observing ecological processes such as settlement and recruitment (Crisp and Barnes 1954), and exposure blocks are widely used in geomorphology as a way of examining the physical response of materials (i.e. weathering and erosion) in different environments and over different timescales (see Moses 2000 for a review). Although the same material types were used in all experimental work, specific details of block characteristics for each experiment (e.g. dimensions and surface textures) are given in their respective chapters; this chapter is reserved for description and general characterisation as a baseline for all subsequent discussions.

4.2 Selection and Procurement

Each of the three materials introduced into the tidal zone during field experiments are described in turn below; general characteristics of each are also summarised in Table 4-1.

4.2.1 Portland Limestone

Jurassic limestone from the Isle of Portland was chosen for use in field trials due to the relative ease of obtaining samples in a useable form (as dimension stone) and for its historical use in defence schemes along the Dorset coast, mainly as rock rubble armouring. Portland stone has been favoured over pre-cast concrete blocks in this part of the UK for its aesthetic qualities, and for considerably reduced transport costs compared to imported, more resistant rock (Clarke 1988). Notable examples of use include the Portland Harbour breakwaters between Portland and Weymouth (1872) and a succession of repair works to The Cobb harbour at Lyme Regis (in 1792, 1817, 1827 and the 1970s; Clarke 1988); both of these structures remain in operation today. Other examples include protection works at Hurst Castle Spit, Lepe beach and Durlston Bay cliff (Price 2002). More recently, Portland limestone was used for armouring a section of the West Bay esplanade, Dorset, as part of a larger flood defence scheme completed in 2004/5 (N. Browning, West Dorset District Council, personal communication, February 2009). Structures built from Portland limestone have also been studied in an ecological context in Dorset (Pinn et al. 2005a).

With respect to work presented in Chapters 7 and 8, Portland limestone has also been widely used in geomorphological research, including lab-based and field-based assessments of weathering processes (e.g. Trudgill et al. 1990; Viles 1990; Viles et al. 2002; Searle and Mitchell 2006) offering the opportunity for comparison with previous studies. The use of Portland limestone in this study represents a lower bounding example of the range of rock strengths used in UK coastal defence works.

Pre-cut (sawn) slabs of 40 mm thick Portland limestone were obtained directly from Perryfield Quarry on the Isle of Portland. Perryfield Quarry is operated by Stone Firms Ltd. as a relatively new quarry on Portland with reserves of stone expected to last beyond the current extraction licence up to 2042 (http://www.stonefirms.com/perryfield.php, accessed June 2008). The quarry provides a range of stone types from the Portlandian sequence, primarily as building dimension stone. The material obtained for this research was Whitbed limestone of Jurassic age. This stone is formed from micrite (calcium carbonate) ooids, with elongated to rounded shell fragments in a carbonate matrix. The stone is moderately compacted, with a fairly high intergranular porosity (BRE 1997b, Table 4-1).

Table 4-1 Summary of materials used in experimental work.

Material	Source	Description	Compressive strength (MPs)	Porosity (%)[†]	Surface finish	Example uses
Portland (Whitbed) Limestone	Perryfield Quarry, Isle of Portland (Stone Firms Ltd.)	A buff white oolitic limestone of Jurassic age. Representative of a relatively soft construction material.	62	15.64	Smooth, diamond sawn surface representative of quarried Portland dimension stone.	The Cobb, Lyme Regis (1820s) West Bay esplanade (2002) Portland Breakwater (1872)
Cornish Granite	De Lank Quarry, Bodmin (Ennstone Johnston Ltd.).	A dense silver-grey granite with a visible quarts, orthoclase and microcline crystalline structure. Representative of a relatively hard construction material.	212	0.90	Artificially textured (flamed), chosen to represent rough-dressed surfaces used in coping and irregular surface of rock rubble armour.	St. Ives lifeboat station (1994) Penzance seawall and rock rubble frontage (1970s) Eddystone lighthouse (1882)
Marine Concrete	Cast for purpose (University of Exeter Department of Engineering)	Portland cement and crushed granite aggregate mix to block armour specification (Allen 1998). Representative of a standard marine concrete mix.	36(48)*	13.61	Smooth, steel mold cast representative of pre-cast concrete armour units and *in situ* cast concrete structures. Some surface air holes.	Brighton marina (Akmon units, 1972-1977) Bangor North Breakwater (SHED units, c.1985)

[*]Concrete strength was determined 7 days after curing, strength after 28 days shown in brackets.
[†]Porosity was measured after 1 week soaking in distilled water (see Section 4.3.5).

4.2.2 Cornish Granite

Granite is a commonly used rock type in coastal defence given its durability properties (Fookes et al. 1988; CIRIA 2007). Most of the granite used in recent defence schemes in the UK has been imported from Europe to reduce costs, a notable example being Larvikite granite (monzonite) from Norway (Sims 1996a, b). In the South West, granite from local quarries has been widely used as a building stone in historic harbours (Stanier 1999) and in major defence structures such as the Plymouth Breakwater (1841, see Section 9.8.1.3), Dawlish Bay (1920s) and more recently at Par Harbour (http://www.aggregate-uk.com/rock_armour_b.htm, accessed June 2008).

Due to its widespread use in marine engineering, colonisation of introduced granite substrata by intertidal organisms has been previously studied (e.g. Pister 2007, 2009). Granite is also widely used in weathering studies, including the work by Mottershead (2000) who examined historical granite structures on the South West coast of England, and more recently by researchers examining mechanical weathering processes relating to temperature (e.g. Gómez-Heras et al. 2006) and bioweathering by microorganisms (e.g. Brehm et al. 2005; Hall et al. 2005a; Song et al. 2007; Chapter 7: Strand 1).

Granite was sourced from De Lank Quarry, Bodmin, Cornwall (Ennstone Johnston Ltd., now Breedon Aggregates Ltd.) as pre-cut slabs of various sizes. De Lank granite is a dense silver-grey granite with a quartz, orthoclase and microcline crystalline structure, recognised as a high-quality building stone in the UK. The granite was also used in the construction of three lighthouses on the south coast; Bishop's Rock, Scilly Isles (1858 and 1887), Eddystone, Rame (1882), and Beachy Head, Eastbourne (1900). More recently De Lank granite was used for rubble armouring at Penzance and Egloshayle, Cornwall (1970s), and for walls at St. Ives lifeboat station (1997; I. Skinner personal communication, December 2007).

4.2.3 Marine Concrete

Concrete provides a cheaper alternative to natural rock for coastal defence works, in both pre-cast and site-cast forms, and is consequently widely used as a construction material in the intertidal zone (Allen 1998; CIRIA 2007). Concrete was used in this study to improve understanding of ecological and geomorphological responses of artificial materials (compared to 'natural' rock) placed in the coastal zone, and to build upon recently published guidance on the use of concrete in maritime engineering within which ecological considerations are notably absent (CIRIA 2010, see Section 2.7.1 p. 94).

Concrete durability in the intertidal zone continues to be subject of intense research and debate in the engineering community (Benfeld and Newman 1986; Moukwa 1990; Novokshenov 1995; Matthews 2002; Sibbick et al. 2003; Neville 2004; Thaulow and Sahu 2004; Haynes et al. 2010; Liu et al. 2010b; Liu et al. 2010a, also see discussions in Chapters 7 and 9). Concrete has also been used in weathering simulations (e.g. Goudie 1993), although less frequently than rock and stone (see Chapter 7). Ecological studies on marine concrete have also been undertaken, including the DELOS Project in Europe (Section 2.5.1 p. 76), although the type of concrete used in colonisation trials is rarely specified (see Section 2.7.1 p. 94).

Within the bounds of engineering standards of practice, the selection of specific concrete mixes for marine structures is complicated owing to the broad range of options for aggregate type and size, water and cement content, and the use of admixtures (Allen 1998; CIRIA 2010). For the purposes of this study, a standard marine concrete mix with crushed granite aggregate was selected for all experimental work based on published guidelines (Allen 1998; CIRIA 2007) and through discussions with William Allsop, Technical Director of the Coastal Structures Group at HR Wallingford (Table 4-2). Concrete blocks were cast individually in a specially made steel mold at the College of Engineering, Mathematics and Physical Sciences, University of Exeter. The mold was coated with releasing fluid before filling with the concrete mix, and vibrated to remove air bubbles. Once set, blocks were removed from the mold and placed in a lime-water curing tank (at 21 °C) for 7 days. Compressive strength was determined using 150 mm cubes after 7 and 28 days (BS EN 12390-2, Table 4-1).

Table 4-2 Specification of marine concrete mix used in experimental work.

Portland Cement (BS EN 197-1)	350 kg/m³
Sand	640kg/m³
Nominal Max aggregate size (crushed granite aggregate)	40mm 1280 kg/m³
Free water cement ratio	0.50
Admixtures	None
Curing temperature	21°C

4.2.4 Natural substrata

Ecological and geomorphological responses of materials commonly used in marine engineering were the primary focus of this research (Chapter 1). However, properties of the rocks forming shores on which experimental blocks were exposed were also examined were appropriate. The geology and geomorphology of experimental shores is described specifically in Chapter 5.

4.3 Geomechanical Characterisation

4.3.1 Introduction

Various geomechanical and laboratory tests were used to characterise the bulk properties of the three experimental materials. The tests described below were carried out on control (i.e. unexposed) samples from the same stock materials used to make experimental blocks for field exposure (as described in Chapters 5 and 6), and were repeated after materials had been exposed in the sea for different amounts of time (described in Chapter 7: Strand 2). Bulk strength was measured using the Point Load Test (Section 4.3.2) as well as surface hardness using the Equotip (Section 4.3.3), 'soundness' using ultrasonic velocity tests (Section 4.3.4) and absorption properties using standard laboratory procedures (Section 4.3.5). Surface morphology of the materials was also quantified using a simple roughness parameter (Section 4.4).

These tests were primarily undertaken as an assessment of the materials in an engineering context, with respect to their durability as construction materials, and how this changed after field exposure (Chapter 7: Strand 2). Geomechanical rock properties were also of relevance in a rock coast geomorphology context (e.g. Sunamura 1992). Other than the expectation that the physical properties of the materials would vary, specific hypotheses were not tested in this chapter (which serves as a characterisation exercise). These tests were, however, used to inform questions and hypotheses concerning the ecological and geomorphological responses of the same material types in subsequent chapters (Chapters 5 – 8, see Table 3-2 and Supplementary Material B).

4.3.2 Point Load Test

The Point Load Test (PLT) is used in engineering geology and rock mechanics as a standard measure of bulk rock strength and durability (Norbury 1986; Ulusay and Hudson 2007). The test can be used as an index of strength for a range of material types (e.g. Broch 1983), including soft (e.g. Bowden et al. 1998) and hard rocks (e.g. Singh and Singh 1993). Point Load strength can be used to derive a range of other geotechnical parameters, including uniaxial compressive strength (Chau and Wong 1996; Çobanoğlu and Çelik 2008) or may used itself as an index of strength in comparisons between material types (Moses 2001; Moses et al. 2006). Point Load strength provides a quick and simple alternative to more time-consuming and expensive strength tests, and has commonly been used in durability assessments of marine armourstone (Latham et al. 2006).

The procedure consists of placing individual rock samples within a testing rig between two conical steel platens. The upper platen is hydraulically lowered by the operator using a lever until the sample fractures. The force required to break the sample (the failure load) is recorded from a pressure gauge (Norbury 1986). For the PLT it is recommended that samples have one long axis at least twice that of the short axis (ISRM 1985). Samples with the dimensions 100 x 40 x 40 mm ± 5 % were used here; control samples (described in this chapter) and field-exposed samples (described in Chapter 7: Strand 2) with the same dimensions were tested for comparability. In both cases, the test was carried out on 8 replicate samples of each material type, cut from a different parent block following a similar protocol used in the European Shore Platform Erosion Dynamics (ESPED) project (Moses 2001). The force (pressure, P) required to fracture each sample was recorded in kilonewtons (kN).

4.3.3 Equotip hardness

The Equotip is a device originally designed to test the hardness of metals (Aoki and Matsukura 2007a). It is increasingly being applied in a geomorphological context as a way of assessing variability and change in rock strength, and as a measure of weathering state (e.g. Aoki and Matsukura 2004; Mol and Viles 2010). The device is small, portable, non-destructive and quick and simple to use, with the added advantage of being more sensitive to hardness variations than the Schmidt Hammer test widely used in geomorphological studies (Goudie 2006a; Viles et al. 2011). The Equotip (standard model) was used in this study, therefore, as a way of assessing changes in a durability parameter (surface hardness) that is more sensitive to variation compared to other bulk testing procedures (including the Point Load Test described above).

The Equotip is an impact device, firing a 3 mm tungsten carbide ball at the measurement sample with an impact energy of 11 N/mm (Viles et al. 2011). The velocity of the ball as it rebounds from the surface is electronically measured and converted to a hardness value (the Leeb Number, *L*) which is recorded digitally by the device. The *L* value can also be used to estimate unconfined compressive strength (Aoki and Matsukura 2008), although raw hardness values (*L*) are used in this study as a simple, comparable measure of hardness between the experimental materials.

Features of the measurement sample such as moisture content, surface roughness and geometric dimensions are known to influence the test outcome (Verwaal and Mulder 1993; Hack and Huisman 2002; Feal-Pérez et al. 2010), although the results of Viles et al. (2011) suggest that block volume is less important for the Equotip. All samples were, however, cut to the same dimensions (100 x 40 x 40 mm ± 5 %) and allowed to air dry for several weeks before testing to ensure comparability. The sawn, smooth surface of limestone and granite, and the plain-cast surface of concrete were measured. A roughened (flame-textured) granite surface was also tested, which best reflected this material ‘as-used’ in rock rubble structures (see Chapter 5). Because the Equotip is known to be less reliable on rough materials (Feal-Pérez et al. 2010; Viles et al. 2011) measurements made on the smooth, sawn surfaces were used in comparisons with field-exposed samples described in Chapter 7: Strand 2. For each material type, the mean surface hardness (*L*) of 10 measurements (taken in different locations on the test surface) was calculated for each sample (n = 8 per material type).

4.3.4 Ultrasonic velocity

The ultrasonic velocity test is a non-destructive test based on the principle that the velocity of an ultrasonic pulse passing through a material is related to its density (and hence porosity) and elastic properties (Kahraman 2001). The test is particularly well applied in rock and concrete engineering research as a measure of rock and concrete 'soundness', with the advantage that the ultrasonic pulse passes though the complete thickness of the sample, allowing any significant defects to be detected (Winkler 1997; Demirboğa et al. 2004). Its particular attraction in this study was that the test is sensitive to the presence of imperfections, such as voids and cracks, and changes in strength and porosity which may result from weathering; such changes are expressed as a reduction in wave velocity (e.g. Begonha and Sequeira Brago 2002; Sousa et al. 2005; Ceryan et al. 2008).

The procedure involves placing two transducers (one emitting a longitudinal P-wave pulse and one receiving the pulse) at either ends of a sample. The velocity of the wave transmission through the sample (V_P) is recorded from an electronic display. The device was calibrated using a plastic sample of known dimensions and density before experimental samples were tested (BS 1881-203 1986). For each material type, V_P was calculated for the same 8 replicate samples used in other tests (above) as the mean of three repeat measurements (block dimensions = 100 x 40 x 40 mm ± 5 %).

4.3.5 Water absorption

The operation of various weathering and erosion processes, such as wetting-drying (Hall and Hall 1996; Trenhaile 2006), freeze-thaw (Hall 1987; Nicholson and Nicholson 2000), chemical dissolution (Trudgill and Viles 1998) and salt weathering (Goudie et al. 1970), are largely moisture-dependent. Water absorption properties are therefore widely recognised as one of the most important parameters affecting the susceptibility of rocks to weathering and erosion (e.g. Goudie and Viles

1997; Sumner and Loubser 2008). In a biogeomorphological context, the presence or absence of moisture also has implications for the occurrence of biological activity, both at the surface and within hard substrata (Viles 1995; Dornieden et al. 2000; Smith et al. in press). Furthermore, porosity and water absorption are closely related to concepts of rock durability in coastal engineering (Allsop et al. 1985; Fookes et al. 1988; Latham et al. 2006; CIRIA 2007, see Chapter 7 for further discussions), as well as the performance of concrete in the marine environment, where conditions for moisture-related deterioration are optimal (Allen 1998; Newy 2008; CIRIA 2010). Ecologically, substratum absorption properties (such as drying rate for example) may also influence colonisation by modulating micro-climatic conditions at the surface related to desiccation stress (e.g. Table 2-11 p. 91, see Chapter 8 for detailed discussions).

A standard measure of water absorption is Water Absorption Capacity (WAC), measured as a percent uptake of water. WAC has commonly been used to characterise rocks in weathering studies (e.g. Goudie et al. 1970; Cooke 1979; Goudie 1990). WAC provides an indication of material susceptibility to mechanical weathering (i.e. salt crystallisation, wetting and drying, and frost action) and chemical weathering processes (i.e. solution; Goudie 2004). WAC was determined for four replicate blocks of each material type in the laboratory (50 x 50 x 40 mm ± 5 %). Before the test, blocks were sealed on all but one face using three coats of polyurethane varnish for two reasons: first, sealing blocks restricted water movement through the one exposed face, which better replicates *in situ* structures and larger rock masses (e.g. Smith and McGreevy 1983); secondly, sealing was necessary in order to allow meaningful comparisons between control samples (described here) and those cut from larger blocks after a period of exposure in the field, which were also sealed (i.e. so that any differences in WAC could be attributed to alteration of the exposed, weathered face; described in Chapter 7: Strand 2). Sealing blocks in this way was also consistent with the experimental procedure used to characterise the warming-drying behaviour of the same materials under simulated intertidal conditions, as described in Chapter 8.

Sealed blocks were first washed and dried at 105 °C for 24 h and allowed to cool in a desiccator for two hours. The dimensions of each block were then measured using callipers and weighed to two decimal places. Volume (V), dry mass (M_s) and mass density (p_d) were subsequently calculated. Blocks were submerged in water (5 cm depth) at room temperature and periodically agitated to dislodge air-bubbles. After one week, samples were removed from the water and their varnished sides thoroughly dried with paper towels. The unvarnished surface of each sample was patted dry with a moist cloth to remove excess surface water and weighed to determine saturated wet mass (M_{SAT} ; Brown 1981). WAC was then calculated using Equation 1. WAC was determined in both distilled and artificial sea water (see Chapter 8 for specific details), the latter better reflecting field conditions in the intertidal zone (Moses 2001). Pore Volume (V_V) was also calculated using Equation 2, which was used to determine a measure of Porosity (*n*, Equation 3). All calculations were based on the recommendations of the International Society for Rock Mechanics (Brown 1981).

Equation 1: Water Absorption Capacity (WAC, %) $$\left(\frac{M_{SAT} - M_S}{M_S}\right) \times 100$$

Equation 2: Pore Volume (V_v, cm^3) $$\left(\frac{M_{SAT} - M_S}{1}\right)$$

Equation 3: Porosity (*n*, %) $$\left(\frac{V_v}{V}\right) \times 100$$

4.4 Surface Roughness

The importance of substratum surface roughness (i.e. texture/morphology) for the establishment of rocky shore epibenthic communities was discussed in Chapter 2. Furthermore, surface roughness is a property of engineering materials that may offer opportunities for manipulating the ecological potential of hard coastal structures (see Chapter 6).

Irrespective of the scale of concern, a common approach to measuring surface roughness is to record relative heights at set distances, from which topographic variability can be calculated (McCarroll and Nesje 1996). This principal can be applied at a landscape scale using remote sensing and Digital Elevation Models (DEMs) down to a sub-millimetre scale using laser scanning (see Chapter 7: Strand

3 for detailed discussions). For rapid and simple assessments of surface roughness, more sophisticated methods of measurement are inappropriate, particularly in the intertidal zone where scanners can be difficult to deploy (Swantesson et al. 2006). Alternative methods include profile-based systems of measurement such as the micro-roughness-meter (MRM; e.g. McCarroll 1992; Whalley 1994; Williams et al. 2000). The MRM approach involves tracing a detector attached to a reference frame across the test surface, either manually or in an automated fashion, to derive relative topographic data along the length of the trace (see McCarroll 1992). Profile data can also be extracted from 3D scans (e.g. Gómez-Pujol et al. 2006, Chapter 7: Strand 3).

The simplest method for collecting topographic data on rock surfaces is the carpenters profile gauge (Figure 4-1). This method involves pushing a set of moveable pins against the rock to create an 'imprint' of the test surface which may be either traced onto paper (e.g. Haigh 1981) or photographed (e.g. Crowther 1998) in the field. Profile data collected in this way can be used for qualitative visual representations of the test surface (e.g. Hall et al. 2008a), or can be analysed manually or digitally using spatial reference software (see below). The technique has been widely used in geomorphology to derive profile-based topographic information (e.g. Table 4-3) and has also been adopted in an engineering context (e.g. Barton et al. 1974).

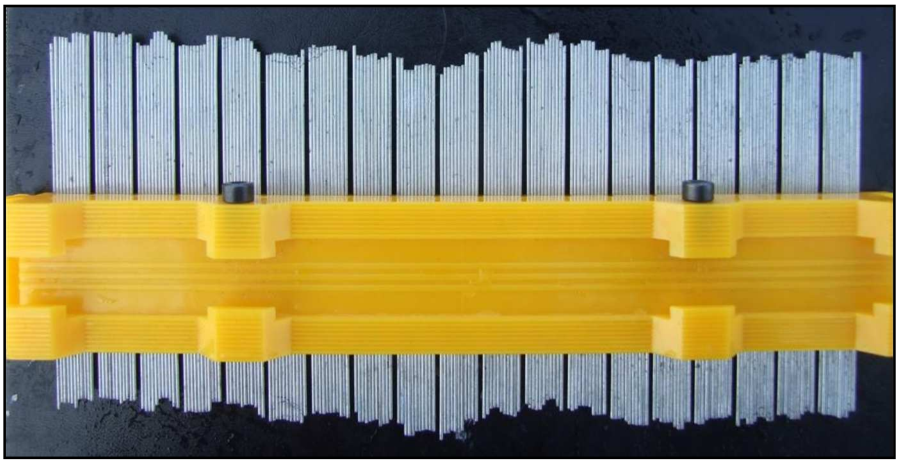


Figure 4-1 Carpenters profile gauge used to assess surface roughness in geomorphology (each pin = 0.8 mm).

Table 4-3 Example use of topographic profiles and associated roughness indexes in geomorphological research.

Reference	Research application	Technique	Sample size (no. of profiles) /means of collection	Resolution (measurement interval)
McCarroll and Nesje 1993	Rock surface roughness (granite) as a proxy for time since deglaciation, Nordfjord, Norway.	Profile gauge, MRM	10 per site, manual collection.	5 mm – 10 cm
Stewart 1996	Roughness of fault scarps as a proxy for time since exposure and seismic activity, Greece.	Profile gauge, MRM	20 per site, manual collection.	5 mm
McCarroll and Nesje 1996	Roughness as an indicator of rock weathering (hornblende picrite boulders) following coastal cliff erosion, Wales, UK.	Profile gauge	4 per boulder, manual collection.	5 – 30 mm
McCarroll and Nesje 1996	Roughness as an indicator of coastal limestone weathering, Gower Peninsular, South Wales.	Profile gauge	4 per site, manual collection.	5 – 30 mm
Crowther 1998	Morphometric analysis of rillenkarren, Mallorca, Balearic Islands.	Profile gauge	20 per site, manual collection and digitised for analysis.	1 mm
Gómez-Pujol et al. 2006	Morphological quantification and comparison of limestone surfaces at different tidal heights, Mallorca, Balearic Islands.	Profiles extracted from a laser scan	200 digitally extracted from laser scans.	1 – 30 mm
Guglielmin et al. 2005	Visual representation of weathered granite surfaces, Antarctica.	Profile gauge	4 presented (no analysis)	n/a
Hall et al. 2008	Visual representation of roughness of granite as an influence (i.e. shading effects) on thermal stress, Antarctica.	Profile gauge	2 presented (no analysis)	n/a

In rocky shore studies, ecologists have similarly adopted a range of methods to measure topography and surface roughness in the context of 'habitat heterogeneity' (see Chapter 2). The 'chain method' can be used to measure habitat heterogeneity at a meso-scale (m's), calculated as the ratio of the length between two points following the contours of a surface and the horizontal distance between the same two points (Trudgill 1988; Raffaelli and Hawkins 1996). At a smaller scale (< cm) Pinn et al. (2008) used a carpenters profile gauge to quantify the importance of bioerosion (by bivalve molluscs) for habitat heterogeneity on rocky shores, showing a positive correlation between boring activity and species diversity. Moschella et al. (2005) describe a technique involving the collection of cross-sectional profile data using plasticine imprints of rock surfaces. More recently, Martins et al. (2010) used soft aluminium strips to make surface imprints as a measure of substratum rugosity on basalt rocks and seawalls. More elaborate methods of measuring habitat complexity include fixing a habitat (such as a mussel bed) in plaster-of-Paris and removing it to the laboratory for sectioning (e.g. Commito and Rusignuolo 2000).

Here, the protocol outlined by McCarroll and Nesje (1996) for rapid assessment of rock surface roughness using a carpenters profile gauge was used as a simple characterisation of materials and textures used in field trials. A profile gauge with moveable pins (0.8 mm diameter, Figure 4-1) was pushed against the surface of control (unexposed) blocks of each material type and texture combination used in experiments described in Chapters 5 and 6. Four profiles (50 mm length) were collected in this way, each from different blocks (McCarroll and Nesje 1996), photographed against graph paper using a digital camera (Crowther 1998).

Digital images were subsequently scaled using ImageJ software (http://rsbweb.nih.gov/ij/, accessed February 2008) and used to extract *XY* coordinate data at 5 mm intervals along each profile trace (Figure 4-2). Coordinates were imported into a Microsoft Excel spreadsheet and used to calculate height differences (*Y*) between adjacent points at 5 mm, 10 mm, 15 mm, 20 mm and 25 mm intervals based on McCarroll (1997). The standard deviation (σ) of height differences measured along each profile trace (*n* = 10) were then used to calculate the ‘Index A’ roughness parameter at each measurement interval (McCarroll and Nesje 1996). Index A was also calculated for platform rock on both experimental shores (see Chapter 5) using the same procedures.

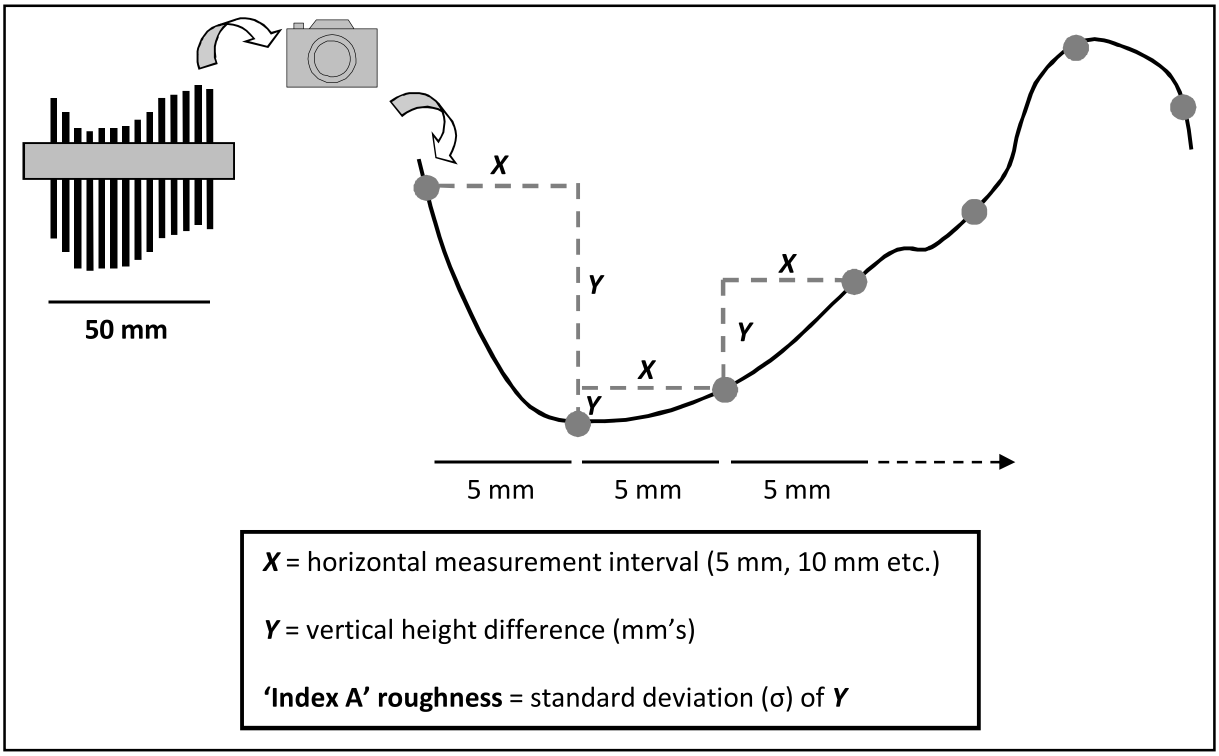


Figure 4-2 Calculation of the ‘Index A’ roughness parameter (after McCarroll and Nesje 1996) using vertical height differences at set intervals across profiles collected using a carpenters profile gauge (not drawn to scale).

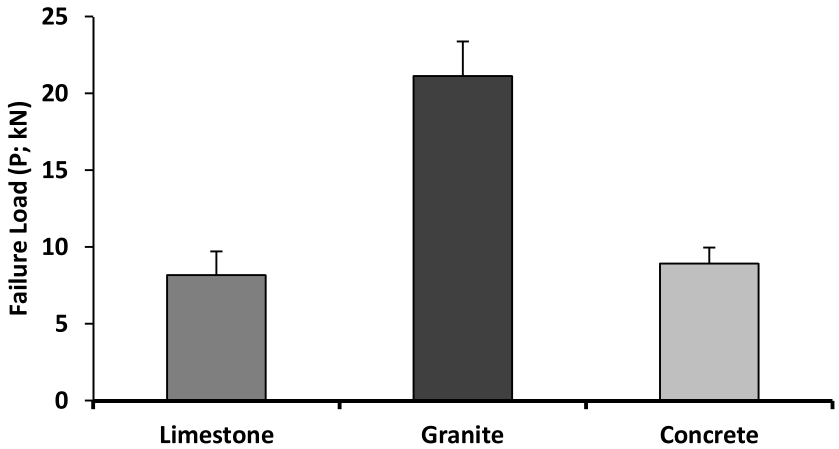
4.5 Results

4.5.1 Geomechanical properties

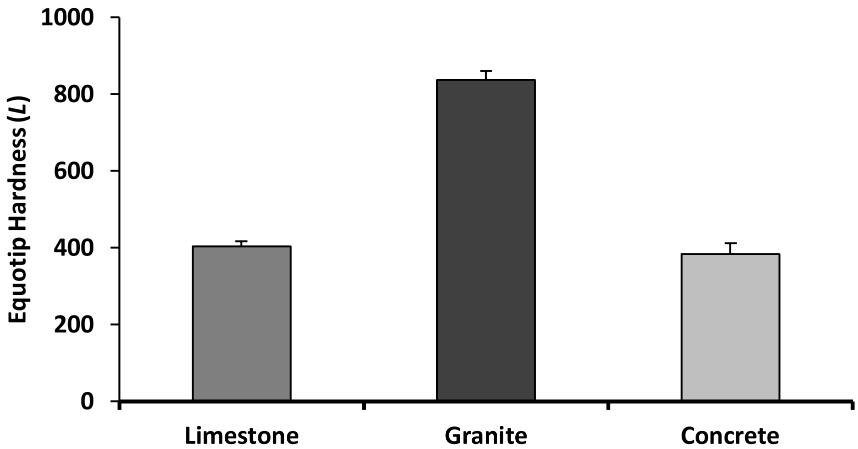
Measures of bulk strength (failure load, P, measured using the PLT), surface hardness (Equotip *L*) and soundness (sonic velocity) are shown in Figure 4-3 for the three materials (unexposed controls) used in this thesis. Water absorption properties (WAC and porosity) are shown in Figure 4-4, calculated in both fresh and synthetic sea water. Measured parameters were compared between material types using ANOVA and post-hoc Student Newman–Keuls tests (SNK; see 5.2.6 p. 180 for a detailed description of statistical procedures) to test the general hypothesis that they would be different.

The strength of the experimental materials was significantly different (Point Load, ANOVA $p < 0.000$, Figure 4-3a). As expected, Cornish granite was stronger than Portland limestone and marine concrete ($p = 0.01$). Concrete tended to have higher bulk strength values than limestone, but this was not significant using the PLT ($p > 0.05$). Measures of surface hardness showed the same trend (Equotip *L*, ANOVA $p < 0.000$, SNK test: concrete = limestone < granite, Figure 4-3b). Ultrasonic wave velocity (soundness) was also different between the three materials (ANOVA $p = 0.002$, SNK test: concrete = limestone < granite, Figure 4-3c). There was strong correlation between Point Load and Equotip strength measures (Pearson correlation $r = 0.93$), but relationships between these parameters and soundness were weaker ($r = 0.74$ and $r = 0.71$ for strength and hardness, respectively). Further discussions of correlations are made for field-exposed blocks in Chapter 7: Strand 2.

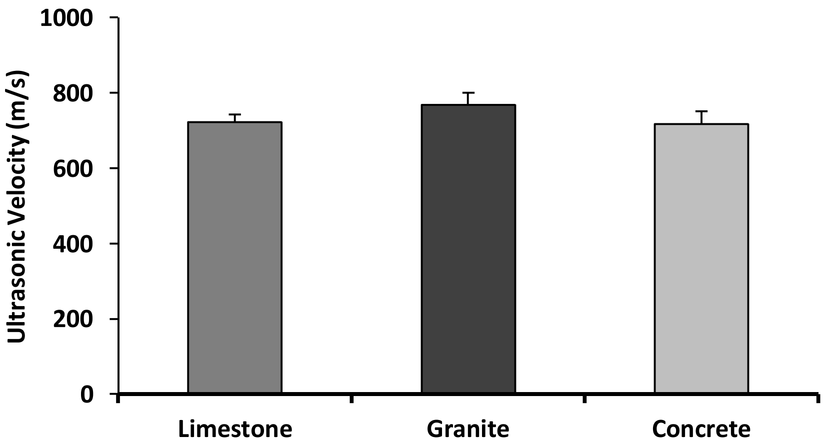
In synthetic seawater, measures of absorption correspond well to the other parameters; the strongest and hardest materials absorbed less water. Cornish granite had very low WAC (0.19 %) and porosity (0.50 %), both of which were significantly lower than both marine concrete (2.62 % and 6.10 % respectively) and Portland limestone (6.66 % and 14.38 % respectively). These differences were statistically significant (unpaired Student's t-test $p < 0.000$ for all comparisons). The same trends were measured in distilled freshwater.



(a) Bulk Strength (failure Load, PLT)

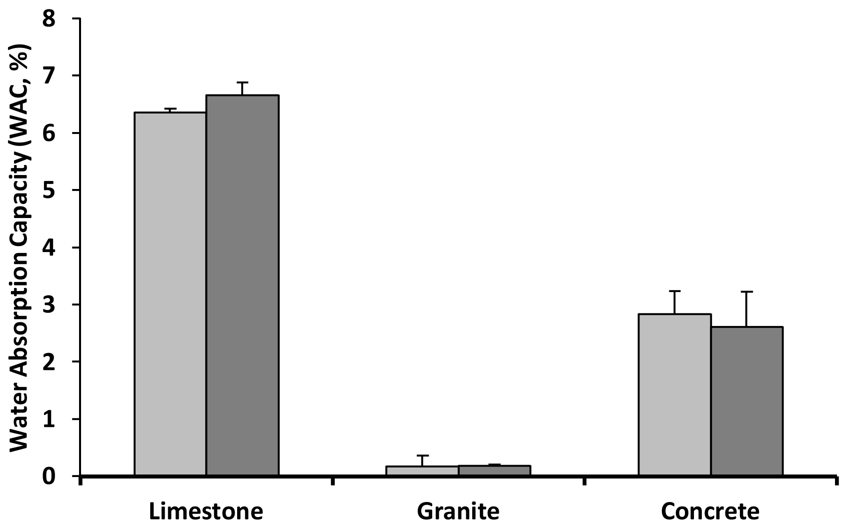


(b) Surface Hardness (Equotip)

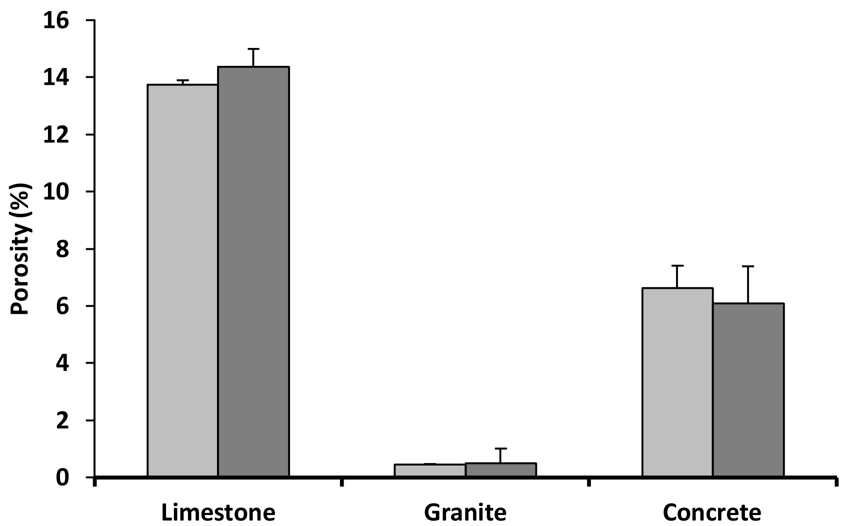


(c) Soundness (ultrasonic velocity)

Figure 4-3 Geomechanical parameters for construction materials (unexposed controls) used in experimental work: (a) Point Load Strength (P, kN); (b) Equotip Rebound Hardness (*L*); (c) Ultrasonic Velocity (soundness; mean + SD, *n* = 8).



(a) Water Absorption Capacity



(b) Porosity

Figure 4-4 Water absorption properties of construction materials (unexposed controls) used in experimental work, determined in distilled water (darker fill) and synthetic seawater (lighter fill): (a) Water Absorption Capacity; (b) Porosity (mean + SD, *n* = 4).

4.5.2 Surface roughness

‘Index A’ roughness values calculated from digitised profiles are shown in Figure 4-5 as a ‘deviogram’, representing roughness at different scales (5 – 25 mm; after McCarroll and Nesje 1996). The roughness of each material x texture combination used in field trials (see Chapters 5 and 6) are presented here alongside roughness measures for platform rock on the two experimental shores (see Section 5.2.1 p. 165).

Platform rock was rougher than all experimental treatments at all measured scales (Figure 4-5). Blocks of granite and limestone artificially textured for field trials (described in Chapter 5) were rougher than smooth alternatives at this scale (> 5 mm’s). Of four concrete treatments used in field trials (described in Chapter 6), blocks with an ‘exposed aggregate’ finish were roughest at the measured scales. ‘Plain-cast’ concrete was the next roughest, although this reflected the presence of air-holes rather than texture across the entire surface (e.g. Figure 6-1 p. 209). ‘Brushed’ and ‘wiped’ concrete showed similar roughness values at this scale (Figure 4-5); grooves created on brushed concrete were, however, too fine to be recorded at the smallest scale of measurement used in this general characterisation (5 mm), but see Chapter 7: Strand 3 for measurements at a smaller scale.

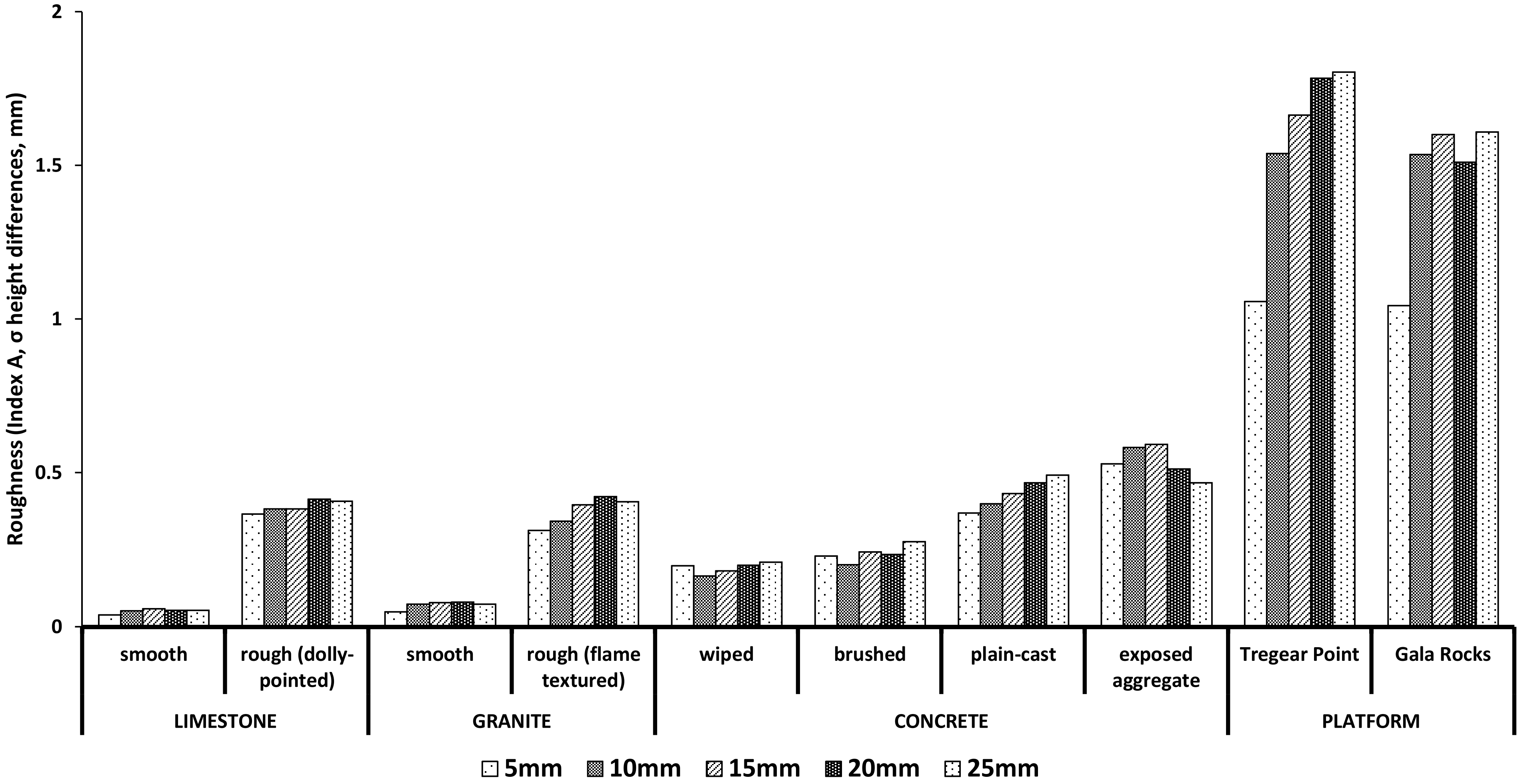


Figure 4-5 'Deviograms' for control (unexposed) materials and textures used in block exposure trials described in Chapter 5 and 6 (bars represent mean roughness [Index A, after McCarroll and Nesje 1996] at different measurement scales, as indicated, *n* = 4).

4.6 Discussion and Conclusions

The results of the tests described above correspond well with known durability properties of the three experimental materials. Cornish granite showed very high bulk strength and hardness, and very low water absorption and porosity; this material is therefore expected to perform very well under aggressive marine conditions in an engineering context (Dibb et al. 1983; Sousa et al. 2005). Portland limestone and marine concrete showed similar geomechanical properties, however significant differences in water absorption and porosity (limestone > concrete, Section 4.5.1) suggested that the limestone may be more susceptible to alteration in the intertidal zone (CIRIA 2007). The efficiency of salt crystallisation, for example, is largely dependent on the ability of salts to occupy internal pore spaces in solution (Goudie and Viles 1997). The porosity and hardness of substrata is also known to influence the development of microbiological communities (e.g. Gorbushina and Broughton 2009) and the potential efficiency of biological weathering agents (e.g. Miller et al. 2010, also see detailed discussions in Chapter 7).

The characterisation presented in this chapter serves as a baseline for assessments of the ecological and geomorphological responses of the same material types described in the following four chapters (Chapters 5 – 8). Specifically, differences in the geomechanical properties described above were considered in relation to: (i) the nature of colonisation on the different material types (by barnacles [Chapters 5 and 6] and microorganisms [Chapter 7: Strand 1]); (ii) the operation of weathering processes and resulting morphological change (Chapter 7: Strands 1 and 3); (iii) the durability of the materials in response to marine conditions and colonisation (Chapter 7: Strand 2), and; (iv) the warming-drying behaviours of the materials in relation to weathering and their properties as biological substrata (Chapter 8). These themes were subsequently used to inform the discussion of biogeomorphological interactions and ecological enhancement of coastal structures presented in Chapter 9.

CHAPTER 5

ECOLOGICAL RESPONSE (A): MATERIAL TYPE

Settlement, Recruitment and Mortality of Barnacles on Common Construction Materials

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CHAPTER 5. ECOLOGICAL RESPONSE (A): MATERIAL TYPE

Settlement, Recruitment and Mortality of Barnacles on Common Construction Materials

5.1 Introduction, Aims and Hypotheses

5.1.1 Introduction

There is an abundance of experimental work examining biological colonisation of a range of substrata in the intertidal zone (Barnes and Powell 1950; Crisp and Barnes 1954; MacLulich 1986; Chabot and Bourget 1988; Raimondi 1988b; McGuinness 1989; Johnson 1994; Glasby and Connell 2001; Bulleri and Chapman 2004; Herbert and Hawkins 2006). However data on materials that reflect those used in the construction of coastal defences is limited, particularly for artificial materials such as concrete (see Chapter 2 for a review). Understanding how marine organisms respond to materials 'as-used' in construction (i.e. with surface finishes representative of those commonly used) is important in order to predict the ecological consequences of coastal defence, and to identify potential ways to improve the ecological value of defence structures in line with conservation aims and policy requirements (Moschella et al. 2005; Burcharth et al. 2007, Directive 2000/60/EC, Section 2.4).

This chapter describes a field block exposure trial (referred to as '*Exposure Trial 1*' throughout) to examine the response of a common intertidal organism (the barnacle) to different hard substrata introduced to the intertidal zone through hard coastal engineering, and to allow comparisons with responses on *in situ* rocky shore substrata. Barnacle responses to textural manipulations on the same materials are described in the following chapter (Chapter 6). Observations of biological responses at a micro-scale (microorganisms) are then discussed in Chapter 7 on the same materials in a context of weathering and erosion.

5.1.2 Study organisms

Barnacles (subphylum: Crustacea, infraclass: Cirripedia) are globally abundant organisms, typically found on the mid-shore in moderately exposed locations. Adults are generally small (< 1 cm) and are permanently fixed (i.e. sessile) to the substratum. The morphology and distribution of British species has been described in detail by Southward (2008). Briefly, adults consist of the organism body (made up of the prosoma, thorax and cirri structures) encased in a shell (or 'test') formed of multiple calcareous (calcium carbonate) plates forming the operculum, variations of which are used in identification (Figure 5-1a-d). Common to all species (except Verrucomorpha) is the presence of two pairs of moveable plates which retract during immersion to allow the cirrial fan to extend into the water column for filter feeding. Plates are closed during periods of emersion to protect the body from predation and environmental stresses, particularly desiccation (Southward 2008).

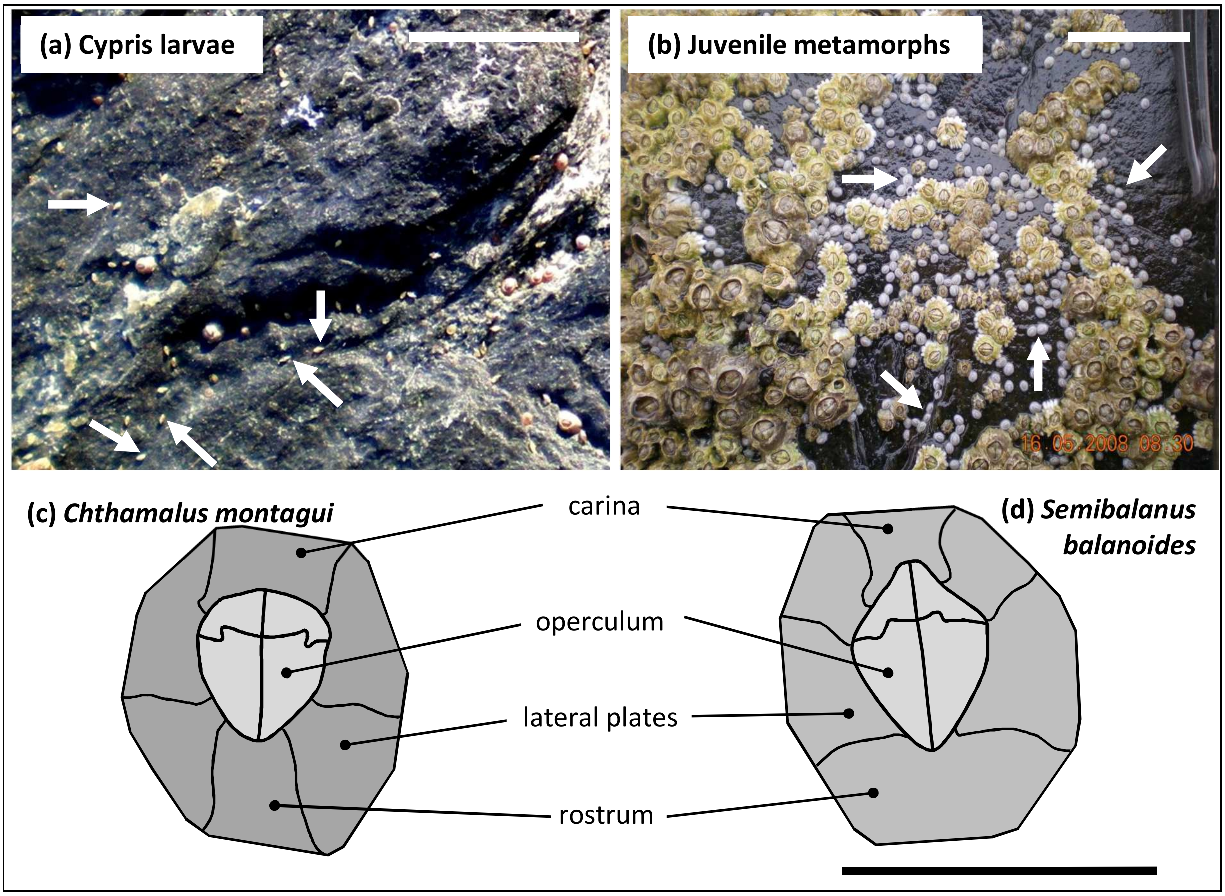


Figure 5-1 Study organisms: (a) barnacle cyprid larvae (b) barnacle juvenile metamorphs (spat) and adults (c) *Chthamalus montagui* (d) *S. balanoides* (line indicates 1 cm for scale).

Barnacles have been used widely as a model organism in ecological studies for a number of reasons. First, barnacles are globally abundant on rocky shores and are also commonly found on artificial structures (Mann 2000; Southward 2008). Second, the life-cycle of barnacles is typical of many epibiotic marine invertebrates, having free-swimming larval stages (nauplii and cyprid) which settle and metamorphose into sessile adults (Southward 2008). Thirdly, settling cyprids and metamorphosed juveniles can be seen with the naked eye (Figure 5-1a-b), which lends itself particularly well to field monitoring (Jenkins and Hawkins 2003). Barnacles therefore provide an ideal organism to study the mechanisms of, and influences on, colonisation of hard substrata by marine invertebrates (e.g. Crisp and Barnes 1954; Hawkins and Hartnoll 1982a; Fletcher and Callow 1992; Rodriguez et al. 1993; Walters and Wethey 1996; Thompson et al. 1998; Delany et al. 2003; Herbert and Hawkins 2006; Pendergast et al. 2009; Aldred and Clare 2009).

Ecologically, barnacles have been described as ecosystem engineers (see Chapter 3) in the intertidal zone (Harley 2006), demonstrating positive influences on the recruitment and survival of other organisms including algae (Hawkins 1981; Farrell 1991; Williamson and Rees 1994; van Tamelen and Stekoll 1996), molluscs (Creese 1982; Navarrete and Castilla 1990) and arthropods (Harley 2006). Thompson et al. (1996), for example, found that more species were typically associated with barnacle test matrixes compared to bare rock, at multiple spatial scales. In a wider context, barnacles have been used as an indicator species for change in marine environments, including productivity (Leslie et al. 2005) and, in particular, climate change (Southward et al. 1995; Hawkins et al. 2003; Herbert et al. 2007; Hawkins et al. 2008; Poloczanska et al. 2008, also see Chapter 8).

For *Exposure Trial 1*, colonisation of experimental blocks by intertidal Chthamalid barnacles was monitored on two shores in Cornwall, UK, during spring and summer of 2008 and 2009. On the south coast of the UK, two species of *Chthamalus* (Figure 5-1c) are found with overlapping distributions on the shore. *Chthamalus montagui* is abundant from High Water Spring (HWS) down to Low Water Neap (LWN; Southward 1976; Kendall and Bedford 1987; Southward 2008) while *Chtamalus stellatus*

(Poli) also occurs from Mean Tide Level (MTL) to Mean Low Water Spring (MLWS). *C. montagui* is typically the dominant species (Crisp et al. 1981; Burrows et al. 1999; Southward 2008). *Chthamalus* breed from April to September and larvae settle on the shore from early summer to late autumn. No distinction was made between the two *Chthamalus* species in this study for simplicity. *Semibalanus balanoides* (Linnaeus) is a typically more dominant species that reproduces in winter, releasing larvae in early spring and settling in April and May (Figure 5-1d); settlement of *S. balanoides* was monitored alongside *Chthamalus* spp. in '*Exposure Trial 2*' described in the following chapter (Chapter 6).

5.1.3 Experimental hypotheses

Hypotheses were chosen relating to three principal stages of barnacle colonisation (Table 5-1): **(1) Settlement** – the arrival of the settling cypris larva on the substrate (e.g. Figure 5-1a); **(2) Recruitment** – the persistence of the metamorphosed organism for a defined period of time, here recorded as a recruitment of adults at the end of the settlement season (e.g. Figure 5-1b), and; **(3) Mortality** – which can result from various environmental and ecological stresses and disturbance (Connell 1985; Wahl 1989; Hawkins and Jones 1992; Connell and Glasby 1999; Connell 2001; Chapman 2003; Delany et al. 2003; Bulleri and Chapman 2004; Bulleri 2005b, see later discussions). Hypotheses were based on previous experimental research and a review of studies comparing colonisation of different substrata on natural shores and artificial structures (Chapter 2). In each case, the experimental design allowed for comparisons between introduced substrata representing those used in construction (see Section 5.2.2 below), and between the introduced substrata and *in situ* platform rock. The design also enabled spatial comparisons at the metre and kilometre scale between replicate plots, and between shores (Table 5-1).

Table 5-1 *Exposure Trial 1* research questions and experimental hypotheses (see Table 3-2).

	Research Question	Hypothesis
1	How does colonisation compare between natural rocky shore substrata and introduced construction materials?	(1a) Settlement of barnacle cyprids is lower on introduced construction materials compared to natural platform rock. (1b) Recruitment of adult metamorphs is lower on introduced construction materials compared to natural platform rock.
2	How does colonisation compare between different types of construction material 'as-used' in coastal defence?	(2a) Settlement of barnacle cyprids is not the same between different materials representative of those 'as-used' in construction. (2b) Recruitment of adult metamorphs is not the same between different materials representative of those 'as-used' in construction.
3	How does mortality compare between natural rocky shore substrata and introduced construction materials?	(3) Morality of barnacle recruits is higher on representative construction materials compared to natural platform rock.
4	How does mortality compare between different types of construction material 'as-used' in coastal defence?	(4) Mortality of barnacle recruits is different between material types representative of those 'as-used' in construction.

5.2 *Exposure Trial 1*: Experimental Design

5.2.1 Experimental shores

In order to test for generality and to allow spatial comparisons, two rocky shore platforms were selected in Cornwall as independent replicate shores on which experimental blocks (described in the following section) were placed. Shore 1 was located on the south coast of Cornwall at **Tregear Point**, west of Porthleven harbour (50:05:07N 5:19:60W). Shore 2 was located on the north coast of Cornwall at **Gala Rocks** near Zennor, 20 km north-west of Tregear Point (50:12:05N 5:33:50W) (Figure 5-2). The specific locations of both experimental shores were selected for the reasons described in Table 5-2.

Table 5-2 Parameters for selection of experimental shores.

1	**Barnacle cover**	Both shores had a dense cover of adult barnacles on the mid-shore (mostly *C. montagui* with some *C. stellatus* and *S. balanoides*), indicating that settlement would likely occur on experimental substrata during the course of the trial.
2	**Platform gradient**	Shores were relatively flat, which maximised time available for sampling between subsequent tides, and facilitated block attachment (Section 5.2.3).
3	**Proximity to research base**	Shores were within an hour's reach of the University of Exeter Tremough Campus, Penryn, by car and public transport, enabling frequent visits during installation and periods of barnacle monitoring.
4	**Public access**	Tregear Point is situated out of sight of the well-used South Coast Path and Gala Rocks is not easily accessed from the coast path; this was intended to minimise the risk of disturbance and vandalism.
5	**Proximity to existing hard defences**	Both field sites are within 5 miles of towns with existing defended harbours and active coastal management issues. Both Porthleven (east of Tregear Point) and St. Ives (north-east of Gala Rocks) are important commercial fishing harbours and areas of local tourist interest.
6	**Permissions**	Permissions were successfully sought at both sites from all relevant bodies, organisations and landowners. This included the Environment Agency, Natural England, the Nation Trust, Local and District councils, and the Duchy of Cornwall.

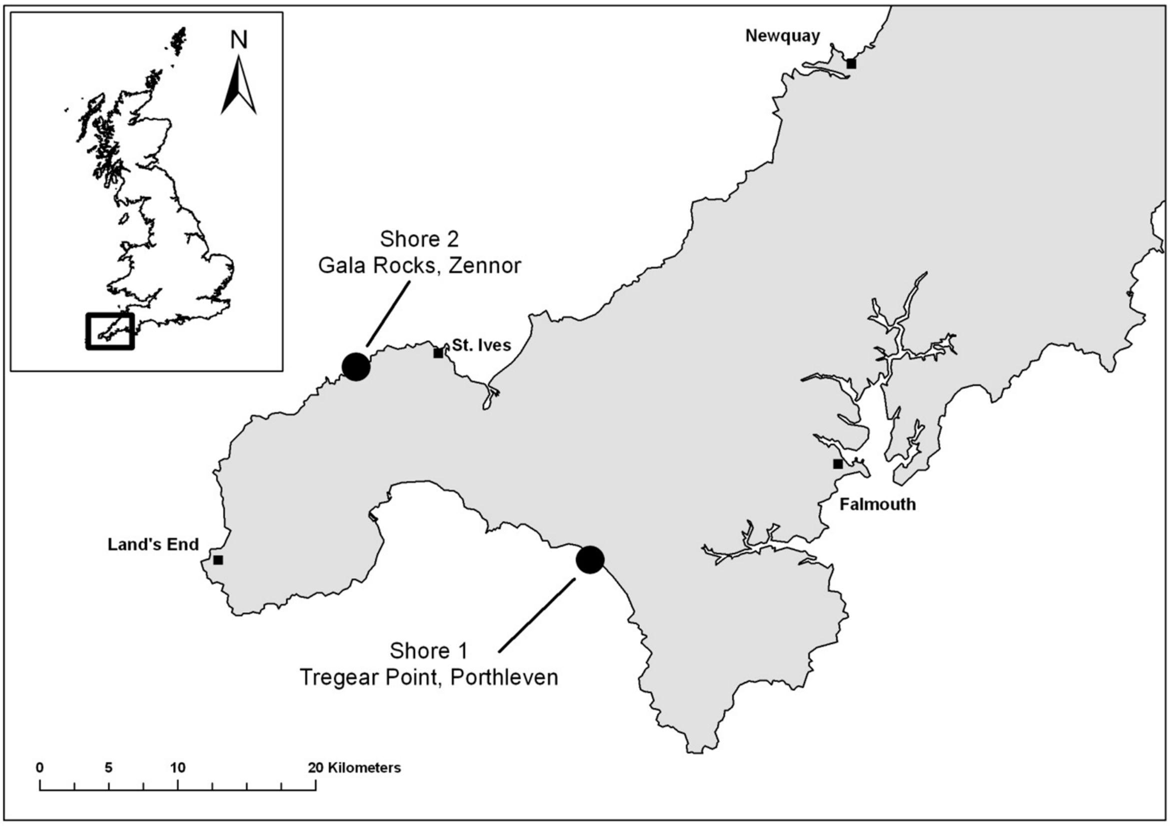


Figure 5-2 Locations of experimental shores.

5.2.1.1 Tregear Point, Porthleven (Shore 1)

A site map of Tregear Point, Porthleven, is shown in Figure 5-3. Materials were fixed on a rocky platform 0.7 km west of Porthleven harbour, formed of rocks of Devonian (Famennian) age, predominantly the dark grey slates of the Mylor Slate Formation (Kratinova et al. 2003; Schmidt Hammer hardness = 33.6, n = 60). The cliff backing the shore is near vertical, formed of the same rock type with poorly developed head deposits overlain by a thin layer of loess (Ealey and James 2001). The slates consist of thinly interbedded mudstone, and cross-laminated siltstone and fine-grained sandstone, with occasional harder quartz dolerite sills (Leveridge and Hartley 2006).

The morphology of the platform is dominated by a series of stepped rock ledges extending in a south-western direction from the cliff. Experimental blocks were attached in relatively flat, but heavily jointed areas of rock at MTL (Figure 5-3). Long profiles across the platform are shown in Figure 5-4a, recorded using a hand-held GPS. Several major faults dissect the platform in NW – SE and NE – SW directions, which have been widened by wave action and abrasion. Tafoni weathering forms are present on the upper shore, while evidence of joint-block and scar erosion (at a scale of tens of centimetres) was common on the bedded slates in the middle and lower areas of the platform. Flaking and exfoliation of slates is also common where bedding is particularly thin.

Barnacles (*Chthamalus* spp. and *S. balanoides*, see Section 5.1.2) occupied 85 ± 10 % of available space at MTL (quadrat counts, n = 15) and it was not uncommon for encrustations to be several individuals thick in some areas (an indication of overcrowding e.g. Dungan 1985; Bertness 1989). Limpets (*Patella* spp.) were also abundant on the mid-shore (24 ± 3 individuals per 1 m^2, n = 15), while mussels (*Mytilus edulis*) and algae (mainly *Fucus serratus*) occurred in isolated clumps. Barnacle abundance generally decreased from the mid-shore to MHWN, where surface cover was 30 ± 20 % (n = 15). There were very few limpets at MHWN (see discussions in Chapter 7: Strands 1 and 4) while small Littorinid snails were abundant here (*L. plena* and *L. scutulata*). Bare rock constituted the greatest proportion of the surface at MHWN.

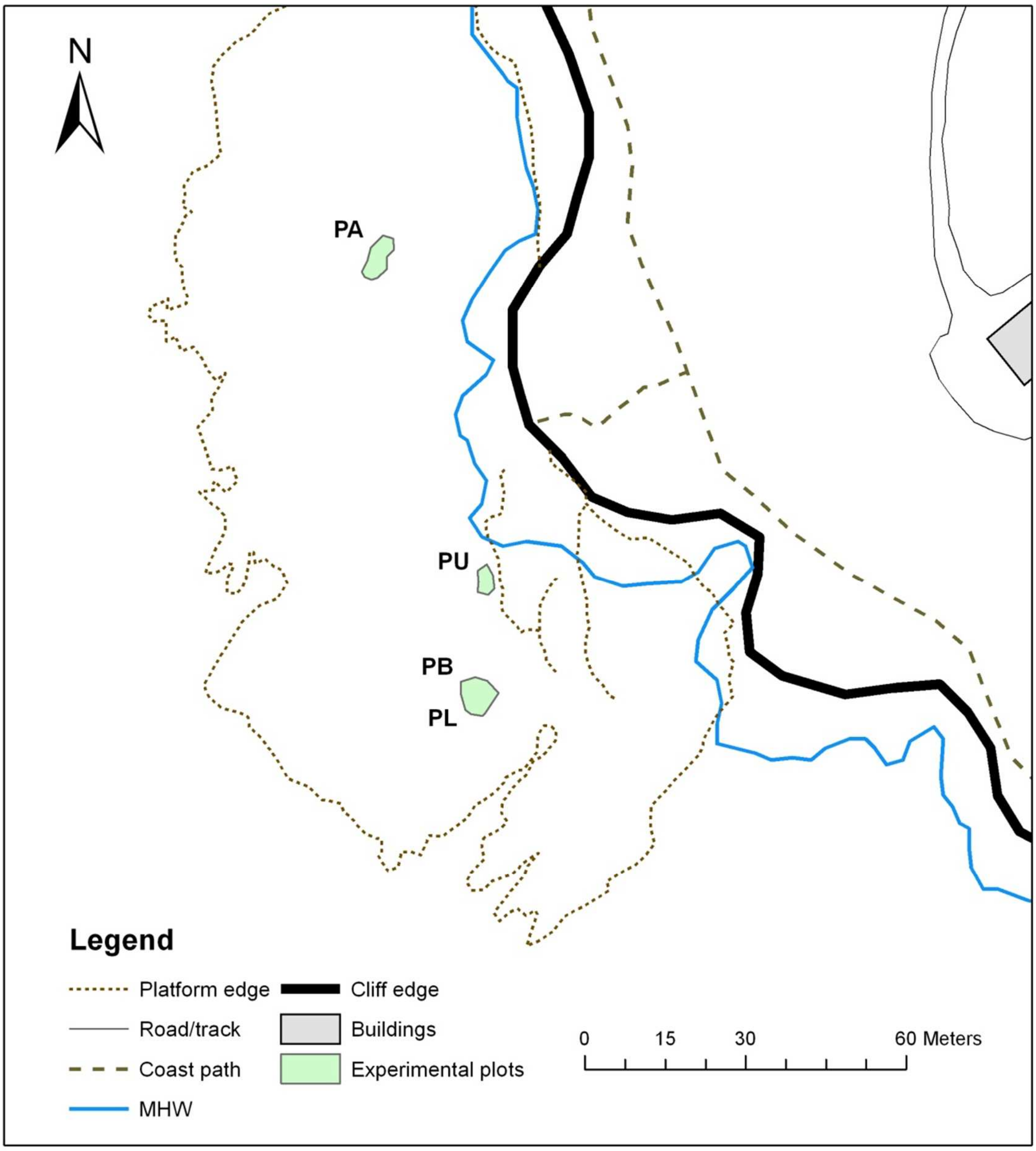
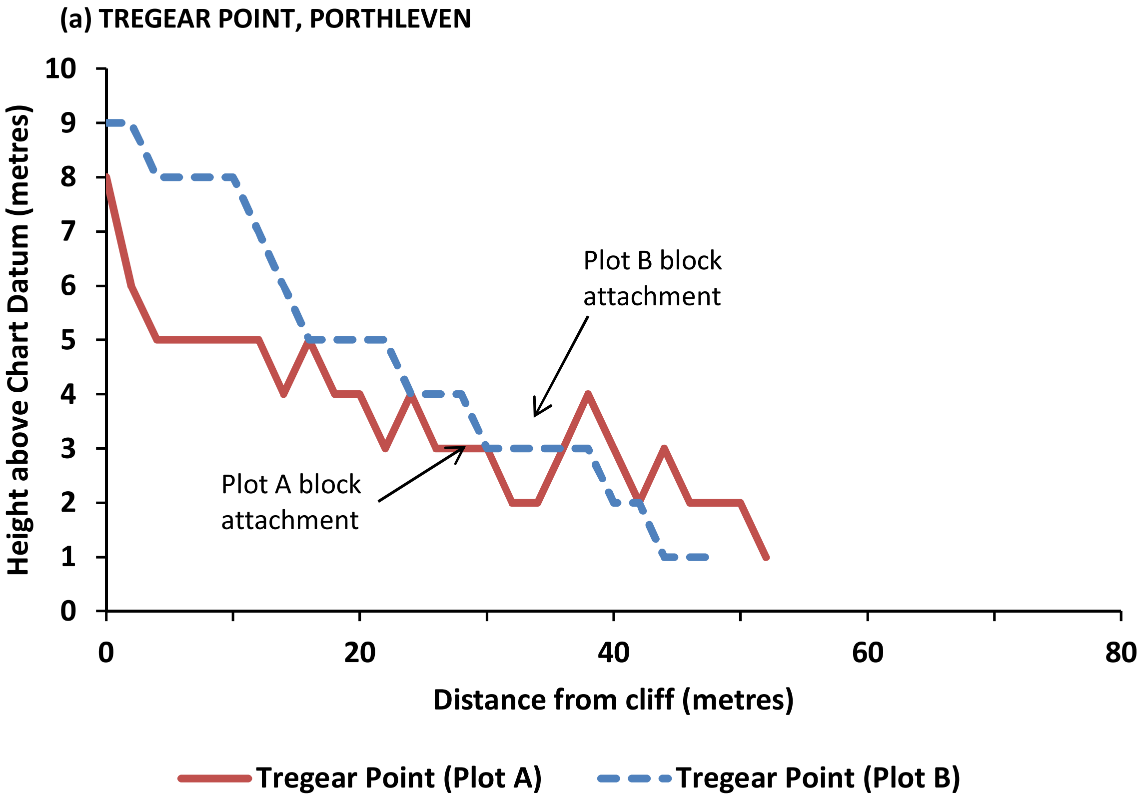


Figure 5-3 Site map of Tregear Point, Porthleven, Cornwall (Shore 1) showing location of replicate plots where materials were attached (NB: *Exposure Trial 1* blocks were attached in plots PA and PB; *Exposure Trial 2* blocks [see Chapter 6] were attached in plots PU and PL; platform edge data courtesy of J. Burdon).



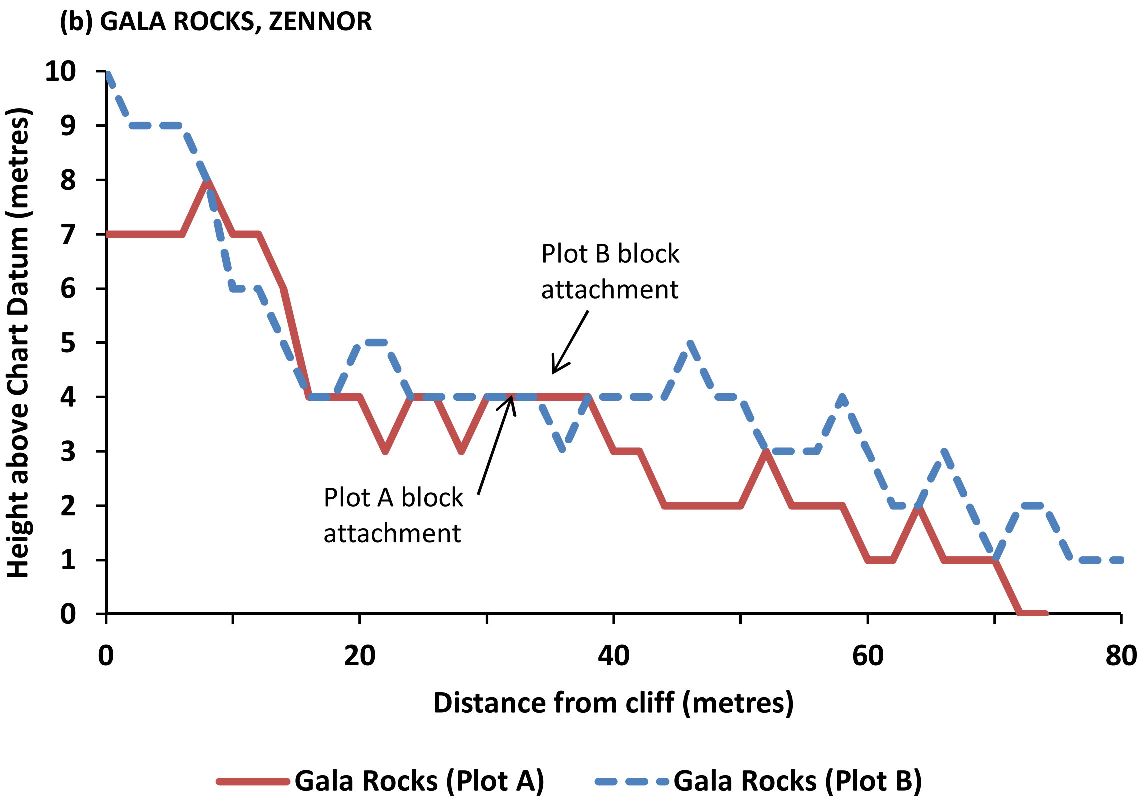


Figure 5-4 Across-shore long profiles of platform elevation for both experimental shores: (a) Tregear Point, Porthleven and (b) Gala Rocks, Zennor, Cornwall, UK (location of block attachment indicated).

5.2.1.2 Gala Rocks, Zennor (Shore 2)

A site map of Gala Rocks, Zennor, is shown in Figure 5-5. The rock platform at Gala Rocks extends out in a north-western direction, formed of dolerite, gabbro and serpentine rocks (the so-called 'Cornish Killas'; Schmidt Hammer hardness = 58.3, n = 60) with basaltic pillow lavas with granite intrusions (Floyd et al. 1993). The platform is backed by a steep sedimentary cliff incorporating gravels and clays of the Tertiary period and Quaternary head deposits, with a granite boulder beach on its north-eastern edge (Natural England 1997). An elevated area of basaltic rock lies at the back of the beach, while the middle section of the platform is relatively flat, extending seaward over 100 m at its widest point at MLW (Figure 5-4b). The platform is dissected by runnels (several meters in width) which connect large pools at the back of the beach; these features have been greatly enlarged by abrasion and wave forces. Meso-scale joint and block erosion (cm – m) appears to be the dominant mechanism of platform change, evidenced by the presence of fresh scars (i.e. clear of biological growth).

The ecological community at Gala Rocks was similar in composition to Tregear Point (above). The mid-shore was dominated by barnacle encrustations (*S. balanoides* and *Chthamalus* spp., see Section 5.1.2) covering 80 ± 20 % of the rock surface (n = 15). Grazing organisms (*Patella* spp. and *Littorina* spp.) were also abundant at MTL (26 ± 4 limpets per 1 m^2, n = 15) alongside clumps of *F. serratus*. *Patella* spp., encrusting algae (*Lithothamnion*) and the red algae *Corallina officinalis* were particularly abundant in pools, while *Laminaria* spp. dominated the shore at MLW. At MHWN, there were lower abundances of barnacles and limpets, and a high proportion of bare space.

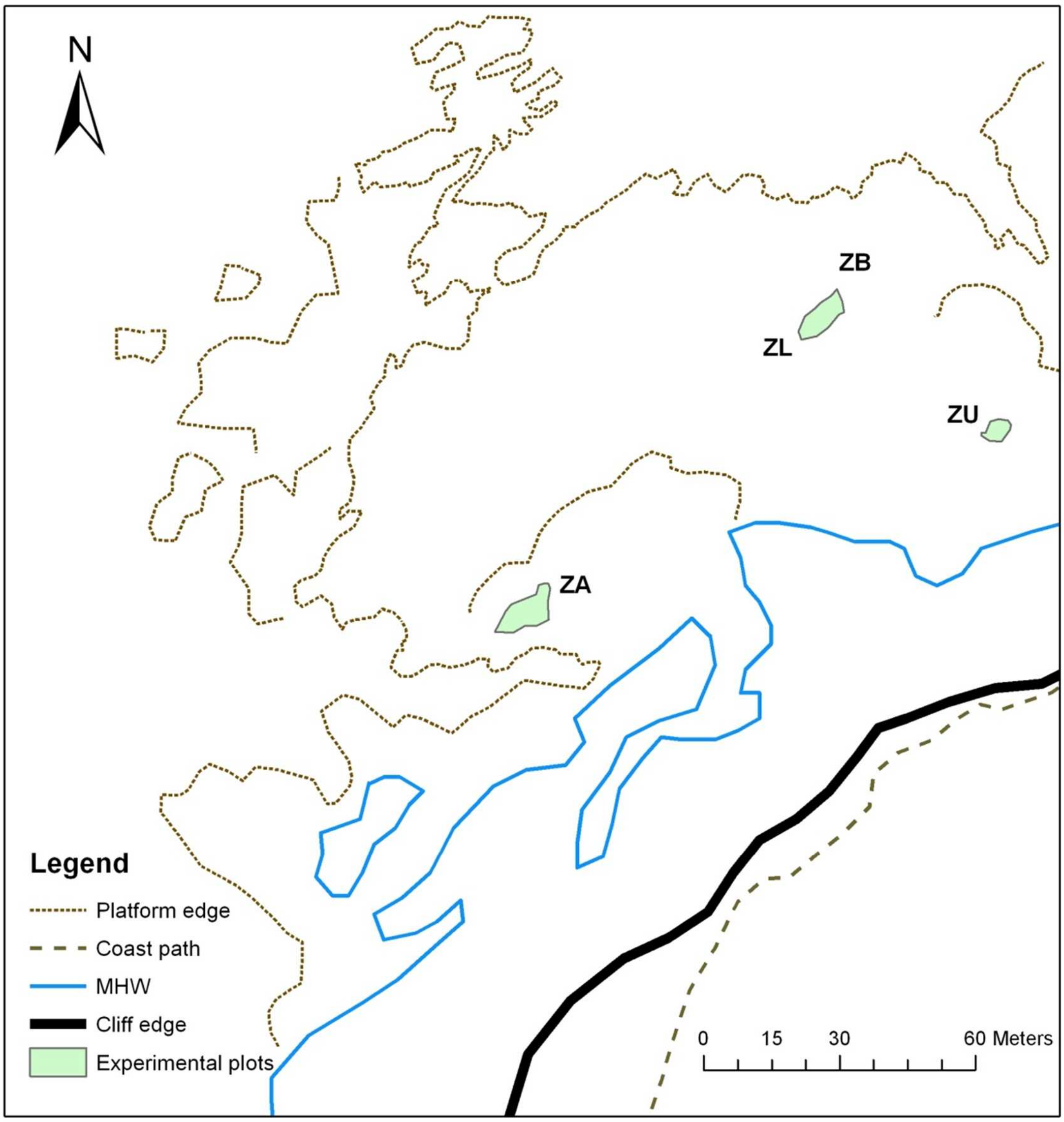


Figure 5-5 Site map of Gala Rocks, Zennor, Cornwall (Shore 2) showing location of replicate plots where blocks were attached (NB: *Exposure Trial 1* blocks were attached in plots ZA and ZB; *Exposure Trial 2* blocks [see Chapter 6] were attached in plots ZU and ZL).

5.2.2 Experimental blocks

The three materials described in Chapter 4 (Portland limestone, Cornish granite and marine concrete) were used in *Exposure Trial 1*. Limestone and granite slabs obtained from quarries were cut into blocks using a diamond rock saw. Concrete blocks were cast individually (see Chapter 4). All blocks were prepared with the dimensions 100 x 100 x 40 mm ± 5 %. The textural finishes applied to upper surfaces of blocks (on which colonisation was monitored in the field) were chosen to reflect materials as commonly used in coastal defence (below). Surface texture was not, therefore, controlled for in this trial, but was instead examined separately in *Exposure Trial 2* (Chapter 6). *Exposure Trial 1* therefore enabled comparisons of colonisation on surfaces that best represented these material types as currently used in coastal engineering.

For limestone blocks, the smooth surface created during cutting was used; this finish is typical of dimension stone and the smooth faces which form when fractured owing to the fine-grained oolitic texture of the rock. A roughened surface texture was applied to granite blocks using a fame-texturing technique used in stone dressing; this texture was chosen to replicate rough quarry rock as used in rubble armouring (W. Allsop personal communication, December 2008). The surface resulting from the casting process (referred to as 'plain-cast' throughout) was used for concrete blocks; this produced a comparable surface finish to larger pre-cast armour units commonly used in defence schemes (Allen 1998; CIRIA 2007). Visual representations of the experimental surfaces are shown alongside those used in *Exposure Trial 2* in Chapter 6 (see Figure 6-1 p. 209) and a simple comparison of roughness was presented in Chapter 4 (see Section 4.5.2 p. 156).

All blocks were prepared for field installation by drilling an 8 mm ø hole through their centre using a pillar drill and diamond core bit. Drilled blocks were then washed to remove surface grit and dust, and stored in the dark at room temperature before field installation. Fifty blocks of each material type were prepared in this way (a total of 150 blocks). For recording purposes, all blocks were labelled with a unique number code by gluing punched stainless steel tags along one edge with clear marine epoxy (Devcon 2 Ton®).

5.2.3 Field installation

The experimental design for *Exposure Trial 1* is shown schematically in Figure 5-6. On each shore (Tregear Point, Porthleven and Gala Rocks, Zennor) the same design was applied in two replicate plots (PA and PB, and ZA and ZB respectively). Plots were chosen to be: (i) sufficiently spaced from each other to ensure independency (> 50 m apart); (ii) at a comparable tidal height (2.5 – 3 m AOD) determined on calm days using tide tables and visual observations (e.g. Hawkins and Jones 1992); (iii) within the same biological zonation (middle eulittoral zone); (iv) relatively flat for block attachment, and; (v) suitably accessible for installation and regular monitoring. Further details of each replicate plot are given in Table 5-3.

Table 5-3 Descriptive data of experimental plots used in *Exposure Trial 1*.

Plot ID	Shore	Co-ordinates	Area (m^2)	Aspect	Wave exposure (°)*	Fetch (km)$^{\psi}$
PA	Tregear Point, Porthleven	500509: 051938	48.3	SW	133(108)	254
PB	Tregear Point, Porthleven	500506: 051937	40.8	SW	142(108)	254
ZA	Gala Rocks, Zennor	501206: 053349	38.4	NW	130(165)	965
ZB	Gala Rocks, Zennor	501205: 053352	42.4	NW	130(165)	965

*angle of local and regional (in brackets) wave exposure, based on methods of Trudgill 1988
$^{\psi}$indicative fetch calculated assuming wave approach parallel to the shore

Experimental blocks were attached on semi-horizontal areas of platform rock. This replicated surfaces that become available to colonisation through the construction of low crested structures such as breakwaters (e.g. Burcharth et al. 2007) and horizontal surfaces within rubble revetments and groynes formed of rock or concrete armour units (e.g. CIRIA 2007). Compared to the surfaces of vertical structures (i.e. walls), horizontal surfaces also offer greater potential for ecological gains through textural manipulation as a result of water ponding (e.g. Glasby 2000; Glasby and Connell

2001; Moschella et al. 2005, also see Section 2.3.3). Furthermore, blocks attached in a horizontal position during pilot tests were lost to waves less frequently than those attached to vertical surfaces. Supplementary observations of materials attached to vertical walls (undertaken as part of the experimental work presented in Chapter 7) are described in Appendix 3.

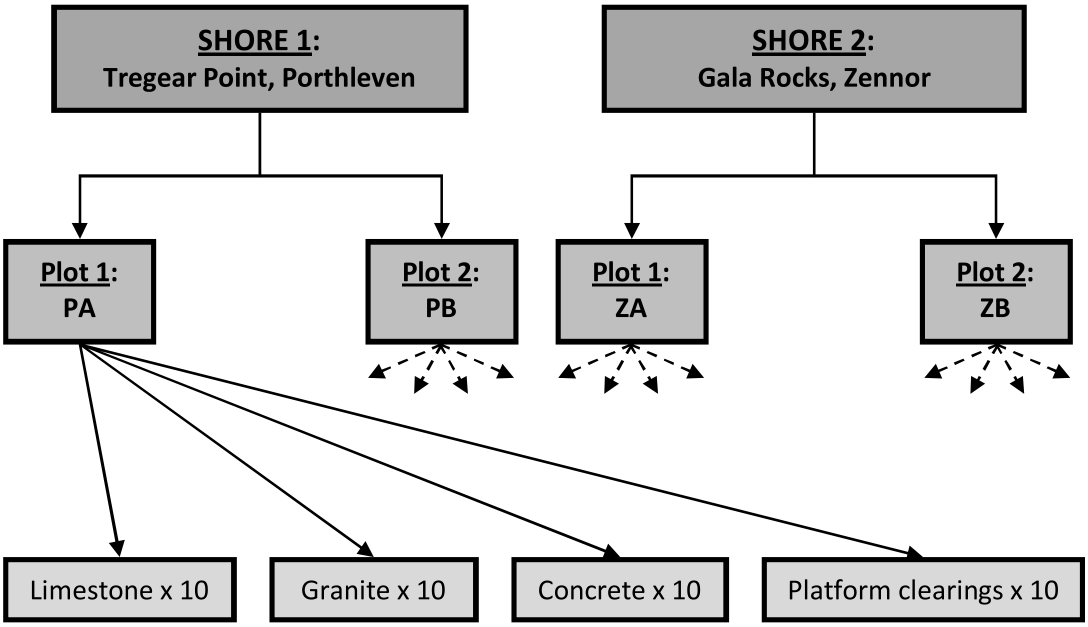


Figure 5-6 Schematic of *Exposure Trial 1* experimental design.

Four different experimental treatments were applied in each replicate plot: (1) limestone blocks; (2) granite blocks; (3) concrete blocks, and; (4) clearings on the platform rock, which were compared with the three introduced materials. Treatments were assigned using a semi-randomised design (R.C. Thompson personal communication, March 2008). First, 100 suitable attachment points were marked in each plot using plastic counters. Attachment points were chosen to be at least 25 cm away from each other (e.g. Herbert and Hawkins 2006), having a surface angle of no more than 20 degrees (to minimise potential aspect effects, e.g. Blockley and Chapman 2006) and with a relatively flat topography to aid block attachment. Random number tables were then used to select 40 of the marked attachment points for treatment. A 15 x 15 cm area of platform was then cleared of visible organisms at each of the selected points using a paint scraper and stout wire brush (Thompson et al.

1998; Blockley and Chapman 2006; Figure 5-7). A 10 mm ø hole was then drilled into the centre of each clearing to a depth of 40 mm using a DeWalt DW005 cordless rotary hammer drill.

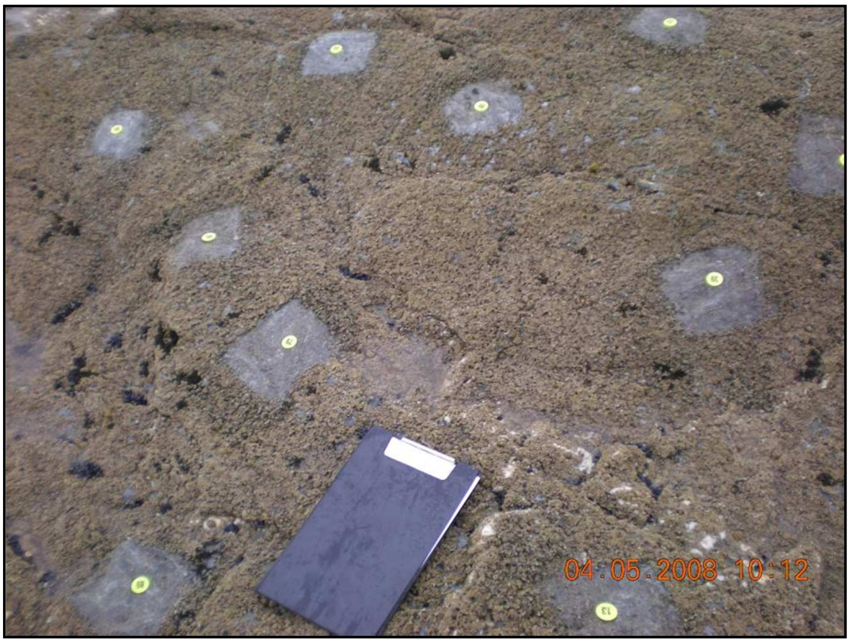


Figure 5-7 Semi-randomised selection of block attachment points, Tregear Point, Porthleven.

One of the four treatments (blocks and control clearings) was then attached in rotation across the plot, to maximise randomisation (Herbert and Hawkins 2006). To secure the blocks, 40 mm plastic Rawl® plugs were inserted into each drilled hole in the platform and tapped flush to the rock surface using a hammer. An 80 mm A4 grade stainless steel screw and washer was then screwed through each prepared block into the plastic plug (e.g. Blockley and Chapman 2006, Figure 5-8a). A two-part marine epoxy filler (Plastic Padding Products) was also applied around the edges of each block using a metal spatula for additional security (e.g. Naylor and Viles 2000; Naylor 2001; Naylor and Viles 2002, Figure 5-8b).

For the platform controls, cleared areas were left with no block attached but a stainless steel screw and washer was inserted, and a punched stainless steel ID tag glued along one edge of the clearing for recording purposes. Only the visible organisms were removed from the control clearings in *Exposure Trial 1*, by scrubbing the surface. The experiment therefore represented a comparison of barnacle colonisation on previously uncolonised construction materials (as would be the case for a new structure) and bare areas of platform rock which may remain colonised by microbial biofilms (see discussion, Section 5.4). Bare space can become available to new colonists on rocky shores through biological disturbance events, such as mortality by grazer bulldozing and predation (Dayton 1971; Denley and Underwood 1979; Hawkins 1983), and through physical disturbance such as abrasion (Lubchenco and Menge 1978), dislodgement by waves (Underwood 1980; Paine and Levin 1981) and mass mortalities associated with prolonged low tides and/or extreme thermal events (Connell 1961; Helmuth and Hofmann 2001; Harley 2008, also see Chapter 8). *Exposure Trial 1* therefore provided a comparison of colonisation on 'fresh' materials introduced through construction and bare space on platform rock occurring through disturbance. The potential influence of the presence of biofilms on barnacle settlement was assessed specifically in *Exposure Trial 2* (Chapter 6).

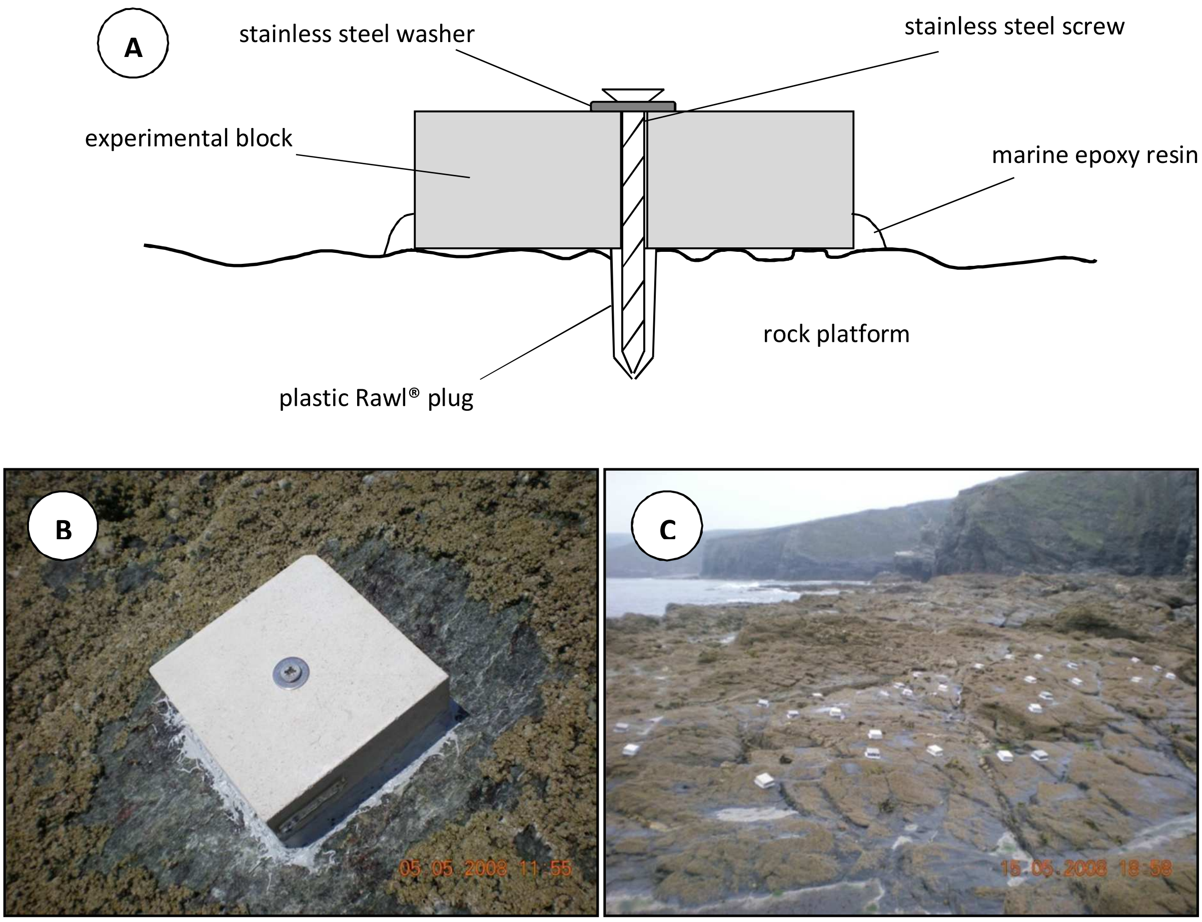


Figure 5-8 Block attachment: (a) schematic cross-section (b) attached limestone block (c) Plot PA (blocks dimensions = 100 x 100 x 40 mm).

Between 5th and 16th of May 2008, 10 blocks each of limestone, granite and concrete were attached to the platform and 10 control clearings were prepared in each plot (Figure 5-8c, a total of 160 treatments across both shores). This level of replication allowed for periodic removal of blocks for subsequent lab-based analyses (described in Chapter 7) and provided some level of contingency against possible losses to waves. In addition to those attached in the field, 10 blocks of each material type were kept in the laboratory during the duration of the trial as controls, and for the baseline geomechanical tests described in Chapter 4.

5.2.4 Barnacle settlement and recruitment

After installation, experimental plots were initially visited weekly from the end of May 2008 until the first Chthamalid cyprids (*C.montagui* and *C. stellatus*) were detected on the platforms. *S. balanoides* also settled on one of the shores during and immediately after installation (at Gala Rocks). *S. balanoides* cyprids were distinguished from the two *Chthamalus* species' by the timing of settlement (the former typically settling earlier in the year, Burrows et al. 1999; Southward 2008) and based on morphology in the case of juveniles and adults (Southward 2008, Figure 5-1).

After the first *Chthamalus* cyprids were detected (27th July 2008 at Tregear Point and 31st July 2008 at Gala Rocks) shores were visited every few days. On each occasion, the number of barnacle cyprids and metamorphosed forms present on the top surface of each block and in each clearing was recorded. Counts were made by centring a 6 x 6 cm clear, flexible plastic quadrat over the crosshairs of the screw fixings, and cumulatively counting individual cyprids and metamorphosed barnacles (by eye) in each cm^2 (e.g. Hawkins and Hartnoll 1982a; Kendall and Bedford 1987; Raimondi 1988b; Thompson et al. 1998; Herbert and Hawkins 2006). Counts were not made within the centre four squares to eliminate any potential influence of the fixings, nor within 2 cm of block and clearing edges to avoid potential edge effects (e.g. Barnes and Powell 1950; Wieczorek et al. 1996b; Bulleri et al. 2005; Blockley and Chapman 2006; Dobretsov and Wahl 2008). Quadrats were aligned with the labelled edge of blocks (or the metal tags in the case of the rock clearings) so that counts were made within the same 32 cm^2 on each visit. On some occasions close-up photographs were taken parallel to the rock surface using a Nikon S200 camera in macro mode to enable counts out of the field; this was necessary on wet days when the quadrat method was impractical, and when time for counting was limited by the tide. Counts from photographs were made by drawing a digital quadrat on scaled images using ImageJ (e.g. Munroe and Noda 2009).

In July and August 2008 counts were made on 10 occasions at Tregear Point and 8 occasions at Gala Rocks when settlement was heaviest. Subsequent counts of metamorphosed adults were made towards the end of the settlement season (in November) as a measure of seasonal recruitment (Connell 1985).

5.2.5 Barnacle mortality

Post-recruitment mortality of barnacles was compared between introduced materials and platform clearings at Tregear Point, where settlement was heaviest. A similar method to that used by Jarrett (2000), Delany et al. (2003) and Herbert and Hawkins (2006) was employed, although mortality was monitored over a longer period of time (12 months) than in these previous studies.

Photographs of all treatments (blocks and clearings) were taken in November 2008, after settlement had largely finished. A random sample of 10-25 individual *C. montagui* recruits (e.g. Herbert and Hawkins 2006) was then marked on the photographs of four randomly selected replicates of each treatment using ImageJ. The same treatments were then photographed in January 2009 (2 months after the end of settlement), March 2009 (after 4 months), May 2009 (after 6 months), August 2009 (after 9 months) and November 2009 (after 12 months). For each set of photographs, the same individuals marked in the original images were relocated. Barnacles that were no longer present or which had died (having empty shell tests) were recorded and mortality calculated as a cumulative percentage loss of the original sub-sample (Herbert and Hawkins 2006).

Re-location of individuals was achieved based on: (i) spatial positioning, with reference to other recruits and distinctive marks on the substrata; (ii) size and colour of individuals, which was important for distinguishing 2008 recruits from 2009 settlers, and; (iii) orientation of the operculum (see Figure 5-1), which proved an effective method for distinguishing individuals at high densities. Heavy settlement on treatments during the 2009 season (particularly on platform clearings) made re-location of some original 2008 recruits difficult; individuals that could not be identified with confidence were therefore excluded from the analysis.

5.2.6 Data analysis

Numbers of cyprids counted on peak days of settlement (27th July at Tregear Point and 10th August at Gala Rocks) and adult recruits counted at the end of the settlement season (18th November at Tregear Point and 29th November Gala Rocks) were compared between shores, plots and treatments using two separate analysis of variance (ANOVA) tests. ANOVA is a robust parametric statistical test widely used in benthic marine ecology to compare experimental variables ('factors') and assumes data are: (i) normally distributed, (ii) have homogeneous variance, and (iii) are independent measurements (Underwood 1997). For both analyses, 'material type' was a fixed factor (4 levels: limestone, granite, concrete and platform clearings), 'shore' was a random factor (2 levels: Shore 1 and Shore 2) and 'plot' was a random factor nested in 'shore' (2 levels: Plot A and Plot B). Further tests were undertaken to compare mortality between treatments using percent mortality data calculated from photographs taken at different periods of time after the end of settlement (see Section 5.2.5 above). For these analyses, 'material type' was treated as a fixed factor (4 levels: limestone, granite, concrete and platform clearings) and 'plot' as a random factor (2 levels: Plot A and Plot B).

All ANOVAs were performed using GMAV5 statistical software, specially designed for ecology-based statistical texting (Underwood et al. 1997). Once data were imported into the software, built in tests were performed to confirm data met the general assumptions of ANOVA (above). A Cochran's test was used to test for homogeneity of variance and data were square root or log transformed where appropriate. If heterogeneity could not be rectified then untransformed data were used in the test; while ANOVAs are generally robust to heterogeneous variances given sufficient and balanced replication (Underwood 1997), a conservative significance level (p_{crit} = 0.01) was used where Cochran's test $p < 0.05$ (see Underwood 1997 for details, and Blockley and Chapman 2006 for an example). Subsequent Student-Newman-Keuls (SNK) tests were used to examine interactions between factors where significant.

5.3 Results

5.3.1 Cyprid settlement

Numbers of cyprids recorded on all treatments on each visit are shown in Figure 5-9. Peak settlement was recorded at Tregear Point (27th July) two weeks before Gala Rocks (10th August). Numbers of cyprids counted on these peak settlement days are shown in Figure 5-10 for each experimental shore.

Statistical comparisons (ANOVA, Table 5-4) showed that settlement was lower at Gala Rocks than Tregear Point (p = 0.021), although this was just short of significance where p_{crit} = 0.01 given unrectified data heterogeneity (Cochran's test C = 0.522, p < 0.01). Interactions between 'material' and 'shore' factors (p < 0.000) indicated significant differences in settlement between material types, but that this varied at each shore. Subsequent SNK tests showed no difference in settlement between limestone, granite and concrete blocks at Tregear Point, but settlement was significantly lower on all introduced materials compared to clearings made on the slate platform on this shore (p = 0.01, Figure 5-10a). There was no difference in numbers of cyprids counted on any treatment at Gala Rocks (p > 0.05, Figure 5-10b). Settlement patterns were spatially consistent on each shore, showing no difference between the experimental plots (p = 0.61, Table 5-4).

Table 5-4 Analysis of variance for counts of *Chthamalus* spp. cyprids on peak settlement days on two experimental shores in Cornwall, UK.

Source of variation	***df***	**MS**	***F***	***p***
Material (*n = 4*)	3	5871.583	1.13	0.462
Shore (n = 2)	1	7049.025	45.34	**0.021***
Plot(Shore, *n = 2*)	2	155.463	0.49	0.614
Material x Shore	3	5207.375	74.75	**0.000*****
Material x Plot(Shore)	6	69.663	0.22	0.970
Residuals	144	317.386	-	-
Total	159	-	-	-

df = degrees of freedom; MS = mean square variance; *F* = ratio of variance; *p* = significance.
Cochran's test C = 0.522 (p < 0.01), therefore p_{crit} = 0.01.
p values: *p < 0.05, **p < 0.01, ***p < 0.001.

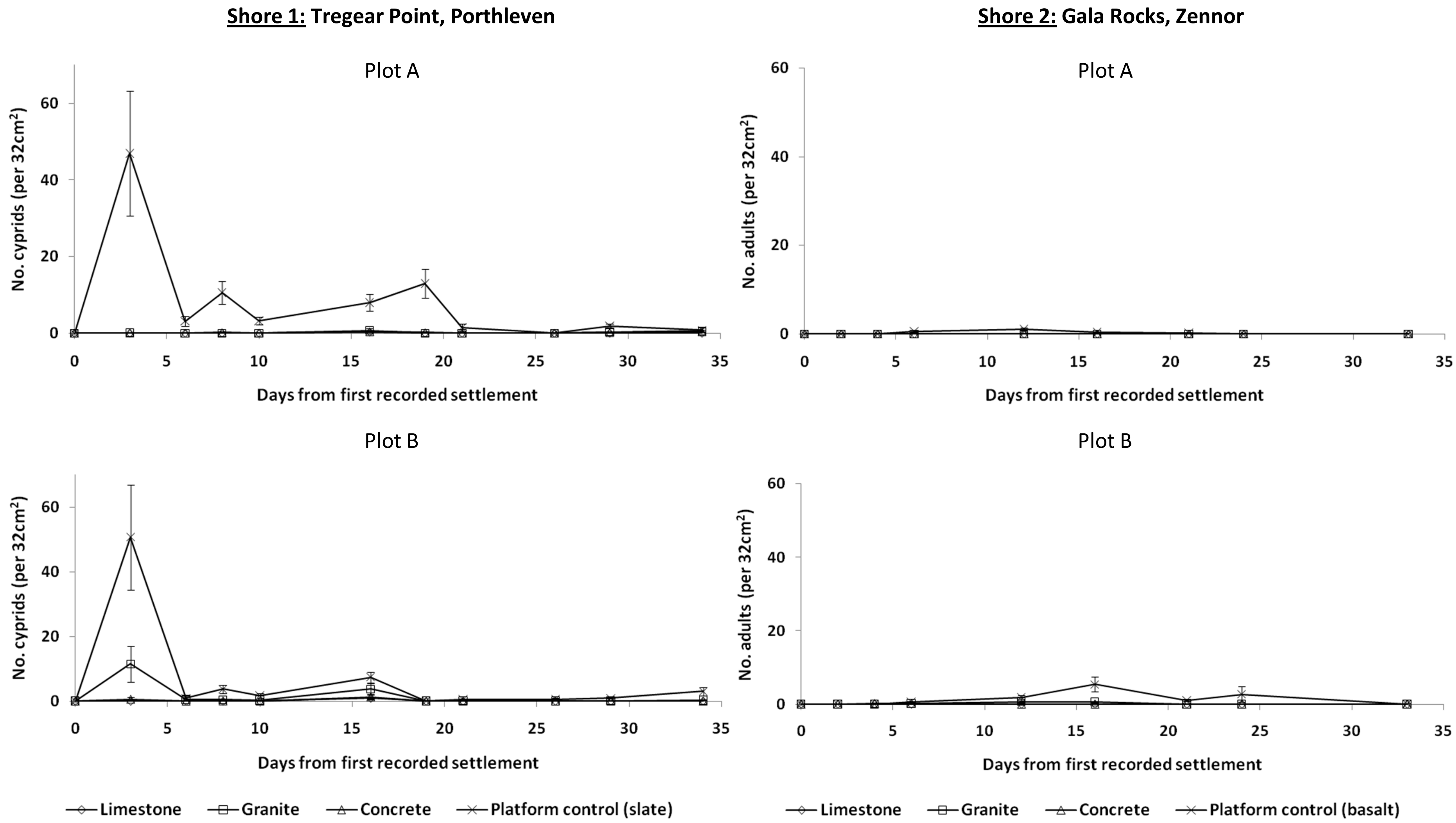


Figure 5-9 Number (mean ± SE) of *Chthamalus* spp. cyprids counted on experimental treatments (July – August 2008) on two shores in Cornwall, UK.

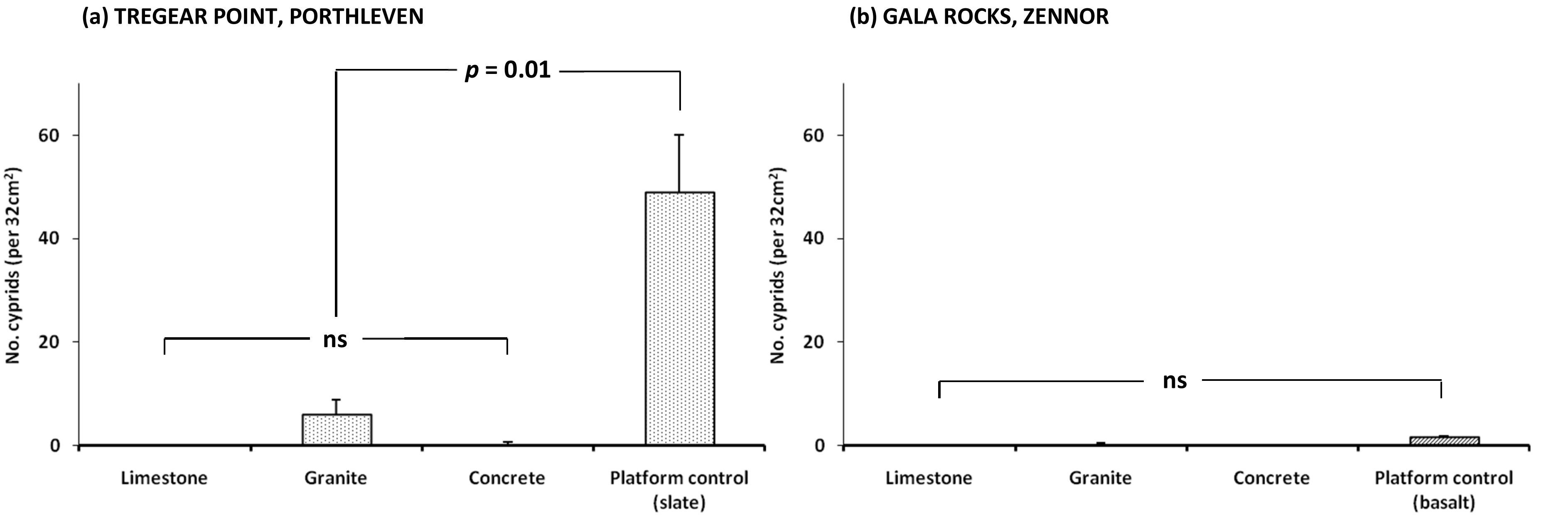


Figure 5-10 Number (mean + SE) of *Chthamalus* spp. cyprids counted on experiment treatments on peak days of settlement at (a) Tregear Point (27th July 2008) and (b) Gala Rocks (10th August 2008), Cornwall, UK.

5.3.2 Adult recruitment

Numbers of metamorphosed barnacles recorded on all treatments on each visit are shown in Figure 5-11. Numbers of recruits counted towards the end of the settlement season (November 2008) are shown in Figure 5-12 for both shores. Representative photographs of each treatment type at the end of the year are also shown in Figure 5-13.

Statistical comparisons (ANOVA, Table 5-5) showed that barnacle recruitment at Gala Rocks was lower than at Tregear Point (p = 0.021), although this was short of significance using a conservative significance level adopted due to data heterogeneity (Cochran's test C = 0.46 therefore p_{crit} = 0.01, see Section 5.2.6). As with the settlement data (above), significant interaction between 'material' and 'shore' factors (p < 0.000, Table 5-5) indicated that there were differences in recruitment between treatments, but the extent of these differences was not consistent between shores. At Tregear Point, recruitment was significantly lower on limestone than both granite and concrete (p = 0.05), which themselves were no different (p > 0.05, Figure 5-12a). At Gala Rocks there was no difference in recruitment between the three introduced materials (p > 0.05, Figure 5-12b), but there were significantly fewer recruits on all construction materials compared to clearings on platform rock on both shores (Tregear Point p = 0.01, Gala Rocks p = 0.05, Figure 5-12). Recruitment patterns were spatially consistent on each shore, with no differences between replicate plots (p = 0.36, Table 5-5).

Table 5-5 Analysis of variance for counts of *Chthamalus* spp. recruits at the end of the 2008 settlement season on two experimental shores in Cornwall, UK.

Source of variation	*df*	MS	*F*	*p*
Material (*n = 4*)	3	43166.223	1.74	0.331
Shore (*n* = 2)	1	58713.906	45.38	**0.021***
Plot(Shore, *n = 2*)	2	1293.706	1.04	0.355
Material x Shore	3	24847.423	100.36	**0.000*****
Material x Plot(Shore)	6	247.573	0.20	0.976
Residuals	144	1238.669	-	-
Total	159	-	-	-

df = degrees of freedom; MS = mean square variance; *F* = ratio of variance; *p* = significance.
Cochran's test C = 0.460 (p < 0.01), therefore p_{crit} = 0.01.
p values: *p < 0.05, **p < 0.01, ***p < 0.001.

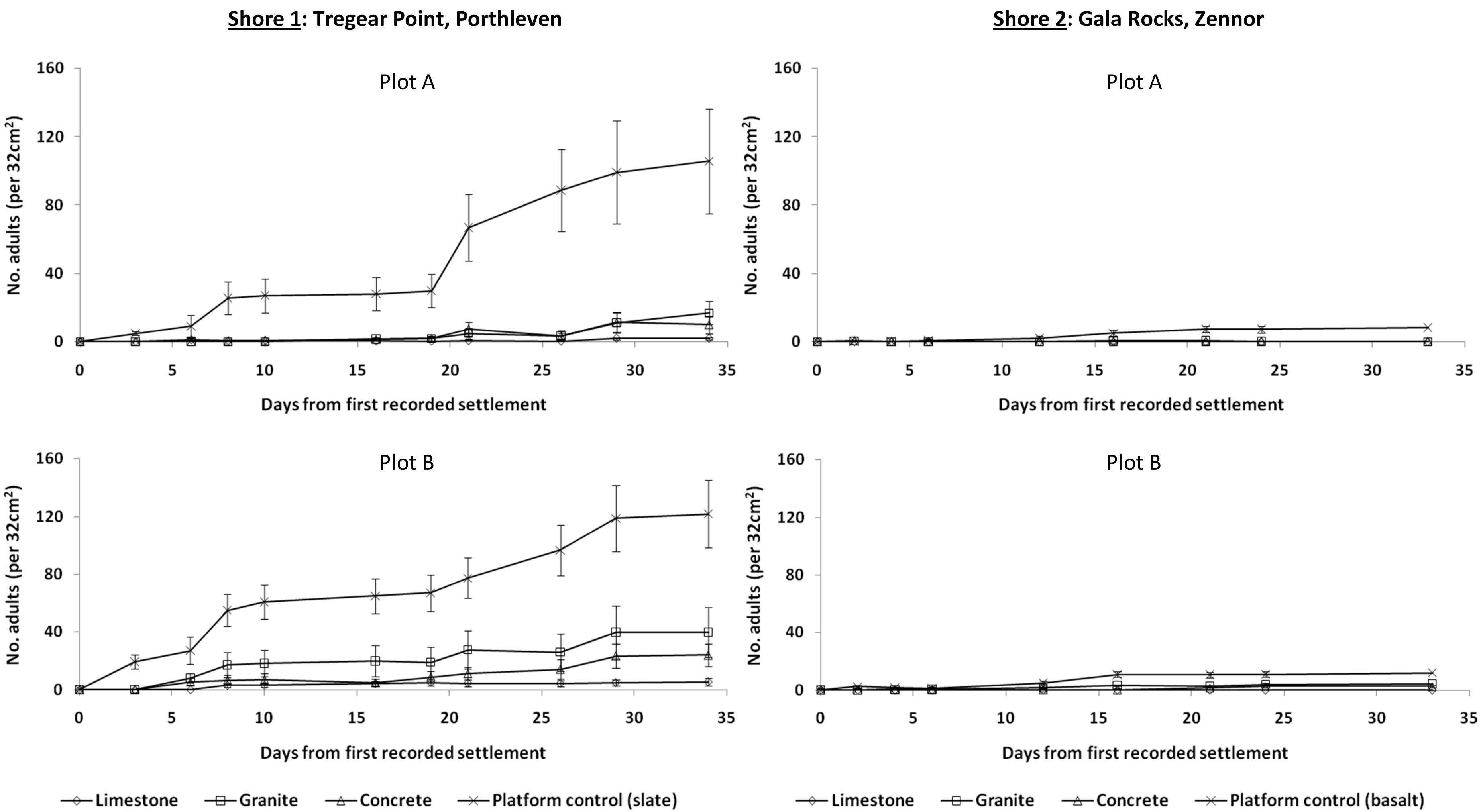


Figure 5-11 Number (mean ± SE) of *Chthamalus* spp. adults counted on experimental treatments (July-August 2008) on two shores, Cornwall, UK.

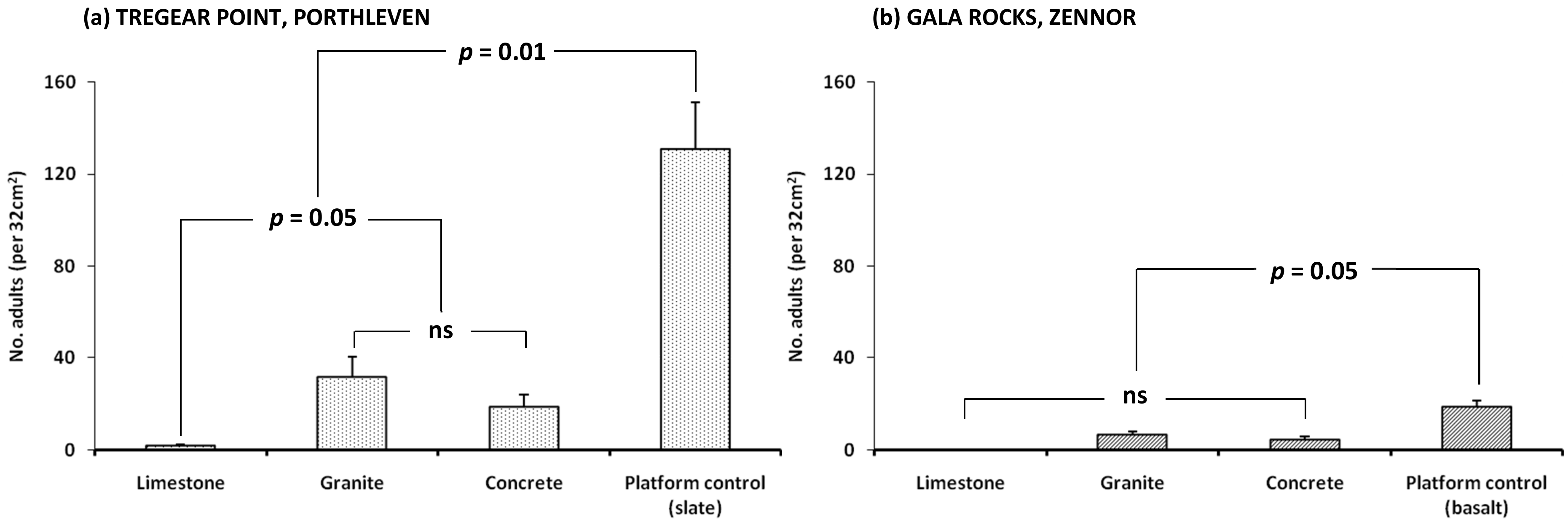


Figure 5-12 Number (mean + SE) of *Chthamalus* spp. adult recruits counted on experiment treatments at the end of the settlement season at (a) Tregear Point (18th November 2008) and (b) Gala Rocks (29th November 2008), Cornwall, UK.

Figure 5-13 Representative photographs of each treatment (Plot PB) at the end of the first year of settlement, November 2008 (clockwise: flame-textured granite, sawn limestone, plain-cast concrete and cleared [slate] platform; washer diameter = 2 cm for scale).

5.3.3 Mortality

Mortality of *C. montagui* recruits (which settled in 2008) over a 12 month period is shown in Figure 5-14a-b for Tregear Point. There were significant differences in mortality between materials after two months (in January 2009, ANOVA $p = 0.04$, Table 5-6); more recruits had detached or died on concrete and limestone compared to granite ($p = 0.05$), but there was no difference between the three introduced materials and the platform rock ($p > 0.05$). Differences were also significant after 12 months (in November 2009, $p = 0.03$, Table 5-6); the same percentage of recruits had died on limestone and concrete, which was higher than on granite and the platform clearings ($p = 0.05$, Table 5-6, Figure 5-15). Differences on treatments attached in different replicate plots at Tregear Point were also observed after two months, and were significant after 12 months ($p < 0.01$, Table 5-6).

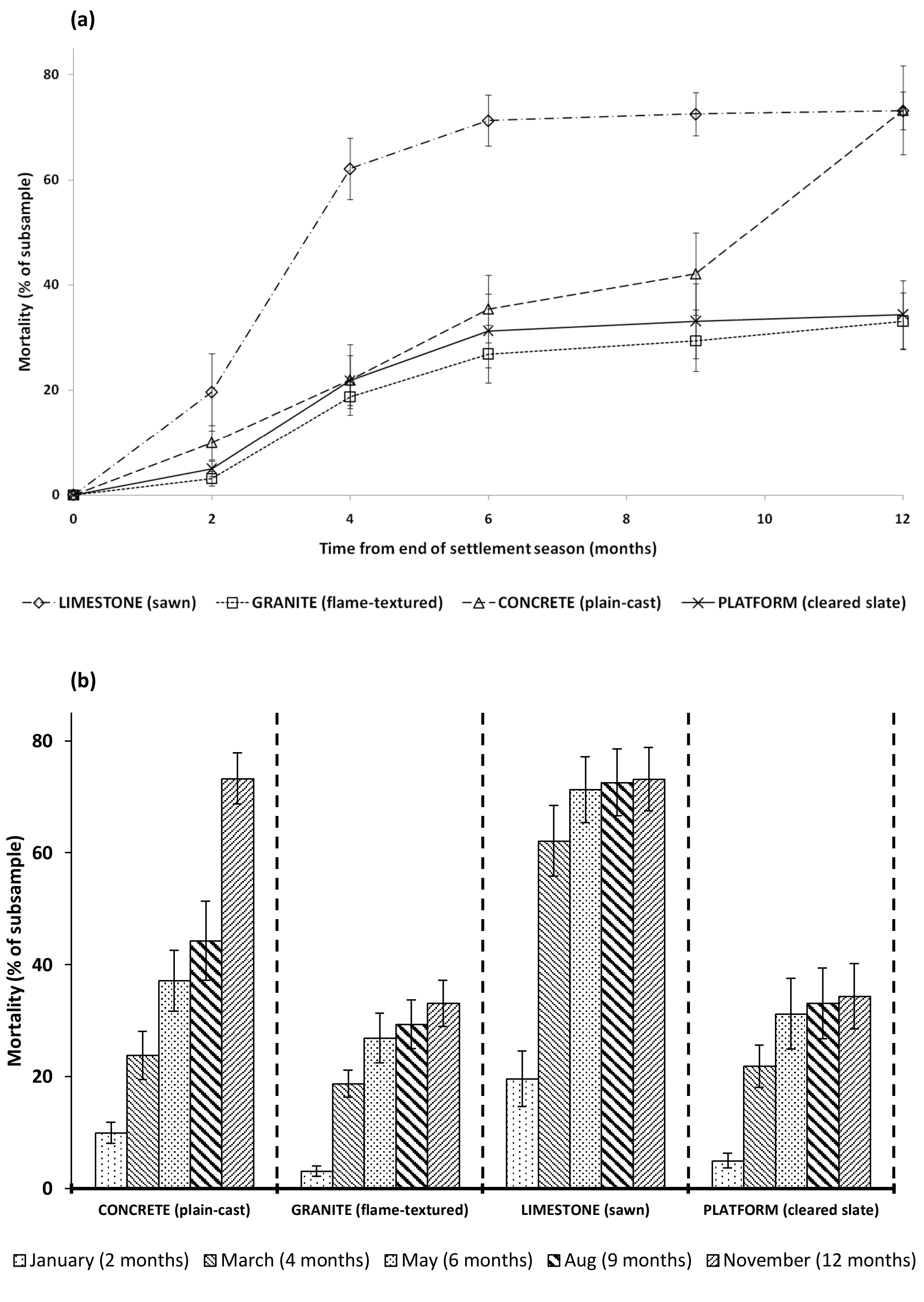


Figure 5-14 Mortality (mean ± SE, *n* = 8) of *C. montagui* recruits on experimental treatments at MTL: (a) during the 12 months following the end of the 2008 settlement season and (b) by material type at Tregear Point, Porthleven, Cornwall.

Table 5-6 Analysis of variance for mortality of *C. montagui* recruits 2 and 12 months after the end of the 2008 settlement season at Tregear Point, Cornwall, UK.

		2 MONTHS			12 MONTHS		
Source of variation	***df***	**MS**	***F***	***p***	**MS**	***F***	***p***
Material (*n = 4*)	3	3.847	12.12	**0.035***	4157.326	14.92	**0.026***
Plot (*n = 2*)	1	3.332	3.95	0.059	1401.137	9.34	**0.005****
Material x Plot	3	0.318	0.38	0.771	278.716	1.86	0.164
Residuals	24	0.845	-	-	150.084	-	-
Total	31	-	-	-	-	-	-

df = degrees of freedom; MS = mean square variance; *F* = ratio of variance; *p* = significance.
Cochran's test: 2 months log transformed data $C = 0.387$ (*ns*); 12 months $C = 0.298$ (*ns*).
p values: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

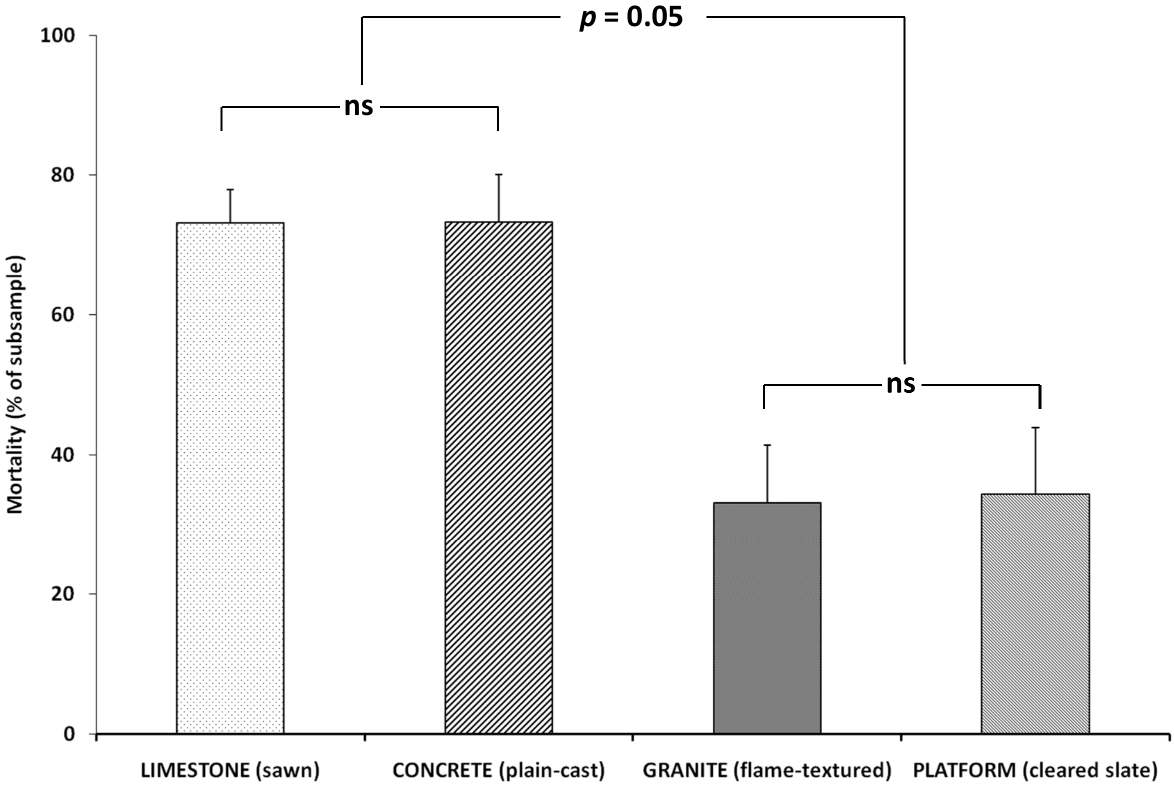


Figure 5-15 Mortality (mean + SE, *n* = 8) of *C. montagui* recruits 12 months after the end of the 2008 settlement season at Tregear Point, Porthleven, Cornwall, UK.

5.4 Discussion

5.4.1 Settlement and recruitment

On both shores, the number of barnacle cyprids settling on three materials commonly used in coastal engineering (limestone, granite and concrete) was lower compared to cleared platform rock on peak settlement days; this difference was statistically significant at Tregear Point (Hypothesis 1a p. 165). At the end of the 2008 settlement season, the same pattern was observed for numbers of adult recruits, and was significant on both shores (Hypothesis 1b p. 165). This suggests that the introduced materials used in this trial did not replicate conditions that led to settlement of a common intertidal organism on natural platform rock. This supports other workers who have observed differences in the settlement and recruitment of barnacles on various substratum types (Raimondi 1988b; McGuinness 1989; Holmes et al. 1997; Herbert and Hawkins 2006), but who have rarely compared materials which adequately reflect those 'as-used' in construction, particularly marine concrete.

Settlement and recruitment are important processes controlling the development of intertidal epilithic assemblages (Lubchenco and Menge 1978; Paine and Levin 1981; Gaines and Roughgarden 1985; Wahl 1989; Hawkins and Jones 1992; Rodriguez et al. 1993). Differences at this early stage may therefore have important long-term implications for the abundance and diversity of species found on artificial structures (Bulleri 2005a; Bulleri 2005b) and, at a larger scale, the biodiversity value of urbanised coastlines compared to 'natural' rocky shores (Connell and Glasby 1999; Connell 2001; Chapman 2003; Bulleri and Chapman 2004; Bulleri et al. 2005). The influence of these initial stages of colonisation on longer-term succession trajectories may, however, become less important over time as ecological interactions between organisms become more important (see specific discussions in Chapter 9).

Differences in settlement and recruitment of barnacles between blocks and platform clearings may be explained by the presence or absence of various physical and biological cues known to influence the behaviour of settling larvae in complex, interacting ways (Crisp 1974; Rodriguez et al. 1993; Hills et al. 1998). In this experiment, all visible organisms were removed within platform clearings by scrubbing the surface, while microbial films and chemical compounds from previously colonised barnacles may have remained present on the rock; this was done in order to represent bare space which becomes available through natural disturbance events, rather than controlling for potential biofilm influences on settlement (see Section 5.2.3). Barnacles are known to preferentially settle on biofilmed substrata (Wieczorek et al. 1996a; Thompson et al. 1998; Faimali et al. 2004) and cyprids generally show a positive response to physical and chemical signals from previous and existing adults (Crisp 1974; Raimondi 1988a; Rodriguez et al. 1993; Hills et al. 1998). Statistically higher settlement within platform clearings may therefore be explained to some extent by the presence of biological settlement cues on this treatment, and conversely the absence of this cue on introduced blocks. Previous experimental work suggests that the presence or remnants of conspecifics (i.e. adult barnacles) may be a stronger cue for cyprid settlement than biofilming, although it has proved difficult to determine their relative influences in the field, which may not be consistent between spatial scales (Raimondi 1988a; Thompson et al. 1998).

In a context of coastal engineering, new structures built in the intertidal zone initially offer surfaces for colonisation which have not previously been colonised (as replicated in this experiment). If previous colonisation is important for settling larvae, 'new' engineered surfaces will be less favourable for barnacles than natural bare space, at least during the first settlement season after 'construction' as was monitored here. Given that biofilming can occur rapidly on most hard substrata in the intertidal zone (within a matter of hours and days e.g. MacLulich 1986), the importance of micro-scale biological cues for barnacle colonisation (i.e. biofilming) over longer timescales is probably less compared to other features of the substratum such as texture (see below) or the presence of other adults once colonisation has begun. Similarly, while cyprids are known to distinguish between immature and mature biofilms at a scale of days and weeks (Thompson et al. 1998; Hung et al. 2008), the strength of this cue over longer timescales is not known. Wethey (1986) further suggests that cues from settled barnacles are probably short lived in the intertidal zone, and so are less important than physical characteristics of the substratum such as texture (see below).

In order to allow direct comparisons of barnacle settlement and recruitment on introduced materials and previously *uncolonised* platform rock, which may become available following an erosion event for example (e.g. Naylor and Stephenson 2010), an additional treatment of sterilised clearings was used in *Exposure Trial 2* (Chapter 6). Differences in the characteristics of microbial communities developing on the same materials used in this experiment are also specifically discussed in Chapter 7.

In addition to differences between introduced materials and platform clearings (above), cyprid settlement was also different between limestone, granite and concrete blocks (granite > concrete > limestone), although SNK tests revealed this was not statistically significant (Hypothesis 2a p. 165). This lack of significance may, however, have resulted from the generally low settlement at Gala Rocks (e.g. Figure 5-9 p. 182). Assuming patterns were similar during successive tides, the cumulative effect of differences in cyprid settlement between treatments probably explains significant variance in adult recruitment recorded at the end of the season (Hypothesis 2b p. 165, Figure 5-12). Post-settlement mortality, caused by grazing disturbance or from desiccation stress for example, may also have contributed to measured differences in adult recruitment between treatments (Connell 1985). Post-settlement mortality can be high for barnacles in the first few days following initial attachment (up to 40 % for example, Gosselin and Qian 1996) but this was not tested in this experiment; significant differences in post-recruitment mortality (occurring over longer-timescales) were, however, recorded between treatments (see Section 5.4.2 below).

Relating differences in barnacle colonisation to rock type (that is to say lithology, see Section 2.3.3.3) is extremely difficult owing to inherent nano-micro scale (µm – mm) variations in mineralogy and grain size (Holmes and Holmes 1978) and associated problems of how to adequately control for surface texture. Moore and Kitching (1939) suggested that rock type has a strong influence on the distribution of *C. stellatus* in Britain, while Caffey (1982) reports no consistent effects of naturally occurring rock types on recruitment and survivorship of *Tessoropra rosea* on Australian shores. Both of these studies did not, however, control for variations in substratum surface texture which are likely to have influenced these observations (Bourget et al. 1994). Raimondi (1988b) attributes differences in the settlement and recruitment of *C. anispoma* on basalt and granite shores in California to the thermal properties of the rock (see Chapter 8 for detailed discussions of rock thermal influences). While Raimondi attempted to control for texture, the relative influence of material type versus material texture was not considered. Holmes et al. (1997) state that they observed differences in settlement of *S. balanoides* cyprids on different rock types independently of surface roughness and colour, as a function of substratum chemical and physio-chemical heterogeneity (mineralogy); these author's do not clearly state how texture was controlled for however.

Herbert and Hawkins (2006) observed differences in the recruitment of *C. montagui* on four calcareous rock types in South West England, which they largely attributed to variation in surface roughness. In this trial, there were significant differences in recruitment between the introduced material types on one of the shores (limestone < concrete = granite at Tregear Point) which corresponded with simple measures of roughness (see Figure 4-5 p. 157 and Figure 6-1 p. 209); fewest barnacles were recorded on smooth limestone blocks and most on the rough granite. The same pattern was observed at Gala Rocks, although differences were not statistically significant on this shore. The importance of substratum texture on colonisation by marine invertebrates (including barnacles) has been well demonstrated (Pomerat and Weiss 1946; Crisp and Barnes 1954, see Section 2.3.3.3) and is thought to be a key factor influencing recruitment on different rock types (e.g. Raimondi 1988b; Herbert and Hawkins 2006). Importantly, surface texture may be a limiting factor on artificial structures which are generally smooth compared to naturally weathered rock (e.g. Chapman 2003; Chapman and Bulleri 2003, see further discussions in Chapters 6 and 9).

Given that the principal aim of *Exposure Trial 1* was to compare barnacle responses on materials with surfaces that best reflected their use in structures (Section 5.1), texture was not controlled for. However, observations indicated that settlement was positively associated with textural features in this experiment, including grooves and pits on the platform rock, and the metal fixings and marine epoxy used to attach the blocks. Interestingly, while settlement was rare on smooth areas of concrete, cyprids commonly settled in surface air-holes which formed during the curing process (e.g. Figure 5-13 p. 187). Settlement in air-holes probably explains why there was no difference in numbers of recruits counted on the rough granite and the otherwise smooth concrete at the end of the settlement season (Figure 5-12), but see below with respect to mortality associated with air-holes on concrete. The influence of texture on barnacle colonisation, and more specifically how texture may be manipulated for ecological gains, was assed in *Exposure Trial 2* (Chapter 6).

5.4.1.1 Spatial variability

At the largest spatial scale studied (kilometres), barnacle colonisation was significantly different between shores, with greater numbers of cyprids and recruits counted at Tregear Point compared to Gala Rocks (Table 5-4 and Table 5-5). At this scale, differences in the settlement of marine invertebrate larvae are generally thought to be controlled by factors influencing larval supply, including tidal patterns, wind and shore orientation (Hawkins and Hartnoll 1982a; Raimondi 1990; Bertness et al. 1996; Hills et al. 1998; Blythe 2008; see discussions in Chapter 9). Hawkins and Hartnoll (1982), for example, attributed spatial differences in the settlement patterns of *S. balanoides* on the Isle of Man to shore orientation. In this study, the experimental shores had contrasting orientations (SW and NW for Tregear Point and Gala Rocks, respectively) which may have influenced differences in barnacle recruitment.

Geographically, *S. balanoides* is a cool-water species which typically out-competes the warm-water *Chthamalus* spp. where they overlap (Herbert et al. 2007). In Cornwall, *S. balanoides* is rare on warmer southern shores but abundant on cooler northern shores as a function of temperature and the intensity of competition between the two species (e.g. Southward and Crisp 1956; Crisp and

Southward 1958; Southward 1958). In this trial only Chthamalid barnacles were counted (Section 5.2.4), but overall differences in numbers of cyprids and adult recruits observed between shores may relate to geographic-climatic controls (Figure 5-2) and the relative abundance of the competitive species *S. balanoides* (see Chapter 6).

5.4.2 Mortality

Although short of significance, post-recruitment mortality was higher on limestone and concrete than on the platform rock at Tregear Point two months after the end of the 2008 settlement season (in January 2009, Figure 5-14). After four months (in March 2009) mortality on limestone was significantly higher than the platform rock, as was concrete after 12 months (in November 2009) (Hypothesis 3 p. 165). These results suggest that in addition to lower settlement and recruitment (above), mortality of recruits was higher on common engineering materials compared to natural rocky substrata. The exception was granite, which had the same level of mortality as platform clearings after 12 months (Figure 5-15). Herbert and Hawkins (2006) recorded similar mortality rates on Blue Lias shore platforms at Lyme Regis, Dorset, and experimental blocks made of the same material type with a naturally weathered surface. This suggests that treatments similar to those used in this study (i.e. exposure blocks) did not have an impact on mortality rate, and so can be assumed a function of barnacle responses to the materials rather than the experimental design.

Considering the three introduced materials alone, mortality was significantly higher on limestone than granite and concrete four months after the end of settlement. There was no difference in mortality on concrete and granite after nine months (in September 2009), but significantly more individuals had died on concrete 3 months later (after 12 months; Hypothesis 4 p. 165). Herbert and Hawkins (2006) also found significant differences in mortality of the same barnacle species between different rock types after 7 months.

Roughness is known to be important for refuge of juvenile marine invertebrates from competitors (e.g. Walters and Wethey 1986), wave dislodgement (e.g. Granhag et al. 2004), grazing disturbance (e.g. Skov et al. 2010) and desiccation (e.g. Raimondi 1988a, b). In this respect, the rough granite used in this trial probably offered refuge to juvenile barnacles in a similar way to pits and grooves on naturally weathered rock; mortality on granite blocks was significantly lower than on smooth concrete and limestone, which probably offered few physical refuge sites for settlers. On concrete, air-holes (in which settlement was often associated, above) may have afforded refuge to cyprids and juvenile barnacles in the same way as the roughness of the granite and weathered rock platform; indeed, mortality rates were no different between these materials after nine months.

In contrast, mortality was significantly higher on concrete compared to the rougher materials after 12 months, matching that of the smooth limestone (Figure 5-15 and Table 5-6). This marked increase in mortality on concrete between 9 and 12 months may have been a result of growth of recruits within air-holes, whereby individuals became too large for the holes they originally settled in. However, barnacles are known to adapt their morphology to a columnar form in confined spaces (i.e. in crowded populations e.g. Hills and Thomason 2003; Southward 2008). Therefore, space restrictions imposed on individuals growing within air-holes probably do not explain the marked increase in mortality on concrete after this time. More likely, is that preferential settlement within holes led to crowding between conspecifics; it was common for several cyprids to settle in individual holes so that subsequent growth over the following year would have intensified competition for space (e.g. Figure 5-16). Visual observations suggested that holes in which several juveniles were present at the end of the 2008 settlement season were occupied by only one or a few full-sized adults a year later. While air-holes forming on the surfaces of plain-cast concrete (also common on armour units and concrete defence structures, W. Allsop personal communication, December 2008) appear to facilitate initial colonisation by barnacles, there may be higher mortality over longer periods of time as a result of growth of individuals and intraspecific competition.

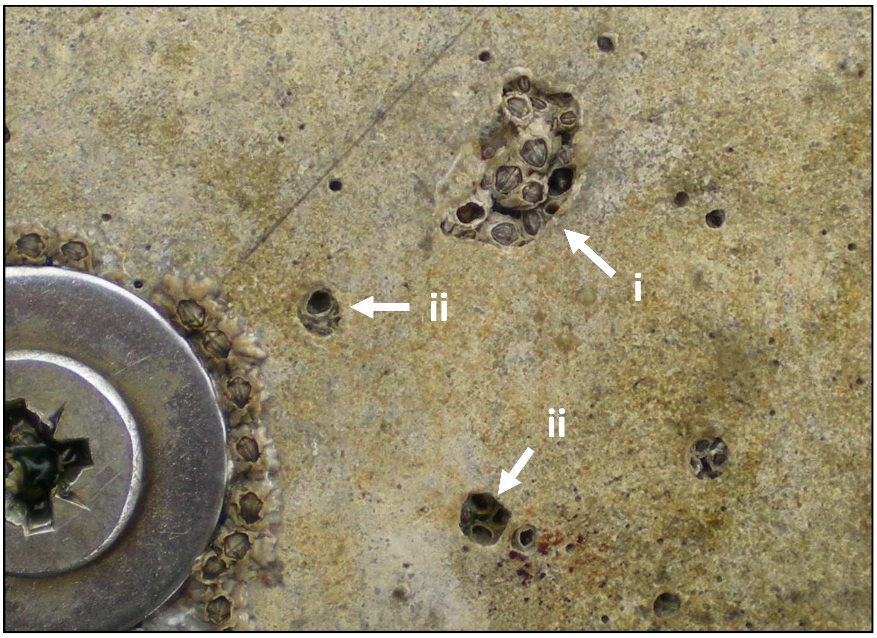


Figure 5-16 Settlement of barnacles in association with air-holes and surface imperfections on plain-cast concrete: crowding of individuals (arrow i) and mortality due to intraspecific competition for space (arrow ii).

In addition to the influence of texture, Herbert and Hawkins (2006) suggest that material hardness affected mortality of *C. montagui* on different rock types. They attributed higher mortality on chalk panels to its friable nature, which they suggest may have hindered secure attachment of cyprids and barnacle spat (juveniles). In contrast, Savoya and Schwindt (2010) found that the survival of the barnacle *B. glandula* was greater on 'soft' sandstone compared to 'hard' substrata (commercial tiles) in Patagonia, Argentina. In this study, limestone, which was the softest material type (although much harder than chalk) and which got softer over the course of the experiment (see Chapter 7: Strand 2), had the highest rates of mortality. However, very high levels of settlement and recruitment on artificially roughened limestone blocks in *Exposure Trial 2* (Chapter 6) suggest that the relative softness of the limestone was less important than its lack of texture as used in this trial.

5.4.3 Spatial variation

Differences in mortality between replicate plots located roughly 50 m apart at Tregear Point were first observed after four months, and were highly significant after 12 months (Table 5-6). Mortality as a result of grazing disturbance was unlikely the cause of these differences because the density of grazing limpets was similar between plots (see discussion in Chapter 7). Despite an attempt to select plots with similar physical conditions (see Section 5.2.1 p. 165), localised wave behaviour may have contributed to mortality variations at this spatial scale (m's); observations at Tregear Point under various wave conditions indicated that blocks attached in Plot PB (where mortality was lower) were subject to relatively higher energy waves than Plot PA as a result of the stepped platform morphology (see Section 5.2.1). This was further suggested by higher losses of experimental blocks from Plot PB to waves (four during 2008) compared to Plot PA (where no blocks were lost).

Differences in wave exposure have been suggested to influence the distribution and abundance of *Chthamalus* on European shores at a scale of tens of meters (Crisp et al. 1981; Sousa et al. 2000). Menge (2000) suggests that the importance of wave dislodgement in post-recruitment mortality is typically low for mid-shore barnacles compared to other invertebrates, such as mussels, but can be important in crowded populations. The observation that mortality was higher in Plot PA, which had calmer wave conditions, indicates that physical disturbance from waves had limited influence on mortality on this shore. However, wave conditions can exert influences on barnacle population structure through feeding conditions and desiccation stress in time and space (Southward and Orton 1954; Hawkins and Hartnoll 1982a; Harley and Helmuth 2003). Turbulent waves in Plot PB may have improved feeding conditions or reduced stress during hot weather relative to Plot PA due to enhanced wave-splash, for example.

5.5 Conclusions

Significant differences in the settlement, recruitment and mortality of barnacles (*Chthamalus* spp.) were observed on substrata representative of those used in coastal engineering and clearings made on weathered platform rock. These results indicate that colonisation by a common intertidal organism may be significantly reduced on construction materials compared to natural rocky shore substrata over annual timescales. There were also significant differences between the three introduced substrata (limestone, granite and marine concrete) with surface finishes chosen to represent those 'as-used' in engineering. This provides the first comprehensive evidence to suggest that the type of material used in coastal engineering can have important influences on early colonists. This may be important for community development and ultimately ecological potential over longer periods of time (see discussion in Chapter 9).

Surface texture appeared to be particularly important in causing differences in colonisation and survival of barnacles on the different treatments through the provision of favourable settlement sites and physical refuge in association with surface roughness elements. These observations also suggested that colonisation of materials used in engineering may be manipulated by artificial texturing. However, texture was not directly controlled for in this trial so it was not possible to conclude the extent to which the observed patterns could be attributed to roughness alone. *Exposure Trial 2*, described in the following chapter (Chapter 6), was therefore designed to address specific questions relating to texture, and to examine the potential for manipulating biological responses to construction materials at a smaller spatial scale than previously studied.

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CHAPTER 6

ECOLOGICAL RESPONSE (B): MATERIAL TEXTURE

Settlement and Recruitment of Barnacles in Response to Small-Scale Texture Manipulation

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CHAPTER 6. ECOLOGICAL RESPONSE (B): MATERIAL TEXTURE

Settlement and Recruitment of Barnacles in Response to Small-Scale Texture Manipulation

6.1 Introduction, Aims and Hypotheses

6.1.1 Introduction

Exposure Trial 1 (Chapter 5) showed that the settlement, recruitment and mortality of barnacles varied significantly between introduced materials and natural platform rock, and between different materials commonly used in coastal defence. These data along with qualitative field observations indicated that the differences were probably influenced by the texture of the materials. Existing work within experimental marine ecology has also demonstrated the strong influence of surface texture on settlement and recruitment of sessile marine invertebrates in the intertidal zone (e.g. Hills and Thomason 1998; Berntsson et al. 2000; Wahl and Hoppe 2002; see Chapter 2 for details).

In *Exposure Trial 1* materials were exposed with surfaces that best reflected their use in coastal engineering, and so texture was not specifically controlled for (see Section 5.2.2 p. 172). This chapter (Chapter 6) describes a separate field trial (referred to as '*Exposure Trial 2'* throughout) designed to quantitatively test the influence of fine-scale (< cm) texture on barnacle settlement and recruitment. This was done by applying artificial textures to the same material types used in the previous trial. More specifically, *Exposure Trial 2* was used to examine the potential for using texturing to manipulate early biological responses to structures, so that they may better mimic natural rocky shores in-line with current legislation and conservation goals (see Chapter 2).

6.1.2 Study organisms

Settlement and recruitment of Chthamalid barnacles (*C. montagui* and *C. stellatus*) was monitored on two shores during the 2009 settlement season*. S. balanoides* was also recorded, but settlement and recruitment of this species were only sufficient on one shore for meaningful statistical analysis. These species are described in Section 5.1.2 p. 162, along with a rationale for using barnacles as a model rocky shore organism in the context of this study.

6.1.3 Experimental hypotheses

Three principal hypotheses were tested in *Exposure Trial 2* (Table 6-1). First, the hypothesis that barnacle settlement (cyprids) and recruitment (metamorphosed forms) would be greater on rough versions of construction materials compared to smooth alternatives was tested (Hypothesis 5a-b). This hypothesis was based on observations made in the previous trial (Chapter 5) and current ecological theory (Section 2.3 p. 55). Second, the assumption that the *type* of texture is important for barnacles was examined on concrete, which could be easily manipulated during the block casting process (see below; Hypothesis 6a-b). Furthermore, a specific need for research on ecological responses to concrete and potential for enhancement has been identified (Section 2.7 p. 93). Thirdly, the opportunity for using texture to manipulate early colonisation of construction materials, so that they may better replicate natural substrata was examined. This was achieved by comparing barnacle settlement and recruitment on artificially textured blocks with clearings on the naturally weathered rock platforms (Hypothesis 7a-b, Table 6-1).

In addition to the main hypotheses relating to substratum texture (Hypothesis 5, 6 and 7), the potential influence of microbial biofilms and other bio-chemical cues on barnacle colonisation was explored on platform rock using sterilised clearings (Hypothesis 8a-b, see 6.2.3 below). This was undertaken to test whether the presence or absence of biofilms may have influenced significant differences in settlement and recruitment between clearings and blocks described in *Exposure Trial 1*, in which the presence of biofilm was not controlled for (see discussion in Section 5.4 p. 190).

Table 6-1 *Exposure Trial 2* Research questions and experimental hypotheses (see Table 3-2 p. 129).

	Research Question	Hypothesis
5	How does colonisation compare between smooth and rough versions of the same material type?	(5a) Settlement of barnacle cyprids is greater on roughened construction materials compared to smooth replicates. (5b) Recruitment of adult metamorphs is greater on roughened construction materials compared to smooth replicates.
6	Is the type of texture (at a mm-scale) important for colonisation of marine concrete – are some textures better than others?	(6a) Settlement of barnacle cyprids is not the same on concrete with different types of mm-scale surface texture. (6b) Recruitment of adult metamorphs is not the same on concrete with different types of mm-scale surface texture.
7	Can artificial texturing of construction materials be used to replicate early colonisation of a dominant organism occurring on natural rocky shore substrata?	(7a) Settlement of barnacle cyprids is no different on construction materials with roughened surfaces compared to natural platform rock. (7b) Recruitment of adult metamorphs is no different on construction materials with roughened surfaces compared to natural platform rock.
8	Does the presence of bio-chemical cues influence colonisation of rock substrata in this environment?	(8a) Settlement of barnacle cyprids is lower on sterilised platform clearings compared to unsterilised clearings. (8b) Recruitment of adult metamorphs is lower on sterilised platform clearings compared to unsterilised clearings.

6.2 *Exposure Trial 2*: Experimental Design

6.2.1 Study sites

In this trial, experimental blocks were exposed on the same two shores used in *Exposure Trial 1*; Tregear Point, Porthleven, and Gala Rocks, Zennor. Both shores are described in detail in the previous chapter (Section 5.2.1 p. 165).

6.2.2 Materials, surface finish and texture manipulation

The same three material types used in *Exposure Trial 1* were used in *Exposure Trial 2*; Portland limestone, Cornish granite and marine concrete, each described in detail in Chapter 4.

To test the influence of texture on each material type, smooth and roughened surfaces were prepared using standard stone finishing techniques. For limestone and granite, the smooth surface resulting from sawing at the quarry was used; for limestone this was the same surface finish used in *Exposure Trial 1* to represent building dimension stone (Section 5.2.2 p. 172). Granite was roughened using flame-texturing, a heat treatment that uses propane and oxygen combustion to create an irregular undulating surface; the same technique was used to recreate rough rock rubble in *Exposure Trial 1* (Section 5.2.2). Flame-texturing was ineffective on the Portland limestone and so rough versions of this material type were prepared using dolly-pointing (bush-hammering) which created a dimpled texture using a pneumatic hammer; texturing of limestone and granite was undertaken at De Lank Quarry, Bodmin. While textures created using the two techniques are not assumed to be identical, flame-textured granite and dolly-pointed limestone were chosen to be as comparable as possible (as opposed to other texturing techniques available at the quarry). This allowed comparisons of barnacle settlement and recruitment on 'rough' versus 'smooth' versions of the same material types (i.e. Hypothesis 5a-b).

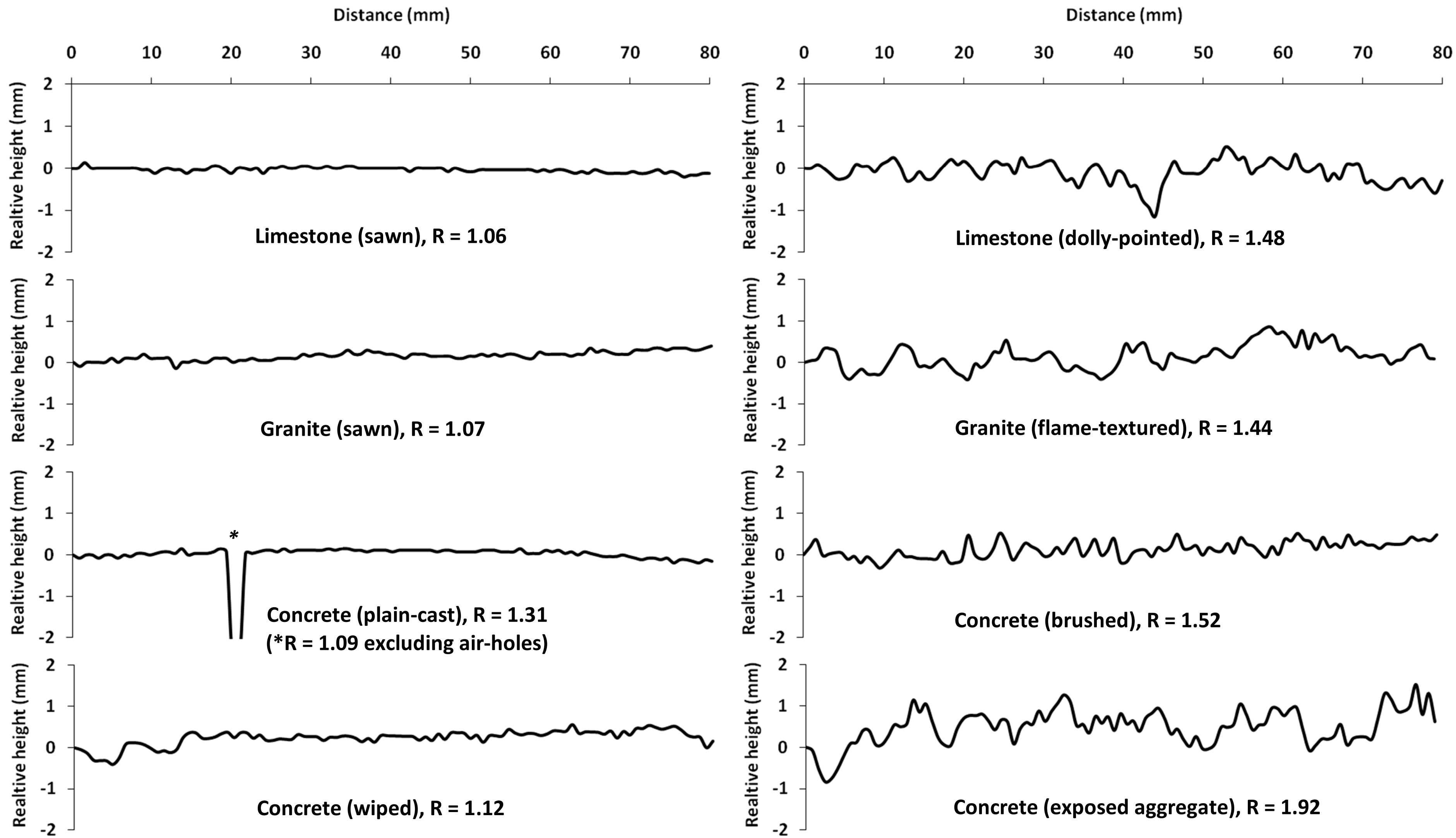
Concrete could be manipulated during the casting process by applying various treatments when wet. In addition to the 'plain-cast' finish used in *Exposure Trial 1*, concrete blocks were cast with three additional types of texture: (i) one batch was wiped with a cloth during curing (referred to as 'wiped'). Wiping removed the air-holes otherwise present on plain-cast blocks, which were observed to influence barnacles in the previous trial (see discussion in Section 5.4 p. 190), and as such gave a concrete treatment more comparable with the two 'smooth' rock treatments (above); (ii) a second batch of concrete blocks were wiped with a wire-brush when wet, which created regular, grooved texture, and; (iii) a water jet was used to remove the surface layer of cement on a third batch of blocks, which produced a more variable texture by exposing the crushed granite aggregate used in the concrete mix.

Materials with the surface finishes described above are summarised in Table 6-2. Representative surface profiles of each treatment are also shown in Figure 6-1. All limestone, granite and concrete blocks were cut with the dimensions 50 x 50 x 30 mm (± 5 mm), washed to remove loose debris and stored in the dark prior to field installation. In addition to the blocks, clearings were made on the platform (see below). Representative profiles of the platform rock are also shown in Figure 6-1 alongside block treatments. The roughness of all treatments used in this trial was also broadly assessed as part of the baseline characterisations described in Chapter 4 (see Figure 4-5 p. 157).

Table 6-2 Treatments used in *Exposure Trial 2*.

Material		Surface treatment	Code	Roughness (*R*)*
Portland Limestone	1	Diamond sawn	LS – Smooth	1.06
	2	Dolly-pointed	LT – Rough	1.48
Cornish Granite	3	Diamond sawn	GS – Smooth	1.07
	4	Flame-textured	GT – Rough	1.44
Marine Concrete	5	Plain-cast	CS – Smooth (with air-holes)	1.31
	6	Brushed	CTA – Texture 1 (grooves)	1.52
	7	Wiped	CTB – Texture 2 (smooth)	1.12
	8	Exposed aggregate	CTC – Texture 3 (rough)	1.92
Platform Clearing	9	Scrubbed	NA – Sterilised	1.87**
	10	Scrubbed & torched	NB – Un-sterilized	1.87**

*Indicative roughness (*R*) = Tr / Tt, where Tr is length of the profile trace and Tt is the measurement distance e.g. Trudgill 1988.
**Roughness of platform at Tregear Point shown here (also see Figure 6-1).


Distance (mm)
0 10 20 30 40 50 60 70 80
Realtive height (mm)
2 1 0 -1 -2
Limestone (sawn), R = 1.06
Limestone (dolly-pointed), R = 1.48
Granite (sawn), R = 1.07
Granite (flame-textured), R = 1.44
*
Concrete (plain-cast), R = 1.31
(*R = 1.09 excluding air-holes)
Concrete (brushed), R = 1.52
Concrete (wiped), R = 1.12
Concrete (exposed aggregate), R = 1.92

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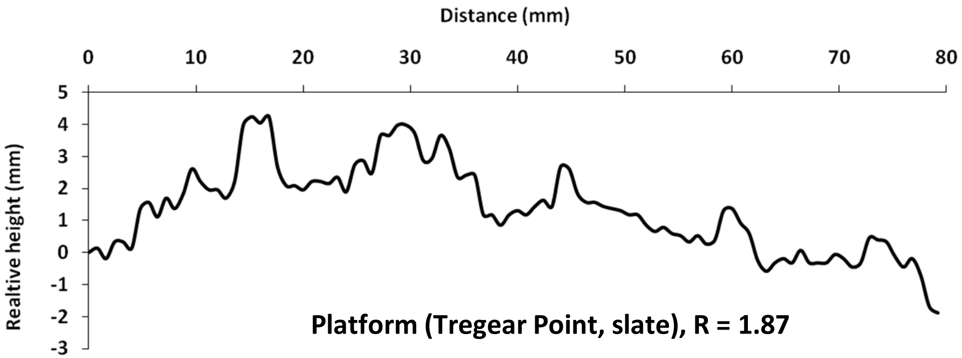


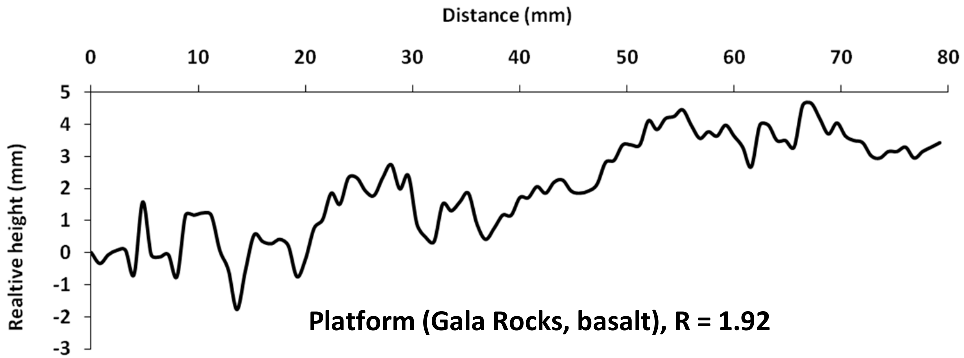


Figure 6-1 Representative surface profiles of treatments used in *Exposure Trial 1* (sawn limestone, flame-textured granite and plain-cast concrete, see Chapter 5) and *Exposure Trial 2* (all treatments, see Table 6-2): Roughness [R] = Tr / Tt, where Tr is length of the profile trace and Tt is the measurement distance e.g. Trudgill 1988.

6.2.3 Treatment application

The experimental design for *Exposure Trial 2* is shown schematically in Figure 6-2. On both shores (Tregear Point and Gala Rocks) blocks of each material type and surface texture combination (Table 6-2 above) were attached in a semi-horizontal position using marine epoxy filler, in batches of five, using the procedures described in Section 5.2.3 p. 173. In total 40 blocks were attached in one plot at MTL on each shore. One plot was used in this trial rather than two replicate plots (as used in *Exposure Trial 1*, see Figure 5-6 p. 174) because spatial differences in barnacle settlement and recruitment were not significant on these shores in the previous trial (e.g. Section 5.2.4 p. 178). A lower level of replication was also justified owing to the additional number of treatments used in this trial (i.e. six more types of texture).

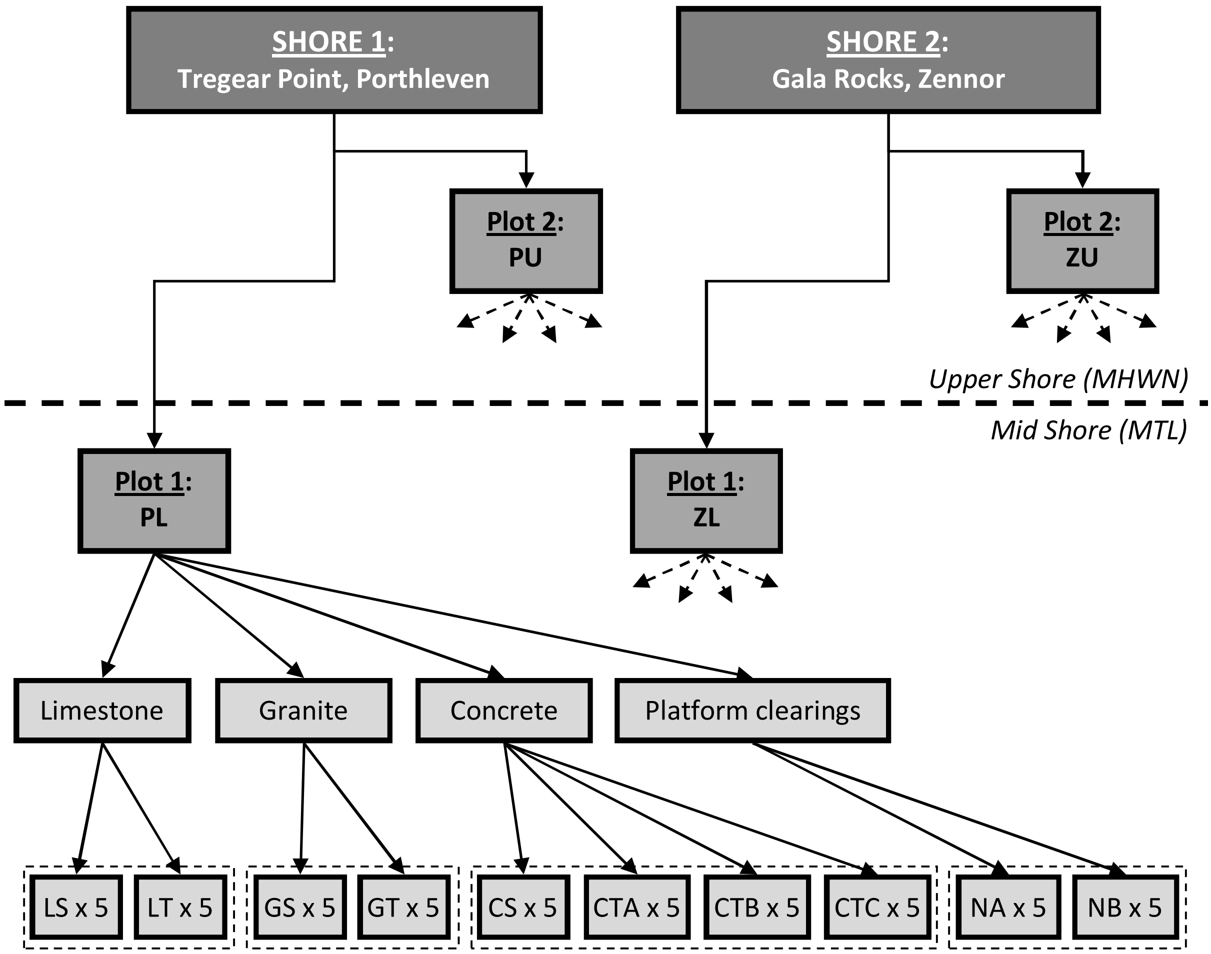


Figure 6-2 *Exposure Trial 2* experimental design (see Table 6-2 for code explanations).

Clearings were also made on the platform rock using a wire brush and paint scraper (see Section 5.2.3 p. 173). In each plot, five clearings were left without further treatment and five were sterilised using a blow-torch to remove microorganisms in order to control for the possible influence of bio-chemical cues (e.g. Thompson et al. 1998, Hypothesis 8a-b). All treatments were prepared on both shores on alternative days between 28th March and 2nd April 2009. This was done earlier in the year compared to *Exposure Trial 1* (May 2008) so that settlement of *S. balanoides* could be monitored, this species typically settling before the two *Chthamalus* species (Section 6.1.2).

The whole experimental design was replicated higher on the shore, at the upper limit of the barnacle zone (at MHWN, Figure 6-2). The location of the upper shore plots ('Plot PU' at Tregear Point and 'Plot ZU' Gala Rocks respectively) are shown in Figure 5-3 (p. 168) and Figure 5-5 (p. 171) respectively. In total, 160 blocks were attached and 40 clearings prepared across both shores. This design was originally intended to test for consistency in the effect of texture at different shore levels, as theory indicated refuge associated with surface complexity may be more important for colonising organisms higher on the shore (e.g. Chapman and Blockley 2009, see review in Chapter 2). Settlement on blocks attached at MHWN was, however, very low during the course of the study so that meaningful analyses could not be undertaken for these plots; therefore only data recorded from mid-shore plots (i.e. PL and ZL) were used in the analyses presented in this chapter. Blocks attached higher on the shore were used, however, for observations of microorganisms and weathering described in Chapter 7.

6.2.4 Barnacle settlement and recruitment

In summer 2009 (July – August) *Chthamalus* spp. cyprids and metamorphosed juveniles on top surfaces of blocks and within platform clearings were counted on 16 occasions at Tregear Point where settlement was high, and 4 occasions at Gala Rocks where settlement was markedly less. Barnacles were counted in the field using quadrats or from photographs using the same methods described in Chapter 5; counts were not made within 0.5 cm of the edge of blocks and clearings, giving a sampling area of 16 cm^2 for each treatment. *S. balanoides* was also counted at Gala Rocks before *Chthamalus* had started settling (in April – June 2009); *S. balanoides* settled in very few numbers at Tregear Point as so only *Chthamalus* spp. were counted on this shore. Final counts of *Chthamalus* recruits were made towards the end of the settlement season on both shores (in October/November) as a measure of annual recruitment.

6.2.5 Data analysis

Separate ANOVAs were undertaken to test each of the hypotheses listed in Table 6-1 as described below (GMAV5 was used for all analyses, Underwood et al. 1997). Only data collected within MTL plots were used in these analyses due to low settlement within upper shore plots (see Section 6.2.3). In all tests data were checked for homogeneity using a Cochran's test and transformed where necessary. Untransformed data were used where heterogeneity persisted after transformation, when a conservative significance level (p_{crit} = 0.01) was adopted (Underwood 1997). Subsequent Student-Newman-Keuls (SNK) tests were used to examine significant interactions among factors.

6.2.5.1 Hypothesis 5: Rough vs. smooth materials

To test whether settlement and recruitment differed between 'rough' and 'smooth' versions of the same material types (Hypothesis 5a and 5b), numbers of *Chthamalus* cyprids counted on peak days of settlement were compared (peak settlement = 13th August at Tregear Point and 19th August at Gala Rocks). Recruitment on the same treatments was compared using counts of adults made towards the end of the settlement season.

For this test, data for the smoothest and roughest versions of each material type were used as the 'smooth' and 'rough' treatments (i.e. Figure 6-1). For limestone and granite, blocks with a sawn surface (LS and GS) and textured surface (LT and GT) were used (see Table 6-2). For concrete, blocks with a wiped surface (CTB) and exposed aggregate finish (CTC) were used as the 'rough' and 'smooth' treatments, respectively. For both analyses (cyprids and recruits) 'shore' was a random factor (2 levels: Tregear Point and Gala Rocks), 'material type' was a fixed factor (3 levels: limestone, granite and concrete) and 'texture' was a fixed factor nested in 'material' (2 levels: 'smooth' and 'rough').

6.2.5.2 Hypothesis 6: Types of texture

To examine whether settlement and recruitment differed between blocks of concrete with different surface finishes (Hypothesis 6a and 6b), counts of *Chthamalus* cyprids and recruits on the four concrete treatments were compared. For these tests 'shore' was a random factor (2 levels: Tregear Point and Gala Rocks) and 'texture' was a fixed factor (4 levels: plain-cast, wiped, brushed and exposed aggregate, see Table 6-2).

6.2.5.3 Hypothesis 7: Artificial texture vs. platform rock

To determine whether certain types of material x texture combinations were able to replicate barnacle settlement and recruitment on the natural rock substrata (Hypothesis 7a and 7b), numbers of *Chthamalus* cyprids and recruits counted within platform clearings were compared with limestone, granite and concrete treatments on which the highest settlement and recruitment was recorded during the experiment; these were dolly-pointed limestone (LT), flame-textured granite (GT) and brushed concrete (CTA). Data recorded on sterilised platform clearings (NB) were used in this comparison to control for potential bio-chemical cues, which may otherwise be present without sterilisation. 'Shore' was a random factor (2 levels: Tregear Point and Gala Rocks) and 'treatment' was a fixed factor (4 levels: rough limestone, rough granite, rough concrete and sterilised control clearings).

6.2.5.4 Additional tests

Additional ANOVAs were used to test whether *Chthamalus* settlement and recruitment differed between sterilised and un-sterilised clearings on the platforms, to examine whether the presence of microbial films or other bio-chemical cues influenced barnacle colonisation on the natural rock substrata (Hypothesis 8a and 8b). For this test 'shore' was a random factor (2 levels: Tregear Point and Gala Rocks) and 'treatment' was a fixed factor (2 levels: sterilised and un-sterilised).

Settlement and recruitment of *S. balanoides* on all introduced materials (limestone, granite and concrete) was generally very low during the experiment meaning quantitative comparisons for this species could not be made at either shore. However, the influence of rock sterilisation on *S. balanoides* was tested using data collected at Gala Rocks, where *S. balanoides* settled in sufficient numbers within clearings made on the platform.

6.3 Results

6.3.1 Hypothesis 5: Rough vs. smooth materials

Numbers of *Chthamalus* cyprids recorded on 'rough' and 'smooth' replicates of limestone, granite and concrete on peak days of settlement, and numbers of recruits counted towards the end of the settlement season are shown in Figure 6-3. Figure 6-4 shows numbers of recruits counted on each sampling occasion at Tregear Point, where settlement was highest.

Across both shores, significantly more cyprids settled on rough blocks than smooth (p = 0.03, Table 6-3). Interaction between the factors 'shore' and 'treatment' (p = 0.007, Table 6-3) indicated that the influence of texture was stronger at Tregear Point than Gala Rocks, where settlement was significantly lower (p = 0.05, Table 6-3). No test could be resolved for material type in the ANOVA, however this was not a specific consideration of Hypothesis 5, and other significant interactions (above) precluded the necessity to obtain a test for material type through data pooling (Underwood 1997).

Subsequent SNK tests showed that the number of cyprids counted on rough versions of each material was significantly higher than on smooth versions (p = 0.01) with the exception of concrete at Tregear Point where the difference was significant at the 0.05 confidence level (Figure 6-3a). The influence of artificial texture was most obvious on limestone, particularly at Tregear Point where roughened (dolly-pointed) blocks had significantly more cyprid larvae from the very start of the settlement season (Figure 6-4).

Table 6-3 Analysis of variance for numbers of *Chthamalus* spp. cyprids counted on peak settlement days on 'smooth' and 'rough' blocks of limestone, granite and concrete on two shores in Cornwall.

Source of variation	***df***	**MS**	***F***	***p***
Shore (*n* = 2)	1	10.916	10.22	**0.049***
Material (*n* = 3)	2	4.962	-	no test
Texture(Material, *n* = 2)	3	13.144	12.31	**0.034***
Shore x Material	2	0.895	0.84	0.514
Shore x Texture(Material)	3	1.068	4.52	**0.007****
Residuals	48	0.236	-	-
Total	59	-	-	-

Cochran's test $C = 0.243$ (not significant).
p values: **p* < 0.05, ***p* < 0.01, ****p* < 0.001.
Treatments: limestone (sawn and dolly-pointed), granite (sawn and flame-textured), concrete (wiped and exposed aggregate).

At the end of the settlement season differences in recruitment between rough and smooth versions of each material were also significant ($p < 0.001$), but interaction between 'shore' and 'texture' factors ($p < 0.001$) indicated that the magnitude of the effect was not consistent between shores (Table 6-4). At Tregear Point, recruitment was significantly higher on rough blocks compared to smooth for all material types ($p = 0.01$, Figure 6-3b); at Gala Rocks, recruitment was significantly higher on rough compared to smooth concrete ($p = 0.01$) but there was no difference between rough and smooth versions of limestone and granite on this shore ($p > 0.05$, Figure 6-3b). Again, no test could be resolved for material type, but this was not necessary for the specific hypothesis being tested.

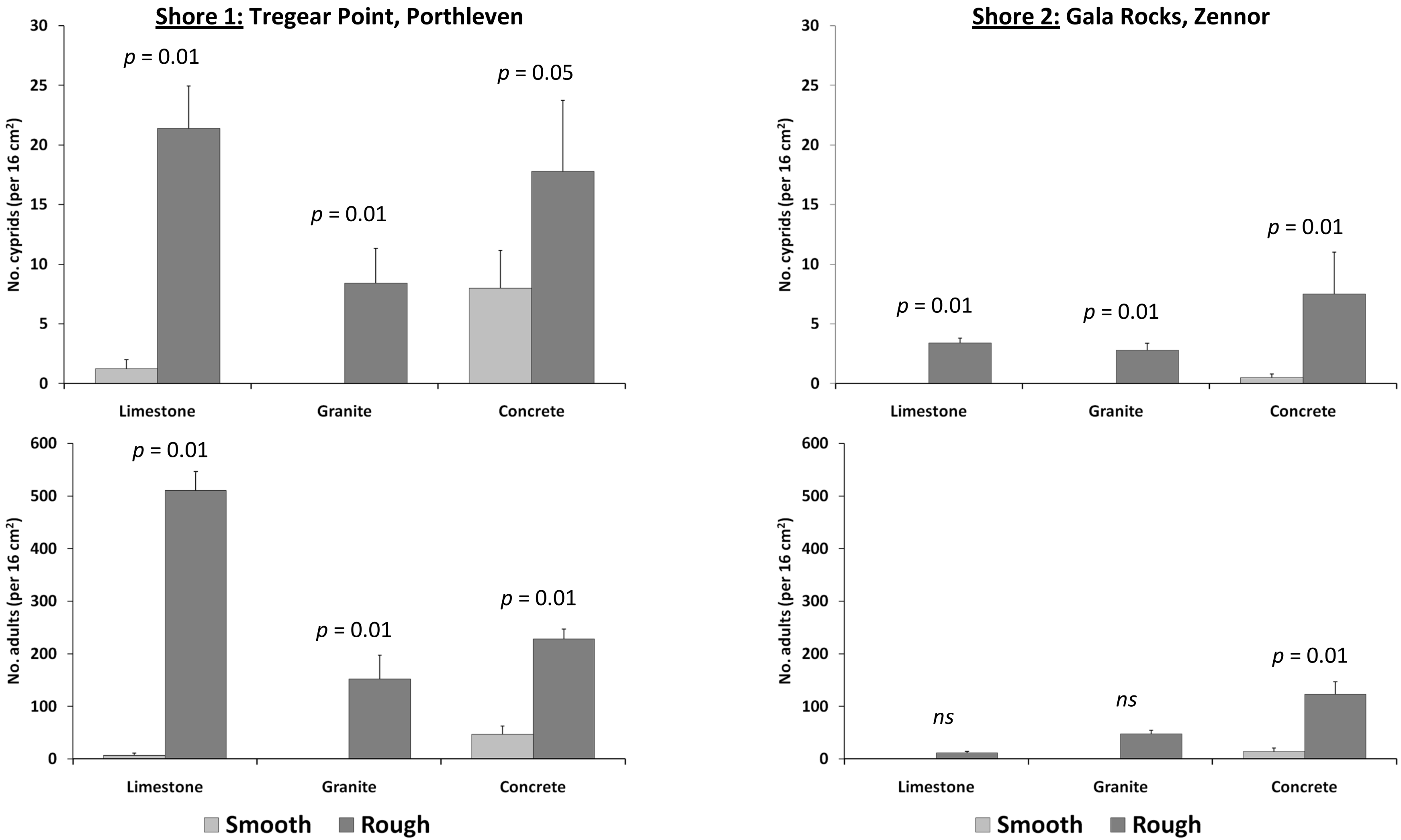


Figure 6-3 Number (mean ± SE) of (a) *Chthamalus* spp. cyprids on peak settlement days (*above*) and (b) recruits at the end of the settlement season (*below*) on smooth and rough blocks of limestone, granite and concrete on two shores in Cornwall, UK (SNK significance as shown).

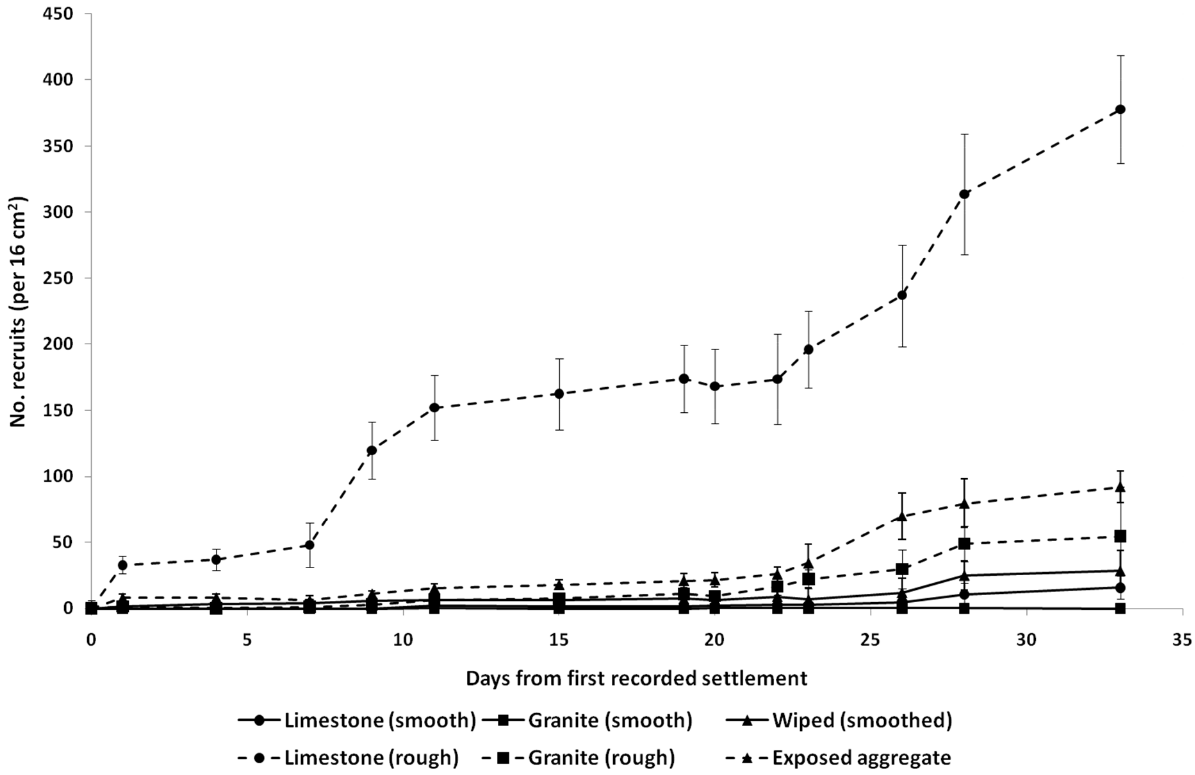


Figure 6-4 Cumulative number (mean ± SE) of barnacle recruits (*Chthamalus* spp.) counted on 'rough' and 'smooth' blocks of limestone, granite and concrete at Tregear Point, Porthleven, UK (July – August 2009).

Table 6-4 Analysis of variance for numbers of *Chthamalus* spp. recruits counted at the end of the settlement season on 'smooth' and 'rough' replicates of limestone, granite and concrete on two shores, Cornwall, UK.

Source of variation	*df*	MS	*F*	*p*
Shore (n = 2)	1	233376.0667	2.17	0.237
Material (n = 3)	2	34869.2167	-	no test
Texture(Material, n = 2)	3	162417.8333	1.51	0.372
Shore x Material	2	62132.8167	0.58	0.614
Shore x Texture(Material)	3	107591.3667	69.97	**0.000*****
Residuals	48	1537.7917	-	-
Total	59	-	-	-

Cochran's test C = 0.428 (p < 0.01), therefore p_{crit} = 0.01.

p values: *p < 0.05, **p < 0.01, ***p < 0.001.

Treatments: limestone (sawn and dolly-pointed), granite (sawn and flame-textured), concrete (wiped and exposed aggregate).

6.3.2 Hypothesis 6: Type of texture

Numbers of *Chthamalus* spp. cyprids counted on peak settlement days, and recruits recorded at the end of the settlement season, are shown in Figure 6-5 for concrete blocks with different types of surface texture. Numbers of recruits counted on each sampling day are shown in Figure 6-6 for the peak months of settlement (July – August 2009) at Tregear Point, where settlement was highest.

The type of texture applied to concrete blocks had a significant effect on cyprid settlement ($p < 0.001$), but interactions between 'shore' and 'texture' factors ($p < 0.001$) indicated that the magnitude of this effect varied between shores (Table 6-5). At Tregear Point, settlement was lowest on plain-cast and wiped blocks, which were themselves no different ($p > 0.05$), while significantly more cyprids settled on blocks with an exposed aggregate finish ($p = 0.05$). More cyprids settled on brushed blocks than all the other treatments on this shore ($p = 0.01$, Figure 6-5a). At Gala Rocks, settlement on plain-cast blocks was higher than those with a wiped finish ($p = 0.01$), but there were no other differences between treatments (Figure 6-5a). Overall, settlement on concrete was significantly lower at Gala Rocks compared to Tregear Point ($p < 0.001$, Table 6-5).

Table 6-5 Analysis of variance for numbers of *Chthamalus* spp. cyprids counted on peak settlement days on concrete with different surface textures on two shores, Cornwall, UK.

Source of variation	*df*	MS	*F*	*p*
Shore (n = 2)	1	8.7738	35.34	**0.000*** **
Texture (n = 4)	3	5.5773	2.69	0.219
Shore x Texture	3	2.0762	8.36	**0.000*** **
Residuals	32	0.2482	-	-
Total	39	-	-	-

Cochran's test C = 0.345 (not significant).
p values: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.
Treatments: plain-cast (CS), brushed (CTA), wiped (CTB) and exposed aggregate (CTC).

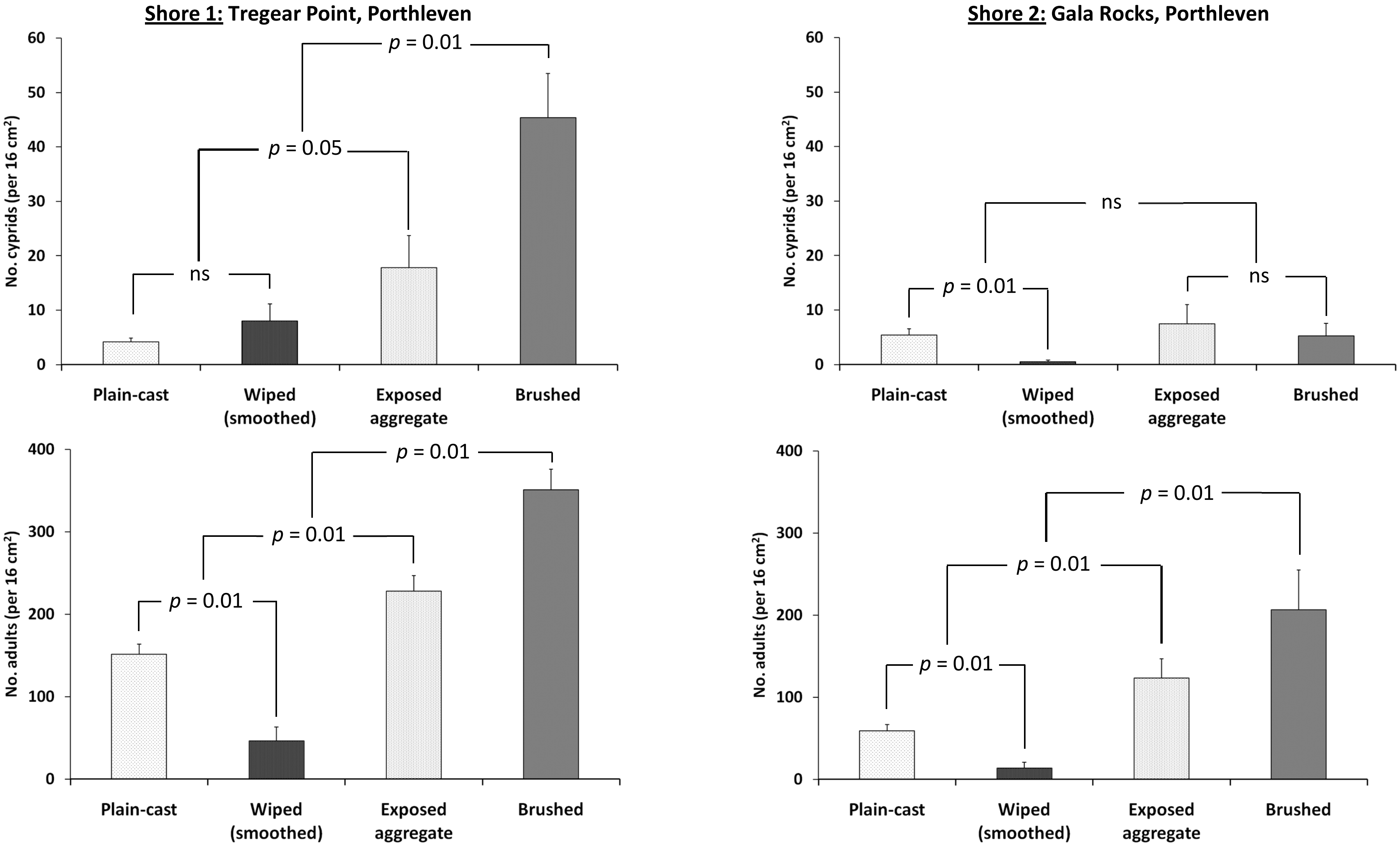


Figure 6-5 Number (mean ± SE) of (a) *Chthamalus* spp. cyprids on peak settlement days (*above*) and (b) recruits at the end of the settlement season (*below*) on concrete blocks with different surface textures on two shores, Cornwall, UK (SNK significance as shown).

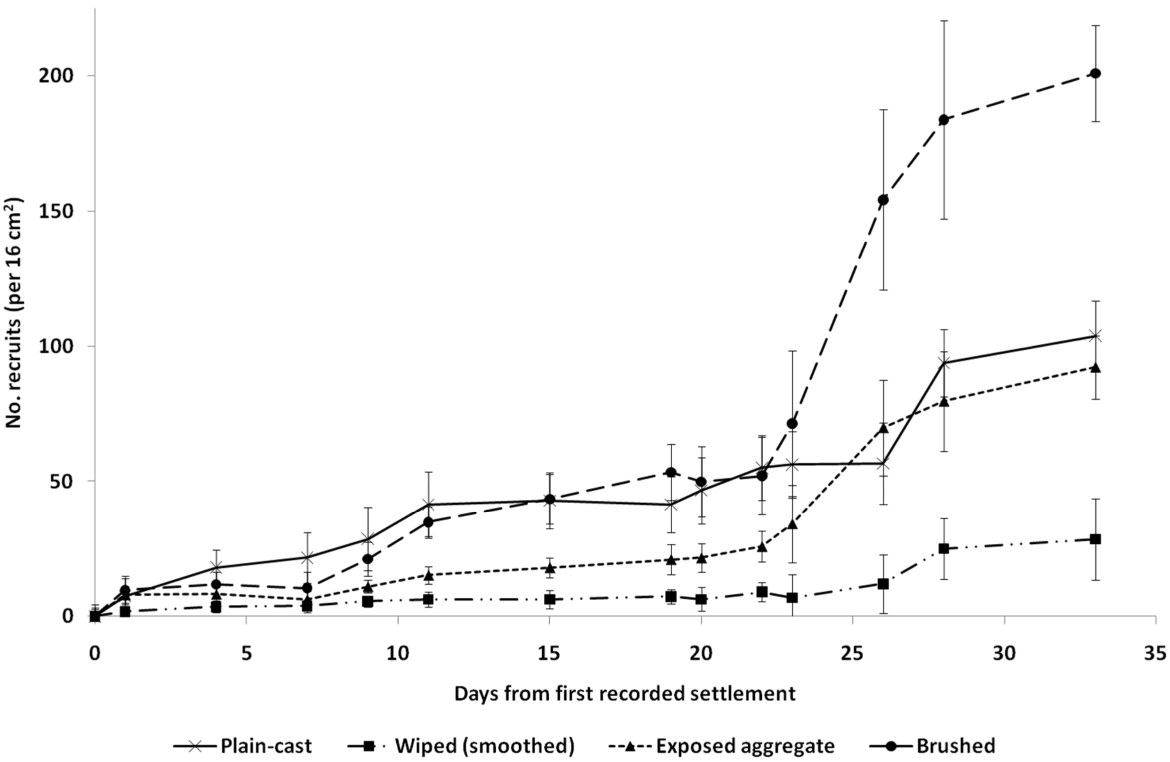


Figure 6-6 Cumulative number (mean ± SE) of barnacle recruits (*Chthamalus* spp.) counted on concrete blocks with different surface textures at Tregear Point, Porthleven, UK (MTL, July – August 2009).

At the end of the settlement season (October/November 2009), there were also significant differences in numbers of *Chthamalus* spp. recruits between concrete treatments (p < 0.001, Table 6-6). On both shores recruitment was lowest on wiped blocks, which was significantly lower than on plain-cast blocks (p = 0.01, Figure 6-5b). Significantly more adults were counted on concrete with an exposed aggregate finish compared to both wiped and plain-cast finishes (p = 0.05 at Tregear Point, p = 0.01 at Gala Rocks). Recruitment was highest on brushed concrete on both shores (p = 0.01, Figure 6-5, Figure 6-6).

Table 6-6 Analysis of variance for numbers of *Chthamalus* spp. recruits counted at the end of the settlement season (2009) on concrete with different surface textures on two shores, Cornwall, UK.

Source of variation	*df*	MS	*F*	*p*
Shore (*n* = 2)	1	147.4702	52.57	**0.000*****
Texture (*n* = 4)	3	244.8405	212.07	**0.001*****
Shore x Texture	3	1.1545	0.41	0.746
Residuals	32	2.8052	-	-
Total	39	-	-	-

Cochran's test *C* = 0.323 (not significant).
p values: $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.
Treatments: plain-cast (CS), brushed (CTA), wiped (CTB), exposed aggregate (CTC).

6.3.3 Hypothesis 7: Artificial texture vs. naturally weathered rock

Numbers of *Chthamalus* spp. cyprids counted on peak settlement days, and recruits counted at the end of the settlement season on roughened blocks of limestone (dolly-pointed), granite (flame textured) and concrete (brushed) are shown in Figure 6-7 alongside numbers recorded on weathered platform rock (sterilised clearings). Recruits counted on each sampling occasion are shown in Figure 6-8 for the peak settlement period (July – August) at Tregear Point, where settlement was highest.

Overall, numbers of cyprids counted on roughened construction materials were no different to the weathered platform rock ($p = 0.206$, Table 6-7a). However, settlement on brushed concrete was significantly higher than all the other treatments at Tregear Point, including platform clearings (Figure 6-7a). As observed in *Exposure Trial 1* (Chapter 5) settlement was lower at Gala Rocks than Tregear Point on all treatments ($p < 0.001$, Table 6-7a).

Table 6-7 Analysis of variance for numbers of *Chthamalus* spp. cyprids counted on peak days of settlement on rough limestone, granite and concrete, and sterilised platform rock on two shores, Cornwall, UK.

Source of variation	*df*	MS	*F*	*p*
Shore (n = 2)	1	65.1944	69.37	**0.000*****
Treatment (n = 4)	3	9.3031	1.93	0.302
Shore x Treatment	3	4.8323	5.14	**0.005****
Residuals	32	0.9399	-	-
Total	39	-	-	-

Cochran's test *C* = 0.374 (not significant).
p values: $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.
Treatments: limestone (dolly-pointed), granite (flame textured), concrete (brushed), natural rock (scrubbed and sterilised).

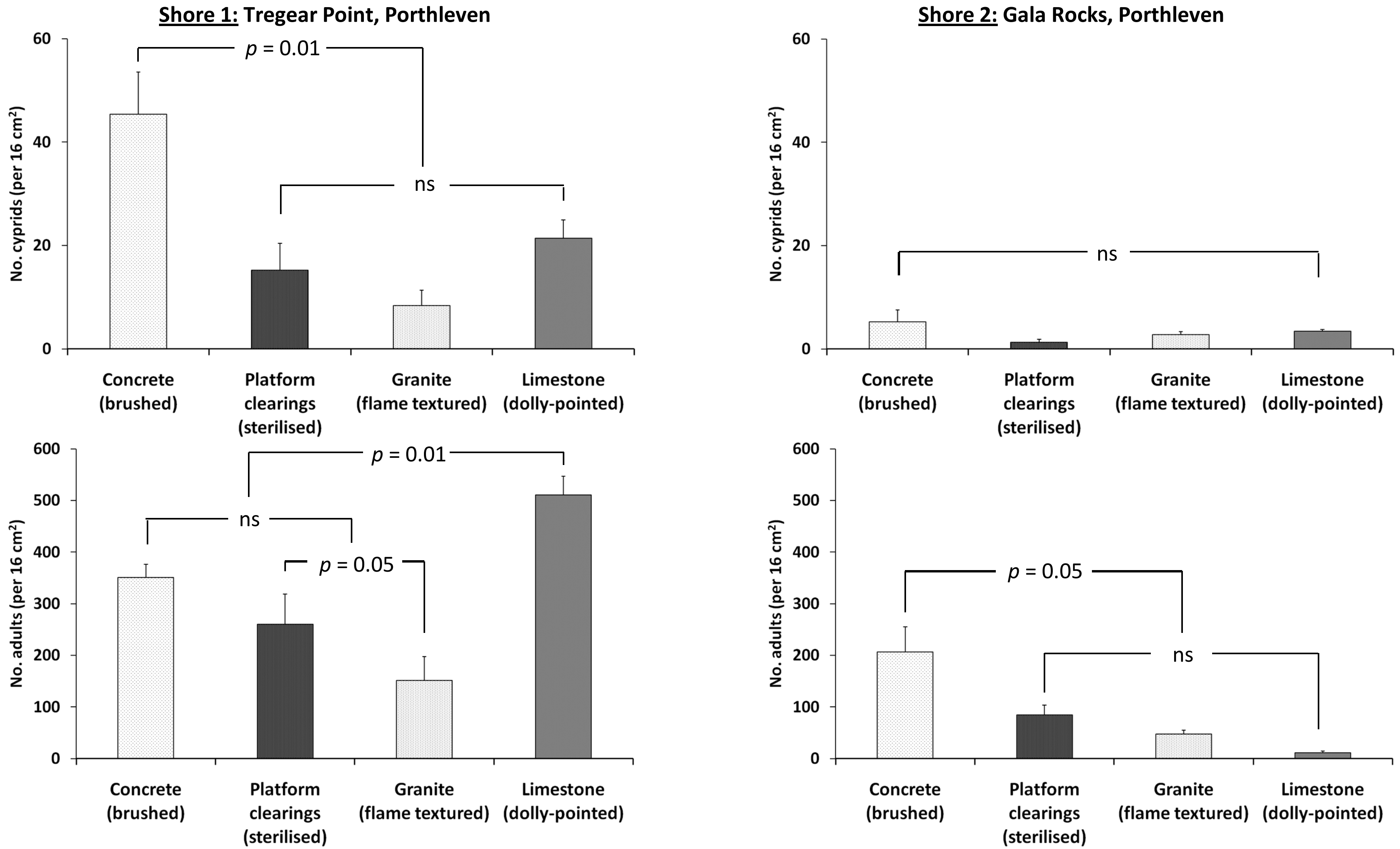


Figure 6-7 Number (mean ± SE) of (a) *Chthamalus* spp. cyprids on peak settlement days (*above*) and (b) recruits at the end of the settlement season (*below*) on artificially roughened construction materials and weathered platform rock on two shores, Cornwall, UK (SNK significance as shown).

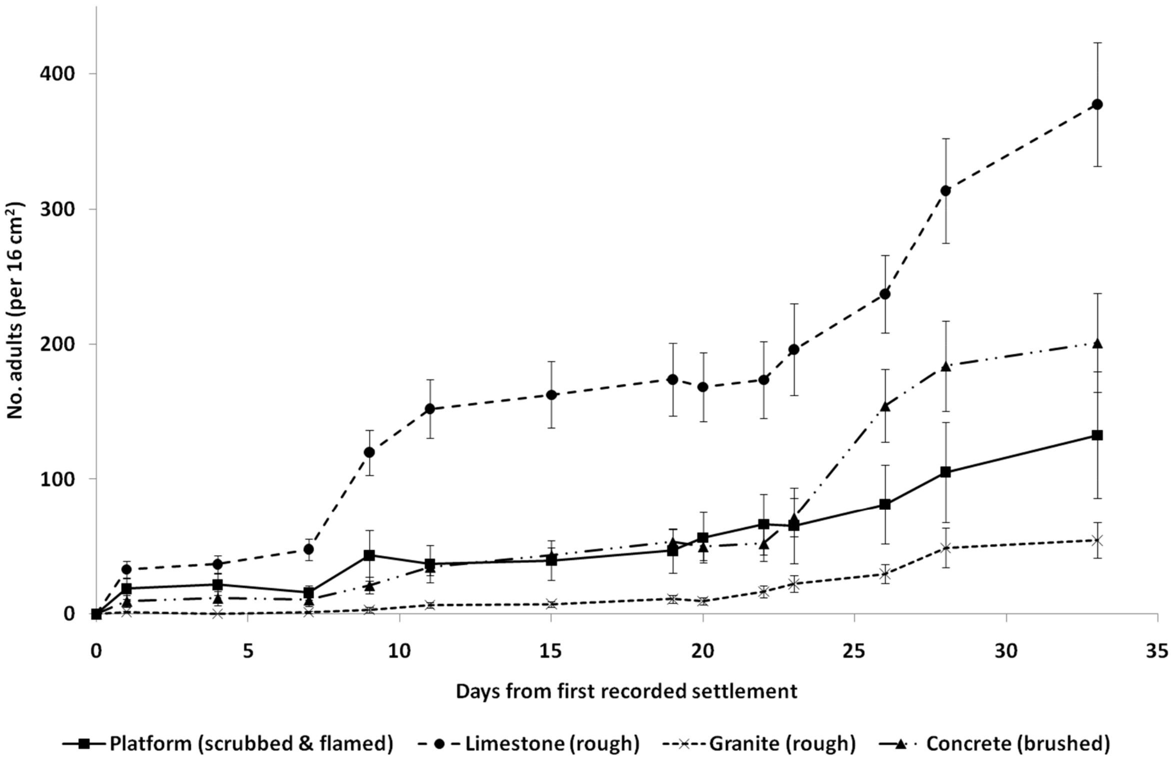


Figure 6-8 Cumulative number (mean ± SE) of barnacle recruits (*Chthamalus* spp.) counted on textured limestone, granite and concrete, and control (sterilised) clearings at Tregear Point, Porthleven, UK (MTL, July – August 2009).

Overall differences in barnacle recruitment (at the end of the season) between roughened materials and platform clearings were not significant (p = 0.555, Table 6-8). There were, however, significant differences on each shore (shore x treatment p < 0.001, Table 6-8). More recruits were counted on the cleared platform than on roughened (flame-textured) granite at Tregear Point (p = 0.05), and recruitment on roughened (dolly-pointed) limestone was significantly higher than all other treatments on this shore, including the naturally weathered rock (p = 0.01, Figure 6-7b). At Gala Rocks, significantly more recruits were counted on the textured (brushed) concrete than the other treatments (p = 0.05), but there was no difference between rough limestone, rough granite or the platform clearings (p > 0.05, Figure 6-7b). In all instances, barnacle recruitment was lower at Gala Rocks compared to Tregear Point (p < 0.001, Table 6-8).

Table 6-8 Analysis of variance for numbers of *Chthamalus* spp. recruits counted at the end of the settlement season (October/November 2009) on rough limestone, granite and concrete, and sterilised platform rock on two shores, Cornwall, UK.

Source of variation	*df*	MS	*F*	*p*
Shore (n = 2)	1	533379.025	88.68	**0.000*** **
Treatment (n = 4)	3	68992.1583	0.84	0.5552
Shore x Treatment	3	82111.6917	13.65	**0.000*** **
Residuals	32	6014.3875	-	-
Total	39	-	-	-

Cochran's test $C = 0.356$ (not significant).
p values: $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.
Treatments: limestone (dolly-pointed), granite (flame textured), concrete (brushed), natural rock (scrubbed and sterilised).

6.3.4 Hypothesis 8: Bio-chemical cues

Numbers of cyprids and metamorphosed recruits counted on sterilised (scrubbed and flamed) and un-sterilised (scrubbed) clearings on the platform rock are shown in Figure 6-9. Sterilisation had no effect on settlement or recruitment on the platforms at either shore ($p = 0.104$ for cyprids on peak settlement days, $p = 0.842$ for adult recruits, Table 6-9).

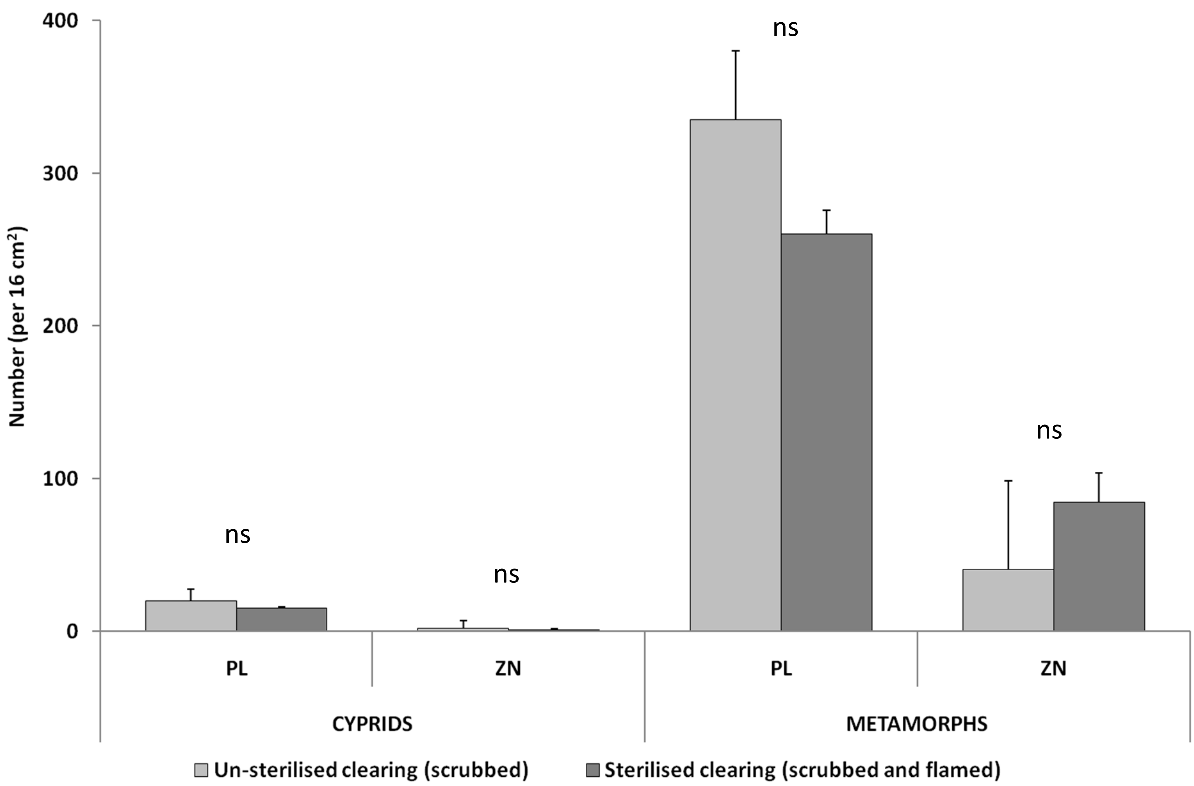


Figure 6-9 Number (mean + SE) of *Chthamalus* spp. cyprids and recruits counted on sterilised and un-sterilised clearings on platform rock on two shores, Cornwall, UK (PL = Porthleven, rock type = Mylor slate; ZN = Zennor, rock type = basalt).

Table 6-9 Analysis of variance for numbers of (a) *Chthamalus* spp. cyprids counted on peak days of settlement and (b) recruits counted at the end of the settlement season (October/November 2009) on sterilised and un-sterilised clearing on platform rock on two shores, Cornwall, UK.

(a) Cyprid settlement

Source of variation	*df*	MS	*F*	*p*
Shore (*n* = 2)	1	15.2266	21.2	**0.000*****
Treatment (*n* = 2)	1	0.2987	37.18	0.104
Shore x Treatment	1	0.008	0.01	0.917
Residuals	16	0.7183	-	-
Total	19	-	-	-

Cochran's test *C* = 0.432 (not significant)

(b) Adult recruitment

Source of variation	*df*	MS	*F*	*p*
Shore (*n* = 2)	1	277183.5125	37.3	**0.000*****
Treatment (*n* = 2)	1	1132.5125	0.06	0.842
Shore x Treatment	1	17612.1125	2.37	0.143
Residuals	16	7431.1875	-	-
Total	19	-	-	-

Cochran's test *C* = 0.576 (not significant).
p values: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.
Treatments: sterilised and un-sterilised clearings.

6.4 Discussion

6.4.1 Hypothesis 5: Rough vs. smooth materials

Significantly more *Chthamalus* spp. cyprids settled on artificially roughened blocks of limestone, granite and marine concrete than smooth replicates; this effect was consistent across both shores (Hypothesis 5a p. 205). These results agree with other field-based studies reporting positive associations between barnacle settlement and substratum roughness (e.g. Pomerat and Weiss 1946; Chabot and Bourget 1988; Skinner and Coutinho 2005; Herbert and Hawkins 2006; Savoya and Schwindt 2010). Laboratory observations have shown that once arriving at a substratum, barnacle cypris larvae exhibit active searching behaviour, followed by behavioural rejection or acceptance of topographically distinct settlement sites (Barnes and Powell 1950; Crisp and Barnes 1954; Hills et al. 1998; Thompson et al. 1998; Thomason et al. 2000). Settlement in association with topographic features in this way may enhance both physical attachment (Barnes 1970; Yule and Walker 1984; Le Tourneux and Bourget 1988; Aldred and Clare 2009) and provide refuge from biological and physical stresses, which are particularly important during larval life-stages (Foster 1971; Wethey 1983; Connell 1985; Hills and Thomason 1998).

Similarly, at the end of the 2009 settlement season, differences in barnacle recruitment were significant between 'smooth' and 'rough' versions of the same material types (Hypothesis 5b p. 205). The most dramatic difference was observed for limestone at Tregear Point, where artificially roughening blocks increased recruitment by more than 70 times. Texturing also had the greatest effect on cyprid settlement on limestone on this shore, where 20 times the number cyprids were counted on dolly-pointed (rough) blocks than on sawn (smooth) versions.

Differences in numbers of recruits between 'rough' and 'smooth' treatments may have been a direct result of settlement patterns (above), or of post-settlement processes (i.e. mortality of individuals soon after attachment, e.g. Connell 1985). Although not monitored in this trial, differences in post-recruitment mortality (after settlement had largely finished) were observed between treatments with different textures in *Exposure Trial 1*, and post-settlement mortality may have similarly varied between treatments in this trial (see Section 5.4.2 for discussions of post-recruitment mortality). In comparison to smooth materials, mortality may be reduced on rough versions of the same material types as a result of refuge provision. This includes refuge from grazers (e.g. Wahl and Hoppe 2002) and the provision of less stressful micro-climatic conditions when exposed to insolation (as a result of water ponding for example, Savoya and Schwindt 2010). The influence of texture on the drying and warming behaviour of hard substrata was assessed in Chapter 8 alongside comparisons of the different material types used in both exposure trials.

In contrast to Tregear Point, differences in recruitment between 'rough' and 'smooth' versions of limestone were not statistically significant at Gala Rocks, nor for granite, although roughened blocks did have more recruits than smooth replicates (Figure 6-3b). This lack of significance at Gala Rocks may have been a function of the very low numbers of adults counted on this shore in general, particularly on smooth-cut limestone and granite (zero in most instances) which may have obscured any significant effects in the ANOVA test (Underwood 1997). Raimondi (1990) also recorded no settlement and lower recruitment on machine cut granite compared to naturally weathered (i.e. rough) granite for *C. anisopoma*. Differences in settlement and recruitment between the two shores (which were always lower at Gala Rocks) are discussed in Section 5.4.1.1 (p. 194).

At the scale of whole structures (m), the physical complexity of design (in terms of the number of habitat niches created) has been suggested as an important factor limiting overall biodiversity potential compared to rocky shores (Chapman 2003; Bulleri et al. 2005; Bulleri 2006; see review in Chapter 2). This principle has been a well-applied in, for example, the design and construction of artificial reefs (Jensen 1997; Jensen et al. 1998; CIRIA 2008). At a smaller scale (cm – m), ways of introducing niches into designs to encourage target species or increase overall biodiversity are starting to be tested, such as the use of holes for limpets (Martins et al. 2010), or artificial rockpools for other macrobiota (Chapman and Blockley 2009). In contrast, there has been much less testing of ecological manipulation at smaller scales (<mm – cm; see review in Chapter 2). The results presented here provide robust evidence demonstrating how artificial texture at a small scale (mm's) can have a significant influence on colonisation of various engineering materials by a common early-coloniser in the intertidal zone; barnacles were consistently more numerous on roughened versions of limestone, granite and marine concrete compared to smooth alternatives.

6.4.2 Hypothesis 6: Type of texture

The general notion that 'rough is better than smooth' for ecological potential (e.g. CIRIA 2007) has been demonstrated for a specific organism (Chthamalid barnacles) colonising various materials used in coastal engineering (Hypothesis 5, above). There were, however, significant differences in both settlement and recruitment of barnacles on marine concrete which had been manipulated in different ways; the *type* of texture is also important for ecological potential (Hypothesis 6a-b p. 205).

Brushed concrete had the greatest response, increasing recruitment of Chthamalid barnacles by 130 % and 248 % at Tregear Point and Gala Rocks, respectively, compared to concrete with a plain-cast finish typically used in coastal engineering (Figure 6-5b). Although general roughness appears to facilitate colonisation by this organism, previous studies have demonstrated that direct geometric measures of roughness can be poor predictors for barnacle settlement (e.g. Hills and Thomason 1996; Holmes et al. 1997). Brushed concrete for example, which had highest settlement and recruitment, was not the roughest of the concrete treatments using a standard index of roughness ('*R*', see Figure 6-1). As an alternative to geometric roughness, it has been suggested that the provision of particular scales of roughness elements is more important for barnacles (Bourget et al. 1994; Hills and Thomason 1998). For *S. balanoides*, Hills and Thomason (1996) found that fine and medium scale roughness (0.5 mm and 2.0 mm respectively) were favoured by cyprids compared to smoother and rougher textures. Le Tourneux and Bourget (1988) also observed barnacle preference for substrata with high micro-heterogeneity (< 300 µm). Much less work has been done on the influence of particular scales of texture on Chthamalid barnacles, but the strong response to brushed concrete in this trial indicated broadly similar requirements for fine-scale texture, at a mm scale (e.g. Figure 6-10).

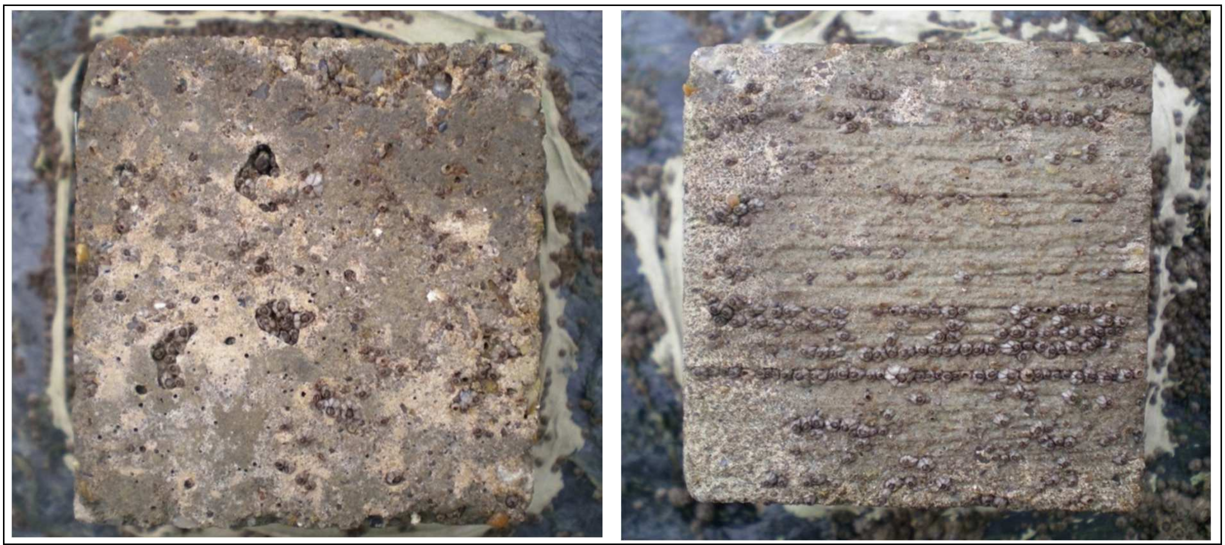


Figure 6-10 Recruitment of Chthamalid barnacles in association with air-holes on plain-cast concrete (*left*) and grooves on brushed concrete (*right*; Tregear Point, 31st October 2009).

Measures of roughness other than geometric parameters have proved more successful at predicting the likely attractiveness of substrata to barnacle larvae. For example, 'Potential Settlement Sites' (PSS) has been used to describe the number of locations on a substratum that offer a particular scale of texture known to be important for the organism of interest (Hills and Thomason 1996). Although these kinds of measures have not always proved effective predictive or explanatory tools (e.g. Herbert and Hawkins 2006) the concept of PSS offers an explanation for observed inconsistencies in *Chthamalus* cyprid settlement on concrete treatments between shores (Figure 6-5a) as a function of overall differences in the levels of settlement. In the Gulf of Mexico, for example, Raimondi (1990) observed that where settlement of the barnacle *C. anisopoma* was high, differences between sites could be explained by the number of PSS (or 'Suitable Settlement Sites' as Raimondi calls them). In contrast, the number of PSS was not a limiting factor where settlement was low, so that settlement was similar between sites. In this experiment, all the concrete treatments would have offered some PSS (it is the *number* of PSS that will vary as a function of texture, Hills and Thomason 1996). In this respect, the availability of PSS was probably not a limiting factor at Gala Rocks where settlement was very low throughout the season. At Tregear Point, however, settlement may have been sufficiently high for PSS to become 'saturated' with settlers, and thus a limiting factor; where settlement was very high (i.e. at Tregear Point), differences in numbers of settlers and recruits were therefore more likely to have occurred between treatments as a function of texture.

Similarly, the importance of air-holes in plain-cast concrete (the most common surface finish used in marine engineering) for barnacle colonisation has also been demonstrated (Chapter 5). In this trial, cyprid settlement was significantly lower on concrete on which air-holes had been removed (through wiping when wet) on one of the shores (at Gala Rocks). Recruitment was also significantly lower on concrete without air-holes (wiped) than concrete with air-holes (plain-cast) on both shores (Figure 6-5a-b). This suggests that comparable barnacle responses on plain-cast concrete and roughened granite blocks in *Exposure Trial 1* (see Chapter 5) probably occurred through the functioning of air-holes as PSS. Settlement in air-holes was suggested as a mechanism for increased post-recruitment mortality on concrete however (see Section 5.4.2 p. 195).

6.4.3 Hypothesis 7: Artificial texture vs. naturally weathered rock

A principal conservation goal is for artificial structures to replicate ecological processes occurring on natural shores as far as is feasibly possible (Moschella et al. 2005; Burcharth et al. 2007; Chapman and Blockley 2009, see review in Chapter 2 and discussions on Chapter 9). However, *Exposure Trial 1* showed that construction materials with surface finishes commonly used in engineering did not replicate early colonisation of natural *in situ* rocks (Chapter 5). *Exposure Trial 2* has shown that applying textures to construction materials, artificially, offers opportunities to mimic responses of a common intertidal organism to rocky shore substrata over short time-scales.

Roughening the surface of limestone, granite and marine concrete resulted in barnacle cyprid settlement at the same or higher levels as that recorded within clearings made on naturally weathered platform rock on two different shores (Hypothesis 7a p. 205). Annual recruitment (recorded at the end of the settlement season) was also the same (or higher) on most roughened blocks as on platform clearings on both shores (Hypothesis 7b p. 205); brushed concrete had higher numbers of recruits than the platform at Gala Rocks and matched recruitment on the platform at Tregear Point. Roughened limestone had significantly higher recruitment than the platform rock at Tregear Point and matched that of the platform at Gala Rocks. Although these results show some inconsistency between shores, only in one instance did a roughened material 'under perform' compared to natural rock with respect to barnacle recruitment, which was flame-textured granite at Tregear Point. Incidentally, roughened granite was also found to support fewer recruits than cleared platform rock in *Exposure Trial 1*, although this treatment did support significantly more barnacles than sawn limestone and plain-cast concrete in this trial (see Chapter 5).

Inconsistencies in the ability of certain treatments to 'match', 'under perform', or 'out perform' weathered rock on the different shores may have been related to overall differences in the level of settlement at each site (see discussion above); this may have accentuated differences between treatments at Tregear Point overall where settlement was significantly higher for example (Raimondi 1990). Alternatively, the relative importance of particular treatments for barnacles may have varied between shores. For example, inherent differences in the thermal and drying behaviours of the three introduced materials may have influenced post-settlement mortality of cyprids and/or longer-term post-recruitment mortality of adults to varying degrees on each shore. Tregear Point and Gala Rocks have opposite aspects, so that the importance of insolation and thermal stress (which may be mediated by substratum lithology, e.g. Raimondi 1988b) in structuring barnacle populations may vary between them. Differences in warming-drying behaviours of the construction materials, and how these behaviours may change following initial exposure and colonisation, are specifically assessed in Chapter 8. These potential interactions between biotic and abiotic factors, and how they may be mediated by material type and texture, are further explored in Chapter 9 with respect to opportunities for ecological enhancement.

Differences in wave conditions may also have contributed to inconsistencies between shores. Previous studies have shown that wave-exposed shores generally have higher diversity of organisms as a function of intermediate disturbance (Connell 1972; Paine and Levin 1981; Sousa 1985). The ecology of particular organisms (i.e. abundance, spatial distribution, morphology and reproduction) can also be influenced by wave conditions (e.g. Hawkins and Hartnoll 1982a; Denny 1985; Todgham et al. 1997; Arsenault et al. 2001). The importance of roughness as a physical refuge for cyprids and recruits may, therefore, have varied between shores as Tregear Point consistently receives high energy waves from the North Atlantic while the fetch of waves reaching Gala Rocks is limited by Ireland to the north, and more locally by the Zennor Headland to the east. *Exposure Trial 1* showed that post-recruitment mortality did vary between three of the treatments used in this trial at Tregear Point, however previous attempts to directly link barnacle mortality rates, wave conditions and refuge occupation have not been conclusive (e.g. Gosselin and Qian 1996; also see discussions in Section 5.4 regarding potential influences of wave exposure between shores).

These observations indicate that the importance of substratum texture (and hence the potential opportunities for using texture to manipulate ecology on artificial structures) may not be consistent between different locations and material types. Much more research is needed to test the influences of various material types and textures in different physical and ecological settings, as a standard set of generic 'ideals' for engineering design may prove particularly difficult to establish owing to species-specific preferences, and the diversity of settings in which structures will need to be built in the future (see Section 2.2.2 p. 49). The potential limitations of using small-scale texturing for ecological enhancement of coastal structures are discussed on detail in Section 9.8.4. (p. 426).

6.4.4 Hypothesis 8: Bio-chemical cues

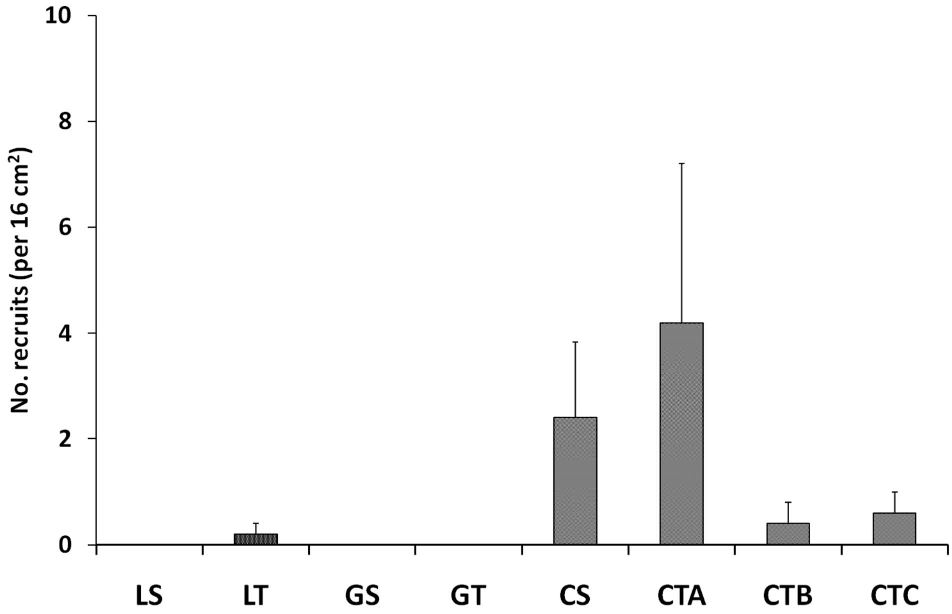
In this experiment, the potential influence of micro-biological and chemical cues on barnacle settlement and recruitment was tested by sterilising half of the clearings made on rock platforms on both shores (Section 6.2.3). Settlement and recruitment were no different between sterilised (scrubbed and flamed using a blow-torch) and un-sterilised (scrubbed only) clearings on either shore. This suggests that the presence of biofilms (which may have been present on the scrubbed clearings for example) did not influence colonisation of Chthamalid barnacles on the platform rock in this study, at least at a level that was detected by the experimental design.

For *Chthamalus*, the apparent lack of response to substratum sterilisation observed here suggests that any differences or similarities between the introduced materials (i.e. limestone, granite and concrete) and the platform rock described above were probably primarily the result of differences in their physical characteristics (i.e. texture) rather than bio-chemical differences. Assuming the same was true in *Exposure Trial 1*, in which platform clearings were not sterilised, the observed differences between clearings and introduced materials with surface finishes commonly used in marine engineering were also probably largely attributed to substratum textural differences (see discussion in Chapter 5).

6.4.5 Consistency between barnacle species

Despite heavy settlement of *S. balanoides* within control clearings at Gala Rocks, very low settlement on all experimental blocks precluded any meaningful statistical testing of Hypothesis 5, 6 and 7 for this species. However, qualitative observations (Figure 6-11) indicated that *S. balanoides* responded positively to roughness, which has been demonstrated elsewhere for this species (Hawkins and Hartnoll 1982a; Le Tourneux and Bourget 1988; Hills and Thomason 1996, 1998, 2003). For different concrete treatments, the pattern of settlement and recruitment for *S. balanoides* was generally consistent with *Chthamalus* spp., with highest counts on brushed blocks and lowest counts on wiped blocks. Roughened limestone also had more cyprids and recruits than smooth, but this was not observed for granite blocks, on which recruitment was minimal regardless of texture (Figure 6-11). Robust conclusions about the consistency of texture influences between species could not be made.

It was possible to test the influence of bio-chemical cues on *S. balanoides* (Hypothesis 8) given sufficient colonisation of platform clearings at Gala Rocks. Here, settlement was no different between sterilised and un-sterilised clearings on peak days (unpaired Student's t-test [df = 6] p = 0.197), which was also observed for *Chthamalus* (Section 6.4.4 above). Numbers of *S. balanoides* recruits were lower on scrubbed and sterilised clearings compared to clearings which had only been scrubbed, but this effect was just short of significance (Student's t-test [df = 6] p = 0.079).



LS = Limestone (sawn)
LT = Limestone (dolly-pointed)
GS = Granite (sawn)
GT = Granite (flame-textured)
CS = Concrete (plain-cast)
CTA = Concrete (brushed)
CTB = Concrete (wiped)
CTC = Concrete (exposed aggregate)

Figure 6-11 Number (mean + SE) of *S. balanoides* recruits counted on various construction materials (25th July 2009) at Gala Rocks, Zennor, Cornwall, UK.

6.5 Conclusions

Artificially roughening construction materials at a small scale (millimetres) resulted in consistent and significant increases in barnacle settlement and recruitment compared to smooth alternatives of the same materials (Hypothesis 5a-b p. 205). The results from *Exposure Trial 1*, which suggested that materials with surface finishes typically used in engineering do not replicate barnacle colonisation of natural rocks (Chapter 5), were therefore also likely to have occurred as a function of differences in texture rather than material type (i.e. lithology alone). At the same time, the method used to create texture – and hence the 'type' of texture created – had a significant influence on colonisation with specific reference to marine concrete (Hypothesis 6a-b p. 205). In this trial, more barnacles recruited to brushed concrete, which appeared to provide 'potential settlement sites' at the correct scale for *Chthamalus* spp. cypris larvae.

Furthermore, certain materials and textures were able to mimic barnacle colonisation of naturally weathered platform rock (Hypothesis 7a-b p. 205) independently of bio-chemical cues (Hypothesis 8a-b p. 205). Perhaps more importantly, both *Exposure Trial 1* and *Exposure Trial 2* indicated that material type (i.e. lithology) was less important for barnacles than substratum texture during initial stages of colonisation. Different geomorphological responses of the same materials occurring as a function of lithology may, however, be more important for ecology more generally over longer time-scales (see Chapter 7 and specific discussions in Chapter 9).

These observations suggest that there is significant potential to manipulate early-stage colonisation of engineering substrata by common intertidal organisms, particularly on concrete which was easily and cheaply modified to increase surface complexity. Given that recruitment is typically a good indicator of community structure in barnacles (Menge 2000), the potential to manipulate settlement and recruitment as demonstrated here, not only has implications for the initial rates of colonisation of artificial structures, but also for the adult populations that they may support and any subsequent influences on longer-term biodiversity value. These interactions are explored in detail in the synthesis presented in Chapter 9.

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CHAPTER 7

GEOMORPHOLOGICAL RESPONSE (A): PHYSICAL ALTERATION OF SUBSTRATA DURING INTERTIDAL EXPOSURE

Strands 1 – 4: Weathering and erosion, geomechanical alteration, morphological change and discussion

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CHAPTER 7. GEOMORPHOLOGICAL RESPONSE (A): PHYSICAL ALTERATION OF SUBSTRATA

Strands 1 – 4: Weathering and erosion, geomechanical alteration, morphological change and discussion

7.1 Introduction and Aims

Chapter 5 and Chapter 6 presented experimental work examining ecological responses (settlement, recruitment and mortality) of a common intertidal organism (the barnacle) on different materials used in coastal engineering. This chapter (Chapter 7) along with the following (Chapter 8) describe and discuss experimental work on the geomorphological response of the same materials when exposed in the intertidal zone; this work constitutes the ‘abiotic’ component of the biogeomorphological research framework presented in Chapter 3 (Figure 3-5 p. 127). The involvement of organisms in these responses is given specific attention as examples of biogeomorphic processes (i.e. Section 3.2 p. 106). Chapter 8 then explores the consequences of the physical alterations discussed for the behaviour (specifically warming and drying behaviours) of the materials under simulated intertidal conditions, in a geomorphological and ecological context.

This chapter is separated in four ‘Strands’, illustrated in Figure 7-1. **Strand 1** examines the colonisation and geomorphological alteration of the experimental materials by microorganisms (at a µm scale). This was undertaken using Scanning Electron Microscopy (SEM). **Strand 2** presents a re-characterisation of the materials using the same geomechanical tests used on control samples, as described in Chapter 4 (p. 137). This was done to assess physical alteration at a scale more relevant to engineering durability (i.e. with respect to ‘bulk’ material properties). **Strand 3** presents an assessment of morphological changes occurring at the surface of the materials using laser scanning.

This was undertaken at a specific scale (mm's) known to be of relevance for the organisms studied in Chapters 5 and 6 (i.e. barnacles).

Strand 4 presents a discussion of the results of Strands 1 – 3. Discussions relevant to each Strand are given, alongside broader consideration of the relationships between the different scales of observation. Potential biotic-abiotic interactions, consequences and feedbacks are highlighted throughout this Chapter where appropriate, but detailed discussion of their operation and implications for the ecological potential of hard coastal structures are reserved for the synthesis presented in Chapter 9.

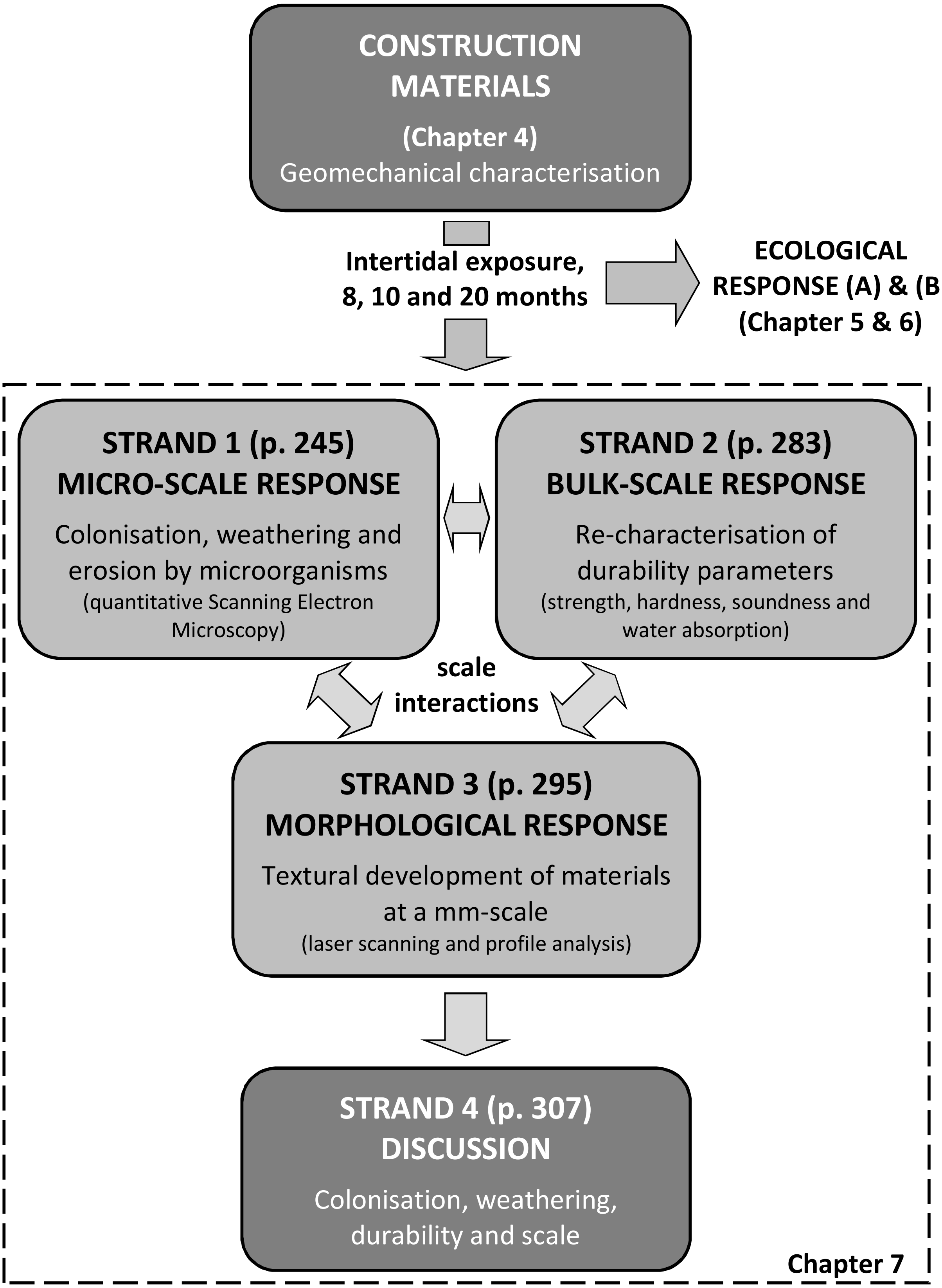

Figure 7-1 Structure of work presented in Chapter 7.

7.2 Experimental Approach

Materials used in Strands 1 - 3 were derived from blocks of Portland limestone, Cornish granite and marine concrete exposed in the intertidal zone as part of the field trials described in Chapters 5 and 6. Baseline descriptions of these material types ('pre-exposure') are given in Chapter 4.

Detailed sampling designs and methods for each Strand are given in their respective introductory sections. In summary, blocks installed at MTL in *Exposure Trial 1* (Chapter 5) were harvested after 8 and 20 months and subdivided as shown in Figure 7-2. For Strand 1, SEM observations of chippings taken from the surface of these blocks were used to compare (a) microbiological growth features and (b) micro-scale geomorphological features (i.e. weathering and erosion micromorphologies) at the surface and near-surface. Comparisons were made between material types and after different periods of exposure. Additional spatial comparisons, using blocks exposed at different shore levels (from *Exposure Trial 2*, see Chapter 6) are described separately in Appendix 2. The bioerosion of limestone was given more detailed attention in Strand 1 as a specific process of interest to biogeomorphologists and rock coast geomorphologists (see Section 7.2) and because it was found to have important ecological consequences with respect to surface texture (see below).

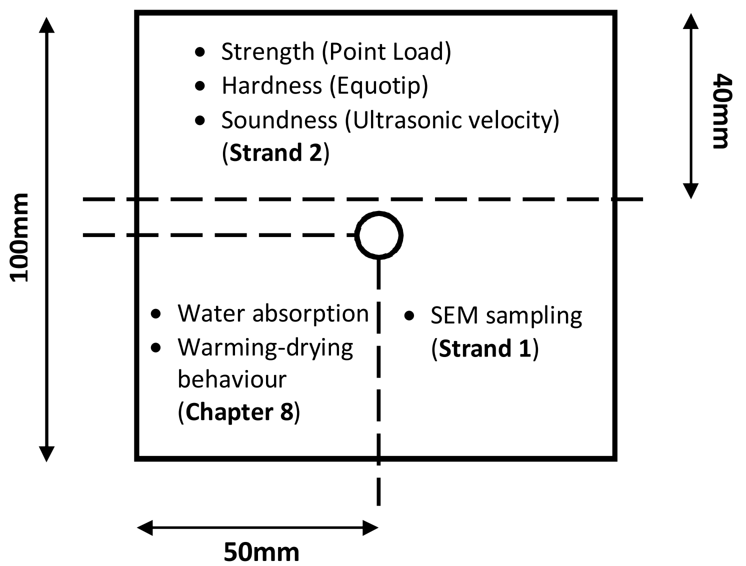

Figure 7-2 Sub-division of *Exposure Trial 1* blocks for different testing procedures.

Materials sampled from existing coastal structures of known age were also examined using SEM as a supplementary assessment of processes operating over much longer time-scales than was possible using exposure blocks alone. This additional work is described separately in Appendix 3, but is referred to in this Chapter where appropriate.

In Strand 2, the geomechanical tests used to characterise control (unexposed) blocks in Chapter 4 were repeated on harvested blocks (Figure 7-2). This was done to assess the extent of alteration of the materials after different periods of exposure, and at a scale more relevant to engineers. Linkages between these measurements and observations made at the micro-scale (i.e. Strand 1) are considered in the discussion (Strand 4).

Morphological changes at the surface of the materials are quantified in Strand 3. These observations represented textural change at a scale known to be of ecological importance in the context of this study, for barnacles (mm-scale). The importance of morphological change for habitat heterogeneity and ecological potential, and specifically the involvement of organisms in this process, is discussed in Strand 4 and in Chapter 9 with respect to coastal structures and ecological potential.

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CHAPTER 7: STRAND 1

Colonisation and Weathering of Engineering Materials by Marine Microorganisms: An SEM study

7.1 The Ecological and Geomorphological Importance of Microorganisms

Microorganisms are a ubiquitous feature of most hard substrata on Earth (Gorbushina 2007). In the intertidal zone, microscopic cyanobacteria, diatoms and algae exist within a mucilaginous matrix of extracellular polymeric substances (EPS); these assemblages are called biofilms (see Wahl 1989). Biofilms form the interface between substratum and water and are of critical ecological importance (Underwood 1984a; Hawkins and Jones 1992; Decho 2000; Thompson et al. 2000). Biofilms are an important component of primary productivity in both soft sediment (e.g. Underwood et al. 2005) and hard substratum coastal environments (e.g. Skov et al. 2010). Epilithic biofilms (existing at the surface) and to a certain extent endolithic biofilms (existing within the substrate; *sensu* Golubic et al. 1981) are also the primary source of nutrients for grazing molluscs (i.e. snails and limpets; Norton et al. 1990; Thompson et al. 2000; Noël et al. 2009) and influence the settlement and survival of other marine invertebrates (Crisp 1974; Huang and Boney 1984; Thompson et al. 1998; Kay 2002, also see Chapters 5 and 6).

Despite their ecological importance, responses of microorganisms to hard substrata introduced into the intertidal zone through coastal engineering have rarely been studied. This is in contrast to the growing body of research examining macro-biota responses to engineered structures (see Chapter 2 for a review). Differences in the nature of microbial colonisation on different construction materials (including types of growth, abundance and spatio-temporal variability) was therefore of interest in an ecological context as these early-stage communities are thought to influence successional trajectories (e.g. Farrell 1991) and the functioning of ecological interactions on rocky shores (e.g. Thompson et al. 2004; Skov et al. 2010, see detailed discussion in Chapter 9). It has been suggested recently, for example, that differences in the types and abundance of micro-algae on different material types may determine relative rates of recruitment and survival of grazing organisms on artificial coastal structures (Iveša et al. 2010).

Geomorphologically, microorganisms are widely recognised as agents of physical and chemical change on rock and stone surfaces (Sand 1997; Viles 2000a). Microorganisms can be involved in the alteration of rock biochemically – through etching, pitting and boring of the surface (the latter typically distinguished as bioerosion; Kobluk and Risk 1977) or biophysically – through the exertion of physical stresses by growth within cracks and fissures (e.g. Dornieden et al. 2000) and the swelling and shrinking of cells in response to changes in moisture (e.g. Moses and Smith 1993; Gómez-Pujol et al. 2007). These processes can involve microscopic bacteria (Song et al. 2007), fungi (Sterflinger 2000), algae (Ortega-Calvo et al. 1991) and macroscopic lichens (Chen et al. 2000) and have been observed in arid (e.g. Smith et al. 2000), tropical (e.g. Viles et al. 2000), temperate (e.g. Gómez-Pujol et al. 2006) and cold (e.g. Etienne 2002) climates. A potential protective role of microorganisms and associated films has also been suggested (see Section 7.2 below).

7.2 Substrate-Biota Interactions in the Intertidal Zone

Much of our existing understanding of organic weathering and erosion has come from the study of terrestrial karst landforms and superficial karren features (e.g. Viles 1988b; Fornós and Ginés 1996; Ginés et al. 2009), building stone decay (e.g. Smith and Warke 1996; Siegesmund et al. 2002) and in the case of marine environments, from coastal and rocky shore weathering studies (e.g. Trudgill 1987a; Viles 1987b; Naylor 2001; Naylor and Viles 2002; Fornós et al. 2006; Gómez-Pujol 2006; Gómez-Pujol and Fornós 2009).

In rocky coastal environments, the combined and interactive effects of a range of flora and fauna are involved in geomorphic change across various temporal and spatial scales (Spencer 1988a, b). A traditional classification of the processes operating is based on the concept of 'bioerosion'. Bioerosion includes bio-chemical processes (termed 'biocorrosion') and the bio-physical actions of boring and grazing organisms (termed 'bioabrasion'; Schneider and Torunski 1983). Schneider and Torunski (1983) and Spencer (1988a, b) make the distinction that biocorrosion produces no erosion product (i.e. it is a solutional process) while bioabrasion produces sediment. Naylor (2001) and Naylor et al. (2002) further suggest that 'bioweathering' may be viewed as a distinct process in the intertidal zone, involving the *in situ* development of weathering rinds. Weathering rind development may not necessarily lead to surface denudation *per se*, but may facilitate subsequent erosion by weakening the surface (Naylor 2001). Lain et al. (2008) have also suggested linkages between microbial weathering processes and the susceptibility of carbonate rocks to subsequent erosion.

Examples of bioerosion in the coastal zone are given in Table 7-1. In temperate environments, the majority of coastal biogeomorphic research has focussed on the conspicuous actions of macro-borers (e.g. bivalve molluscs; Pinn et al. 2005b; Pinn et al. 2008) and grazing organisms (e.g. limpets; Andrews and Williams 2000). Alongside other bioeroders, Trudgill (1987a) describes the involvement of microorganisms in the bioerosion of limestone shores in Ireland, through boring and perforation of the surface. Naylor (2001) also found evidence of microboring on limestone (Blue Lias) platforms in Wales as well as on experimental blocks of Bath Stone (limestone) exposed in tide pools. Carbonate materials used in coastal engineering are expected to be subject to similar processes (Moses and Smith 1994) although such assessments have been generally limited (Section 7.3).

Table 7-1 Some examples of bioerosion studies in the intertidal zone.

Organism	Species (as specified)	Substratum type	Location	Process considered	Reference
Cyanobacteria/ Microflora	Cyanophyta	Reef limestone	Aldabra Atoll, Indian Ocean	Micro-boring, etching and pitting	Trudgill 1976; Viles 1987b; Viles et al. 2000
Algae / Cyanobacteria	Various filamentous and folios forms	Bath Stone (limestone)	Falasarna, Crete	Micro-boring, etching and pitting / bioprotection	Naylor and Viles 2002
Lichen / Algae / Sponges	*Xanthoria* spp. *Cliona* spp.	Limestone	Co. Clare, Ireland	Micro-boring	Trudgill 1987b
Algae	*Ascophyllum* sp. *Lithothamnion* sp.	Granite Limestone	Galway Bay, Ireland	Biochemical and biophysical weathering	Morrison et al. 2009
Cyanobacteria	Cyanophyta	Limestone	Garzotto, Croatia	Micro-boring / biological corrosion	Schneider 1976; Schneider and Le Campion-Alsumard 1999
Algae	Unicellular and filamentous forms	Sandstone	Oregon, USA / Washington, USA	Endolithic growth / bioprotection	Mustoe 2010
Echinoids	*Paracentrotus lividus*	Limestone	Co. Clare, Ireland	Macro-boring	Trudgill et al. 1987
Molluscs	*Pholas dactylus,* *Barnea* spp.	Chalk and clay	South West England, UK	Macro-boring	Pinn et al. 2005; Pinn et al. 2008
Molluscs	*Patella vulgata*	Chalk	Southeast England, UK	Grazing	Andrews and Williams 2000
Molluscs	*Patella rustica*	Limestone	Mallorca, Balearic Islands	Grazing	Fornós et al. 2006
Molluscs	*Hiatella arctuca*	Limestone	Co. Clare, Ireland	Macro-boring	Trudgill 1987a

In warm water and coral reef environments the bioerosive actions of other organisms, such as sponges (e.g. Zundelevich et al. 2007) and fish (e.g. Bruggemann et al. 1996), have been well studied. The importance of microorganisms in erosion and sediment production on reefs has further been demonstrated by the work of Le Campion-Alsumard, Schneider and co-workers (Le Campion-Alsumard 1975; Schneider 1976; Schneider and Torunski 1983; Schneider and Le Campion-Alsumard 1999). On Aldabra Atoll in the Indian Ocean, Viles (1987b) and Viles et al. (2000) monitored colonisation and weathering of limestone by microorganisms (cyanobacteria) in a coastal setting over a 16-year period. They found that rates of colonisation and biological weathering (boring and etching) varied considerably in space on cleared areas of rock, probably as a function of local moisture availability. They further suggest that the nature of the substratum (i.e. its lithological properties) may exert some control on colonisation, although this was not directly studied (Viles et al. 2000).

On limestone coasts, biological weathering and erosion are important processes in landform development and change at a micro-meso scale (µm - m; Trudgill 1987a; Spencer and Viles 2002; Fornós et al. 2006). 'Biokarst' is a term used in geomorphology to describe landscape features that are primarily the result of biological action on limestone rocks (e.g. Schneider and Torunski 1983; Viles 1984; Duane et al. 2003; Moses 2003). Gómez-Pujol and Fornós (2009, 2010) have developed a useful model of the relative roles of mechanical, chemical and biological weathering and erosion processes in the evolution of coastal biokarst landscapes in the Balearic Islands, Western Mediterranean. They suggest that the morphological and biological zonations on these shores are intimately linked. The model suggests that bioerosion by borers and grazers has the greatest influence seaward, as these organisms are restricted to the wave and splash zone, while bioweathering (i.e. biologically driven solution) can operate further inland into the spray zone. Bioerosion rates between 0.369 – 2.095 mm yr^{-1} were attributed to grazing molluscs alone on these shores (Fornós et al. 2006).

There is a traditional bias for biogeomorphological study of limestone coasts. This is not surprising given that biological weathering and erosion features are more conspicuous here, and are arguably more important at a landscape scale (see above). Experiments using carbonate materials are therefore important for theoretical development in biogeomorphology. This has, however, somewhat precluded assessments of process operating on other substrata in the tidal zone, particularly where microorganisms are involved. Biogeomorphological processes operating on other material types used to build coastal structures are lacking (particularly for concrete, see Section 2.7 p. 93) but are of relevance for engineering (see Strand 2) as well as weathering geomorphology. Rock coast geomorphology theory suggests that marine erosion processes (i.e. wave action) will probably dominate morphological development of more resistant rock types at a landscape scale (Trenhaile 1987; Sunamura 1992, 1994). It has been argued, however, that subaerial weathering may be just as important as waves, if not more, in some instances (Stephenson and Kirk 2000a, b; Trenhaile 2002; Naylor et al. 2010; Naylor and Stephenson 2010; Kennedy et al. in press).

Marine organisms may also provide a protective function in the intertidal zone (i.e. 'bioprotection', see Section 3.2.1 p. 106). Several authors have suggested that species involved in the development of organic crusts or which cover the substratum themselves, including microorganisms, encrusting algae, barnacles, mussels and macro-algae, may protect the underlying rock from wave and physio-chemical attack at the coast (Trenhaile 1987; Naylor and Viles 2002; Mottershead et al. 2003; Carter and Viles 2005; Mustoe 2010). Quantitative evidence for coastal bioprotection is very difficult to collect, however, and as such, protective functions have generally only been inferred.

7.3 Weathering of Artificial Coastal Structures

Anthropogenic structures (those built by people) are convenient to weathering scientists because they can be dated relatively precisely, and therefore provide a time period over which observed weathering morphologies can be assumed to have developed (Mottershead 2000). Field block exposure trials also provide a means of examining processes over a known period of time (Moses

2000). Studies of structures built from rock and stone can also provide information on the weathering behaviour of the same (or similar) materials where they occur naturally. In the terrestrial environment, artificial structures have been used widely in geomorphology to examine the nature and rate of weathering of various material types including limestone (e.g. Sharp et al. 1982; Trudgill et al. 2001), sandstone (e.g. Robinson and Williams 1996) and granite (e.g. Sellier 1997). In contrast, the geomorphological response of materials used in hard coastal engineering has rarely been examined.

Where coastal structures have been studied by geomorphologists (see examples in Table 7-2), those in the supratidal zone have received most attention (probably for practicality reasons) with emphasis being placed on salt weathering processes. In the UK, for example, Mottershead and co-workers have examined the weathering of dated coastal structures in the supratidal zone in the South West made of greenschist (Mottershead 1982, 1997, 1998), granite, siltstone and shale (Mottershead 2000) and sandstone (Mottershead 1994; Pye and Mottershead 1995; Mottershead et al. 2003) among others. Salt weathering was deemed most important in a durability context and in the formation of tafoni and alveolar weathering morphologies on these structures. The involvement of microorganisms in supratidal weathering of sandstone structures was specifically considered by Mottershead et al. (2003), concluding that patchy colonisation tended to increase weathering, while abundant growth may protect the rock surface (i.e. bioprotection) from disintegration and salt penetration.

Zonation patterns on rocky shores (both biological and geomorphological) indicate that the nature of weathering on structures built in the intertidal zone, and the relative involvement of organisms in these processes, is likely to be very different from structures in the supratidal zone (e.g. Gómez-Pujol and Fornós 2009). Where intertidal structures have been examined, the weathering role of microorganisms has typically not been considered (e.g. Aoki and Matsukura 2007b), with more attention given to the conspicuous actions of boring macro-invertebrates. Scott et al. (1988), for example, suggest that extensive bioerosion of concrete in Jamaican waters by polychaetes, bivalves

(*Lithophaga*) and sponges (*Cliona*) can significantly reduce engineering performance. These larger bioeroding organisms typically occur less frequently in temperate waters, so that the relative geomorphological importance of marine microorganisms may be more significant. In Europe, the most substantial survey of bioerosion on artificial structures was undertaken as part of the DELOS study (see Section 2.3.3.1 p. 62). A survey was undertaken to record for the presence of bioeroding organisms on 80 coastal (intertidal) structures in the UK composed of limestone, granite and concrete (DELOS D46, http://www.delos.unibo.it/, accessed February 2010). With the exception of some small holes noted on rock groynes in Christchurch and Pool Bay (Dorset), it was concluded that hard limestone, concrete and granite used in defences are 'not suitable for boring organisms'; bioerosion and bioweathering at a micro-scale (by microorganisms) was not assessed however.

Microorganisms are suggested as important weathering agents on construction materials in terrestrial environments, including limestone, sandstone, granite and concrete buildings and monuments (e.g. Wakefield and Jones 1998; Wakefield and Brechet 2000; Warscheid and Braams 2000; Schiavon 2002; Viles 2003; Graef et al. 2005; Gorbushina and Broughton 2009) and on *in situ* coastal rocks (mainly limestone; e.g Moses and Smith 1994; Viles et al. 2000; Naylor 2001; Naylor and Viles 2002; Gómez-Pujol and Fornós 2009). These studies suggest that microorganisms may be involved in similar processes where these material types are exposed in the intertidal zone for engineering purposes.

Table 7-2 Studies of weathering and erosion of coastal building materials and structures, and considerations of biological involvement.

Type of structure	Location	Shore position	Material type	Biological consideration	Organism type	Reference
Fort / castle / wall	South West England, UK	Supratidal	Granite / Siltstone / Shale / Slate	None	-	Mottershead, 2000
Fort / wall	Devon, UK	Supratidal	Greenschist	None	-	Mottershead, 1982, 1997, 1998
Seawall	Devon, UK	Supratidal	Sandstone	None	-	Pye and Mottershead, 1995
Fort / wall	Liverpool, UK	Supratidal	Sandstone	Specific consideration	Microorganisms	Mottershead et al. 2003
Structural columns	Weymouth, UK	Supratidal	Limestone	None	-	Viles and Goudie, 1992
Lighthouses (internal)	Ireland	Supratidal	Granite	None	-	Warke et al., 2010
Pier / wall	Kyushu, Japan	Intertidal	Sandstone	Passing consideration	Macro-organisms	Takahashi et al., 1994; Aoki and Matsukura, 2007
Breakwaters	South West England, UK	Intertidal	Concrete / Limestone / Granite	Specific consideration	Macro-borers (polychaetes, molluscs, sponges)	DELOS Deliverable D38 (http://www.delos.unibo.it/, accessed February 2010)
Experimental blocks	Bay of Bengal, India	Intertidal	Concrete	Specific consideration	Macro algae	Jayakumar and Saravanane, 2009
Pier	Buenos Aires, Argentina	Intertidal	Concrete	Specific consideration	Molluscs	Pérez et al. 2003
Rubble blocks	Jackson Bay, Jamaica	Subtidal	Concrete	Specific consideration	Macro-borers (polychaetes, molluscs, sponges)	Scott et al., 1988

7.4 Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) has been widely used as a semi-quantitative method for micro-scale analysis in geomorphology, ecology, heritage conservation and engineering science (e.g. Baynes and Dearman 1978; Moses 1996; Dornieden et al. 2000; Hall et al. 2005a; Table 7-3). The technique involves bombarding a specimen with a beam of electrons generated within an electron gun. The electron beam is passed across the surface of the specimen, and synchronised with a cathode ray tube (CRT) upon which the signal produced by the electrons is displayed (Chapman 1986). SEM operates under vacuum with samples coated in a conductive layer of gold or carbon, to prevent high voltage discharge. Alternatively, Environmental Scanning Electron Microscopy (ESEM) can be used under low vacuum. The advantage of ESEM is that wet and un-treated biological matter can be viewed *in situ*, which is particularly useful for observing biofilm (e.g. Skov et al. 2010). ESEM has the disadvantage of producing lower resolution imagery compared to high vacuum SEM (Little et al. 1991).

These techniques have proved fruitful in examining interactions between microbiology and mineral substrata, both in geomorphological and ecological studies (McGreevy 1985a; Viles 1987a, b; Moses and Smith 1994; Viles et al. 2000; Naylor and Viles 2002; Thompson et al. 2005; Skov et al. 2010). With respect to weathering studies, the presence or absence of particular features can be used to infer the operation, and relative intensity, of specific processes, whether mechanical or biological in nature for example (Taylor and Viles 2000). In an ecological context, Skov et al. (2010) have recently used SEM to examine the effects of grazing (by snails) on biofilm biomass and productivity on concrete seawalls on the Isle of Wight, UK. In contrast, SEM has rarely been used to observe biotic-abiotic interactions in a weathering context on materials used in (intertidal) coastal engineering.

Table 7-3 Example studies reviewing and/or employing scanning electron microscopy (SEM) in geomorphological, ecological and engineering research.

Discipline	Material type	Examination mode	Focus of study	Reference
Geomorphology (including heritage applications)	Sandstone	SEM	Coastal honeycomb weathering	McGreevy 1985
	Limestone	SEM	Weathering by lichen in a terrestrial environment	Viles 1987a
	Various	SEM	Biodecay of cultural heritage	Dornieden et al. 2000
	Limestone	SEM	Coastal bioerosion and bioprotection	Naylor and Viles 2002
	Limestone	SEM	Sampling design	Taylor and Viles 2000
	Granite	SEM	Bacterial weathering	Song et al. 2007
	Various	SEM / ESEM	Biodeterioration of cultural structures	Herrera and Videla 2009
Ecology	Various	SEM	Review of the technique for observing biofilms	Norton et al. 1998
	Concrete	SEM / ESEM	Effect of grazing on biofilm biomass and productivity	Skov et al. 2010
	Limestone/ Slate	SEM	Biofilm patterns on exposed and sheltered shores	Thompson et al. 2005
Engineering	Various	SEM	Rock weathering and durability / method review	Baynes and Dearman 1978
	Concrete	SEM	Aggregate – cement interactions	Zhang and Gjørv 1990
	Sandstone	SEM	Slake durability testing and mineralogical characterisation	Dhakal et al. 2002

7.5 Aims and Hypotheses

The overall aim of the work presented in Strand 1 was to compare micro-scale (µm) features (biological and geomorphological) present on different construction materials used in coastal engineering after exposure in the intertidal zone, and to provide some assessment of their variability in time and space. The involvement of microorganisms in weathering and erosion relative to other inorganic geomorphological processes was of particular interest in a biogeomorphological context (see Chapter 3).

Specific research questions and hypotheses tested are listed in Table 7-4. The general hypothesis that the occurrence of surface microbiological growth features (Hypothesis 9a) and micro-geomorphological features (Hypothesis 10a) would vary between material types was tested. Succession theory (e.g. Paine 1974; Connell and Slatyer 1977; Connell et al. 1987; Farrell 1991; Raffaelli and Hawkins 1996) and observations of biofilm development on intertidal substrata (e.g. MacLulich 1986; Moschella 2003) suggested that occurrences of biological and geomorphological features would also vary with exposure time (Hypothesis 9b and 10b respectively). Correspondingly, the relative involvement of microorganisms in weathering and erosion was expected to vary through time (e.g. Viles et al. 2000).

The nature of colonisation, and weathering and erosion beyond the immediate surface of the materials was of interest as an indicator of the vertical extent of alteration. As endolithic colonisation is more commonly observed on carbonate materials (Section 7.2), it was predicted that the vertical extent (i.e. depth) of microbial activity would not be the same between material types (Hypothesis 11a). Time was also expected to be an important control on the vertical extent of weathering and erosion (Hypothesis 11b; e.g. Kobluk and Risk 1977; Scott et al. 1988).

Testing of supplementary hypotheses relating to spatial variability is presented separately in Appendix 2. For these hypotheses, the surface occurrence and subsurface extent of biological and geomorphological features was compared between individual blocks, plots and shores (using

Exposure Trial 1 blocks) and between different tidal heights (using *Exposure Trial 2* blocks, see Appendix 2). Additional samples taken from existing structures were used to: (i) assess the extent of subsurface weathering after a longer period of exposure; (ii) compare weathering in sheltered and exposed aspects of the same structure, and; (iii) observe features present on vertical surfaces (i.e. walls) to support those described below for horizontal surfaces (i.e. experimental blocks and breakwaters); this work is described in detail in Appendix 3.

Table 7-4 Chapter 7: Strand 1 Research questions and experimental hypotheses (see Table 3-2).

	Research Question	Hypothesis
STRAND 1: MICRO-SCALE WEATHERING AND EROSION		
9	How do microorganisms respond to different material types used in coastal engineering?	(9a) The occurrence of microbiological growth features varies between materials representative of those used in construction after a period of exposure in the intertidal zone.
		(9b) The occurrence of microbiological growth features on different materials varies after different periods of exposure.
10	How does **surface** weathering and erosion (at a micro-scale) compare between material types used in coastal engineering?	(10a) The occurrence of surface micro-weathering and erosion features varies between materials representative of those used in construction after a period of exposure in the intertidal zone.
		(10b) The occurrence of surface micro-weathering and erosion features on different materials varies after different periods of exposure.
11	How does **subsurface** weathering and erosion (at a micro-scale) compare between materials types used in coastal engineering?	(11a) The vertical extent (depth) of weathering and erosion varies between materials used in construction after a period of exposure in the intertidal zone.
		(11b) The vertical extent (depth) of weathering and erosion varies with exposure time.

All hypotheses were chosen to contribute to geomorphological understanding of the involvement of microorganisms in weathering and erosion on different materials, as well as ecological understanding of colonisation of hard substrata by intertidal microorganisms. Furthermore, these hypotheses informed understanding of the involvement of microorganisms in the modification of coastal engineering materials in a durability context (Strand 2), substratum surface heterogeneity (Strand 3) and substratum geomorphological behaviour (i.e. warming and drying, see Chapter 8).

7.6 Methods

7.6.1 Introduction

The majority of SEM analyses were undertaken using blocks from *Exposure Trial 1* (Chapter 5). Forty blocks each of limestone, granite and marine concrete were initially installed at MTL across two shores in Cornwall in May 2008. Blocks were attached in two replicate plots roughly 50 m apart on each shore for ecological monitoring (see Chapter 5). In January 2009 (after 8 months of exposure) and January 2010 (after 20 months of exposure) four randomly selected blocks of each material type were harvested from both shores for SEM observations, giving a sample size of 8 blocks per material type. Blocks were used to compare micro-scale features (biological and geomorphological) between material types (i.e. limestone, granite and concrete; Hypothesis 9a, 10a and 11a) and between periods of exposure (i.e. 8 months and 20 months; Hypothesis 9b, 10b and 11b). Blocks attached on the same shores at different tide levels (MTL and MHWN) during *Exposure Trial 2* (Chapter 6) were removed in January 2010 (after 10 months) to examine variability across the shore (see Appendix 2).

Supplementary observations of materials obtained from existing structures in Ilfracombe Harbour (Devon) and Newlyn Harbour (Cornwall) are described in Appendix 3. Observations of *in situ* rock sampled from the platforms at Tregear Point and Gala Rocks were also made. However, quantitative comparisons of the platform rocks are not described here due to difficulties obtaining coherent samples on the slate at Tregear Point and from the hard basalt at Gala Rocks, and because biogeomorphological responses of the construction materials were the primary aim of this research.

All materials were harvested at the same time of year (in January) to minimise seasonality effects, which could otherwise confound comparisons of surface microbiology between time-steps (e.g. Underwood 1984a; Wieczorek et al. 1996a; Thompson et al. 2000; Thompson et al. 2005; also see discussion [Strand 4]). Block removal at this time of year also tied-in with the end of the barnacle settlement season (see Chapter 5 and 6).

7.6.2 SEM observations

7.6.2.1 Block sampling

Once harvested, residual epoxy (used to secure blocks to the shore) was carefully removed from the bases and sides of blocks using a chisel. Blocks were then rinsed to remove loose debris and allowed to dry at room temperature for several days; blocks were air dried rather than using an oven or desiccator to minimise distortion of growth forms and salt distribution patterns with the substrata (e.g. Gómez-Heras and Fort 2007). When dry, blocks were wrapped and stored in newspaper (in the dark) to prevent contamination from subsequent mold growth (L. Gómez-Pujol personal communication, January 2009). Samples taken from structures at Ilfracombe and Newlyn were stored in the same way (see Appendix 3).

For SEM analyses, harvested blocks (100 x 100 x 40 mm) were sub-sampled by taking chippings from their upper surfaces using a hammer and chisel (e.g. Viles 1987a; Naylor and Viles 2002). SEM chips were taken randomly within one quarter of each block before being subdivided for subsequent testing described in Strand 2 (see Figure 7-2 p.210). Chippings were taken before blocks were subdivided to prevent contamination of the surface with sawing dust. *Exposure Trial 2* blocks (used for spatial comparisons in Appendix 2) were not used in these subsequent tests and so were not subdivided. The surfaces of some blocks from *Exposure Trial 2* were also scanned using a laser scanner before taking chippings for assessments of morphological change before and after exposure (see Strand 3).

7.6.2.2 SEM pilot study: Classification of features and sampling strategy

A pilot study was undertaken following the recommendations of Taylor & Viles (2000) using 8 month blocks to determine: (i) the types of micro-scale biological growth features, and micro-geomorphological (weathering and erosion) features that were visible on SEM chips; (ii) the number of SEM observations needed to obtain a representative sample of these features on individual chips, and; (iii) the number of SEM chips that adequately represented the occurrence of features across the whole block surface. Control samples (unexposed) were also examined as part of the pilot study. The pilot study was undertaken using a Hitachi S-3400N Type II SEM at the University of the Balearic Islands in January 2009. The pilot study, including detailed sampling and preparation procedures used for all SEM analyses, is described in Appendix 1 and is summarised below.

First, biological growth features were observed using carbon coated SEM chips, while micro-geomorphological features present at the mineral surface were observed after bleaching to remove organic cover. In each case, features identified on unbleached and bleached samples, respectively, were categorised into the five main groups listed in Table 7-5. Note that boring entrance holes were used in both cases (i.e. as a biological and geomorphological feature) as an indirect indicator of endolithic colonisation (on unbleached samples) and as a direct artefact of bioerosion (on bleached samples). Example images and general descriptions of each type of feature are included in Appendix 1. Classification was based on published SEM imagery, existing micro/nano-geomorphology classification systems used elsewhere (Viles 1987a, b; Moses et al. 1995; Moses and Viles 1996; Viles and Moses 1998; Nicholson and Nicholson 2000; Viles et al. 2000; Naylor and Viles 2002; Viles et al. 2002; Gómez-Pujol 2006; Gorbushina and Broughton 2009) and in consultation with L. Gómez-Pujol and J. J. Fornós at the University of the Balearic Islands.

Observations of control samples confirmed that none of the selected biological growth features (Table 7-5) were present on any of the materials prior to field exposure. Control concrete and limestone samples also had no evidence of the weathering and erosion features recorded on field samples. The texturing process used on granite prior to exposure (flame-texturing, see Chapter 4) was, however, responsible for some artificial occurrences of weathering-like morphologies on this material type and is therefore given due consideration in the discussion (Strand 4). Pilot testing also showed no significant changes in the appearance of experimental materials before and after the bleaching process used to remove organic cover (Appendix 1).

Table 7-5 Micro-scale surface features observed using SEM on different materials exposed at MTL, listed in order of abundance in a pilot study (see Appendix 1 for descriptions and examples).

Material Type	Biological growth features (unbleached samples)	Weathering and erosion features (bleached samples)*
Limestone	Boreholes Bio-chemical crust Extracellular polymeric substances (EPS)	Boreholes (biological) Dissolution forms (chemical) Biological etching/pitting (biological)
Granite	Coccoid cell colonies (cyanobacteria) Extracellular polymeric substances (EPS) Biological filaments (cyanobacteria/algae)	Cleavage/flaking (mechanical) Micro-cracking (mechanical)
Concrete	Bio-chemical crust Biological filaments (cyanobacteria/algae) Coccoid cell colonies (cyanobacteria) Boreholes Extracellular polymeric substances (EPS)	Biological etching/pitting (biological) Micro-cracking (mechanical) Boreholes (biological) Dissolution forms (chemical)

**Inferred origin of weathering and erosion features shown in brackets (biological, chemical or mechanical), see Moses and Viles 1996; Viles and Moses 1998.*

The pilot study showed that 30 SEM observations were sufficient for representing the occurrence of the selected microbiological and micro-geomorphological features on individual sample chips (Appendix 1). Observations of these features using one SEM chipping was also adequate for broadly characterising their occurrence on individual experimental blocks (see Appendix 1); unless otherwise stated these sampling procedures were adopted for all subsequent SEM work.

7.6.3 Analysis of field samples

7.6.3.1 Top-surface observations

For comparisons of surface microbiological and micro-geomorphological features between material types, chippings taken from the surface of five different blocks of limestone, granite and concrete were analysed. For the main analysis, all samples were taken from blocks exposed at MTL (*Exposure Trial 1* blocks). The analysis was repeated using chippings taken from blocks exposed for 8 and 20 months. First, one carbon coated chip from each block was viewed using a JEOL JSM-5400LV SEM equipped with Energy Dispersive X-ray Spectroscopy (EDS) facilities at the Camborne School of

Mines, University of Exeter. The occurrence of each biological growth feature listed in Table 7-5 was then recorded from micrograph images of the surface (x 700 magnification) taken in 30 random locations. The occurrence of each weathering and erosion feature listed in Table 7-5 was subsequently quantified in the same way using a second group of chips after bleaching to remove organic cover (see Appendix 1 for full details).

Borehole erosion, which was mainly observed on limestone samples, was quantified as a distinguishing biogeomorphic feature that could further be compared in space and time. Boring was analysed in scaled micrograph images using ImageJ software (http://rsb.info.nih.gov/ij/, accessed June 2008). As a measure of boring intensity (e.g. Naylor and Viles 2002) the density of boreholes was quantified by counting all individual perforations within a 100 μm^2 box drawn in the centre of randomly selected images of the (bleached) limestone chips. For comparisons between exposure periods (8 and 20 months), boring density was measured in this way in 15 images of five chips taken from different blocks. This gave a sample size of 75 images of the limestone surface for each time period. The widths of up to 20 boring entrance holes were also measured at the rock surface in the same images (a total of 1,366 measurements for 8 month samples and 1,394 for 20 month samples).

7.6.3.2 Cross-section observations

Chippings were also viewed in cross-section under the SEM to compare the vertical extent (depth) of colonisation and mineral alteration (e.g. Viles 1987a, b; Viles et al. 2000; Naylor and Viles 2002; Tingstad 2008; Hypothesis 11a and 11b). Unbleached chips were used for cross-section observations to observe organic features *in situ*. Four features were quantified where possible: (i) the depth of weathering, measured as the zone of visible mineralogical change (i.e. combined biological, physical or chemical alteration); (ii) the depth and width of individual subsurface boring tunnels (which were only visible within limestone); (iii) the depth of cryptoendolithic growth (characterised as biological structures occurring beneath – but not in direct contact with – the surface, *sensu* Golubic et al. 1981), and; (iv) the depth of subsurface micro-cracking where present.

Salt penetration depth was also measured where possible using Backscattered Electron Imaging (BEI). BEI mode enabled quantitative comparisons of the subsurface occurrence of salts, visible as lighter areas under the SEM (e.g. Baynes and Dearman 1978; Chapman 1986; Naylor 2001). The presence of chlorides in these observations was confirmed using EDS analysis. All subsurface features were measured in as many locations as possible along the top edges of chippings taken from five different blocks, harvested after exposure for 8 and 20 months at MTL.

7.6.4 Data analysis

Occurrences of surface features were compared between material types and exposure periods in two separate ANOVAs using GMAV5 software (Underwood et al. 1997). For both tests, 'material type' (three levels: limestone, granite and concrete), 'time' (two levels: 8 months and 20 months) and 'feature' (five levels for [a] microbiological growth features and [b] micro-geomorphological features, see Table 7-5) were all treated as fixed factors. 'Time' could be treated as an independent factor in the analyses as different blocks were used to quantify features after each exposure period (Underwood 1997).

Data were checked for homogeneity of variance using a Cochran's test and square root transformed where appropriate to satisfy the assumptions of ANOVA. Where homogeneity persisted after transformation, untransformed data were used and a conservative significance level was adopted (p_{crit} = 0.01). Subsequent comparisons of interactions between factors were made using Student Newman-Keuls (SNK) tests where these were significant (Underwood 1997).

Subsurface features (depth of weathered zone, cryptoendolithic growth, boring, micro-cracking and salt penetration) were compared between material types and exposure periods using unpaired t-tests. Data were tested using the F-statistic and where variance was not equal between samples a Welch's t-test was performed (Burt et al. 2009). T-tests were also used to compare borehole erosion (boring density and entrance hole width) at the surface of limestone. Spatial variability of features was assessed using the same procedures, as described in Appendix 2.

7.7 Results

7.7.1 Surface features

7.7.1.1 Hypothesis 9a and 10a: Material type

For comparability and consistency, the occurrence of surface microbiological and micro-geomorphological features was classified using a 'SACFOR' abundance scale (Superabundant, Abundant, Common, Frequent, Occasional, Rare) commonly applied in ecological rocky shore studies (Hiscock 1996, Table 7-6). Unless otherwise stated, all occurrence values described were derived from 30 random observations of five SEM chips sampled from different experimental blocks (n = 150 observations per material type, see Section 7.6.3.1 above).

Table 7-6 SACFOR abundance scale used to classify the occurrence of micro-scale biological growth, and weathering and erosion features in SEM observations.

Occurrence of feature	Abundance classification
80 – 100 %	Superabundant
40 – 79 %	Abundant
20 – 39 %	Common
10 – 19 %	Frequent
5 – 9 %	Occasional
1 – 4 %	Rare

Figure 7-3 and Figure 7-4 show the occurrence of the selected microbiological and micro-geomorphological features, respectively, on Portland limestone, Cornish granite and marine concrete after 8 and 20 months of exposure at MTL. There were significant differences in the occurrence of each growth feature between material types ('material' x 'feature' $p < 0.00$, Table 7-7, Hypothesis 9a p. 257). Occurrences of weathering and erosion forms were also significantly different between the materials ('material' x 'feature' $p < 0.00$, Table 7-8, Hypothesis 10a p. 257). Relative occurrences of each feature on the three material types are summarised in Table 7-9.

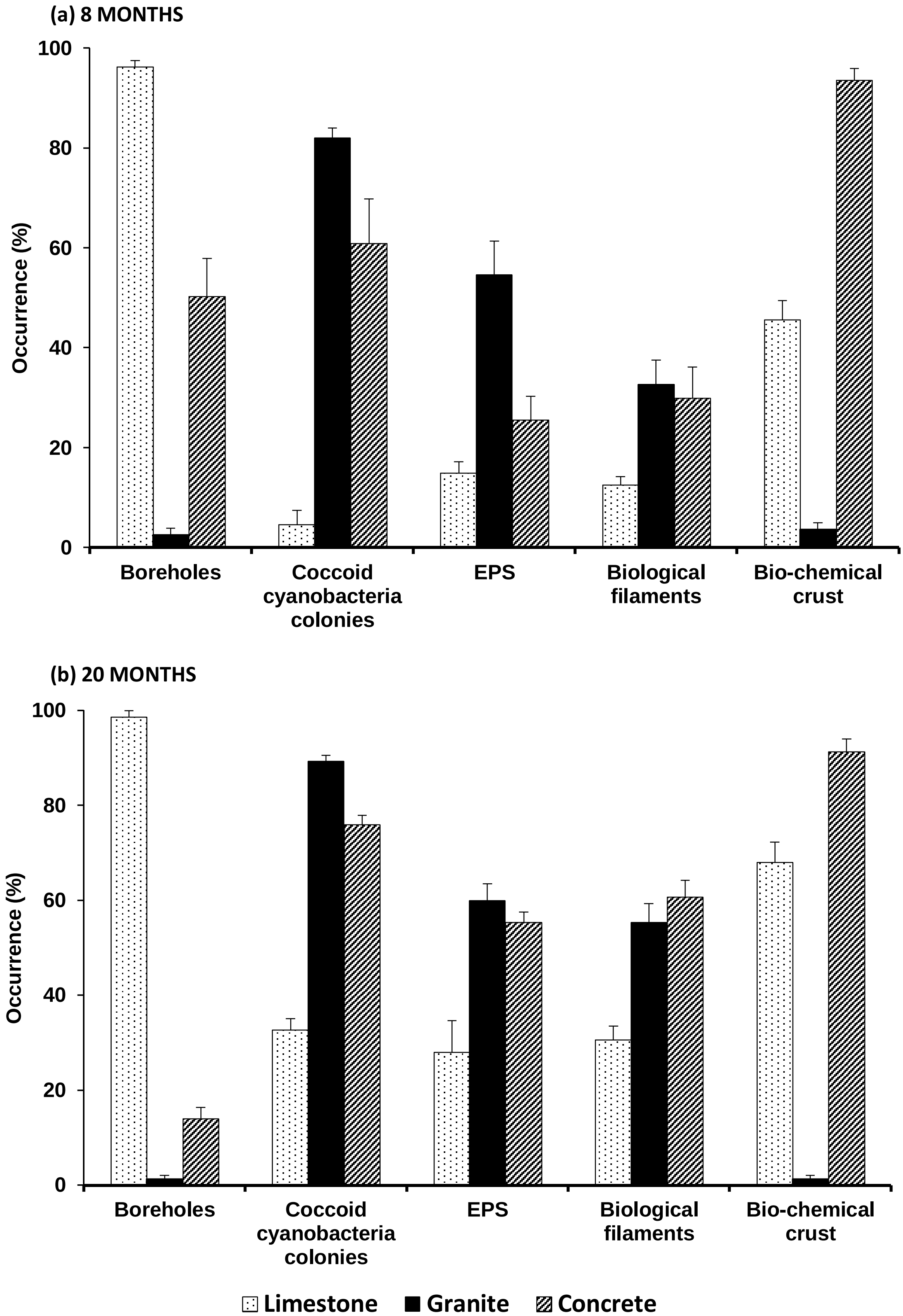


Figure 7-3 Occurrence (%) of microbiological growth features at the surface of different construction materials exposed for (a) 8 months and (b) 20 months at MTL in Cornwall, UK (mean + SE, 150 observations per material type).

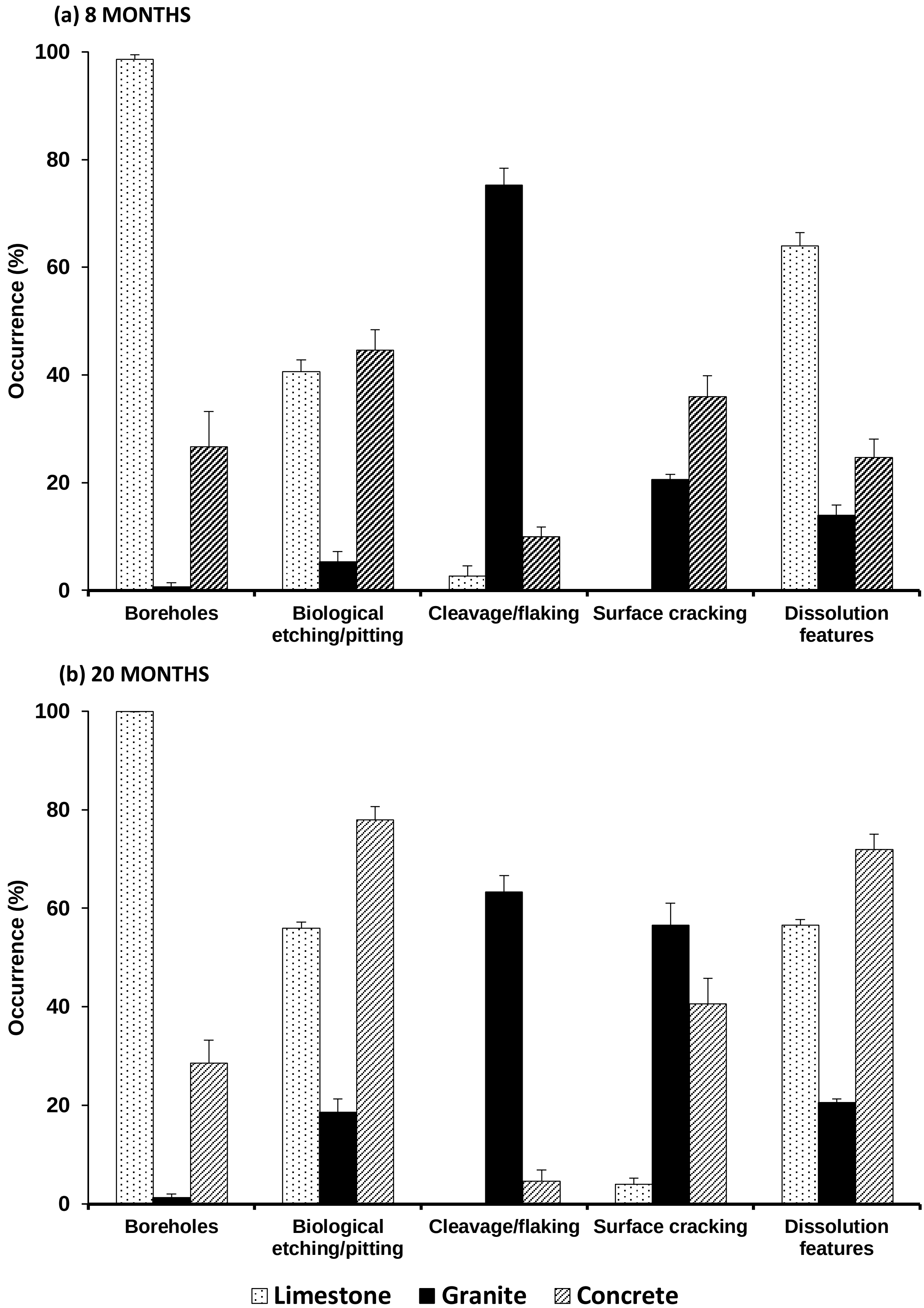


Figure 7-4 Occurrence (%) of micro-scale weathering and erosion features at the surface of different construction materials exposed for (a) 8 months and (b) 20 months at MTL in Cornwall, UK (mean + SE, 150 observations per material type).

Table 7-7 Analysis of variance for occurrences of micro-scale biological growth features on different material types exposed for 8 and 20 months at MTL, Cornwall, UK.

Source of variation	*df*	MS	*F*	p
Material (*n* = 3)	2	45.4983	80.09	**0.00*** **
Time (*n* = 2)	1	26.3551	46.39	**0.00*** **
Feature (n = 5)	4	9.5465	16.8	**0.00*** **
Material x Time	2	7.4386	13.09	**0.00*** **
Material x Feature	8	103.5543	182.27	**0.00*** **
Time x Feature	4	12.8062	22.54	**0.00*** **
Material x Time x Feature	8	3.7131	6.54	**0.00*** **
Residuals	120	0.5681	-	-
Total	149	-	-	-

df = degrees of freedom; MS = mean square variance; *F* = ratio of variance; *p* = significance.
Cochran's test C = 0.116 (not significant).
p values: ****p* < 0.001.

Table 7-8 Analysis of variance for occurrences of micro-scale weathering and erosion features on different material types exposed for 8 and 20 months at MTL, Cornwall, UK.

Source of variation	*df*	MS	*F*	*p*
Material (*n = 3*)	2	2712.705	70.04	**0.00*** **
Time (*n* = 2)	1	3138.2214	81.02	**0.00*** **
Feature (*n = 5*)	4	2201.9428	56.85	**0.00*** **
Material x Time	2	635.9486	16.42	**0.00*** **
Material x Feature	8	13310.6353	343.65	**0.00*** **
Time x Feature	4	969.9996	25.04	**0.00*** **
Material x Time x Feature	8	643.9588	16.63	**0.00*** **
Residuals	120	38.7335		-
Total	149			-

df = degrees of freedom; MS = mean square variance; *F* = ratio of variance; *p* = significance.
Cochran's test *C* = 0.187 (*p* < 0.01, therefore untransformed data were used).
p values: ****p* < 0.001.

Occurrences of filamentous and coccoid growth forms and associated EPS were significantly lower on limestone than concrete and granite (*p* = 0.01 in all instances, Table 7-9). However, boreholes were superabundant on this material type (97 % on unbleached samples) indicating the development of an extensive euendolithic microbial community beneath the rock surface after 8 months of exposure (e.g. Figure 7-5a). Crusting forms on limestone, incorporating organic structures, were also abundant after 8 months (46 % occurrence).

Table 7-9 Relative occurrence of selected microbiological growth, and micro-scale weathering and erosion features at the surface of different material types after exposure for 8 and 20 months at MTL, Cornwall, UK.

	Relative Occurrence*	
Biological feature (unbleached)	**8 Months**	**20 Months**
Boreholes	Granite << Concrete << Limestone	Granite << Concrete << Limestone
Coccoid cell colonies	Limestone << Concrete << Granite	Limestone << Concrete = Granite
EPS	Limestone < Concrete << Granite	Limestone << Concrete = Granite
Biological filaments	Limestone << Concrete = Granite	Limestone << Concrete = Granite
Bio-chemical crust	Granite << Limestone << Concrete	Granite << Limestone << Concrete
Geomorphological feature (bleached)	**8 months**	**20 months**
Boreholes	Granite << Concrete << Limestone	Granite << Concrete << Limestone
Biological etching/pitting	Granite << Limestone = Concrete	Granite << Limestone << Concrete
Cleavage/flaking	Limestone = Concrete << Granite	Limestone = Concrete << Granite
Surface cracking	Limestone << Granite << Concrete	Limestone << Concrete << Granite
Dissolution features	Granite << Concrete << Limestone	Granite << Limestone << Concrete

*SNK statistical test result:
"=" denotes no difference, "<" denotes $p = 0.05$, "<<" denotes $p = 0.01$.

Concrete showed evidence of both epilithic and endolithic colonisation. EPS and filamentous growth forms were common at the surface (26 % occurrence and 30 % occurrence respectively) while colonies of coccoid cyanobacteria were abundant after 8 months (61 % occurrence). Boring holes were recorded in 50 % of observations on unbleached concrete samples, although occurrences were lower on bleached samples (see below). The greatest evidence of biological colonisation on concrete was in association with crusting forms, which were superabundant after 8 months (94 % occurrence, e.g. Figure 7-5b). At the surface of granite, colonies of coccoid cyanobacteria were superabundant after 8 months (82 % occurrence, e.g. Figure 7-5c). Filamentous growth forms (cyanobacteria and algae) were also common (33 % occurrence) and associated EPS abundant (55% occurrence). An absence of boring holes on granite indicated limited endolithic colonisation of this material type (see Section 7.7.2).

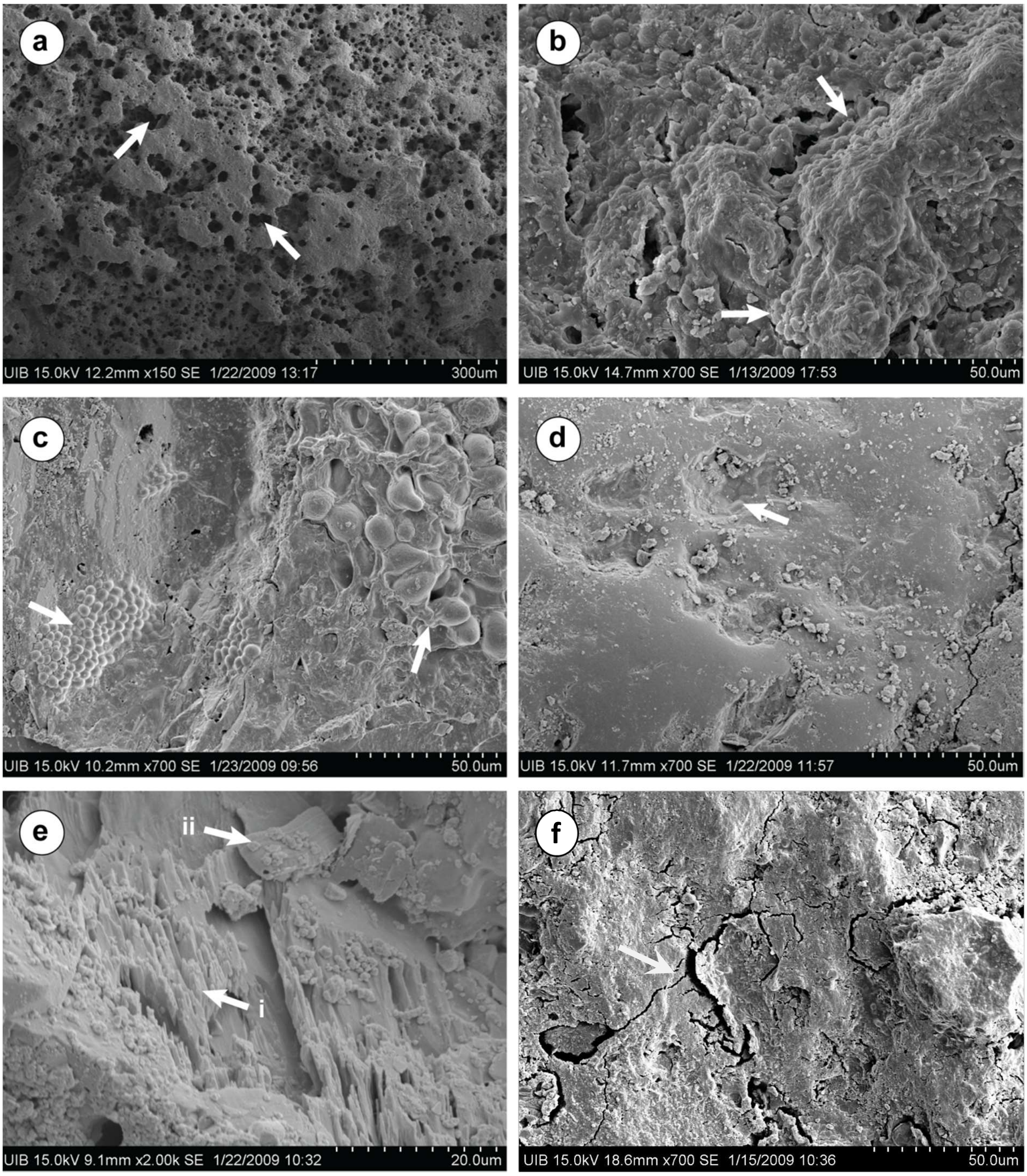


Figure 7-5 SEM micrographs of surface features observed on construction materials after 8 months of exposure at MTL: (a) borehole erosion on exposed limestone (unbleached), note coalescence of individual boreholes (indicated); (b) bio-chemical crusting of exposed concrete (unbleached), note extensive incorporation of biological cells (indicated); (c) extensive epilithic growth on granite (unbleached) showing, colonies of coccoid cyanobacteria (indicated); (d) biological pitting of concrete (bleached), note residual cells within pits (indicated); (e) V-in-V etching (arrow i) of limestone (bleached), residual diatom also indicated (arrow ii); (f) cracking of bio-chemical crust (indicated) on concrete (unbleached); scales as shown.

At the mineral surface (on bleached samples), bioerosion of limestone was superabundant after 8 months (99 % occurrence). Boreholes were also observed on concrete after organic cover had been removed, but holes were significantly less common compared to the limestone (27 % occurrence) (SNK p = 0.01). Evidence of biological weathering in the form of circular- and filament-shaped etch pits was abundant on both concrete and limestone after 8 months (45 % and 41 % occurrence, respectively e.g. Figure 7-5d) whilst being rare on granite samples (< 5 % occurrence).

Dissolution morphologies, including V-in-V etching, grain boundary widening and rounding of calcite crystals (Viles and Moses 1998), were abundant on limestone (64 % occurrence, e.g. Figure 7-5e) and common on concrete (25 % occurrence) after 8 months. However, the most striking feature of exposed concrete after this time was an extensive cover of bio-chemical crusting forms (e.g. Figure 7-5b) which persisted after bleaching. Organic cells incorporated in crusting forms on limestone were also present after bleaching (e.g. Figure 7-6a). When viewed in cross-section, crusts contained abundant biological cells alongside salts and chemical precipitates (see Section 7.7.2 below). Deformation and cracking of these crusts was common on concrete (36 % occurrence e.g. Figure 7-5f). The loss of sand grains from the surface of concrete was also sometimes observed in association with organic structures at higher shore levels (e.g. Figure 7-6b, also see Appendix 2).

On granite, etching forms and mineral flaking (including feldspar, mica and quartz, e.g. Figure 7-6c) and surface cracking (e.g. Figure 7-6d) were observed, however these forms were also present on control samples, although at a lower frequency; it could not, therefore, be determined if these features were derived exclusively from weathering in the field or were an inherited artefact of the heat-based texturing process used on granite blocks prior to exposure (see discussion in Strand 4).

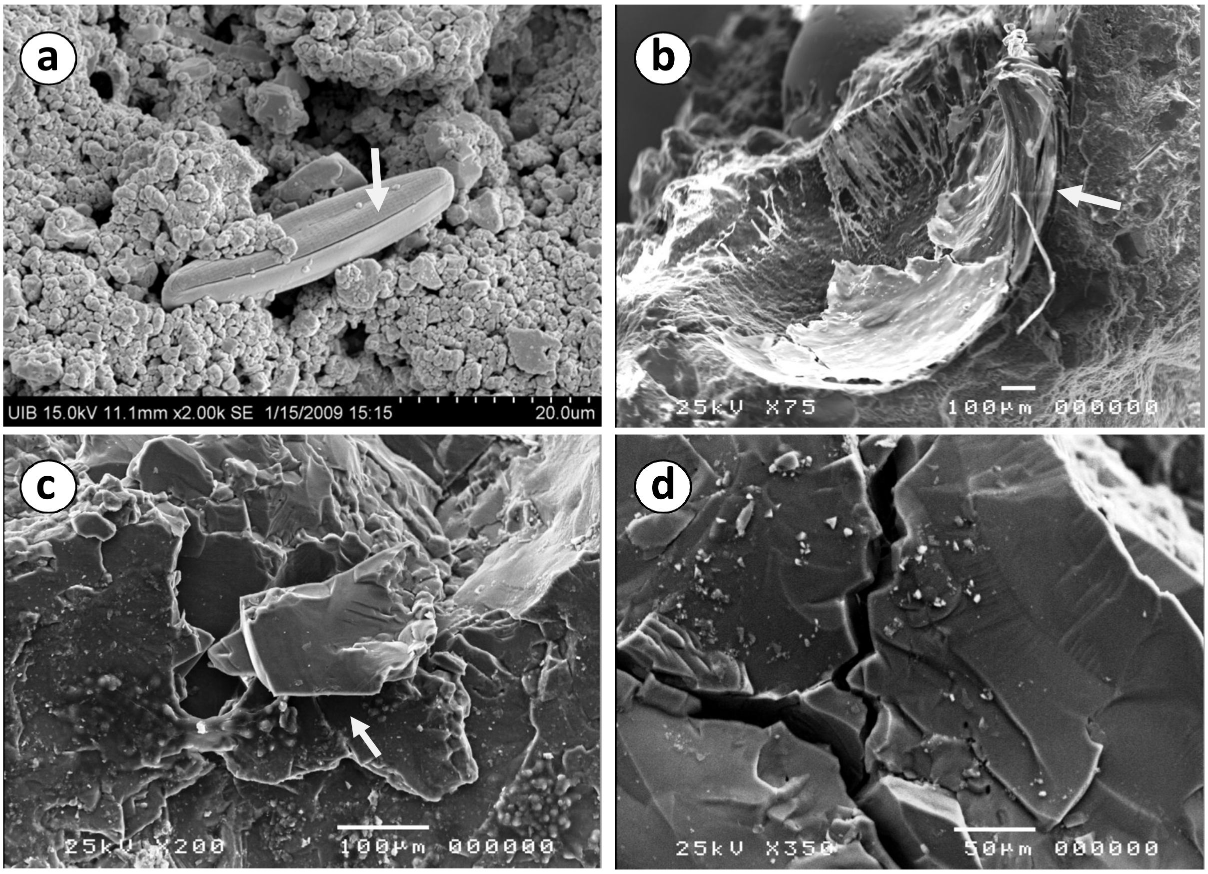


Figure 7-6 SEM micrographs: (a) Diatom (indicated) encased in calcite and salts on limestone (8 months at MTL, bleached); (b) EPS and biological filaments in association with detachment of sand grains on concrete (10 months at MHWN, unbleached); (c) detaching quartz fragment (indicated) on granite (20 months at MTL, bleached); (d) micro-cracking of granite (20 months at MTL, bleached); scales as shown.

The relative abundance of biological and geomorphological features on the different material types was very consistent between blocks exposed for 8 and 20 months (Table 7-9). The only differences for microbiological growths was the occurrence of EPS and coccoid cell colonies on concrete and granite, which were significantly different after 8 months (SNK $p = 0.01$) but no different after 20 months (SNK $p > 0.05$). This change represented an increase in the occurrence of these growths on concrete after the longer period of time in the sea. Relative occurrences of weathering and erosion features between exposure periods were only different for biological etching and pitting on limestone and concrete; occurrences were no different after 8 months (SNK $p > 0.05$) but significantly different after 20 months (SNK $p = 0.01$). This was the result of a larger increase in the occurrence of biological weathering forms on concrete after 20 months relative to that observed on limestone.

7.7.1.2 Hypothesis 9b and 10b: Exposure time

Differences in the occurrence of surface micro-scale biological, and weathering and erosion features were significant between exposure periods (8 and 20 months) when each material type was considered individually (‘material’ x ‘time’ x ‘feature’ $p < 0.00$, Table 7-7 and Table 7-8, Hypothesis 9b and 10b p. 257). The relative occurrences of features after each period of exposure are shown in Table 7-10.

Table 7-10 Relative occurrences of selected microbiological growth, and weathering and erosion features at the surface of different material types exposed for 8 and 20 months at MTL.

	Relative Occurrence*		
Microbiological feature (unbleached)	**Limestone**	**Granite**	**Concrete**
Boreholes	8 = 20	8 = 20	8 >> 20
Coccoid cell colonies	8 << 20	8 = 20	8 < 20
EPS	8 << 20	8 << 20	8 << 20
Biological filaments	8 << 20	8 = 20	8 << 20
Bio-chemical crust	8 << 20	8 >> 20	8 = 20
Micro-geomorphological feature (bleached)	**Limestone**	**Granite**	**Concrete**
Boreholes	8 = 20	8 = 20	8 = 20
Biological etching/pitting	8 << 20	8 << 20	8 << 20
Cleavage/flaking	8 = 20	8 >> 20	8 = 20
Surface cracking	8 = 20	8 << 20	8 = 20
Dissolution features	8 = 20	8 = 20	8 << 20

*SNK statistical test result:
“=” denotes no difference, “<” denotes $p = 0.05$, “<<” denotes $p = 0.01$.

On limestone, all surface growth forms (coccoid cells, filaments and EPS) were more common after 20 months. Correspondingly, organic weathering forms (biological etching and pitting) were significantly more abundant at the mineral surface of limestone after 20 months (56 % occurrence) compared to 8 months (41 % occurrence, SNK $p = 0.01$). There was no difference in the occurrence of other mechanical or chemical weathering features between exposure periods on this material type (Table 7-10). Bioerosion of limestone (i.e. borehole erosion) is discussed specifically in the following section.

On concrete, coccoid cells, filaments and EPS were abundant at the surface of concrete after 20 months, and bio-chemical crusting remained superabundant (91 % occurrence). There was also greater evidence of biological weathering (etching and pitting) and dissolution on concrete exposed for 20 months (both abundant) compared to blocks harvested a year earlier (Figure 7-4, Table 7-10). On granite, boreholes and bio-chemical crusting remained rare after 20 months, while occurrences of some epilithic growth forms (EPS) were significantly higher after this time (Figure 7-3, Table 7-10). At the mineral surface, etching forms (19 % occurrence) and surface cracking (57 % occurrence) were more frequent on granite after 20 months, while cleavage and flaking was less common (Figure 7-4, Table 7-10).

7.7.1.3 Bioerosion

Statistically, there was no difference in the occurrence of microbial boring holes on limestone exposed for 8 and 20 months (Table 7-10); the measure of 'occurrence' did not account for variations in the intensity (i.e. density) of boring between exposure periods, however, and as such this non-significant result was probably an artefact of the generally very high abundances of boring of this material type. The density of boring entrance holes was indeed significantly higher on limestone exposed for longer; the density of boreholes after 8 months was 19.45 ± 8.23 per 100 μm^2 compared to 26.44 ± 7.06 per 100 μm^2 after 20 months (Student's t[df = 145] = 5.58, $p < 0.001$).

The mean width of boring entrance holes was consistent through time (5.84 ± 2.55 µm after 8 months and 5.51 ± 2.79 µm after 20 months). There were, however, interesting differences in the distribution of width data between the two exposure periods (Figure 7-7). Data were more positively skewed after the longer period of exposure (8 months skewness = 1.65, 20 months skewness = 11.32) indicating that larger (i.e. wider) surface perforations were more common on limestone exposed for a longer period of time. This was probably a function of hole coalescence (see specific discussions in Strand 4). For unbleached concrete, there were fewer occurrences of surface holes after 20 months (SNK $p = 0.01$), but there was no difference in the occurrence for boreholes observed at the mineral surface when bleached. This suggested that either holes observed on colonised (unbleached) concrete chippings did not represent boring occurring at the mineral surface, or that identification of boreholes was not reliable for unbleached concrete under the SEM.

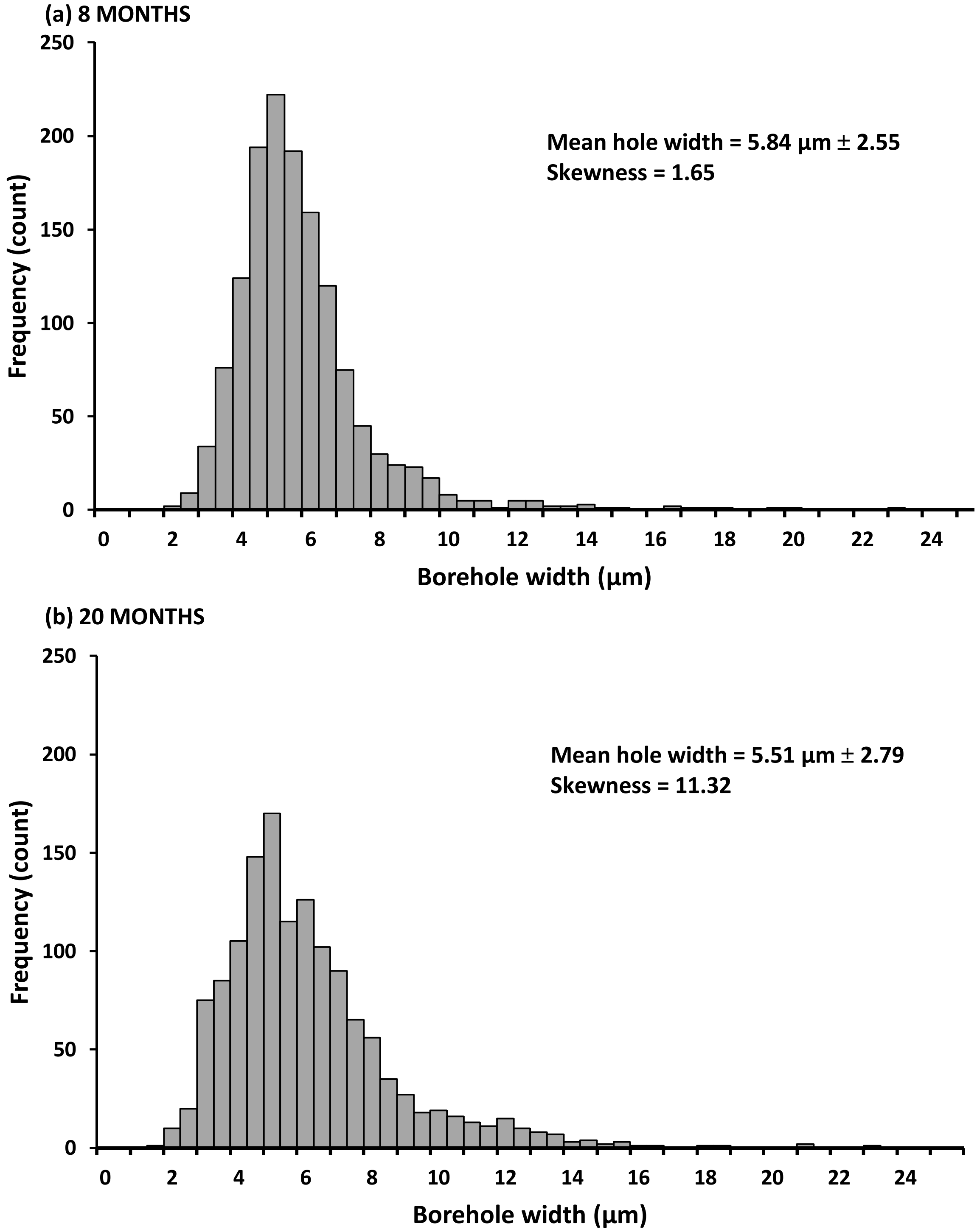


Figure 7-7 Frequency histograms of boring entrance hole width at the surface of Portland limestone after exposure for (a) 8 months and (b) 20 months at MTL, Cornwall, UK (*n* = 1366 for 8 months, *n* = 1394 for 20 months).

7.7.2 Subsurface features

7.7.2.1 Hypothesis 11a: Material type

Figure 7-9 shows depths of weathering zones, cryptoendolithic growth and micro-cracking measured in cross-section observations of Portland limestone, Cornish granite and marine concrete after exposure for 8 and 20 months at MTL. There were significant differences between material types (Hypothesis 11a). Limestone had weathered to a significantly greater depth (125.0 ± 39.0 µm, n = 45) than concrete (45.1 ± 27.7 µm, n = 20) after 8 months (Student's t-test, t[df = 50] = 9.40, p < 0.00; Figure 7-9a). The weathered zone in limestone typically consisted of a shallower zone of boring (34.0 ± 12.3 µm after 8 months) with evidence of mechanical and chemical alteration at greater depth (Figure 7-8a-c). Boring was typically perpendicular to the surface, and tunnels were narrower when viewed in cross-section (3.9 ± 1.5 µm, n = 50) than entrance holes measured at the surface (5.8 ± 2.6 µm, n = 1366, Section 7.7.1.3). This difference may have been the result of entrance hole coalescence and/or abrasion and grazing disturbance of the top surface (see discussion in Strand 4). Halite was also observed on the surface of limestone (e.g. Figure 7-10a), particularly on samples exposed higher on the shore (at MHWN, see Appendix 2). Subsurface salt deposition was commonly observed in limestone using BEI examination mode. Salts were typically precipitated in pore-spaces between ooliths (e.g. Figure 7-8c).

Cryptoendolithic growth was observed within both limestone (e.g. Figure 7-8e) and concrete (e.g. Figure 7-8f) when viewed in cross-section, below the upper weathered zone, whilst being completely absent from granite. After 8 months, cryptoendoliths occurred deeper within limestone (185.9 ± 73.1 µm, n = 15) than concrete (136.7 ± 35.1 µm, n = 5) but occurrences were spatially patchy and were not statistically significant (Welch's t-test, t[df = 15] = 1.92, p = 0.07; Figure 7-9b). The difference in depth was, however, highly significant after 20 months of exposure (Welch's t-test, t[df = 35] = 9.80, p < 0.00, Figure 7-9b).

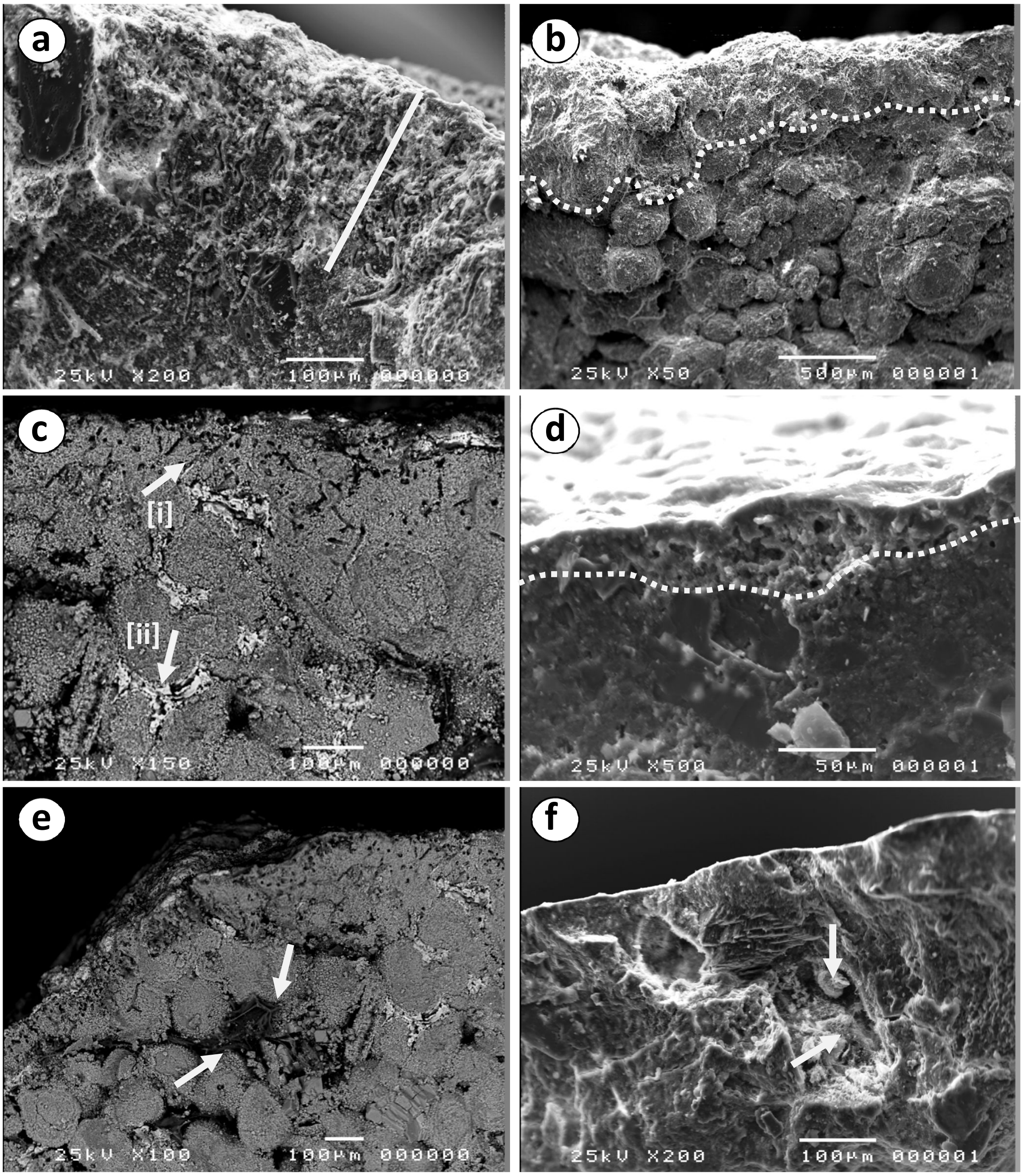


Figure 7-8 SEM micrographs of subsurface weathering features in materials exposed at MTL for 8 months (all unbleached samples): (a) subsurface boring zone in limestone (indicated); (b) weathering zone and pore-infilling in limestone (indicated); (c) upper zone of boring (arrow i) and deeper salt deposition (arrow ii) in limestone; (d) bio-chemical crusting and subsurface dissolution of the cement paste (indicated) of concrete; (e) organic structures (indicated) in inter-oolith pore spaces of limestone; (f) organic structures (indicated) in subsurface cavities of concrete; scales as shown.

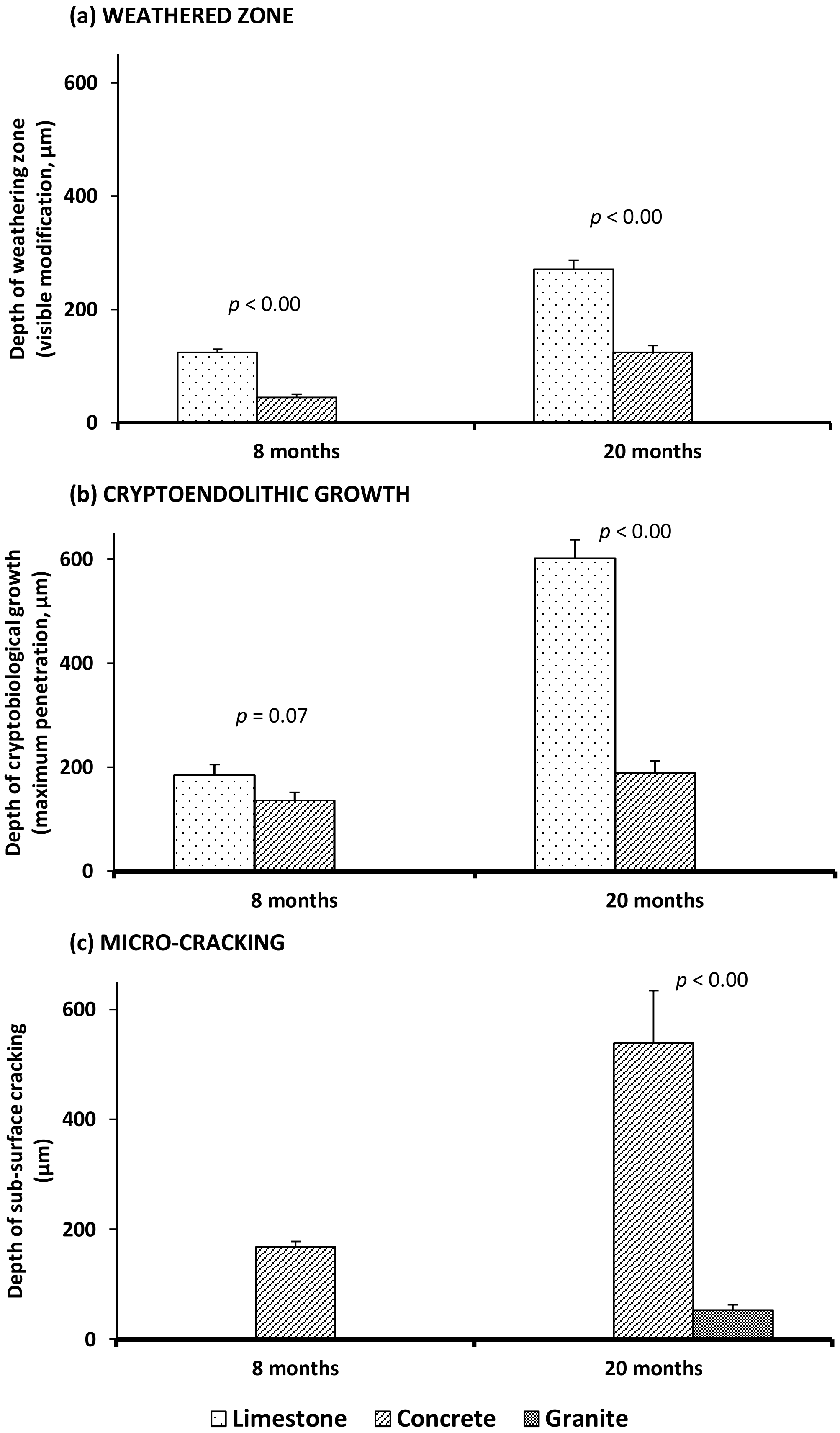


Figure 7-9 Depths of subsurface (a) weathering zone (b) cryptoendolithic growth and (c) micro-cracking observed on different material types after exposure for 8 and 20 months at MTL, Cornwall, UK (mean + SE, t-test significance as shown).

Weathered zones on concrete corresponded to the thickness of the bio-chemical crusts characterised in surface observations (Section 7.7.1). There was evidence of dissolution and pore-space enlargement of concrete beneath surface crusts (e.g. Figure 7-8d). EDS analysis of the crusts showed the presence of salts (Figure 7-10b) and brucite (magnesium hydroxide, Figure 7-10c) alongside abundant organic structures.

In contrast to limestone and concrete, there was little evidence of mineralogical change in granite beyond the very top surface of the rock, even after 20 months. There was, however, some evidence of deterioration deeper within the rock in the form of micro-cracking after 20 months. The morphology of these cracks was similar to *en echelon* micro-cracks reported in studies of mechanical weathering of rock by wetting and drying, and salt weathering (e.g. Nicholson 2000). Similar micro-cracking was also observed at the surface of concrete, and at a significantly greater depth than in granite after 20 months of exposure (Figure 7-9c). There was no evidence of subsurface cracking in limestone samples.

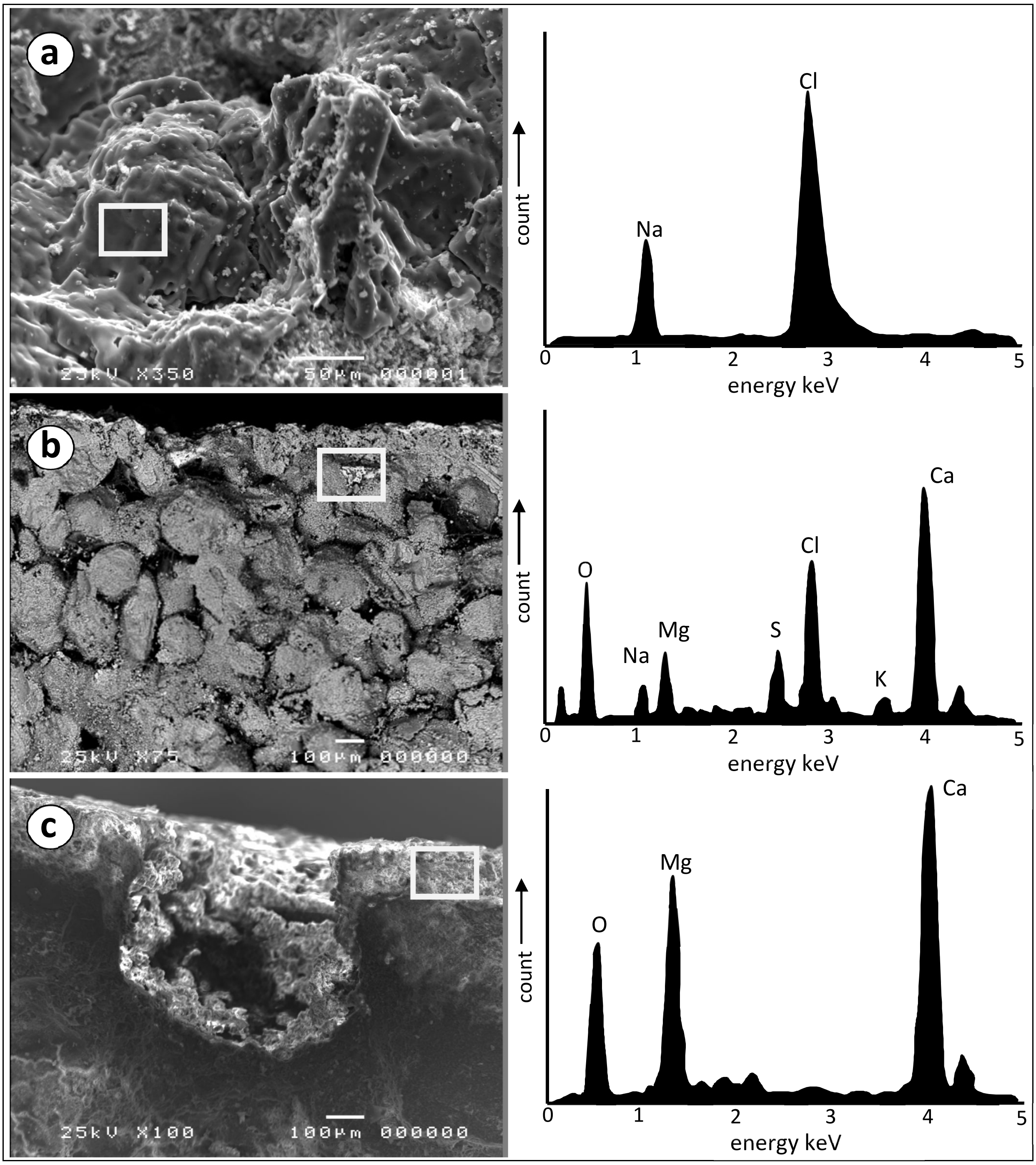


Figure 7-10 SEM micrographs and corresponding EDS spectra (location of X-ray measurements indicated by box): (a) halite (NaCl) crust at the surface of limestone (10 months at MHWN, unbleached); (b) subsurface deposition of salts in limestone (BEI image, 8 months at MTL, unbleached); (c) brucite ($Mg[OH]_2$) associated with bio-chemical crusting in and around a surface air-hole on concrete (BEI image, 10 months at MTL, unbleached); scales as shown.

7.7.2.2 Hypothesis 11b: Exposure time

For each material type, there were significant differences in the depth of subsurface biological and geomorphological features after 8 and 20 months' exposure at the same shore position (Figure 7-11, Table 7-11, Hypothesis 11b p. 257). The weathered zone in limestone exposed for 20 months (271.9 ± 99.5 µm) was more than twice the depth of samples removed a year earlier (Student's t[df = 51] = 8.85, p < 0.00, e.g. Figure 7-11a). After 20 months, concrete had weathered to a depth of 124.6 ± 75.8 µm, which was more than double that recorded for blocks removed the previous year (Student's t[df = 44] = 5.46, p < 0.00, Figure 7-11a).

The depth of cryptoendoliths observed in limestone after 20 months (602.4 ± 183.6 µm, n = 27) was, on average, more than three times that measured in samples removed after 8 months (185.9 ± 73.1 µm, n = 15; Student's t[df = 37] = 10.23, p < 0.00, Figure 7-11b). Similarly, organic structures were observed deeper in concrete after 20 months (189.9 ± 72.4 µm, n = 10) compared to blocks removed the year before (136.7 ± 35.1 µm, n = 5), although this was not significant (Student's t-test, t[df = 13] = 1.92, p = 0.08, Figure 7-11b). There was no evidence of colonisation of granite by cryptoendoliths after 20 months of exposure.

Although highly variable, the average depth of micro-cracking was significantly higher in both concrete and granite after the longer period of exposure (Figure 7-11c). In concrete, micro-cracks were measured at an average depth of 168.5 ± 47.2 µm (n = 20) after 8 months compared to 539.7 ± 382.4 µm (n = 16) after 20 months (Student's t[df = 15] = 3.86, p = 0.002, Figure 7-11c). Micro-cracking was generally absent from granite after 8 months, and shallower than in concrete after 20 months (53.6 ± 25.0 µm, n = 7; Figure 7-11c, Table 7-11).

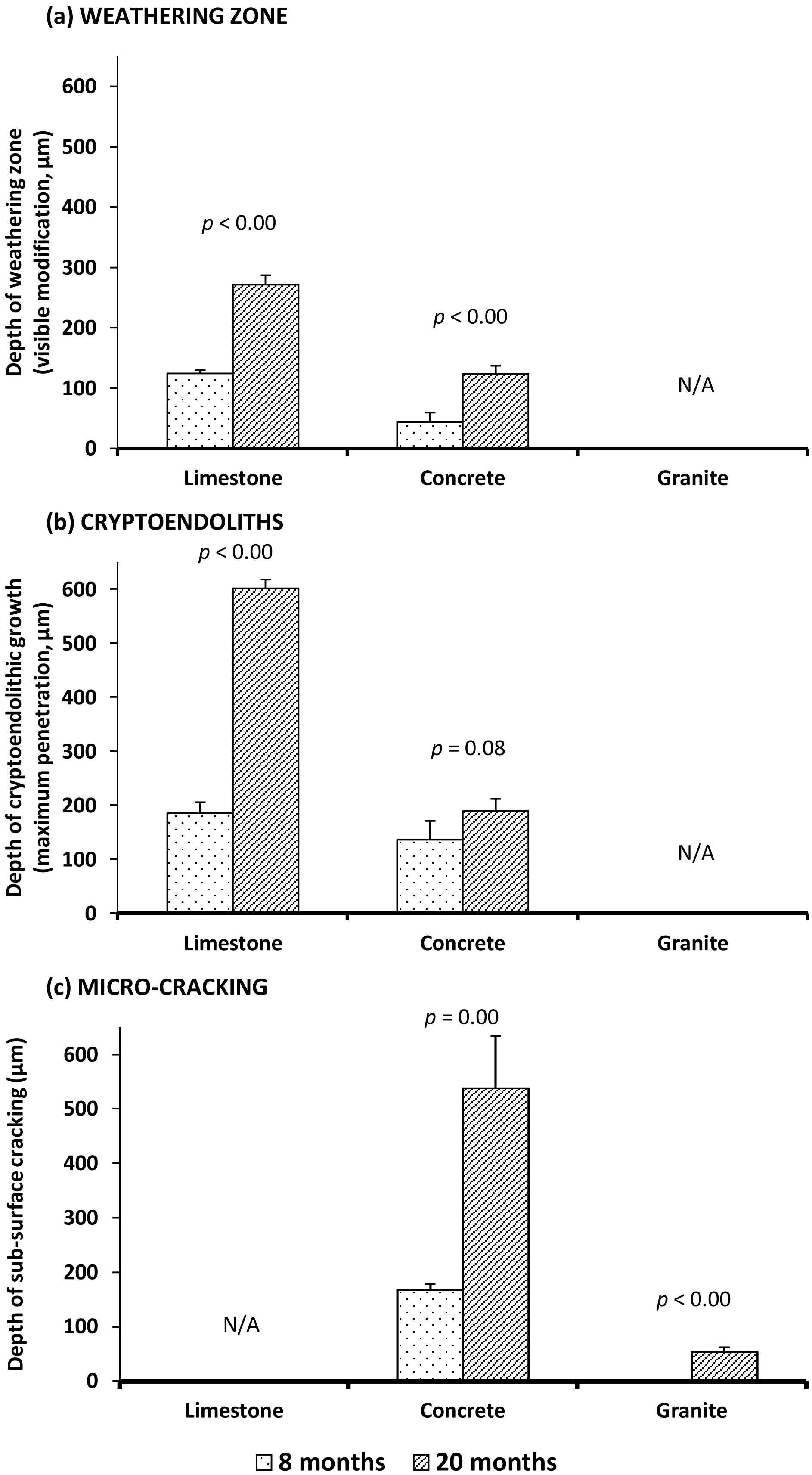


Figure 7-11 Depths of subsurface (a) weathering zone (b) cryptoendolithic growth and (c) micro-cracking observed in different material types after exposure for 8 and 20 months at MTL, Cornwall, UK (mean + SE, t-test significance as shown).

Table 7-11 Relative depths of subsurface micro-scale biological and geomorphological features observed in various material types after exposure for 8 and 20 months MTL, Cornwall, UK.

	Relative Depth*		
Subsurface feature (unbleached)	**Limestone**	**Granite**	**Concrete**
Depth of boring	8 << 20	na	na
Weathered zone	8 << 20	na	8 << 20
Cryptoendolithic growth	8 << 20	na	8 = 20
Micro-cracking	na	8 << 20	8 << 20

*Student's t-test result:
"=" denotes no difference, "<" denotes $p = 0.05$, "<<" denotes $p = 0.01$.
"na" denotes that no test could be performed.

7.7.2.3 Bioerosion

Euendolithic microorganisms had bored to a significantly greater depth in limestone after the longer period of exposure (Figure 7-12); boring tunnels penetrated, on average, more than four times deeper in blocks exposed for 20 months compared to those removed the previous year (8 month depth = 34.0 ± 12.3 µm, 20 month depth = 162.9 ± 55.7; Student's t[df = 28] = 11.76, $p < 0.00$; Figure 7-12). It was not possible to compare boring depths in concrete as this was rarely observed when viewed in cross-section. No boreholes were observed in granite after both periods of exposure.

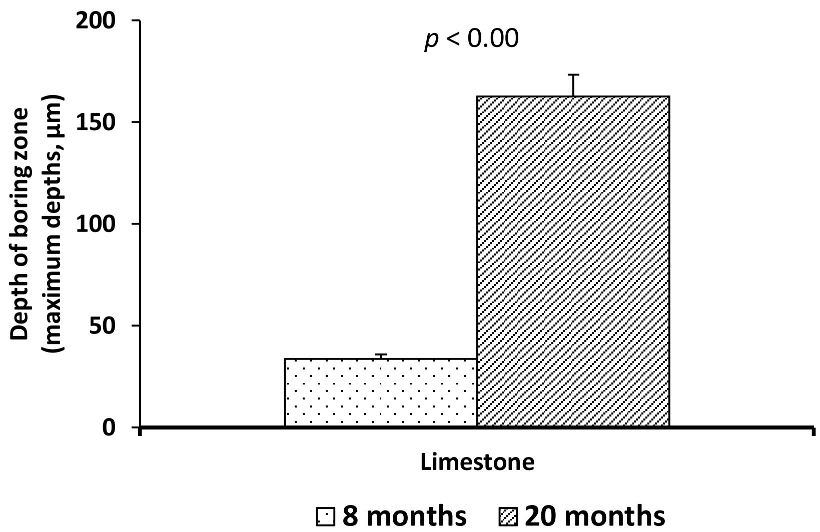


Figure 7-12 Depth of the zone of borehole erosion on Portland limestone exposed for 8 and 20 months at MTL, Cornwall, UK (mean + SE, *n* = 28 for 8 months and *n* = 27 for 20 months, t-test significance as shown).

CHAPTER 7: STRAND 2

Alteration of Bulk Material Properties during Intertidal Exposure: Implications for weathering and durability

7.1 Introduction and Aims

The same tests used to characterise the three experimental materials before field exposure (see Chapter 4) were repeated on blocks exposed for 8 and 20 months at MTL. This was done to test whether material properties (such as strength and porosity) changed at a scale more relevant to engineering durability (Fookes et al. 1988; Fookes et al. 2005). Rapid changes in the durability of rock and concrete that might occur once exposed (i.e. within the first few years of service) are not typically monitored by engineers. Durability issues may not therefore be detected until major structural problems become apparent (Latham 1991; Latham et al. 2006).

There are generally negative opinions regarding growth on structures by engineers (see Section 2.5.2 p. 83). At a micro-scale, for example, Ortega-Morales et al. (2010) state that microbial activity on engineered infrastructure may enhance the occurrence of fatigue cracks that "*eventually propagate and lead to mechanical failure…increasing the risk of catastrophic loss of human lives and economically valuable assets*" (p.348). Giannantonia et al. (2009) also suggest that mitigation *against* microbial colonisation of concrete structures is needed as this can lead to 'significant economic loss' from maintenance and repair (Gu et al. 1998; Gaylarde and Morton 1999; Nasrazadani and Sudio 2010). Quantitative evidence of links between microorganism activity and engineering durability are, however, largely lacking for coastal structures. Inkpen et al. (2000) suggest that (in the context of stone weathering) seeing durability as a property inherent in, and retained by, the material is misleading as changes occurring as a result of weathering and erosion mean that durability cannot be assumed static in time or space. The nature of such changes, and the extent of biological involvement, has not been assessed for materials commonly used in coastal engineering.

Geomorphologically, linkages between bulk material properties and observations made at a micro-scale (Strand 1, above) were of theoretical interest (Viles 2001). Materials may also become more or less susceptible to subsequent weathering and erosion processes after a period of exposure, which was of interest in a rock coast geomorphology context (Sunamura 1992, 1994; Naylor et al. 2010). In an ecological context, bulk material properties relating to hardness and strength were relevant for assessing the nature of colonisation at the micro-scale (Strand 1, above) and water absorption and porosity properties may also be important for micro-climatic conditions at the material surface (see Chapter 8). Changes in the geomechanical properties of materials were also associated with morphological change and habitat heterogeneity (Strand 3).

The geomechanical properties of the same three materials used throughout the thesis were compared after different periods of exposure in the intertidal zone to test questions and hypotheses relating to: (i) the relative differences in bulk-scale physical properties between the material types (Hypothesis 12) and; (ii) the influence of time (period of exposure) on the physical properties of each material type (Hypothesis 13a) and the nature of alteration (direction and relative significance) between material types (Hypothesis 13b; Table 7-12).

Table 7-12 Chapter 7: Strand 2 Research questions and experimental hypotheses (see Table 3-2).

	Research Question	Hypothesis
STRAND 2: BULK GEOMECHANICAL PROPERTIES		
12	How do bulk geomechanical properties of different construction materials compare (relative to each other) after exposure in the intertidal zone?	(12) Geomechanical properties of limestone, granite and marine concrete are different after initial exposure (< 2 years) in the intertidal zone.
13	How do bulk geomechanical properties of construction materials vary after different amounts of time in the intertidal zone?	(13a) Geomechanical properties of materials exposed for different amounts of time (8 and 20 months) are not the same. (13b) The degree (statistical significance) and direction of change in geomechanical properties after exposure is not the same between material types.

7.2 Methods

The same blocks of limestone, granite and concrete harvested for SEM analyses (Chapter 7: Strand 1, above) were used for geomechanical re-characterisation (Figure 7-2 p.210). Strength (failure load), surface hardness (Equotip *L*), soundness (ultrasonic velocity) and water absorption (WAC) were compared after exposure for 0 months (controls), 8 months and 20 months at MTL. This approach is shown schematically in Figure 7-13. Full details of each test and the procedures used for control blocks are given in Chapter 4; the same procedures and levels of replication were used on harvested blocks where possible to enable statistical comparisons.

Given that some of the characterisation tests were destructive (namely the Point Load Test), comparisons between periods of exposure do not represent changes occurring on the same individual blocks through time. Rather, comparisons represent differences in the same material types before and after a period of field exposure. In order to ensure valid comparisons, care was taken to prepare control blocks (after 0 months) and field blocks (after 8 and 20 months) from the same stock of material obtained from the same quarries. For most of the tests, eight blocks of each material type was deemed a sufficient level of replication with appropriate statistical analyses to account for inherent variation between blocks (Section 7.2.1).

Control blocks were stored in the laboratory (in the dark) and tested on the same day as field-exposed blocks, which were air-dried for several months once harvested. This was to ensure that any measured differences between controls and field samples could be attributed to exposure with confidence, rather than as a function of time alone, and to ensure valid comparisons with respect to water content. This was particularly important for concrete which continues to strengthen for a period of time after initial curing (typically a matter of weeks, Allen 1998).

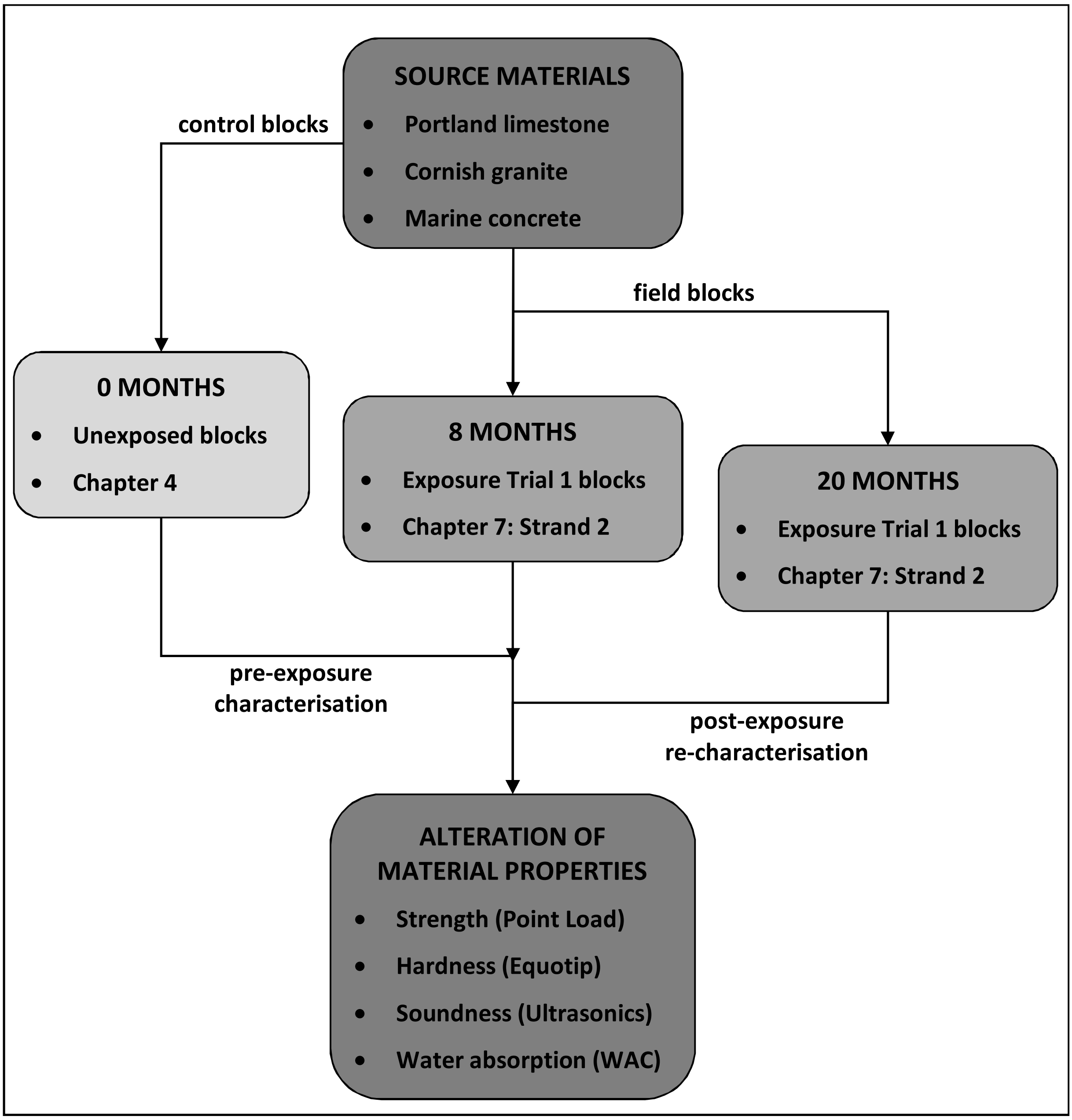


Figure 7-13 Schematic of approach used for the physical characterisation of construction materials before and after different periods exposure in the intertidal zone.

7.2.1 Statistical analysis

A separate two-factor ANOVA was used to test for differences in each measured parameter (strength, hardness, soundness and water absorption). In each instance ‘material type’ (three levels: limestone, granite and concrete) and ‘time’ (three levels: 0, 8 and 20 months) were fixed factors. Because tests were carried out on different blocks after each period of exposure (above), measurements were independent and therefore valid for ANOVA.

Data were tested for homogeneity of variance using a Cochran’s test and transformed where necessary. Where heterogeneity could not be corrected untransformed data were used and a conservative significance level (p_{crit} = 0.01) was adopted (Underwood 1997). Student Newman–Keuls (SNK) tests were used to compare interactions between factors where significant. With respect to SNK test results, ‘=’ is used in the following discussions to denote a non-significant difference between variables, ‘<’ to denote significance where p_{crit} = 0.05, and ‘<<’ where p_{crit} = 0.01.

A simple assessment of correlation between the different geomechanical parameters was also undertaken using the Pearson coefficient (*r*). This was useful to examine whether trends in each set of data were consistent between material types and exposure periods, and to complement more detailed evaluations of comparability of results obtained using the different methods and equipment (e.g. Viles et al. 2011).

7.3 Results

7.3.1 Bulk strength (Point Load)

Figure 7-14a shows bulk strength (failure load) determined using the Point Load Test (PLT) for limestone, granite and concrete after exposure for 0, 8 and 20 months at MTL. Differences in strength between the materials were significant at all time-steps (limestone << concrete << granite, Table 7-13, Hypothesis 12 p. 284). There were, however, no detectable differences in strength after each period of exposure for any of the materials ($p = 0.72$, Table 7-13, Hypothesis 13a, 13b p. 284).

Table 7-13 Analysis of variance for bulk material strength (failure load) of various construction materials (limestone, granite and marine concrete) after different lengths of time exposed at MTL (0, 8 and 20 months).

Source of variation	*df*	MS	*F*	*p*
Material ($n = 3$)	2	5.7203	317.15	**0.000***
Time ($n = 3$)	2	0.0058	0.32	0.724
Material x Time	4	0.0183	1.02	0.406
Residuals	63	0.018	-	-
Total	71	-	-	-

df = degrees of freedom; MS = mean square variance; *F* = ratio of variance; *p* = significance.
Cochran's test $C = 0.229$ (not significant; untransformed data).
p values: ***$p < 0.001$.

7.3.2 Surface hardness (Equotip)

Figure 7-14b shows surface hardness (Equotip *L* values) for limestone, granite and marine concrete after exposure for 0, 8 and 20 months at MTL. For this analysis, measurements taken on smooth faces of granite were used as this was more comparable to the texture of the other materials, and also produced much more consistent measurements with the Equotip compared to rough surfaces (see Chapter 4). Differences in surface hardness between the material types were significant at all time-steps (limestone << concrete << granite, Table 7-14, Hypothesis 12 p. 284). There were also significant differences with exposure time ($p = 0.004$, Table 7-14, Hypothesis 13a, 13b p. 284).

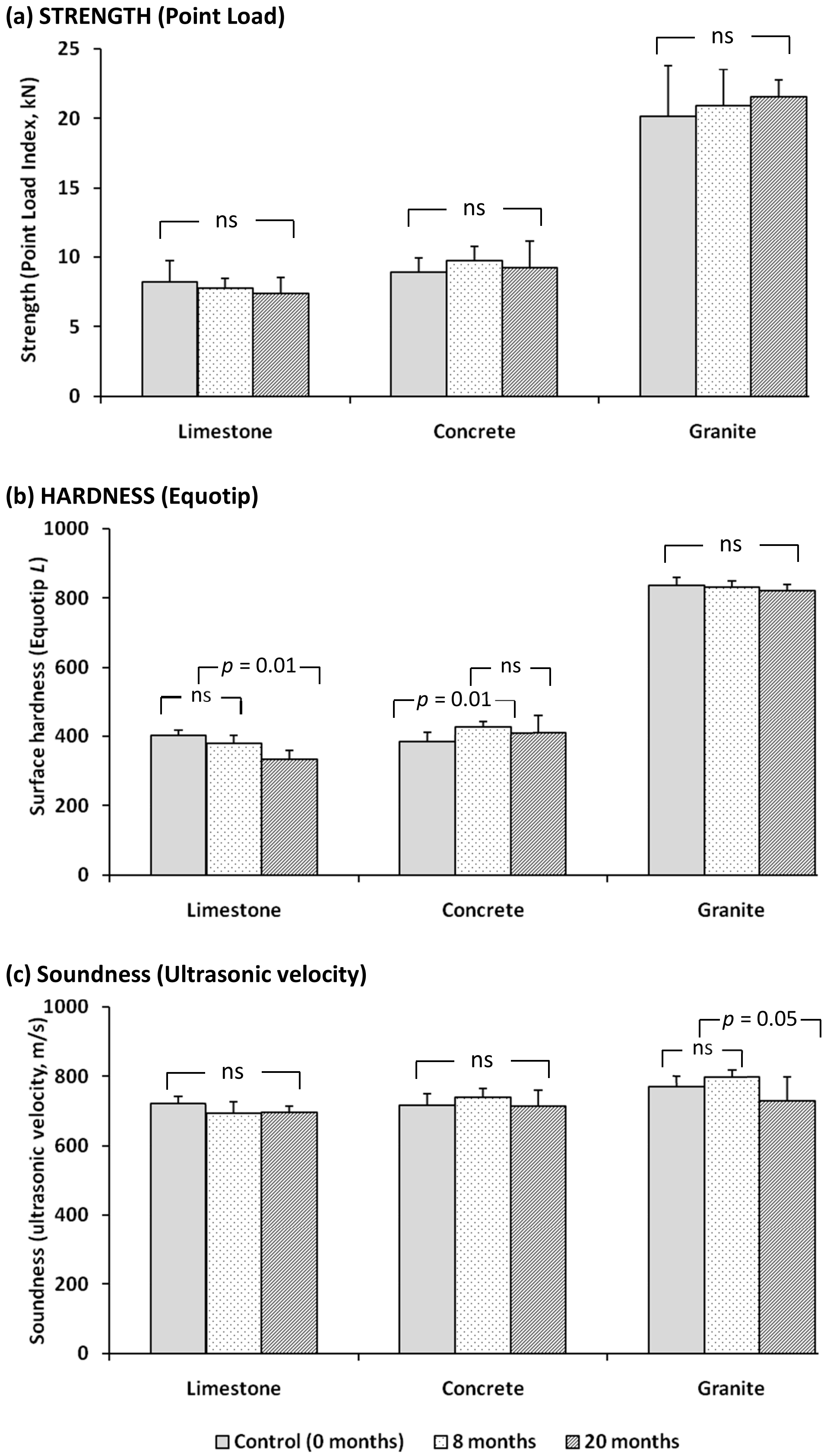


Figure 7-14 (a) Strength (b) surface hardness and (c) soundness of limestone, granite and concrete after different periods exposure at MTL (mean + SD, *n* = 8, SNK significance as shown).

Table 7-14 ANOVA for surface hardness (Equotip *L*) of various construction materials (limestone, granite and marine concrete) after different lengths of time exposed at MTL (0, 8 and 20 months).

Source of variation	*df*	MS	*F*	*p*
Material (n = 3)	2	1558051.4255	2416.49	**0.000*** **
Time (n = 3)	2	3997.7981	6.2	**0.004** **
Material x Time	4	5306.8971	8.23	**0.000*** **
Residuals	63	644.7583	-	-
Total	71	-	-	-

df = degrees of freedom; MS = mean square variance; *F* = ratio of variance; *p* = significance.
Cochran's test C = 0.413 ($p < 0.01$; untransformed data, p_{crit} = 0.01).
p values: ** p = 0.01, ***$p < 0.001$.

The surface hardness of limestone exposed for 8 months was lower than controls (0 months), but the difference was not statistically significant ($p > 0.05$, Figure 7-14b). Limestone blocks exposed for 20 months were, however, significantly softer than both 0 and 8 month blocks (limestone hardness at 20 months << 8 months = 0 months). Interestingly, concrete showed the opposite trend; blocks exposed for 8 months were significantly harder than controls (p = 0.05), as were blocks exposed for 20 months (Figure 7-14b). The hardness of granite did not change with time (granite hardness at 0 months = 8 months = 20 months).

7.3.3 Soundness (Ultrasonic velocity)

Figure 7-14c shows the soundness of limestone, granite and marine concrete after exposure for 0, 8 and 20 months at MTL, measured using the ultrasonic velocity test. Differences in P-wave velocities between the material types were significant at all time-steps (limestone < concrete << granite, Table 7-15, Hypothesis 12 p. 284). Overall velocity values (for all three materials) were significantly lower for blocks exposed for 20 months than those exposed for 0 and 8 months (20 months < 8 months = 0 months, p = 0.011, Table 7-15), although this was just short of the conservative p_{crit} adopted due to unrectified data heterogeneity. When considered separately, SNK tests revealed that the soundness of granite exposed for 20 months was lower than blocks removed a year earlier (20 months blocks < 8 months = 0 months), but this may have been an artefact of the measurement technique (see discussion in Strand 4). In comparison, there were no detectable differences in limestone or concrete soundness between the two periods of exposure (Figure 7-14c, Hypothesis 13a, 13b p. 284).

Table 7-15 ANOVA for soundness (ultrasonic wave velocity) of various construction materials (limestone, granite, and marine concrete) after different lengths of time exposed at MTL (0, 8 and 20 months).

Source of variation	*df*	MS	*F*	*p*
Material (n = 3)	2	24321.3854	20.04	**0.000*** **
Time (n = 3)	2	5922.8607	4.88	**0.011** **
Material x Time	4	3492.1545	2.88	**0.030** **
Residuals	63	1213.5538	-	-
Total	71	-	-	-

df = degrees of freedom; MS = mean square variance; *F* = ratio of variance; *p* = significance.
Cochran's test $C = 0.370$ ($p < 0.01$; untransformed data, $p_{crit} = 0.01$).
p values: ** $p = 0.01$, ***$p < 0.001$.

7.3.4 Water absorption (WAC)

Figure 7-15 shows the Water Absorption Capacity (WAC) of limestone, granite and marine concrete after exposure at MTL for 0, 8 and 20 months, determined in both freshwater (Figure 7-15a) and synthetic seawater (Figure 7-15b). Differences in WAC between the material types were significant at all time-steps (granite << concrete << limestone, Table 7-16, Hypothesis 12 p. 284). There were also significant differences between time periods, although this varied with material type (Figure 7-15, Hypothesis 2a, 2b p. 284).

Limestone exposed in the field had a higher WAC than controls, although this was only significant in freshwater ($p = 0.05$, Figure 7-15b). In contrast, concrete exposed for 8 months showed a reduction in WAC compared to controls in freshwater and synthetic sea water ($p = 0.01$), but was significantly higher for concrete exposed for 20 months compared to blocks removed a year earlier ($p = 0.01$, Figure 7-15b). There were no differences in WAC for the granite samples.

Table 7-16 Analysis of variance for Water Absorption Capacity of various construction materials (limestone, granite and marine concrete) in freshwater and synthetic seawater after different lengths of time exposed at MTL (0, 8 and 20 months).

		Freshwater			Synthetic seawater		
Source of variation	***df***	**MS**	***F***	***p***	**MS**	***F***	***p***
Material (*n* = 3)	2	120.3509	2550.76	**0.000*** **	130.6274	1728.84	**0.000*** **
Time (*n* = 3)	2	4.5165	95.72	**0.000*** **	3.7981	50.27	**0.000*** **
Material x Time	4	2.8577	60.57	**0.000*** **	3.1946	42.28	**0.000*** **
Residuals	27	0.0472	-	-	0.0756	-	-
Total	35	-	-	-	-	-	-

df = degrees of freedom; MS = mean square variance; *F* = ratio of variance; *p* = significance.
Cochran's test for freshwater $C = 0.384$ (not significant; non-transformed data);
for synthetic seawater $C = 0.545$ ($p < 0.01$; untransformed data, $p_{crit} = 0.01$).
p values: ***$p < 0.001$.

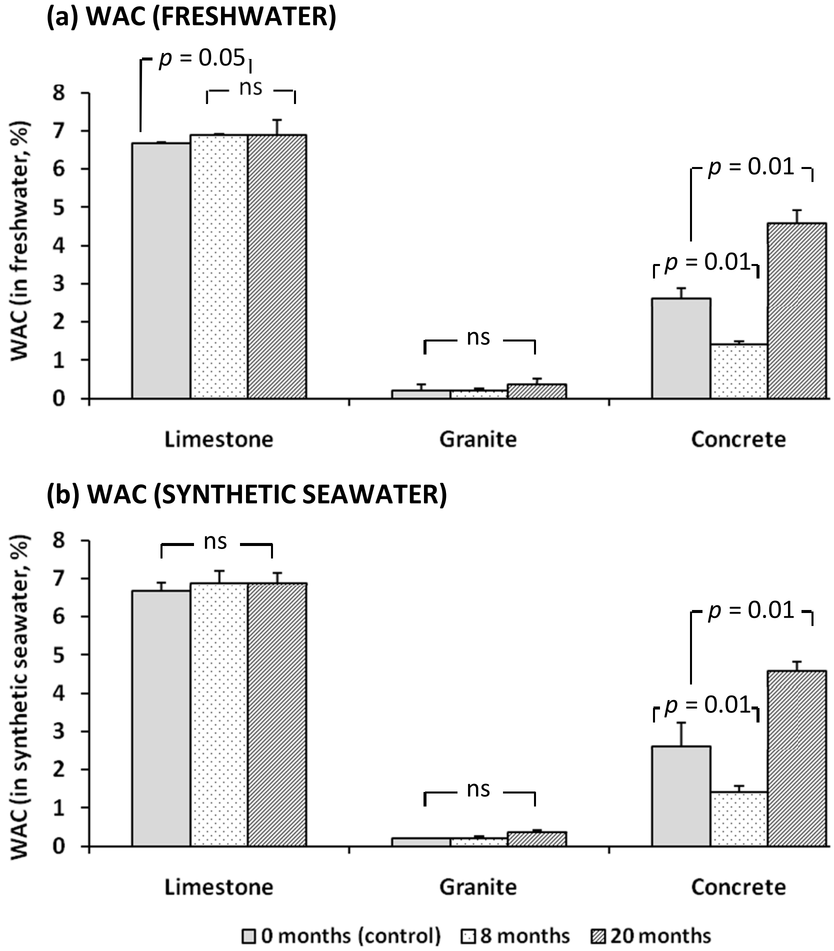


Figure 7-15 Water Absorption Capacity (%) of limestone, granite and marine concrete after exposure for 0, 8 and 20 months at MTL determined in (a) freshwater and (b) synthetic seawater (mean + SD, *n* = 4, SNK significance as shown).

7.4 Data Correlations

Figure 7-16 shows XY plots of strength, hardness and soundness measurements for each material type and each period of exposure. WAC could not be compared as this test was done using different parts of harvested blocks, and had a smaller number of replicates (see Section 4.3.5 p. 146). There was generally good positive correlation between all the tests; a difference in one parameter typically matched differences in the other parameters. Correlations associated with the ultrasonic velocity test were weaker (Figure 7-16a and Figure 7-16b), although still highly significant ($p < 0.00$). Correlation between bulk strength and hardness, as determined using the PLT and Equotip respectively, was very high (Pearson's $r = 0.90$, $p < 0.00$). In all instances, measurements were more variable on granite compared to limestone and concrete, probably because granite blocks were heavily encrusted with barnacles after 20 months, which would have influenced the readings (see discussion in Strand 4).

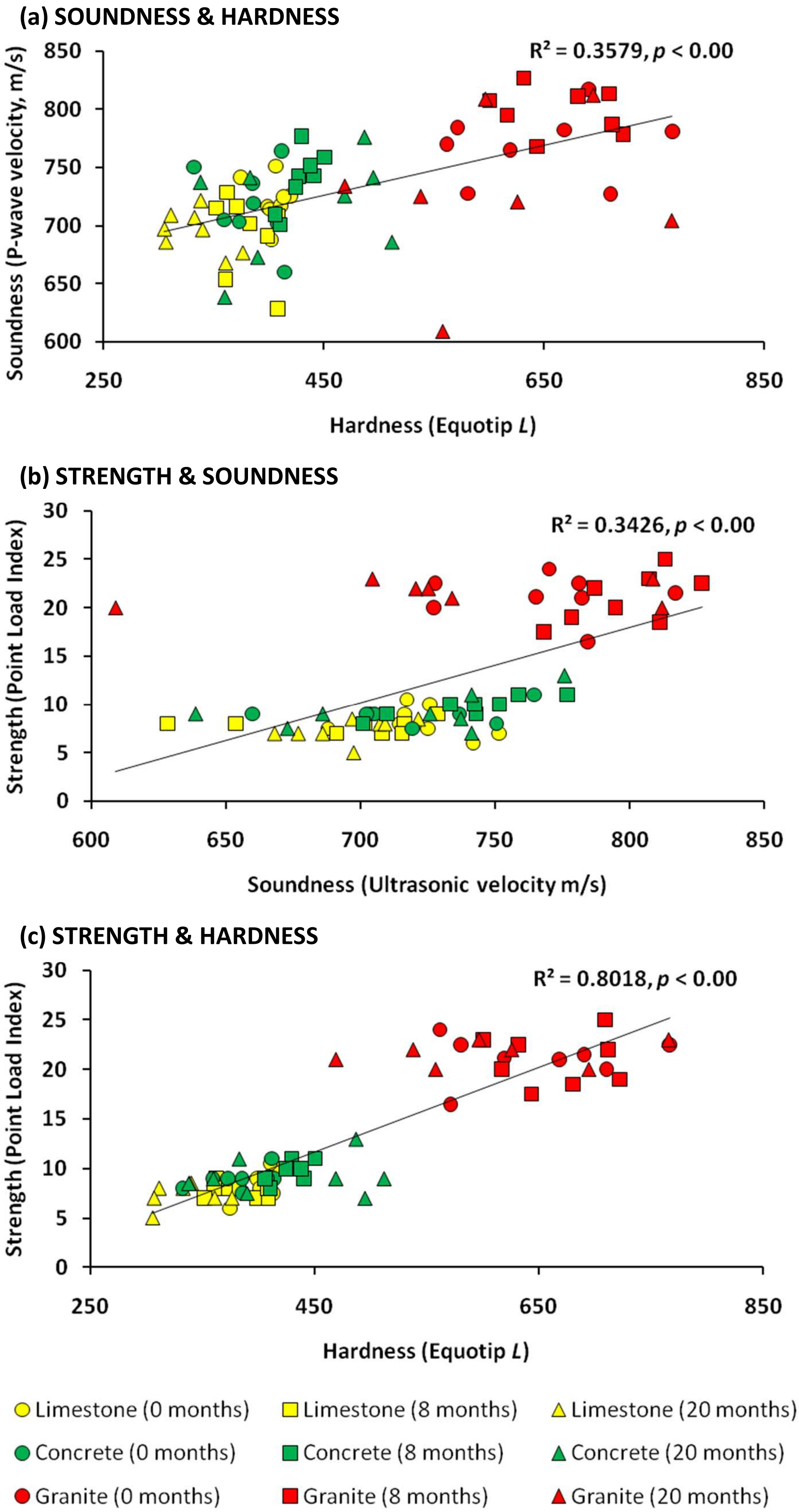


Figure 7-16 Scatter plots of geomechanical parameters for materials exposed at MTL for 0 (control), 8 and 20 months: (a) soundness against hardness, (b) strength against soundness, and (c) strength against hardness (*n* = 24 for each material type, correlation [R^2] as shown).

CHAPTER 7: STRAND 3

Morphological Response of Construction Materials during Intertidal Exposure: Millimetre-scale texture development

7.1 Introduction and Aims

Surface morphology (or roughness) is a vague concept that is largely scale-dependent (Evans 1981; Goudie 1990). Morphology can be measured in many different ways and at various spatial scales. Whilst each method has advantages and disadvantages, they are more or less appropriate for use depending on the scale of interest. In ecological studies, for example, methods are typically dictated by the specific habitat and/or organism of interest (Frost et al. 2005; Wilding et al. 2010). Similarly, in geomorphology surface roughness is not an objective property but is a construct predefined according to the scale of irregularity of concern (McCarroll and Nesje 1996). The greatest value of measuring roughness will be achieved, therefore, where the reasons why roughness is of importance are made clear in the specific context of the study (McCarroll and Nesje 1996).

In rock geomorphology, surface roughness has been used as an indicator of weathering state, assumed to relate to the nature and rate of geomorphic processes acting upon a material, and which can provide information on the relative age of surfaces (e.g. Nesje et al. 1994; McCarroll and Nesje 1996; White et al. 1998; Gómez-Pujol et al. 2006; Ehlmann et al. 2008). Texture analysis is also important in soil science and remote sensing (e.g. Huang and Bradford 1992; Ben-Dor et al. 2003; Croft et al. 2009; Anderson and Croft 2009) and at much larger scales for morphometric classification of landforms in time and space (e.g. Székely and Karátson 2004; Lyew-Ayee et al. 2007; Rodriguez-Gonzalez et al. 2010). In the intertidal zone, ecologists are more typically concerned with surface 'complexity' or 'heterogeneity' rather than roughness and texture *per se*, as these terms are more akin to well established theories of habitat complexity and habitat heterogeneity (see Chapters 2 and 6 for further details). Habitat complexity is of particular interest in marine benthic ecology as it is known to influence species diversity at a range of spatial scales (e.g. Archambault and Bourget 1996; Blanchard and Bourget 1999; Johnson et al. 2003).

Strand 3 describes work undertaken following qualitative field observations of textural change of experimental blocks during exposure in the intertidal zone. Barnacle cypris larvae and juveniles were frequently observed in association with pitted weathering morphologies developing on smooth limestone after one year at MTL (e.g. Figure 7-17). This suggested that while colonisation was very low on smooth limestone during the first settlement season (Chapter 5), weathering morphologies developing naturally on this material type facilitated colonisation in subsequent years. The strong response of barnacles to mm-scale texture in *Exposure Trial 2* (Chapter 6) also indicated that natural geomorphic processes altering the substrata at this scale were of importance for the ecological potential of materials used in coastal engineering. The involvement of microorganisms in the textural development of their substrata was of interest as a potential example of 'biogeomorphic ecosystem engineering' (see Chapter 3) and for linking µm and mm scales in a biogeomorphological context.

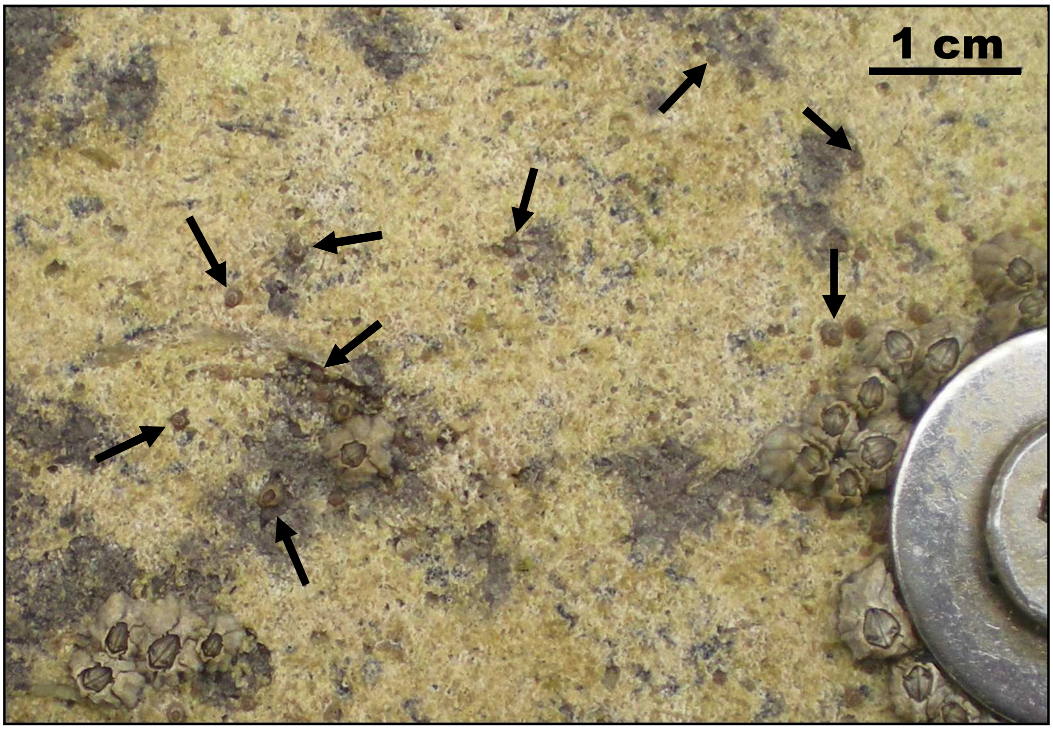


Figure 7-17 Association between weathering of limestone and barnacle recruitment (juvenile recruitment in weathering pits developed after exposure for 14 months at MTL indicated).

Morphological change was assessed using topographic profiles derived from laser scans of experimental blocks before and after exposure in the field. Blocks exposed on the shore at MTL and MHWN in *Exposure Trial 2* (Chapter 6) were used for this work. Rather than a detailed assessment of surface 'complexity' typically used to describe combined scales of heterogeneity (e.g. Crisp and Barnes 1954; Bourget et al. 1994; Lapointe and Bourget 1999; Frost et al. 2005), the analysis was restricted to morphological change at a particular scale known to be of importance for barnacles and other early colonising organisms (i.e. a mm-scale, Chapter 2 and Chapter 6). This was undertaken to illustrate the potential importance of microbial bioerosion for substratum ecological potential (with respect to barnacles).

The general hypothesis that the roughness of limestone and concrete (at a mm scale) would be higher after field exposure was tested (Hypothesis 14a) and that the degree of change would vary between material types (Hypothesis 14b, Table 7-17). The nature of textural development was also expected to vary between tidal heights (Hypothesis 15) as a function of differences in the relative intensity of biological, chemical and mechanical weathering and erosion processes across the shore (e.g. Gómez-Pujol and Fornós 2009, Appendix 2). Granite was not tested due to practical constraints (see Section 7.2.2 below).

Table 7-17 Chapter 7: Strand 3 Research questions and experimental hypotheses (see Table 3-2).

	Research Question	Hypothesis
STRAND 3: MORPHOLOGICAL RESPONSE		
14	How do construction materials change morphologically (at an ecologically relevant scale) during intertidal exposure?	(14a) Surface roughness (at a mm-scale) is higher after exposure in the intertidal zone. (14b) Different materials types respond differently (morphologically, at a mm-scale) during exposure in the intertidal zone.
15	How do morphological responses vary across the shore?	(15) Morphological development (surface roughness) varies between shore levels.

7.2 Methods

7.2.1 Introduction

McCarroll and Nesje (1996) suggest that the carpenters profile gauge method for assessing surface roughness (described in detail in Chapter 4) can yield anomalous results at fine scales (< 5 mm), with 'Index A' roughness values underestimating highly variable surfaces. The method is also less accurate than other techniques specifically designed to quantify fine-scale topography, such as digital Micro Roughness Meters (MRMs) and laser scanners. In rock weathering studies, laser scanning has increasingly been used to derive large amounts of topographic data at high spatial resolution, including on rocky shore platforms (Swantesson et al. 2006; Gómez-Pujol et al. 2006; Vogt and Edsall 2010). The technique involves the detection of distortion and travel time of a laser beam of known wavelength as it is reflected from a test surface (Schaefer and Inkpen 2010). Scan data can be used for morphometric analysis, monitoring surface change and for visualisation purposes (see Williams et al. 2000; Schaefer and Inkpen 2010 for reviews). Scanning procedures have also been used to produce 3-dimensional physical models of rocks using prototype printing techniques (Bourke et al. 2008), and is increasing being used in an applied context for classification and cataloguing of rock and stone surfaces (e.g. English Heritage 2007).

Gómez-Pujol et al. (2006) used a combination of scanning and profile analysis in their assessments of intertidal rock roughness. They used McCarroll and Nesje's (1996) procedure to calculate Index A roughness (see Chapter 4) of profiles extracted from laser scans. This approach allowed an assessment of roughness at a finer spatial resolution (mm scale) than was possible using manually collected profiles. A similar method was used here to assess surface morphology of experimental materials at a scale known to be of ecological relevance. Whilst Gómez-Pujol et al. (2006) analysed profiles extracted from scans made in the field, the use of exposure blocks in this study enabled use of a static (desktop), automated scanning device. This had the benefit of minimising errors associated with portable devices and repeat scanning in the field (e.g. Lane and Chandler 2003; Schaefer and

Inkpen 2010) as the same scan distance, lighting, orientation and scanning angle could be used for control ('before') and field-exposed ('after') blocks, as described below.

7.2.2 Procedure

The top surfaces of experimental blocks were scanned using an automated Roland® LPX-600DS desktop laser scanner at University College Falmouth before being exposed on intertidal shore platforms as part of *Exposure Trial 2* (Chapter 6). Scans were made at the maximum possible spatial resolution (0.02 mm) perpendicular to the test surface (see Table 7-18 for further specifications of the scanning device). The analysis was limited to limestone and concrete only as granite returned data errors due to laser reflectance. Observations made at a micro-scale (Strand 1) and bulk-scale (Strand 2), however, showed limited evidence of physical change on granite during the course of the study.

Table 7-18 Specification of laser scanner used to assess mm-scale changes in surface morphology of limestone and concrete during intertidal exposure.

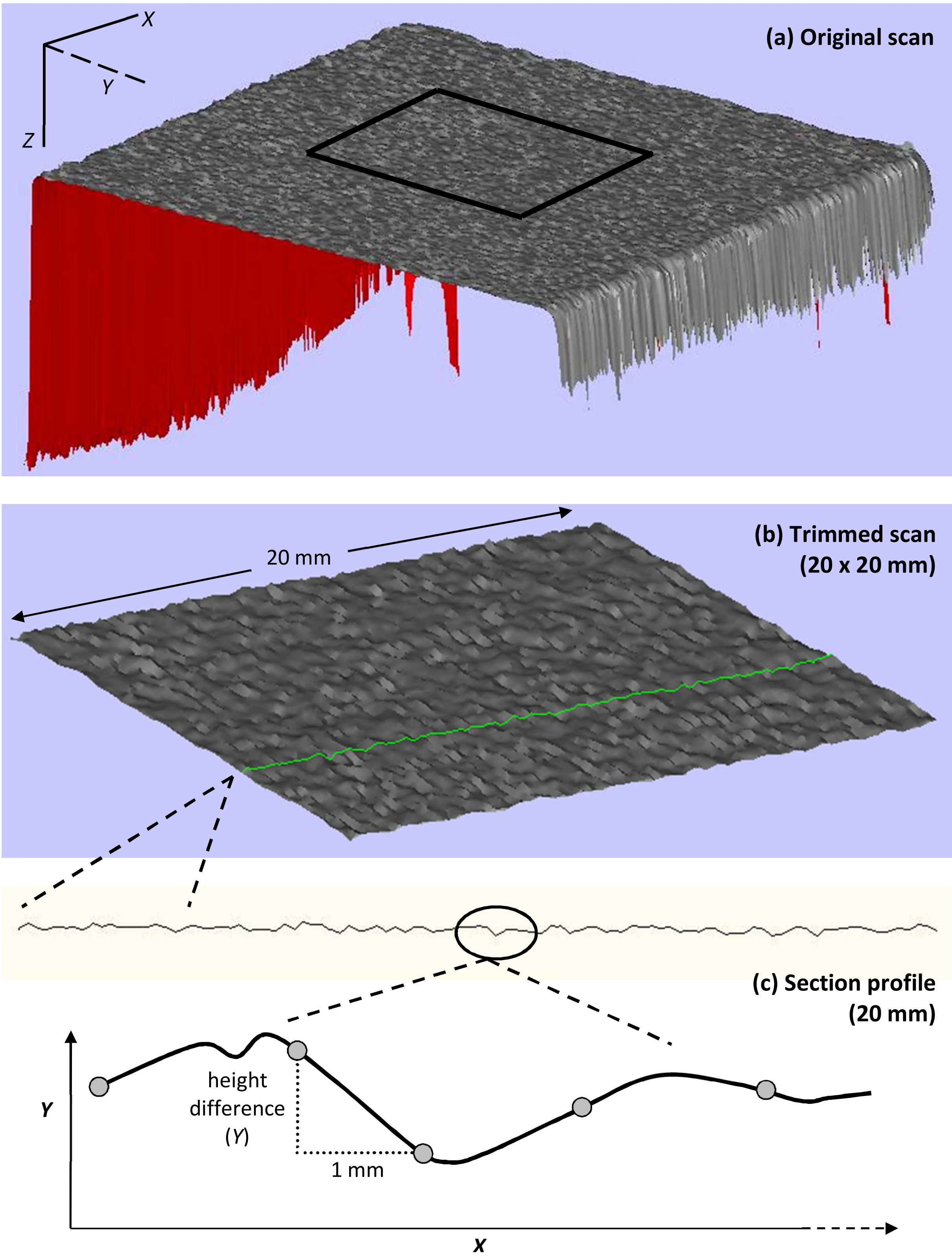
Scanner make and model:	Roland® LPX-600DS
Scanning pitch:	Plane scanning: width direction 0.2 - 254.0mm, height direction 0.2 - 406.4mm. Rotary scanning: circumference 0.18 - 3.6 degrees, height direction 0.2 - 406.4 mm
Repeat accuracy:	±0.05 mm
Laser:	Wavelength: 645 to 660 nm (red light) Maximum output: < 0.39 µW (maximum output of the laser light emitted inside housing is 0.1 mW)
Sensor:	Noncontact laser sensor
Scanning method:	Spot-beam triangulation

Source: http://www.rolanddga.com/products/scanners/lpx600/, accessed October 2010.

Eight blocks of smooth (sawn) limestone and plain-cast concrete were initially scanned. Half of the blocks were then attached at MTL and half at MHWN at Tregear Point, Porthleven, in March 2009 (see Chapter 6). As the smooth limestone and plain-cast concrete supported very low numbers of barnacles during the first year of exposure (Chapter 5 and 6), changes in the morphology of these particular material and texture combinations were of interest. Surface roughness was critical for barnacle colonisation (e.g. Chapter 6) and so morphological evolution of smooth materials used in coastal engineering during exposure was of greatest relevance for ecological potential (Chapter 9).

In January 2010, after 10 months of exposure, two of the scanned blocks of each material type were retrieved from both shore levels. These blocks were re-scanned using the same procedures and equipment used for the 'before' scans (above). Additional blocks from *Exposure Trial 1* (Chapter 5) were also scanned, as a comparison of the same material types after a longer period of exposure (i.e. 20 months); these blocks were only exposed at MTL.

The procedure used for extraction and analysis of cross-section data from laser scans is shown schematically in Figure 7-18. Scans were obtained as Sterio Lithography 3D objects (.stl format) used with rapid prototyping technology (Figure 7-18a). Scans were initially viewed and edited in the Magics software package (v.12.01, Materialise Group). A 20 x 20 mm area was first cut from the centre of each scan to remove 'bad edges' and to minimise file sizes for easier data handling (D. Masterton personal communication, April 2009; Figure 7-18b). In Magics, the sectioning tool was then used to extract 2D (XY) topographic profiles ('sections') at five different points across the surface of each trimmed scan (Figure 7-18c). Whilst in the majority of cases sections were extracted at equally-spaced intervals across the surface, section locations were manually selected to eliminate the inclusion of barnacles which had settled during field exposure. This was necessary to ensure sections represented the rock surface, rather than 'biogenic topography' (i.e. an autogenic ecosystem engineering effect, see Chapter 3), which was not the subject of this study.



'Index A' roughness = standard deviation (σ) of *Y*

Figure 7-18 Procedure for extraction and analysis of profile sections from laser scans of blocks for calculation of 'Index A' roughness (1 mm scale), after McCarroll & Nesje 1996.

Sections were saved in Drawing Exchange Format (DXF) for subsequent analysis in CAD software (DWG TrueView™ Autodesk®). For the analysis, the 'point-to-point' measurement tool was used to extract vertical (*Y* axis) height difference values at 1 mm-spaced intervals (*X* axis) across the length of each section; the same method was used for larger-scale (> 5 mm) roughness characterisation of the materials described in Chapter 4 using a carpenters profile gauge. For each of the 10 profiles (five extracted from two different blocks), twenty measurements of *Y* (at 1 mm spacing) were made giving a total of 200 height difference measurements (*Y*) for each material type (e.g. Gómez-Pujol et al. 2006; also see Table 4-3). The procedure was repeated for 'before' and 'after' blocks, and for blocks exposed at MTL and MHWN.

7.2.3 Data analysis

The 'Index A' measure of roughness was calculated for each profile as the standard deviation of relative height differences (Y, n = 20) measured at 1 mm-spaced intervals (McCarroll and Nesje 1996; McCarroll 1997; Gómez-Pujol et al. 2006, Figure 7-18c). 'Index A' roughness values for control blocks (0 months) and field-exposed blocks (10 months) of limestone and concrete were then compared using t-tests. Separate tests were done for MTL and MHWN blocks. Although scans of the same blocks were analysed before and after field exposure, the use of markers to relocate cross-section positions was impractical due to their small size, and because of barnacle settlement on the scanned surfaces during exposure (see above). Therefore, two-sample (unpaired) t-tests were used to compare roughness measurements rather than paired t-tests (Burt et al. 2009). Comparisons therefore represented differences in general roughness of the materials before and after a period of field exposure rather than rates of change at specific locations on the block surface; this was adequate as a simple indication of changes in general roughness (and surface heterogeneity) at the scale of interest in the context of this study. Additional comparisons with the same material types (but different blocks) exposed for 20 months at MTL were also made using blocks from *Exposure Trial 1*.

As a further assessment of changes in morphology through time, raw height difference values (i.e. *Y* values in Figure 7-18c) were used to construct frequency histograms. Histograms were used to visualise changes in the frequency of vertical height differences between 1 mm-spaced points (using 0.02 mm bins) after the different periods of exposure. Changes in the frequency distributions of *Y* data represented changes in surface morphology at the selected scale, occurring as a function of intertidal exposure.

7.3 Results

Figure 7-19 shows the roughness (Index A) of limestone and concrete before and after exposure at MTL and MHWN. Limestone was significantly rougher at the mm-scale after 10 months on the mid-shore (Student's t [df = 18] = 2.74, $p = 0.01$) and at MHWN (Student's t [df = 18] = 4.14, $p < 0.001$) (Figure 7-19; Hypothesis 14a, Hypothesis 15 p. 297). In contrast, there was no quantifiable change in surface roughness of concrete blocks at either shore level after 10 months using this method (Figure 7-19; Hypothesis 14a, 14b p. 297). Limestone blocks exposed at MTL for 20 months (as part of *Exposure Trial 1*) were also rougher than those exposed for 10 months (Student's t [df = 18] = 3.72, $p = 0.002$), but no statistically significant changes in concrete roughness were detected after this time (Figure 7-20).

Histograms showing changes in the frequency distribution of vertical height differences at the surface of limestone and concrete after 0, 10 and 20 months of exposure at MTL are shown in Figure 7-21a and 7-21b, respectively. On limestone, the relative frequency of larger height differences increased with exposure time, indicative of progressive surface roughening at a mm scale (Figure 7-21a; Hypothesis 14a p. 297). For concrete, changes in the frequency of vertical height differences through time were less clear (Figure 7-21b; Hypothesis 14b, p. 297).

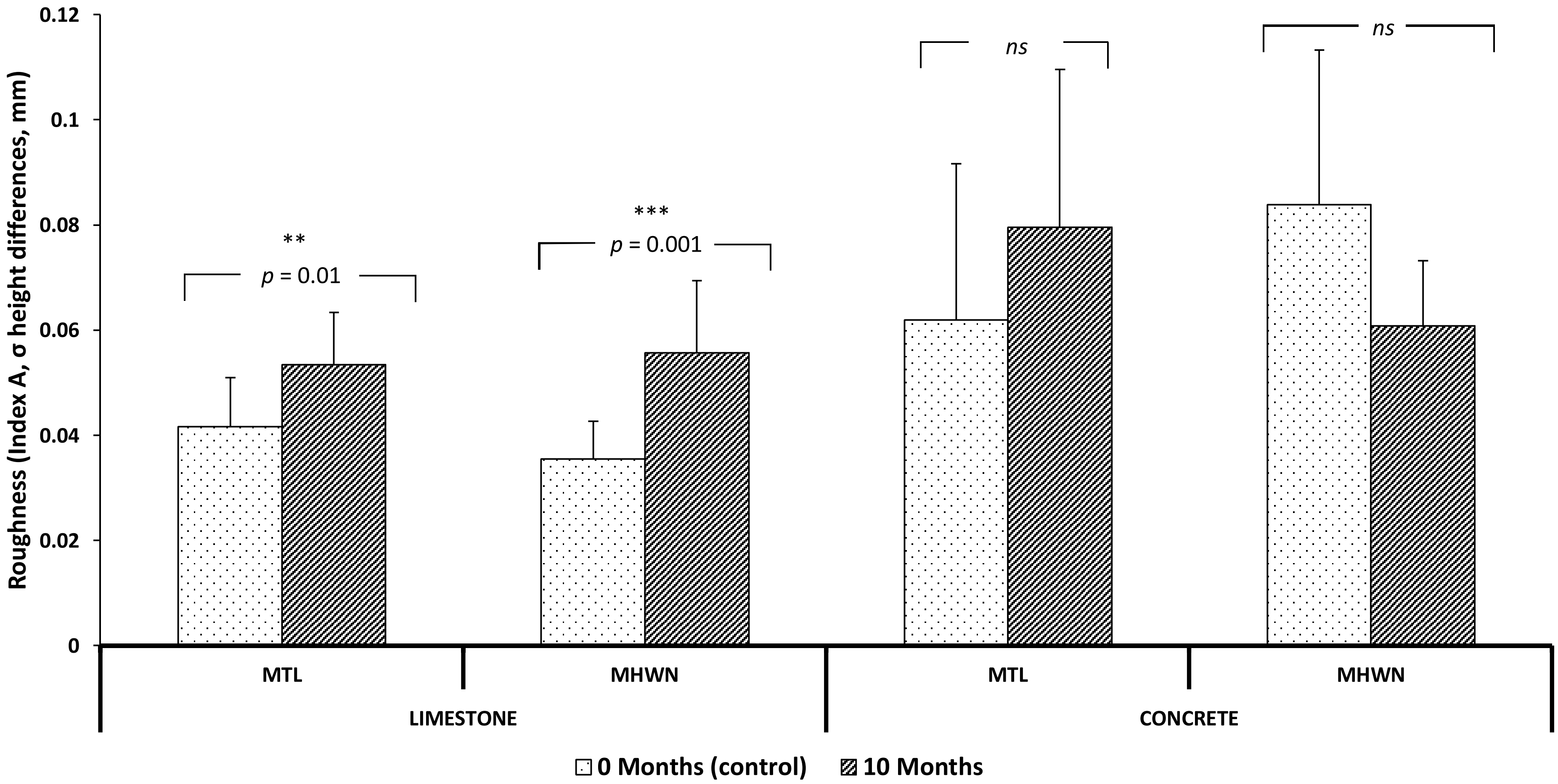


Figure 7-19 Millimetre-scale roughness (Index A, 1 mm intervals) of limestone and concrete exposed for 0 months (control) and 10 months in the intertidal zone (MTL and MHWN), Porthleven, Cornwall, UK (mean + SD, *n* = 10; Student's t-test significance as shown).

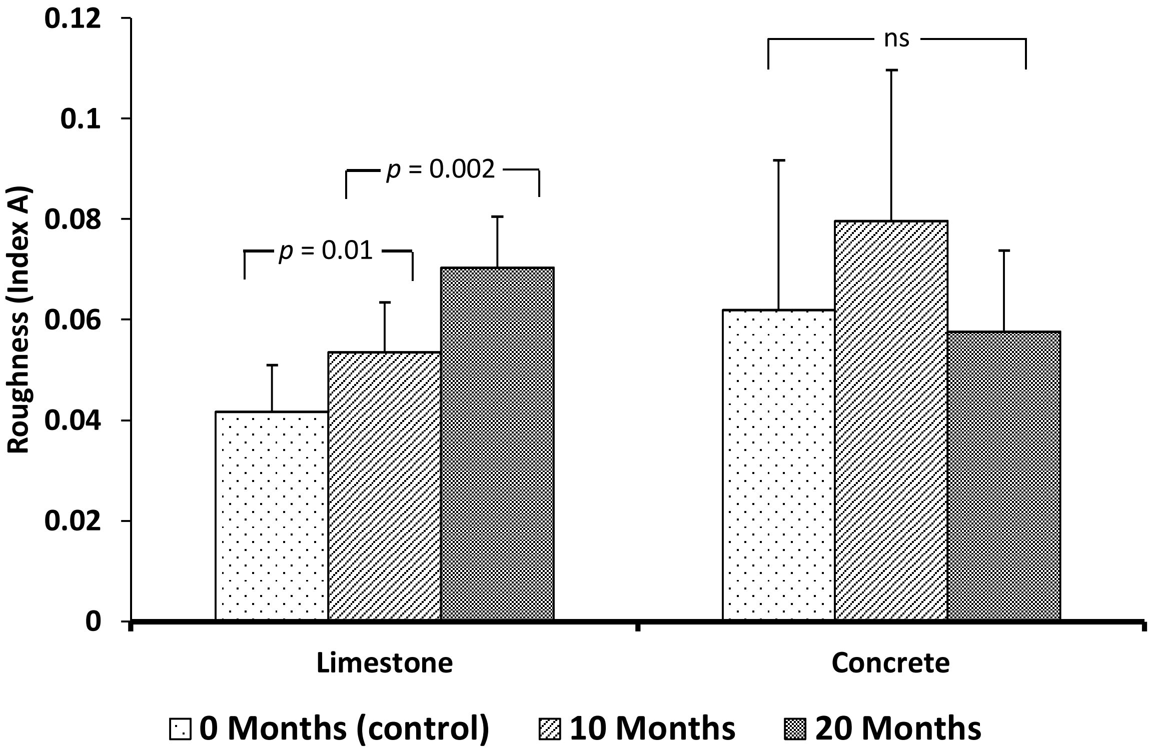


Figure 7-20 Millimetre-scale roughness (Index A, 1 mm intervals) of limestone and concrete exposed for 0 months (control) and 10 months (*Exposure Trial 2* blocks) and 20 months (*Exposure Trial 1* blocks) at MTL, Porthleven, Cornwall, UK (mean + SD, n = 10; Student's t-test significance as shown).

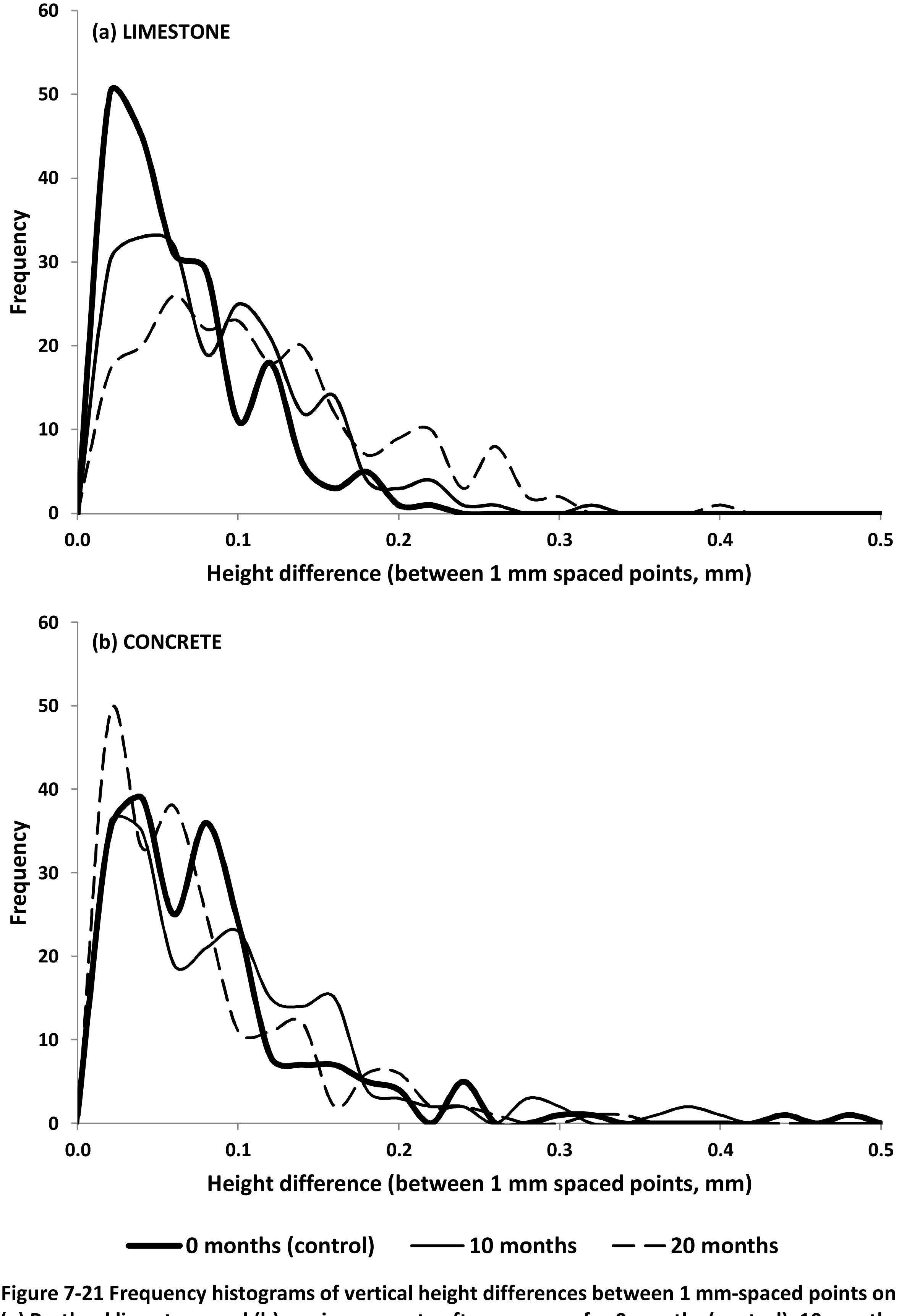


Figure 7-21 Frequency histograms of vertical height differences between 1 mm-spaced points on (a) Portland limestone and (b) marine concrete after exposure for 0 months (control), 10 months (*Exposure Trial 2* blocks) and 20 months (*Exposure Trial 1* blocks) at MTL, Porthleven, Cornwall, UK (*n* = 200 for each time period, 0.02 mm histogram bins).

CHAPTER 7: STRAND 4

Discussion

7.1 Lithological Control on Micro-scale Response

SEM observations (Strand 1 p. 245) showed that the types of microbial growth, and the lithobiontic niche which they occupy, were significantly different between limestone, granite and marine concrete after exposure in the intertidal zone (Strand 1: Hypothesis 9a p. 257). Superabundant occurrences of boreholes at the surface and near-surface of limestone indicated that this material type was dominated by microorganisms occupying the euendolithic niche after just 8 months (Golubic et al. 1981). An average borehole entrance diameter of 5.8 µm is comparable to observations made by Naylor (2001) of boring activity on experimental blocks of Bath Stone exposed for a similar period of time in a temperate intertidal environment in Wales, UK. This suggests the action of a similar suite of microorganisms, namely cyanobacteria (Le Campion-Alsumard 1979; Schneider and Le Campion-Alsumard 1999; Pohl and Schneider 2002; Budel et al. 2004).

In contrast to limestone, endolithic growth forms were totally absent from granite after 20 months, while epilithic forms (colonies of coccoid cyanobacteria and filamentous algae) were always abundant. On concrete, there was evidence of colonisation by both epilithic and endolithic microorganisms, with algae and cyanobacteria cells most commonly observed in association with crusting forms at the surface (Strand 1, see below).

Differences in the nature of microbial colonisation between material types can largely been explained by substratum lithology. Endolithic colonisation of carbonate substrata is common on rocky shores and in the built environment (Strand 1: Section 7.2 p. 246), believed to involve the secretion of acids and/or the sequestration of calcium ions from the rock (Garcia-Pichel 2006). In contrast, non-carbonate materials like granite may be too hard for endolithic colonisation to occur (at least at this scale). The presence of boreholes in the calcitic tests (shells) of barnacles which had settled on granite blocks after installation indicated that differences in niche occupation between material types was a function of lithology, rather than the local presence or absence of micro-boring organisms on the shore.

While microbial colonisation of all materials was rapid, SEM evidence showed that the lithological control on the nature of growth (whether endolithic or epilithic) largely dictated the importance of organic weathering and erosion at this scale. Correspondingly, significant differences in the relative occurrence of organic and inorganic weathering morphologies were observed between material types, both at the surface (Strand 1: Hypothesis 10a p. 257) and near-surface (Strand 1: Hypothesis 11a p. 257). For materials in which organisms were able to establish endolithically (i.e. carbonate substrata) bioerosion was a more important, geomorphologically, compared to inorganic chemical or mechanical process, which are typically more important on non-carbonate rocks (Sunamura 1992). On natural limestone coasts, for example, organisms are widely recognised as dominant weathering and erosion agents, particularly on the mid-shore (e.g. Schneider 1976; Spencer 1988b; Moses and Smith 1994; Spencer and Viles 2002; Gómez-Pujol and Fornós 2009).

Trudgill (1987a) concluded that boring by microorganisms (algae) was the dominant process of erosion of limestone in the mid-intertidal zone on temperate shores in Ireland, while chemical weathering and abrasion were only locally dominant where biological cover was limited. Evidence of mineralogical change within limestone (observed below the upper boring zone) suggested that organic processes were the dominant mode of alteration at the surface during the first two years of exposure, whilst inorganic processes (dissolution and salt weathering) were probably more important deeper within the rock.

While micromorphologies associated with biological weathering were abundant at the mineral surface of concrete, the importance of organic processes below the surface was not as obvious as it was for limestone. Biological activity in association with chemical crusting was, however, extensive on concrete, which had occurred to depths up to 126 μm after 20 months. Whether crusting is a biodeteriorative or bioprotective process was not immediately clear, but may be dependent on exposure time (see Section 7.5.2 below).

The relative contribution of biological processes in the short-term breakdown of harder, non-carbonate materials, which are more commonly used to build artificial coastal structures (CIRIA 2007), is arguably less. Biological activity was sometimes observed in association with detaching rock fragments on granite, but establishing a causal link between the two was not possible given that flaking and cleavage may have resulted from salt weathering (e.g. Chabas and Jeannette 2001; Cardell et al. 2003) or from the preparation technique used on this material (flame texturing). There are few studies of granite weathering in the intertidal zone, but observations of terrestrial granitic rocks also indicate that biologically-mediated breakdown (by microorganisms) is typically restricted to a relatively shallow zone compared to softer, calcareous materials within which endolithic activity is more common (e.g. Mottershead 2000; Schiavon 2002; Hall et al. 2005a).

As well as mineralogical properties, other features of the substrata may have influenced the efficiency of weathering by endolithic microorganisms. Light penetration, for example, plays an important role in the vertical distribution of microorganisms in hard substrata (Matthes et al. 2001). The removal of surface layers of rock by grazers where they occur on the shore therefore facilitates deeper penetration of borers relative to the original surface (Schneider and Torunski 1983; Schneider and Le Campion-Alsumard 1999; Tribollet 2008). The efficiency of bioerosion by boring organisms can also be affected by substratum porosity. Calcinai et al. (2008), for example, concluded that differences in the intensity of boring by the sponge *C. albimarginata* on different types of calcareous substrata could be attributed to variations in porosity. Moses et al. (1995) also suggest that mineralogical and particle size properties of calcareous rocks exert an influence on the distribution and weathering role of microorganisms. On concrete, Giannantonia et al. (2009) also note that porosity is an important control on ‘bioreceptivity’ for microorganisms.

The influence of substratum texture on spatial patterns of organic weathering and erosion has not been examined in detail by geomorphologists, although textural properties associated with crystalline rocks have been shown to influence the nature of colonisation at this scale (e.g. Calcinai et al. 2008). On granite, a positive association between microbial activity (epilithic forms at least) and micro-scale roughness elements was observed qualitatively, with similar influences having been suggested in rocky shore ecology studies (e.g. Wahl 1989; Wahl and Hoppe 2002). Hutchinson et al. (2006) found that occurrences of cyanobacteria and diatoms were higher on granite in association with roughness features, which probably act as favourable attachment sites for cells and as sites of refuge from waves, abrasives, thermal stress and predation (i.e. grazing). Hutchinson et al. (2006) conclude that the fine-scale texture of materials will largely control small-scale (mm) patchiness of biology on hard substrata in the intertidal zone; this may have implications for the micro-spatial variability of organic weathering and erosion on the shore. Grazing is also thought to be an important influence in the distribution and abundance of microorganisms on artificial structures built in the tidal zone (e.g. Bulleri et al. 2000; Chapman 2006; Skov et al. 2010).

Weathering morphologies associated with salt crystallisation and microbes were observed independently on all materials as well as in association (in crusting forms on concrete and limestone for example). Whether microbes enhance mechanical salt action is difficult to say however. Contact between salts and the rock surface may in fact be limited where epilithic growth is abundant (Mottershead et al. 2003), as was observed on granite in this study. Furthermore, biofilms have been suggested to alter the drying regime of stone surfaces, so that salt crystallisation may be reduced (Smith et al. in press, see Chapter 8).

7.1.1 Ecological implications

The influence of inherent material properties (i.e. lithology, porosity and micro-texture) on the distribution and abundance of microbiology on materials used in coastal engineering has important implications for ecological potential. Productivity and biomass, the availability of food resources for grazers and subsequent rates of colonisation by other organisms are inherently linked to biofilm development in the intertidal zone (Connell et al. 1987; Farrell 1991; Viles et al. 2000; Skov et al. 2010). Iveša et al. (2010), for example, observed greater survival of limpets on concrete in Sydney Harbour compared to sandstone because concrete supported a greater abundance of micro-algae and cyanobacteria as a food source. This being said, field experiments discussed in Chapters 5 and 6 suggest that the relative importance of microbiological differences for early colonists may be overshadowed by textural properties of the substratum, at least for barnacles which do not graze on biofilm (see discussions in Chapter 9). Natural (or artificial) variations in substratum texture (at a range of scales) therefore make it extremely difficult to reach absolute conclusions about the ecological (and biodiversity) importance of differences in microbial communities between them, in the absence of texture influences. Examining differences in more ecologically relevant parameters on different construction materials, such as biomass and productivity (e.g. Kaehler and Froneman 2002; Thompson et al. 2005) are needed to help answer these questions.

7.2 Exposure Time

The lithological control on the nature of microbial colonisation and associated geomorphological processes (above) were generally consistent between materials exposed for different lengths of time. There were, however, increases in the occurrence of biological growths on all material types with time (after 20 months), which tallied with higher occurrences of organic weathering and erosion morphologies on limestone and concrete (Strand 1: Hypothesis 9b and 10b p. 257). Initial colonisation of hard substrata is rapid in the intertidal zone (MacLulich 1986) and temporal variations in biofilm abundance and composition have been observed as a function of natural succession on coastal rocks (e.g. Viles et al. 2000; Moschella 2003; Fierer et al. 2010) and artificial substrata (e.g. Lee et al. 2008).

While bioerosion and bio-chemical crusting remained the dominant processes of alteration on limestone and concrete after 20 months, respectively, the vertical extent of modification was significantly deeper compared to 8 month samples (Strand 1: Hypothesis 11b p. 257). Organic structures were also observed deeper within the substrata after this time; although the geomorphological role of cryptoendoliths within the substrata was not immediately clear. Features associated with mechanical weathering (such as subsurface micro-cracking) were also observed at a greater depth in concrete and granite after a longer period of exposure.

Micro-scale ecological and geomorphological responses observed during the first few years of exposure (occurring as a function of lithology) are likely to dictate the nature of geomorphic evolution of these substrata over longer timescales, as well as their durability in an engineering context (see Section 7.5 below). The importance of micro-scale endolithic growth for morphological development of limestone rocks over longer periods of time has been well documented for example (e.g. Torunski 1979; Spencer 1988b; Pohl and Schneider 2002; Gómez-Pujol and Fornós 2009). Given sufficient time, a similar suite of processes can be expected to occur on carbonate materials introduced into the tidal zone for coastal defence purposes (Moses and Smith 1994). These modifications can have important implications for texture, as illustrated in Strand 3, and longer-term ecological potential (see discussion of Plymouth Breakwater in Chapter 9).

Compared to experimental blocks, observations of concrete taken from existing structures in Ilfracombe, Devon, indicated that this material type had been modified to a greater depth after 10 years of exposure (> 600 µm). Weathering depths were, however, different on sheltered and exposed sides of the same structure indicating aspect influences (Appendix 3). Concrete sampled from a > 100 year old wall at Newlyn Harbour had also been modified to a greater depth than experimental blocks, but this was no deeper than 10 year old samples (Appendix 3). Larger-scale deteriorative processes such as surface scaling where, however, more advanced on the older structure. Chemical processes appeared to be more important on *in situ* concrete structures when viewed under the SEM, particularly the subsurface deposition of magnesium compounds (salts and brucite, see Section 7.5.1 below). Whilst concrete mixes used in coastal engineering vary considerably (Section 4.2.3 p. 142), these observations suggested that weathering depth in standard marine concrete increases with time (Allen 1998; Neville 2004; CIRIA 2010), but that these trends may not be linear (see Chapter 9).

In contrast to concrete, granite sampled from a > 100 year old breakwater at Newlyn showed no evidence of weathering and microbial colonisation beyond the immediate surface (Appendix 3). Observations of limestone exposed for more than 180 years on Plymouth Breakwater however suggested that the biogeomorphological response of this material type can be dramatic over engineering timeframes in association with ecological gains (see Section 9.8.1.3 p. 420). These observations indicate that lithological control on the nature of biogeomorphic responses of materials used in coastal engineering persisted over the typical lifetime of a structure, although the importance of this control (relative to ecological influences, for example) may change through time and will vary between material types (see Chapter 9 discussions).

7.3 Spatial Variation

Differences in microbial niche occupation between material types were consistent in space (between plots, shores and tidal heights); limestone was always dominated by endoliths, granite by epiliths and concrete a combination of the two (Appendix 2). After 10 months, there were significantly higher occurrences of growth features on blocks exposed at MHWN compared to those at MTL, although the strength of this trend varied between material types. This variation is probably largely explained by differences in grazing intensity between shore levels and grazing efficiency on the different material types (see Appendix 2).

SEM observations of weathering and erosion features also indicated differences in the intensity of organic and inorganic processes between shore levels (described in Appendix 2). Limestone blocks exposed on the mid-shore had weathered to a greater depth than those exposed at MHWN after 10 months, while bio-chemical crusts on concrete were thicker on blocks placed higher on the shore.

Salt crystallisation and micro-cracking were also observed more frequently, and at greater depths, in blocks exposed at MHWN. These differences corresponded to the relative occurrence of biota and salts, and the frequency of wetting and drying across the shore (Gómez-Pujol and Fornós 2009; 2010, see Appendix 2).

7.4 Seasonality

Materials used for SEM observations were intentionally removed from the shore at the same time of year (January) to ensure comparability between time-steps. It is important to note, therefore, that observations of microbial colonisation represented wintertime communities only, and seasonal variation in the abundance of epilithic marine microorganisms has been well demonstrated. Thompson et al. (2004), for example, proposed a model of reduced photosynthetic activity by microbiota on temperate shores during summer months when both biotic stress (predation pressure from grazing organisms) and abiotic stress (heat and desiccation) are greatest. The opposite processes in winter and early spring (when blocks were removed in this study) typically led to a greater abundance of algae.

The implications of seasonal variations in microbial activity for biological weathering and erosion are not clear, but may influence the spatial and temporal occurrence of epilithic and endolithic activity, as well as the relative importance of bioweathering and bioerosion compared to other chemical and mechanical processes at different scales. Assuming an equal exposure time, for example, the abundance of certain biological growth features observed under the SEM, such as cyanobacteria colonies and algal filaments, may differ on blocks removed in winter compared to summer. This is likely to affect the intensity of grazing (Jenkins et al. 2001) and associated bioerosion at different times of the year. The potential influence of seasonality on the occurrence of organic features in SEM-based biogeomorphological studies is therefore an important consideration.

7.5 Linking Micro-scale Processes and Bulk-scale Properties

In an engineering context, the concept of biodeterioration of building materials is well established in terrestrial environments (see Sanchez-Silva and Rosowsky 2008; Scheerer et al. 2009 for recent reviews). At the coast, it has been suggested that the durability of carbonate-based materials (including concrete) could be compromised by bioerosive organisms such as bivalve molluscs (*Lithophaga* spp.) and boring polychaetes where they occur at high densities, such as in tropical and sub-tropical regions (e.g. Scott et al. 1988; Snow 1988). Morrison et al. (2009), Jayakumar and Saravanane (2009), Jayakumar et al. (2010) have also recently suggested that marine macro-algae are involved in biochemical and biophysical weathering of hard substrata in the intertidal zone.

In contrast, the potential role of marine microorganisms in the deterioration of materials used in coastal engineering has received much less attention. Eglinton (1987) for example, suggests that no microorganisms can exist within concrete, and Thomas and Hall (1992), with reference to sea walls, state that the only material susceptible to organic attack or decay is timber. More recently, halophilic/halotolerant microorganisms have been suggested to accelerate physical and chemical deterioration associated with salt weathering of building stone in supratidal environments (Ortega-Morales et al. 2004; Ortega-Morales et al. 2005) and civil infrastructure such as pilings, breakwaters and seawalls (Ortega-Morales et al. 2010). Javaherdashti et al. (2009) also suggest that sequestration of chemicals from cement by algae can lead to the development of cracks and voids in concrete. There are, however, difficulties linking weathering processes which may involve microorganisms (particularly in the intertidal zone) and changes in bulk material properties – which are of more relevance to engineers. Weathering typically operates over much longer timescales than might be considered in civil engineering (Fookes et al. 1988). More generally, the relevance of fine-scale processes at larger scales is a fundamental challenge in weathering geomorphology (Viles 2001).

In this study, three construction materials used in coastal engineering responded differently to intertidal exposure at a bulk scale (Strand 2: Hypothesis 12 and 13a p. 284). The extent of change, measured using tests of surface hardness, bulk strength, soundness and water absorption, was different between the material types during the first 20 months of exposure (Strand 2: Hypothesis 13b p. 284). Importantly, observations made using SEM (Strand 1) suggested that micro-scale processes can dictate the nature of change at a bulk-scale (Strand 2), even after a relatively short period of time; bioerosion of limestone and bio-chemical crusting of concrete are specifically discussed in this context below.

7.5.1 Bioerosion of limestone

7.5.1.1 Implications for geomechanical properties

The surface hardness of limestone exposed in the intertidal zone was significantly reduced after 20 months (Strand 2: Hypothesis 13a p. 284). This change is attributed to direct removal and weakening of the surface by boring euendolithic microorganisms (Strand 1). Weakening of the surface in this way may facilitate subsequent biological erosion by grazing organisms (Schneider and Torunski 1983; Naylor 2001) as well as increasing the surface area available for chemical reactions, and the efficiency of mechanical weathering on this material type (Trudgill 1976, 1987a).

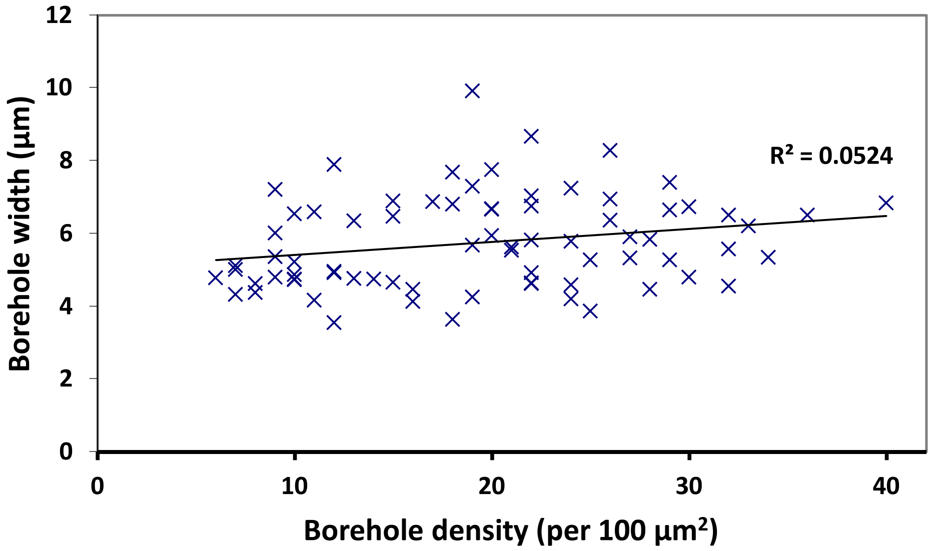
Similarly, the amount of water absorbed by colonised (bored) surfaces of limestone was higher than uncolonised (un-bored) surfaces (Strand 2), which may increase the efficiency of surface weathering processes associated with porosity (Goudie et al. 1970; Sousa et al. 2005; Yu and Oguchi 2009). Whether boring activity facilitates the penetration of seawater beyond the near-surface of rock is not clear, but the occurrence of chloride deposits in inter-oolith spaces well below the zone of boring suggested that the natural porosity of limestone was probably more important than the presence or absence of boreholes for enabling salt penetration and crystallisation at depth (e.g. Goudie 1999). Millimetre-scale pitting of the surface was also observed as a result of µm-scale bioerosion on limestone (specifically discussed below), which may enhance the retention of surface water during low tide, particularly on horizontal surfaces. As well as having implications for weathering, changes in the way materials absorb, retain and lose water in this way has consequences for their suitability as ecological substrata, by mediating physiological stress experienced by epibiota (see Chapter 8).

7.5.1.2 Implications for surface morphology

Where boring of limestone was particularly dense in SEM observations, holes had become coalesced facilitating the collapse and detachment of material from the mineral surface (Strand 1). Coalescence of individual holes may explain the occurrence of much larger perforations than would be expected from micro-boring organisms alone (up to 23 µm wide) and differences in the distribution of hole width data observed after different periods of exposure (e.g. Strand 1: Figure 7-7 p.242). To investigate this relationship further, the density of surface perforations was plotted against their widths. This was done by pairing data of the number (density) and width of holes (measured at the mineral surface) in the same SEM images (Figure 7-22). After 8 months, there was a significant positive relationship between hole density and width (R^2 = 0.0524, n = 75, p = 0.05, Figure 7-22a). Conversely, this relationship was inverted after 20 months (R^2 = 0.1886, n = 75, p < 0.000, Figure 7-22b).

These patterns may be explained by borehole coalescence as a function of time. During initial stages of colonisation, for example, larger (i.e. coalesced) holes will only occur where the density on individual borings is high enough so that they make contact with each other. As colonisation progresses, a greater proportion of the surface will become occupied by larger, but fewer coalesced holes. This model is shown schematically in Figure 7-23.

(a) 8 MONTHS



(b) 20 MONTHS

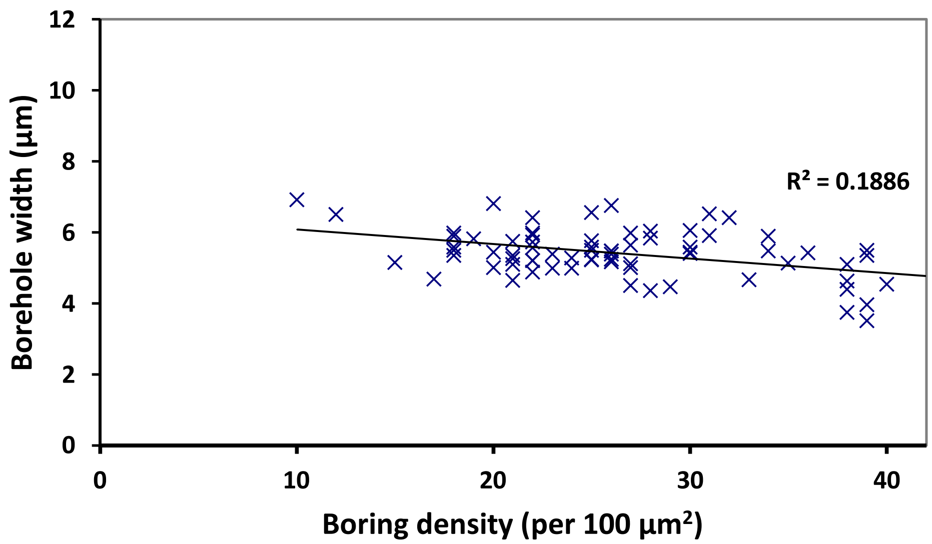


Figure 7-22 Scatter plots of borehole density and borehole width at the surface of Portland limestone after exposure for (a) 8 months and (b) 20 months at MTL in Cornwall, UK (*n* = 75).

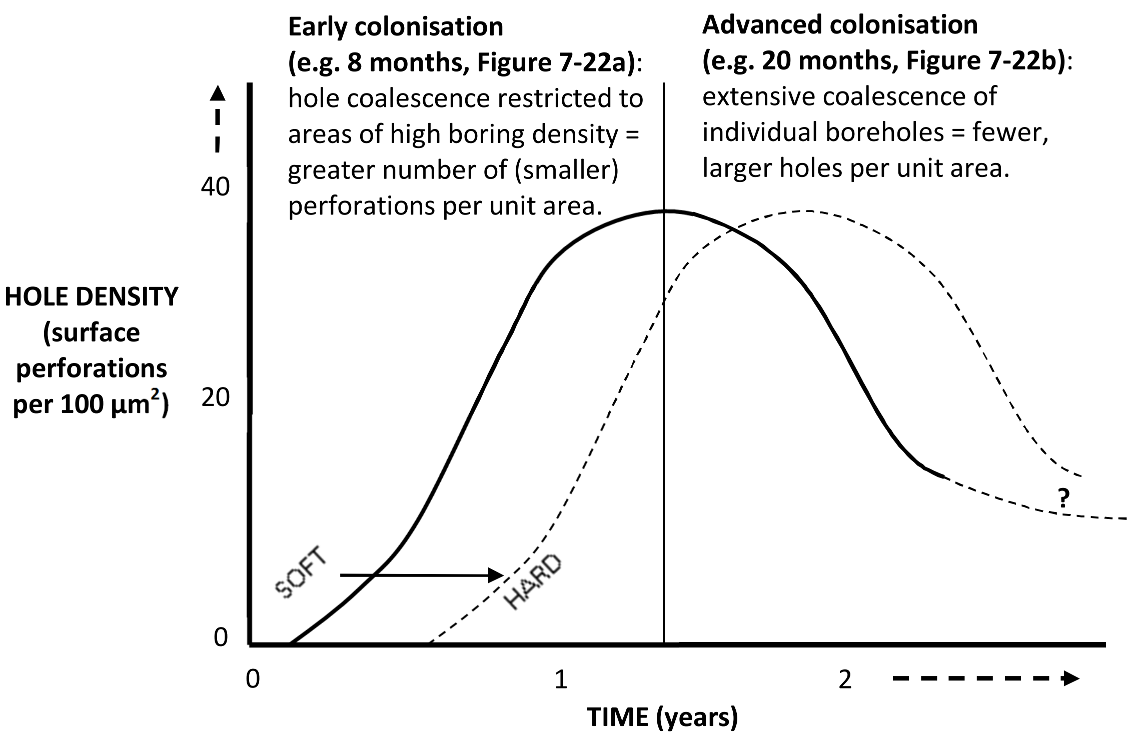


Figure 7-23 A model of early stages of microbial bioerosion and borehole coalescence on carbonate substrata: initially coalescence is restricted to areas of highest boring density, while fewer but larger holes occupy a greater proportion of the surface as bioerosion progresses.

The point at which the relationship between boring density and hole coalescence becomes inverted (e.g. Figure 7-22) may vary depending on the rate of euendolithic colonisation. Boring rates can vary as a function of substratum lithology and hardness (e.g. Strand 4: Section 7.1 above, Figure 7-23), grazing intensity and exposure conditions (e.g. tidal height). The density of borings on limestone blocks exposed at different shore levels, for example, was significantly different after the same period of time (Student's t[df = 78] = 3.61, p = 0.001; Appendix 2) suggesting that shore position strongly influences the nature of micro-scale biogeomorphic interactions. Differences in the rate of boring and hole coalescence may explain variations in textural change of limestone blocks exposed at different shore positions (Strand 3: Figure 7-19; e.g. Gómez-Pujol et al. 2006). A limitation of the model (Figure 7-23) is that relationships between boring and hole coalescence are complicated over longer periods of time because different 'generations' of boring occur where bioerosion is intense (Gómez-Pujol 2006). This can lead to a mosaic of smaller (i.e. individual) boring holes and larger (i.e. coalesced) holes at the surface (e.g. Figure 7-24a-b). A causal relationship between boring density, time and topography may therefore exist, whereby higher ('older') surface are dominated by larger perforations formed from the coalescence of several boreholes, and lower ('younger') surfaces are dominated by smaller, individual borings (e.g. Figure 7-24a-b).

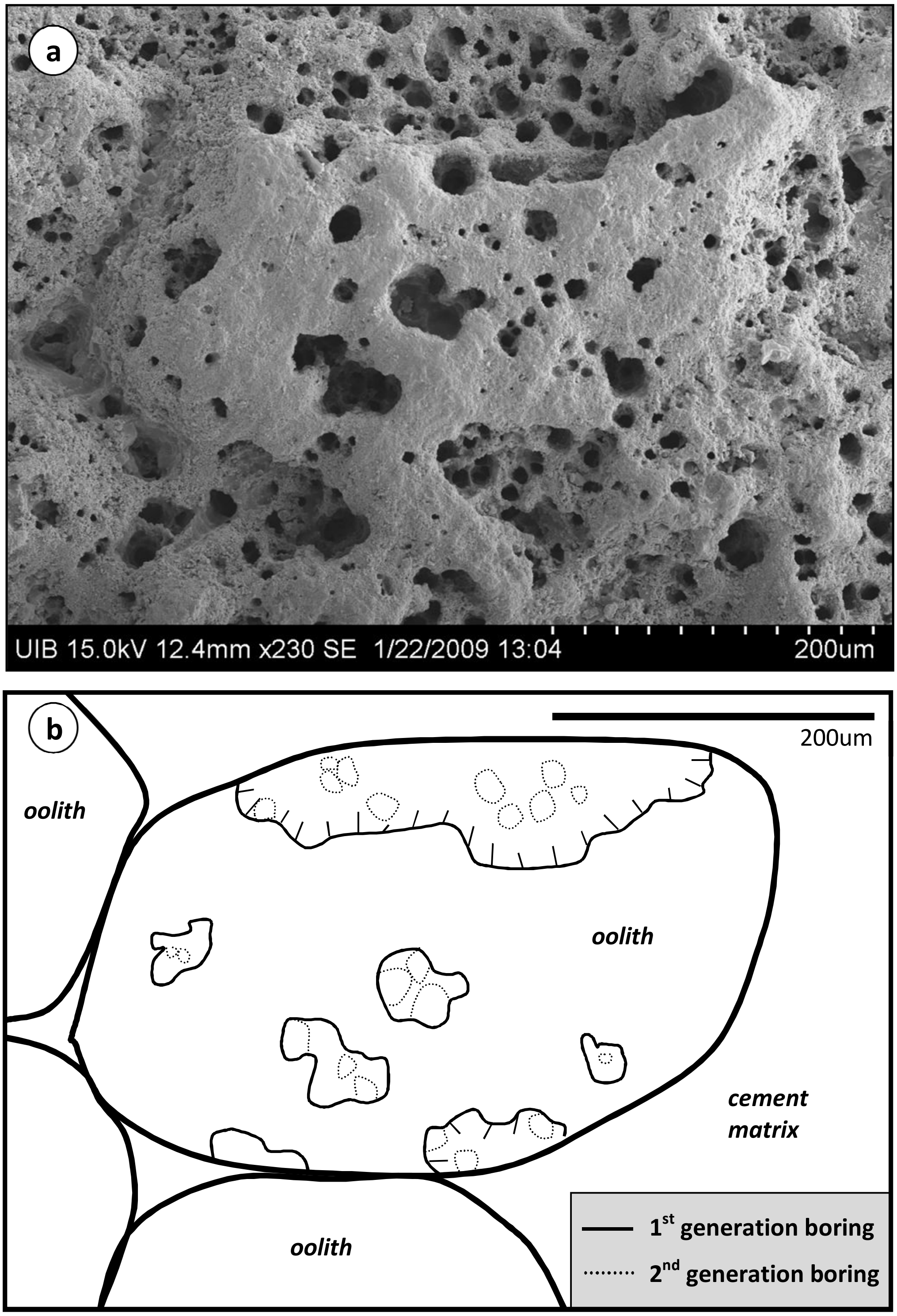


Figure 7-24 (a) SEM micrograph and (b) sketch of generations of boring on Portland limestone after 20 month exposure at MTL.

Morphologically, bioerosion and borehole coalescence was shown to be important on limestone substrata at an ecologically relevant scale (Strand 3). Barnacle cyprids respond positively to µm – mm scale texture (e.g. Crisp and Barnes 1954; Lapointe and Bourget 1999) and as well as a general increase in roughness as this scale, profiles extracted from laser scans showed that the frequency of mm-scale topographic features increased with time during exposure largely as a result of bioerosion on limestone. Weathering processes have been suggested to be important for the generation of ecologically favourable surface complexity on rocky shores (Moschella et al. 2005; Herbert and Hawkins 2006). In this study, the bioerosion of limestone by microorganisms and an associated increase in surface roughness (Strand 3) appeared to facilitate subsequent colonisation of this material type by barnacles (e.g. Strand 3: Figure 7-17 p.264). Although causal links between different morphological scales are difficult to establish (Viles and Pentecost 1994; Viles 2001), other workers have suggested similar µm – mm scale linkages associated with endolithically colonised carbonate rocks (Kobluk and Risk 1977; Danin 1992; Pohl and Schneider 2002); the ecological relevance of these biogeomorphic processes has not previously been recognised however (see synthesis in Chapter 9).

Over longer periods of time, the importance of biological activity in the morphological development of natural limestone shores, at a landscape scale, has been well documented (Spencer 1988b; Gómez-Pujol and Fornós 2009). A similar suite of processes appeared to operate on carbonate materials placed in the intertidal zone. The strength of these relationships will vary on other material types (because lithology largely dictates the strength of biogeomorphic interactions, see Section 9.3), and will vary in time and space (see Sections 9.4 and 9.5). Variations in the spatial distribution and abundance of microorganisms (and associated boring activity), for example, probably explain differences in the nature of bioerosion observed at larger scales (between plots and shores, Appendix 2). Spatial variations in microbial activity in the intertidal zone can result from mineralogical and particle size variations within the rock (Moses et al. 1995; Crispim et al. 2003) and/or environmental factors, such wave exposure and light intensity (aspect), which would have varied between plots and shores (Kobluk and Risk 1977; Naylor and Viles 2002; Thompson et al. 2005; also see Chapter 6).

Weathering leads to topographic change on rock and stone surfaces because both organic and inorganic processes do not progress uniformly in space. Smith and Greenaway (1995), for example, observed spatial differences in rates of downwearing on limestone slabs exposed in Eastern Australia, attributed to fine-scale lithological variations including the presence of shell fragments. Trudgill et al. (1989) made similar observations in their study of weathering of Portland limestone at St Paul's Cathedral, London. While bioerosion was clearly most important, localised downwearing (though solution) of the micrite cement matrix relative to fossil shell fragments on blocks of Portland limestone in this study (which were observed to protrude above the surface in some instances) may have contributed to measured increases in mm-scale roughness after 10 months (Strand 3). On granite, the presence of micro-fractures can lead to fine-scale variations in the efficiency of mechanical weathering processes (Sousa et al. 2005), which may contribute to textural development over much longer timescales (e.g. López-Arce et al. 2010, Chapter 9).

7.5.2 Crusting of concrete

In contrast to a reduction in the hardness of limestone, concrete blocks showed a significant increase in hardness after 8 months exposure in the field (Strand 2). SEM observations showed that this material type was dominated by the development of bio-chemical crusts (Strand 1). Crusting results from reactions between salts in the seawater (particularly magnesium sulphate) and components of the concrete cement paste (mainly calcium hydroxide; Eglinton 1987). This reaction explains the presence of magnesium hydroxide (brucite) along with calcium sulphate (gypsum) within these crusts (Neville 2004; Lee 2007; e.g. Figure 7-10).

It has been suggested that the formation of brucite, which is an expansive mineral, may induce stresses within cement which lead to cracking (Sibbick et al. 2003). Micro-cracking of the concrete cement matrix was observed in this study under the SEM, but this was not found to be spatially associated with crusting or brucite formation, occurring deeper within the substratum. A similar conclusion was made by Lee et al. (2002) in their study of the role of brucite in concrete deterioration in the terrestrial environment. Although a causal link between brucite formation and expansion cracking in marine concrete cannot be ruled out, micro-cracking may equally have been associated with other expansive processes common in intertidal environments such as wetting and drying, heating and cooling, and salt crystallisation (Moukwa 1990; Akman and Özyurt 2002).

Brucite, which develops as an insoluble precipitate, can also seal pores and reduce rates of leaching and the subsequent penetration of seawater into marine concrete (Neville 2004). Pore-infilling associated with crust development, which can also occur through the precipitation of secondary calcite within calcareous substrates (e.g. Moses and Smith 1994; Pentecost and Whitton 2000), therefore probably explains the increase in surface hardness of concrete after 8 months in the field. Similarly, bio-chemical crusting may explain an initial reduction in the water absorption capacity of concrete (e.g. McCabe et al. 2011). Buenfeld and Newman (1986) suggest a similar process is involved in the development of stable ‘skins’ on concrete exposed to seawater, and Moukwa (1990) suggests that the formation of mineral ‘additives’ within marine concrete once exposed to seawater may strengthen the paste-aggregate interface. These kinds of changes, involving both chemical and biological processes, are comparable to case hardening and weathering rind development on terrestrial rocks at larger scales (e.g. Etienne 2002; Viles and Goudie 2004; Gordon and Dorn 2005).

Recent research has further demonstrated the potential benefits of biological colonisation in concrete for engineering durability (Decho 2010; De Muynck et al. 2010; Ortega-Morales et al. 2010). Achal et al. (2010, 2011), for example, report that concrete inoculated with a bacterium culture showed a reduction in porosity and an increase in strength, attributed to calcite cementation and pore-filling by the bacteria. The performance of ‘microbial concrete’ in different weathering simulations compared to standard concrete mixes remains to be tested. In addition to hardening effects, epibiota may also consume close-surface oxygen before it is able to diffuse deeper into concrete and become involved in chemical reactions, thereby reducing the rate of deterioration in the marine environment (Comité Euro-International du Béton 1992). Biota may be also regulate near-surface temperatures of construction materials, which may have bioprotective implications (English Heritage 2010; Sternberg et al. 2011); this requires further investigation in the context of coastal structures.

Crusting forms were also observed on limestone, although bioerosion was clearly a more important control on surface hardness for this material type (Strand 4: Section 7.5.1 above). Crust-like deposits were also sometimes observed on the surface of limestone, which may not necessarily denote alteration of the original surface as was evident for concrete. Such surface crusts on limestone have, for example, been suggested as an explanation for apparent 'accretion' measured using the Micro Erosion Meter (MEM) on terrestrial stone (e.g. Trudgill et al. 1989; Smith and Greenaway 1995).

7.5.3 Time, space and engineering durability

There are very few comparable studies measuring changes in the surface hardness (as opposed to bulk strength, see below) of intertidal rocks with time, but the Equotip has been used to detect differences occurring as a function of tidal exposure (Takahashi et al. 1994; Matsukura and Takahashi 2000). Aoki and Matsukura (2007) for example found a correlation between Equotip hardness and the depth of tafoni depressions on a sandstone masonry wall in the tidal zone in Kyushu, Japan. This suggests that the differences in hardness measured through time in this study (in which microorganisms were involved to some extent on limestone and concrete, Strand 2) reflected changes in the susceptibility of the materials to subsequent intertidal weathering processes.

Whilst the processes inferred from SEM observations may explain measured changes in hardness and water absorption of limestone and concrete, no detectable changes in bulk strength were measured using the Point Load Test. The importance of weathering for bulk strength reduction of intertidal rocks has, however, been demonstrated using the Schmidt hammer. The Schmidt hammer was not appropriate here given the size of the experimental blocks (Goudie 2006a; Viles et al. 2011), but

Stephenson and Kirk (2000b) measured strength reductions (up to 50 %) of mudstone and limestone rock platforms of the Kaikoura Peninsula, New Zealand, using this device, which they attributed to subaerial weathering. Chelli et al. (2010) also attributed a 15 % strength reduction of limestone and dolomite platforms in Italy to weathering, which included bioerosion by microorganisms.

Scott et al. (1988) suggested that bioerosion by macro-organisms (*Cliona*, *Lithophaga* and polychaetes) had reduced the strength of limestone and concrete blocks used to build artificial reefs in Discovery Bay, Jamaica, after 13 years in the sea. They found that boring activity was more spatially uniform in limestone than concrete, which varied in relation to the presence of aggregates. Similar observations were made in this study, where boring was intense across the whole surface of experimental limestone blocks, but more patchy on concrete. In an ecological context, Scott et al. (1988) note that the number of bioeroding species was always higher in limestone than concrete, suggested to relate to the relative $CaCO_3$ content of each material type (e.g. Strand 4: Section 7.1 above). In contrast to superficial bioerosion by microorganisms observed in this study over 2 years, macro-borers are of more concern for coastal engineering, particularly within reinforced concrete structures, as they can expose steel reinforcing and lead to rapid deterioration from sulphate attack (e.g. Snow 1988).

What is clear is that relationships between micro-scale biogeomorphological processes and bulk-scale properties observed are not simple. For example, while concrete absorbed less water after 8 months (associated with bio-chemical crusting and an increase in surface hardness), water absorption increased dramatically after 20 months (Strand 2: Section 7.3.4). The relationship between crusting, hardening and water absorption of concrete was not, therefore, linear with time. Degradation may have continued below the surface crusts after 8 months, through chemical dissolution of the cement paste for example (Allen 1998; Neville 2004; CIRIA 2010; e.g. Figure 7-8d). 'Core softening' is a similar processes sometimes associated with case hardened rocks (Dorn 2004), which involves an increase in subsurface pore-space but retention of the hardened surface. Over much longer periods of time (> 100 years) this process may lead to surface scaling, such as that observed on older concrete structures at Newlyn (Appendix 3).

Limestone geomorphological responses were also non-linear. Surface hardness, for example, was lower than controls after 8 months, but this was only significant after 20 months of exposure. Water absorption had increased significantly after 8 months, but was no different a year later (Strand 2). Pohl and Schneider (2002) proposed a model of endolithic colonisation on carbonate substrata, whereby colonisation is initially destructive as organisms actively penetrate the surface, but which subsequently stabilises the surface through binding effects. With reference to terrestrial stone, Hoppert et al. (2004) also suggest that endolithic microbial activity stabilises and strengthens the colonised surface after a few years, as an adaptive (evolutionary) strategy that 'protects' the growing medium (the rock surface in this instance). This relationship is complicated in the tidal zone where other inorganic weathering processes are typically more intense compared to terrestrial environments. Studies of marine bioerosion do, however, indicate that initial rates of penetration may be high on 'fresh' substrata, but become reduced after a period of months – years (e.g. Rutzler 1975; Kobluk and Risk 1977). Observations of the experimental blocks over a longer period of time are required to test this model.

While the hardness of limestone and concrete varied over a time-frame of months, detectable changes in bulk material strength resulting from weathering may only occur after several decades (Fookes et al. 1988). It is worth noting, however, that deterioration of concrete can be particularly rapid in the tidal zone (e.g. Novokshenov 1995). Rock and stone can also deteriorate episodically and catastrophically after a period of relative stability (Smith et al. 1994; Smith and Viles 2006). Rock armourstone used in coastal structures may degrade in a similar fashion, but over longer timescales (Latham 1991). Geomorphological concepts of equilibrium, sensitivity and threshold response (e.g. Howard 1965; Chorley et al. 1984; Brunsden 2001) can be employed here, which might predict that small-scale changes in surface hardness operate during initial years of exposure (as reported in

Strand 2) until a certain threshold is passed sufficient to give rise to a measurable change in bulk strength. The involvement of organisms in these temporal relationships has not been studied in a coastal engineering context, or more broadly in rock coast geomorphology (e.g. Sunamura 1994). The length of time before such a threshold is passed will largely depend on inherent durability properties of the particular material in question (a function of lithology), the weathering history of the material and the particular conditions under which it is exposed (Fookes et al. 1988; Fookes et al. 2005; CIRIA 2007; McCabe et al. 2007).

On granite, there were no detectable changes in hardness over the time-frame of the experiment (20 months). There was an overall reduction in soundness of the materials through time (measured using ultrasonic velocity tests), but this was only significant for granite. However, soundness data were highly variable on granite (Strand 2: Section 7.3.3) and are treated with some caution; this material type was heavily encrusted with barnacles during exposure (a function of its initial roughness, see Chapter 5 and 6) which probably influenced the reliability of ultrasonic measurements of field-exposed blocks. Indeed, granite is known to retain its highly durable properties over a time-frame of decades and centuries in the marine environment (Latham et al. 2006), although there are always exceptions (e.g. Clark and Palmer 1991).

Changes in bulk strength (such as those measured using the Schmidt hammer or Point Load Test) are of more immediate relevance at an engineering scale. Although some physical properties of construction materials relevant for the operation of subsequent weathering processes (i.e. hardness, water absorption and surface roughness) changed fairly rapidly in this study, the importance of these properties for engineering performance and durability at larger spatial scales and over longer temporal scales was less clear. Water absorption, which was altered over a period of 20 months, is however considered the best single indicator of durability in an engineering context (Latham et al. 2006). Bulk strength increases observed in concrete inoculated with bacteria have also been measured over a timescale of months (Achal et al. 2010), although the procedure involved colonisation throughout the entire concrete matrix rather than just in surface layers, as was the case here. The involvement of microorganisms in bioerosion of limestone and crust formation on concrete are considered unlikely to be of any concern at an engineering scale over the typical lifetime of a defence structure (50 – 100 years; British Standard 6349; W. Allsop personal communication 2009, Appendix 3). These processes do, however, have implications for the ecological potential of the materials through texture development (Strand 4: Section 7.5.1.2 above) and the regulation of micro-climatic conditions at their surface (see Chapter 8).

7.6 Summary

SEM observations showed that significant differences in biological and geomorphological responses of construction materials at a micro-scale were largely a function of lithology (Strand 1). Colonisation by endolithic microorganisms and associated bioerosion dominated change at the surface and near-surface of limestone blocks regardless of exposure time and location. Colonisation of granite was restricted to the epilithic niche, with some limited evidence of modification by inorganic weathering processes. Concrete showed a combination of epilithic and endolithic colonisation, including an association between microbial activity and the formation of bio-chemical crusts.

Micro-scale biogeomorphological features are suggested to relate to changes occurring at a bulk-scale to varying degrees, depending on material type (Strand 2). Bioerosion of limestone was associated with a reduction in surface hardness and an increase in water absorption capacity. At the same time, extensive bioerosion and borehole coalescence resulted in roughening of the substrata at a spatcial scale known to of importance for a common intertidal organism (i.e. barnacles, Strand 3); more detailed measurement of three-dimensional textural parameters would be particularly valuable to further explore linkages between bioerosion and morphological change. On concrete, bio-chemical crusting was associated with an increase in surface hardness and an initial reduction in water absorption. Water absorption increased significantly, however, after a longer period of exposure. Changes in material properties were not, therefore, linear through time. These observations demonstrate the difficulties of isolating specific weathering and erosion processes, whether organic or inorganic, erosive or protective, which may be acting in combination to varying degrees and at different spatial and temporal scales (Viles 2001).

Whilst changes in some material properties occurred relatively quickly on limestone and concrete, only the material surface and near-surface was altered; bulk strength did not change for any material type during the 20 month experiment. SEM observations of samples taken from older structures (Appendix 3) suggested that short-term biogeomorphological responses were largely consistent with those occurring over longer periods of time. Associations between micro-scale colonisation and bulk-scale changes in surface hardness, water absorption and surface morphology (roughness) may alter the susceptibility of the materials to subsequent geomorphological processes, and the nature of their behaviour as biological substrata (see Chapter 8). However, these changes probably have only limited implications for engineering durability in the intertidal zone over the typical lifetime of a structure (100 years).

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CHAPTER 8

GEOMORPHOLOGICAL RESPONSE (B): SUBSTRATUM WARMING – DRYING BEHAVIOUR

Simulating intertidal conditions, geomorphological and ecological implications

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CHAPTER 8. GEOMORPHOLOGICAL RESPONSE (B): SUBSTRATUM WARMING – DRYING BEHAVIOUR

Simulating intertidal conditions, geomorphological and ecological implications

8.1 Introduction and Aims

This chapter describes work based on traditional geomorphological weathering simulations to characterise the warming-drying behaviour of the materials used in the work described in the previous three chapters (Chapters 5 – 7) under simulated intertidal conditions; 'warming-drying' is used throughout to collectively refer to warming-cooling and wetting-drying processes. Specifically, the implications of the physical changes described in Chapter 7 for the warming-drying behaviour of the materials were of interest. Results are discussed in a weathering context and with reference to the materials as substrata for colonising organisms. Geomorphological approaches to understanding the physical behaviour of rock and stone have rarely been applied in intertidal ecology. The ways in which different materials used in coastal engineering behave when exposed to air and heat is therefore a component of ecological potential that has not previously been explored in detail (see Table 2-11 p. 91). Furthermore, alteration of substratum behaviours of relevance to weathering and colonisation (e.g. rates of warming and near-surface micro-climatic conditions) as a result of intertidal exposure are examples of biogeomorphic feedbacks (or 'consequences') which have not typically been considered in biogeomorphic and ecosystem engineering studies in this environment (see Section 3.2.2 p. 109).

Specific research questions and hypotheses examined are shown in Table 8-1. The study was not intended as a weathering simulation (i.e. rates of breakdown were not the primary concern, although this was broadly considered), but aimed to design and test procedures for examining the warming and drying behaviour of different materials under intertidal conditions (in the laboratory and in the field), before and after a period of colonisation and weathering in the field. The implications of these behaviours for geomorphology and ecology were specifically considered.

Table 8-1 Chapter 8 Research questions and hypotheses (see Table 3-2).

	Research Question	Hypothesis
Chapter 8: Substratum Warming-Drying Behaviour		
16.	How does the warming-drying behaviour of construction materials very under intertidal conditions?	(16a) Warming-drying behaviours vary between material types under simulated and field intertidal conditions. (16b) Warming-drying behaviours are altered after a period of colonisation and weathering in the field.
17	What are the implications of substratum warming-drying behaviour for weathering and erosion, and colonisation?	N/A [Discussion]

8.2 Rock Weathering and Laboratory Simulation

Intertidal rock platforms are subject to a complex physical, chemical and biological weathering regime involving continuous cycles of wetting and drying, and heating and cooling in the presence of salts, waves, abrasives and often abundant biology (Sunamura 1992; Trenhaile 2002; Naylor et al. 2010). Materials used to build coastal structures positioned in the intertidal zone are subject to similar geomorphological processes (e.g. Takahashi et al. 1994; Mottershead 1997, 2000; Matsukura and Takahashi 2000; Mottershead et al. 2003).

The effects of heating and cooling (thermoclasty), wetting and drying (slaking) and salt weathering (haloclasty) processes have received considerable attention within geomorphological research in relation to the breakdown of natural rocks and urban stone decay (e.g. Hall and Hall 1996; Smith and Warke 1996; McGreevy et al. 2000; Viles 2003; Smith et al. 2008). Differential and repeated mineral expansion and contraction (fatigue effects) are mechanisms implicated in the gradual weakening of rock and stone (Yatsu 1988; Hall 1988; Searle and Mitchell 2006; Gómez-Heras et al. 2006).

Whilst the work described below was not specifically designed as a weathering study (see Section 8.1), the techniques used were developed from a long history of weathering simulations in geomorphology. Laboratory-based simulations have proved fruitful for our understanding of how different rock types respond to mechanical weathering processes involving insolation, moisture, frost and salt (see review by Goudie 2000). In the laboratory, materials can be exposed to consistent and comparable environmental regimes by controlling the period and intensity of heating, moisture application, air movements and shading (see Section 8.2.1 below). This is particularly useful given that these factors vary considerably in time and space under natural field conditions (e.g. Jenkins and Smith 1990; Halsey et al. 1998; Viles and Goudie 2000; Gómez-Heras et al. 2006). The co-influence of moisture and heating on thermal behaviour is difficult to study, particularly in the intertidal zone where the deployment of temperature sensors is challenging (Harley 2008). A fundamental benefit of lab-based simulations, therefore, is the potential to isolate the effects of different mechanisms from each other – although the limitations of such experiments in replicating field conditions must equally be recognised (Smith et al. 2005).

The importance of rock properties relating to water uptake was recognised in early salt weathering studies (Evans 1970; Goudie et al. 1970; Cooke 1979) and these findings are particularly relevant to materials in the intertidal zone which are frequently immersed in saltwater. McGreevy (1982, 1985b) also notes the influence of surface colour (closely related to albedo, discussed below), thermal conductivity and specific heat capacity on rock surface temperatures. These properties define the exchange of thermal energy between the substratum and the external environment, as well as within the material itself. A dark coloured (low albedo) material such as basalt, for example, with a low specific heat capacity is expected to reach higher temperatures than a light coloured rock (high albedo) such as chalk with a high specific heat capacity when exposed to the same insolation conditions (McGreevy et al. 2000).

Albedo relationships are not always simple, however. Using different coloured bricks Hall et al. (2005b), for example, observed instances where lighter surfaces reached higher temperatures than darker replicates. These observations were interpreted as an artefact of differential rates of heat loss during cooling phases. Most materials also have different colour and albedo characteristics when wet compared to their dry state, which can further influence temperature gain and loss through time (e.g. Levinson and Akbari 2002). Furthermore, studies in terrestrial environments have shown that changes in the surface colour of building stone as a result of soiling and biological growth can have significant effects on the surface and near-surface thermal regimes of construction materials (McGreevy et al. 2000; Searle and Mitchell 2010). Warke et al. (1996), for example, found that soiled stone had higher maximum surface temperatures, sharper internal temperature gradients and faster rates of heat gain and loss. Importantly, the same workers found that the relative influence of soiling was not the same between different material types. Colonisation of granitic rocks by lichen have also been shown to change their reflectance (and hence albedo) properties (Satterwhite et al. 1985).

Given that the surface colour of coastal rocks changes as they are colonised by microorganisms (e.g. Viles 1987b; Viles et al. 2000), biological growth at this scale (see Chapter 7: Strand 1) may influence thermal behaviour. Albedo is not, therefore, a fixed factor in the intertidal environment, but changes over the tidal cycle in response to drying and over longer time-scales (days, months and years) in response to discolouration and biological colonisation. The potential interaction of these effects is likely to be complicated, and has not been previously studied in a tidal context.

A further consideration for intertidal rocks and construction materials is that any period of weathering results in modification of physical properties to some extent, such as changes in mass, strength and water absorption (e.g. Latham 1991; Latham et al. 2006, see Chapter 7: Strand 2 for specific discussions). As well as changes in colour (above), the grain cohesion and porosity of rocks are altered by weathering, which may have implications for wetting-drying and heating-cooling (e.g. Tuğrul 2004; McCabe et al. 2011). Weathered rocks generally exhibit an increase in porosity and water holding capacity than unweathered rocks (Fookes et al. 1988). This was true for limestone and marine concrete after 20 months in the field (Chapter 7: Strand 2). If weathered materials absorb and retain more moisture when immersed, they may be expected to remain wet and cool for a longer period of time when exposed at low tide.

Compared to salt weathering and thermal effects, far less attention has been given to the process of wetting and drying (slaking) as a weathering mechanism. Slaking is believed to function through rock expansion and contraction during the absorption (and adsorption in the case of surface films) and desorption of water (Hall and Hall 1996; Trenhaile 2006; Sumner and Loubser 2008). In their studies of wetting and drying of sandstone and dolerite, Hall and Hall (1996) and Sumner and Louber (2008) showed that rock breakdown can occur as a function of wetting and drying alone, in the absence of salts. Kanyaya and Trenhaile (2005) and Trenhaile (2006) also used a MEM to measure expansion and contraction of sandstone, basalt and argillite slabs (up to 0.14 mm) when subjected to a simulated tide cycle (see Section 8.2.1). Samples of the same rock types also showed variations in moisture content during the experiments (Trenhaile 2006).

All of these studies indicate that inherent differences in water absorption properties, thermal capacity and albedo mean that the range of materials placed in the intertidal zone through coastal development are likely to demonstrate very different behaviours under the same warming and drying conditions. Material type is therefore likely to influence micro-environmental conditions at the material-air interface (Warke et al. 1996). These differences, and how warming-drying behaviours are altered once exposed under tidal conditions, will have implications for subsequent weathering process (e.g. Rodriguez-Navarro and Doehne 1999; Goudie 1999; Angeli et al. 2010). More importantly in the context of ecological potential, ways in which construction materials warm-up and dry-out have been suggested as factors influencing the survival and reproductive success of organisms colonising their surfaces (see Section 8.3 below), yet quantitative data of warming-drying behaviour under intertidal conditions has rarely been collected.

8.2.1 Experimental procedures

Both field and lab-based studies of rock and stone temperature have been biased towards 'extreme' climates (very hot or very cold) where mechanical responses to large temperature fluctuations are thought to play an important role in weathering through fatigue and stress effects (including 'thermal shock'; e.g. Cooke 1979; Smith and McGreevy 1983; McGreevy et al. 2000; Zhu et al. 2003; Viles 2005). Much less attention has been given to the thermal behaviour of rocks under temperate climate regimes, where mechanical weathering is assumed to be less efficient (Goudie 1993). Exceptions include the 'cool air' conditions simulated by Warke et al. (1996), and Tingstad (2008) who replicated temperate conditions (7 – 20°C) in an environmental chamber.

For simulations incorporating moisture, saline solutions are commonly used but the type of solution and application procedure has not typically reflected those occurring in the field (Smith et al. 2005). For example, the relative influence of different salts in weathering has been assessed using saturated solutions (e.g. Goudie et al. 1970; Yu and Oguchi 2009) which may only occur in specific, extreme environments (such as on the margins of desert salt pans for example, e.g. Viles and Goudie 2007). Moisture and salt is usually applied either as a spray or by immersing samples in solution for an arbitrary amount of time (e.g. Goudie et al. 1970; Goudie 1974; Cooke 1979; Smith and McGreevy 1988; Tingstad 2008; Yu and Oguchi 2009). The procedure used to apply moisture determines the amount of water the sample can take-up and the degree of saturation attained during the experiment (Hall 1988; Hall and Hall 1996; Sumner and Loubser 2008). The type of salt used, the saturation of the solution, its application method and the drying regime used (see below) all, therefore, influence the nature and rate of alteration and breakdown (Ruiz-Agudo et al. 2007; Gómez-Heras and Fort 2007; Yu and Oguchi 2009; Angeli et al. 2010). Further complexity arises because the relative importance of each of these variables may vary between material types (Smith et al. 2005; Smith et al. 2008).

The use of seawater in weathering studies is altogether less common. Seawater contains a mix of salts which hydrate readily and therefore generate hydration pressures alongside haloclastic responses (Mottershead 1982). The efficiency of seawater in salt weathering is expected to be less than solutions made from particular salts, although appreciable breakdown has been recorded using seawater in laboratory simulations (e.g. Goudie 1974). Mottershead (1982) used a cycle of 1-hour immersion – 23-hour drying using seawater in his study of greenschist weathering. Tingstad (2008) reported limited breakdown of Carboniferous limestone fragments periodically sprayed with seawater during a short-term (28 days) simulation of cliff weathering, although micro-scale weathering artefacts were observed using SEM. Weathering simulations undertaken during the European Shore Platform Erosion Dynamics (ESPED) project (Foote et al. 2000) used synthetic seawater to compare the susceptibility of different platform rocks to tidal weathering, although warming-drying behaviours were not measured (Moses 2001).

Only a handful of workers have attempted to measure weathering under full tidal conditions in the laboratory. Kanyaya and Trenhaile (2005) and Trenhaile (2006) examined slaking processes using tidal simulation, but used freshwater rather than seawater to control for the presence of salts. The limitation of these studies is that the wetting and drying behaviour of rocks may function differently in saline solutions compared to freshwater. Other dissolved ions in seawater may also be involved in chemical weathering processes which are not simulated using freshwater. Yatsu (1988), for example, suggests that the higher surface tension and viscosity of salt water may result in less being absorbed upon immersion. Physical changes in rock properties involving salts, such as water absorption capacity or crusting, may also alter the way materials dry-out due to accumulation of salts in surface pores (Yatsu 1988, also see discussions in Chapter 7). Rates of thermal flux from the surfaces of materials immersed in fresh and salt water have also been shown to vary (Zhu et al. 2003). The author is aware of only one experiment where (synthetic) seawater has been used to quantify rock responses under tidal conditions. Porter and Trenhaile (2007) measured surface expansion of rock due to salt crystallisation over one 12h semi-diurnal cycle, both in the lab and in the field; thermal and drying behaviour of the rock was not, however, assessed.

More generally, important developments have been made in trying to best replicate field conditions in laboratory simulations (McGreevy et al. 2000; Smith et al. 2005). These include sealing rock samples to restrict the movement of moisture through one face (Smith and McGreevy 1983) and, similarly, insulating samples to better simulate unidirectional thermal transfers occurring within *in situ* rock masses (e.g. McGreevy 1985b; Warke et al. 1996; Carter and Viles 2004). Importantly, McGreevy (1985b) and Warke and Smith (1998) strongly advocate the use of direct heating methods (such as infrared lamps) in lab-based simulations, which replicate field conditions far more effectively than indirect heating methods (such as oven-based heating). Indirect methods of heating induce changes in material temperature as a function of the surrounding air, but not the thermal properties of the material (Warke and Smith 1998). Heating using lamps induces warming both by raising ambient air temperature, and by direct adsorption of thermal energy at the surface of the test sample; lithological controls on thermal behaviour, such as albedo, can therefore operate.

Using a direct heat source also allows some component of insolation variability to be incorporated into the experimental design using shading. In their study of limestone, sandstone and marble weathering (under terrestrial conditions), for example, Warke et al. (1996) employed a rotating blade to periodically interrupt the heat source as a way of simulating passing cloud. More simply, Warke and Smith (1998) used electric timers to switch lamps on and off during the course of their experiments to simulate periods of shading.

Whatever experimental procedures are employed, the collection of some field data is imperative for laboratory weathering simulations to evaluate the extent to which the simulated regime replicates natural conditions and, ideally, to validate the data collected wherever possible (Smith et al. 2005).

8.3 Ecological Importance of Substratum Warming – Drying Behaviour

Although there is some reference to the role of rock temperatures in terrestrial ecology, including plant (Rejmánek 1971), invertebrate (Dean and Turner 1991) and reptile (Litzgus and Brooks 2000) populations, the influence of substratum temperature on intertidal communities has largely only been inferred (see Table 2-11 p. 91). This is surprising given that environmental stress gradients (such as temperature and moisture) are a keystone concept in intertidal ecology (Hutchins 1947; Wethey 1983, 1984; Menge and Olson 1990; Harley and Helmuth 2003). Early rocky shore ecology research acknowledged the importance of heat and desiccation tolerance in spatial zonation (Hutchins 1947; Southward 1958; Newell 1969; Foster 1971). Species adapted for (or tolerant of) longer periods of exposure can colonise higher on the shore, while others are limited to the low shore – where they may only be exposed to the air occasionally at very low (spring) tide (Raffaelli and Hawkins 1996). The abundance, mortality and reproductive success of a species can be expected to decrease towards the edges of these spatially defined 'optima', where environmental conditions such as temperature, desiccation and wave exposure exert physiological and/or ecological stress (Menge and Sutherland 1987; Menge and Olson 1990).

Substrates that remain wetter and cooler during periods of exposure to air are generally thought to provide less stressful conditions for intertidal epibiota than substrates that heat and dry quickly (McGuinness and Underwood 1986; Raimondi 1988a, b). Differences in these behaviours may arise through natural variations in albedo, thermal capacity and porosity (see Section 8.2 above). Settling organisms may exhibit active settlement choice for cooler or wetter surfaces (e.g. Raimondi 1988b; although this is not clear cut and may be mediated by biofilms e.g. Rittschof and Costlow 1989; Dahlström et al. 2004; Hung et al. 2008), while mortality of settled individuals can be associated with prolonged stress over time (e.g. Walters and Wethey 1996; Delany et al. 2003). Mass mortality events have also been reported for intertidal epibiota when low tides coincide with very hot (e.g. Helmuth and Hofmann 2001) and very cold weather (e.g. Crisp 1964). It is worth noting that construction materials used in the tidal zone are typically selected for having low porosity (Fookes et al. 1988; Latham 1991; Latham et al. 2006; CIRIA 2007) and may not, therefore, offer favourable micro-climatic conditions for ecology compared to naturally occurring rocks (in hot weather at least), particularly where physical refuge in association with surface complexity (e.g. shade) is often limiting (Chapman and Bulleri 2003; Chapman and Blockley 2009).

The extent to which material choice mediates thermal conditions experienced by epibiota on artificial structures is an interesting and understudied biogeomorphological question. These relationships are likely to be complex (see discussions in Section 8.2) because physical-biological interactions are not expected to be static in time and space. A fresh (previously uncolonised) material may exhibit very different warming-drying behaviours after a period of exposure to colonisation and weathering for example. The potential influence of engineering materials' warming-cooling and wetting-drying behaviours on organisms when first placed in the tidal zone, and how these interactions may change through time, was therefore of considerable interest in the context of urban marine ecology. At the same time, the ways in which organisms alter the thermal and drying regime of substrata may have consequences for the operation of geomorphological processes; these interactions provide examples of feedbacks between biotic and abiotic components of intertidal environments of interest under an integrated biogeomorphological conceptual framework (e.g. Figure 3-5 p. 126).

8.4 Climate Change

Intertidal organisms are considered to be living close to their thermal tolerance limits (Wethey 1983). They may therefore be particularly sensitive to climate change (Helmuth et al. 2002; Thompson et al. 2002). In the context of this study, an important consideration was that substrata are unlikely to respond uniformly to changes in air temperature and solar forcing, as a function of inherent physical properties (above). Some construction materials will be more or less responsive (in terms of warming and drying) to changes in temperature and moisture than others, just as different rocks heat-up and dry-out at different rates (Yatsu 1988; Smith et al. 2008).

Differences in the warming-drying behaviour of materials may also have implications for the ability of organisms to shift their geographic range in response to changes in sea level, sea surface temperature (SST) and air temperature (e.g. Mieszkowska et al. 2006). Warm and cool water barnacle species (*C. montagui* and *S. balanoides*, respectively) in the English Channel, for example, have shown changes in relative abundance and spatial distribution over the last 75 years in response to climate change (primarily in relation to SST; Southward et al. 1995; Hawkins et al. 2003; Herbert et al. 2007; Hawkins et al. 2008; Poloczanska et al. 2008). Coastal defence structures have been suggested to facilitate these processes by offering refuge sites or ‘stepping-stones’ for range shifts (Hawkins et al. 2003). As sea level rises, more artificial structures will become ‘available’ to marine epibiota for colonisation (Thompson et al. 2002). The ability of different construction materials to function as biological substrata under a warmer climate is therefore of interest for urban marine ecology.

In a geomorphological context, the implications of climate change for rock weathering are not clear, but may involve changes in the relative importance of biological, chemical and mechanical processes (Viles 2002). Relative changes in temperature and moisture regimes are also likely to vary considerably around the globe (IPCC 2007a), so that relative weathering responses to these changes are not expected to be consistent between different locations. Based on UK climate predictions, Viles (2002) suggests that chemical weathering may become more important in the northwest, while salt crystallisation may be more effective in the southeast in the future. Smith et al. (2004) and McCabe et al. (2010), considering Northern Ireland, suggest that increases in moisture and warmth are likely to alter the distribution and impacts of salts and biological colonisation on stone. Such changes may alter the physical properties of rock and stone (colour and porosity for example) and hence warming-drying behaviour. Recently, Smith et al. (in press-a) suggested that climate change is likely to have chemical, physical and biological weathering implications for terrestrial building stone, including aesthetic consequences, but that much more research is needed by geomorphologists to predict climate change impacts on rock weathering.

At the coast, weathering associated with salts may be enhanced under a warmer and wetter climate (Mottershead et al. 2003) and sea level rise will alter the zone where salt weathering and tidal wetting-drying processes will be most efficient. Artificial structures and rocks higher on the shore, for example, may become wetted more frequently by the tide and by sea spray as sea level and storminess increases.

8.5 Materials and Methods

8.5.1 Introduction

A laboratory experiment was designed to characterise the warming-drying behaviour of three different construction materials used in coastal engineering under simulated intertidal conditions. Materials were the same as those used in field trials, described in detail in Chapter 4. As with *Exposure Trial 1* (Chapter 5), materials had surface textures representative of those commonly used in construction (see Section 5.2.2 p. 172). Additional experiments were used to assess the potential influence of surface texture on material behaviour using granite, which exhibited the most pronounced thermal response during preliminary tests.

8.5.2 Sample preparation

For the main experiment, two sets of three blocks (50 x 50 x 40 mm) were prepared of each material type (limestone, granite and marine concrete). The first set was cut from larger slabs of stock material using a diamond-tipped saw so that all surfaces were fresh and unweathered. The second set were cut from blocks (100 x 100 x 40 cm) randomly sub-sampled from those exposed at MTL for 8 months as part of *Exposure Trial 1* (i.e. Figure 7-2 p. 242). Field-exposed blocks (8 months) were not yet colonised by barnacles, but were discoloured to varying degrees as a result of microorganism colonisation and the weathering processes described in Chapter 7: Strand 1 (Figure 8-1).

Blocks were first immersed in distilled water for 7 days to remove loose debris, sawing dust and accumulated salts (in the case of field-exposed blocks) as far as was possible before being dried at 105°C for 24h and weighed (Cooke 1979; Moses 2001). Blocks were then sealed on all but one face using three coats of polyurethane varnish to restrict water movement to one face. This was done to better replicate the surfaces of *in situ* structures and intact rock masses (e.g. Smith and McGreevy 1983, see above). For field-exposed blocks, the top surfaces (i.e. the weathered/colonised faces) were left unsealed).

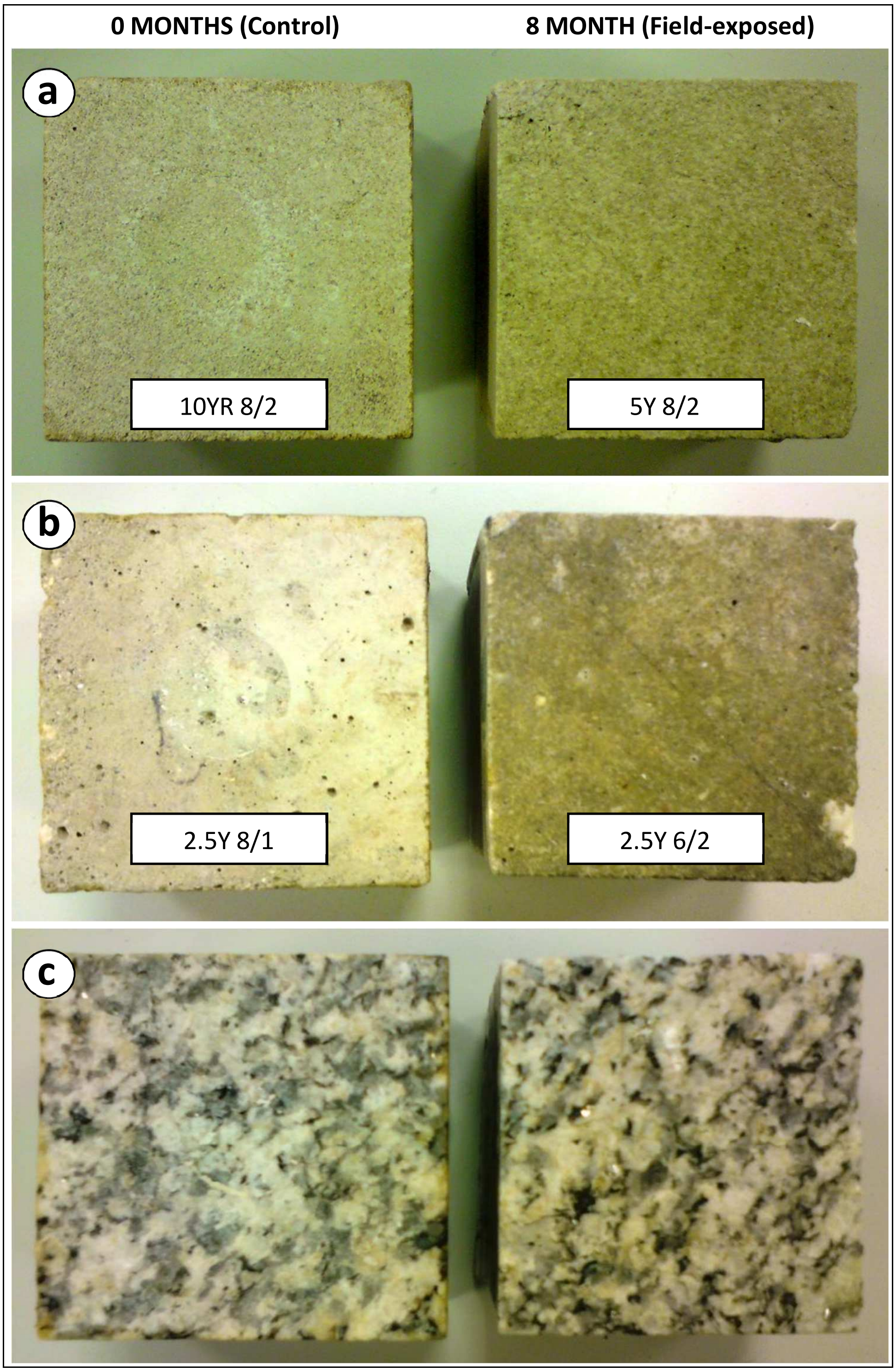
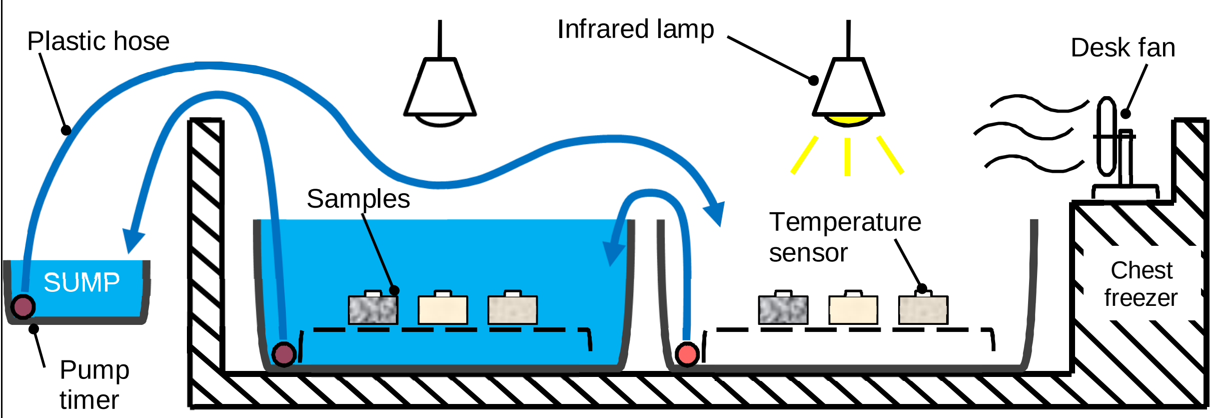


Figure 8-1 Example samples used to measure surface warming-drying behaviour under simulated intertidal conditions: (a) limestone (b) concrete and (c) granite; corresponding Munsell Colour System classification as shown (granite was not classified due to highly variable colour).

8.5.3 Experimental procedure

The experimental set-up is shown in Figure 8-2. Two plastic tanks were placed inside an open-topped, insulated chest freezer. A further tank was placed outside the freezer as a holding sump for freshly mixed and cycled seawater (see below). Electric timers were used to establish an automated circulation of water between the tanks and sump using plastic hosing and aquarium pumps. The system was designed to simulate conditions at mean tide level (MTL) on a UK shore. A pilot study was used to establish a 24h semi-diurnal cycle alternating between each tank, consisting of two 6h 'immersion' (wet) periods and two 6h 'exposure' (dry) periods. Synthetic seawater was used rather than freshwater used elsewhere (e.g. Kanyaya and Trenhaile 2005; Trenhaile 2006) to best represent intertidal conditions (e.g. Moses 2001). Synthetic seawater was mixed from KENT® Sea Salt™, which is used in marine aquariums to precisely replicate the chemical composition of natural seawater. During the experiment, cycled water in the sump was replaced with freshly mixed seawater every few days to maintain consistent dissolved loads as far as was possible, and to prevent the water becoming unrealistically warm (see later).



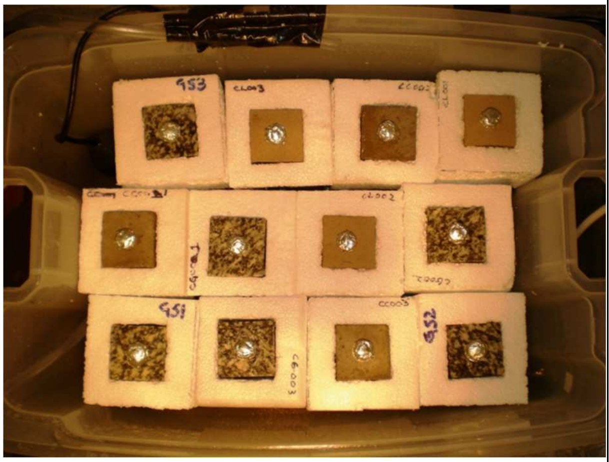


Figure 8-2 Experimental set-up used to simulate intertidal conditions in the laboratory: illustration (*above*) and photographs (*below*) of set-up and experimental blocks.

Following the recommendations of Warke and Smith (1998), warming was induced directly by securing one 250 watt infrared lamp 40 cm above each tank. Each lamp was attached to a timer set to come on during one of the 6h exposure (dry) periods per 24h cycle. During each warming period, a 30 minutes on – 15 minutes off lamp cycle was used to simulate periodic shading, such as that caused by passing cloud (e.g. Jenkins and Smith 1990). An oscillating fan was also set on a continuous 15 minute on-off cycle to simulate periodic air movements (Warke et al. 1996) and to prevent unrealistically high air temperatures (see below). The full wetting and heating regime used in the experiment is illustrated schematically in Figure 8-3. The set-up simulated one 'daytime' (with heating) and one 'night-time' (without heating) exposure (dry) period, and two corresponding immersion (wet) periods, per day.

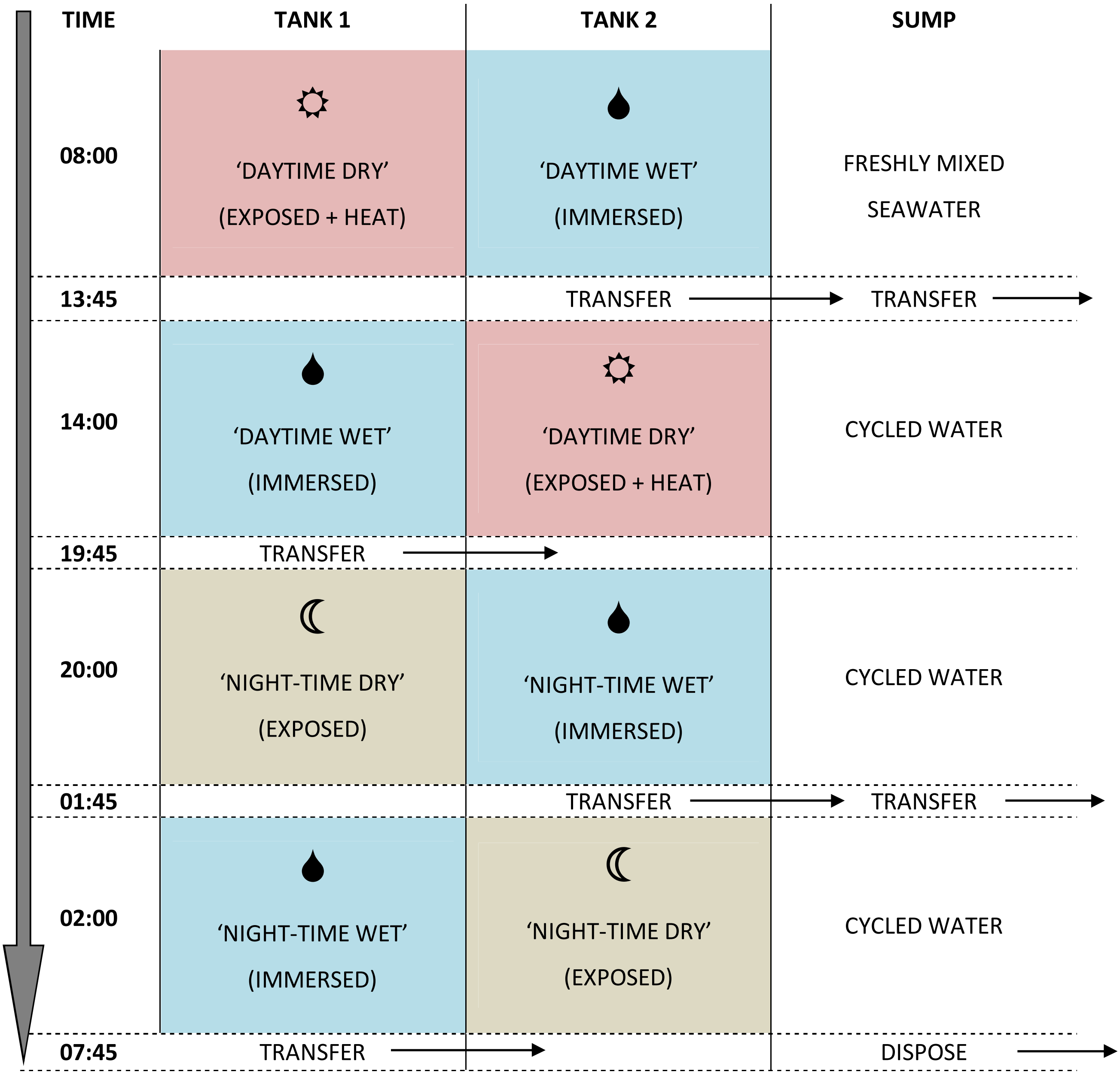


Figure 8-3 Immersion-exposure and warming regime used to simulate mid-tide conditions in the laboratory.

Preliminary testing showed that a relatively stable air temperature of 24-26°C was maintained during 'daytime warming' periods when the lamps and fan were used as described. 'Night-time' temperatures (no heating) also remained high due to the ambient temperature of the laboratory, and therefore the fan was set to be on continuously during night-time periods in an attempt to reduce temperatures further. Simulated 'daytime' temperatures fell between mean daily summertime temperatures (19-22°C) and extreme summertime maxima (32-35°C) recorded at St. Mawgan and Yeovilton in Cornwall and Devon (www.metoffice.gov.uk/climate/uk/, accessed April

2009). As meteorological observations are of limited value in representing conditions experienced in the intertidal environment (Helmuth 1999; Helmuth et al. 2002), temperature recorders were also installed on rock platforms in Cornwall to record air temperatures in summer 2009. Air temperatures maintained under simulated 'daytime warming' conditions reflected those recorded on warm days on the shore very well (see Section 8.7.3).

At any one time, samples in one tank were under immersion (wet) conditions, while blocks in the other were under exposure (dry) conditions. This allowed different experimental runs to be carried out independently, but at the same time (Figure 8-3, described below). The number of samples that could be run together in any one simulation was limited by the size of the tanks. Therefore, three replicate blocks of each material type were used in each experiment to make best use of the available space; three replicates was deemed suitable based on previous laboratory studies of rock temperature, which typically use little or no replication (e.g. Warke et al. 1996).

Three different experimental runs were undertaken to inform the study aims (Table 8-1). In the first, the warming-drying behaviours of control (fresh, unexposed) blocks of each material type were compared, including a smooth and rough comparison for granite to assess the influence of texture. The second experiment compared blocks previously exposed at MTL for 8 months (i.e. Chapter 5). These two experiments were run simultaneously (one in each tank) for a period of two weeks, during which temperature and drying data were measured during two 'daytime dry' phases, as described below. The third experiment compared the behaviour of control and exposed blocks together, at the same time (i.e. in the same tank), and was run over 2 months as a pilot study for a subsequent, longer-term weathering study (Weller 2010). As control and field-exposed blocks of all three material types could not be run in the same tank due to space limitations, both versions of limestone and concrete (i.e. control and field-exposed blocks) were run together in one tank, and could therefore be directly compared. Control and field-exposed granite blocks were run separately in the other tank, and are therefore considered separately (see Section 8.6.2 below).

In all cases, block samples were placed on top of plastic crates so that their bases remained above the 'low tide' water level. Blocks were also allowed to cycle for a period of one week before temperature and drying data were collected. This was done to ensure that both control and field-exposed blocks had attained a quasi-equilibrium state (with respect to water and salt content) before measurements were taken (A. Trenhaile personal communication, October 2008). Cooke (1979) also notes that there is an initial period upon immersion during which pore spaces in rocks are progressively filled by salts and water, suggesting this initial cycling was important. Weights of the blocks measured at the beginning of each 'daytime exposure' period during the first few weeks of the experiment indicated that 7 days was sufficient for water content to become stabilised.

8.5.3.1 Temperature measurement

Surface temperatures were measured as an indicator of heat stress experienced by epibiota colonising these materials (Section 8.3). One wireless iButton® thermochron temperature logger (DS1921H-F5: range +15°C to +46°C, accuracy ± 1°C) was secured to the centre of the unsealed face of each sample block using thermally conductive adhesive (850-984 TC Adhesive, RS Components). Loggers were pre-programmed to continuously record surface temperatures at one minute intervals at 0.125°C resolution. Aluminium foil shields were secured over the surface of each iButton® with tack to minimise direct heating of the sensor (e.g. Carter and Viles 2004); initial tests showed that shielded sensors consistently recorded temperatures 2-3°C lower than un-shielded sensors. It was necessary to coat the shields with varnish to prevent them becoming tarnished in the salt water. iButtons were also secured inside each tank to record air and water temperatures. Ambient air temperature was continuously recorded inside the freezer using shielded loggers placed at the same level as the test blocks, but outside of the tanks.

While internal thermal gradients are potentially more important in the rock weathering process (McGreevy et al. 2000; Smith et al. 2011), sub-surface temperatures were not recorded during this experiment. This is justified given that the primary aim of the study was to characterise the warming-drying properties of materials' as biological substrata. Surface temperatures of rock best reflect the temperature of epibiota body tissue (Denny and Harley 2006) and so were of most interest in an ecological context. Geomorphologically, the thermal behaviour of materials at their surface is also of relevance for the operation of chemical and mechanical weathering processes (Jenkins and Smith 1990; Waragai 1998; Carter and Viles 2003; Viles 2005; Gómez-Heras et al. 2008). Furthermore, the surface temperatures of rocks fluctuate more quickly than their interiors (Zhu et al. 2003) and given that heat shock effects are associated with rapid changes in body temperature (e.g. Helmuth and Hofmann 2001), rates of surface temperature change were of most interest. More practically, the use of subsurface temperature probes (e.g. Warke et al. 1996; Warke and Smith 1998; Carter and Viles 2004; Smith et al. 2005) would have proved difficult given the experiment involved repeated wetting and because blocks were frequently removed for weighing (see Section 8.5.3.2 below).

8.5.3.2 Drying measurements

The rate and nature of water loss (through evaporation) from the surface of blocks was used as in indicator of the potential for epibiota desiccation stress (Section 8.3). After the initial period of cycling (Section 8.5.3), water loss from the one unsealed surface of samples was measured during two different 'daytime dry' periods (i.e. Figure 8-3). During these phases, blocks were briefly removed from the tanks and the varnished sides thoroughly dried. Each sample was also lightly shaken to remove water ponded around the temperature sensor, but the surfaces of blocks were otherwise allowed to dry naturally under the lamps. Each sample was placed inside a pre-prepared casing of 2 cm thick expanded polystyrene (e.g. Smith and McGreevy 1983; McGreevy 1985b; Carter and Viles 2003, Figure 8-3) and weighed. Encased samples were then returned to the tanks to dry under the lamps for the 6h duration of the 'daytime dry' phase. Whilst drying, samples were removed periodically (in their casings), every 30 minutes, and re-weighed to allow calculation of evaporative water loss, measured as a weight change.

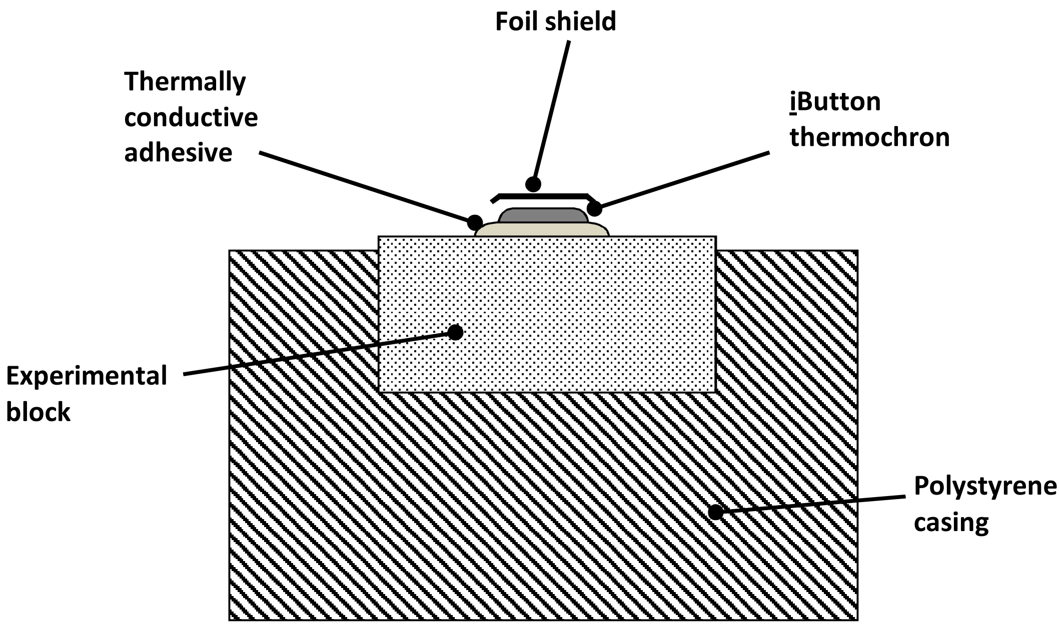


Figure 8-4 Measurement of surface temperature during 'daytime dry' phases of an intertidal cycle (not to scale, sample block dimensions = 50 x 50 x 40 mm).

Pilot tests showed that while overall patterns of temperature change were comparable between insulated and un-insulated blocks, consistently lower surface temperatures and rates of heat gain/loss were recorded on insulated samples; this highlighted the value of this procedure for realistic simulation. The continuous use of insulation during the experiment (i.e. during wetting periods) was not possible however given difficulties stopping the encased sampled floating. Nevertheless, the purpose of using insulated samples was to obtain the most representative surface temperatures during drying phases, rather than measuring thermal loss and gain during immersion.

8.5.3.3 Weathering

Although not the primary aim of the study, an attempt was made to measure weathering rates during the longer experiment, run over two months (Section 8.5.3). To do this, blocks were removed from the set-up at the end of a 'daytime dry' phase each week and their surfaces brushed with a soft brush. Loosened debris was collected on white paper, weighed and then re-weighed after soaking in distilled water for two days to remove salts (e.g. Smith and McGreevy 1983). Weight measurements of debris were made cumulatively over the course of the experiment. At the end of the experiment, blocks were dried and weighed before and after desalinisation (in distilled water for 7 days) to provide data on overall block weight change (e.g. Goudie et al. 1970; Moses 2001; Tingstad 2008).

8.5.4 Field data

Additional sealed blocks with shielded iButtons were attached to the platform at Tregear Point, Porthleven (see Section 5.2.1.1 p. 167 for details) to measure surface temperatures of the same materials used in the simulation under field conditions. As well as control blocks of limestone, granite and concrete, blocks of the platform rock (Mylor Slate) were also prepared with the same dimensions and with freshly sawn surfaces for comparison. Two blocks of each material type (with temperature sensors) were attached at MTL (horizontally) as a comparison with conditions simulated in the lab. Additional blocks were attached at MHWN to provide a spatial comparison of thermal responses across the shore. Air temperature was measured on the shore using iButtons wrapped in foil and secured in the shade – but not in direct contact with the rock. Field blocks were periodically re-visited during the summer to download temperature data for the previous few days under various weather conditions.

Several temperature loggers and foil shields were lost to waves during the experiment. Only data from iButtons that had their shields in place upon return to the shore were used in comparisons, therefore, to ensure data were comparable with those in the lab and reflected rock surface temperature rather than direct heating of the sensor. For practical reasons, blocks placed in the field could not be encased in polystyrene.

8.5.5 Data analysis

For comparisons of surface temperature, the mean of data collected from replicate blocks of each material type was plotted in time-series graphs for each experimental run. Only blocks run under the same conditions (in the same tank) were directly compared to ensure comparability. As well as a qualitative comparison of data trends, parameters such as peak temperature, and rates of warming and cooling were used for comparisons of thermal behaviour (McGreevy 1985b; Warke et al. 1996;

Warke and Smith 1998). The amount of water lost from the surface of blocks during drying phases, and the rate of loss, was plotted as drying curves for comparison.

Quantitative comparisons of peak temperatures and evaporative water loss were made between material types and exposure conditions (i.e. control or field-exposed blocks) were possible using sample means and t-tests. Data were tested for normality using the F-statistic.

8.6 Results

An indicative 24h temperature dataset collected using the experimental set-up is shown in Figure 8-5. The four phases of the cycle were clearly captured in the data (i.e. Figure 8-3). During the 'daytime dry' phase (when heating was induced) the temperature of the air fluctuated in 15 – 30 minute cycles as the lamps and fan came on and off periodically. The surface temperatures of blocks rose rapidly when first exposed to the air, and increased progressively in spikes. During the 'daytime wet' phase, temperatures of the blocks sharply declined as water entered the tanks and covered the samples; air temperature continued to respond to the heating cycles during this phase. During the 'night-time dry' phase, a temperature 'kink' was observed when blocks were first exposed to the air (Figure 8-5), probably reflecting initial evaporative cooling. Blocks then continued to cool as ambient air-temperature dropped, when lamps were off. When samples were re-submerged during the 'night-time wet' phase, block surface temperatures initially increased because the cycled water was warmer than the blocks, and thereafter declined until re-exposed and heated at the start of the next 'daytime dry' phase (Figure 8-5).

8.6.1 Control materials

Figure 8-6 shows the thermal response of control blocks (unexposed, with insulating cases) during the 'daytime dry' phase of the simulated tidal cycle. Block surface temperatures mirrored changes in ambient temperature throughout, but quickly rose above the temperature of the air within the first 8 minutes of heating. Granite blocks remained above air temperature for the remainder of the drying phase, while concrete had two warming-cooling cycles, and limestone three, before remaining above air temperature for the remainder of the drying phase (Figure 8-6). Air temperature peaked at 26.5°C, while limestone peaked at 30.7°C, concrete at 30.8°C, rough granite at 32.2°C. The surface temperature of smooth granite peaked at 33.0°C, and was consistently higher than rough granite throughout the drying phase by an average of 0.9°C.

Figure 8-7a shows drying curves for control blocks (with insulating cases) during the same 'daytime drying phase'. Limestone lost water through evaporation at a relatively constant rate throughout the drying phase, having lost 50 % of the total loss after 2.5 hours. Water evaporated from the surface of concrete more quickly, having lost 50 % within 1.5 hours. Rough granite lost 63 % of the total water loss in the first hour of warming. Water loss from the surface of smooth granite was similar to rough granite, but was initially faster and typically slowed over the remainder of the drying phase (Figure 8-7a).

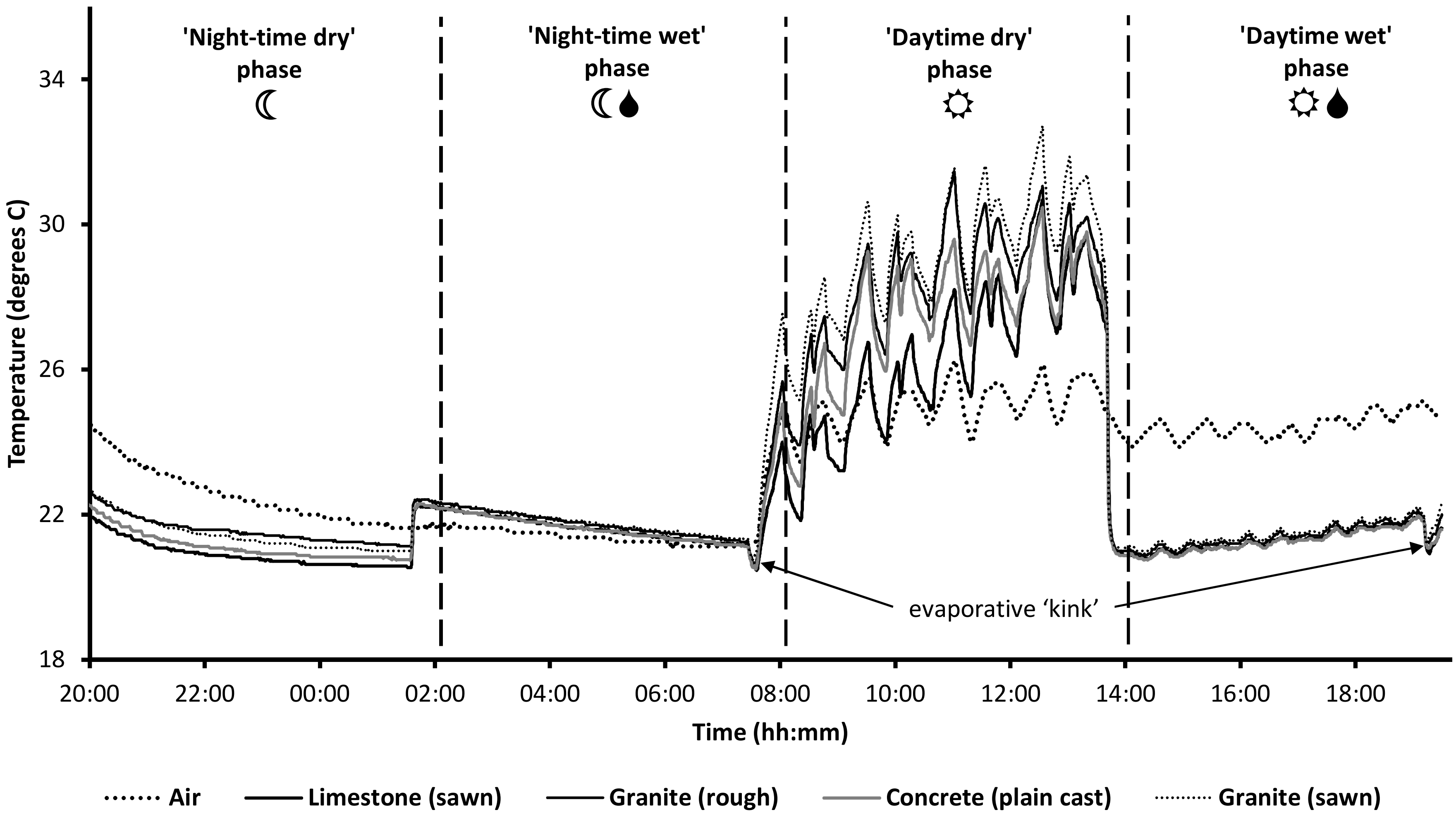


Figure 8-5 Example temperature record for air and block surfaces (controls) collected over a 24h simulated semi-diurnal tide cycle (mean, *n* = 3).

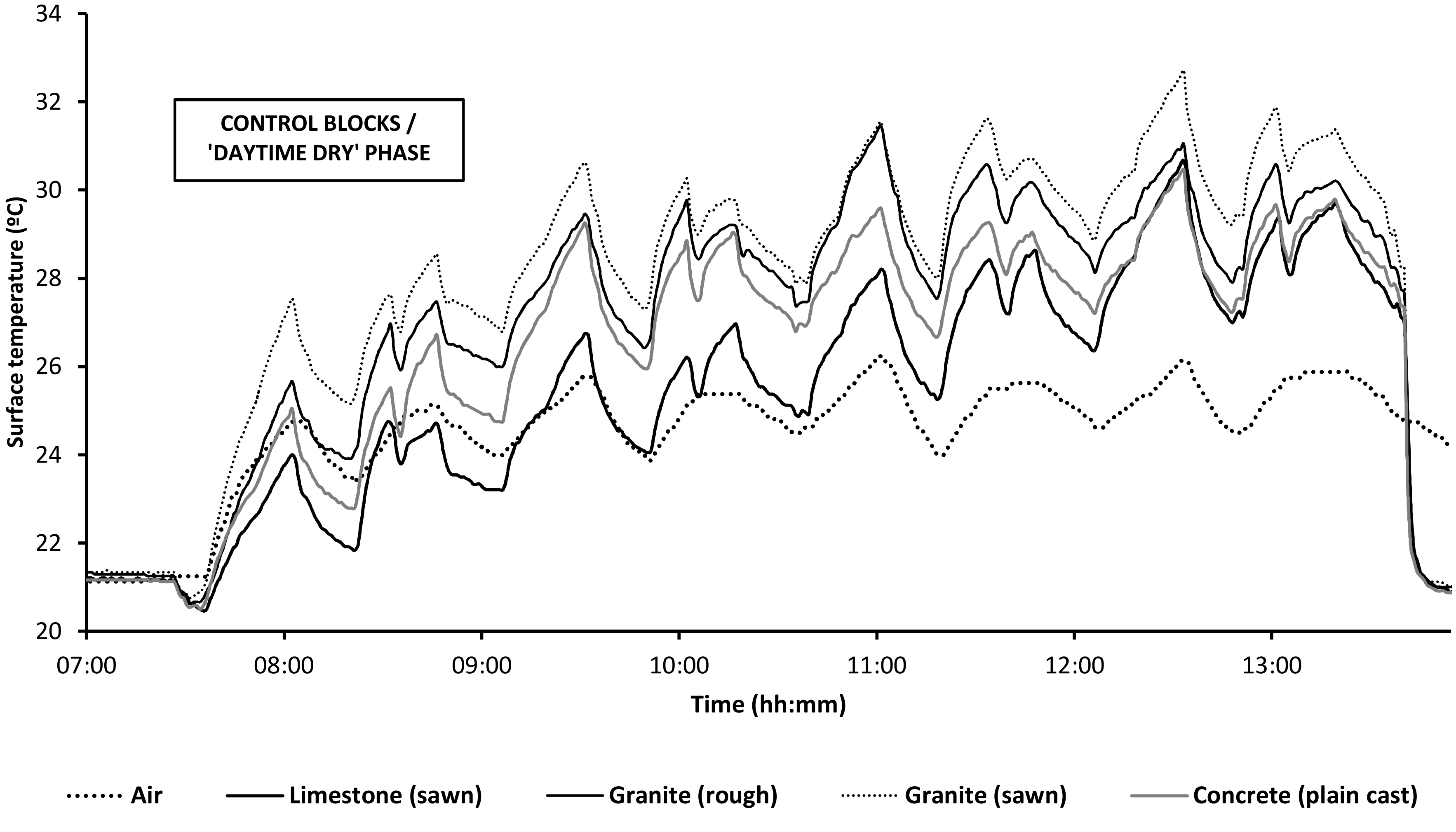
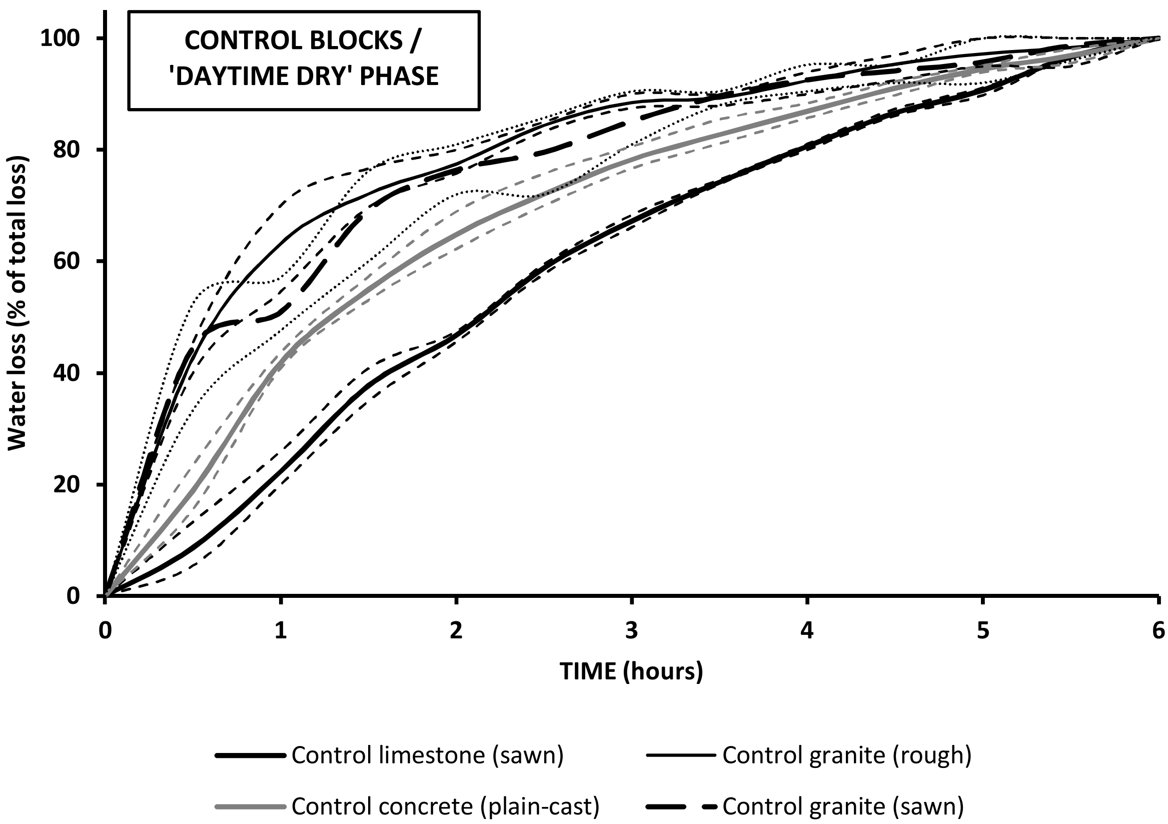


Figure 8-6 Surface temperatures of control blocks (unexposed) during the 'daytime dry' phase of a simulated intertidal cycle (mean, *n* = 3).

(a)



(b)

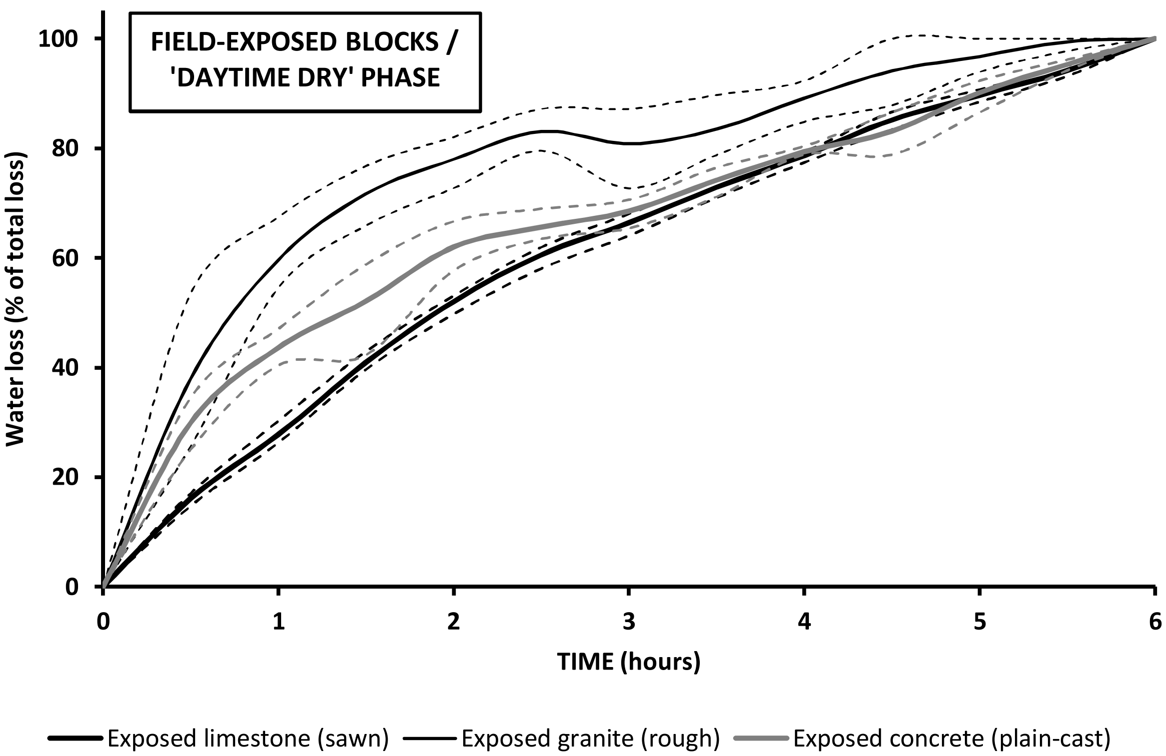


Figure 8-7 Drying curves for (a) control blocks and (b) field-exposed blocks (8 months at MTL) during the 'daytime dry' phase of a simulated intertidal cycle (solid lines show mean water loss by weight; dashed lines show maximum and minimum values).

8.6.2 Field-exposed materials

Figure 8-8 shows the thermal response of different construction materials after previous exposure at MTL for 8 months. As with control blocks, surface temperatures cycled in response to changes in ambient air temperature. Both concrete and granite got hotter than the air within 30 minutes of exposure, while limestone fluctuated above and below air temperature for 2.5 hours before remaining above ambient temperature (Figure 8-8). Air temperature peaked at 28.9°C and the surfaces of limestone at 32.1°C. Temperatures of the concrete and granite were very similar during the entire drying phase, but concrete tended to be slightly cooler during the first three hours and slightly warmer during the last three hours; the surface temperature of concrete peaked at 35.2°C, which was 0.5°C hotter than granite.

Drying curves for the field-exposed blocks are shown in Figure 8-7b. Limestone generally lost water more slowly and at a more consistent rate during the drying phase. Granite had lost 50 % of the total water loss after 1 hour, and concrete after 1.5 hours. Limestone had lost 50 % of the total water loss after 2 hours warming. Drying curves also showed periods of adsorption, where moisture was re-absorbed by the blocks from the humid air, captured in the data as a slight weight gain (Figure 8-7b).

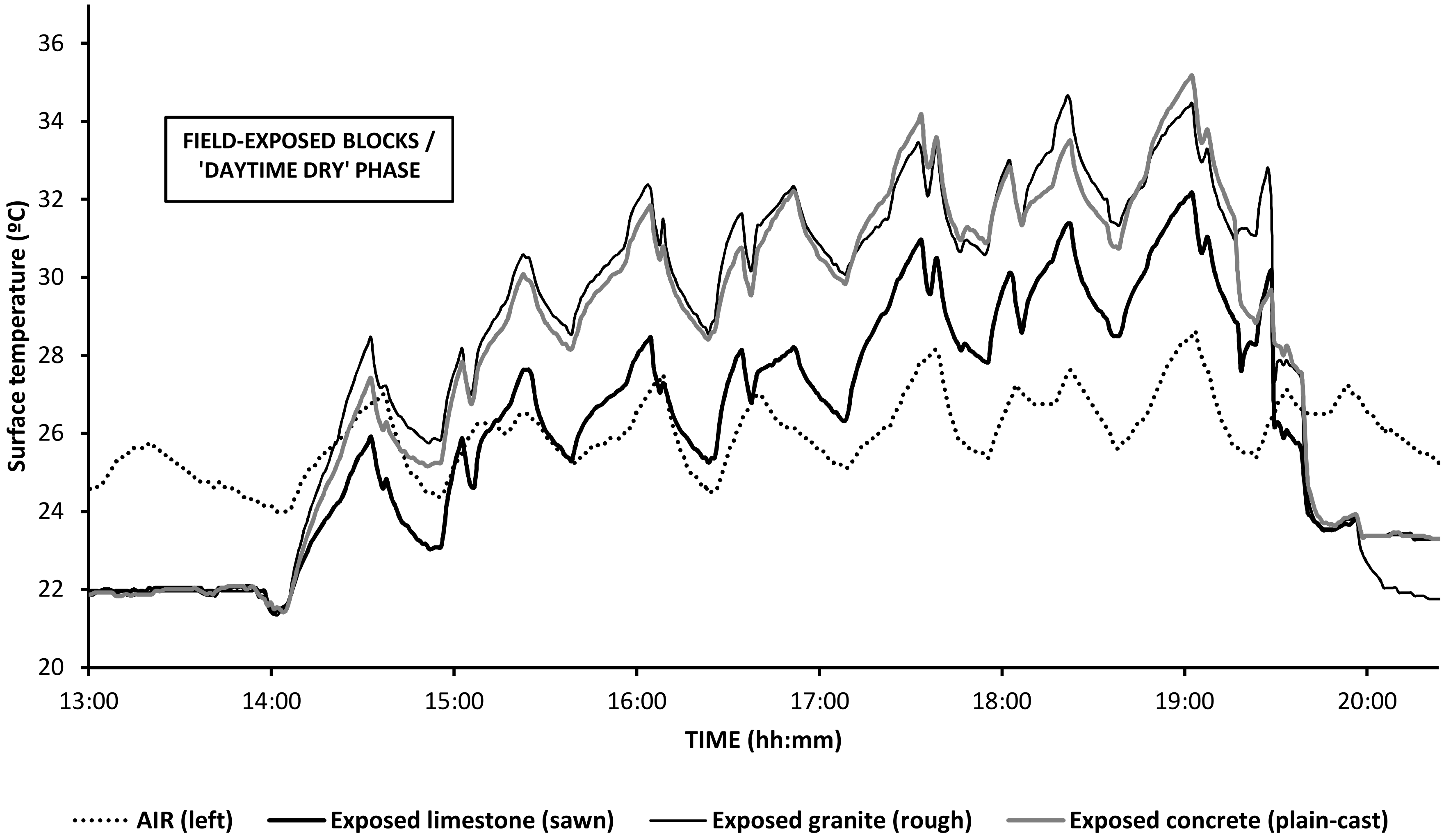


Figure 8-8 Surface temperatures of field-exposed blocks (8 months at MTL) during the 'daytime dry' phase of a simulated intertidal cycle (mean, *n* = 3).

8.6.3 Control vs. field-exposed blocks

Figure 8-9 shows surface temperatures of control blocks (unexposed) and field-exposed blocks (8 months at MTL) of limestone and concrete during the same drying phase of a simulated tidal cycle (cylcled in the same tank). Granite blocks could not be assessed during the same run due to space restrictions (see Section 8.5.3) and so are discussed separately below. Table 8-2 shows various thermal parameters for the control and field-exposed blocks of limestone and concrete. Concrete was always hotter than limestone, although difference between field-exposed limestone and both sets of concrete were only very slight during the first 30 minutes of heating, all peaking within 0.1°C of each other. In contrast, limestone previously exposed in the field was 1.6°C cooler than the other blocks at the end of the first warming period (Figure 8-9).

Table 8-2 Warming-drying parameters for control and field-exposed blocks of limestone and concrete under simulated intertidal conditions (mean, *n* = 3).

		LIMESTONE		CONCRETE	
Thermal parameters*	**AIR**	**Control**	**Exposed**	**Control**	**Exposed**
Thermal range (during drying phase, °C)	4.88	10.63	10.67	11.17	13.08
Peak temperature (°C)	27.13	30.75	30.63	31.17	33.00
Time to peak (from on-set of warming, hrs)	3.47	4.88	3.70	4.88	4.88
Warming in first 15 minutes (°C)	1.25	2.04	2.50	2.54	2.59
Cooling from first peak (5 minute, °C)	2.00	2.04	2.83	2.37	1.71
Highest rate of change (in 1 minute, °C)	0.38	2.08	2.83	3.71	2.88
Maximum different to air (°C)	/	4.46	4.50	4.96	6.63
Drying parameters$^{\psi}$					
Total water loss (g)	/	1.61	2.07	1.00	0.50
Loss in first 30 minutes (%)	/	15.35	16.30	26.31	30.83
Loss in first 60 minutes (%)	/	26.76	28.44	42.86	46.34
Rate of loss (g/h)	/	0.27	0.35	0.17	0.08

*thermal parameters calculated over one 24h simulated semi-diurnal cycle.
$^{\psi}$drying parameters calculated over one 6h 'daytime dry' warming period.

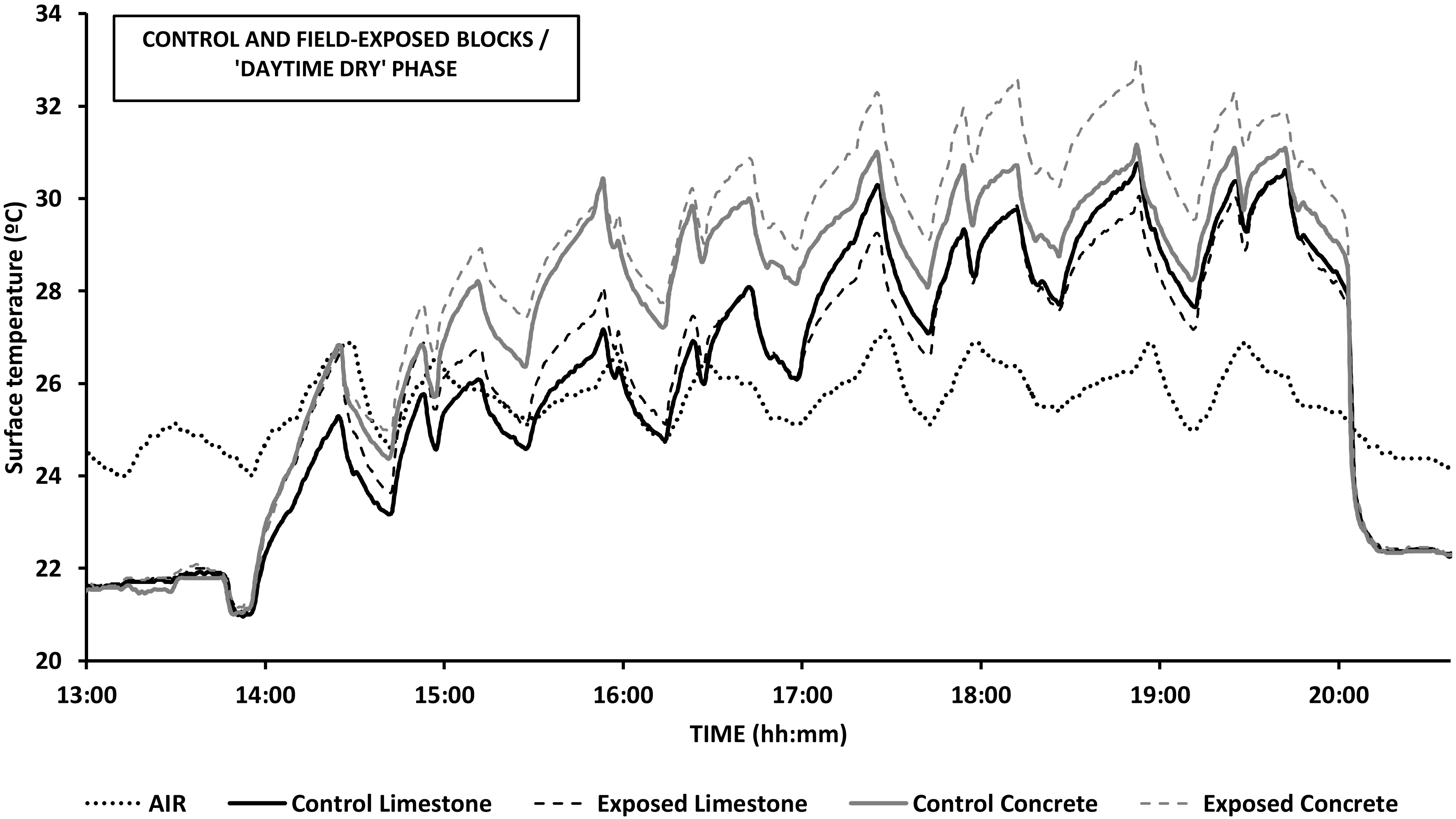


Figure 8-9 Surface temperatures of control (0 months) and field-exposed (8 months at MTL) limestone and concrete during the drying phase of simulated intertidal conditions (mean, *n* = 3).

Field-exposed concrete blocks were consistently hotter than control replicates after the first hour of warming (Figure 8-9). Field-exposed blocks peaked at 33°C (1.8°C hotter than controls), while the largest difference occurring at any one point in time was 2.0°C. The difference in peak temperatures between the two groups of concrete was just short of significance (Student's t [df = 4] = 1.98, *p* = 0.06). Interestingly, limestone blocks previously exposed in the field were slightly warmer than controls during the first three hours of drying, but were cooler during the following three hours (Figure 8-9). Peak surface temperatures of the two limestone treatments were not significantly different (Student's t [df = 4] = 0.80, *p* = 0.23), but field-exposed blocks were more than 1°C cooler than controls for the two highest temperature peaks (Figure 8-9).

Figure 8-10a shows drying curves for control and field-exposed limestone and concrete, as a percentage of the total water lost during the same drying phase. Figure 8-10b also shows the cumulative loss of water (in weight) from the surface of blocks. Water evaporated form the surface of field-exposed limestone blocks faster than controls, and also lost significantly more water (in total) during the drying phase (Student's t [df = 4] = 2.77, *p* = 0.03). In contrast, control concrete lost significantly more water than field-exposed replicates during this drying phase (Student's t [df = 4] = 11.46, *p* < 0.000; Figure 8-10b).

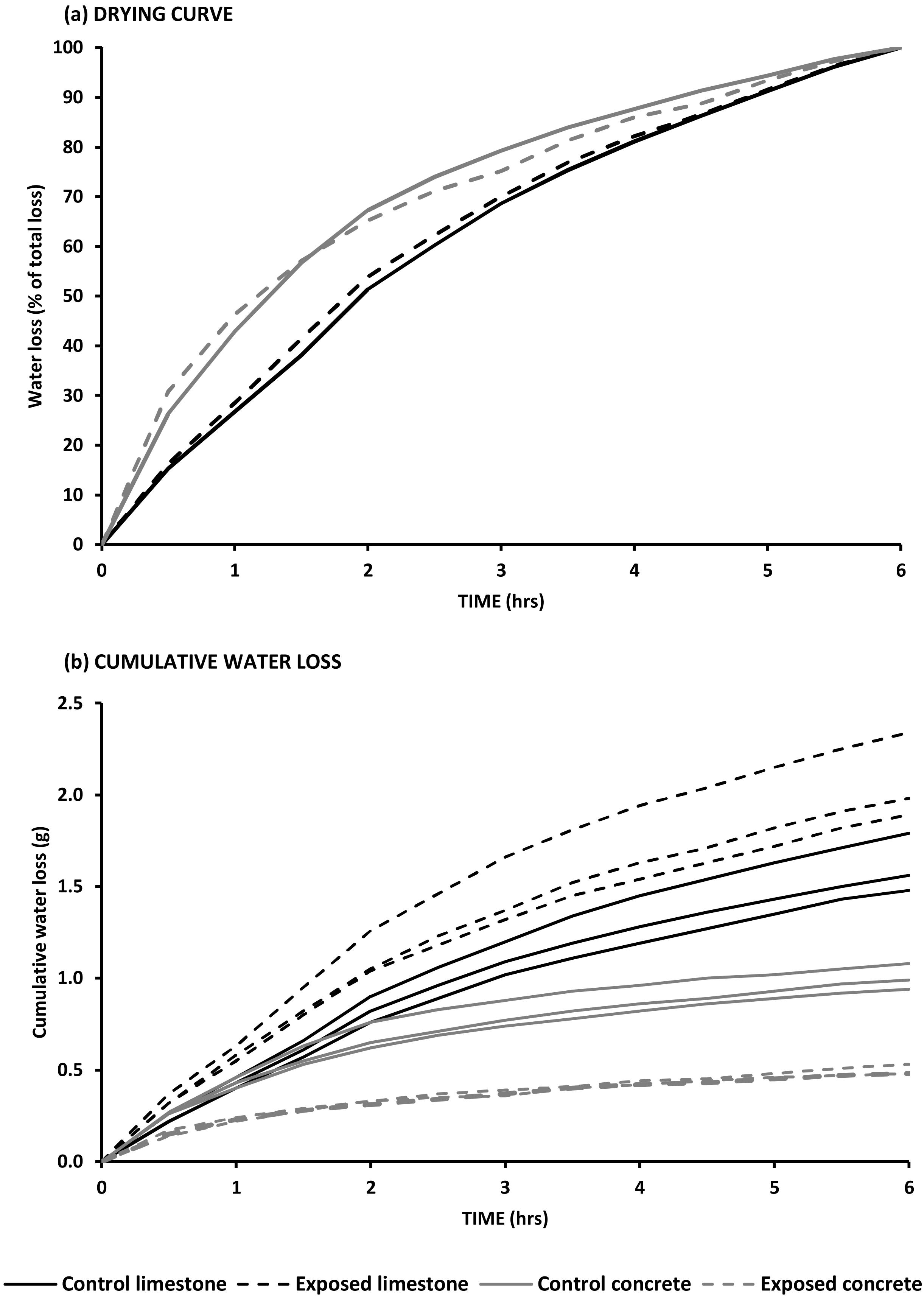


Figure 8-10 (a) Drying curves and (b) cumulative water loss for replicate control (0 months) and field-exposed (8 months) blocks during the 'daytime dry' phase of a simulated intertidal cycle.

Figure 8-11 shows surface temperatures of control and field-exposed granite blocks during the drying phase of a simulated intertidal cycle. Evaporative water loss for granite is shown in Figure 8-12. Granite previously exposed in the field was generally cooler than unexposed controls when subject to heating, although surface temperatures were very similar for the first three hours of drying (exposed blocks were on average less than 0.1°C cooler). Differences were accentuated during the latter half of the drying phase, with control blocks on average 0.5°C hotter. The maximum temperature difference between control and field-exposed granite blocks during the drying phase was 0.9°C. Both sets of granite blocks absorbed and lost very little water when immersed and exposed to air, respectively. While field-exposed blocks tended to lose more water than controls, and at a slightly slower rate, differences were very small (Figure 8-12).

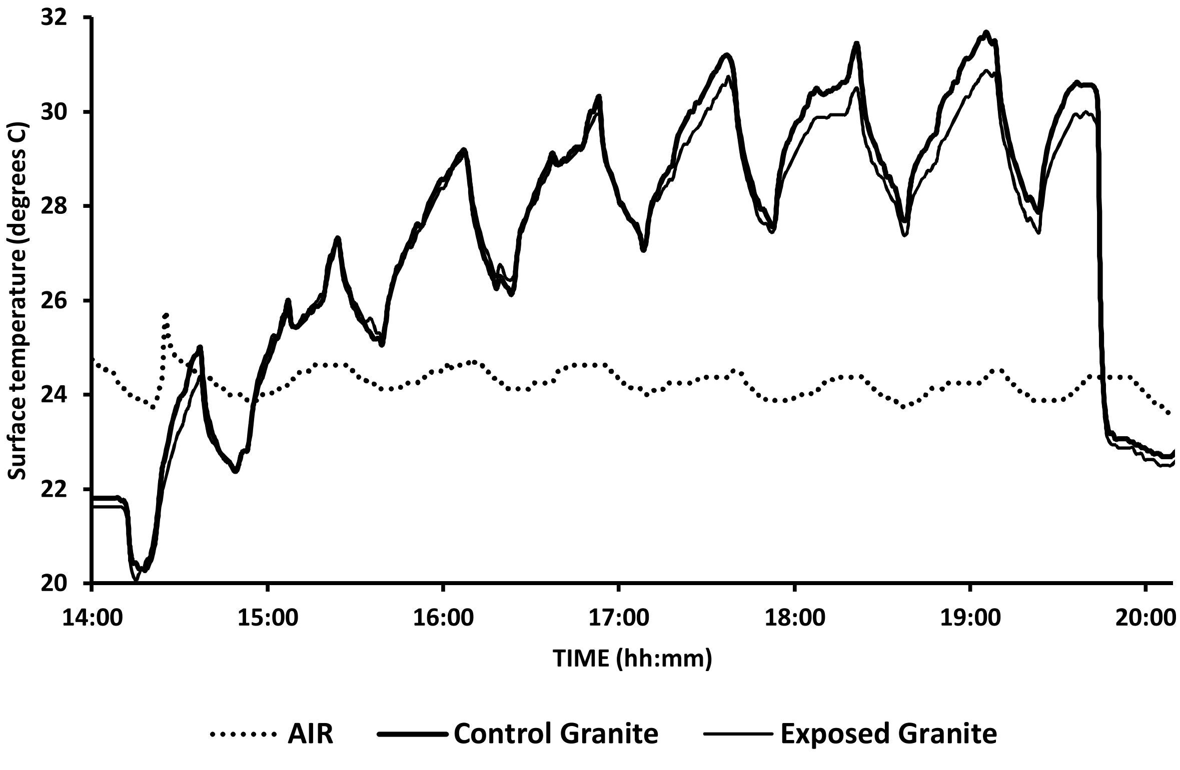


Figure 8-11 Surface temperatures of control (0 months) and field-exposed (8 months at MTL) granite during the 'daytime dry' phase of a simulated intertidal cycle (mean, *n* = 3).

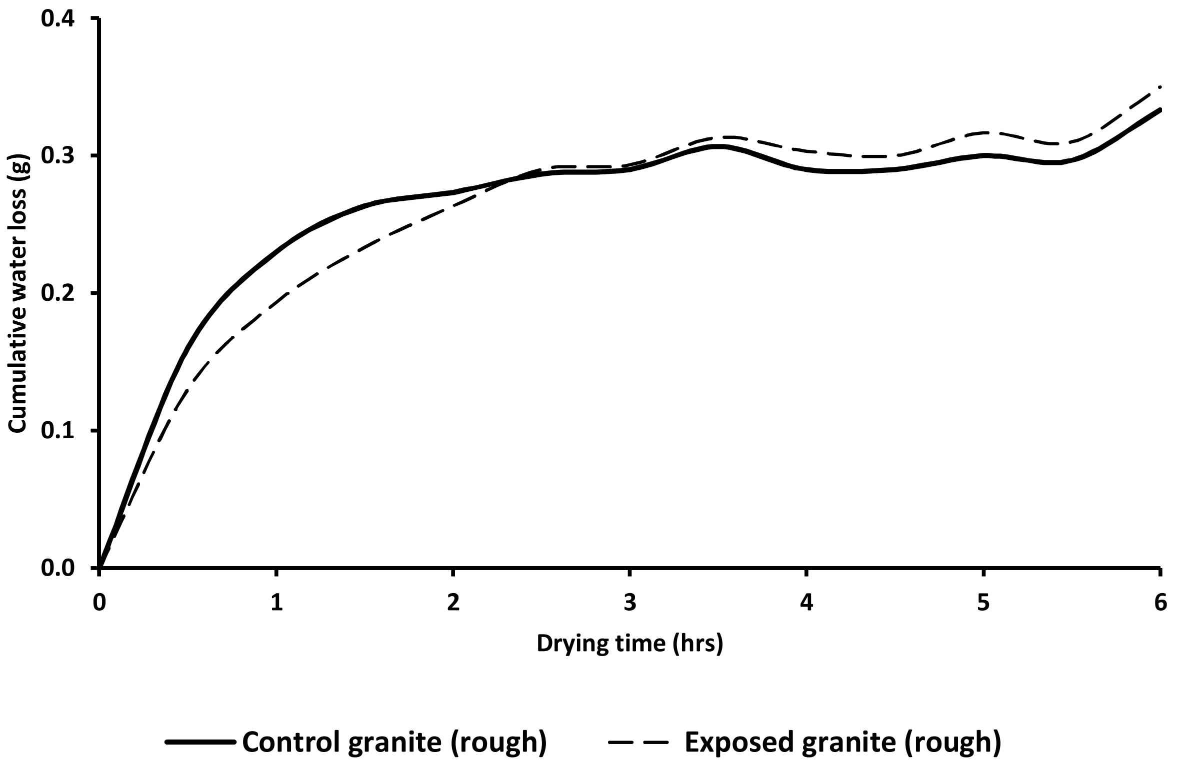


Figure 8-12 Cumulative water loss from the surface of control and field-exposed (8 months at MTL) granite blocks during the drying phase of a simulated tidal cycle (mean, *n* = 3).

8.6.4 Field data

Figure 8-13 shows temperature data collected in the field during a low spring tide on a warm sunny day with frequent cloud at Tregear Point, Porthleven. Figure 8-14 shows data collected during a neap tide on a hot, sunny day for the same blocks. Surface temperatures of blocks rapidly rose above ambient air temperature at low tide. Limestone was consistently cooler than all other materials, both at mid tide level and higher on the shore. At MTL, concrete was warmer than limestone while the platform rock (Mylor Slate) was the hottest; no data was available for granite at MTL as all loggers were lost to waves. At MHWN, concrete and granite blocks had very similar surface temperatures for the first few hours of exposure, but concrete tended to become warmer later in the day. In all instances, blocks cut from the platform rock (Mylor Slate) were hotter than the introduced materials. The slate also lost heat more quickly during periods of shade and/or wind (Figure 8-14).

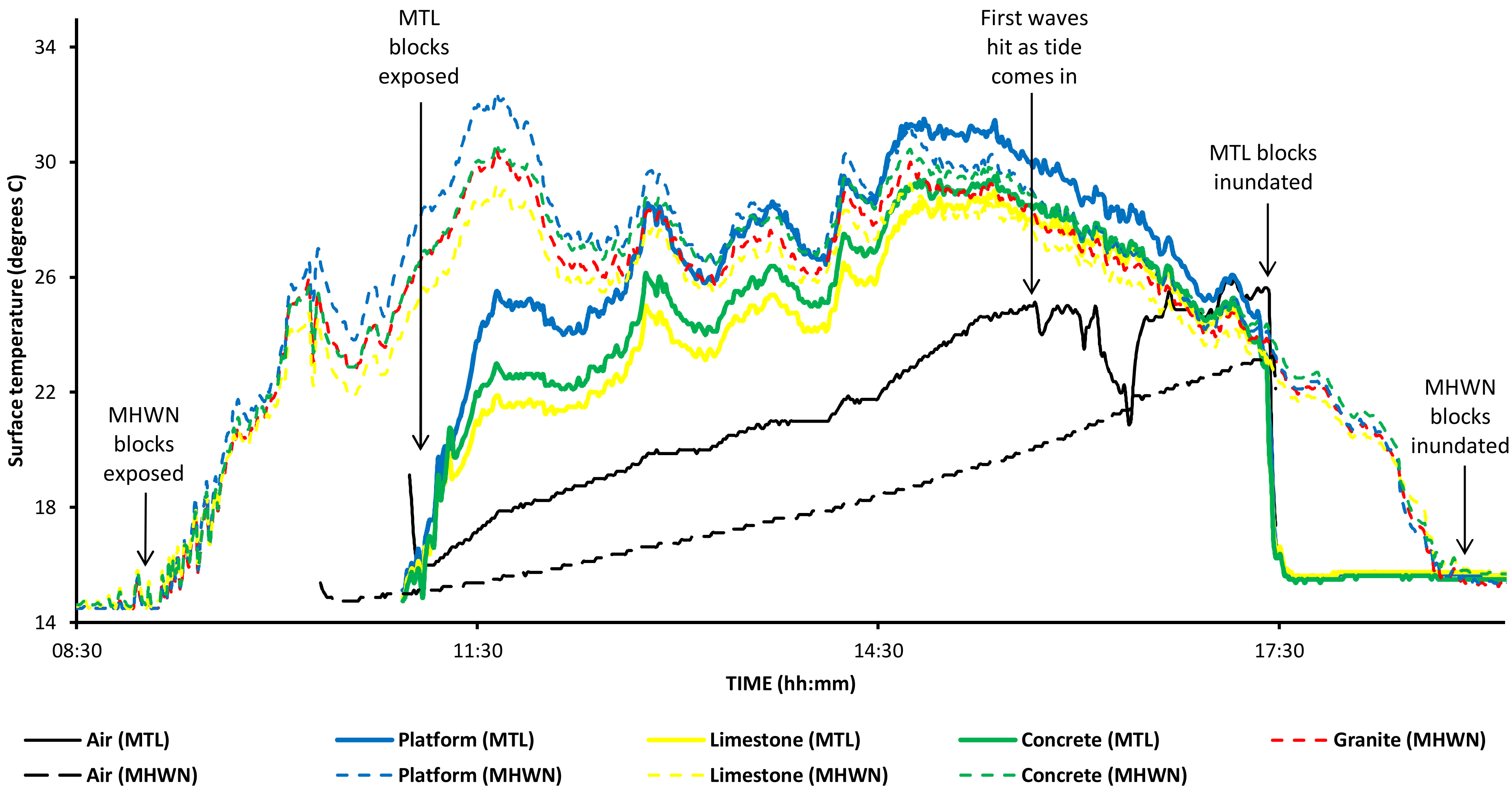


Figure 8-13 Surface temperatures of blocks (no insulation) of different construction materials and platform rock (Mylor Slate), and ambient air temperature, at MTL and MHWN at Tregear Point, Porthleven, during a low (spring) tide on a warm, sunny day with frequent cloud (25th July 2009; each line = mean of two replicate records).

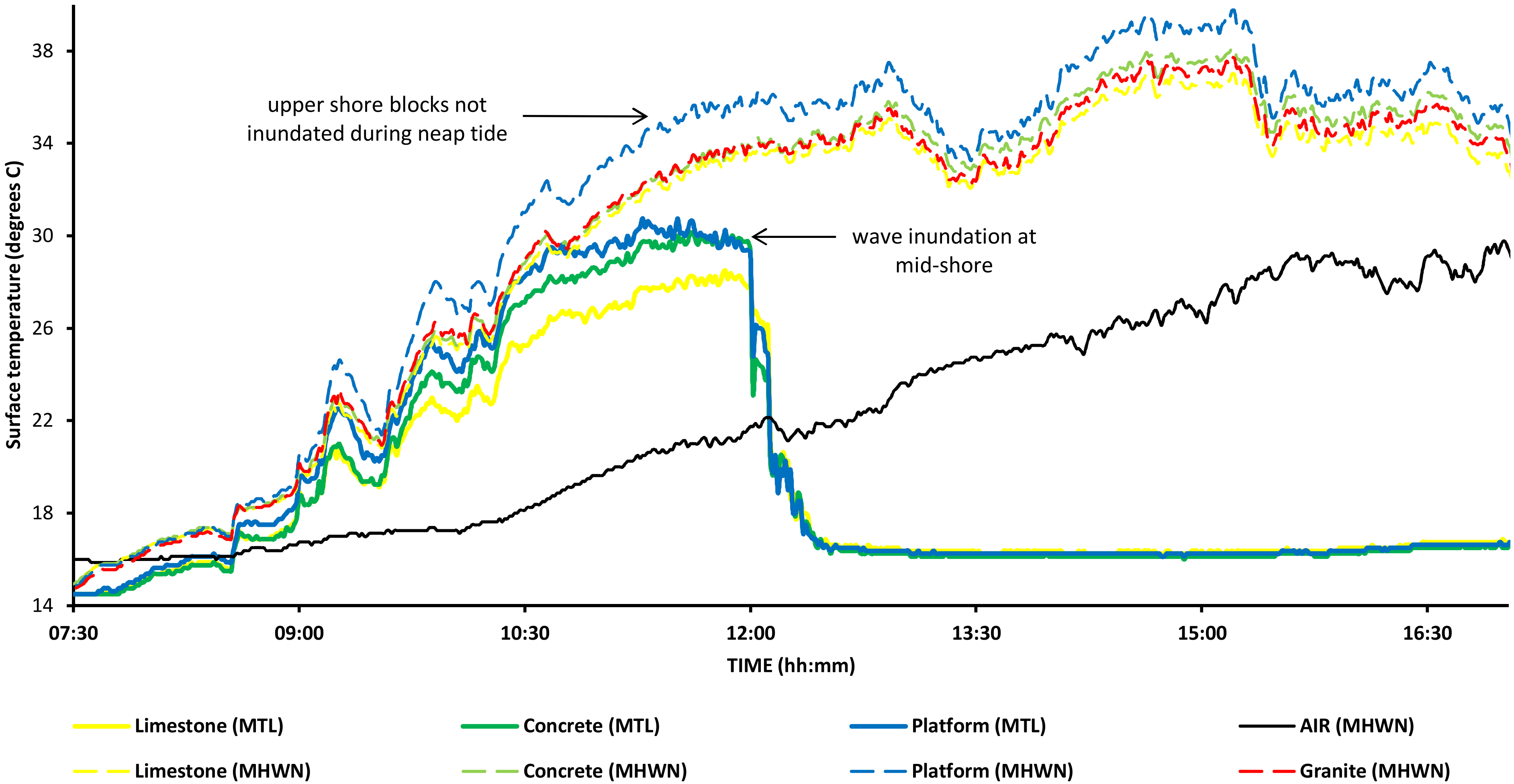


Figure 8-14 Surface temperatures of blocks (no insulation) of different construction materials and platform rock (Mylor Slate), and ambient air temperature, at MTL and MHWN at Tregear Point, Porthleven, during a low (neap) tide on a hot, sunny day (17th August 2009; each line = mean of two replicate records).

Table 8-3 shows surface temperature data for blocks attached in the field on the hottest day recorded (17th August 2009), when air temperature on the shore peaked at 29.8°C. Blocks on the upper shore reached and maintained higher temperatures during neap tides when they were not inundated by the returning tide, and so continued to warm over a longer period of time. Mid-tide blocks did, however, occasionally get hotter than those higher on the shore when upper shore blocks lost heat at a faster rate later in the day, when insolation is reduced (e.g. Figure 8-13).

Table 8-3 Thermal parameters calculated for blocks exposed at different shore levels during a low spring tide on a hot, sunny day at Tregear Point, Porthleven (blocks = 50 x 50 x 40 mm and uninsulated; temperature measured at the block surface, mean *n* = 2).

		LIMESTONE		CONCRETE		GRANITE		PLATFORM*	
	AIR	**MTL**	**MHWN**	**MTL**	**MHWN**	**MTL**$^{\Phi}$	**MHWN**	**MTL**	**MHWN**
Thermal range (°C)$^{\Psi}$	11.50	12.63	22.69	15.63	23.50	/	22.69	16.25	24.81
Peak temp. (°C)	29.75	28.50	37.00	30.13	38.13	/	37.69	30.75	39.75
Time to peak (hrs, from 06:00)	11.00	5.91	9.20	5.60	9.20	/	9.20	5.28	9.20
Max warming (1 min, °C)	1.00	1.00	1.375	1.25	0.88	/	0.88	0.75	1.00

*platform rock was Mylor Slate.
$^{\Psi}$thermal range = difference between maximum and minimum temperature recorded between initial exposure to air and re-immersion by the next incoming tide.
$^{\Phi}$No data available for granite at MTL.

8.7 Discussion

8.7.1 Warming-drying behaviour of construction materials

All materials showed the same pattern of warming and cooling in response to fluctuations in ambient air temperature, but there were consistent differences in the rate and amplitude of change between material types (Hypothesis 16a p. 334). At the beginning of drying, when the lamps first came on, granite warmed faster than concrete, which warmed faster than limestone; these represent responses of materials in the intertidal zone to initial exposure to air by the receding tide. In the first 15 minutes of warming, when air temperature increased by 2.6°C, limestone temperatures rose by 2.1°C, concrete by 2.5°C, and granite (smooth) by 4.0°C. Rough granite warmed by 2.9°C during the same period of time (see discussions below).

Simulated periods of sun (lamp on), shade (lamp off) and wind (fan on) resulted in surface temperature fluctuations in the order of 1 – 2°C every 30 minutes, although some direct warming of the sensors by the lamps and cooling by the fan would have occurred. Warke et al. (1996) describe rapid heat loss from blocks of limestone and sandstone during simulated periods of shade, reporting temperature drops of around 50% within the first five minutes of shade. In this study, in the five minutes of shade following peak air temperature, smooth granite and limestone cooled by 2.3°C, rough granite by 1.8°C and concrete by 1.7°C. The maximum rate of change of air temperature during drying phases was only 0.38°C in one minute, while block surface temperatures changed by 2 – 3°C in the same period of time (Table 8-2).

Albedo and other intrinsic rock properties probably largely explain differences in thermal response of construction materials upon heating (McGreevy 1985b; Hall et al. 2005b; Warke and Smith 2007, see Section 8-2). The lightest coloured material used in experiments was limestone (Figure 8-1), which warmed at a slower rate and had the lowest temperatures throughout drying phases. The limestone also absorbed more water when immersed (see Chapter 4), which probably enabled evaporative cooling at a more consistent rate in association with water loss (Searle and Mitchell 2010, Figure 8-6 and Figure 8-9). The surface of concrete was slightly darker than limestone, and heated up more quickly. Evaporation from the surface of concrete was also quick, losing 50 % or more of the total water loss within the first hour of exposure to air (Figure 8-7). Concrete was consistently hotter than the limestone (the maximum difference at any one point in time was 2.6°C) although surface temperatures tended to converge during the drying phase for control blocks (Figure 8-6). Differences between limestone and concrete were, however, accentuated after a period of field exposure (see Section 8.6.3 above). Warke and Smith (1998) recorded similar relative differences in thermal response of limestone and granite under simulated hot desert conditions to those reported here. Differences were attributed to the intrinsic thermal properties of the materials. The same authors also recorded slower rates of change for limestone compared to granite during warming and cooling phases which was also generally observed here.

Granite heated up the quickest, and reached the highest temperature in the lab (peaking at 32.2°C and 33.0°C on rough and smooth blocks respectively). Granite is darker in colour, with a high thermal capacity (directly related to density) enabling higher temperatures to be attained compared to other rock types (Hall et al. 2008a). The colour of granite is not uniform, however (Figure 8-1), which may induce small-scale, inter-grain stresses through differential expansion (Gómez-Heras et al. 2006).

8.7.2 Texture influences

The surface texture of samples used in weathering simulations is known to influence thermal behaviour (Kwaad 1970; Goudie 2000). Granite was used here to examine the influence of surface texture as this material exhibited the most pronounced thermal response during preliminary testing. The surface temperature of smooth granite was consistently higher than rough (flame-textured) replicates during drying phases (e.g. Figure 8-6). The maximum difference in surface temperature of smooth and rough granite measured at any single point in time was 3.5°C. The average difference during drying phases was 1.9°C.

At the start of the 'daytime dry' phase (0 – 30 minutes) water evaporated from the surface of smooth blocks quicker than rough blocks. After this, more water was lost from the rough blocks (at a faster rate) for the remainder of the drying phase (Figure 8-7a). Cooling of roughened blocks through evaporation of water held at the surface during these later stages therefore probably explains the consistently lower surface temperatures compared to smooth replicates. Rough blocks also tended to loose heat more quickly during periods of 'shading' (i.e. lamps off) and air movement, suggesting evaporative processes. Radiative heat loss may also have been more efficient on rough blocks when insolation was interrupted, as a function of surface area, and thermal gain may have also been reduced by small-scale shading effects on the rough surface (Hall et al. 2008a; Gómez-Heras et al. 2008; Balick et al. 2010).

8.7.3 Comparisons with field data

Relative differences in warming and cooling between materials measured in the laboratory were consistent with blocks placed in the field. Limestone was always the coolest material type. No data were available for granite at MTL, but concrete and granite exposed at MHWN had very similar surface temperatures, although concrete was frequently warmer than granite both in the field and in the lab (for the field-exposed blocks). All introduced materials remained cooler than blocks made of the platform rock, which was probably a function of albedo as Mylor Slate was the darkest of all the materials.

On sunny days, the surface temperatures of blocks exposed at MTL in the field matched well with those simulated in the laboratory, although there would have been unavoidable differences in the intensity of insolation in the field (i.e. weather conditions) and the infrared lamps in the lab. Field blocks also did not have insulating cases and so rates of thermal loss and gain were probably higher for blocks, having more faces exposed to the air. Both lab and field data therefore provide an indication of surface temperatures and relative differences in thermal behaviour that might be expected under a range of heating conditions.

Materials placed higher on the shore were exposed to air and began to warm up earlier than those lower on the shore, which remained covered by the tide for a longer period of time (e.g. Figure 8-13). During neap tides, blocks at MHWN therefore reached higher temperatures than replicates at MTL, which could only heat up until inundated by the incoming tide (e.g. Figure 8-14). In contrast, during spring tides, blocks at both shore levels were able to reach similar temperatures, with some MTL blocks remaining hotter than those higher on the shore due to different rates of cooling (e.g. Hall et al. 2005b). Differences in exposure to wind between upper and lower areas of the shore (due to sheltering by the cliff for example) may have contributed to variations between shore levels. Harley (2008) suggested that thermal conditions experienced by epibiota in the intertidal zone can vary considerably over small spatial scales (at the rock surface) as a function of topography, tide dynamics, and sheltering from the sun and wind.

Short-term temperature fluctuations induced in the lab experiment by simulating shade and wind were also recorded in the field data (e.g. Figure 8-15). This suggests that incorporating periods where insolation is interrupted in lab-based weathering simulations is important for replicating field conditions (Jenkins and Smith 1990; Warke et al. 1996; Smith et al. 2005).

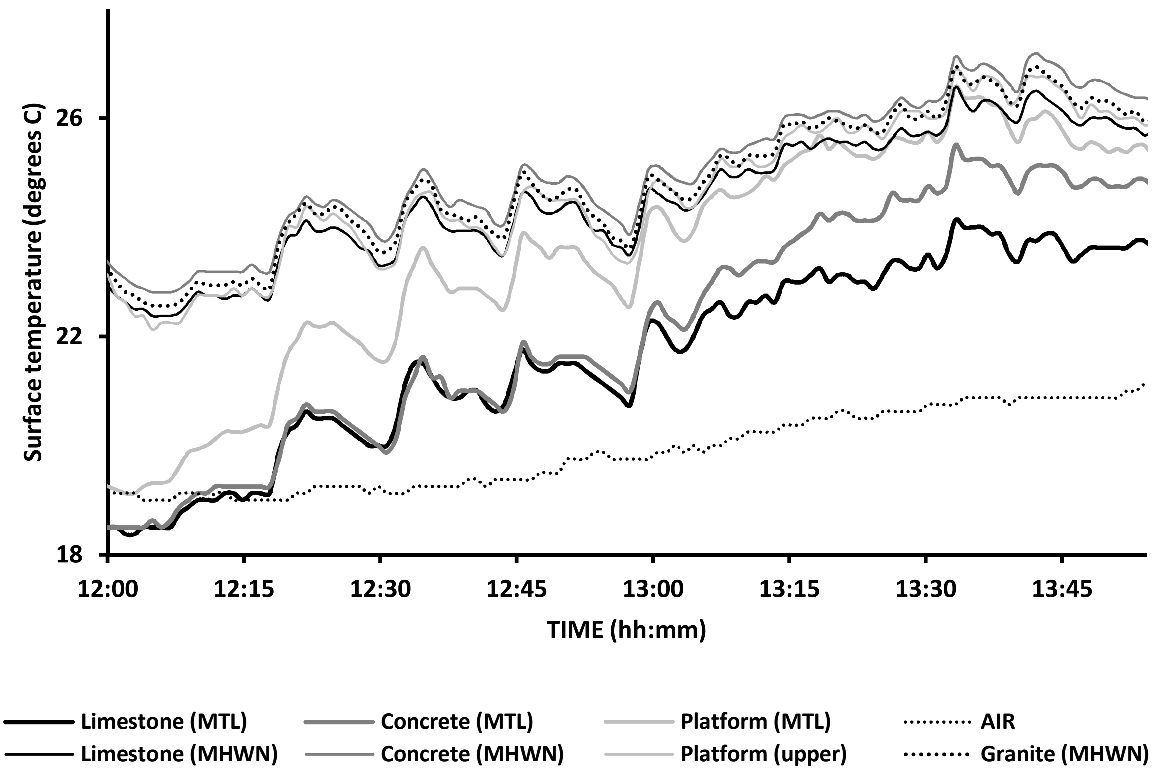


Figure 8-15 Short-term temperature fluctuations of different materials in response to shading (passing cloud) and wind at Tregear Point, Porthleven (each line = mean of two replicate records).

8.7.4 Influence of field exposure on warming-drying behaviour

8.7.4.1 Limestone

Under simulated intertidal conditions, surface temperature patterns of control blocks (unexposed) of Portland limestone were broadly similar to blocks previously exposed in the field for 8 months, but there were interesting differences (Hypothesis 16b p. 334). Control blocks tended to remain cooler during the initial stages of drying (1-2h), while field-exposed blocks were consistently cooler than controls as drying progressed (Figure 8-9). At the time of peak air temperature (26.38°C), control blocks had reached 30.75°C while exposed blocks peaked at 29.96°C (0.79°C cooler).

Observations made at the surface of limestone using SEM (Chapter 7: Strand 1) provide possible explanations for these differences. When initially exposed to drying conditions, evaporative cooling would have occurred on both control and field-exposed blocks when ‘free water’ was available at the surface and near-surface. Water availability is unlikely to be a limiting factor on evaporative cooling during this period (when blocks are first exposed) so that other factors, such as albedo, probably account for temperature differences. Field-exposed blocks were visibly darker than controls following colonisation by microorganisms in the field (no macro-biota had colonised the samples; Figure 8-1), and were indeed hotter during the first two hours of drying (e.g. Figure 8-9). Warke et al. (1996) reported a 40 % increase in the surface temperature of soiled Portland limestone under simulated 'cool ' air conditions, as a function of albedo. In this study, changes in albedo resulting from colonisation in the field (after just 8 months) probably explains the slightly warmer (by 3.2 %) surface temperatures of these blocks compared to control replicates during initial stages of drying.

As drying progressed, the amount of water available for evaporative cooling probably became a more important control on limestone surface temperatures. After two hours, field-exposed blocks were consistently cooler than controls (Figure 8-9). Importantly, previous testing showed that limestone absorbed more water after a period of exposure in the field, probably as a result of bioerosion of the surface by microorganisms (Chapter 7: Strand 4). In comparison to control blocks, it is reasonable to assume that any additional water absorbed by field-exposed blocks (owing to bioerosion and increased porosity) was held near the surface and was therefore available for evaporation (e.g. Donn and Boardman 1988). Indeed, measurements of weight change during drying phases indicated that more water evaporated from field-exposed blocks, at a faster rate, for a longer period of time compared to controls (Figure 8-10a-b).

In a similar way, other weathering processes have been suggested to alter the way rocks wet and dry. Tuğrul (2004) observed changes in the pore structure of a weathered Devonian limestone from Turkey, which she linked to an increase in interparticle and intraparticle spaces and an overall enhanced porosity. Similarly, Sumner and Loubser (2008) recorded changes in porosity, water holding capacity and saturation coefficients of sandstone subject to repeated immersion in distilled water and air drying. Hall and Hall (1996) also attributed increases in the size of pores and micro-fissures in rock to wetting and drying alone. Smith et al. (in press-a) further suggest that surface biofilms and associated EPS retain moisture at the surface of stone substrata, which may have also enhanced water retention and evaporative cooling in this study compared to control (i.e. uncolonised) materials. The specific influence of micro-scale bioerosion on water absorption and evaporative cooling of rock has not previously been recognised as a biogeomorphic feedback, which may have both geomorphological and ecological consequences (see discussions below).

A model of changes in the warming-drying behaviour of limestone following a period of weathering and early colonisation in the intertidal zone is shown in Figure 8-16. The model suggests that when water is available for evaporation from the surface of blocks during initial stages of drying (i.e. when first exposed by the tide), properties such as albedo will be more of a control on surface temperature. As drying progresses, the efficiency of evaporative cooling becomes limited by the availability of water; as relatively more water is absorbed and held at the near-surface of limestone exposed in the field as a function of bioerosion and increased porosity (Chapter 7), evaporative cooling can operate more efficiently, and over a longer period of time, when exposed at low-tide.

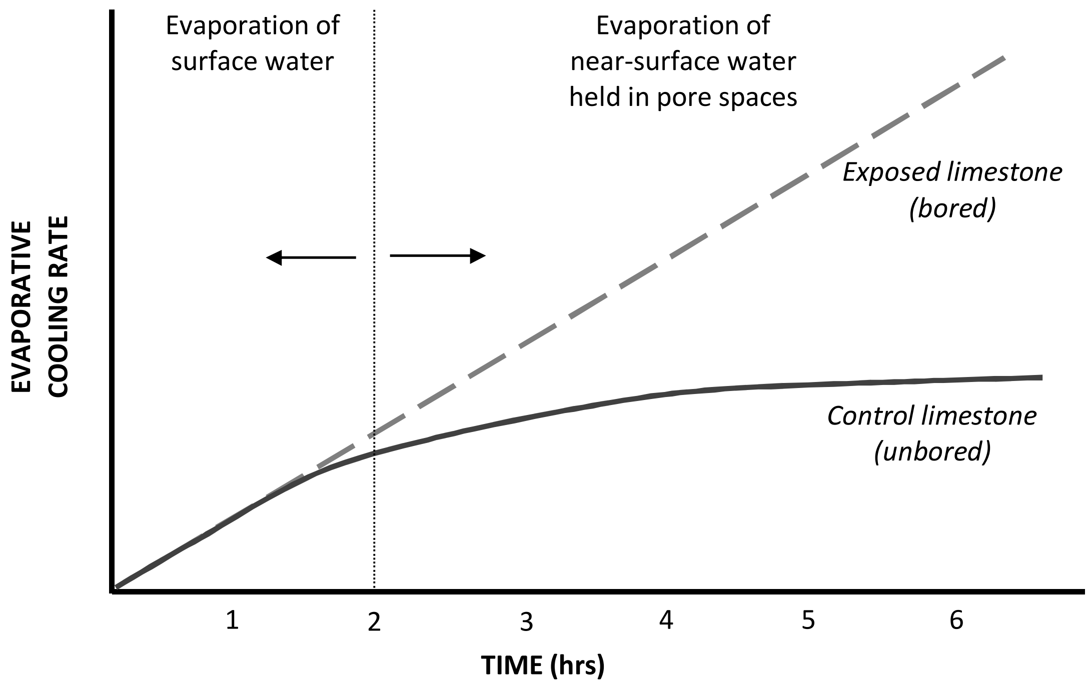


Figure 8-16 A model of bioerosion influences on the efficiency of evaporative cooling of limestone.

8.7.4.2 Concrete response

Differences in the surface temperature of control and field-exposed concrete blocks were marked throughout the drying phase of the simulated intertidal cycle, becoming more accentuated as drying progressed (Figure 8-9; Hypothesis 16b p. 334). Field-exposed blocks were consistently hotter than controls. For the three consecutive peaks in surface temperature, exposed blocks were on average 1.3°C, 1.9°C and 1.8°C hotter than controls.

As with limestone, microscope observations suggest that changes occurring at the surface of concrete during exposure in the intertidal zone, at a micro-scale, influenced subsequent warming-drying behaviour at a bulk-scale. The dominant surface feature (at a micro-scale) on field-exposed concrete was bio-chemical crusting (Chapter 7: Strand 1). These crusts were associated with a significant reduction in water absorption after 8 months (Chapter 7: Strand 2). Drying curves for the concrete indicated that water loss from these blocks occurred at a faster rate during the first few hours of drying, but became reduced during subsequent hours (Figure 8-10a). Evaporative cooling was therefore probably less efficient on exposed blocks (those with a bio-chemical crust) over the full 6h drying phase (i.e. Figure 8-10b) resulting in hotter surface temperatures.

In addition to differences in evaporation, there was visible discolouration (darkening) of concrete after exposure in the sea (Figure 8-1). As with limestone, this would have increased the absorption of thermal energy as a function of albedo (Hall et al. 2005b). Blocks removed after 20 months of exposure (not tested in this experiment) were even darker in colour (10YR 5/2, greyish brown). The relative importance of albedo effects and surface properties (i.e. bio-chemical crusting) for the thermal behaviour of concrete could not be determined, but observations supported the notion that micro-scale biogeomorphological process occurring in the field influenced subsequent thermal behaviour by altering the efficiency of evaporative cooling.

8.7.4.3 Granite response

The warming-drying behaviour of control and field-exposed granite was very similar; differences in surface temperature were always less than 1°C (Hypothesis 16b p. 334). Although exposed granite was very slightly darker than controls (Figure 8-1), colour change was less marked, and more variable, over the surface (owing to its crystalline structure) compared to limestone and concrete. Differences in albedo resulting from colonisation (at least after 8 month exposure in the field) were therefore probably minimal on granite.

The drying behaviour of exposed granite suggests that epilithic biofilms, which were found to be extensive on this material type after 8 months in the field (Chapter 7: Strand 1), may have retained moisture at the surface (e.g. Smith et al. in press) and prolonged the efficiency of evaporative cooling during the drying phase. Conclusions were difficult to make, however, due to the small scale of the differences observed on this material type, requiring more replication to establish consistent trends. In any respect, changes in warming-drying behaviour over a timeframe of months appeared to be less important on granite than limestone and concrete.

8.7.5 Implications for weathering

In addition to purely thermoclastic effects, rock temperatures can influence salt weathering by increasing crystallisation pressures (Sperling and Cooke 1980) and by concentrating salts in surface layers (Davison 1986; McGreevy et al. 2000). In the field, salt efflorescences were often observed on rock platforms and experimental blocks during summer months, and also developed on blocks subjected to simulated intertidal conditions in the laboratory. Salt crystallisation occurs when a critical concentration of salts is achieved through the evaporation of water (Smith and McGreevy 1983). Goudie and Parker (1998) suggest that materials may not experience breakdown despite an abundance of salt if they do not dry out sufficiently for crystallisation to occur; this is important in the intertidal zone where the time during which rocks can dry out is limited by the tide. Whilst granite may have been subject to crystallisation forces more frequently given its ability to lose water more quickly (drying out completely during each drying phase), the aggressiveness of this mechanism may have been limited on this material by the very low amounts of seawater absorbed when immersed. Inter-grain bonds are also much stronger in granitic rocks than the other materials, and are therefore expected to be more resistant to mechanical weathering processes in the tidal zone (Yatsu 1966; Sunamura 1994; Latham et al. 2006), although they may be more important relative to organic weathering processes (see Chapter 7: Strands 1 and 4).

A continued loss of water from the surface of limestone during drying phases, on the other hand (Figure 8-10a-b), indicated that this material did not dry out completely after 6h (under mid-tide conditions) and as such may be less susceptible to salt crystallisation. Surface salt efflorescences were common on the limestone however (as well as other materials), but this may not necessarily be conducive to salt weathering (see Section 8.7.5.1 below). Concrete absorbed significantly more water than granite when immersed (Chapter 7: Strand 2) and dried out more fully than limestone (Figure 8-10a-b) – indicating that salt crystallisation near the surface may have occurred more frequently on this material type.

Increases in the absorption of seawater through micro-bioerosion (µm) of limestone may facilitate salt weathering at the surface, while SEM observations suggested that bulk-scale porosity is probably more important for salt penetration deeper within the rock (Chapter 7: Strand 1). An increase in micro-porosity of the surface also appeared to alter evaporation rates through the retention of moisture at the surface (i.e. Figure 8-16), which may effectively reduce salt weathering efficiency (Rodriguez-Navarro and Doehne 1999; Nicholson 2000) and buffer thermal change at the surface. Discolouration following the development of bio-chemical crusts on marine concrete is suggested to have accentuated temperature fluctuations, and reduce evaporative cooling. Similarly, a reduction in water absorption of concrete placed in the tidal zone may increase the efficiency of salt weathering by allowing crystallisation to occur more frequently (Goudie 1999; Ruiz-Agudo et al. 2007; Yu and Oguchi 2009). These relationships may change over longer periods of time, however, as water absorption did not always show a linear trend with exposure time (see Chapter 7: Strand 2). Observations of warming-drying behaviour after longer periods of exposure are needed to establish clearer relationships.

In contrast to salt weathering, Hall and Hall (1996) suggest that weathering by wetting and drying alone can function even when rocks do not fully dry out. Those materials which did not dry completely during the experiment (principally limestone and concrete) cannot, therefore, be considered free from wetting and drying influences. Limestone also remained wet during low tide when attached on shore (visibly), except at MHWN where all blocks were probably able to dry out during neap and spring tides in summer. The relative importance of salt crystallisation for weathering was probably higher on blocks attached at MHWN, therefore, as a function of tidal height (Mottershead 1989; Stephenson and Kirk 2000b; Gómez-Pujol et al. 2006). Shore position also dictates the frequency of inundation and exposure to air and hence the potential importance of wetting-drying processes (Kanyaya and Trenhaile 2005; Trenhaile 2006; Porter and Trenhaile 2007). The thermal and drying responses of materials under different tidal regimes (occurring as a function of shore position in the field) could be investigated further in the laboratory by altering timing of inundation and exposure (e.g. Trenhaile 2006; Weller 2010).

During the first few hours of drying, both limestone and concrete blocks previously exposed in the field got hotter than unexposed replicates, probably a function of changes in albedo following microbial colonisation (Smith et al. in press-a). Warke et al. (1996) suggest that changes in albedo as a result of surface soiling will be more important for light coloured stone (such as Portland limestone) than darker materials. Drying behaviour (specifically the efficiency of evaporative cooling) appeared to be a more important control on surface temperature over longer periods of drying. Hall et al. (2005) suggest that ‘bulk’ albedo effects are more likely to be implicated in fracturing (‘heat shock’) processes, while grain-to-grain differences will be more important for granular disintegration (Hall et al. 2008a). Granite attained the highest temperatures of the experimental materials in the lab and field, and also changed temperature more quickly; thermoclasty and fatigue effects may therefore be more important for this material type (Gómez-Heras et al. 2006).

Warke et al. (1996) highlight the importance of short-term (minutes) fluctuations in temperature for the breakdown of building stone. In this study, simulated periods of shading and wind induced repeated increases and decreases in surface temperatures that may contribute to the weakening of inter-grain bonds and subsequent breakdown over long periods of time. Similar short-term temperature fluctuations were recorded in the field. Interestingly, limestone showed a slight reduction in the amplitude of short-term temperature fluctuations after a period of exposure in the field (Figure 8-9), which may reduce the susceptibility of this material type to weathering by heating and cooling over extended periods of time. Data on subsurface temperature gradients would be useful here to evaluate the importance of these kinds of changes in thermal behaviour for weathering rates (Warke et al. 1996; Warke and Smith 2007; Smith et al. 2011).

8.7.5.1 Weight loss

Figure 8-17 shows the weight of material collected from the surface of blocks during the two-month experimental run. All material collected (cumulatively, every week) was dried and weighed, then soaked in distilled water for three days, centrifuged to remove dissolved salts, and then re-dried and re-weighed (after Smith and McGreevy 1983). Generally very little material was collected, however there were some key differences between material types. More salt was collected from the surfaces of limestone blocks, although surface efflorescences (in comparison to subflorescences) are not necessarily indicative of salt weathering efficiency (Wright 2002; Thaulow and Sahu 2004). These observations did suggest, however, that crystallisation at the surface was more common on the limestone. The higher amounts of water absorbed by this material when immersed, and lost through evaporation when drying (Section 8.6), probably explains the amount of salt collected from limestone blocks (Goudie 1999).

More debris (by weight) was collected from the surfaces of granite blocks. This suggested that granular disintegration was more effective on this material type, probably resulting from salt crystallisation (Rivas et al. 2003) and/or thermal processes (Gómez-Heras et al. 2006, 2008). Overall block weight changes (see below) indicated that granite was, however, the most durable material type under these conditions (e.g. Warke and Smith 2007).

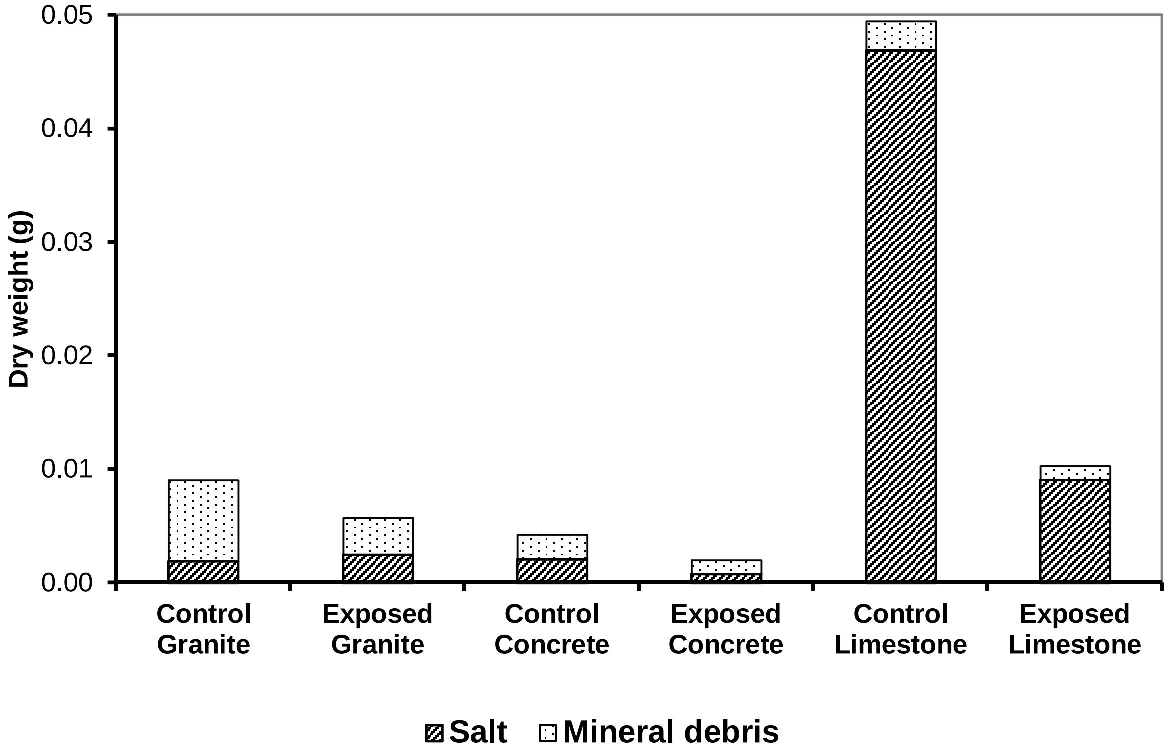


Figure 8-17 Weight of salt and mineral debris collected from the surface of experimental blocks during 2 months exposure to simulated intertidal conditions (mean, *n* = 3).

Generally, less salt and mineral debris was collected from blocks previously exposed in the field (Figure 8-17). This may indicate an initial period of adjustment to new weathering conditions, with higher weathering rates proceeded by relative stability (Pope and Vera 2004; Warke and Smith 2007). Importantly, rock weathering is unlikely to operate in a linear fashion, but is known to be complex and variable in space and time associated with the crossing of stress/strength thresholds which can result in rapid breakdown (Viles 2001; Smith et al. 2005; Smith and Viles 2006).

Measurement of weathering processes under intertidal conditions over longer periods of time would be advantageous (see Weller 2010).

Figure 8-18 shows overall weight change of the blocks after two months, calculated after soaking for one week in distilled water to remove salts (Moses 2001). Most materials lost weight during the experiment, although exposed granite gained weight slightly, which was probably as a result of salt retention even after soaking (Moses 2001; Tingstad 2008). There were no significant differences in weight loss between control and field-exposed blocks for any of the materials (Figure 8-18). Concrete blocks lost the most weight, followed by limestone and then granite. Salt weathering has been shown to cause disintegration of concrete in lab-based experiments (e.g. Liu et al. 2010b; Haynes et al. 2010) and under field conditions (e.g. Matthews 2002; Thaulow and Sahu 2004), associated with the formation and deposition of halite, ettringite, gypsum and brucite (see discussions Chapter 7).

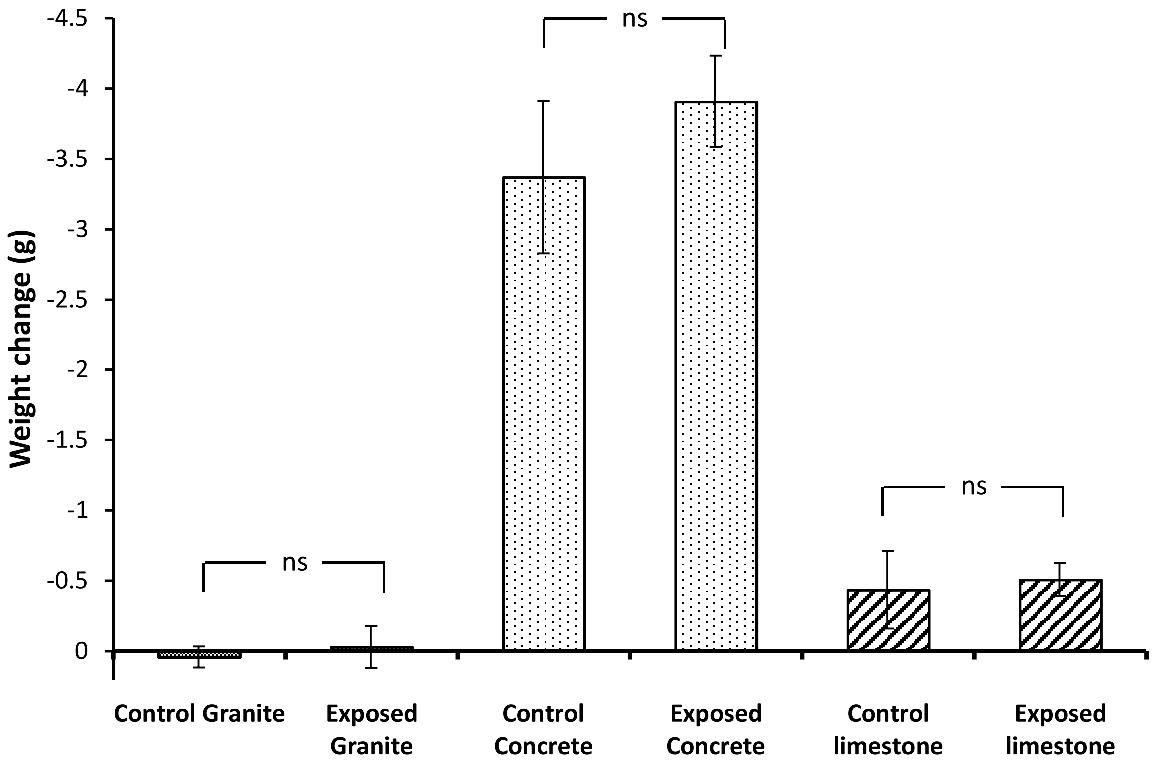


Figure 8-18 Weight loss of different construction materials after two months exposure to simulated intertidal conditions (mean ± SD, *n* = 3, Student's t-test significance as shown, ns = no significant difference).

Overall weight losses did not tally with the amount of debris collected from the surfaces of blocks during the course of the experiment – concrete blocks lost the most weight overall but had least debris for example. This suggests that weight changes cannot be fully attributed to mechanical processes, or that additional material was dislodged and removed in the water during cycling (which could not be collected in the present set-up). Complete desalinisation of the blocks would also have been difficult, which may have affected calculated weight losses (Mottershead 1982; Moses 2001). Due to the nature of the experiment, which aimed to characterise warming-drying behaviour in the presence of moisture and salts, distinction between different breakdown processes such as salt action and wetting and drying could not be made. Chemical weathering was also not assessed here (by analysing water for dissolved loads for example) owing to the combination of material types cycled in each tank, and the exchange of water between tanks; refinements to the method are required to enable these kinds of assessments in a geomorphological context.

8.7.6 Implications for intertidal organisms

Denny and Harley (2006) suggest that the body temperatures of rock habiting organisms such as limpets closely match that of the rock substratum they are attached to. The warming-drying behaviours observed in this study therefore indicate that material choice will influence the micro-climatic conditions experienced by organisms colonising artificial structures and rocky shores. The thermal stress imposed on organisms depends both on maximum body temperature (‘acute stress’) and the duration of temperatures (‘chronic stress’) leading up to that maximum (Helmuth et al. 2002). Materials used in construction that remain wetter and cooler for longer when exposed to the air and insolation (limestone in this case) may therefore offer favourable ecological conditions by mitigating heat and desiccation stress (Moschella et al. 2005). Rocks which heat up more quickly and which reach higher temperatures are expected to accentuate potentially lethal conditions when low tide coincides with peak insolation, particularly in hot weather (Harley 2008). These behaviours varied as a function of inherent geological properties of the substrata. Porosity was shown to be important both for drying rates (and hence surface wetness) and for regulating surface temperatures as a function of evaporative cooling during drying phases. In addition, observations on granite suggested that surface roughness has additional benefits for epibiota beyond habitat heterogeneity (see Chapter 6 and discussions in Chapter 9) by retaining more water and remaining cooler for longer when exposed to the air. This suggested that textural changes on limestone occurring as a function of bioerosion may provide desiccation and thermal benefits for ecology in addition to increases in surface complexity (e.g. Chapter 7: Strand 3).

Raimondi (1988b) suggested that differences in the thermal properties of granite and basalt (as a function of albedo) were responsible for barnacle zonation patterns on natural shores. Similarly, Caffey (1982), McGuinness (1989) and Pister (2007) suggest that differences in colonisation on materials introduced into the intertidal zone may occur as a function of water absorption and retention properties (see Table 2-11 p. 91). In this study, barnacle recruitment on limestone (when roughened) was significantly higher than other materials with similar surface textures (Chapter 6). Although not directly tested, this may have occurred through reduced post-settlement mortality of cyprid larvae on the cooler limestone relative to the other materials, which also got hotter under field conditions. Barnacle larvae are known to be more susceptible to desiccation-related mortality than adults (Foster 1971). The thermal properties of substrata are therefore likely to be most important during initial stages of colonisation, which may have an important influence on succession trajectories (see Chapter 9). These potential effects may be particularly important for organisms colonising higher in the tidal frame (whether on a horizontal shore or vertical seawall) where desiccation stress is expected to be greatest (Chapman and Blockley 2009).

As well as macro-organisms like barnacles, the warming-drying behaviour of a substratum can influence micro-scale colonisation. On seawalls, for example, Iveša et al. (2010) suggested that microbial biomass was enhanced on concrete compared to sandstone, which dried out more quickly. Moist and cool conditions on limestone may equally provide favourable conditions for microorganisms compared to the drier, hotter surfaces of granite in sunny weather. SEM observations suggested that microorganisms where abundant on all materials, however biomass was not directly quantified. Differences at this scale are important for later colonisers which graze on these microbial communities (Donn and Boardman 1988; Iveša et al. 2010; Skov et al. 2010, see Chapter 9). The importance of substratum warming-drying properties on microorganisms is expected to be greatest in summer, when hot and dry weather is known to limit microbial abundance in the intertidal zone (Thompson et al. 2000). Conversely, materials which retain heat under very cold conditions might have ecological benefits in certain climates (e.g. Crisp 1964).

It should not be assumed that substratum heating and drying properties will have equal importance for all organisms. Species that exhibit lower tolerances for desiccation and heating will benefit more from a substratum that remains wet and cool than species able to conserve water more efficiently when exposed. Mussels, for example, which have limited contact with their substrate, are less likely to be influenced by rock temperatures (Helmuth 1988, 1999; Fitzhenry et al. 2004). Limpets and barnacles, on the other hand, have a significant proportion of their body tissue in direct contact with the substrate and may therefore be more influenced by substratum warming-drying behaviour (Lively and Raimondi 1987; Williams and Morritt 1995; B. Helmuth personal communication, June 2009). Denny and Harley's (2006) thermal budget models, for example, indicate that the temperature of limpet body tissue is typically within 1°C of the rock surface. They also found that air temperature does not adequately reflect the body temperatures of epibiota, suggesting that thermal properties of substrata are critical in thermal budgets (Denny and Harley 2006). Furthermore, they note that heat flux is very sensitive to wind speed, so that thermal interactions between substrata and colonising organisms can vary significantly under different weather conditions. Establishing clear and consistent links is therefore difficult.

As well as differences between species, an individual species may be more vulnerable to heat and desiccation stress at a particular stage of its lifecycle. Adult barnacles, for example, are able reduce desiccation by conserving water within their tests (Southward 1958) while newly settled cyprids are far more susceptible to desiccation (Foster 1971, see above). The role of micro-climatic conditions at the substratum surface in mediating environmental stresses experienced by epibiota may therefore be most important when first exposed in the tidal zone i.e. on new structures, when new colonists are arriving. As colonisation proceeds, the warming-drying behaviour of the substratum will change as direct heating of the organisms themselves probably becomes more important than heat transfer from the substrate they are attached to. This is particularly true for organisms that are darker than the rock (Denny and Harley 2006). Rock temperatures are also likely to be more important for organisms during periods of shade and in the evening, when direct insolation stops but the substrata can continue to conduct heat (Denny and Harley 2006).

Results presented here represent the warming-drying behaviours of materials as they are initially exposed in the intertidal zone and during the early stages of succession, in the absence of macro-organisms. The importance of substratum properties (including texture as well as warming-drying behaviour) for epibiota probably decreases as succession proceeds and a greater proportion of the surface is covered by biology (see discussion in Chapter 9). Further work is required to examine the influence of different types of biological growth (including macro-organisms) on the warming-drying behaviour of substrata both in a geomorphological and ecological context. Importantly, more work is needed to test whether these kinds of interactions lead to measureable ecological benefits, such as reduced or enhanced mortality rates, as they may provide a potential example of physical ecosystem engineering and facilitation not previously recognised in the intertidal zone (e.g. Harley 2006, also see discussions in Chapter 9).

8.7.7 Climate change

On rocky shores, the biological response to climate change on a decadal scale is expected to be a spatial one, involving shifts in the distribution of species and populations (Helmuth et al. 2006; Poloczanska et al. 2008; Hawkins et al. 2009). Spatial responses may, however, be limited by the availability of hard substrata (Hawkins et al. 2008). Importantly, coastal structures are increasingly recognised as important components of the coastal habitat as they become more common (see Chapter 2). Artificial coastal structures therefore offer alternative habitat for epibiota responding to climate change, including those species shifting up the shore in response to sea level rise (Thompson et al. 2002). In southern England, for example, geographical responses of barnacles to increasing SST may be facilitated by sea defence structures (Herbert et al. 2007; Hawkins et al. 2009).

Importantly, observations made here (and in a subsequent experiment, Weller 2010) suggest that different materials used to build structures do not respond equally under warming conditions. Ecological processes such as recruitment and mortality are affected by climate (Herbert et al. 2007) so it is reasonable to assume that the ability of organisms to colonise different materials will be influenced, to some extent, by the micro-climatic conditions experienced at their surface (Savoya and Schwindt 2010). Under a warmer climate, recruitment of those organisms (or particular life-stages) susceptible to heat and desiccation stress on construction materials which remain cool and wet for longer periods of time (at low tide) may be enhanced compared to those which offer more stressful conditions. Measurements made in the field and under simulated intertidal conditions suggested that light coloured, porous materials such as limestone stay cooler and wetter at low tide compared darker, dense materials like granite. These factors have been assumed rather than tested in marine ecology (Section 2.7 p. 93). Furthermore, limestone, concrete and granite had consistently cooler surface temperatures than the Mylor Slate platform at Tregear Point, suggesting that artificial structures may offer more favourable (thermally) substrata for epibiota than some *in situ* rocky shore substrata under a warmer climate. These kinds benefits would only be of relevance, however, if the surface complexity (roughness) of construction materials and platform rocks was comparable – which is typically not the case (see discussions in Chapter 9).

Alongside geographic range shifts, climate change will increase the frequency of extreme temperature events experienced by intertidal organisms (Helmuth et al. 2002). Materials which attain higher temperatures during low tide may exacerbate these effects. There will, however, be spatial and temporal variability in the importance of climate change for shore organisms, because particular species may be more sensitive to change and because complex bio-physical factors create a mosaic of thermal conditions at the coast (Helmuth et al. 2002). Substratum-mediated thermal conditions are likely to be more important higher on the shore where rocks and structures heat-up and dry-out more frequently, as they are exposed for longer periods of time.

Unlike weathering processes which typically operate over long time-scales, mortality events associated with heat and desiccation can occur during a single tide (Harley 2008). Thus, the temporal scale at which rock responses to heating are important may be very different in geomorphological and biological contexts. The experimental observations do, however, suggest that changes in insolation and air temperature (in the order of 1 – 2°C) give rise to measurable differences in thermal and moisture conditions at the material surface. Furthermore, the strength of these interactions can be modified by the geomorphological actions of colonising organisms, even at a micro-scale (e.g. bioerosion and crust formation).

8.8 Conclusions

A method was developed to simulate intertidal conditions in the laboratory, during which surface temperatures and rates of water loss could be measured. The thermal responses of different material types in the presence of salts and under tidal conditions have not previously been reported. The procedure effectively replicated conditions measured in the field. Importantly, different materials used in coastal engineering exhibited distinct warming and drying behaviours during the simulation, as well as in the field. Alongside maximum temperatures, differences in rates of surface warming and cooling, and thermal range were observed. For control (previously unexposed) materials, limestone remained coolest, while concrete and granite were increasingly hotter. Differences were attributed to physical material properties, particularly albedo and porosity, the later exerting an important control on the efficiency of evaporative cooling.

Materials exposed to weathering and colonisation in the field for 8 months showed different responses to controls. Field-exposed concrete was hotter than controls, probably as a result of surface discolouration and the restriction of water exchange by the development of bio-chemical crusts observed at a micro-scale (Chapter 7). Micro-scale bioerosion of limestone blocks in the field also probably explained differences compared to control blocks; absorption and retention of more water at the surface of weathered (i.e. bioeroded) limestone was associated with more efficient evaporative cooling of the surface during periods of drying. Granite showed limited change in warming-drying behaviour after field exposure, but retention of water at the surface by microbial biofilms may have facilitated evaporative cooling on this material type.

The implications of substratum warming-drying behaviour for weathering and epibiota are complex. However, greater temperature extremes on granite may be indicative of enhanced thermoclastic mechanisms, while wetting-drying and chemical weathering may be more efficient on the porous limestone. Salt crystallisation occurred on all material types, although the relative efficiency of salt weathering between material types could only be inferred. Importantly, the warming-drying behaviours of different substrata represent the micro-climatic conditions experienced by organisms colonising their surfaces. In this context limestone – which remained cooler and wetter during drying phases – is likely to provide less stressful conditions for epibiota than granite for example, which dried-out and heated-up more quickly. These kinds of differences will be most important during the initial stages of colonisation of artificial structures, and for those organisms and life-stages most sensitive to temperature and desiccation. Differences in the warming-drying behaviour of engineering materials may also become more important for epibiota in the future as artificial structures offer alternative habitat for organisms responding to climate change and sea level rise.

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CHAPTER 9

SYNTHESIS

Biogeomorphology of Hard Coastal Structures: A tool for ecological enhancement

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CHAPTER 9. SYNTHESIS

Biogeomorphology of Hard Coastal Structures: A tool for ecological enhancement

9.1 Introduction

Different ecological and geomorphological aspects of work have been presented in the previous four chapters (comprising *Part 3*) which are interrelated in various ways. Chapter 9 discusses these interactions using the biogeomorphological framework introduced in Chapter 3. Specifically, interactions and feedbacks between biotic (biota) and abiotic (substratum) components are explored using a series of conceptual models, illustrated with examples from experimental work. The models are then discussed specifically in the content of ecological enhancement of artificial hard coastal structures. This kind of conceptual thinking provides a framework within which geomorphological and ecological concepts, and how they relate to each other, can be considered in an interdisciplinary way to achieve holistic understanding (Beers 2009).

9.2 Biogeomorphology of Introduced Hard Substrata

A conceptual model of biogeomorphic interactions occurring on hard substrata placed in the intertidal zone through coastal engineering is shown in Figure 9-1, developed from the theoretical principles discussed in Chapter 3 (see Figure 3-5 p. 126) and experimental work described in the previous chapters. Essentially, each piece of work discussed represents a different component of two interacting feedback loops. The first (Feedback [1] in Figure 9-1) involves biotic responses i.e. colonisation of the surface over time and space. The second feedback loop involves the abiotic response (alteration) of the substratum, through weathering and erosion (Feedback [2] in Figure 9-1). These two types of response, though interacting (Feedback [3], see below), are grounded within the traditionally quite separate disciplines of marine ecology and weathering geomorphology, respectively.

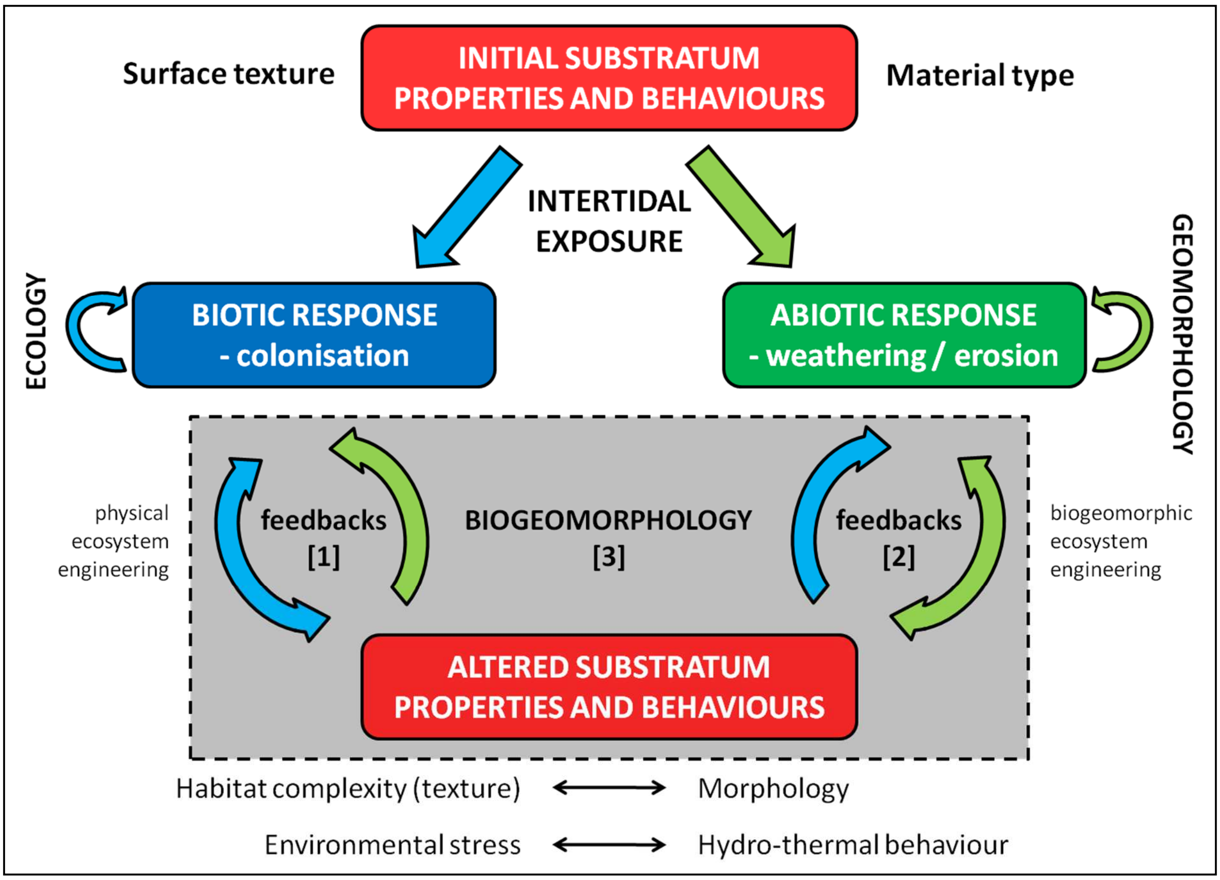

Figure 9-1 Conceptual model of biogeomorphic interactions and feedbacks occurring on hard substrata introduced into the intertidal zone; biotic (blue) and abiotic (green) responses are linked through interacting feedbacks involving the alteration of, and responses to, substratum properties and behaviours (red).

In this study, initial biotic and abiotic responses were largely dictated by material type (lithology) and surface texture, which are themselves closely associated (Section 9.4 below). In field trials, the susceptibility of different substrata to biological, chemical and mechanical weathering and erosion processes once exposed in the sea varied due to inherent lithological and geomechanical differences (e.g. Yatsu 1966; Trenhaile 1987; Yatsu 1988; Chapter 7: Strand 1). The operation of these processes was also of interest in the context of engineering durability (Allsop et al. 1985; Latham et al. 2006; CIRIA 2007; Chapter 7: Strand 2). At the same time, lithology and surface texture influenced biotic responses; microbial colonisation varied between material types, particularly with respect to lithobiontic niche occupation (Section 9.3 below), while fine-scale surface texture (mm-scale) was more important for common macro-organisms (i.e. barnacles, Chapters 5 and 6).

Importantly, the two types of response (biotic and abiotic) were linked through the alteration of substratum properties and behaviours (Figure 9-1). Substratum alteration has implications for the subsequent operation of geomorphological and ecological processes. Certain biotic responses, for example, are involved the direct modification of the substratum (e.g. bioerosion of limestone by microorganisms); these types of direct biotic-abiotic interactions are currently given most attention by biogeomorphologists (Chapter 3). If, in turn, these processes influence the distribution, abundance and interaction of other organisms – by altering habitat heterogeneity for example – then this constitutes 'physical ecosystem engineering' (Figure 9-1, Section 9.4.1 below). The involvement of microorganisms in the textural development of limestone (Chapter 7: Strand 3) and alteration of micro-climatic conditions at the surface through bioerosion, and of concrete through formation of bio-chemical crusts (Chapter 8), are examples of physical ecosystem engineering *processes*. Subsequent monitoring of organisms' responses to these processes are needed to assess ecosystem engineering *consequences* (Jones and Gutiérrez 2007; Gutiérrez et al. In press).

As a further clarification of the ecosystem engineering concept, specific consideration of biogeomorphic processes and associated ecological and geomorphological consequences may better be classified as '*biogeomorphic ecosystem engineering*' (after Francis et al. 2009). Biogeomorphic ecosystem engineering can be thought of as a specific type of biotic-abiotic interaction that has positive or negative feedbacks for the engineering organism and/or other species that interact with the 'engineered' habitat (Jones et al. 1997b; Jones and Gutiérrez 2007). The 'biogeomorphic' prefix denotes that the ecosystem engineering *process* has geomorphic *consequences* (landform building / modification, whether direct or indirect) alongside 'traditional' ecological *consequences* considered under the original concept of ecosystem engineering (Figure 9-1, also see Figure 9-5 later).

In their discussion of fluvial systems, Francis et al. (2009) and Corenblit et al. (2010) suggest that biogeomorphic ecosystem engineers can be inherently linked to particular landscape features, involving reciprocal feedbacks between the engineer and geomorphic processes. This type of association necessarily involves the creation of conditions which favour the establishment or persistence of the engineering organism, and promotes the development of particular geomorphic features (Corenblit et al. 2008). In the context of this study, the creation and potential maintenance of particular types of habitat heterogeneity – whether on construction materials or platform rock – by bioerosion and bioweathering (and potentially bioprotection and bioconstruction), and associated consequences for organisms, may constitute such an interaction. The morphological development of substrata through biogeomorphic processes (as observed on limestone) may facilitate subsequent colonisation and enhance survival of biota by providing favourable surface textures for settlement (e.g. Chapter 5 and 6) and by mediating environmental stresses for example (e.g. Chapter 8). These ecological consequences may further alter subsequent biogeomorphic processes, by facilitating or impeding weathering and erosion. More broadly, these kinds of feedback loops may constitute self-organised systems (e.g. Phillips 1995b; Rietkerk and van de Koppel 2008) where interactions between biotic and abiotic system components result in the emergence of larger-scale, self-perpetuating structures or patterns (Francis et al. 2009; Phillips 2009). Importantly, Francis et al. (2009) stress that biogeomorphic ecosystem engineering and self-organisational processes can occur without any 'intent' from the 'engineering' organism.

Alongside these complex biotic-abiotic interactions involving changes in substratum properties and associated feedbacks to geomorphology and biota, ecological interactions between organisms (e.g. competition and predation) concurrently shape developing communities (Figure 9-1). The relative importance of biogeomorphic processes and feedbacks compared to purely ecological interactions for epibiota is therefore a key theoretical question in epibenthic systems (specifically considered in Section 9.4.2 below). Geomorphologically, purely abiotic weathering and erosion processes also alter the substratum at the same time, changing geomechanical properties and behaviours (Figure 9-1).

SEM observations indicated that inorganic weathering was more important on non-carbonate materials like granite for example (Chapter 7: Strand 1). While these processes may have equally important implications for texture development (and hence habitat heterogeneity), these feedbacks probably operate over a timescale less relevant for ecological potential of coastal structures made of very hard materials (see Section 9.4.1).

In an applied context, improving understanding of these kinds of interactions is the first step in identifying which could be manipulated for ecological (and potentially engineering durability) gains. This involves identifying feedbacks which are likely to be most important for different successional stages, and how the strength of biogeomorphic interactions varies between different materials, and in time and space. These questions are necessary to ensure that appropriate and realistic goals can be set for any particular enhancement scheme (e.g. Ehrenfeld 2000), and necessarily involves the integration and application of ecological and geomorphological understanding (see Chapter 3 and Section 9.8 below).

In the following sub-sections, experimental work from the thesis is used to explore how the strength and relative importance of biotic – abiotic interactions and feedback pathways (as conceptualised in Figure 9-1) can vary between materials types used in coastal engineering. The importance of material 'type' and microbial niche occupation as a control on the strength of biogeomorphic associations is discussed first (Section 9.3). The nature of biogeomorphic interactions in time and space is then explored, placing emphasis on the importance of surface texture as a consequence of 'biogeomorphic ecosystem engineering' (Section 9.4 and 9.5). These discussions are specifically applied to the ecological enhancement of hard coastal structures in the final section (Section 9.8).

9.3 Material Type and Niche Occupation

Figure 9-2 shows a preliminary model of relationships between the nature of hard substratum colonisation by microorganisms and the strength of biogeomorphic associations, as mediated by material type. The model suggests that the geomorphological importance of organisms will be greater on materials within which endolithic colonisation can occur, typically softer and porous substrata (Hoppert et al. 2004). Microorganisms, for example, can penetrate calcareous rocks by secreting chemicals that actively dissolve the substratum (Garcia-Pichel 2006), while larger boring species can penetrate through mechanical means (e.g. Pinn et al. 2005b). In this study, limestone was rapidly colonised by endolithic (specifically euendolithic) microorganisms, involving direct bioerosion of the surface (Chapter 7: Strand 1). Euendolithic colonisation of rock in this way will, by definition, involve geomorphological alteration of the substratum to some extent (Golubic et al. 1981; Pohl and Schneider 2002). These kinds of alterations are expected to have ecological consequences as well as geomorphological consequences (see Figure 9-1 above, and Section 9.4.1 below).

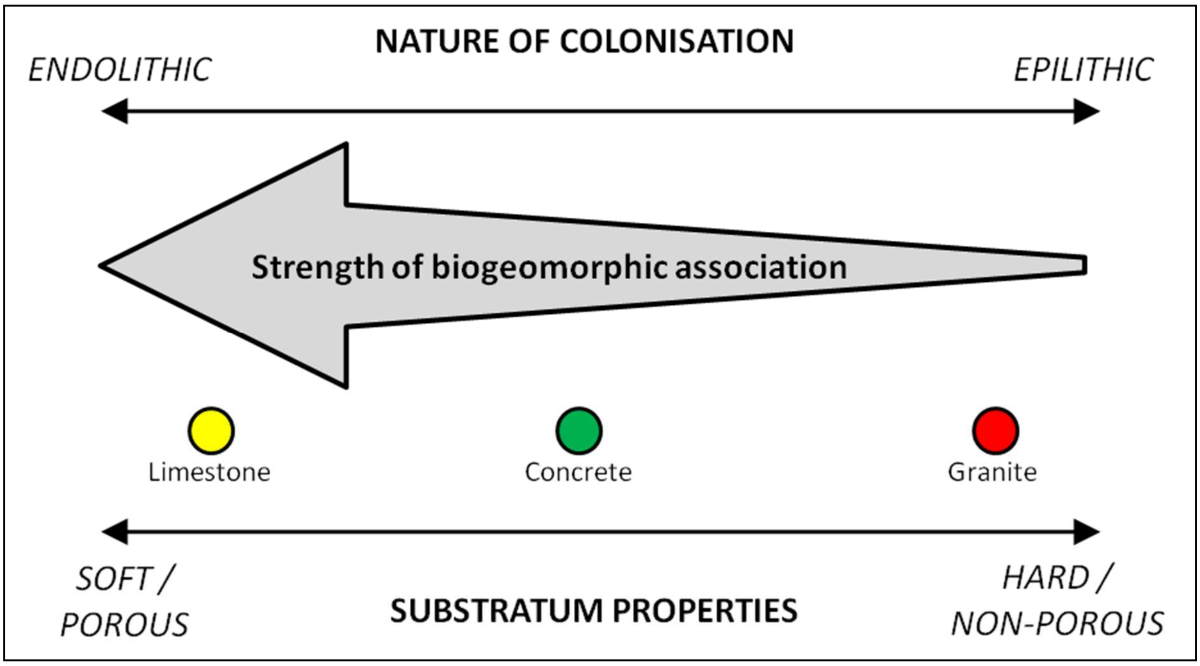

Figure 9-2 Model of substratum-biota association relative to material properties and lithobiontic niche occupation.

In contrast, the model predicts that where colonisation is restricted to the epilithic niche, as was observed on the harder, less porous granite (Chapter 7: Strand 2), the strength of biogeomorphological associations will be limited. Epilithic organisms (as well as endoliths in some instances) can be involved in geomorphological processes on hard rocks like granite (e.g. Guglielmin et al. 2005; Hall et al. 2005a; Song et al. 2007), but the efficiency of bioweathering and bioerosion (and the importance of any associated feedbacks for geomorphology and ecology) on these materials is expected to be much less compared to inorganic processes (Yatsu 1966; Trenhaile 1987). Consequently, the timescale over which organic weathering and erosion processes modify the properties and behaviours of very hard substrata (such as morphology and warming-drying rates) will be much longer than for materials in which endoliths can establish (see Section 9.4.1 below for temporal considerations).

Viles (1995) also suggests that the relative importance of organic processes for terrestrial rock weathering is linked to lithobiontic niche occupation as well as environmental stress gradients (particularly moisture). At a global scale, for example, Viles developed a model which predicts that the efficiency of biological weathering by epiliths will be higher in wet (unstressed) environments, while endolithic colonisation will be more important in dry (stressed) environments. Importantly, Viles recognises that these interactions are mediated by material properties, so that the efficiency of biological weathering will be much reduced on hard rock types, and *vice versa*.

The importance of biogeomorphic feedbacks for epibiont ecology on artificial structures (in an engineering time-frame of decades to centuries) is therefore expected to be less on hard rocks compared to substrata in which organisms can develop endolithically (Figure 9-2). Crucially, the model above suggests that the efficiency of biogeomorphic ecosystem engineering processes, and the relative importance of consequences for colonising organisms and for geomorphologic evolution of the substratum, will vary between materials used in coastal engineering (Figure 9-1). This is of applied relevance because the strength (i.e. efficiency/rate) of such interactions may have direct consequences for ecological potential over the lifetime of an engineered structure (see Section 9.8).

In Figure 9-2, limestone and granite were placed towards two ends of a continuous scale of strength of biogeomorphic interactions based on experimental observations. Other materials may be placed on this scale depending on their inherent physical properties, and hence their susceptibility to endolithic and/or epilithic colonisation. SEM observations showed that marine concrete, for example, lies somewhere between these two extremes (Figure 9-2), being colonised by mixed epilithic and endolithic communities in field experiments (Chapter 7: Strand 1).

It is important to note that the three materials examined here (limestone, granite and marine concrete) represent only three particular examples of a broad range of different lithological types. The strength of biogeomorphological associations on soft limestone like chalk (e.g. Andrews and Williams 2000; May 2005) is likely to be very different than on very hard limestone like Blue Lias (e.g. Naylor 2001) for example. In Grand Cayman, Jones (1989) reports that euendolithic communities were more common within limestone compared to harder, but chemically similar, dolostone – on which epilithic growth was more abundant. Gül et al. (2008) also suggest that the inherent geological differences between various types of limestone (Miocene vs. Jurassic-Cretaceous forms) used in coastal armouring at Mersin, southern Turkey, have influenced the relative rates of bioerosion by polychaetes, boring bivalves and limpets since emplacement, and hence their rates of breakdown and textural development.

A limitation of the model in Figure 9-2 is that it may not hold true for very soft rocks, which may be too friable for both endolithic and epilithic colonisation (Viles 1995; Herbert and Hawkins 2006). Figure 9-3 illustrates this potential control further, suggesting that biogeomorphological interactions will be strongest on calcareous, but coherent substrata like Portland limestone, and weakest on very hard and very soft substrata like granite and chalk, respectively. As another example, sandstone – typically having porosity and strength characteristics more similar to limestone than concrete – may be placed somewhere between the two in Figure 9-3. Biological weathering of sandstone by endoliths and epiliths has been observed under terrestrial (e.g. Budel et al. 2004) and maritime conditions (e.g. Mottershead et al. 2003), although the ecological consequences of these interactions have not yet been assessed on this material type.

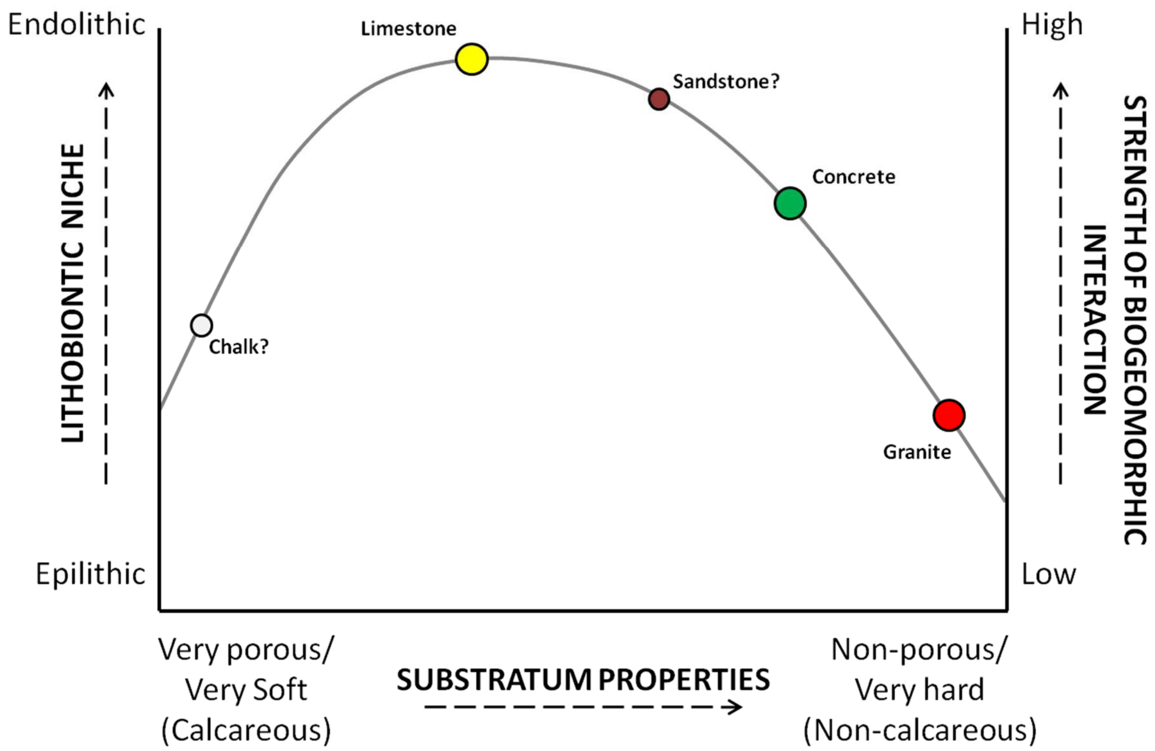

Figure 9-3 Model of lithological control on lithobiontic niche occupation and biogeomorphic interactions.

While both models (Figure 9-2 and Figure 9-3) predict that biogeomorphological processes will be less important on very hard rocks, granitic substrata are subject to endolithic colonisation at least in some terrestrial environments (e.g. Hall et al. 2008b). The models are therefore intended to apply specifically to intertidal rocks based on current understanding, and may best represent differences in the efficiency of organic weathering and erosion relative to inorganic processes on different substrata in this environment. In their broadest sense, the models suggest that an important relationship exists between substratum material properties (i.e. lithology and geomechanical properties and behaviours), the style of microbial colonisation when placed in the sea (whether predominantly epilithic, endolithic, or mixed), the relative strength of biogeomorphological interactions and, importantly, their potential consequences for ecology and geomorphology through time (Figure 9-1). More study of colonisation and biogeomorphic interactions on a range of other substratum types is therefore needed to further test these models.

9.4 Temporal Considerations

9.4.1 Texture as a biogeomorphic ecosystem engineering consequence

A principle question that emerges from the work presented in this thesis is how, and to what extent, the weathering and erosion of different substrata is linked to their colonisation and, essentially, their ecological potential when used to build artificial structures (Chapter 3). It is suggested that a fundamental link between the two is surface texture. Existing ecological research on rocky shores has clearly demonstrated strong associations between habitat heterogeneity and ecological processes at a range of spatial scales, including the importance of micro-scale surface texture (< mm) for early colonising species (see 2.3.3.3 p. 64). Field experiments demonstrated that these interactions also operate on materials commonly used in coastal engineering, and perhaps more importantly, that they may be manipulated for ecological gain (e.g. Chapter 6, see Section 9.8).

A limitation of existing intertidal ecology research has been an assumption that hard substrata are largely static in time (see 2.7 p. 93). It has been shown here, however, that rocks and construction materials respond geomorphologically to intertidal exposure at different temporal and spatial scales, through inorganic and organic weathering and erosion. The nature of interactions and feedbacks between substrata and colonising organisms (i.e. Figure 9-1) consequently also varies in time and space.

Figure 9-4 shows a model of the relationship between fine scale (< cm) substratum surface roughness and time, based on experimental observations described in Chapter 7. When first exposed, surface roughness (and hence fine-scale habitat heterogeneity in ecological terms) is defined by the initial texture of the substratum, whether placed in the sea for engineering purposes or becoming available following disturbance on natural rocky shores (see Section 9.6 for considerations of disturbance). Fundamentally, the model suggests that once exposed, the roughness of a substratum is altered through time by weathering and erosion, but that the efficiency of these processes in creating roughness varies according to material type. The surface roughness of limestone, for example, increased in the field at a millimetre scale during the first two years of exposure (Chapter 7: Strand 3). Microscope observations showed that this relatively rapid textural response was a result of bioerosion by euendolithic microorganisms (Chapter 7: Strand 1 and Strand 4). In contrast, biogeomorphological processes were less efficient on a hard, less porous material (granite) over the same period of time. Microscope observations of granite from structures over 100 years old also showed limited evidence of alteration beyond the material surface (Appendix 3). The model predicts, therefore, that the surface texture of harder materials will remain relatively constant over an engineering timeframe of decades and centuries (Figure 9-4).

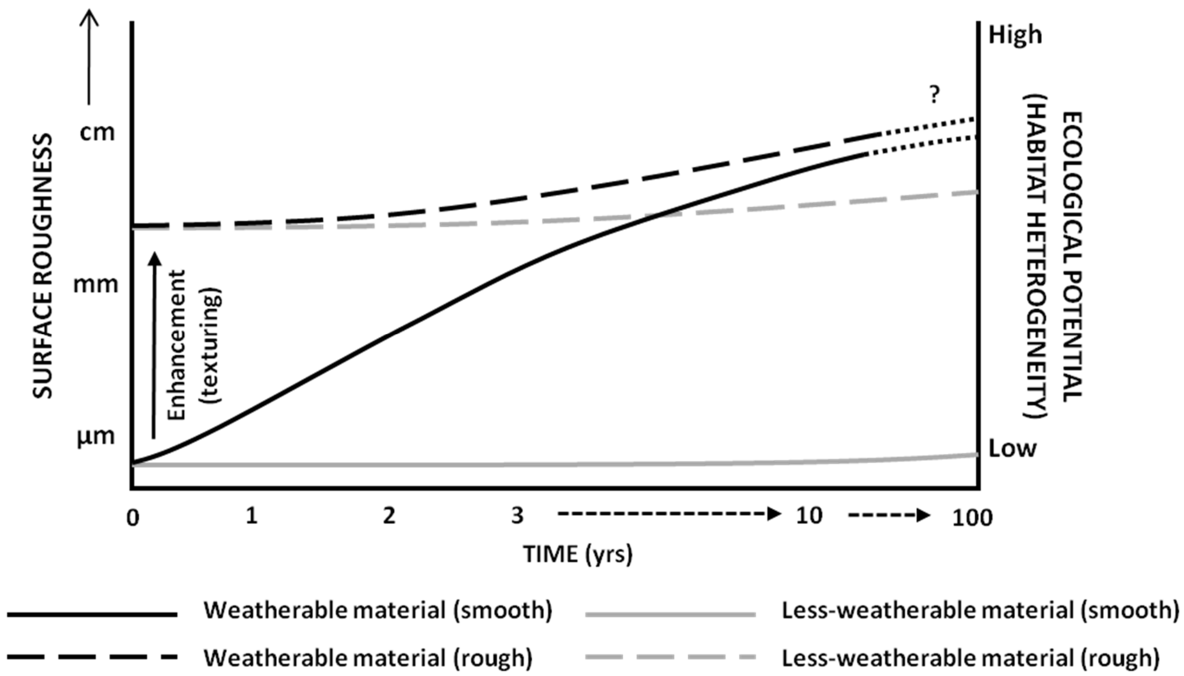

Figure 9-4 Model of changes in surface roughness and associated ecological potential (habitat heterogeneity) of weatherable (soft/calcareous) materials and less-weatherable (hard/non-calcareous) materials following initial exposure in the intertidal zone (see text for details).

Assuming a relationship between habitat heterogeneity and ecological potential (supported by the current research), surface roughening by weathering and erosion may constitute an increase in ecological potential of the substratum. This initial geomorphic 'conditioning' (cf. Wahl 1989) of the surface may be necessary on smooth materials before early colonists can become established and succession can continue (i.e. weathering of natural rocks, e.g. Moschella et al. 2005; Herbert and

Hawkins 2006, Section 9.7). Colonisation of rock in terrestrial environments also shows relationships with material hardness and roughness. Lichen colonisation rates, for example, are typically lower on hard and smooth rocks compared to weathered (i.e. rougher) surfaces (Innes 1985). Similarly, Koestler et al. (1985) also suggest that rock hardness and roughness (at a micro-scale) are important for bacterial colonisation.

Importantly, the rate at which texture develops can vary greatly between material types (Figure 9-4). In field trials, sawn limestone and granite and smoothed (wiped) concrete had low surface roughness (at a µm-mm scale) when initially exposed, and consequently supported very low barnacle recruitment during the first settlement season (Chapter 5 and 6). In subsequent years, recruitment to smooth granite and concrete remained minimal, as the morphology of these materials did not change dramatically, while measurable increases in the roughness of limestone (Chapter 7: Strand 3) probably facilitated cyprid settlement on this material type over the same period of time; the biogeomorphic responses and consequences for ecology varied between material types exposed in the same location after only two years.

In this context, roughening of intertidal substrata by euendolithic microorganisms provides a previously unrecognised example of physical ecosystem engineering, having positive consequences for other organisms (barnacles in this example; Jones et al. 1994, 1997b; Jones and Gutiérrez 2007). Observations discussed in Chapter 8 further suggest that alteration of limestone by microorganisms may modify micro-climatic conditions at the surface during low tide in a favourable way. Given that these interactions also have geomorphological consequences, by weakening or strengthening the surface (e.g. Chapter 7: Strand 2) and by altering wetting-drying rates (e.g. Chapter 8) for example, bioerosion and modification of intertidal substrata by microorganisms constitutes ‘biogeomorphic ecosystem engineering’ (Section 9.2 above); this is shown schematically in Figure 9-5.

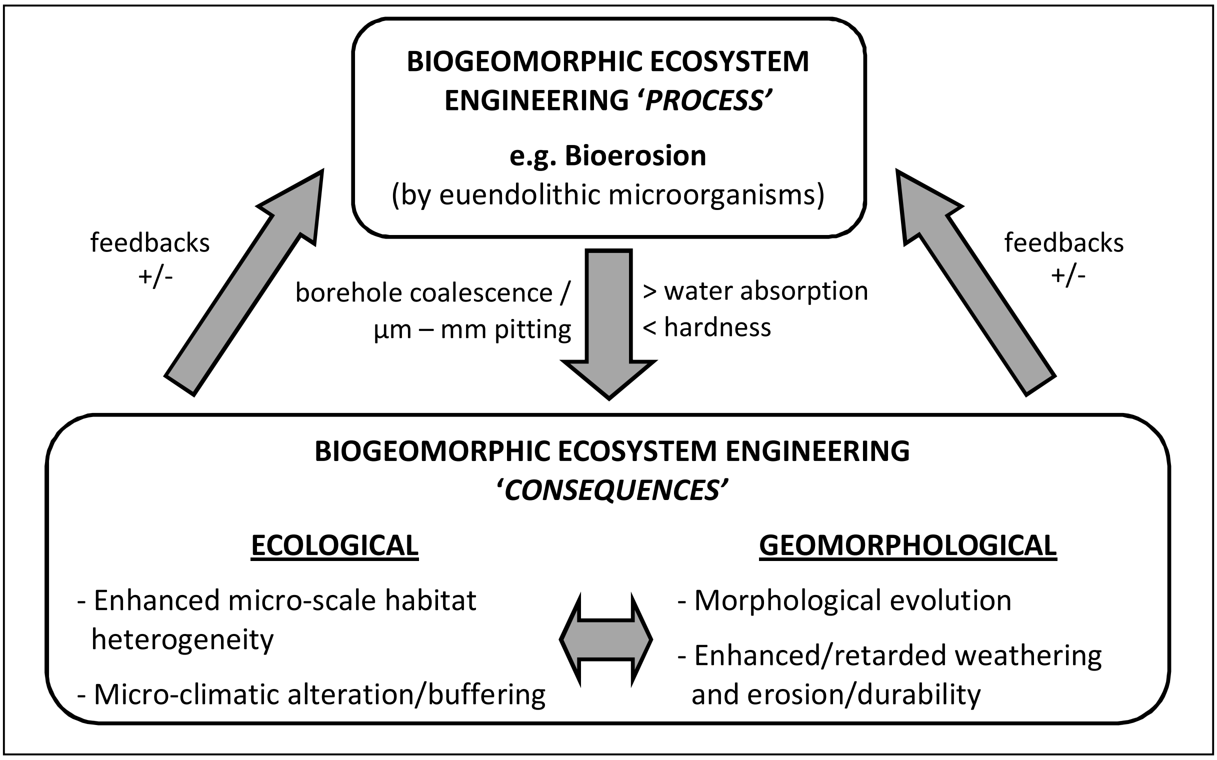

Figure 9-5 Bioerosion of limestone as an example of 'biogeomorphic ecosystem engineering' in the intertidal zone: biogeomorphic *processes* have ecological and geomorphological *consequences* (*sensu* Gutiérrez et al. in press).

9.4.2 Substratum vs. ecological influences through time

The processes, rates and trajectories of succession in the rocky intertidal zone have been well studied using observational and manipulative field experiments (e.g. Farrell 1991; Palmer-Zwahlen and Asletine 1994; Anderson and Underwood 1994; McKindsey and Bourget 2001; Martins et al. 2007). These studies suggest that in many instances, colonisation of hard substrata is broadly predictable, at least in the absence of major disturbance events (see Section 9.6). Microbial biofilms can develop within a matter of hours (MacLulich 1986; Wahl 1989) becoming mature after several weeks (Moschella 2003). These communities are followed by ephemeral algae and sessile invertebrates (e.g. barnacles), then perennial algae and the recruitment of motile grazers over the course of a few years (Dayton 1971).

Once colonisation of a surface begins, epibiotic assemblages may converge with mature communities given sufficient time. Such convergence has been observed on artificial structures (e.g. Southward and Orton 1954; Osman 1977) and on experimental panels made of various materials (e.g. Anderson and Underwood 1994). This assumes, however, that ecological conditions (e.g. larval supply) and physical conditions (e.g. wave exposure and substratum properties) and are not limiting factors on engineered structures, which they may well be (Bulleri and Chapman 2010, see below). More recently, the complexity of succession trajectories and, specifically, the importance of interactive mechanisms such as facilitation, inhibition and tolerance, have been stressed in the intertidal zone (Bulleri 2009; Thomsen et al. 2010). These kinds of interactions may be purely biotic (occurring between organisms) or involve interactions with the physical environment, including the substratum (Viejo et al. 2008; Thomsen et al. 2010). Subtle differences in the physical properties of structures, and ecological responses to them, therefore mean that successional pathways can be divergent even where environmental conditions are broadly similar (e.g. Chapman and Underwood 1998).

The extent to which traditional theories and models of rocky shore succession can be applied to artificial structures has not been established, but is probably limited due to fundamental differences in the nature (i.e. physical complexity) of construction materials compared to weathered shorelines (Bulleri and Chapman 2010). Farrell (1991), for example, suggests that ecological 'end-points' may in fact be easier to predict for less diverse communities, as is typically the case on artificial structures. Weathered rocks forming shore platforms generally provide more structurally complex habitat at a range of spatial scales (e.g. Archambault and Bourget 1996) than newly built artificial structures (Chapman 2003; Chapman and Bulleri 2003); such differences have been suggested as major factors contributing to their ecological divergence (Chapter 2).

Southward and Orton (1954), for example, suggested that epibiontic assemblages on Plymouth Breakwater had had sufficient time (c. 100 years in their study) to become similar to nearby rocky shores (see specific discussions of this structure in Section 9.8.1.3). Pister (2009) also found that 50 –

100 year old riprap structures in California supported a similar community to nearby rocky shores. Chapman and Bulleri (2010) argue that the age of the riprap examined by Pister may have given sufficient time for the materials to weather, creating more ecologically favourable surfaces. Moschella et al. (2005) and Herbert and Hawkins (2006) also note the importance of weathering processes in an ecological context over long time-scales (see other examples in Table 2-10 p. 90).

Figure 9-6 presents a model of changes in the relative importance of substratum properties (such as surface roughness, above) for intertidal epibiota through time. Fundamentally, the model predicts that substratum properties are critical for early successional stages, but that the relative influence of the substratum will decrease as biological cover increases, after which ecological interactions become more important.

For example, in this research, early colonists (microorganisms and barnacles) were strongly influenced by lithology and substratum surface roughness (above). The importance of substratum warming-drying behaviour in mediating environmental stress is also expected to be greatest during early stages of colonisation, when there is direct contact between the substratum and settling organisms (Chapter 8). As succession continues, a more complete and thicker cover of biofilm, encrusting barnacles and macro-algae develops over the substratum (depending on tidal height, see Section 9.5), reducing direct interaction between the substratum and subsequent colonisers (Hutchinson et al. 2006). Kaehler and Williams (1997), for example, suggest that invertebrates may only be influenced by substratum roughness when they first settle, and that tropic and facilitative ecological interactions between species become more important during later successional stages. Similarly, differences in micro-algal communities observed during initial stages of colonisation were attributed to substratum microtopography and composition by Edyvean et al. (1985), but no differences were observed in mature biofilms. Canopy-forming species like fucoid algae are also probably more important for proving refuge from desiccation and thermal stress, and hence in facilitating colonisation and survival of other species, in mature communities than warming-drying properties of the substratum (e.g. Hawkins 1983; Thompson et al. 1996; Harley 2006; Chapter 8).

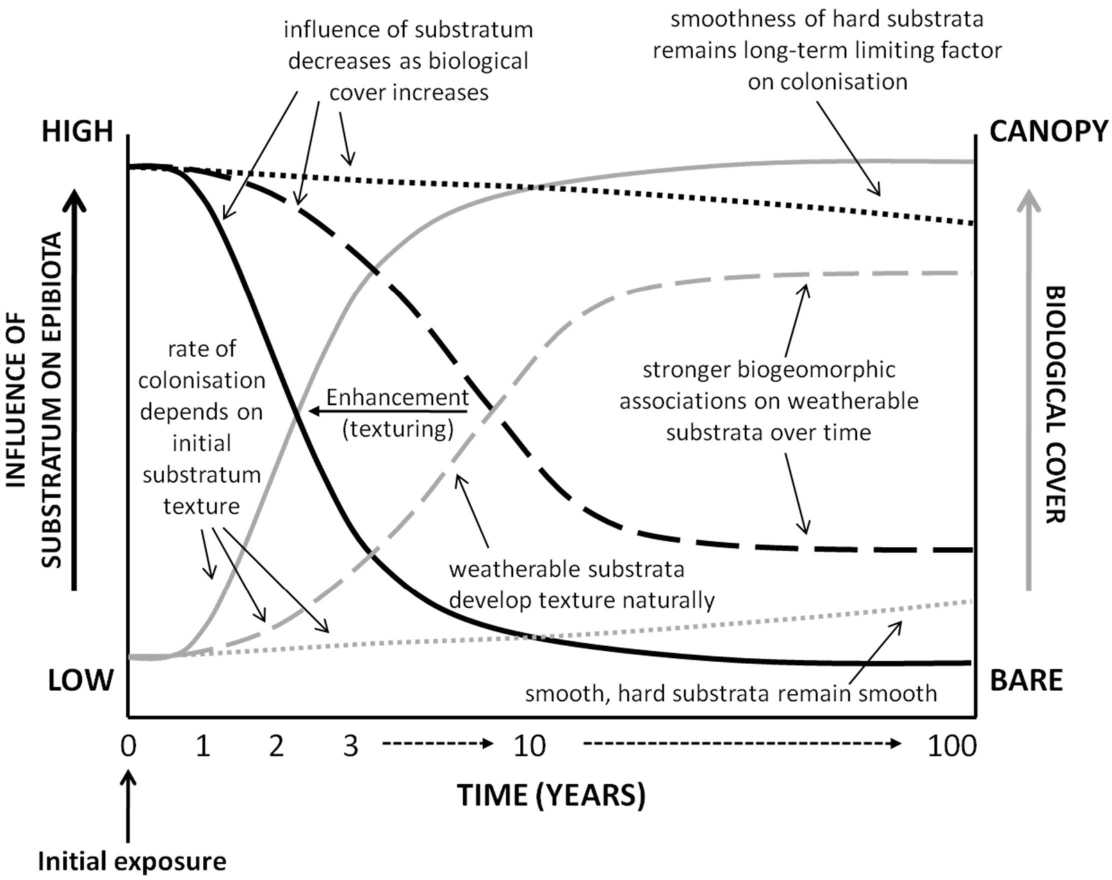

Figure 9-6 Model of changes in the relative influence of substratum properties on intertidal epibiotic communities (black lines) and biological cover through time (grey lines): solid lines = rough material; dashed lines = smooth but weatherable material (e.g. limestone); dotted lines = smooth, less-weatherable material (e.g. granite).

The model predicts a general inverse relationship between biological cover and the relative influence of substratum over purely ecological interactions (for epibenthic assemblages) through time, but that this relationship is mediated by material type and initial surface texture (Figure 9-6). In the field, for example, rough materials placed on the mid-shore became covered by barnacles within the first two years of exposure (Chapter 5 and 6). The model therefore predicts that on rough substrata, ecological interactions like predation, competition and facilitation will quickly become more important than initial biogeomorphic influences. In contrast, initial colonisation of smoother materials was slower, so that the importance of the substratum (as a limiting factor in this instance) is expected to remain relatively high for longer (Figure 9-6). Importantly, while any limits placed on colonisation by smooth substrata may persist throughout the design life of a structure if that material is less-weatherable like granite, a smooth but weatherable material like limestone may develop roughness naturally through organic and inorganic weathering and erosion (i.e. Figure 9-4; Chapter 7: Strand 3). The importance of substratum properties for epibiota on weatherable materials is therefore predicted to remain high over longer periods of time, as biogeomorphic processes can continue to operate (see Section 9.8.1.3 for an example).

In the model (Figure 9-6), artificial texturing results in a shift in the point at which the relative influence of substratum and ecological interactions cross, to the left of the diagram. That is to say, colonisation is expected to be quicker on roughened substrata (as observed in field experiments, Chapter 6) so that biological cover will increase faster, and ecological interactions will become more important for developing communities more quickly compared to smoother, harder materials. This may constitute ecological enhancement, by increasing the rate of initial colonisation and enabling succession to continue. The importance of these early-stage interactions for later succession and, ultimately, ecological potential, are emphasised in Section 9.7 below.

9.5 Spatial Considerations

As well as variations through time (above), the relative importance of substratum properties for biota varies in space. Various features of the environment (abiotic and biotic) become more or less influential at different spatial scales (e.g. Hills et al. 1998). Figure 9-7 suggests that in the context of artificial structures, substratum material properties like roughness are most important at a small scale (< cm; e.g. Le Tourneux and Bourget 1988; Bourget et al. 1994; Anderson and Underwood 1994; Lapointe and Bourget 1999; Chapter 6), while engineering design features (such as block size and arrangement, wave exposure, presence/absence of pools and shore position) will be more influential at the meso-scale (cm – m; e.g. Moschella et al. 2005; Thompson et al. 2005; Moreira et al. 2007; Chapman and Blockley 2009; Martins et al. 2010). At larger scales (> m), environmental controls such as larval supply and climate are expected to be most influential on the nature of epibiontic assemblages (e.g. Hawkins and Hartnoll 1982a; Minchinton and Scheibling 1991; Davenport and Stevenson 1998; Menge et al. 2009).

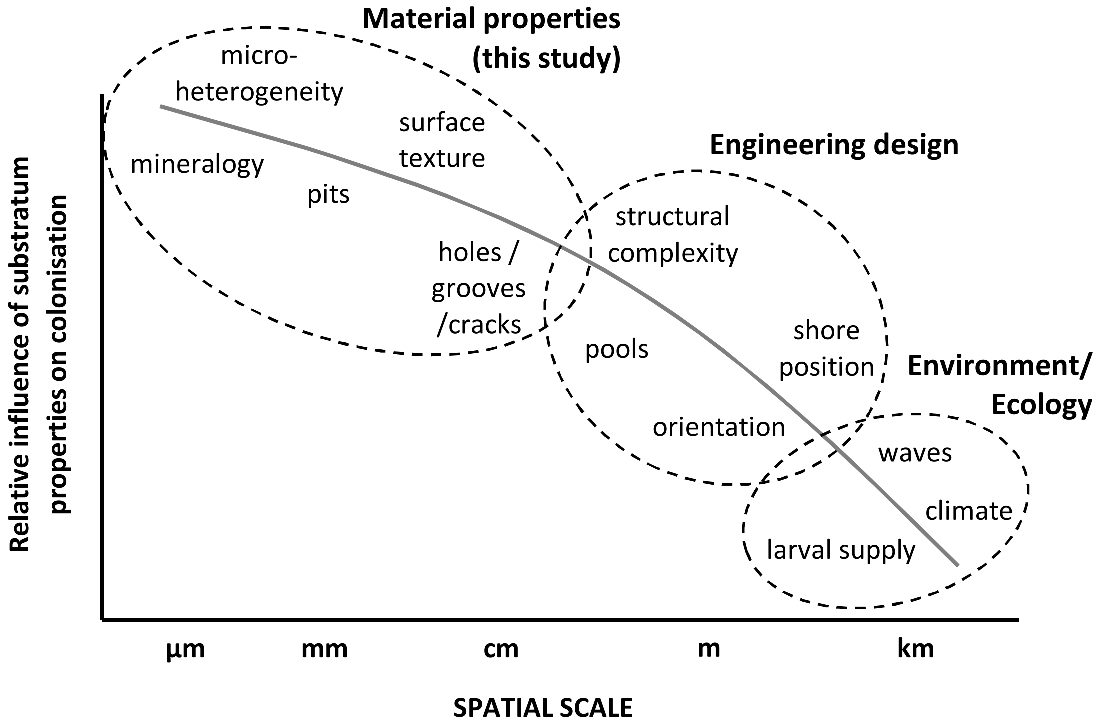

Figure 9-7 Model of the relative influence of substratum properties on the establishment of epibiontic communities on artificial coastal structures at different spatial scales.

Given that refuge requirements for different species may not be the same, the presence or absence of refuges at a range of spatial scales will be an important control on community structure (Walters and Wethey 1996). Particular scales of refuge will also be more or less important at different life-stages, and may also change as succession proceeds. Settling larvae typically show strong responses to fine-scale texture for example (e.g. Chapter 5 and 6), while pools and crevices are of greater importance for later colonists, which tend to be larger in size and may actively move to these refuges at low tide (e.g. Menge and Lubchenco 1981; Martins et al. 2007).

The strength of biogeomorphic interactions and feedbacks are also expected to vary across the shore. Textural development through bioerosion is predicted to be greatest lower on the shore for example, while inorganic processes like salt weathering are expected to be more important for substratum alteration at higher tide levels (e.g. Gómez-Pujol et al. 2006; Gómez-Pujol and Fornós 2009; Appendix 2). The importance of texture (whether the result of artificial manipulation or via weathering) for settlement and survival of early colonists may also be greatest higher on the shore, where environmental stress is more critical (Paine 1974; Hawkins and Jones 1992), and on exposed shores where disturbance events may be more frequent (see below). With respect to Figure 9-6 above, the relative importance of competition and facilitative interactions between species also varies vary across the shore (the 'stress-gradient hypothesis' e.g. Maestre et al. 2009), but these relationships are not always predictable (Viejo et al. 2008). Grazing influences, for example, appeared to explain differences in the general abundance of microbial growth features between shore levels (Appendix 2). An important implication of these complexities is that the influence of particular enhancement interventions is likely to vary spatially across the shore and, importantly, may be more or less effective for different organisms (see Section 9.8.4).

9.6 Disturbance

Disturbance is known to be important both for intertidal ecology (e.g. Sousa 1985; Hutchinson and Williams 2003a) and in biogeomorphology (e.g. Viles et al. 2008). For simplicity, the temporal models presented above (Figure 9-4 and Figure 9-6) assume the absence of major disturbing influences, which can include both environmental and ecological factors. Interactions between substratum and epibiota may be greatly modified in highly abrasive environments for example, where colonists may be largely excluded (e.g. Moyse and Nelson-Smith 1963; Airoldi 1998). Similarly, morphological development and physical alteration of the substratum in high-energy environments may be dominated by inorganic processes (e.g. localised abrasion and wave erosion) rather than biogeomorphic processes (e.g. Blanco-Chao et al. 2007). Ecologically, colonisation of a surface is predicted to take much longer than a few years if larval supply is a limiting factor, even if surface roughness is favourable (e.g. Minchinton and Scheibling 1991; Olivier et al. 2000); for artificial structures, larval supply relates to shore orientation and proximity to source areas of settlers, that is to say other natural hard-bottomed communities (e.g. Garcia et al. 2007).

Disturbance in the intertidal zone creates a patchy mosaic of bare space both in space and time, re-exposing substrata to ecological and geomorphological processes. Following such an event, the relative importance of substratum properties for biota will be similar (if not equal) to that when initially exposed. In this respect, the relationships suggested in Figure 9-6 between substratum influences and biological cover through time should not be regarded as uni-directional, but may revert back to the left of the model following disturbance (where substratum influences are most important). For engineered structures, maintenance activities or the partial or complete replacement of the structure may constitute such a disturbance; these activities may expose new substrata and/or re-exposure previously colonised surfaces, on which biogeomorphological interactions may be 'reactivated'.

9.7 The Importance of Biogeomorphic Interactions for Ecological Potential

While Figure 9-6 predicts that substratum influences on epibiota will decrease through time as colonisation progresses, initial biogeomorphic interactions (when materials are first exposed) are of relevance for ecological potential over longer time-scales because the timing and magnitude of colonisation by early settlers influences later successional stages (Farrell 1991).

Field exposure trials and microscope observations have demonstrated that the physical nature of the substratum (lithologically and geomorphologically) strongly influenced the rate and abundance of primary colonisers (microorganisms and barnacles) on materials commonly used in construction. Models of succession predict that these differences will influence the rate of arrival of other species (e.g. Connell 1972; Connell and Slatyer 1977; Connell et al. 1987; Farrell 1991; Pawlik 1992; Wieczorek and Todd 1998). The presence of biofilms, for example, influences the settlement and development of macroalgal propagules (Huang and Boney 1984; Callow and Callow 2000), as well as provide settlement cues for other colonists including barnacles (Le Tourneux and Bourget 1988;

Thompson et al. 1998) and mussels (Satuito et al. 1997). Differences in microbial communities developing on materials used in coastal engineering may also influence the abundance and reproductive success of grazing organisms (Iveša et al. 2010).

As an illustration of these potential influences, a subsequent survey of experimental blocks remaining in the field towards the end of the study (September 2010) showed that limpets and macro-algae (*Fucus* spp.) had become established on treatments on which barnacle cover was initially very high (i.e. artificially roughened blocks and clearings on the weathered rock platforms, Figure 9-8). In contrast, treatments which had remained sparse of barnacles (the smooth blocks) supported no macro-algae after the same period of time. Farrell (1991) also notes the importance of early colonisers for the subsequent establishment of other species on rocky shores.

Recognising that early colonisation is important for successional trajectories (above), manipulating the substratum (through material type and texture, Section 9.8.1) remains important for enabling colonisation and subsequent succession to progress in the first place, and in influencing the rate at which succession proceeds. It may also be possible to target specific colonists that are known to facilitate colonisation and/or the survival of other species of particular conservation or economic interest. This was the approach adopted in Seattle, where the research team aimed to enhance populations of Pacific Salmon by facilitating colonisation of seawalls by their prey species' (Goff 2010).

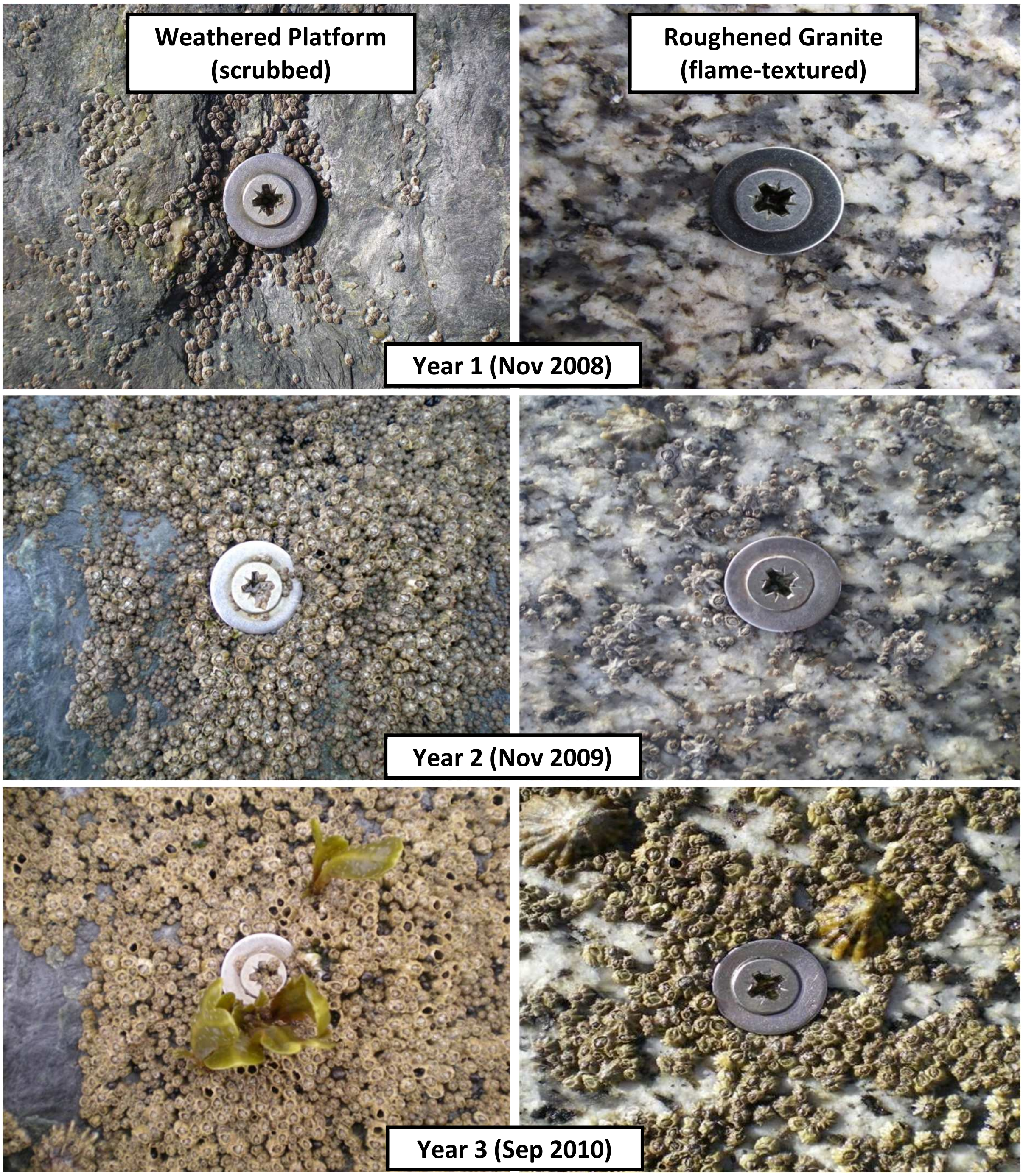

Figure 9-8 Algal recruitment in experimental clearings on Mylor Slate, Tregear Point, Porthleven (*left*) and limpet recruitment on roughened (flame-textured) granite at Gala Rocks, Zennor (*right*) (width of metal washer = 2 cm for scale, all blocks attached at MTL).

9.8 Ecological Enhancement of Hard Coastal Structures

The following discussions place the experimental work and conceptual ideas developed above in a context of ecological enhancement of hard coastal structures. The potential for achieving ecological gains using textural manipulation at smaller scales than has previously been considered in urban marine ecology is discussed. Texture may be manipulated by directly roughening materials (Section 9.8.1.1) and indirectly through material choice (Section 9.8.1.2). Emerging concepts about the use of physical ecosystem engineers in environmental management and restoration are also explored in this context (Section 9.8.3).

Limitations to these kinds of manipulations, and more generally to ecological enhancement of coastal structures, are then considered in Section 9.8.4. Broader practical considerations necessary for successful design of enhancement schemes, including the need for disciplinary integration, economic and engineering issues, and wider benefits beyond ecological gains are then briefly outlined (Section 9.8.5).

9.8.1 Texture manipulation

Experimental observations described in Chapter 5 showed that a common, space-occupying organism responded differently to materials commonly used in coastal engineering compared to *in situ* platform rock. Discussions above suggest that differences in the early stages of colonisation such as these can be important for longer-term ecological potential, by altering rates and end-points of succession. This research, coupled with work showing that the lower community diversity typically found on artificial structures (see Section 2.3 p. 55) can be explained at least in-part by a comparable lack of habitat complexity (e.g. Chapman and Bulleri 2003; Moschella et al. 2005), suggests that facilitating the establishment of early colonists such as barnacles using texture will be of ecological value on artificial structures.

Importantly, the models described above indicate that alongside manipulations to engineering design at medium – large scales (cm's – m's) that have been tested elsewhere (see Table 2-9 p. 79), manipulating substratum heterogeneity at a small scale (< cm) can elicit significantly different responses by early colonists. The sections below discuss how substratum may be manipulated at this scale for ecological gain, first by direct texturing of materials during construction (Section 9.8.1.1), and secondly through material choice, based on the biogeomorphic concepts discussed above (Section 9.8.1.2); Plymouth Breakwater is used here as a case study.

9.8.1.1 Direct textural manipulation

Field experiments described in Chapter 6 provide the first robust evidence of positive biological responses to small-scale (millimetres) texture manipulations on common materials used in coastal engineering. Barnacle settlement and recruitment was always higher on artificially roughened materials. Short-term survival of barnacles also showed positive associations with texture at this scale (Chapter 5). Furthermore, surface roughness was important for drying and heating rates under simulated intertidal conditions (Chapter 8). Textural manipulation at this scale, before or shortly after construction, has the advantage of offering almost immediate ecological benefits, as succession can proceed as soon as the structure is exposed to the tide. In comparison, indirect textural manipulation through material choice can only offer gains over much longer time-scales (see Section 9.8.1.2 below).

In this research, rock substrata were manipulated using commercial stone dressing techniques such as flame-texturing and dolly-pointing (Chapters 4-6). The use of smooth replicates as controls in *Exposure Trial 2* clearly showed that the roughness of rock was important for ecological response. It is, however, important to recognise that the surfaces of quarried rock are likely to be just as rough, if not more so, than the textures tested here; flame-textured granite was used as a good representation of quarried rock surfaces for example (Chapter 5). Manipulating fine-scale (mm's and less) texture on quarry rock is therefore almost pointless when used in rubble structures. Selecting materials with particularly rough surfaces may be advantageous however, an example of this being the use Portland Roach Stone, which has an extremely shelly composition, and hence a particularly rough surface when fractured and weathered (BRE 1997a). What the field trials did show is that where smooth rock is planned for use in designs (for decorative coping or cladding for example), incorporating some artificial textures at this scale is likely to offer ecological benefits.

Manipulating texture on concrete is far more flexible. Various methods were used in this study to alter surface roughness whilst concrete was being cast. Simple brushing of the surface proved particularly effective for barnacle colonisation (Chapter 6). Importantly, the most commonly used surface finish on marine concrete (plain-cast) was a poor substitute for weathered platform rocks in field trials, and had higher rates of mortality (in association with air-holes) for this organism (Chapter 5 and 6).

Innovations in the use of concrete in marine engineering have been made, such as the 'ecopode™' - a concrete armour unit designed with a 'mock-rock' texture (Concrete Layer Innovations, www.concretelayer.com, accessed November 2010). Ecopode™ units were designed primarily for aesthetic benefits, but are likely to offer additional ecological gains compared to the more widely used smoother alternatives, although this has never been tested. Research is needed to test the practicalities (as well as ecological outcomes) of fine-scale texturing of concrete on a commercial scale, as this may prove most effective using molding techniques during casting (see Section 9.8.2). Alternatively, concrete surfaces could potentially be manipulated *in situ* after construction, while still wet (in the case of site-cast structures), or by developing field-based texturing methods like sand-blasting for example.

Figure 9-7 suggests that habitat manipulation at a range of spatial scales (µm - m) may be the best strategy for maximising ecological potential on artificial coastal structures. Fine-scale texture (cm's and less) will facilitate the settlement of pioneer species like microorganisms and barnacles (this research), while meso-scale features (cm’s – m’s) such as crevices and holes will provide habitat for later (often larger) colonists which feed on the pioneers, like limpets and dog-whelks (e.g. Moreira et al. 2007; Iveša et al. 2010; Martins et al. 2010). Larger-scale design features (> m’s), including position on the shore and orientation, have an over-riding influence on community structure by defining environmental conditions such as wave exposure and tidal immersion patterns (Moschella et al. 2005; Burcharth et al. 2007). Importantly, Figure 9-4 and Figure 9-6 above predict that direct texture manipulation will be of most benefit on very hard materials, especially if initially smooth, because they will evolve (morphologically, at ecologically relevant scales) at a much slower rate than more weatherable materials (below).

9.8.1.2 Indirect textural manipulation: material choice

Observations of biogeomorphological associations on experimental blocks discussed in Chapter 7 and above suggest that an alternative to direct textural manipulation for ecological gain (above) is the use of materials that are able to develop favourable physical complexity ‘organically’, through weathering and erosion.

Figure 9-4 predicts that coastal structures built of very resistant materials like granite are essentially morphologically ‘static’ over an engineering time-scale (50 – 100 years), unless exposed to exceptionally aggressive conditions in which case such geomorphic ‘stasis’ would be desirable in a durability context (CIRIA 2007). For ecology, the habitat complexity provided by a very hard material is therefore essentially limited by its initial characteristics (Figure 9-4). Furthermore, while biological habitat provision by certain species can be important in intertidal communities once established (through the provision of shade and moisture in algae clumps for example e.g. Thompson et al. 1996), these facilitative interactions cannot operate if settlement of these species is initially limited by the substratum (e.g. Figure 9-6).

In contrast, materials which respond (geomorphologically) to intertidal exposure over a timescale of decades cannot be considered to have static ecological potential; natural weathering and erosion can create measurable changes in surface roughness and physical habitat complexity over time (Figure 9-4). In this study, limestone substratum evolved at a µm - mm scale in just two years, having observable positive influences on early colonisers, which may in turn have consequences for succession (Section 9.7). Alongside morphological benefits, Moschella (2003) also suggests that the ecological value of softer, carbonate materials (i.e. more weatherable) is higher than harder rock types because the microbial communities that are able to develop on porous rocks are typically more diverse (endoliths as well as epiliths for example, e.g. Figure 9-2). This may therefore increase primary productivity and microbial standing stock for grazers, as well as having feedbacks on the morphological evolution of the substratum (e.g. Figure 9-3).

9.8.1.3 Case study: Plymouth Breakwater

Over engineering timescales, calcareous materials are expected to have ecological advantages as potentially beneficial biogeomorphological processes can operate during exposure (above). While observations described in Chapters 5 – 8 were limited to a two year period, supplementary work was undertaken on Plymouth Breakwater to illustrate these interactions over a period of decades – centuries; this work is described in detail in Appendix 4 and is summarised below in the context of this study.

Plymouth Breakwater (Plymouth, Devon) was constructed over 180 years ago and incorporates both granite and limestone, placed side-by-side at MTL in a horizontal orientation. The structure therefore provided exposure conditions analogous to those of blocks exposed in Chapters 5 and 6. Measurements of surface roughness on the breakwater provided quantitative evidence of differences in the complexity of the two material types after the same period of exposure (Appendix 4). Limestone blocks have weathered significantly relative to the granite, creating cm – m scale features like tide pools (see Appendix 4 p. 504 for illustrations). Importantly, these pools support a greater diversity of species compared to the relatively ‘smooth’ granite surfaces, which remain dominated by a cover of barnacles (J. Jackson personal communication, March 2010, see Appendix

4). Qualitative observations indicated that bioerosion by grazing limpets has been (and continues to be) particularly important in the development of these pools on limestone, alongside inorganic weathering processes. Bioconstruction by encrusting algae (*Lithothamnion* spp.) in the pools has also greatly contributed to their morphological complexity (Appendix 4). This provides an excellent example of biogeomorphic ecosystem engineering (Section 9.2), whereby the relative efficiency of bioerosion, bioweathering and bioconstruction *processes* on limestone has resulted in measureable geomorphological and ecological *consequences* (e.g. Figure 9-1 and Figure 9-5, Appendix 4).

Although an unintentional artefact of the original construction, Plymouth Breakwater illustrates that the incorporation of 'biogeomorphologically responsive' materials like limestone in structures can give marked ecological gains over much longer time-scales than could be directly observed in field experiments. Crucially, from a practical perspective, these kinds of 'indirect ecological enhancements' need not compromise engineering performance or durability over the typical design-life of a structure, particularly where 'weatherable' materials are used alongside more durable materials, as is the case for the breakwater.

A benefit of manipulating ecological potential in this way, through material choice, is that it will involve minimal additional capital investment, while artificial texturing (above) necessarily involves some up-front costs (Section 9.8.1.1). Furthermore, 'natural' weathering and erosion of hard substrata results in morphological heterogeneity at a range of spatial scales (including pits, ridges and pools in the case of the breakwater, Appendix 4) analogous to the diversity of karstic forms found on natural limestone coasts (e.g. Schneider and Torunski 1983; Viles 1984; Spencer 1988b; Spencer and Viles 2002; Gómez-Pujol and Fornós 2009). This is important because habitat complexity (requiring heterogeneity at a range of scales), which may otherwise be difficult to replicate artificially, is key to establishing and maintaining diverse, stable and productive communities in the intertidal zone (Archambault and Bourget 1996; Blanchard and Bourget 1999; Johnson et al. 2003).

9.8.2 Practical considerations

The relative benefits and disadvantages of using artificially textured hard materials or weatherable alternatives for direct and indirect ecological gains, respectively, must be balanced with numerous other considerations. First, choosing a material deliberately to weather for habitat gains has obvious durability implications. The results of geomechanical testing presented in Chapter 7 suggest that even materials that weather relatively quickly in the intertidal zone (like Portland limestone) are modified at a scale unlikely to be of concern at an engineering scale; while properties like surface hardness and water absorption may be altered relatively quickly by a combination of organic and inorganic processes, the relevance of these processes for durability and performance over the lifetime of a structure is expected to be negligible in the vast majority of cases (W. Allsop personal communication, December 2008). On Plymouth Breakwater, for example, weathering of limestone over a period of c.180 years has given significant ecological gains (Appendix 4) without any implications for engineering performance. A strong caveat is required here, in that these assumptions must be considered in the context of the environment in which a structure is being placed, and the specific function it has been designed for; these are factors that must be fully considered in the planning and design process (CIRIA 2007; Burcharth et al. 2007; CIRIA 2010).

Secondly, time is a key consideration for the types of enhancement discussed here. The design-life of a structure defines the amount of time that its constituent materials are exposed to biogeomorphological processes. A structure expected to be in service for only 50 years, for example, may benefit more from direct texture manipulation at the start of construction to achieve immediate ecological benefits. Allowing habitat complexity to develop naturally, by incorporating limestone, and in combination with less weatherable materials for example, would be more feasible for structures expected to be in service for 100 years or more. In this context, it is important to recognise that many structures remain in service well beyond their initial design-life, including Plymouth Breakwater. The high ecological value of pool habitat on the breakwater also suggests that creating these features artificially through engineering design, by setting blocks at different levels on horizontal surfaces for example, would provide immediate ecological benefits.

It is clear that the potential success of incorporating these ideas in enhancement schemes depends on a number of factors including: (i) the nature of the environment and the primary purpose of the structure being built (which must always remain paramount in engineering designs); (ii) the timescale over which ecological gains and/or mitigation is required – whether immediate or more flexible; (iii) the resources (financial and expertise) available for a specific project, which dictates the type of enhancement that might be possible, and; (iv) the feasibility of enhancement to achieve the ultimate goals of the scheme – whether this be general (local) biodiversity gains or targeting specific species' for example (see Section 9.8.4 below).

In summary, the ecological potential of a construction material cannot be viewed as static in time. Natural rocks and concrete used to build structures will respond morphologically to organic and inorganic weathering and erosion processes acting at their surface once deployed. The rate at which materials are altered in this way depends on inherent material properties. The initial texture of very hard materials used in engineering for their durability properties (such as granite) is unlikely to vary at an ecologically-relevant scale during the typical lifetime of a structure (100 years); smooth granite is therefore expected to have low ecological potential throughout its service life for example. In contrast, the ecological potential of a material that responds more quickly through weathering and erosion, such as limestone, is expected to change over timescales relevant to ecology and management needs; smooth limestone will become rougher over a period of years (this research) and decades (Plymouth Breakwater) as it is weathered and eroded by early colonising microorganisms alongside other inorganic weathering processes, and hence offer a more ecologically favourable, physically complex habitat.

9.8.3 'Biogeomorphic Ecosystem Engineering' and ecological enhancement

Recently, it has been recognised that physical ecosystem engineers have the potential to be 'used' in environmental management and ecosystem restoration, and may provide cheaper, easier, faster and more sustainable solutions to management problems than other kinds of human intervention (Byers et al. 2006). The principle is based on the notion that organisms modify the physical environments in which they live (i.e. physical ecosystem engineering/biogeomorphology, see Chapter 3) and hence are involved in niche construction to some degree (Byers et al. 2006).

Niche construction enables other species to survive in otherwise stressful environments through the provision of critical resources (Laland and Boogert 2010). In the intertidal zone, this constitutes the provision of shade, moisture and refuge (Paine 1974; Menge and Lubchenco 1981; Menge and Sutherland 1987; Menge and Olson 1990; Harley 2006). Laland and Boogert (2010) argue that taking niche construction into account will facilitate efforts to understand and conserve ecosystem functioning, and ultimately biodiversity. Furthermore, Crain and Bertness (2006) suggest that understanding ecosystem engineering and niche construction is essential to conservation more widely. An example of where these concepts are currently being applied is the restoration of degraded grasslands by introducing burrowing mammals, whose activates create a dynamic landscape of patchy resources including food and shelter for other organisms (e.g. Martin 2003; Eldridge and James 2009; Newell 2009). The importance of bioturbators (spatangoid urchins) for the health and productivity of marine soft-sediment benthic habitats has also been highlighted (Loher et al. 2004). While facilitative interactions between organisms are well studied in the intertidal zone (e.g. Bulleri 2009; Thomsen et al. 2010), ideas relating to the potential conservation value of manipulating interactions between hard substrata and epibiota remain underdeveloped. Similarly, the concept of 'ecosystem services', that organisms provide and regulate services to humans (e.g. Everard et al. 2010), has not been explored in this context.

While intentionally introducing organisms for their ability to 'engineer' physical habitat complexity in the intertidal zone is unlikely to be feasible, the work presented in this thesis indicates that there is potential to at least facilitate these kinds of interactions on artificial structures through material choice (Section 9.8.1). Incorporating materials in designs (where technically and practically feasible, see above) on which 'biogeomorphic ecosystem engineering' may be particularly efficient (such as limestone) could serve as one method to improve ecological potential in the long-term. This is particularly true where resources for other active intervention like manual texturing or building larger-scale artificial niches are limited.

While this study has highlighted the potential for applying biogeomorphic concepts in the context of artificial coastal structures, much more research is needed to explore the extent to which such applications can be successful, affordable and feasible at scales relevant to particular conservation goals and policy targets (Laland and Boogert 2010, Section 9.8.4 below). What is clear is that geomorphologists can contribute greatly to, and benefit from, these discussions because (allogenic) physical ecosystem engineering and niche construction inherently involve modification of the physical environment by organisms, understanding of which is at the core of biogeomorphology as a discipline (e.g. Figure 3-3 p. 121 and Figure 9-1 p. 396). Theoretically, improving understanding of the operation of these complex interactions and feedbacks can contribute to much broader discussions of emerging concepts about the co-evolution of organisms and their physical environment, including 'biogeomorphic succession', 'biogeomorphic inheritance' and 'self-organisation' over longer time-scales (Corenblit et al. 2007; Corenblit et al. 2008; Corenblit and Steiger 2009; Francis et al. 2009; Laland and Boogert 2010; Reinhardt et al. 2010, see Chapter 10).

9.8.4 Limitations of ecological enhancement

The addition of new, structurally complex habitat can have positive influences on local community diversity, through the provision of favourable attachment sites and refuge from ecological and environmental stress (Chapman and Blockley 2009; Bulleri and Chapman 2010, above discussions).

However, there are important exceptions and limitations which mean that developing generic models and guidelines is difficult. McGunness and Underwood (1986), for example, showed that while artificially increasing the diversity of micro-habitats on concrete did influence the number of species, not all species groups were affected in all locations, nor was the direction of influence as expected. Indeed, these workers note that there was ‘considerable variation’ in response to habitat manipulation among species. In this study, the marked response of Chthamalid barnacles to the brushed texture used on concrete, for example, cannot be assumed to apply to all other species. Raimondi (1988) suggests that *Chthamalus* favours specific sizes of pits on the surfaces of granite and basalt for example, so that the presence or absence of texture at this particular scale may have more bearing on the success of this species than any general increase in roughness – although such enhancement may subsequently benefit other species (see Section 9.7).

Spatially, the ecological outcomes of manipulating habitat complexity (in terms of species abundance and diversity) have often been most pronounced at higher shore levels (McGuinness and Underwood 1986; Chapman and Blockley 2009). Structures built higher in the tidal frame may therefore benefit most from enhancement interventions involving refuge provision (Bulleri and Chapman 2010), but not where they are so high in the tidal frame that they are not frequently wetted (Naylor et al. in preparation). Furthermore, the effectiveness of ecological enhancement will depend greatly on the presence and intensity of many other biotic and abiotic factors (e.g. Section 9.6) which must be taken into account when scoping enhancement options.

While general guidelines on ecological enhancement for practitioners would be useful, it should be made clear that applying generic designs will be challenging and potentially misleading (Bulleri and Chapman 2010). It is essential that ecological enhancement schemes fully consider the specific conditions in question, so that the most appropriate design can be developed, and realistic expectations of the scheme can be established for all those involved (Box 1996). At best, only improvements to local biodiversity can be expected, and structures will certainly not be able to replicate rocky shore environments (Bulleri and Chapman 2010; Naylor et al. in preparation). This being said, manipulating engineering design could have regional ecological benefits in areas where a significant proportion of the coastline is artificial, such as in the Mediterranean (Airoldi and Beck 2007). In Sydney Harbour, where the vast majority of the coastline is engineered, it has been suggested that habitat manipulation could have a relatively high impact on regional biodiversity (Chapman 2003; Chapman and Blockley 2009).

A more pragmatic approach is to consider the maximum ecological potential that a structure could achieve. This is the framework adopted under the WFD, which sets a target of 'maximising ecological potential' for heavily modified waterbodies (see Chapter 2). Similarly, Airoldi et al. (2005) suggest that identifying 'desired environmental states' is an important challenge that needs to be addressed if the requirements of different stakeholders, and regulatory and scientific groups involved in enhancement design, approval, construction and maintenance are to be met. These kinds of targets, rather than aiming to achieve the impossible of complete habitat creation, are likely to prove much more effective conservation goals (Ehrenfeld 2000).

While it is widely acknowledged that rough surfaces are generally better than smooth in ecological terms (e.g. Moschella et al. 2005; CIRIA 2007), targeting specific species – including those which are threatened, commercially valuable (i.e. foodstuffs), or of particular ecological importance (such as a 'keystone' or 'engineer' species) – may offer the greatest opportunities for enhancement. Martins et al. (2010) demonstrated the effectiveness of this approach for a commercially valuable species of limpet in the Azores. Such an approach requires understanding of the specific habitat requirements of the target species, at all life stages. Replicating niche requirements in structure designs, or retrofitting them into existing structures (e.g. Martins et al. 2010), should increase the value of the structure for the target organism. For barnacles, which may be targeted to increase the rate of initial colonisation – for aesthetic reasons as well as for the ecological reasons discussed above – manipulating texture at a small scale (millimetres) was shown here to have significant effects

(Chapter 5 and 6). Effort is now needed to establish quantifiable links between different types and scales of habitat enhancement and epibiota reproductive success, as this is key for maintaining stable populations through time (e.g. Moreira et al. 2006, 2007).

9.8.5 Broader practical consideration

9.8.5.1 Integrated research

This thesis has demonstrated that successful research on ecological enhancement requires interdisciplinary knowledge. This has its own practical challenges because disciplines typically have different approaches to research design, have interest at different scales, and ultimately may have different end-goals (Boulton et al. 2008, see Chapter 3). A specific motivation of this research has therefore been to demonstrate the need and benefits of interdisciplinary research in the context of the study, through the integration of ecological and geomorphological approaches from the outset, under a framework of biogeomorphology (Chapter 3). Benda et al. (2002) argue that identifying feasible questions of common interest and developing experimental designs that satisfy the requirements of each discipline are critical for successful integrated research. This project has demonstrated the potential of such an approach for the advancement of academic theory and knowledge alongside useful, applied outcomes.

Applying research in practice involves an even wider range of stakeholders, with different responsibilities, expectations and motivations (Naylor et al. in preparation). Implementing enhancement schemes at the coast, for example, requires collaborative research projects between academic researchers, engineers and coastal managers to demonstrate the types and scales of enhancement that can be used to achieve different ecological outcomes, without compromising durability and structural performance. Such research could ultimately lead to guidance on which enhancement options may be most applicable in different situations and, just as importantly, which ones will be inappropriate.

9.8.5.2 Monitoring

Monitoring of operational trials where they are implemented is critical to produce meaningful evidence of the ecological outcomes of particular enhancement options, and to demonstrate how measures may or may not be applied elsewhere. This can be a problem if resources available for monitoring activities are limited, especially considering that ecological responses to any trialled enhancement may only become clear after several years. The EA, for example, normally allocates costs for new flood defence projects in England and Wales on a 12-month basis only (O. Venn, personal communication, October 2010). Tethering academic research projects to enhancement trials could offer opportunities here to increase the duration of post-construction monitoring to several years, rather than months. Indeed, much of the pioneering research on urban marine ecology, and more frequently on how structures might be manipulated for ecological gain, remains associated with academic groups rather than and industry-led activity (e.g. Section 2.5 p. 76).

9.8.5.3 Benefits beyond ecological gains

Given the range of statutory and mandatory drivers for adopting enhancements in coastal structure designs (Section 2.4 p. 70), trialling enhancements can be used to help secure planning permissions, meet wider conservation targets, and increase public awareness and acceptance of new developments. A good example of this is the Seattle Seawalls project for which the University of Washington is conducting a pilot study of enhancement options to assist a planning application by the City of Seattle for a replacement seawall (http://wsg.washington.edu/research/ecohealth/, accessed January 2011). Alongside an ecological aim of enhancing declining Pacific salmon stocks (Goff 2010), the study has helped win public support and improve the likelihood of securing co-funding (J. Noble personal communication, October 2010). The role of coastal structures in society is also becoming more widely considered (e.g. Simm 2009), and there remains much scope for further study of the social implications of enhancements. The aesthetic and scenic value of 'enhanced' versus 'unenhanced' structures might be one such avenue of research for example (e.g. Ergin et al. 2004; Williams et al. 2005).

9.8.5.4 Engineering considerations

The influence of any enhancements on engineering is a key concern that must be considered if measures are to be taken up more widely in coastal management. The implications of substratum changes observed during this study, and over longer time-scales, for engineering are specifically discussed in Chapter 7: Strands 2 and 4. These discussions concluded that the role of biota in deterioration of construction materials at an engineering scale is likely to be negligible, but requires further research (see Chapter 10).

9.8.5.5 Economics

Economics is an important constraint on conservation activities (Wackernagel and Rees 1997; Costanza et al. 1999), and the potential costs and benefits of applying the kinds of enhancements discussed above at an engineering scale requires more investigation in collaboration with industrial partners. Texturing a 1 m^2 area of granite using the flame-texturing and dolly-pointing techniques used in field trials, for example, would cost in the order of £45 - £55 respectively (I. Skinner personal communication, January 2009). The costs of applying these kinds of textures to entire structures is much more difficult to estimate, but manipulating only a few parts of a structure in this way may yield ecological benefits if these areas can function as recruitment sites from which organisms can colonise other parts of the structure (e.g. Chapman and Blockley 2009). It is also worth noting that enhancement costs may be minimal in the context of entire budgets associated with coastal structures, particularly flood and erosion control schemes (e.g. Environment Agency 2009a).

9.8.5.6 Biodiversity conservation and climate change

By definition, ecological enhancement (as opposed to habitat restoration and creation) is undertaken where the primary goal of the feature being ‘enhanced’ is not ecological (Box 1996; House of Commons 2009; Naylor et al. in preparation). It is emphasised, therefore, that in the case of coastal structures, which are built primarily for flood and erosion control, and for infrastructure purposes (see Chapter 2), enhancements such as those considered above cannot be seen as a solution to more general concerns for the loss of biodiversity attributed to coastal urbanisation (Thompson et al. 2002; Airoldi and Beck 2007; Bulleri and Chapman 2010). Enhancement interventions are perhaps best considered to seek to improve ecological quality (whether targeting a specific species or aiming to increase general ecological potential of a structure) compared to structures without any enhancements. Using textured materials, choosing particular material types, or 'designing in' particular habitat niches may therefore achieve habitat that is intermediary between natural systems (i.e. rocky shores) and unmodified structures, but which cannot compensate for wider losses occurring at a regional or global scale.

This being said, improving the ecological potential of structures through enhancement has an important role in broader conservation challenges at the coast. This is particularly true in the face of climate change which is recognised as a major driver of change in the intertidal zone now and in the future (Thompson et al. 2002; Hawkins et al. 2003; Helmuth et al. 2006; Hawkins et al. 2008; Hawkins et al. 2009). The potential value of structures in enabling the establishment of viable populations and facilitating range-shifts necessary for epibenthic communities to respond to changing climate and sea level rise (e.g. Helmuth et al. 2002; Poloczanska et al. 2008; Firth et al. 2009) was highlighted in Chapter 8. More broadly, managing artificial structures as a component of the coastal landscape, for which combined ecological and geomorphological knowledge is required, is an approach still lacking in comparison to terrestrial urban environments (e.g. Gray 1997; Bulleri 2006; Bryant 2006; Angold et al. 2006). Furthermore, Berke et al. (2010) have recently argued that when ecological responses to climate change at the coast (i.e. range shifts) involve physical ecosystem engineers, cascading shifts in ecosystem function are expected. Understanding biogeomorphic interactions and feedbacks on coastal structures, which may facilitate ecological responses to climate change (see above), are therefore of value. Finally, the engineering durability implications of biogeomorphic interactions under current and future climate scenarios need to be clarified; this may involve bioprotective as well as biodeteriorative effects, which have not previously been investigated.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

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CHAPTER 10. CONCLUSIONS AND RECOMMENDATIONS

This final chapter gives a summary of the research findings structured using the four main thesis aims (Table 1-1 p. 37 and Table 3-2 p. 129, also see Supplementary Material B). The main conclusions of the research and recommendations for future work are included here.

10.1 Thesis Aim 1

> **'To improve understanding of biological responses (at a < cm scale) to different material types and textures used in coastal engineering.'**

Three construction materials with surface finishes similar to those used in coastal engineering did not replicate settlement and recruitment of a common intertidal organism (Chthamalid barnacles) on natural *in situ* rock (**Hypothesis 1a-b**, Chapter 5). There were also significant differences between the introduced materials (**Hypothesis 2a-b**, Chapter 5). Similarly, post-recruitment mortality, which was measured over a longer period of time than in previous studies (12 months), was higher on introduced materials than on platform clearings (**Hypothesis 3**, Chapter 5) and varied significantly between material types (**Hypothesis 4**, Chapter 5). These observations support concerns that coastal structures are generally poor surrogates for undisturbed rocky shores (see Chapter 2).

Differences in settlement, recruitment and post-recruitment mortality were largely attributable to substratum surface roughness, which is known to be a critical influence on barnacle colonisation through the provision of favourable settlement sites and refuge from environmental and ecological stresses (Chapters 2, 5 and 6), but which has not previously been tested on materials commonly used in engineering. The importance of substratum roughness and texture was confirmed in a separate field trial, which showed that rough materials consistently had higher numbers of settlers and recruits than smooth replicates of the same material type (**Hypothesis 5a-b**, Chapter 6). These experiments indicate that the texture of materials used in engineering is more important for early colonisation that material type (i.e. lithology), at least for barnacles.

Importantly, the *type* of texture (i.e. the method by which it was created) had a significant effect on colonisation, as demonstrated using marine concrete (**Hypothesis 6a-b**, Chapter 6). For Chthamalid barnacles, applying a brushed texture had the greatest influence on recruitment. Concrete with an exposed aggregate finish also 'out-performed' plain-cast concrete – by far the most commonly used finish in coastal engineering – and this difference was significant on one of the experimental shores. While surface air-holes common on plain-cast concrete were important for cyprid settlement, they were associated with increased rates of mortality over time as a result of growth and competition for space between conspecifics. Nevertheless, these surface features (typically mm's in size) were important for initial colonisation of concrete, demonstrated by a significant reduction in recruitment when air-holes were removed by wiping the surface during the curing process.

Levels of settlement and recruitment on materials which had been artificially roughened, at the mm-scale, at the least matched those recorded on weathered platform rock (**Hypothesis 7a-b**, Chapter 6), the only exception being flame-textured granite, which had lower recruitment on one of the shores. Brushed concrete at Gala Rocks and dolly-pointed limestone at Tregear Point supported significantly more barnacles than nearby areas of weathered platform rock. These responses were observed independently of biochemical cues, which are known to influence settlement over shorter timeframes (**Hypothesis 8a-b**, Chapter 6).

The field experiments described in Chapters 5 and 6 suggest that there are significant opportunities for manipulating early colonisation of construction materials in a positive way – so that they may at least be comparable to natural *in situ* rock – using finer-scale textures than have previously been tested. This study is therefore the first to demonstrate the ability to manipulate early interactions between intertidal organisms and, specifically, material types commonly used in coastal engineering at this scale. This is important because the rate of arrival of other species may be largely dependent on the successful establishment of these early communities. The conceptual models discussed in Chapter 9, for example, suggest that a smooth material will have very limited long-term ecological potential (as least if it is less-weatherable like granite, see below) while adding a texture will facilitate initial colonisation, so that succession may continue.

10.2 Thesis Aim 2

> **'To improve understanding of the geomorphological responses of construction materials (at a < cm scale) during exposure in the intertidal zone, with particular attention on the role of biology in geomorphological change and implications for engineering durability.'**

This is one of the first studies to examine weathering processes operating on multiple material types placed in the same intertidal location (Chapter 7). Quantitative microscope observations showed that the nature of microbial communities developing on common construction materials were significantly different, and varied between periods of exposure in the sea (**Hypothesis 9a-b**, Chapter 7: Strand 1). Limestone was dominated by euendolithic microorganisms associated with direct bioerosion of the substratum, while colonisation on granite was limited to the epilithic niche. Concrete was colonised by both epilithic and endolithic microorganisms. These differences, which are largely attributed to lithology and inherent material properties of the substrata, dictated the relative importance of organic weathering and erosion processes observed at the surface (**Hypothesis 10a-b**, Chapter 7: Strand 1) and the vertical extent (depth) of alteration (**Hypothesis 11a-b**, Chapter 7: Strand 1). Future collaborations with microbiologists are needed to help identify key differences in microbial communities more precisely (taxonomically and molecularly), so that the implications of these differences for productivity and ecology (e.g. grazer recruitment and fecundity) can be adequately assessed alongside evaluations of their role in geomorphic processes (e.g. Fernandez 2006).

Supplementary observations made at a scale more relevant to engineering (at a bulk scale, > mm) demonstrated measureable differences in geomechanical properties, both between material types (**Hypothesis 12**, Chapter 7: Strand 2) and after different periods of exposure in the field (**Hypothesis 13a-b**, Chapter 7: Strand 2). Measurable changes in the roughness of limestone after 8 and 20 months, at an ecologically-relevant scale, were also observed. These changes were largely attributed to bioerosion by microorganisms, at the µm scale, and subsequent coalescence of holes leading to surface pitting and morphological change at the mm-scale. This provides an example of cross-scalar linkage in weathering geomorphology (Viles 1995, 2001). Changes in the roughness of concrete over the same period of time were less clear (**Hypothesis 14a-b**, Chapter 7: Strand 3). While relative rates of morphological change between material types may be largely consistent across the shore, the intensity of particular weathering and erosion processes is expected to vary considerably at different tidal heights in relation to biological and physical zonation (**Hypothesis 15**, Chapter 7: Strand 3, Appendix 2). Assessments of textural changes using more sophisticated techniques could be used to investigate the role of biological weathering and erosion in the morphological development of natural and artificial substrata (across different spatial scales) in more detail, and the consequences this may have for ecology and geomorphology (see below).

A novel laboratory-based procedure was developed to observe the warming-drying and heating-cooling behaviour of materials under simulated intertidal conditions (Chapter 8). The procedure successfully replicated conditions measured on rock platforms during summer. There were measurable differences in the thermal and drying behaviours both between different construction materials, and before and after a period of colonisation and weathering in the field (**Hypothesis 16a-b**, Chapter 8). Differences were associated with changes in the efficiency of evaporative cooling when exposed to air, attributed in part to bioerosion of limestone and bio-chemical crusting of concrete (Chapters 7 and 8). Differences in thermal and drying behaviours are of importance for the efficiency of other weathering and erosion processes (e.g. slaking, salt crystallisation, thermal fatigue) as well as the potential role of substrata in mediating near-surface micro-climatic conditions relevant to heat and desiccation stress, and climate change (Chapter 8).

Further work is needed to assess the importance of changes in thermal behaviour for weathering in the intertidal zone through time, for which sub-surface temperature measurements would be particularly useful. Observations of warming and drying behaviour after longer periods of exposure are also needed as properties known to relate to these behaviours (e.g. absorption and porosity) did not change linearly through time on the materials tested here (Chapter 7: Strands 2 and 4). Direct measurements of surface wetness and of larvae survival on different materials, both in the field and under controlled heating regimes in the laboratory, would greatly contribute to discussions surrounding the potential of substratum to mediate stressful conditions experienced by epibiota, particularly under scenarios of climate change. Geomorphologically, observations of substratum warming-drying behaviour with different types of biological cover, and at different stages of community development, would be useful to evaluate both the bioweathering and bioprotective potential of these mechanisms on natural *in situ* rocks as well materials used in coastal engineering.

10.2.1 Engineering considerations

Observations using experimental blocks and samples taken from existing *in situ* structures indicated that micro-scale biological weathering and erosion of common construction materials (rock and concrete) is not expected to be of any concern at an engineering scale, over the typical lifetime of a coastal structure (100 years; Chapter 7: Strand 4). The biogeomorphological processes given most attention in this work (such as bioerosion) are unlikely to have any bearing of overall durability, even for materials on which they are expected to be most efficient, and may rather provide ecological gains in the long-term (e.g. Appendix 4). Microorganisms are also suggested to be involved in hardening of concrete to a certain extent through the formation of bio-chemical crusts (Chapter 7: Strands 1, 2 and 4). Some caution must be expressed here, however, that the potential for bioerosion, bioweathering and bioprotection processes at this scale is considered on a case-by-case basis. Further observations over longer periods of time are required to establish the extent to which fine-scale (< mm) processes may be a pre-cursor for larger-scale deteriorative mechanisms such as surface scaling in this environment (e.g. Smith and Viles 2006; Appendix 3). The potential benefits of growth on structures for engineering durability (see above) also warrant further investigation, as this may prove an important tool for encouraging the uptake of enhancements by practitioners.

10.3 Thesis Aim 3

> **'To improve understanding of the interactions and feedbacks between geomorphological and ecological processes on different materials exposed in the intertidal zone, within a framework of biogeomorphology.'**

With specific reference to hard coastal structures, the experimental work described in this thesis has shown that materials and their physical properties exert a control on early-stage epibiotic communities (**Thesis Aim 1**), while, at the same time, these developing communities are involved in the geomorphological alteration of the substratum (**Thesis Aim 2**). These different aspects represent the two-way interaction between biology and geomorphology originally conceptualised as biogeomorphology (Viles 1988; Naylor et al. 2002; Chapter 3). Importantly, these interactions are further linked through reciprocal feedbacks at multiple spatial and temporal scales, which have ecological and geomorphological consequences (**Thesis Aim 3**, Figure 9-1 p. 396).

The strength of biogeomorphic interactions on hard substrata (in time and space) is heavily influenced by lithology. In the intertidal zone, microorganism niche occupation (i.e. epilithic, endolithic or mixed communities) dictated the extent of substratum geomorphic alteration associated with colonisation over two years. Over these short timescales, biogeomorphic processes are expected to be more efficient on calcareous, softer, porous materials like limestone and less efficient on non-calcareous, less-porous, harder materials like granite. Observations of *in situ* structures also indicate that lithological controls dictate the relative involvement of organisms in geomorphic alteration over longer periods of time (i.e. decades – centuries; Appendix 3).

As succession continues and biological cover increases, the importance of substratum influences on epibiota (relative to ecological interactions) is predicted to decrease (Chapter 9). Importantly, the rate at which biological cover develops in the intertidal zone is strongly influenced by initial substratum roughness, alongside broader spatial controls like tidal height and larval supply. This suggests that manipulating early biogeomorphic processes on structures, through direct texturing and indirectly through material choice for example, can have a significant influence on initial rates of colonisation. Furthermore, the efficiency of biogeomorphic processes places a control on the strength of substratum-biota interactions (and associated consequences for geomorphological change and ecological potential) as succession continues over longer timescales (Chapter 9). Weatherable materials will be modified to a greater extent, more quickly, as organic weathering and erosion processes operate more efficiently than on less-weatherable materials. Alteration of surface morphology (i.e. texture), hardness, absorption properties and potentially strength (over much longer time-scales; Chapter 7), and wetting-drying and warming-cooling behaviour (Chapter 8) on limestone rocks has consequences for subsequent fine-scale weathering (µm – mm) and erosion (µm – cm), the development of landforms (i.e. biokarst), near-surface micro-climatic conditions, and habitat heterogeneity and the colonisation, abundance and diversity of organisms (Chapters 5-9, Appendix 4). While these interactions have been suggested in rocky shore ecology (see Section 2.7 p. 93), this thesis is the first to demonstrate the value of combined ecological and geomorphological approaches to understanding their operation in time and space, and how they are relevant in an applied context (**Thesis Aim 4**, see below).

The involvement of organisms in the alteration of materials requires much more research both in a rock coast and weathering geomorphology context, and with respect to coastal structures and ecological potential, and engineering durability. Crucially, the strength of biogeomorphic interactions, and their consequences for both geomorphology and ecology, are expected to vary considerably as a function of material type (i.e. lithology, Figure 9-2 p. 400 and Figure 9-3 p. 403), material texture (Figure 9-4 p. 405), time (Figure 9-6 p. 410 and Appendix 3) and space (Figure 9-7 p. 412 and Appendix 2). Biogeomorphology provides a framework under which interdisciplinary research can define these links more clearly, which may be cross-scalar in nature, operating indirectly and in combination with other processes, and hence requires the development of new, integrated methodologies and measurement techniques.

10.4 Thesis Aim 4

> **'To apply biogeomorphological understanding as a tool for identifying opportunities for the ecological enhancement of hard coastal structures.'**

While growing research interest in marine urban ecology is encouraging (Chapter 2), there are many questions and uncertainties surrounding ecological responses to urban structures and the functioning of particular ecological processes on their surfaces, because they cannot be seen to replicate those observed on rocky shore substrata (Bulleri and Chapman 2010). Identifying ways to facilitate settlement is an important first step, for which textural and material manipulations such as those examined in this thesis have particular opportunities (Chapter 9, above). However, while ecological variables such as abundance and spatial distribution are useful, the maintenance of populations on structures is dependent on successful recruitment, survival, and reproduction and productivity over longer time-scales (e.g. Moreira et al. 2007); these processes need much more attention in an urban marine context as parameters more indicative of long-term population viability and general ecosystem health.

Based on a policy framework (see Chapter 2), a key future research goal needs to be the identification of exactly what might constitute 'maximum ecological potential' or 'desired environmental states' for coastal structures, not only in ecological terms, but for all groups involved in coastal developments (Box 1996; EU 2000; Ehrenfeld 2000; Airoldi et al. 2005). This will not be simple as the end-goals and requirements of enhancements may vary considerably from one scheme to the next, depending on factors such as the function and location of the structure being built, and the resources available for enhancement (Chapter 9). Furthermore, a range of stakeholders are typically involved in the research, design and implementation of coastal structures (including academics from various disciplines, engineers, coastal managers, local authorities and the general public); identifying and managing the expectations of these individuals and organisations, so that they are realistic, must therefore be as much a priority as the testing and scientific outcomes of future trials (Chapter 9).

Crucially, increasing overall 'biodiversity' cannot be assumed to be the primary objective of enhancement, nor can it be expected to always be achievable (Chapter 9). Only when the desired outcomes of enhancement are clearly defined can an appropriate design and method of enhancement be selected, which must be based on previous experience and established scientific understanding. While general guidelines on what might constitute 'maximum ecological potential' under the WFD are still being developed (in which ecological enhancement, and more specifically 'mitigation measures', are being outlined e.g. Bolton et al. 2009), where and how the kinds of enhancements discussed in this thesis fit these requirements is not yet clear.

The most effective way of maximising the ecological potential of a structure directly is likely to involve the incorporation of habitat complexity at a range of spatial scales, including fine-scale texturing (mm) to facilitate initial settlement and recruitment of pioneer species (as studied here), meso-scale refuges (mm – cm) such as holes and pools to provide shelter for motile species, and larger-scale design features (> m) including the arrangement of blocks in rubble structures and the positioning of structures on the shore (Moschella et al. 2005; Burcharth et al. 2007). The combined use of enhancements at these different spatial scales needs much more experimental and applied testing.

Alternatively, specific species could be targeted (for fisheries gains for example) using knowledge of particular niche preferences in enhancement design (e.g. Martins et al. 2010); while this may not necessarily constitute increases in overall biodiversity value (locally, see below), making enhancements for one or a few species is better than no enhancements at all. Furthermore, enhancement designs associated with specific beneficial outcomes (i.e. targeting species of commercial or public interest) are more likely to get support from industry and hence could offer a means to trial new enhancement ideas in practice, which needs to be done before they can be applied in other locations.

Importantly, this research found that there was significant variation in the ecological influence of material type and texture between shores. This indicates that the relative effectiveness of any enhancements cannot be assumed to be consistent in space, between different locations, nor between material types. There is a need to test not only the ecological and geomorphological outcomes of different kinds of enhancements and material manipulations, but to undertake these trials in a range of environment settings. Particular designs may be more or less effective on sheltered or exposed shores, at different tidal heights and on different types of structures for example. Much more effort is needed to explore enhancements with these variables in mind so that more practical, targeted guidelines can be developed for practitioners.

Over engineering time (10 – 100 years), the incorporation of materials that are able to generate habitat complexity ‘organically’, through weathering and erosion, offers some opportunities. Calcareous substrata can evolve morphologically at a mm-scale in a matter of years (Chapter 7, above), having beneficial effects on early colonisation comparable to direct texture manipulation (Chapter 9). Plymouth Breakwater demonstrates that the ecological influence of material choice can be significant over longer periods of time (Appendix 4). The involvement of organisms in the geomorphic evolution of substrata – through processes of bioweathering, bioerosion, bioprotection and bioconstruction – is equally significant in an ecological context, with respect to the concepts of physical ecosystem engineering and facilitation, as it is in a geomorphological context, with respect to biogeomorphology (Chapters 3 and 9).

Practically, much more academic research needs to be done to examine the influence of different kinds of manipulation on different successional stages in intertidal ecology. Exploring the ways in which the ecological outcomes of initial interventions (i.e. incorporating enhancements into a new structure) can be maximised for the *long-term ecological value* of a structure requires more work. Research also needs to be undertaken alongside practitioners where possible, as testing how different enhancements can be implemented at an operational scale is needed just as much as research into their ecological outcomes. For concrete, for example, it was found that textural manipulation at a fine scale (i.e. mm) had significant influences on the establishment of a common early colonist. How these kinds of textures could be applied commercially, along with any other type of enhancement, is an important question to address if they are to be more widely tested and, ultimately, applied as standard. In the case of concrete, it may prove most effective to manipulate surfaces using molding techniques during the manufacture of pre-cast armour units. Alternatively, surfaces could potentially be manipulated *in situ* after construction, either while still wet (in the case of site-cast concrete structures) or by developing field-based texturing methods like sand-blasting for example. These kinds of broader, pragmatic questions are essential if a 'recipe book' of enhancement options is to be developed for practitioners, which should be seen as the end-goal of this kind of applied research (Bulleri and Chapman 2010; Naylor et al. in preparation).

10.5 Concluding Remarks

The overriding aim of this thesis has been to advance and integrate geomorphological and ecological understanding of biota-substratum interactions under a framework of biogeomorphology to help identify ways of enhancing the ecological value of hard, artificial coastal structures.

The challenge and complexity of understanding environments (both natural and built) as coupled bio-physical systems has been emphasised, consisting of biotic and abiotic components which can be linked through interacting feedbacks. Coastal structures built in the tidal zone for flood protection and erosion control, and for infrastructure purposes elicit biological responses involving their colonisation, and geomorphological responses involving weathering and erosion. Crucially, these two types of response interact and influence one another in various ways, and may be considered under a framework of biogeomorphology.

Using this approach, a combination of field trials, laboratory investigations and conceptual discussions has been used to draw four main conclusions. First, using barnacles as a model organism, the type of materials used in coastal engineering, and in particular their surface texture, was shown to have a significant influence on settlement, recruitment and survival of early colonists (Chapters 5 and 6). Associated with this is the suggestion that there is considerable potential to manipulate early-stage succession on construction materials through direct textural manipulation at a smaller scale than has previously been considered. The influence of these kinds of manipulations on later colonists and communities in the long-term requires much more investigation.

Second, materials placed in the intertidal zone during construction cannot be considered geomorphologically static in time, which has been an assumption in much rocky shore ecology and urban marine ecology research. While weathering and erosion processes act to modify materials at a micro-scale (μm), and typically over longer time-scales than ecological processes operate, associated changes in material properties such as hardness, water absorption, warming-drying behaviour and morphology were measured during the first two years of exposure (Chapters 7-8). These changes can have ecological as well as geomorphological consequences through the development of surface texture (i.e. habitat complexity) and through alteration of micro-climatic conditions, and the subsequent efficiency of weathering and erosion. Importantly, organisms can be directly involved in these changes, through processes of bioerosion, bioconstruction and possibly bioprotection. Feedbacks involving substrata modification through biogeomorphic processes, and associated geomorphological and ecological consequences (positive or negative), can be placed within a framework of 'biogeomorphic ecosystem engineering' (Jones and Gutiérrez 2007; Francis et al. 2009; see Chapters 3 and 9); the development of ecologically favourable physical habitat on limestone substrata through bioerosion by microorganisms and grazing organisms is suggested here as one previously unrecognised example.

Third, while evidence of biogeomorphic processes involving the alteration of material properties and behaviours have been presented – and are predicted to be important for weathering and ecology – these interactions are not expected to be of concern for durability (and performance) at the scale of whole structures over engineering timeframes (Chapter 7, Appendix 3). More work is needed, however, to clarify the relevance of biogeomorphological processes in engineering durability in a variety of contexts, whether negative or positive, as this is a crucial step if practitioners are to be expected to adopt enhancements specifically for ecological gains.

Lastly, the complexity of biogeomorphic systems in time and space has been demonstrated using the specific example of hard coastal structures (Chapter 9). Spatial and temporal variation in the influence of substratum properties (i.e. material type and texture) on early colonists was observed alongside differences in the relative importance and efficiency of organic weathering and erosion processes for geomorphology (i.e. morphology, and material properties and behaviours). This means that the consequences of these processes for geomorphology and ecology cannot be considered consistent in time and space, and may be largely scale-dependent. This research therefore highlights the importance of broader concepts of complexity, non-linearity, threshold response, self-organisation and scale in biogeomorphology (Phillips 1992; Viles 2001; Phillips 2003; Murray et al. 2009; Francis et al. 2009), and the need for these ideas to considered in biogeomorphological studies if the relative importance of biology in landform and landscape evolution is to be adequately evaluated and ultimately modelled (Phillips 1995a, 2009; Reinhardt et al. 2010; Wheaton et al. 2011).

Recognising such complexity, a priority for future research needs to be identifying where and when biogeomorphic processes are likely to be most important – both geomorphologically and ecologically – particularly if understanding is to be applied in environmental management (Viles et al. 2008). This mirrors priorities identified in allied concepts in ecology (i.e. physical ecosystem engineering, e.g. Hastings et al. 2007; Jones and Gutiérrez 2007; Jones et al. 2010; Gutiérrez et al. in press) and, as has been clearly demonstrated in this thesis, signifies considerable and exciting opportunities (and a necessity) for future collaborations between biogeomorphologists and ecologists to conceptualise and collect quantitative data to ultimately predict how biotic and abiotic components of the environment are linked and how they behave at different scales, so that they can be more fully understood and effectively managed.

APPENDICES

APPENDIX 1: SEM Pilot Study

APPENDIX 2: SEM Spatial Variability

APPENDIX 3: Existing Coastal Structures SEM

APPENDIX 4: Plymouth Breakwater Case Study

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APPENDIX 1 SEM PILOT STUDY

1.1 Introduction and Aims

This Appendix describes a pilot study undertaken following the recommendations of Taylor and Viles (2000) to determine the necessary level of replication for Scanning Electron Microscope (SEM) work discussed in full in Chapter 7: Strand 1. All SEM work was undertaken using chippings taken from the surface of Portland limestone, Cornish granite and marine concrete blocks exposed on two shores in Cornwall for 8 and 20 months at MTL. The use of SEM in geomorphological and ecological research is outlined in Chapter 7, alongside the background and rationale for using SEM in this study to examine microbiological and micro-geomorphological features on the different types of construction materials, after different periods of exposure.

The pilot study described in this Appendix specifically aimed to:

1. Determine the types of micro-scale biological growth, and weathering and erosion features that were visible on the different materials using SEM;
2. Determine the number of individual observations needed to obtain a representative sample of occurrence for each feature on individual SEM chippings, and;
3. Determine the number of SEM chippings that could adequately represent the occurrence of features across the whole block surface.

10.2 Methods

1.2.1 Initial observations and classification of surface features

For the pilot study, one block of each material type (limestone, granite and concrete) was randomly selected from a set of 8 harvested from two experimental shores after 8 months of exposure at MTL (see Section 5.2 p. 165). Two chippings (roughly 1 cm^2) were taken from the surface of each block, at least 2 cm apart, using a hammer and chisel (e.g. McGreevy 1985; Viles 1987a, b). Blocks were air-dried before chippings were taken to minimise deformation of features associated with rapid drying processes (Norton et al. 1998). Each chip was first viewed uncoated (under low vacuum) using a Hitachi S-3400N Type II SEM (15 Kv, 9 – 15 mm working distance) to assess general characteristics of microbial growths *in situ* (Herrera and Videla 2009). Samples were subsequently sputter-coated with gold or carbon to improve image clarity. A second group of chips (two from one block of each material type) were beached in hydrogen peroxide to remove organic material and viewed in the same way to observe geomorphological (weathering and erosion) features present at the material surface (e.g. Naylor and Viles 2002). Initial testing showed that immersing sample chips in a 5 % hydrogen peroxide solution overnight (8 – 10 hours) was sufficient for removing the majority of organic matter for the types of observations described below. Control materials bleached following the same procedure showed no change in appearance of the mineral surface (Figure A1 - 1); micro-scale features quantified on experimental samples were not, therefore, deemed an artefact of the SEM preparation procedure (Gaffey and Bronnimann 1993; Naylor and Viles 2002; Gómez-Pujol 2006).

Samples were initially examined at random locations on the surface, at varying magnifications, to observe the general characteristics of biological growth (unbleached), and weathering and erosion features (bleached) that could be quantitatively recorded in the main study. The most commonly occurring features observed on each material type are listed in Table A1 - 1. Example images and general descriptions of each feature are given in the following sections and in Figure A1 - 2.

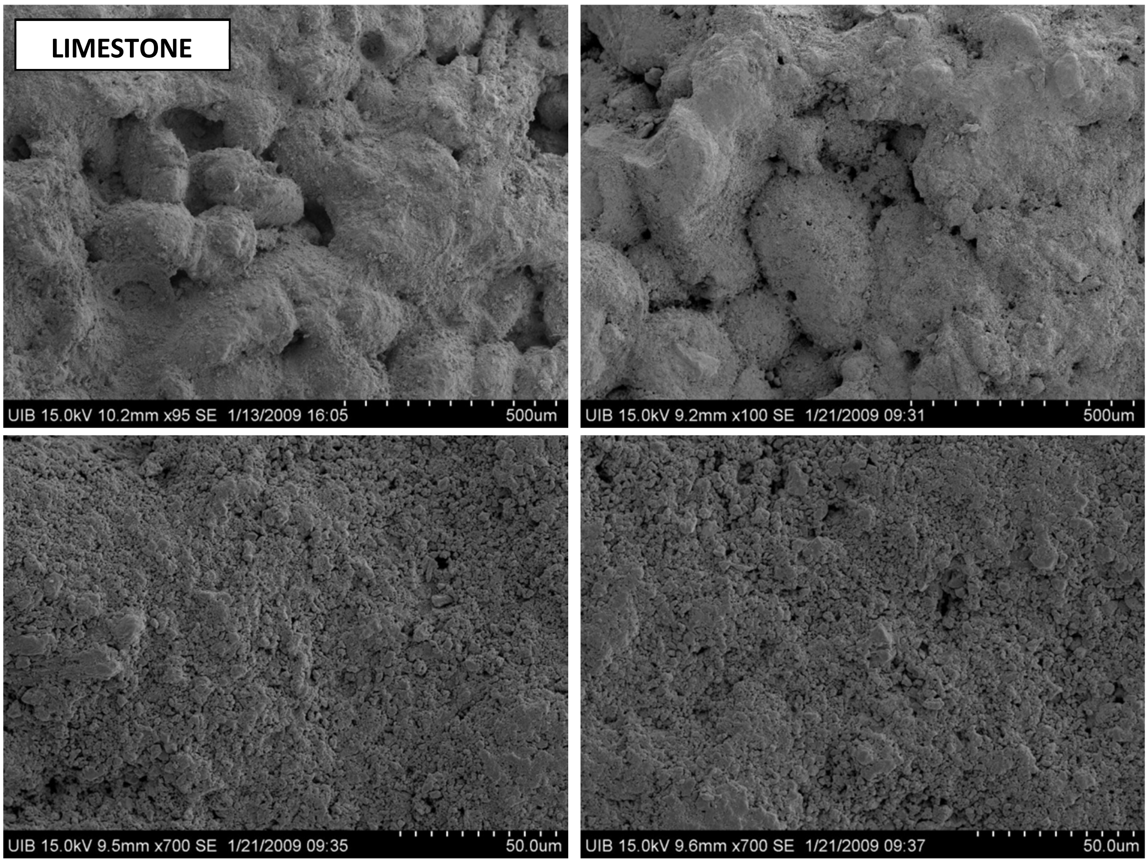
Table A1 - 1 Micro-scale surface features observed using SEM on different materials exposed at MTL, listed in order of abundance in pilot study observations.

Material Type	Biological growth features (unbleached samples)	Weathering and erosion features (bleached samples)*
Limestone	Boreholes Bio-chemical crust Extracellular polymeric substances (EPS)	Boreholes (biological) Dissolution forms (chemical) Biological etching/pitting (biological)
Granite	Coccoid cell colonies (cyanobacteria) Extracellular polymeric substances (EPS) Biological filaments (cyanobacteria/algae)	Cleavage/flaking (mechanical) Micro-cracking (mechanical)
Concrete	Bio-chemical crust Biological filaments (cyanobacteria/algae) Coccoid cell colonies (cyanobacteria) Boreholes Extracellular polymeric substances (EPS)	Biological etching/pitting (biological) Micro-cracking (mechanical) Boreholes (biological) Dissolution forms (chemical)

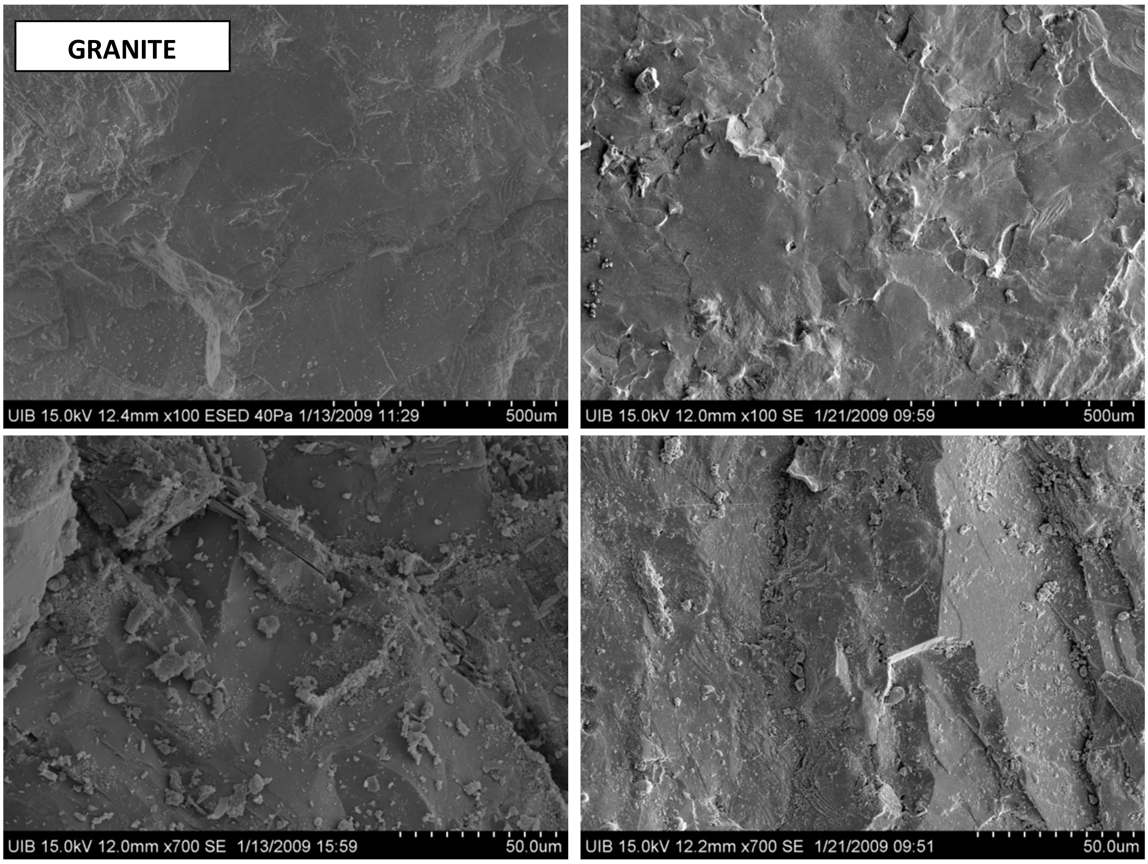
**Inferred origin of weathering and erosion features shown in brackets (biological / chemical / mechanical), after Moses and Viles 1996 and Viles and Moses 1998.*

Control materials (those unexposed in the sea) were also observed. There was no evidence of biological growth on any of the control samples, nor of the weathering and erosion features observed on limestone and concrete (Figure A1 - 1). Some occurrences of weathering-like forms were observed on control granite, which were attributed to the artificial texturing technique used on this material type (flame-texturing); this is given due consideration in the main discussion (Chapter 7).

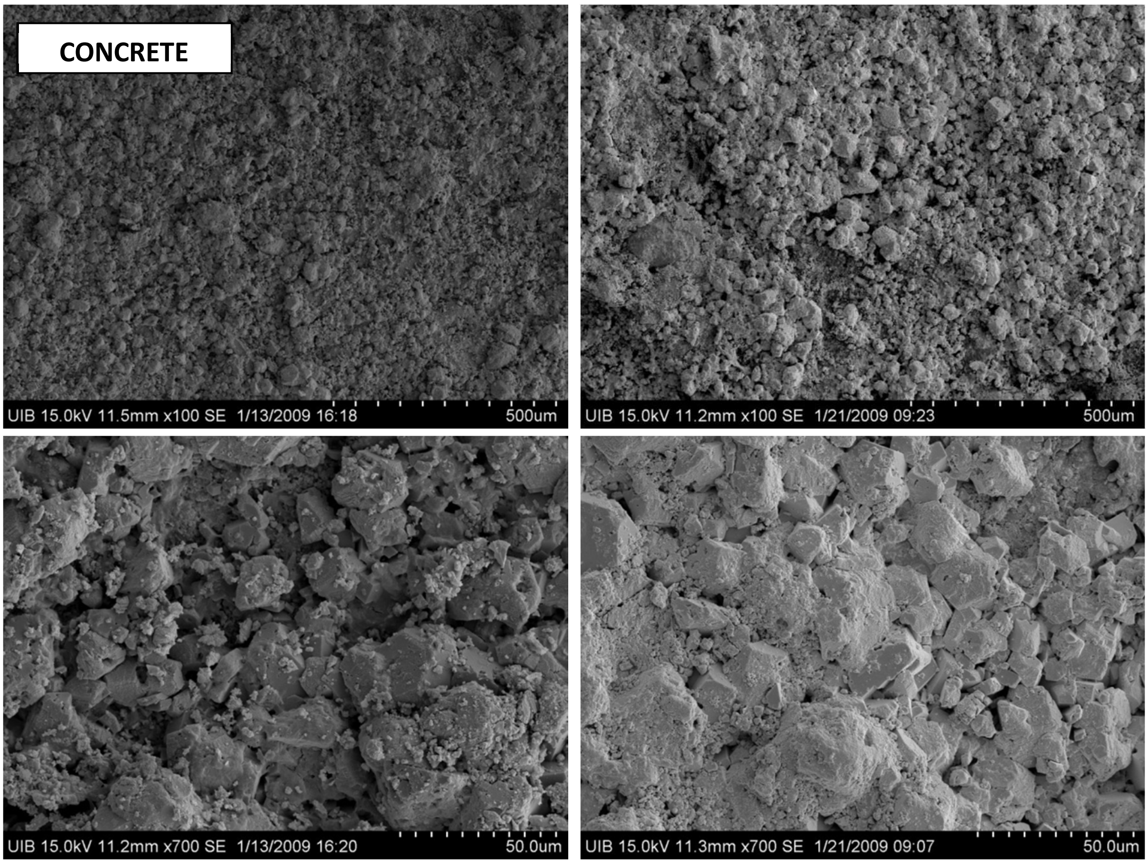
Unbleached samples | **Bleached samples**



***Above*: control limestone, x 100 (top) x 700 (bottom)**



Above*: control granite, x 100 (top) x 700 (bottom)** ***continued…



***Above*: control concrete, x 100 (top) x 700 (bottom)**

Figure A1 - 1 SEM micrographs (gold coated, accelerating voltage = 15 kV) of control (unexposed) surfaces of limestone, granite and concrete at low (x 100) and high (x 700) magnification, as indicated; left-hand images show surfaces without treatment, right-hand images show surfaces after bleaching, scale as indicated.

1.2.2 Biological growth features (unbleached samples)

On unbleached surfaces, boring holes were used to infer colonisation of the substratum by euendolithic microorganisms (e.g. Viles et al. 2000; Garcia-Pichel 2006; Cockell and Herrere 2008). Individual boreholes were circular in form, rarely occurred in isolation, and did not typically exceed 7 µm in width (e.g. Figure A1 - 2a). Larger perforations were formed where boring was particularly dense causing coalescence. Coalesced holes typically had irregular curved edges denoting secondary origin (see Chapter 7 for discussion).

Biological cells were clearly visible under the SEM, which were distinguished based on general morphological groupings (Munn 2003). These were commonly coccoid (i.e. round, e.g. Figure A1 - 2d) or filamentous (e.g. Figure A1 - 2e) in form (probably cyanobacteria), or rod shaped (bacillus form). Colonies of coccoid cells were particularly common on granite surfaces, while chains of cells (i.e. streptobacilli forms) were also observed on concrete.

There is a wealth of biogeomorphological terminology associated with microbiological growths developing on hard substrates (see reviews by Golubic et al. 1987; Viles 2000a). For the purposes of broad comparison used here, EPS (extracellular polymeric substances) is used to refer to the thin mucilaginous coatings associated with epilithic (surface) organisms which are seen under the SEM as irregular, 'shiny' coatings (e.g. Figure A1 - 2c); cracking was also common for thicker accumulations of EPS occupying depressions and against topographic features, probably associated with unavoidable desiccation during drying (Little et al. 1991).

Although typically reserved for accumulations of microorganisms and lichens greater than 5 mm (Viles 1995), the term 'biocrust', or more specifically 'bio-chemical crust', is used here for crust-like forms at an SEM scale. These 'crusts' were characterised by chemical deposits, mineral grains and other detrital particulates alongside dense accumulations of biological cells and filaments (e.g. Figure A1 - 2b). Cracking and flaking, and the exposure of organic cells within (again possibly an artefact of drying) were useful distinguishing features for these crusts.

1.2.3 Weathering and erosion features (bleached samples)

In a geomorphological context, boring holes (as described above) were used as an indictor of direct erosion (specifically bioerosion) of the substrata (e.g. Figure A1 - 2a). Epilithic growths were associated with pitting and etching of the substratum surface, leaving distinguishable cell-shaped depressions (e.g. Figure A1 - 2g). These weathering forms are created through the excretion of organic acids which can dissolve the mineral constituent of a range of rock types (e.g. Burford et al. 2003; Moses 2003) and construction materials (e.g. Sanchez-Silva and Rosowsky 2008).

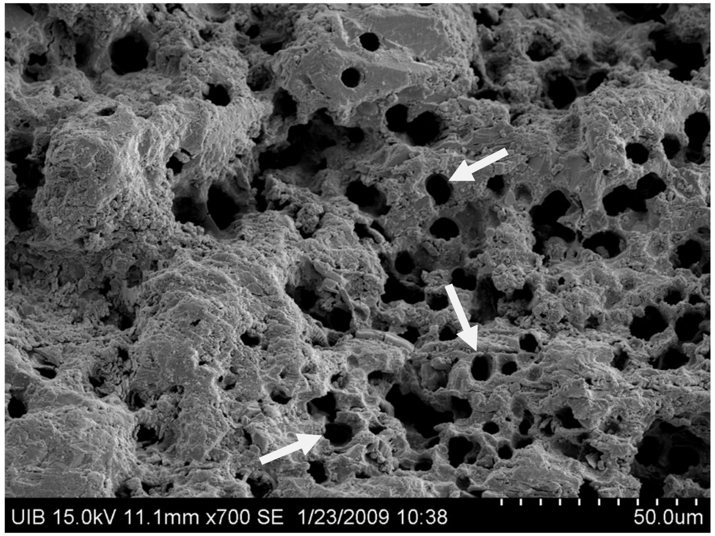
Micro-scale morphological features associated with dissolution (chemical) processes have been observed and classified on carbonate materials exposed under field conditions (Moses and Viles 1996; Gómez-Pujol 2006) and after exposure to chemical weathering agents under controlled laboratory conditions (Viles and Moses 1998). Characteristic features are rounding and disaggregation of calcite crystals, blocky etching, grain boundary widening and V-in-V etching (e.g. Figure A1 - 2f).

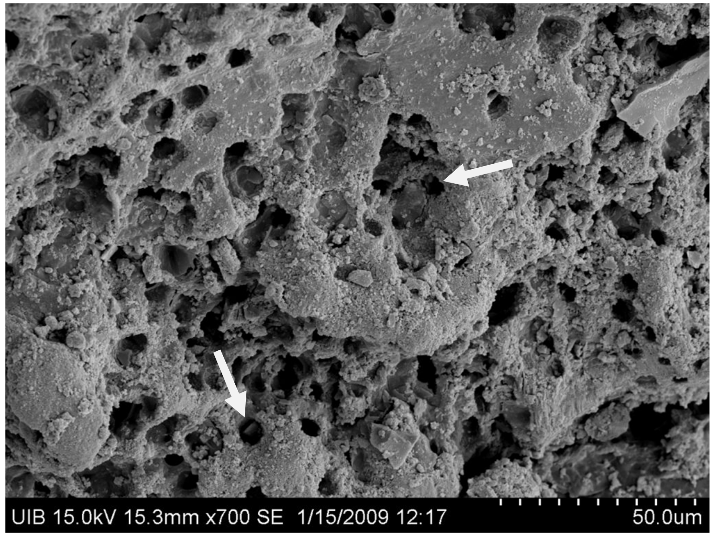
Micromorphologies associated with mechanical weathering processes were also observed on bleached samples. The fracturing, cleavage and flaking of minerals was observed, characterised by angular edges and fragments at the surface (e.g. Figure A1 - 2h). These forms have been linked to thermal weathering processes in both hot and cold environments (e.g. Zhu et al. 2003; Guglielmin et al. 2005) and in tidal and coastal environments in association with salt weathering (e.g. Chabas and Jeannette 2001; Cardell et al. 2003; López-Arce et al. 2010). Micro-cracking (e.g. Figure A1 - 2i) is also associated with expansive processes, such as wetting-drying, warming-cooling and salt crystallisation, which are believed to be particularly efficient weathering mechanisms in the intertidal zone, both on rock and concrete (e.g. Trenhaile 2006; Porter and Trenhaile 2007; Haynes et al. 2010).

(a) Boreholes:
Distinctive circular perforations, rarely occurring in isolation. Particularly common on limestone.
Coalescence of individual holes common where boring is dense, forming irregular shaped perforations with multiple, curved edges (also see Figure 7-5a p.269).

Left: dense boreholes (indicated) on limestone (8 months, unbleached).

Right: boring (indicated) of concrete cement matrix (8 months, bleached).

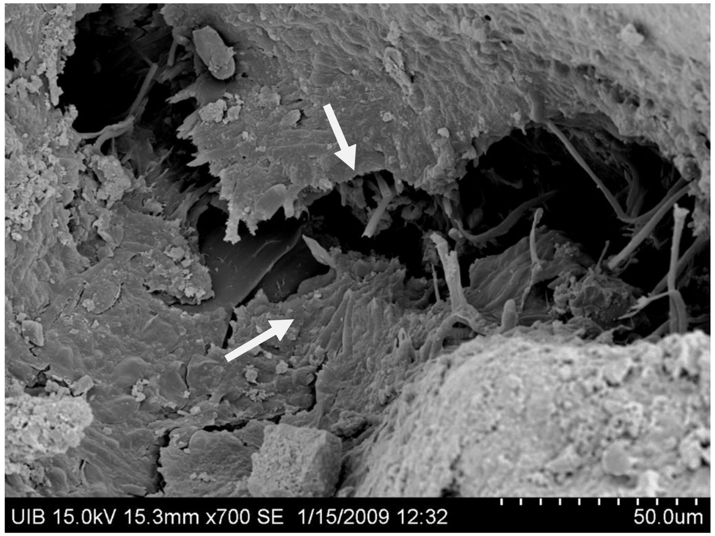


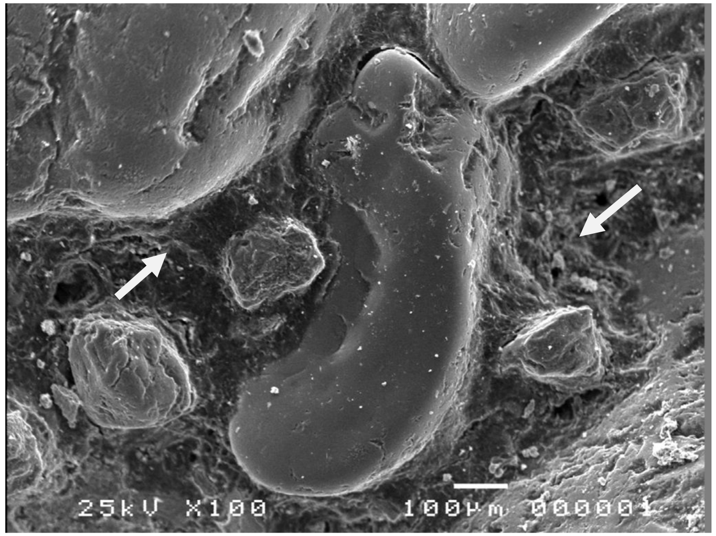


(b) Bio-chemical crust:
Dense accumulations of biological cells and filaments, inorganic particles and chemical precipitates. Often characterised by desiccation cracking (probably from sample preparation).

Left: biological filaments in cracked crust (indicated) on concrete (8 months, unbleached).

Right: protrusion of sand grains above the crust (indicated) after bleaching of concrete 8 months, bleached).

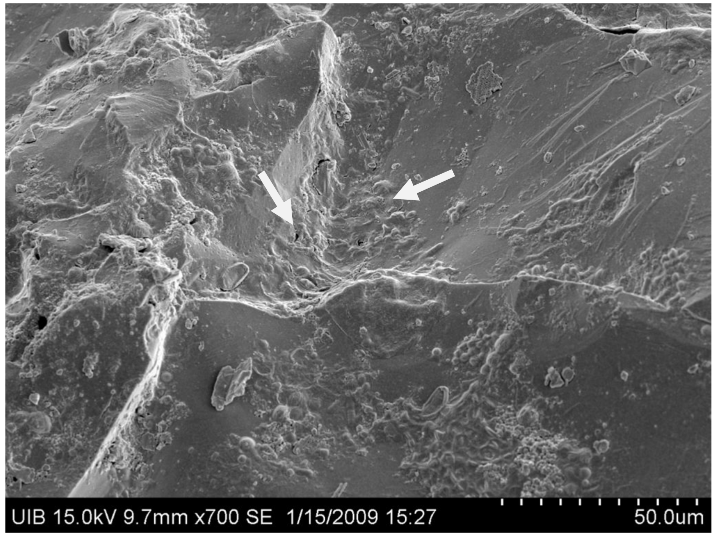




(c) Extracellular Polymeric Substances (EPS):
Thin, organic coverings typically having a shiny 'wet' appearance under the SEM. Most noticeable against topographic features and within surface depressions. Cracking and peeling of the edges is common.

Left: EPS film (indicated) between limestone ooliths (8 months, unbleached).

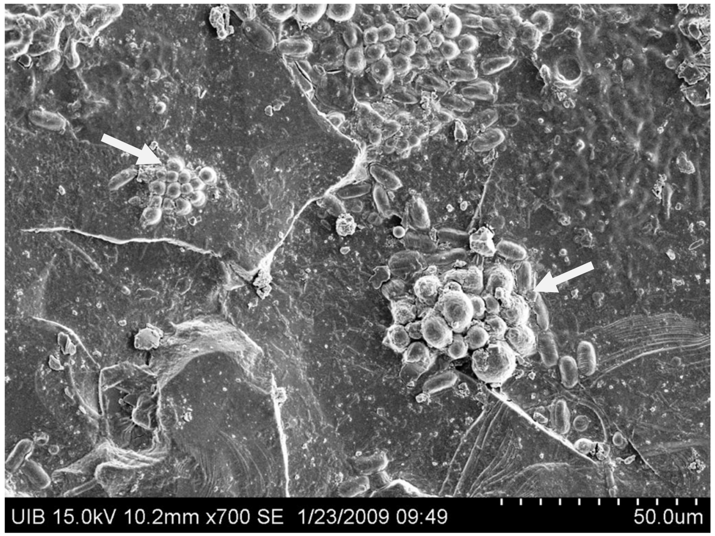
Right: filming (indicated) associated with roughness elements on granite (8 months, unbleached).

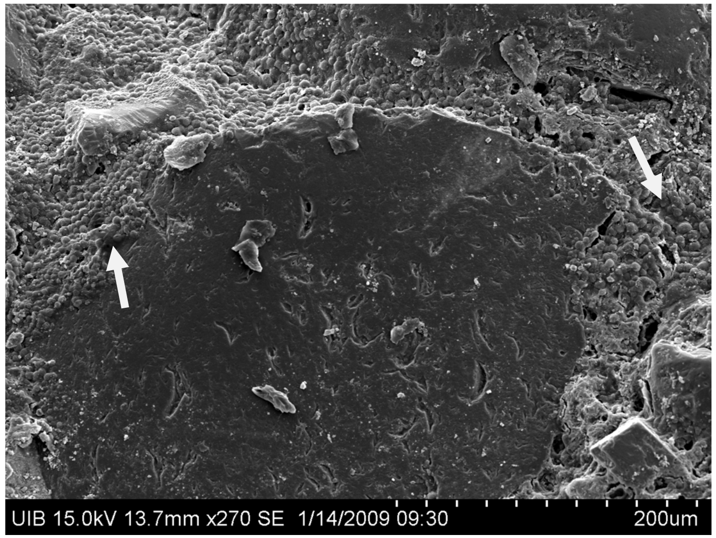


(d) Coccoid cell colonies:
Aggregations of spherical organic cells (cycanobacteria) often occurring in association with EPS or incorporated into thicker crusts (see [b] above). Particularly distinguishable on granite surfaces.

Left: isolated cyanobacteria colonies (indicated) on surface of granite (8 months, unbleached).

Right: dense coccoid cells (indicated) incorporated into bio-chemical crusts between aggregates on concrete (8 months, unbleached).

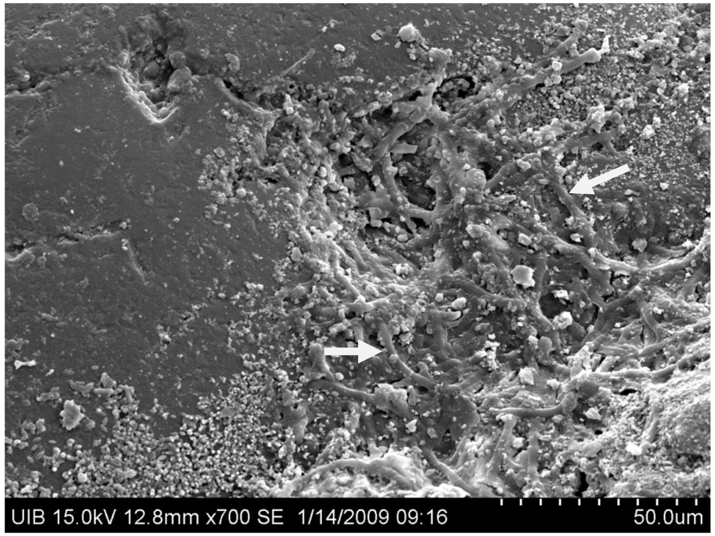




(e) Biological filaments:
Sinuous, elongated organic cells, often dense and interlocking. Variable in size (typically < 7 µm width) and often patchy in distribution.
Often visible within bio-chemical crusts or at the surface in association with EPS.

Left: filaments (indicated) protruding from crusts onto a sand grain on concrete (8 months, unbleached).

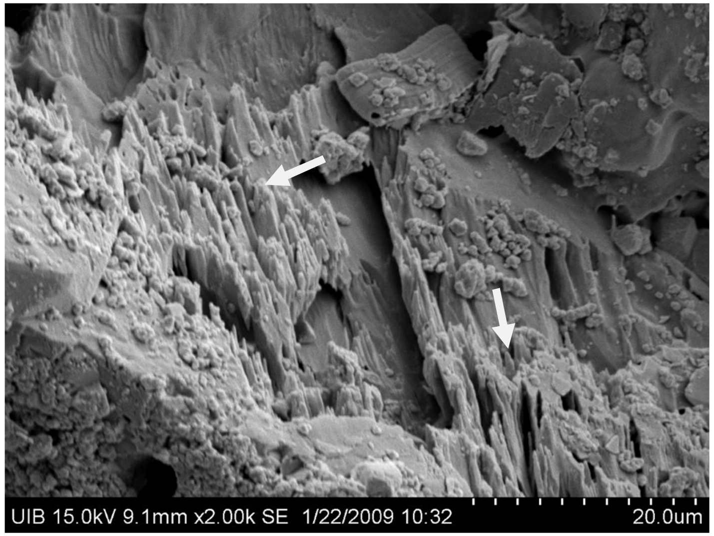
Right: filaments (indicated) on surface of granite (8 months, unbleached).

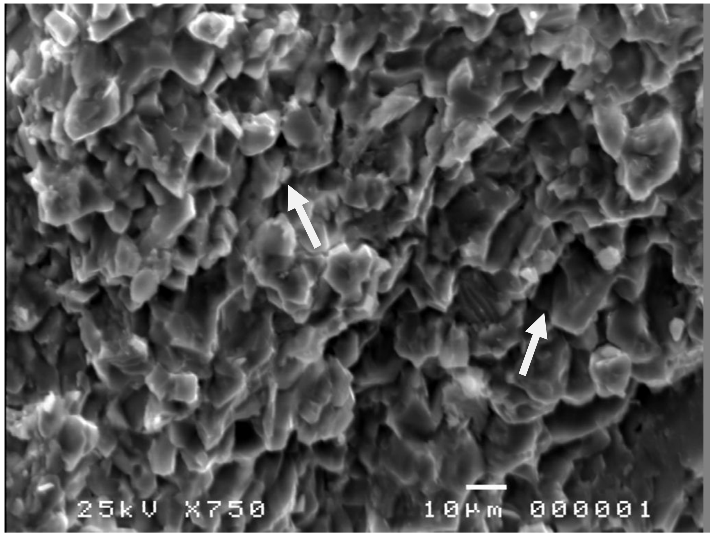


(f) Dissolution features:
Various morphologies including V-in-V etching, crystal rounding, grain boundary widening and blocky etching.
Typically associated with chemical weathering of the substrata (see Moses and Viles 1996; Viles and Moses 1998).

Left: Deep V-in-V etching (indicated) of calcite crystals on limestone (8 months, bleached).

Right: Blocky etching (indicated) and disaggregation of concrete cement (20 months, bleached).

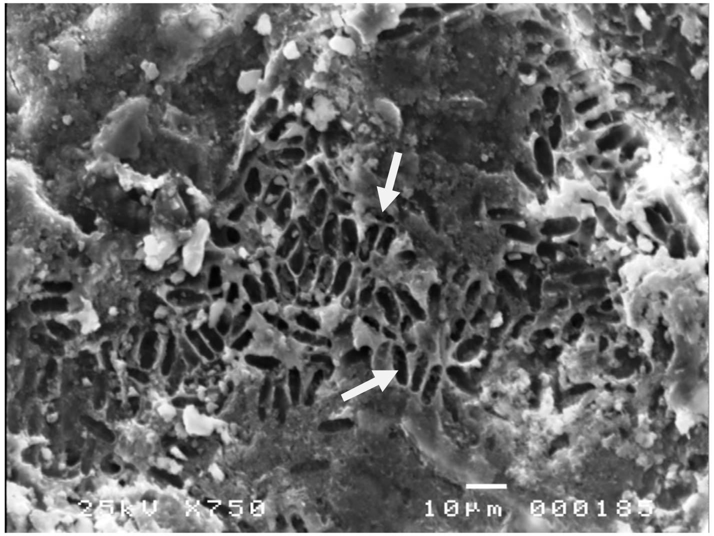


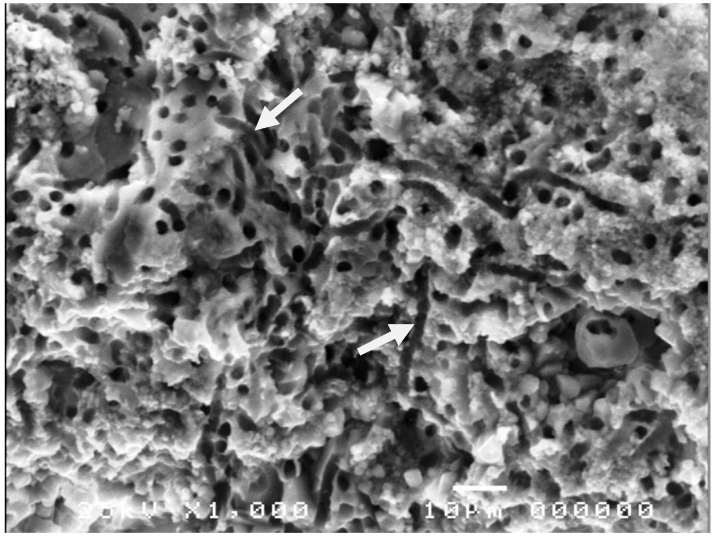


(g) Biological pitting / etching:
Depressions in the mineral surface, having distinct biological form. Pits may be formed by individual cells (cocci or bacilli form) or sinuous trenches associated with biological filaments.

Left: bacilli etch forms (indicated) within cement matrix on concrete (20 months, bleached).

Right: filament-shaped etching (indicated) and boring of limestone (20 months, beached).

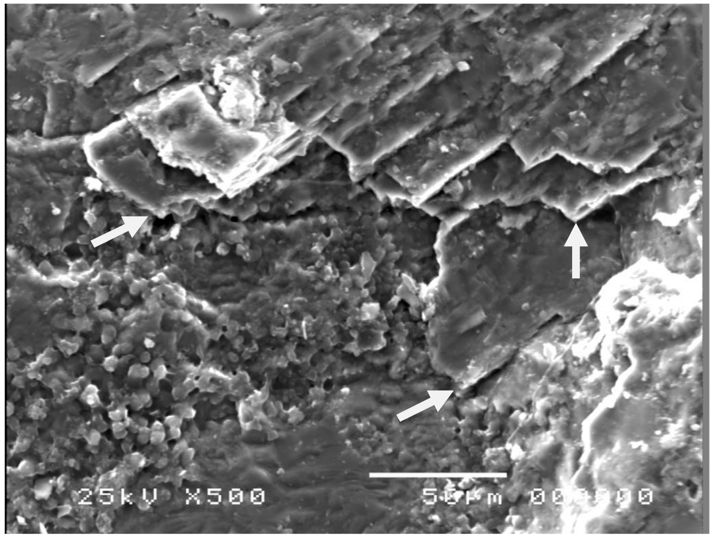


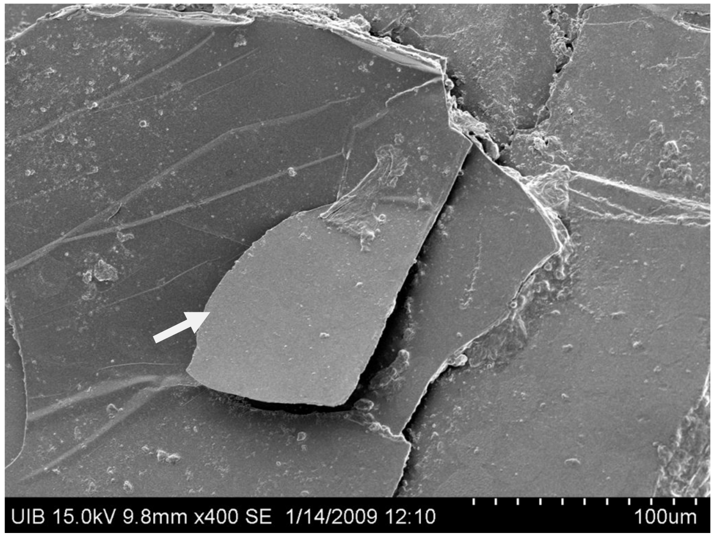


(h) Cleavage / flaking:
Widening or loosening of mineral grains of granular rocks, and flaking or 'peeling' of minerals, typically attributed to mechanical weathering processes.

Left: flaking and disaggregation (indicated) of quartz on granite (20 months, bleached).

Right: flaking (indicated) of mica on granite (8 months, bleached).





(i) Micro-cracking:
Linear cracks on the surface of the substrata, similar in form to stress fractures (*en enchelon* cracks).
May be present within crusts or forming between mineral grains, boreholes and other surface depressions, or in association with detaching fragments.

Left: *en enchelon* cracks (indicated) on concrete (20 months, bleached).

Right: crack (indicated) formed across the surface of a quartz grain on granite (8 months, bleached).

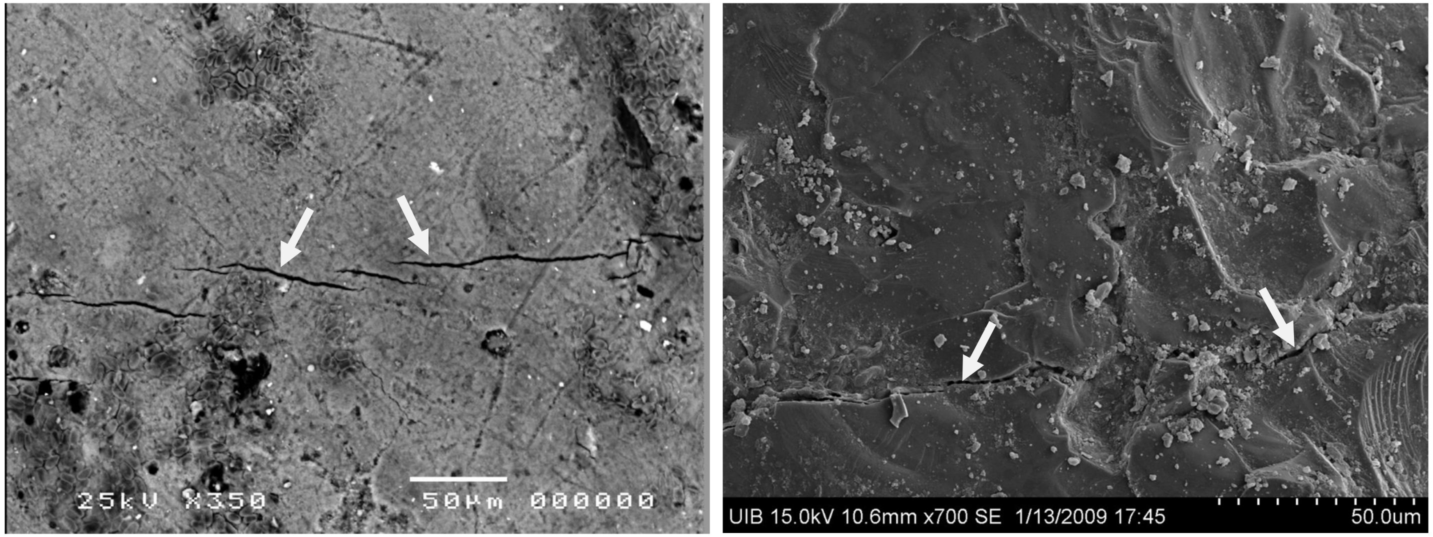


Figure A1 - 2 Examples of micro-scale biological growth, and weathering and erosion features classified on different material types exposed in the intertidal zone, Cornwall, UK: (a) boreholes; (b) bio-chemical crust; (c) EPS, (d) coccoid cells; (e) biological filaments; (f) dissolution features; (g) biological pitting / etching; (h) cleavage / flaking, and; (i) micro-cracking (material type, exposure time, magnification and scale as indicated).

1.3 Determination of Sampling Procedures

After features present on bleached and unbleached samples had been classified (Table A1 - 1), each chipping was inspected systematically using the operator selected coordinates (OSC) method (cf. Viles and Moses 1998). In each instance, the top left of the sample was first located under the SEM at low magnification (x100). The surface was then viewed using a higher magnification (x 700), where surface features could be identified, and a micrograph image of the surface taken. This procedure was repeated 40 times (see below), moving in a zig-zag pattern across the whole sample. Each subsequent sampling point was selected by moving roughly three full turns of the navigation wheel (when zoomed out, at x 100 magnification). Edges of the samples were avoided to prevent the inclusion of artefacts resulting from chipping.

Micrograph images were subsequently inspected for the occurrence of each biological growth, and weathering and erosion feature listed in Table A1 - 1. Occurrences were recorded in a checklist in Microsoft Excel as a presence : absence ratio (Moses and Viles 1996; Viles and Moses 1998; Taylor and Viles 2000), used to calculate percent occurrence values for each feature (see Chapter 7: Strand 1).

1.3.1 Number of observations per sample

To determine the number of observations required to adequately represent the occurrence of each feature (Table A1 - 1) on individual SEM chippings, plots of sample size (number of observations) against percent occurrence values were produced for each feature, on each material type (Taylor and Viles 2000; Naylor 2001). Figure A1 - 3 shows plots for biological growth features observed at the surface of unbleached chipping of each material type. Figure A1 - 4 shows plots for micro-scale weathering and erosion features observed at the surface of bleached chipping. Features occurring in less than 20 % of the images (after 40 observations) are not included in these plots as they were considered uncommon and could not be adequately represented using this sampling method (Taylor and Viles 2000).

For all three material types, percentage occurrence values levelled-off between 20 and 30 observations (Figure A1 - 3 and Figure A1 - 4). It was therefore assumed that a sample size of 30 observations was appropriate to quantify the occurrence of the selected features on each SEM sample. It is recognised that many more observations would be needed to accurately represent occurrences of less common features (Taylor and Viles 2000), but for those quantified in this study (Table A1 - 1), additional observations (beyond 30) did not make a significant difference to the final percent occurrence value obtained (Figure A1 - 3 and Figure A1 - 4). Following these observations, a sample size of 30 observations was used in all SEM work described in Chapter 7.

1.3.2 Within-block variation

Further comparisons were made between observations of different chippings from the same blocks in order to determine whether features recorded on individual chips (above) were representative of those occurring across the whole block surface. To do this, additional chippings sampled from a different area of the same 'parent block' used above (at least 2 cm apart) were analysed following the same methods described in Section 1.3.1.

Occurrence values obtained from the second group of chips showed very good consistency with the first group; for biological growth features, occurrences did not vary more than one or two observations (or 6.67 % occurrence) in most instances. Occurrence values for biological filaments were more variable, reflecting patchier colonisation patterns. All differences, however, did not exceed four observations (or 13.33 % occurrence) between pairs of chips sampled from the same block. A test of independence (Chi Square [χ2], Burt et al. 2009) using paired observations confirmed the null hypothesis that there was no difference in measured occurrence values between chipping taken from the same block, both for biological growth features (e.g. for granite, $\chi^2 = 2.3$ [df = 4], $p > 0.05$, Table A1 - 2a) and weathering and erosion features (e.g. for concrete $\chi^2 = 2.6$ [df = 4], $p > 0.05$, Table A1 - 2b).

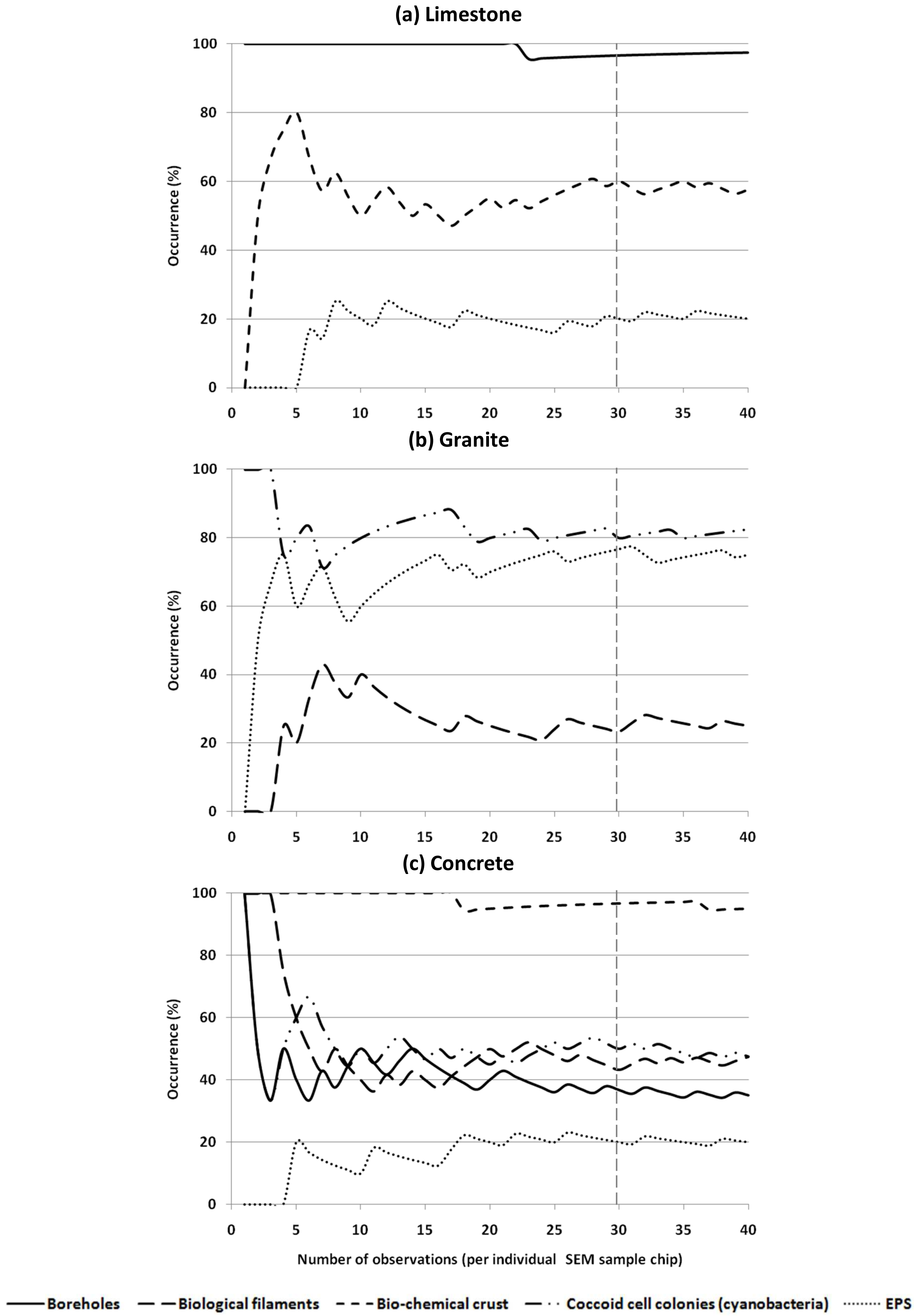


Figure A1 - 3 Occurrence (%) of biological growth features on chips (unbleached) of (a) limestone (b) granite and (c) concrete observed using SEM after 8 months of exposure at MTL, Cornwall, UK.

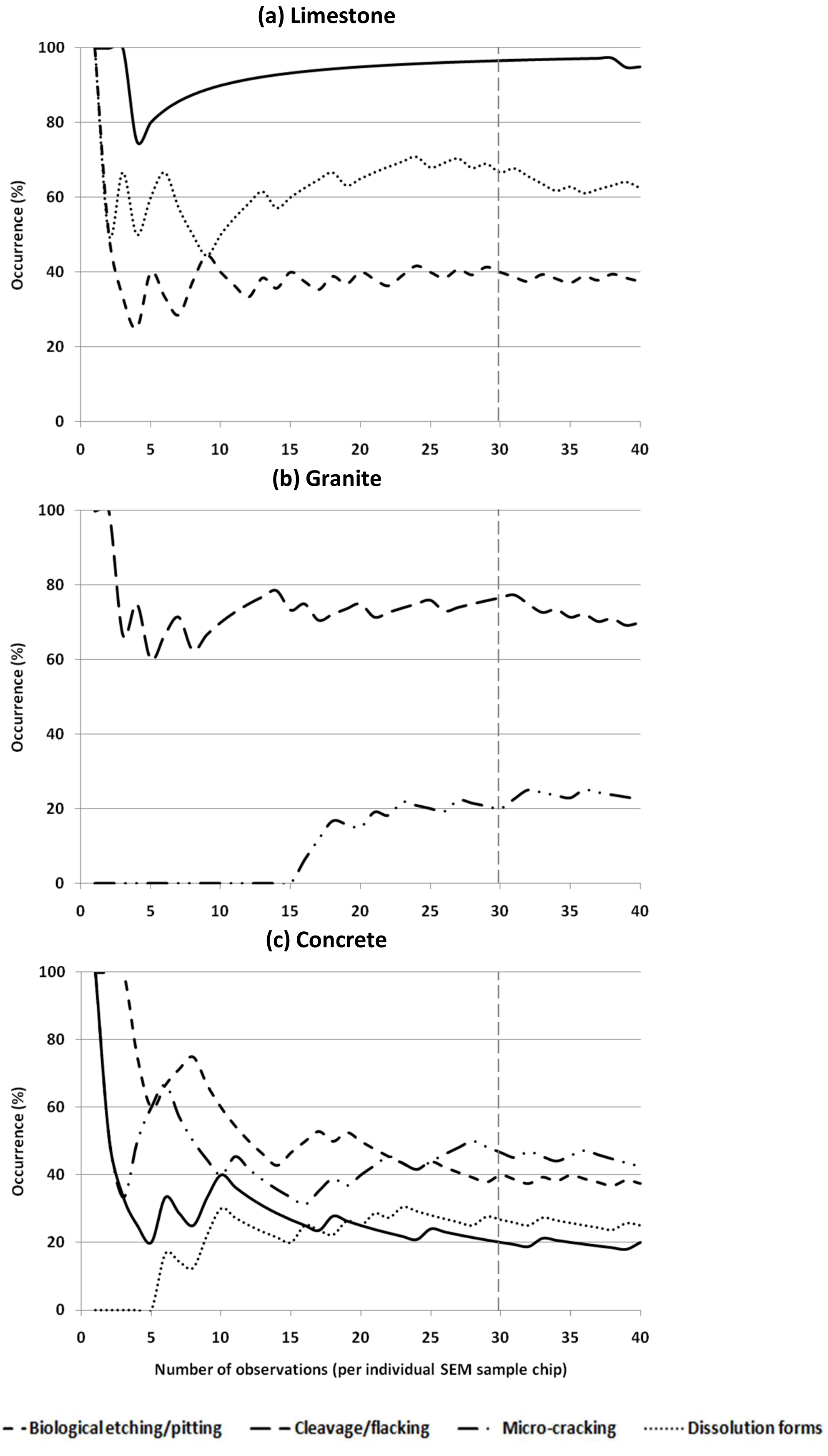


Figure A1 - 4 Occurrence (%) of weathering and erosion features on chips (bleached) of (a) limestone (b) granite and (c) concrete observed using SEM after 8 months at MTL, Cornwall, UK.

Table A1 - 2 Example Chi-square calculations for occurrence (in 30 SEM observations) of (a) biological growth features on two granite chippings and (b) weathering and erosion features on two concrete chippings sampled from the same block (O = Observed, E = Expected, ns = not significant).

(a) Biological Growth Features

	Boreholes	Coccoid cell colonies	EPS	Biological filaments	Bio-chemical crust	TOTAL
Observed data						
Chip 1 (O)	2	24	23	7	0	**56**
Chip 2 (O)	2	24	19	11	1	**57**
TOTAL	**4**	**48**	**42**	**18**	**1**	**226**
Expected data						
Chip 1 (E)	2.0	23.8	20.8	8.9	0.5	**56**
Chip 2 (E)	2.0	24.2	21.2	9.1	0.5	**57**
TOTAL	**4**	**48**	**42**	**18**	**1**	**226**
Chi (O – E)^2/E	0.0	0.0	0.2	0.4	0.5	**1.1**
Chi (O – E)^2/E	0.0	0.0	0.2	0.4	0.5	**1.1**
					Chi-square (χ^2)	**2.3**
					Probability (df = 4)	**0.7 (ns)**

(b) Weathering and Erosion Features

	Boreholes	Biological etching /pitting	Cleavage / flaking	Surface cracking	Dissolution forms	TOTAL
Observed data						
Chip 1 (O)	8	15	3	11	5	**42**
Chip 2 (O)	15	11	4	12	6	**48**
TOTAL	**23**	**26**	**7**	**23**	**11**	**180**
Expected data						
Chip 1 (E)	10.7	12.1	3.27	10.7	5.1	**56**
Chip 2 (E)	12.3	13.9	3.7	12.3	5.87	**57**
TOTAL	**23**	**26**	**7**	**23**	**11**	**180**
Chi (O – E)^2/E	0.7	0.7	0.0	0.0	0.0	**1.4**
Chi (O – E)^2/E	0.6	0.6	0.0	0.0	0.0	**1.2**
					Chi-square (χ^2)	**2.6**
					Probability (df = 4)	**0.6 (ns)**

It is worth noting that while not significant, occurrence values for weathering and erosion forms were more variable between chippings from the same block than for biological growth features. Greatest variability was recorded on concrete, and may reflect less spatial consistency in the efficiency of different geomorphic processes acting on the heterogeneous cement/aggregate surface. For the purposes of this work however, which aimed to broadly compare the nature and relative occurrence of different forms of weathering and erosion between construction materials, these data indicated that one chip was adequate for representing the selected features on each experimental block (Taylor and Viles 2000). A protocol of sampling one chip from individual blocks was therefore used in the analyses described in Chapter 7.

APPENDIX 2 SEM SPATIAL VARIABILITY: THE INFLUENCE OF SHORE POSITION

2.1 Introduction and Aims

Additional semi-quantitative SEM observations were made using blocks exposed as part of *Exposure Trial 2* (see Chapter 6) to assess the spatial variability of microbiological and micro-geomorphological responses of construction materials discussed in the main experimental work (Chapter 7: Strand 1). This supplementary assessment was undertaken to contribute to ecological and geomorphological questions surrounding spatial variability of material responses in the intertidal zone (between shore levels) and because hard engineered structures built in the coastal zone can be placed at different tidal heights depending on their function (a breakwater versus a seawall, for example). Biogeomorphologically, it was of interest to explore whether the nature and relative importance of different weathering and erosion processes described in detail in Chapter 7 were consistent at different shore levels.

The aims of this work were:

1. To examine the consistency of micro-scale biological and geomorphological responses of common construction materials exposed at different tidal heights;
2. To assess whether the relative influence of different weathering and erosion processes (i.e. biological, chemical and mechanical) varied at different tidal heights;
3. To consider any observed variations with respect to the geomorphological, ecological and engineering properties of the different materials.

2.2 Hypotheses

Observations on rocky shores have demonstrated differences in the nature of microbial communities at different shore levels (e.g. Decho 2000; Moschella 2003; Thompson et al. 2004; Thompson et al. 2005) and that the relative intensity of different weathering and erosion processes are also expected to vary across the shore (e.g. Schneider 1976; Schneider and Torunski 1983; Spencer and Viles 2002; Gómez-Pujol and Fornós 2010). Three hypotheses were therefore tested to supplement those discussed in Chapter 7 (Table A2 - 1). First, it was predicted that the occurrence of selected growth features would vary in space (between shore levels, Hypothesis A2-1). Second, spatial variation in the intensity of bioerosion of limestone was also examined as a specific biogeomorphological processes (between plots, shores and shore levels, Hypothesis A2-2). Thirdly, the nature of sub-surface colonisation, and weathering and erosion was expected to vary in space (between shore levels; Hypothesis A2-3).

Table A2 - 1 Research questions and experimental hypotheses for Appendix 2.

	Research Question	Hypothesis
PART 1: MICRO-SCALE WEATHERING AND EROSION		
1	How do microorganisms respond to different material types used in coastal engineering?	(A2-1) The occurrence of micro-biological growth features on different materials varies in space (between shore levels).
2	How does **surface** weathering and erosion (at a micro-scale) compare between material types used in coastal engineering?	(A2-2) The intensity of bioerosion observed at the surface of limestone substrata varies in space (between plots, shores and shore levels)
3	How does **near-surface** weathering and erosion (at a micro-scale) compare between materials types used in coastal engineering?	(A2-3) The vertical extent of weathering and erosion varies in space (shore level).

2.3 Methods

In addition to those exposed at MTL for *Exposure Trial 1* (Chapter 5), SEM observations of experimental blocks attached on the same shores at different tide levels (at MTL and MHWN) as part of *Exposure Trial 2* (Chapter 6) are described in this Appendix. These blocks were removed from the shore in January 2010 after 10 months of exposure.

SEM chips were taken from random locations across the whole surface of blocks (50 x 50 x 30 mm, see Chapter 6) as they were not used for the geomechanical tests described in Chapter 7: Strand 2. The same procedures and sampling protocols used for SEM observations as described in Chapter 7 and Appendix 1 were also used in these examinations. For biological growth features, only occurrences of coccoid cells, filaments and EPS were recorded on *Exposure Trial 2* blocks as these features were considered direct observations of biological activity, and were present on all three material types. Occurrence frequencies of other growth features used in the main study (boreholes and bio-chemical crusting) were not sufficient at both shore levels after the 10 months for meaningful comparisons.

For surface weathering and erosion features, due to time constraints only borehole erosion of limestone was compared as a process of specific biogeomorphological interest. Boring density was measured in 15 fields of view of three different limestone blocks (n = 45) positioned at MTL and MHWN. As a further spatial comparison, borehole density was compared at a cm scale (using chips from the same block), a m-scale (between replicate plots) and km-scale (between experimental shores) using data collected as part of the main study (n = 75, see Section 7.6.3 p. 261). Sub-surface weathering and erosion was compared between shore levels for all three material types. Chippings taken from three different blocks exposed at MTL and MHWN were observed under the SEM in cross-section and the depth of weathered zone, salt penetration (measured using EDS analysis) and sub-surface micro-cracking were recorded (see Section 7.6.3 p. 261).

2.4 Statistical Analyses

An ANOVA was performed to compare occurrences of recorded surface growth features between shore levels for each material type. For this test 'feature' (three levels: coccoid cells, filaments and EPS), 'shore level' (two levels: mid-shore [MTL] and upper-shore [MHWN]), and 'material type' (three levels: limestone, granite and concrete) were treated as fixed factors. Data were checked for homogeneity using a Cochran's Test.

The density of boring holes on limestone exposed at both shore levels, and on individual limestone blocks (5 cm apart), between replicate plots (50 m apart) and between shores (20 km apart) were compared using unpaired t-tests. For all tests, data were first checked for homogeneity using the F statistic. Where homogeneity could not be assumed a Welch's t-test was performed, otherwise ordinary unpaired Student's t-tests were used (Burt et al. 2009). The depth of sub-surface weathering and erosion features were also compared on each material type using the same procedures.

2.5 Results

2.5.1 Surface features

Occurrences of microbiological growth features in SEM observations of blocks exposed for 10 months at MTL and MHWN are shown in Figure A2 - 1. Evidence of biological activity was significantly greater on blocks exposed higher on the shore ($p < 0.00$, Table A2 - 2). There were also differences in occurrences of microbiological features between shore levels for each material type, although trends were not consistent; relative occurrences of coccoid cells, biological filaments and EPS are shown in Table A2 - 3.

While there was no difference in the occurrence of growth features between shore heights for granite, coccoid cells and filaments were more frequently observed on limestone blocks exposed higher on the shore (at MHWN). Biological filaments and EPS were also more common on concrete exposed higher on the shore compared to mid-shore replicates (Table A2 - 3).

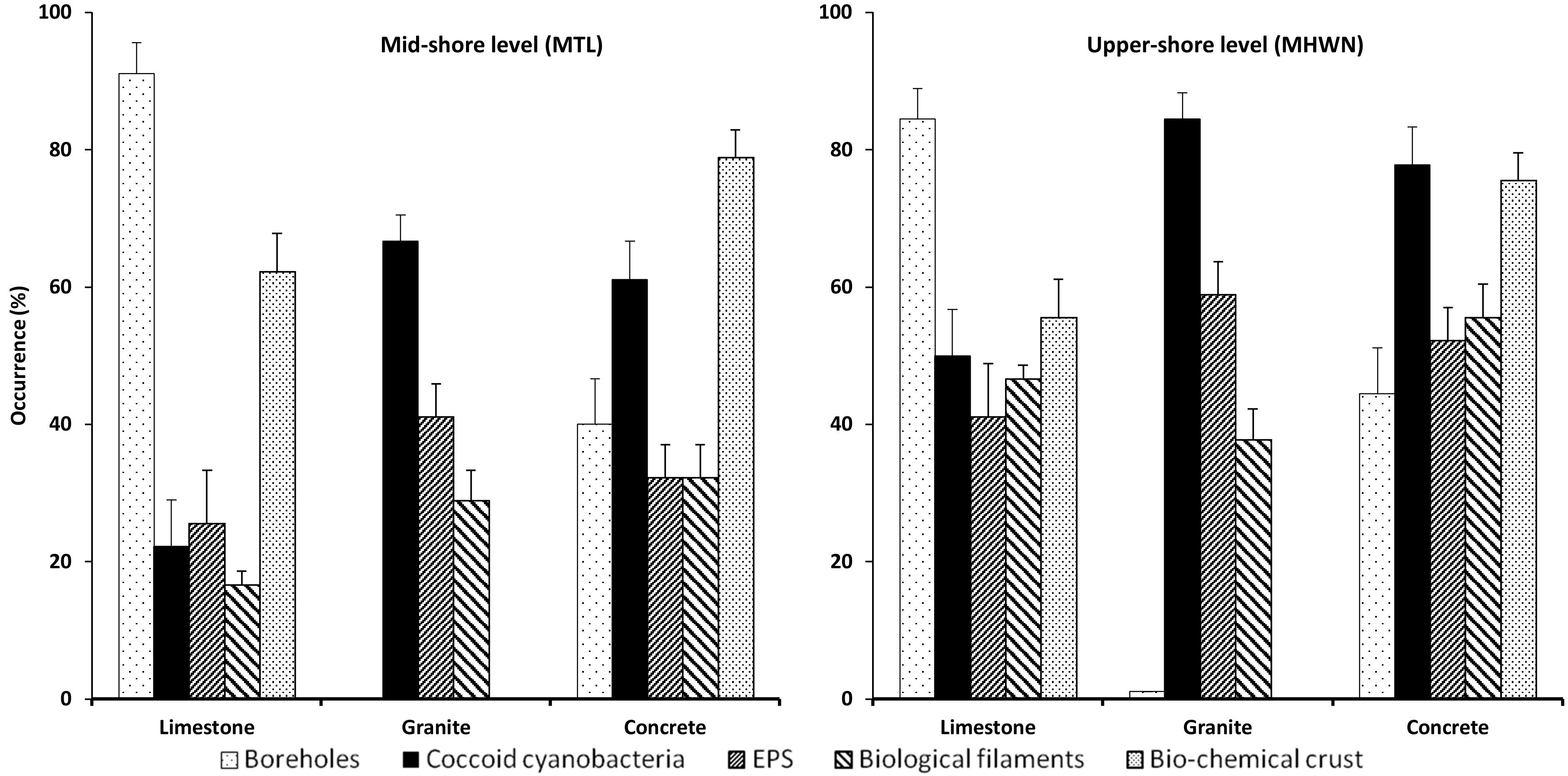


Figure A2 - 1 Occurrences (%) of selected microbiological growth features at the surface of different construction materials after exposure on the mid-shore (*left*, 3m ACD) and upper-shore (*right*, 4m ACD) for 10 months, Cornwall, UK (mean + S.E., *n* = 3).

Table A2 - 2 Analysis of variance for occurrences of micro-scale biological growth features recorded on different material types exposed for 10 months at mid- and upper-shore levels (MTL and MHWN respectively), Cornwall, UK (30 observations of three samples per material type).

Source of variation	***df***	**MS**	***F***	***p***
Feature (*n = 3*)	2	2860.418	21.89	**0.000*****
Shore level (*n* = 2)	1	5268.017	40.31	**0.000*****
Material (*n = 3*)	2	2104.818	16.11	**0.000*****
Feature x Shore level	2	13.1523	0.1	0.905
Feature x Material	4	640.5032	4.9	**0.003****
Shore level x Material	2	104.4868	0.8	0.457
Feature x Shore level x Material	4	66.8754	0.51	0.727
Residuals	36	130.6823	-	-
Total	53	-	-	-

df = degrees of freedom; MS = mean square variance; *F* = ratio of variance; *p* = significance.
Cochran's test $C = 0.351$ ($p < 0.05$, untransformed data)
p values: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

Table A2 - 3 Relative occurrence of selected microbiological growth features recorded at the surface of different material types using SEM after 10 months of exposure at mid- and upper-shore levels (MTL and MHWN respectively), Cornwall, UK (30 observations of three samples per material type).

	Relative Occurrence*		
Biological feature (unbleached)	**Limestone**	**Granite**	**Concrete**
Coccoid cell colonies	Mid << Upper	Mid = Upper	Mid = Upper
Biological filaments	Mid << Upper	Mid = Upper	Mid < Upper
EPS	Mid = Upper	Mid = Upper	Mid < Upper

*SNK statistical test result: '=' denotes no difference, '<' denotes $p = 0.05$, '<<' denotes $p = 0.01$

2.5.1 Bioerosion

Table A2 - 4 shows differences in the intensity of boring (measured as borehole density) at the surface of limestone chippings sampled taken from the same block (centimetres apart), from different replicate plots (meters apart) and from different experimental shores (kilometres apart) after 8 and 20 months. As all *Exposure Trial 1* blocks used in this analysis were positioned at MTL on both shores, these comparisons were independent of tidal height.

The density of borehole erosion was consistent between different areas of the same limestone block after both periods of exposure, and also between blocks attached 50 m apart in different replicate plots on shore 1 (Tregear Point; Table A2 - 4). On shore 2 (Gala Rocks), there was a significant difference in boring density at the metre-scale (between plots) after 8 months (Student's t[df = 24] = 2.87, p = 0.01), but this was not significant a year later (Student's t[df = 25] = 0.35, p > 0.05). Using combined data from both plots on each shore, there was no difference in the density of boring at the km scale (between experimental shores) after 8 months (Student's t[df = 57] = 0.02, p > 0.05), but there was as significant difference after 20 months (Student's t[df = 61] = 3.23, p = 0.002).

Table A2 - 4 Comparisons of borehole density between chippings from the same experimental block (within block), from blocks from different replicate plots (between plots), and from different shores (between shores) after 8 and 20 months' exposure at MTL, Cornwall, UK.

	Scale of Comparison[1,2]			
	Within block (cm)	Between plots (m)		Between shores (km)
		Shore 1 (PL)	Shore 2 (ZN)	
8 months' exposure	*ns*	*ns*	*p = 0.01*	*ns*
20 months' exposure	*ns*	*ns*	*ns*	*p = 0.00*

[1]Comparisons made using Student's t-tests
[2]Boring desnity measured as the number of entrance holes per 100 µm^2 in 15 random SEM micrographs of chips sampled from 5 different blocks (n = 75), see Section 7.6.3
ns = no signficant difference

Figure A2 - 2 shows borehole density on limestone exposed at different shore levels for 10 months. Blocks exposed at MHWN had significantly more surface perforations than replicates exposed at MTL (Student's t[df = 78] = 3.61, p = 0.001).

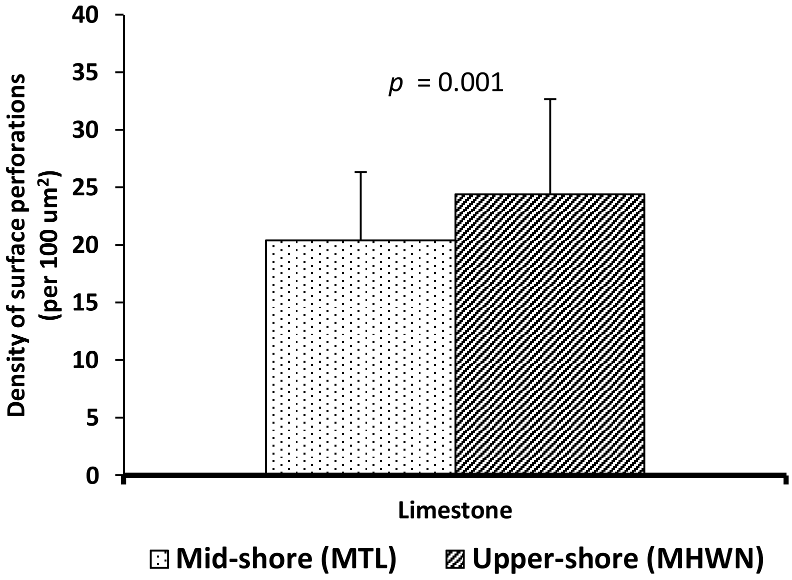


Figure A2 - 2 Mean density of micro-boring holes on Portland limestone after exposure for 10 months at MTL and MHWN (*n* = 45 + SD; Student's t-test significance as shown).

2.6. Sub-surface Features

Figure A2 - 3 shows the depth of various weathering and erosion features measured in cross-section observations of materials exposed at different shore levels. Limestone exposed on the mid-shore (MTL) had weathered to a significantly greater depth (52.0 ± 4.6 µm, *n* = 32) than blocks exposed higher on the shore (MHWN, 32.0 ± 3.4 µm, *n* = 13; Student's t[df = 42] = 3.48, *p* = 0.001, Figure A2 - 3a). Conversely, concrete blocks exposed higher on the shore had been altered to a greater depth (123.23 µm, *n* = 18) than those on the mid-shore after the same period of time (81.28 µm, *n* = 15; Student's t(df = 27) = 2.05, *p* = 0.01, Figure A2 - 3).

Evidence of disaggregation of limestone and concrete (probably from a combination of dissolution and mechanical deterioration) was more frequently observed on upper shore blocks, while modification was more typically limited to bio-chemical crust formation on mid-shore blocks (e.g. Figure A2 - 4a-b).

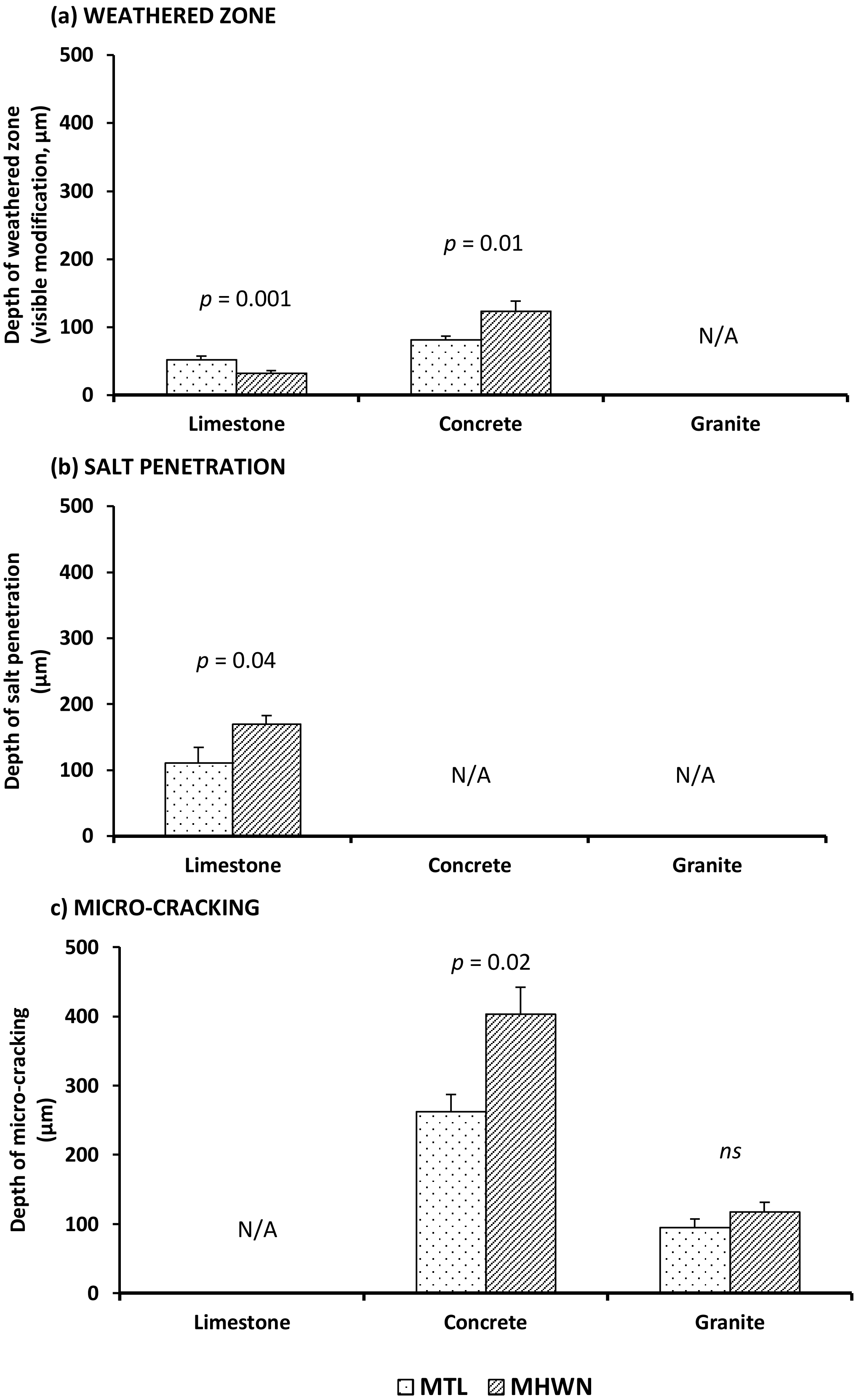


Figure A2 - 3 Depths of (a) weathered zone, (b) salt penetration, and (c) micro-cracking observed in different construction materials after exposure for 10 months at mid- and upper-shore levels (MTL and MHWN, respectively), Cornwall, UK (t-test significance as shown: ns = no significant difference, N/A indicates that no test was possible).

BSE observations showed that the depth of salt penetration in limestone was greater in upper shore blocks (170.4 ± 12.0 µm, n = 16) than mid-shore blocks (111.5 ± 22.4 µm, n = 8; Student's $t_{[df = 11]} = 2.32$, $p = 0.04$, Figure A2 - 3b). Salt deposits (identified using EDS) were usually concentrated in pore spaces in the limestone (inter-oolith spaces e.g. Figure A2 - 5a-b). Interestingly, a salt crust was more typically present on the surface of limestone blocks exposed higher on the shore; these crusts were clearly visible in cross section (Figure A2 - 5a-b) and, in contrast to the bio-chemical crusts were composed entirely of halite (sodium chloride, Figure A2 - 6). These crusts were very variable in thickness, were not continuous over the surface, and occurred independently from the salt deposits observed deeper within the rock.

Salt crusts were not present on concrete, although bio-chemical crusting had occurred (e.g. Figure A2 - 4d). Sub-surface salts could not be identified with confidence in concrete blocks however, and so data for salt penetration in concrete is not presented here; the variable composition of the concrete mix (including the cement matrix, sand and aggregates) made visual distinctions of salt challenging compared to the more uniform composition of the limestone, for example. There was some evidence of biotically-mediated weathering of concrete, where organic structures were observed in association with recent detachment of sand grains (e.g. Figure A2 - 4c).

As with limestone blocks observed during the main experiment (Chapter 7), there was no evidence of sub-surface cracking within limestone after intertidal exposure. Cracking was well developed in concrete, however, particularly in blocks exposed higher on the shore, where micro-cracks were recorded deeper within the substratum (Student's $t_{[df = 12]} = 2.18$, $p = 0.02$, Figure A2 - 3c). Cracking was present within the cement matrix parallel to the surface (as observed in the main experiment), while development of enlarged void spaces between the cement matrix and aggregate particles was also common on upper shore blocks (e.g. Figure A2 - 4e-f). The development of enlarged spaces in this way suggests expansive (i.e. mechanical) modes of deterioration in concrete exposed higher on the shore.

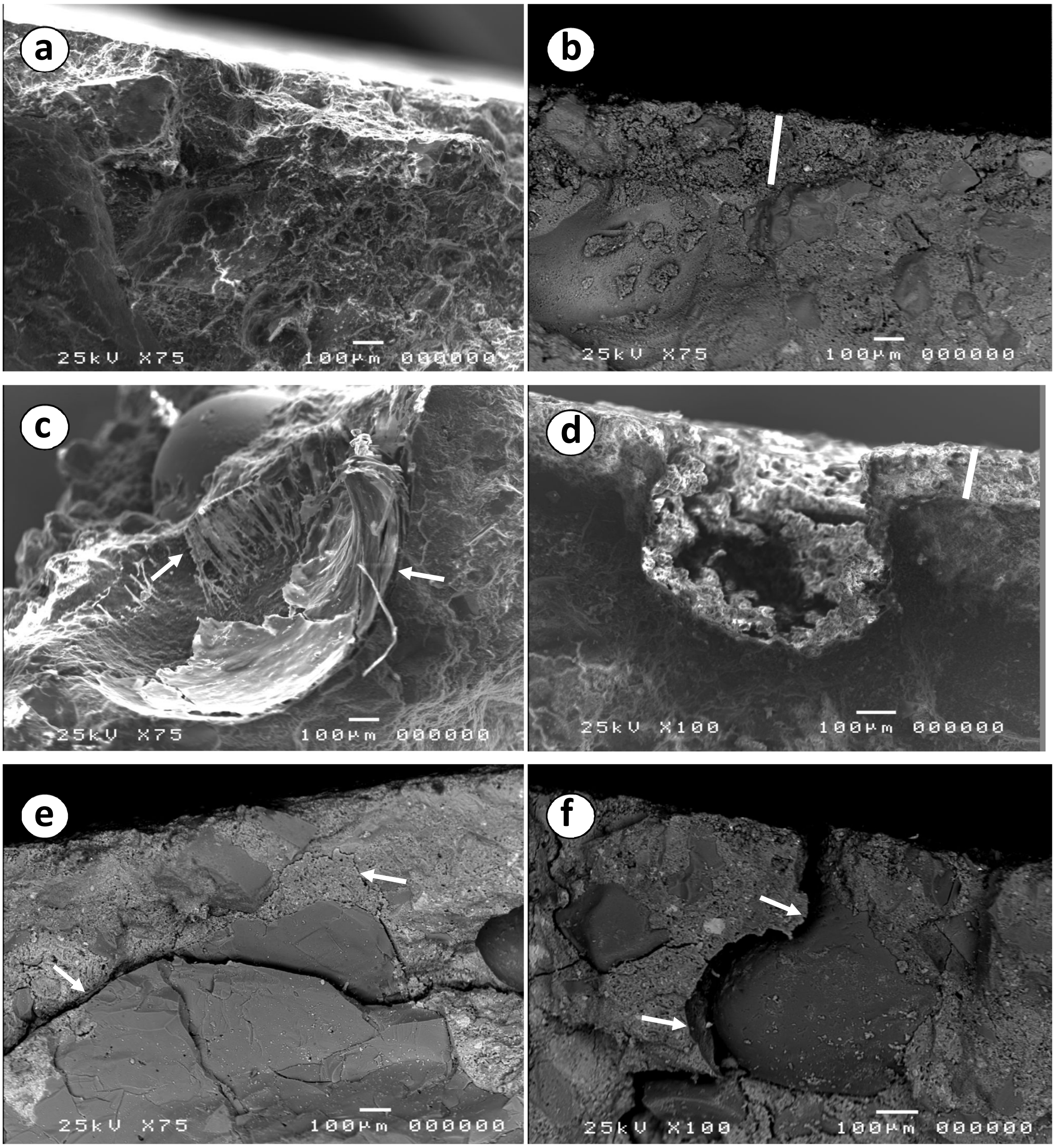


Figure A2 - 4 Cross-section SEM micrographs of marine concrete after 10 months exposure in the intertidal zone, Cornwall, UK (scale as shown): (a) Altered (but coherent) surface of cement matrix (MTL, unbleached); (b) Disaggregation of cement matrix and pore-space enlargement (indicated) (BEI image, MHWN, unbleached); (c) Organic structures (EPS and filaments, indicated) at site of sand grain detachment (MTL, unbleached); (d) Bio-chemical crusting (indicated) around an air-hole (BEI image, MTL, unbleached); (e) Cracking (indicated) of cement matrix (indicated, MHWN, unbleached); (f) Void space enlargement (indicated) (MHWN, unbleached).

As found in the main experiment (Chapter 7), there was limited evidence of weathering beyond the immediate surface of granite, including salt penetration. Some sub-surface cracking was observed, however, but there was no difference in depth of cracking between tidal heights (Figure A2 - 3c).

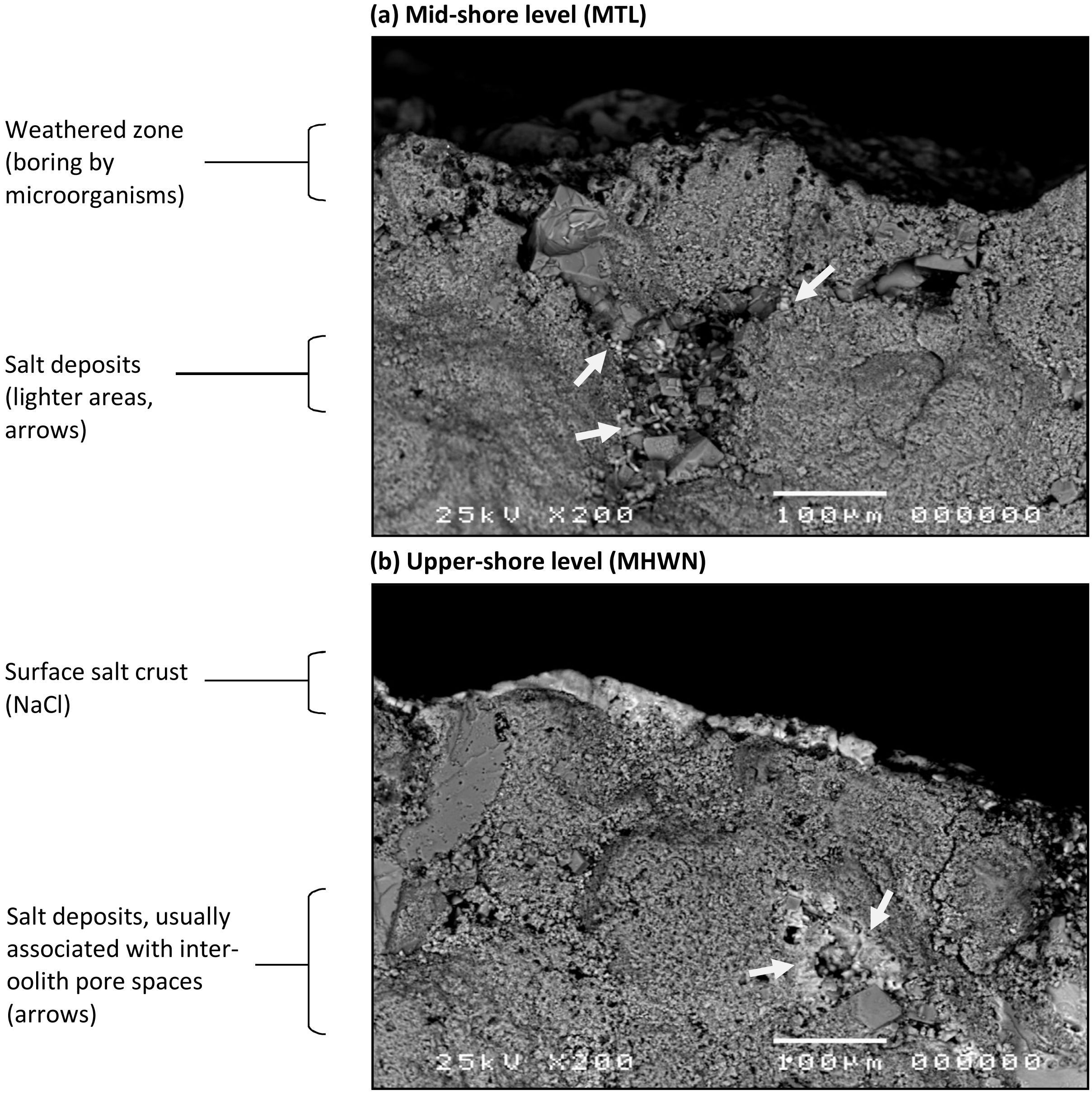


Figure A2 - 5 SEM micrographs (BEI mode) of limestone after exposure at (a) MTL (3 m ACD) and (b) MHWN (4 m ACD) for 10 months, Cornwall, UK.

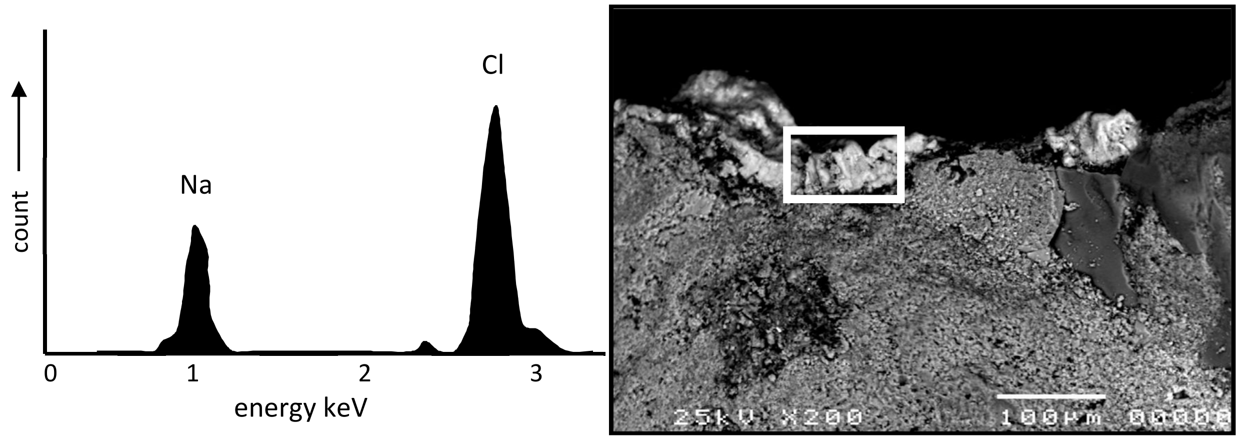


Figure A2 - 6 EDS spectrum (*left*) of salt crust at the surface of limestone exposed on the upper shore for 10 months (*right*), Cornwall, UK (location of X-ray sample indicated).

2.7 Discussion

Biological growths were more common at the surface of limestone and concrete blocks exposed higher on the shore (at MHWN) compared to those exposed at MTL (Hypothesis A2-1). This contrasts researchers who have reported greater abundances and diversity of microorganisms lower on the shore, including diatoms (Aleem 1950; Castenholz 1984), cyanobacteria (MacLulich 1987) and algae (Underwood 1984a). Across-shore variability of microbial assemblages does not always show common patterns, however, because of complicating factors such as seasonality and grazing (Underwood 1984a, b; Moschella 2003, see below). Thompson (1996), for example, observed greater abundances of diatoms on the upper shore than lower in the tidal frame during winter, but the opposite in summer; higher occurrences of biological cells on blocks exposed higher on the shore found in this study, which were removed in winter (January 2010), fit this model.

Small-scale patchiness (cm's and less) of microorganisms has been widely reported on rocky shore studies, although spatial differences in species diversity are less clear (MacLulich 1987; Hill and Hawkins 1991). Grazing is known to influence not only overall microbial biomass but the spatial heterogeneity of microorganisms at various scales, both laterally and vertically across the shore (Underwood 1980; Hawkins and Hartnoll 1983; MacLulich 1987; Thompson et al. 2000; Moschella 2003; Jonsson et al. 2006; Hutchinson et al. 2006; Hillebrand 2008). Grazing has also been shown to be important in structuring microbial assemblages on artificial structures like sea walls (Skov et al. 2010; Ivеša et al. 2010).

To test whether grazing may have contributed to differences in the occurrence of microbial growth features observed between shore levels, the number of limpets in experimental plots was counted in January 2010 (when blocks were removed, see Chapter 6). Counts were made in 15 quadrats randomly placed within experimental plots, at both tide heights, on both shores. The hypothesis that limpets were more common at mid-tide level was tested using a 2-factor ANOVA, where 'shore' (two levels: Tregear Point and Gala Rocks) and 'tide height' (two levels: MTL and MHWN, nested in 'shore') were treated as fixed factors. Data were square-root transformed to correct for heterogeneous variances.

There was no difference in the density of limpets between shores, but there were significantly more limpets at MTL in both instances (Table A2 - 5). These data suggest higher grazing pressure lower on the shore, which might explain lower occurrences of microbial growths on blocks exposed at this tide level. Grazing by periwinkles on sandstone platforms in South Africa, for example, limited microalgae biomass as well as the establishment of macro-algae, which were able to colonise when grazers were experimentally removed (Kaehler and Froneman 2002). It is important to note that grazing influences on microbial abundance are not always simple however. Skov et al. (2010) for example have recently shown that grazing may in fact increase microbial biomass and diversity on hard substrata in the intertidal zone.

The relative difference of growth occurrences between shore levels on each material (which were significant for limestone and concrete but not granite, above) may have been exacerbated by substratum roughness. Substratum roughness is known to influence grazing efficiency (e.g. Wahl and Hoppe 2002) and the spatial patchiness of limpet grazing (e.g. Johnson et al. 2008). Reduced grazing efficiency on the rough granite, for example, may therefore explain why differences in microbiota occurrences between shore levels were less prominent on this material type compared to the smooth limestone and concrete. If grazing was limited on granite, this may also have contributed to the higher levels of barnacle settlement, recruitment and survival rates observed on this material (Chapter 5 and 6) which are also known to relate to grazing pressure (e.g. Hawkins and Hartnoll 1982b). Further experiments are needed to test whether these mechanisms are true, using a greater number of replicates and direct measurement of grazing activity on the different materials, and at different tide levels (e.g. Thompson et al. 1997; Forrest et al. 2001; Hutchinson and Williams 2003b).

Table A2 - 5 Analysis of variance for counts of limpet density at MTL and MHWN on two experimental shores, Cornwall, UK (counts made in January 2009, *n* = 15).

Source of variation	*df*	MS	*F*	*p*
Shore (*n* = 2)	1	19.460	0.32	0.626
Tide level (Shore, *n* = 2)	2	59.903	563.01	**0.000*** **
Residuals	56	0.106	-	-
Total	59	-	-	-

Cochran's test $C = 0.328$ (square-root transformed data)
p values: **p* < 0.05, ***p* < 0.01, ****p* < 0.001

In this study, the density of boreholes at the surface of limestone was greater on blocks placed higher on the shore (Hypothesis A2-2). However, measurements of boring density were complicated by coalescence where boring was very dense, so that these observations may be difficult to attribute directly to differences in the rate of bioerosion (see the discussion in Chapter 7). These differences may, however, have important implications for morphological development and associated habitat complexity of the limestone (Chapter 7: Strand 3).

Below the surface, there were differences in the vertical extent of weathering features between shore levels (Hypothesis A2-3). Le Campion-Alsumard (1975, 1979, 1989) reported differences in the vertical distribution of endolithic microorganism between tidal levels, attributed to stress gradients across the shore in a similar way to the model developed for terrestrial environments by Viles (1995). In these studies, endolithic cyanobacteria dominated upper shore levels, where desiccation and insolation stresses were assumed more intense, while algae (chlorophytes) and fungi were more common lower on the shore. Schneider (1976) and Torounsky (1979) also found that cyanobacteria are mainly distributed at mid- and upper-shore levels. Although distinction between different types of microflora was not a primary aim of this study, all blocks were exposed MTL or above so that observed microbial assemblages were probably dominated by cyanobacteria.

In this study, the depth of weathering measured in limestone was greater in blocks exposed at MTL. Models of biogeomorphic zonation on limestone coasts suggest that this may be the result of more efficient bioerosion lower on the shore (Gómez-Pujol and Fornós 2009, 2010), although this did not tally with observations of boring density at the surface (above); this may reflect a higher occurrence of borehole coalescence at MTL (see model on p.319). Higher on the shore, inorganic weathering processes including wetting and drying, and salt action are expected to be more efficient. Indeed, salt deposition was measured at greater depth in MHWN limestone blocks. Also, the depth of weathering in concrete was greater higher on the shore, which may be indicative of the efficiency of mechanical processes in concrete deterioration at higher shore levels (Moukwa 1990; Allen 1998; Akman and Özyurt 2002; Neville 2004; CIRIA 2010).

The nature of salt penetration in rocks is known to depend largely on the porosity of the substrata (e.g. Evans 1970; Goudie 1999; Sousa et al. 2005) and, as such, lithology can explain general differences in salt penetration between construction materials (see Chapter 7 for further discussions). Differences observed between tide heights for replicate blocks of the same material, however, cannot be explained by lithology. In these instances, variations in the nature of wetting and drying experienced across the shore are probably more important. Experimental work has shown the importance of both moisture amplitudes and heating regimes in generating differences in patterns of salt crystallisation under controlled conditions, particularly in porous rocks (e.g. Gómez-Heras and Fort 2007; Sumner and Loubser 2008). While field and experimental investigations of intertidal heating and wetting-drying regimes are practically difficult to undertake (see Chapter 8), it is reasonable to assume that the efficiency of salt weathering on materials exposed to different periods of exposure and immersion as a function of tidal height will not be the same (Davison 1986; Huinink et al. 2002). Salt crystallisation may have been enhanced in upper shore blocks for example, which would have dried out more fully via evaporation during longer periods of exposure (e.g. Chapter 8).

Observations of micro-cracking in concrete and granite also indicate that expansive processes, such as those associated with mechanical weathering, were more efficient on blocks exposed higher on the shore (Figure A2 - 3; Hall 1988; Hall and Hall 1996; Trenhaile 2006; Porter and Trenhaile 2007). For harder materials like granite, expansive processes such as wetting and drying are expected to be much more important than organic weathering processes (Sousa et al. 2005), particularly at higher shore levels. Any differences in the rates of breakdown and morphological development of very durable materials exposed at different shore levels may only become apparent over much longer time scales than those typically considered in engineering design however (see discussions on Chapter 9).

2.8 Conclusions

This Appendix has presented evidence of variability in the response of microorganisms to materials used in coastal engineering exposed at different tidal heights. This work supplements that described in Chapter 7, which focuses on differences between material types.

There was generally greater evidence of micro-scale biological activity on experimental blocks placed at higher on the shore (at MHWN) than at MTL, although this was not always the case. Spatial variations in grazing pressure, which appeared to be significantly greater on the mid-shore, may explain these differences, although further investigation would be required to confirm this. Spatial considerations such as these are important because tidal height may mediate any differences in micro-scale responses occurring predominantly as a result of material type (Chapter 7). In coastal engineering, structures can be placed anywhere on the shore, so that the relative importance of any difference in microbial communities between material types may be more or less important at different tidal heights. Similarly, the efficiency and relative importance of organic and inorganic weathering and erosion processes in the morphological development, habitat complexity and engineering durability of construction materials may vary between shore levels.

The observations in this Appendix emphasise the need for careful consideration of biogeomorphological processes and feedbacks in ecological enhancement design on a case-by-case basis; differences in the ecological and geomorphological response of construction materials to intertidal exposure, and more importantly how they influence each other, cannot be assumed to be the same at different tidal heights (see further discussion in Chapter 9).

APPENDIX 3 EXISTING COASTAL STRUCTURES SEM

3.1 Introduction and Aims

As a supplementary study to the microscopic examination of experimental blocks presented in Chapter 7: Strand 1, permissions were sought to sample structures from two harbours in South West England for additional analysis; Ilfracombe Harbour (north Devon) and Newlyn Harbour (west Cornwall). This additional work was undertaken for three reasons:

1. To enable semi-quantitative observations of (micro-scale) biological and geomorphological features on common construction materials after longer periods of time than was possible using the experimental blocks alone (i.e. 'space-for-time substitution' e.g. Paine 1985; Pickett 1989);
2. To enable comparisons of the same materials that have been subject to different exposure conditions in one location (e.g. wave-exposed and wave-protected walls);
3. To allow observations of materials exposed in a vertical position in comparison with experimental blocks exposed horizontally in field trials (Chapters 5 and 6).

This work was therefore intended to supplement the main SEM analyses, to test whether features observed at a micro-scale (biological and geomorphological) were consistent in time (between exposure ages), in space (between exposures) and between surface orientations (vertical and horizontal). Qualitative surveys of structures at Ilfracombe and Newlyn were also made to assess general biological communities and geomorphic features of the materials used in construction.

3.2 Methods

3.2.1 Ilfracombe structures

At Ilfracombe, Devon, samples were taken from the vertical faces of a concrete structure currently used for ferry landings built in 2000 (exposure age = 10 years, R. Lawson personal communication, October 2008). Samples were taken from both wave-exposed and wave-protected sides of the wall at low tide (Figure A3 - 1).

Figure A3 - 1 Sampling locations on (a) wave-exposed and (b) wave-sheltered sides of a vertical concrete wall at Ilfracombe Harbour, Devon, UK.

3.2.2 Newlyn structures

Samples were taken from two different structures at Newlyn Harbour, as shown in Figure A3 - 2. Exposed concrete foundations on the outer wall, and severely deteriorating areas of concrete on the inner wall of the North Pier were sampled (built in 1888, age of samples > 130 years). Samples of granite were also taken from the outer facing wall of the North Pier (age of samples > 130 years, Figure A3 - 2a). The concrete facing of the outer South Pier was also sampled (Figure A3 - 2b), built in 1887 (age of samples > 130 years; Austen 1907; A. Munsden personal communication, October 2009).

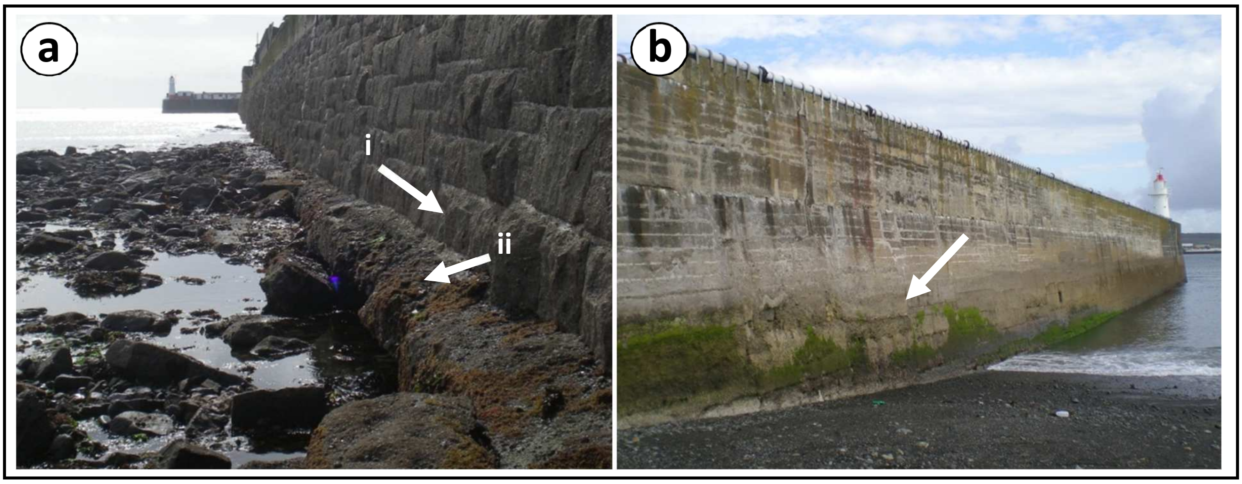


Figure A3 - 2 Location of samples taken from structures at Newlyn Harbour, Cornwall: (a) granite facing (arrow i) and concrete foundations (arrow ii) and of North Pier, and (b) concrete wall of South Pier.

3.2.3 Sampling

In all instances, samples were taken as close to mid-tide level as was practically possible. This was done by estimating the level of the tide using tide-tables and the biological zonation on the structures. At Ilfracombe, all samples were removed using a diamond-core drill bit and rotary drill. Cores were 1.5 cm in diameter and roughly 1 cm in depth. It was necessary to continually cool the sample surface with water when taking cores to prevent the drill-bit overheating, and to remove grit and dust to minimise surface contamination. At Newlyn, some of the walls were in a very poor condition so that coring was not practical. Instead, samples were carefully removed by hand, or using a metal spatula.

As sampling was destructive, numbers of samples were limited to minimise structural and aesthetic impact. In each location, between three and five individual samples were taken wherever possible. Where only one or two samples could be removed, only qualitative SEM observations were undertaken.

3.2.4 SEM observations

General procedures used in SEM observations are described in Chapter 7 and Appendix 1. Samples were viewed in cross-section and plan-view. Qualitative observations were made of as many samples as possible, and the depth of sub-surface features were measured (see Chapter 7: Strand 1) and compared statistically using t-tests where possible. Samples removed from the heavily deteriorated walls at Newlyn could not be examined under the SEM as coherent samples could not be obtained.

3.3 Results

3.3.1 Concrete structures

Biological cells and filaments were observed at the surface of all concrete samples but there was no evidence of bioerosion or cryptoendolithic colonisation in the samples collected. In cross-section, a zone of modification was observed in all samples taken from the wall at Ilfracombe. This zone was similar in appearance to the bio-chemical crusts observed on experimental blocks after two years exposure (Chapter 7: Strand 1), but typically had a distinctive zone of chemical deposition at their deepest extent (e.g. Figure A3 - 3a-b). X-ray analysis identified these deposits as magnesium, aluminium and silicate compounds, distinct form the carbonate cement lower in the profile. This zone of deposition was significantly deeper in samples removed from the wave-exposed side of the wall (Student's $t[df = 33] = 5.72$, $p < 0.001$; Figure A3 - 3; Figure A3 - 4). The weathering layer measured in concrete samples collected from the South Pier (wave-exposed, but sheltered from strongest waves) at Newlyn was a similar depth to the wave-protected side of the wall at Ilfracombe (Figure A3 - 4).

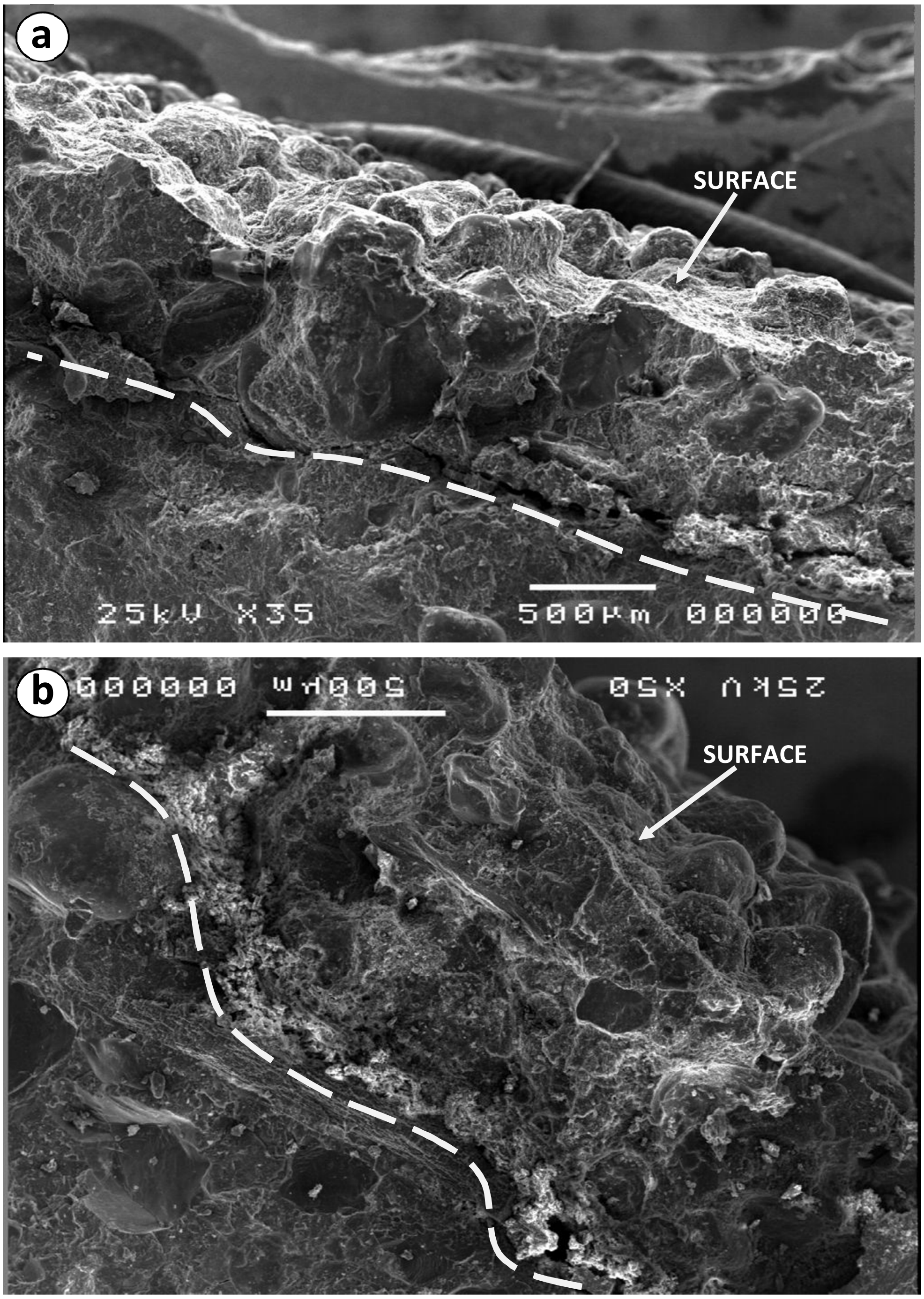


Figure A3 - 3 Cross-section micrographs of concrete exposed for 10 years on a (a) wave-sheltered and (b) wave-exposed vertical wall at MTL, Ilfracombe, Devon (zone of chemical deposition indicated).

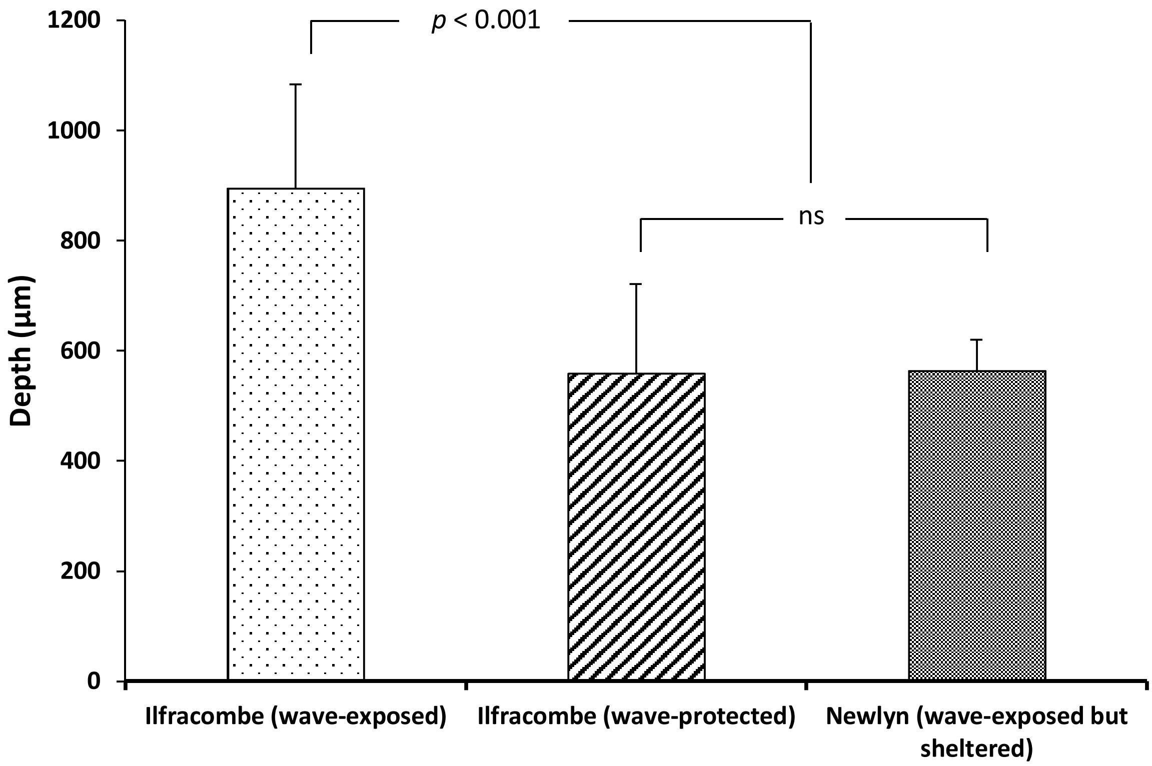


Figure A3 - 4 Depth (mean + SD) of weathering zones and sub-surface salt deposition in concrete sampled from vertical walls at Ilfracombe (> 10 years) and Newlyn (> 130 years), Cornwall, UK (Welch's t-test significance as shown).

Needle-like crystals were observed at the surface of concrete in some areas, although they were not common to all samples (e.g. Figure A3 - 5a). These structures were composed of calcium (Figure A3 - 5b) and, based on crystal morphology, were probably aragonite, which forms in concrete in the presence of salts (Buenfeld and Newman 1986).

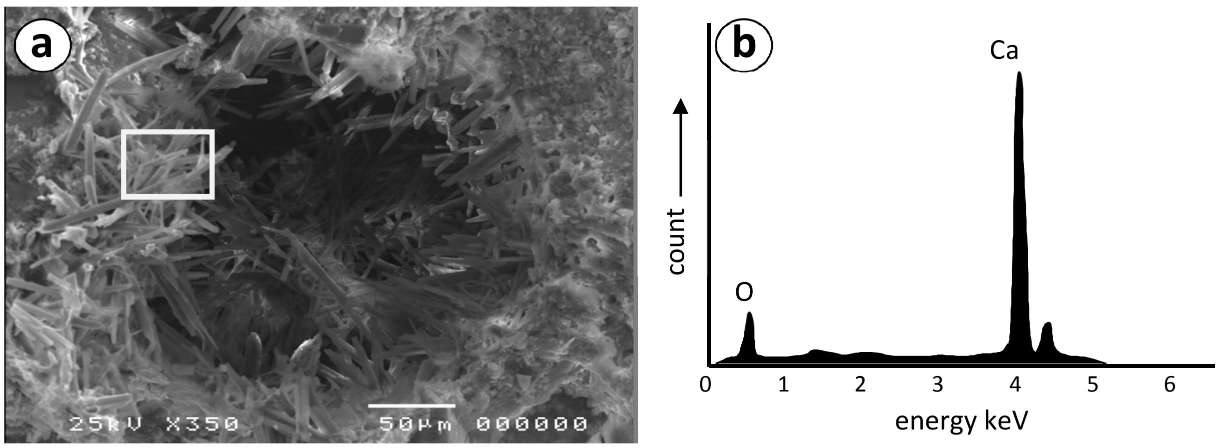


Figure A3 - 5 (a) SEM micrographs and (b) EDS spectra of aragonite crystals in surface layers of concrete on a wave-exposed, vertical wall at Ilfacombe, Devon, after 10 years of exposure.

3.3.2 Granite structures

As was observed for experimental blocks (Chapter 7: Strand 1), there was limited evidence of microbial growth beyond the surface of granite sampled from the North Pier at Newlyn. Epilithic forms were typically abundant however, particularly filamentous forms of cyanobacteria and algae (e.g. Figure A3 - 6a). When viewed in cross section, there was evidence of mechanical deterioration in the form of micro-cracking and fracturing, and loosening of fragments from the surface (e.g. Figure A3 - 6b).

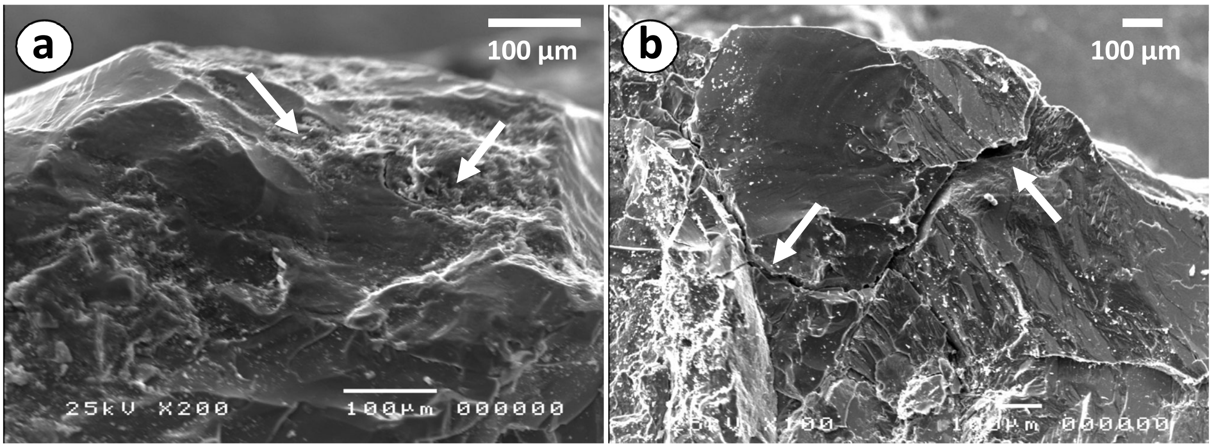


Figure A3 - 6 SEM micrographs of granite sampled from the North Pier (> 130 years old) at Newlyn Harbour, Cornwall: (a) Epilithic growths (indicated) and (b) evidence of mechanical weathering (indicated) below the surface.

3.4 Discussion

A zone of modification was observed in samples of concrete taken from inner and outer vertical walls in Ilfracombe. In both instances the depth of the modified zone was defined by a distinct layer of salt deposits, magnesium, aluminium and silicate precipitates. While present in samples from both sides of the wall, this layer was typically more distinctive, and deeper on the wave-exposed side of the structure; after 10 years of exposure, concrete had been altered to depths up to 559 µm on the sheltered side and 895 µm on the exposed side. This compares to a weathering depth of 125 µm measured on experimental blocks exposed for 20 months (Chapter 7: Strand 1).

These observations suggests that weathering processes are more efficient on the exposed wall, which is subject to greater wave forces and wetted more frequently (in this instance). As well as shelter from waves, the inner wall at Ilfracombe is also shaded from the sun and wind compared to the outer wall. This is potentially important for drying rates, which in the case of salt weathering can influence the extent and depth of crystallisation in rock and concrete (e.g. Rodriguez-Navarro and Doehne 1999; Thaulow and Sahu 2004; Sumner and Loubser 2008). There was no clear evidence of bioerosion in the concrete samples, with mechanical and chemical weathering processes appearing much more important over engineering time-scales (> 10 years).

The weathering depth in concrete sampled from walls at Newlyn (> 130 years old) was similar to that measured in samples from the sheltered wall at Ilfracombe (10 years old). While the concrete mixes cannot be assumed to be the same at both harbours, this suggested that weathering does not progress linearly with time for this material type; old concrete walls at Newlyn were not weathered to a greater depth than the sheltered, younger wall at Ilfracombe. However, comparisons are constrained by variations in exposure conditions between sites, which were shown to be important (above). Also, while SEM observations indicate similar weathering depths in concrete exposed for 10 and > 100 years, larger-scale deteriorative processes were commonly observed on the older structure at Newlyn (below); linkages between different scales of deterioration may therefore be difficult to establish with respect to durability (see discussion in Chapter 7: Strand 4).

Two main mechanisms of deterioration were identified from observations of concrete from existing structures. First, individual sand grains protruding from the surface of the concrete (e.g. Figure A3 - 3a) indicated granular disintegration. Observations of sites of recent sand grain detachment from experimental concrete blocks for example (see Figure 7-6b p. 271) suggested that protruding grains may be lost through progressive weathering of the cement matrix in which they are embedded (possibly through dissolution and/or breaking-away of crusted fragments, below). Expansive processes like salt crystallisation, wetting and drying, and thermal expansion and contraction may facilitate loosening and detachment of sand grains in this way (Zhang and Gjørv 1990; Thaulow and Sahu 2004; Gómez-Heras et al. 2006; Liu et al. 2010b). Moses et al. (1995) proposed a similar model of weathering for the loosening and loss of ooids from the surfaces of limestone exposed under terrestrial conditions in Australia. They suggest this process was an important mechanism for the development of microtopography.

The second mechanism of deterioration in concrete involved the deposition of salts and chemical precipitates in association with dissolution and transformation of the cement compounds (as described above) including brucite (e.g. Figure 7-10 p. 279) and aragonite (e.g. Figure A3 - 5). While these chemical processes may involve hardening of the concrete to some extent (e.g. Buenfeld and Newman 1986; Chapter 7: Strand 2) they may facilitate subsequent flaking and scaling of surface layers where development is extensive (e.g. Figure A3 - 7). Scaling can also occur where concrete repairs are made to coastal walls, involving the subsequent deposition and expansion of chemical precipitates between the original surface and the repair ('cover') cement (e.g. Perry and Holmyard 1992; CIRIA 2010). At a smaller scale, expansion associated with deposition below the surface may facilitate the development of micro-cracks (see discussion in Chapter 7: Strand 4).

Figure A3 - 7 Surface scaling of concrete (indicated) from vertical walls at Newlyn Harbour, Cornwall (hammer handle width = 2.5 cm for scale).

Similar to observations of experimental blocks exposed for 20 months in field trials (Chapter 7: Strand 1), epiliths were abundant at the surface of granite exposed for > 130 years at Newlyn. There was no evidence of colonisation of this material type beyond the immediate surface, however.

Mechanical deterioration was observed below the surface of granite in the form of cracking and fracturing of the rock, although this was not common to all samples. These observations suggested that the involvement of organisms in the weathering of granite remains limited over engineering timescales (decades – centuries).

APPENDIX 4 PLYMOUTH BREAKWATER

A case study of material choice and ecological potential

4.1 Introduction

The conceptual models discussed in Chapter 9 are based on observation of materials exposed for a relatively short period of time (20 months). Supplementary work was therefore undertaken to consider how material type, textural development and ecology interact over much longer timescales using an existing *in situ* structure of known age.

Plymouth Breakwater (Grid Reference SX472 503, Figure A4 - 1a) was selected for several reasons: (i) the breakwater is over 150 years old, constructed between 1812 and 1841 (BBC 2006); (ii) it is built using Plymouth limestone (a Devonian age, medium-grey limestone) and Dartmoor granite (an Eocene age, feldspar-quartz granite), which have been used both individually and in combination in different areas of the structure http://www.plymouthdata.info/Breakwater, accessed February 2009). Whilst these materials did not provide an exact replicate of lithologies used in field experiments (i.e. Portland limestone and Cornish granite) they provided a novel opportunity for comparisons of similar material types after exposure for a much longer period of time. Additional concrete wave-breakers (e.g. Figure A4 - 1b) have also subsequently been added to the south side of the breakwater (in the 1970s and 1990s), but these were not the subject of this piece of work; (iii) in some locations limestone and granite are placed side-by-side in a horizontal position, giving conditions analogous to those of the experimental blocks (see Chapter 5), and lastly; (iv) permission for access to the breakwater was granted by the Ministry of Defence (MOD) in collaboration with Plymouth University Marine and Diving Centre, and researchers at the University of Plymouth undertaking ecological studies on the same structure (Jackson in preparation). The removal of rock samples from the breakwater structure itself was not permitted however, and so observations were necessarily non-destructive and semi-quantitative in some instances. There is also a history of ecological study on the breakwater (e.g. Evans 1947; Southward and Orton 1954; Moschella et al. 2005; Bhadbury et al. 2006), including current on-going work to supplement the observations described here (J. Jackson personal communication, December 2010).

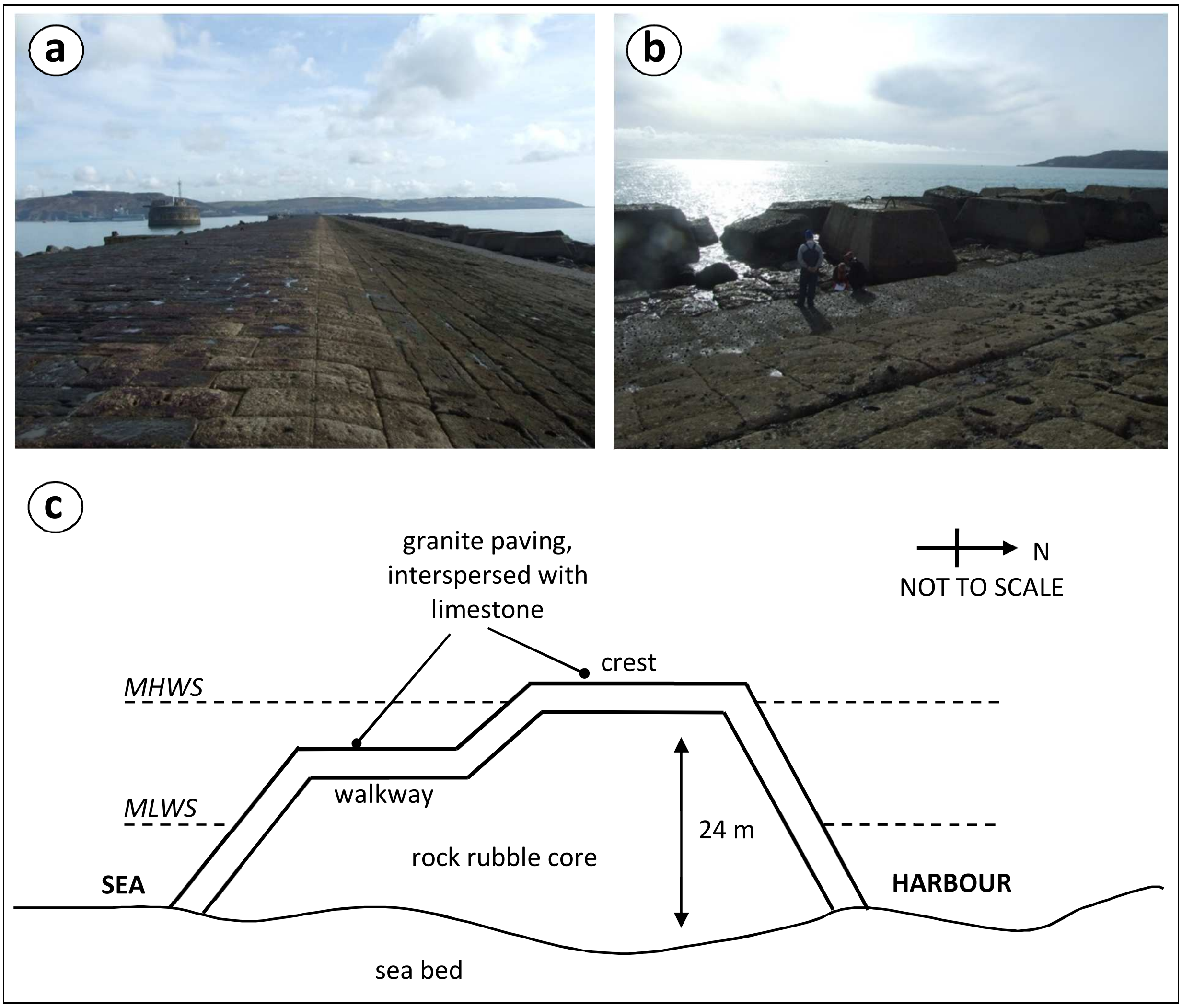


Figure A4 - 1 Plymouth Breakwater: (a) looking east along the upper crest and (b) looking south towards the lower walkway and concrete wave breakers (people for scale), and (c) cross-section sketch of the breakwater (not to scale).

The breakwater is situated in Plymouth Sound, roughly 500 m west of Bovisand Point, Plymouth, Devon. The structure consists of a central portion roughly 900 m in length, and two arms set at a 120° angle, each 200 m length. The structure has an upper horizontal crest and a lower, narrower horizontal walkway on the south side (Figure A4 - 1c). The breakwater is roughly 14 m in width and

24 m in height. The upper crest lies roughly 5 m above MHWN, although it is frequently overtopped during spring tides and stormy weather (http://www.plymouthdata.info/Breakwater, accessed February 2009). Much of the surface of the breakwater is paved with Dartmoor granite slabs, interspersed with blocks of Plymouth Limestone, both placed in the 1820s. The landward, outer face has a slope of around 50°, while the seaward face is set at a 20-30° angle.

4.2. Aims and Objectives

Previous observations indicated that the geomorphological response of materials used to build the breakwater had resulted in significantly different ecological outcomes (R.C. Thompson personal communication, December 2007). The breakwater was of interest, therefore, for illustrating how the choice of construction materials (rather than direct textural manipulation, see Section 9.8.1 p. 417) used in coastal engineering can influence the ecological value of a structure over longer periods of time than could be directly measured during the PhD.

The breakwater was visited once during a low spring tide on 1st March 2010, with three main objectives. First, a qualitative survey of the breakwater was undertaken to identify evidence of associations between the substratum and epibiota. Second, a rapid, quantitative assessment of surface complexity (i.e. roughness) of limestone and granite was undertaken using a carpenter's profile gauge (described below) where blocks are placed horizontally, side-by-side at the western end of the breakwater (see Figure A4 - 3 below). Ecological surveys of the same granite and limestone blocks have previously indicated that the diversity of the communities they support is significantly different (J. Jackson personal communication, March 2010). Thirdly, a qualitative assessment of the processes involved in the morphological evolution of the materials was made based on visual observations of the structure, quantitative observations made of similar material types discussed in Chapter 7, and published weathering literature.

4.3 Methods

4.3.1 Qualitative observations

A visual walk-over survey was made of the structure to identify evidence of associations between substratum and biota at different tidal heights, wave exposures and surface orientations. Photographic records were made of any features of interest. These observations were used to inform understanding of biogeomorphological processes operating on the breakwater, as described in Section 4.5 below.

4.3.2 Surface roughness

Meso-scale (mm's – cm's) surface roughness was quantified using the same method used to measure roughness of field blocks described in Chapter 4, using a carpenter's profile gauge. The rapid sampling protocol suggested by McCarroll and Nesje (1996) was used, which involved recording four 50 mm surface profiles of ten different limestone and granite blocks placed horizontally on the western arm of the breakwater. Sampled blocks were selected at random using plastic counters and number tables (e.g. Section 5.2.3 p. 173), ensuring a spacing of at least 10 m between each block to ensure independency. Profiles were photographed using a digital camera and later digitised using ImageJ software. Surface biology was not removed when taking profiles, although motile species such as limpets which were avoided; profiles therefore represented the morphology of the 'fixed' surface on the two rock types, as is available for colonising organisms.

'Index A' roughness was calculated for each profile as the standard deviation of relative height differences between 5, 10, 15, 20 and 25 mm spaced points (*sensu* McCarroll and Nesje 1996; Gómez-Pujol et al. 2006); further details of the method are given in Section 4.4 p. 148). Mean roughness (Index A, n = 40) at each scale was then plotted as a 'deviogram' for illustrative purposes (*sensu* McCarroll and Nesje 1996; McCarroll 1997).

4.4 Results

4.4.1 Biogeomorphological features on Plymouth Breakwater

Various features of biogeomorphological interest were identified during the visual survey. Macro-organism boring holes were found on a south-facing vertical wall composed of grey Plymouth Limestone, in the splash zone (Figure A4 - 2a). The holes varied in size but were generally between 2 – 8 mm (mean = 5.2 mm ± 1.8 mm, n = 20), possibly attributable to piddock boring (Pholadidae; Pinn et al. 2005). Most of the holes appeared unoccupied, although there was a clear association between bioerosion and the abundance of littorinid snails in this location, particularly where occurring alongside tafoni weathering forms (Figure A4 - 2b). A positive association between piddock bioerosion and biodiversity (linked with increases in topographic complexity) has been previously demonstrated on soft rock shores (clays and chalk) in southern England (Pinn et al. 2008). This association has been described as an example of physical ecosystem engineering (Pinn et al. 2008). Boring at this scale was not observed at lower tide levels where rock surfaces were dominated by different communities (particularly barnacles, see below). The importance of this kind of biogenic habitat for the provision of physical refuge (for snails in this case) will be particularly strong at higher tide levels where environmental stress is predicted to be an important control on mortality and reproductive success (Paine 1974; Underwood and Jernakoff 1984; Chapman and Blockley 2009).

On the seaward (southern) side of the breakwater, where limestone blocks form a c.25° sloping face between MTL and MHW (Figure A4 - 2c), holes originally used to manually lever blocks in place during construction (in the 1820s) have become enlarged, forming pools with characteristic down-slope ‘lobes’ (Figure A4 - 2d). Water remains in these pools at low tide, supporting an abundant and diverse community within them (Figure A4 - 2e). Coralline algae (e.g. *Lithothamnion* spp.) are particularly abundant in these pools, growing in thick layers and nodules. In comparison, similar holes used to position granite blocks have not weathered, presumably remaining closer to their original size, and subsequently support fewer species (Figure A4 - 2f).

At lower tide levels (below MTL) the same holes used during construction have acted as favourable sites for algae attachment on granite blocks (Figure A4 - 2g). These holes, which retain water at low tide, probably provide refuge from grazers which are abundant at this position (Walters and Wethey 1996; Granhag et al. 2004). Although unintentional in this case, these examples provide further evidence of potential enhancement of artificial structures by introducing meso-scale (mm's – cm's) physical habitat complexity (e.g. Martins et al. 2010).

4.4.2 Morphology of limestone and granite

On the western arm of the breakwater, limestone and granite blocks placed horizontally, side-by-side have developed distinct morphologies. Limestone has weathered relative to the granite creating pools (Figure A4 - 3a-c). Although the depth of these pools was variable (see below), measurements of the current rock surface (avoiding any encrusting algae) made relative to the present day granite surface (as a reference surface, e.g. Mottershead 1998, 2000) where between 1 and 8 cm depth (mean = 4.7 cm ± 5.3, *n* = 100). This gives a very rough estimate of localised downwearing in the order of 0.06 – 0.48 mm yr^{-1} based on a completion date of 1841 (see Section 4.5).

Importantly, downwearing of the limestone has not occurred uniformly in space. This has led to the creation of topographic complexity, with relatively higher ('older') and lower ('younger') surfaces (Figure A4 - 3d). Ecologically, raised areas of the limestone (which were exposed to air at low tide) were typically colonised by barnacles, while the bases and sides of the pools (which were always submerged) were dominated by coralline algae and abundant limpets (mostly *P. vulgata*). Other organisms common in pools on limestone included *Actinia*, *Corallina, Fucus* spp.*,* and *Porifera* spp. as well as various other red, brown and green algae (Figure A4 - 3e). Ecological surveys of the pools being undertaken by the University of Plymouth indicate that the limestone habitat supports a significantly higher number of species than adjacent areas of granite (J. Jackson personal communication March 2010), which are dominated by an almost complete cover of barnacles and limpets (Figure A4 - 3f-g).

Figure A4 - 2 Biogeomorphological features on Plymouth Breakwater: (a) Bioerosion (possibly by piddocks, indicated) and (b) associations with tafoni-like morphology and littorinids on limestone in the splash zone; (c - d) Pool and 'lobe' development on sloping limestone blocks following enlargement of holes used in construction; (e) Pool community on limestone and (f) on granite after the same period of time (c.180 years); (g) Attachment of algae in association with engineering artefacts on granite (indicated) between MLW and MTL.

Figure A4 - 3 Influence of material choice on ecological outcomes on Plymouth Breakwater: (a-b) Pools developed following differential downwearing of (c) limestone and adjacent granite after c.180 yrs; (d) habitat complexity resulting from spatially variable downwearing /bioerosion of limestone; (e) Biological community on limestone and (f) granite positioned side-by-side; (g) Biogenic topography resulting from *Lithothamnion* growth [i] and bioerosion by boring worms (possibly *Polydora* or *Boccardia*) [ii] at the base of a limestone pool.

Figure A4 - 4 shows roughness (Index A) 'deviograms' for limestone and granite habitats measured using the carpenter's profile gauge; the limestone was more morphologically heterogeneous than the granite at all measured scales, representing a more physically complex habitat (e.g. Bourget et al. 1994).

Figure A4 - 4 Roughness ('Index A', after McCarroll and Nesje 1996) of granite and limestone at different scales after c.180 years of exposure at mid-tide level, in a horizontal position on Plymouth Breakwater (*n* = 10 + SD).

The topography of the granite represented surfaces heavily encrusted with barnacles, and the profile method would not have captured heterogeneity at scales more relevant for this organism (the profile gauge method is not recommended at resolutions < 5 mm, McCarroll and Nesje 1996, see discussions on Chapter 7: Strand 3). Nevertheless, the complexity of this material at a larger scale – more important for later colonising organisms – was always relatively low compared to the weathered limestone. Whilst the rock at the base of the limestone pools was remarkably smooth (probably as a result of limpet grazing) the growth of coralline algae (*Lithothamnion* spp.) contributed significantly to the topographic heterogeneity of this habitat type (e.g. Figure A4 - 3g); bioconstruction by coralline algae therefore represents an important contribution to habitat complexity in these pools.

4.5 Discussion

4.5.1 Biogeomorphological processes

Plymouth Breakwater provides an excellent example of biogeomorphological interactions occurring on artificial coastal structures. More importantly, it provides evidence of the importance of material type on epibiontic communities developing over much longer periods of time than was possible during the course this research and, in an applied context, illustrates the potential for manipulating ecology (in a positive way) through engineering design.

On the horizontal limestone blocks bioerosion by grazing limpets, which were abundant, appeared to be the dominant process in the downwearing and development of pools. The very smooth surface of the rock in these pools suggested that grazing efficiency may be particularly high, generally showing a negative relationship with meso-scale (mm – cm) substratum roughness (e.g. Wahl and Hoppe 2002). Studies of relationships between limpets and barnacles on rocky shores further suggest that grazing activity may be concentrated in the pools given that surrounding granite blocks are heavily encrusted with barnacles, on which foraging efficiently is typically reduced (Raffaelli and Hawkins 1996). Recent studies by Noël et al. (2009) in South West England, for example, found that grazing intensity in rock pools was twice that of emergent rock surfaces, with limpets actively entering pools at high tide to forage.

A simple estimate of localised downwearing in the pools of 0.06 – 0.48 mm yr^{-1} (Section 4.4.2) is comparable to that attributed to limpet grazing on intertidal chalk platforms in southern England (0.15 – 0.49 mm yr^{-1}, Andrews and Williams 2000). The estimate also lies at the lower end of downwearing rates attributed to grazing organisms on limestone coasts in Mallorca (0.37 - 2.10 mm yr^{-1}, Fornós et al. 2006). On limestone coasts in Ireland, Trudgill (1987a) notes that there is a positive feedback mechanism acting in intertidal pools, whereby ponding of water facilitates the survival of bioerosive organisms which then contribute to the enlargement of the pools; a similar feedback probably operates on limestone blocks on the breakwater.

Alongside bioerosion by grazing organisms, there was evidence of boring at the base of pools by Polychaete worms (possibly Polydora sp. or Boccardia sp., e.g. Naylor 2001, Figure A4 - 3g), although this could not be confirmed in the field. Bioerosion of the rock by macro-borers may be contributing to their development, by weakening the surface and making it more susceptible to subsequent removal by grazers and/or biochemical processes in a similar way to that suggested for boring microorganisms (Schneider and Torunski 1983; Trudgill 1987a; Naylor 2001).

Solutional processes also cannot be ruled out. The presence of well developed 'lobes' in the downslope direction of pools on sloping limestone blocks (e.g. Figure A4 - 2c-d), for example, suggested that chemical weathering (dissolution) may be important in their development in addition to any bioerosive action. The involvement of seawater in the dissolution of limestone is generally thought to be relatively unimportant due to supersaturation with respect to calcium carbonate (Spencer and Viles 2002), although in this instance abundant biological activity within pools may give rise to dissolution by raising the acidity and erodability of the water (e.g. Emery 1946; Trudgill 1987a); indeed, oxygen bubbles were often observed forming in the pools on the day of the visit. Also, that the pools are exposed at low tide means that they will receive rainwater inflow on occasion. This may facilitate the dissolution of calcium carbonate on the sloping blocks (e.g. Trudgill 1979), when water can collect and flow downslope from the holes.

Trudgill (1987a) suggests that dissolution can operate on temperate shores through undersaturation of $CaCO_3$ in intertidal pools, but that biological weathering processes are probably more important. On the breakwater it is suggested that grazing is the dominant macro-scale process involved in the development of pools on horizontal blocks, but that chemical processes are more important for the enlargement of pools on sloped blocks, in which grazers were not typically observed.

On the breakwater, microorganisms must be important for maintaining the high populations of grazers in the pools already suggested as important in their development (above). There was little visual evidence, however, of the direct involvement of microorganisms in small-scale textural development as was observed for Portland limestone in field trials (Chapter 7: Strand 3); apart from *lithothamnion* spp. structures (above), the base of pools were very smooth (e.g. Figure A4 - 3g). This may be attributable to lithological differences, as the Devonian (Plymouth) limestone is typically harder than Carboniferous forms of the Portlandian Formation (Clarke 1988). Using the models outlines in Figure 9-2 (p. 400) and Figure 9-3 (p. 403), limestone used in the breakwater may therefore be less susceptible to euendolithic colonisation than the limestone used in field experiments. Differences in fine-scale morphology between the breakwater and field blocks may also simply represent different stages of a continuum of morphological evolution through time (e.g. Figure 9-4 p. 405). These observations highlight that the modes and rates of biogeomorphic processes, and their ecological and geomorphological consequences, cannot be assumed the same in time and space, nor between similar lithological types.

4.5.2 Implications for ecological potential and ecological enhancement

With respect to ecological value, the community present on granite blocks appears to have become 'arrested' at an early stage, being dominated by barnacles, limpets and some brown algae. Without the presence of larger-scale (> mm's) textural features this may represent the best possible community on this material type (in terms of diversity), which has evolved (morphologically) very little compared to adjacent limestone over the same period of time. The presence of holes in granite blocks used during construction, for example, has enabled additional species to establish on this material type that may otherwise be excluded (e.g. Figure A4 - 2g).

In contrast, geomorphological development of limestone blocks on the breakwater has generated a physically complex habitat supporting a greater diversity and abundance of species. Bioerosion by grazing limpets and boring polychaete worms, and biochemical processes have all probably been involved in the development of pools on these blocks; the role of microorganisms could not be assessed without destructive sampling. Importantly, the growth of encrusting algae (which likely obtain calcium from the rock, e.g. Krumbein 1979) greatly contributes to the topographic complexity of the pools. Bioconstructive processes may be just, if not more, important for generating habitat complexity on artificial structures given suitable substrata and sufficient amounts of time.

While the operation and relative contribution of biogeomorphological processes to the morphological evolution of the breakwater (at a mm – m scale) can only be inferred without further investigation, there is sufficient evidence to suggest a strong association between their operation and ecological communities. Feedbacks between substratum and biota on the breakwater provide excellent examples of 'biogeomorphic ecosystem engineering' (e.g. Figure A4 - 5, also see Section 9.4.2 p. 407). The contribution of bioeroders to the denudation of limestone and the creation of pool habitat is an example of allogenic physical ecosystem engineering, while topographic complexity created by the bioconstructive activities of encrusting algae in the pools constitutes autogenic engineering (*sensu* Jones et al. 1994, 1997).

Figure A4 - 5 A model of pool development on Plymouth Breakwater as an example of biogeomorphic ecosystem engineering.

4.6 Recommendations for further work

There is significant potential for a more detailed assessment of biogeomorphic interactions on Plymouth Breakwater. Possible studies include:

- Investigations involving chemical analysis of water in the pools, over the course of a tide cycle, to provide information on the role of biochemical processes in the formation of ecologically valuable pools on limestone;
- Investigations involving the analysis of limpet faecal pellets may be used to examine the role of grazing in the development of pools on the breakwater (e.g. Andrews and Williams 2000);
- Destructive sample could be undertaken (if permissions could be obtained) to determine the potential contribution of microorganisms to pool development on the limestone using SEM (e.g. Chapter 7: Strand 1);
- The examination of concrete wave-breakers on the south side of breakwater (many of which are date-stamped) may provide information on biogeomorphological processes and consequences for another material type commonly used in coastal engineering;
- Further collaboration with ecologists undertaking surveys on the breakwater is needed to demonstrate quantitative associations between substratum biogeomorphological responses, habitat provision (i.e. niche construction) and ecological potential.

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End.