

# The Use of Recycled Demolition Aggregate and Alkali-Activated Binders for Sustainable Concrete Construction.

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**Abstract.** Investigations into the economics, practicalities and technicalities of using recycled demolition aggregate in concrete precast products started in 2001. At that time, there were six demolition contractors around Liverpool and they were using mobile crushers which were suited for road subbase material but not for the smaller sized aggregate required for precast concrete products. It was estimated that if all six worked round the clock, i.e. assuming there was enough feed material, they would still have found it difficult to maintain the required supplies for a single precast factory. Investment in equipment was therefore required to guarantee supply and improve the quality of the recycled demolition aggregate. The market forces and the incentives/drivers for construction companies to adopt sustainable practises have encouraged investment of several million pounds to be made in new recycling plants and this has resulted in "urban quarries".

Work on reducing the carbon footprint of concrete construction needs to consider not only the replacement of the aggregate with recycled ones but also to consider a reduction or complete replacement of Portland cement in concrete mixes. Alkali activated binders and geopolymers have seen applications in ceramics, hazardous waste containment, fire-resistant construction materials and refractories but the most interesting application is their use to replace Portland cement-based concretes. Several factors affecting the reactivity of fly ash as a precursor for geopolymer concrete have been investigated. These include physical and chemical properties of various fly ash sources, inclusion of ground granulated blast furnace slag (ggbs), chemical activator dosages and curing temperature. Alkali-activated fly ash was found to require elevated curing temperatures and high alkali concentrations. A mixture of sodium hydroxide and sodium silicate was used and this was shown to result in high strengths, as high as 70 MPa at 28 days. The partial replacement of fly ash with ground granulated blast furnace slag (ggbs) was found to be beneficial in not only avoiding the need for elevated curing temperatures but also in improving compressive strengths. It became apparent that the main obstacle to commercialisation of these new alternative binders was the cost of the activating solutions, i.e. the sodium hydroxide and the sodium silicate. The latter is the most expensive one and results in geopolymer concretes that cannot compete on price with Portland cement concretes. Attempts therefore concentrated on developing a procedure for the production of sodium hydroxide from waste streams, which in this case was ground glass cullet. Production of eco-friendly concretes thus becomes commercially possible.

## 1. Introduction

With an increasing need to consider sustainability in concrete construction, research in the UK has focused two approaches to deliver more environmentally friendly concrete, i.e. partial or full replacement of newly quarried aggregate with recycled demolition aggregate, and replacement of Portland cement with alkali activated binders.

### 1.1. *Recycled demolition aggregate in concrete building blocks.*

Investigations into the replacement of newly quarried aggregate with recycled demolition waste, comprising both concrete and masonry coarse and fine aggregate, in construction components started at the University of Liverpool back in 2001. Published work at the time indicated that recycled demolition aggregate could potentially be used to partially replace extracted aggregate in ready mix concrete [1]. However, precast products such as building blocks, pavement blocks and paving flags had been selected because they do not contain reinforcing steel and therefore chloride contamination is not an issue. Construction and demolition waste (C&DW) was selected for such a study as it accounted, in 1999, for approximately 17% of the annual UK waste stream, amounting to a total of 70 million tonnes of waste material [2,3]. Around 30% of the 70 million tonnes arising was at the time reused in low-grade applications such road subbase construction, engineering fill, or landfill engineering where some crushing and separation of materials such as metal and wood is required [3]. Only a small percentage was recycled for high specification applications and this tended to come from easily identifiable sources, e.g., railway ballast. Higher value uses for the majority of C&DW had not in the past been thought possible because of the heterogeneous nature of the material compared with primary aggregate.

Whilst 70 million tonnes of C&DW was being produced there was around 220 million tonnes of natural aggregate being quarried each year in the UK [4]. Because of the environmental impact of quarrying, the Government had introduced legislation - such as the aggregates levy, introduced in April 2002 - in the UK to minimise C&DW production and maximise the use of alternatives to primary aggregate [5]. As C&DW is largely inert, consisting of soil, brick, glass, concrete, plaster, etc., landfill charges for its disposal had traditionally been low.

A study was therefore needed to provide an assessment of the economic and technical aspects of using C&DW for a higher value usage, such as the production of precast concrete building blocks. The research to establish the economic case had involved surveying the producers, the then end users and potential future end users of C&DW. The work included an assessment of the practicalities of using C&DW for higher value usage and the then climate for the construction sector in the North West by establishing likely future demand and the impact of planning controls and other contributing factors, such as Government funding, legislative and financial pressures. How these planning controls and other contributing factors have influenced the developments in recycling of construction and demolition over the last fifteen years in Merseyside are discussed. The developments and especially the expenditure on plant equipment that has taken place shows that recycling is not only sustainable but also profitable.

### 1.2. *Development of alkali activated binders (AABs) and geopolymer concretes.*

The term “geopolymer” was introduced by Davidovits in the 1970s referring to alkali-activated metakaolin [6]. It has since been used for a range of synthetic low-calcium aluminosilicate polymeric materials, as a sub-range of a more general definition which is alkali-activated binders (AAB). Although the initial studies were focused on geological materials such as metakaolin activated with siliceous solutions [7-11], the potential of using other synthetic reactive aluminosilicate materials activated with a range of concentrated alkaline solutions became apparent [6,12,13]. AABs have been studied for the last 40 years [14] and have applications in ceramics, hazardous waste containment, fire-resistant construction materials and refractories [15,16]. One of the most interesting applications is their use as a cement-free binder that can replace Portland cement-based pastes in construction materials such as concrete and mortar products [17]. Geopolymers can provide a desirable alternative to Portland cement (PC) binders, not only for the environmental benefits arising from the avoidance of CO<sub>2</sub> emissions associated with PC production, but also in terms of their performance and durability, where such properties are not only equivalent, but often better than those achieved with PC. Of particular interest is the selection of precursor aluminosilicate materials that arise from waste-streams or as by-product

pozzolans, which are readily available from existing industries [18]. These include fly ash (FA) and ground granulated blast furnace slag (ggbfs). Although ggbfs has a relatively high demand from an existing market-base, and an associated relatively high value, perhaps equivalent to that of Portland cement, waste-stream pozzolans such as FA are not fully recycled into value added products, and excesses are stockpiled or landfilled.

Reaction mechanisms responsible for the creation of an amorphous gel from fly ash are complex and still not fully understood [14]. A wide variability in chemical dosages can be found in the scientific literature related to the activation of FA systems [19], indicating that optimum proportions of alkali species (hydroxides and silicates) in the activating solution, as well as quantity of alkali per binder mass, still need to be investigated to improve our understanding of the reaction mechanisms. Curing parameters such as curing temperature and stand time, i.e. the time elapsed before the start of high temperature curing, play an important role in the full development of the reaction products. Information available in technical literature is relatively limited, and thus a systematic investigation was still needed for determining not only optimum curing conditions but also mix proportions to obtain desired properties. The cost of these new concretes is an issue and attempts have been made to reduce it by developing activators from waste streams to avoid the use of commercially available ones that are costly.

FA-based geopolymers need an external energy source in the form of thermal curing for the reaction to take place. This can be a drawback for the upscaling of the process to the industrial level. On the other hand, Ca-rich slags such as ggbfs react at room temperature since their reaction, i.e. the hydration of Ca species and the creation of a calcium-aluminium-silicate-hydrate (C-A-S-H) gel, is different from low-calcium precursors. Moreover, the reaction develops at a very rapid pace, often resulting in a very short initial setting time. The blend of FA/ggbfs for achieving a system reacting at room temperature without rapid setting would suit most concrete applications. Relatively few publications are available in the literature [20-24] and thus further investigations are needed to provide a better insight into the properties and performance of such binary systems.

## **2. Recycled demolition aggregate – Developments during the last 15 years in the North West of England**

The quantities required for precast concrete factories are significant. These can be up to 500 tonnes daily. A comprehensive study was therefore first carried out to determine the quantities of C&DW arisings that could be recycled. A laboratory study then followed to demonstrate that the C&DW derived aggregate could be used in of precast concrete products. Factory trials of precast concrete confirmed that there were no practicalities that would prevent the use of recycled demolition aggregate in every day production. It is then shown that drivers and incentives for the use of recycled aggregate have encouraged large investments in equipment to process C&DW into aggregates.

### *2.1. Quantities and uses for C&DW in 2001*

The most comprehensive research on C&DW arisings at the time was by Symonds and it had been undertaken for the Office of the Deputy Prime Minister [4]. This research surveyed the industry and a number of users of C&DW and extrapolated the results to estimate the total arisings. This showed that there were more than ten million tonnes of C&DW arisings in the North West each year. Almost half was used as an aggregate in road building, engineering or land restoration. The remaining half of the hard C&D waste could be used in block production.

Merseyside, and more specifically Liverpool, is an urban region that was at the time undergoing regeneration, and it was therefore used to illustrate the advantages of using C&DW derived aggregates in the production of building blocks. Regeneration usually requires the demolition of old infrastructure, e.g., Liverpool Housing Action Trust (LHAT) alone demolished 52 out of the 72 tower blocks that they owned in Liverpool between 2001 and 2006. One of these tower blocks, see Figure 1, that was demolished using explosives, a technique known as “implosion”, produced 15,000 tonnes of construction and demolition waste. Trucks transported this “waste” to a nearby crushing plant where it was converted to road subbase material.

Some of the practicalities that needed to be addressed in order to use C&DW in the manufacturing of precast concrete blocks were:

- **Demolition & Processing Equipment:** The equipment used by demolition contractors to demolish and process C&DW had remained largely unchanged in the 1990s. Demolition contractors typically used mobile jaw crushers to produce a crushed concrete and masonry of a particle size of 75mm which was intended for use as a road subbase material. To produce C&DW of the particle size needed to manufacture precast concrete blocks (6 mm and 5 mm-dust) would require the use of a cone or impact crusher. This would have required a considerable investment by the demolition contractors and they would only have considered it if they were confident that there would be the market for the C&DW aggregate [25]. Screening after the material had been crushed would have been necessary if any control was to be exerted over the particle size of the finished product. Material was typically moved by conveyor from the crushing equipment. As all this equipment tends to be mobile rather than static plant it is possible to introduce variations in the plant layout depending on the requirements of the end product. The particle size of material required to manufacture precast concrete blocks would have required demolition contractors to invest in new screens in order to produce the correctly graded material [26].
- **Consistency of physical properties:** If C&DW derived aggregate are to be used in the production of concrete blocks then the specific gravity, angularity, fineness, and water absorption are all important physical properties that need to be taken into consideration. All these properties will be affected by the source of C&DW. The C&DW from the demolition of tower blocks was, in the majority, concrete. However, a major source of C&DW, once the demolition of the tower blocks was completed, would have been residential council houses that are primarily masonry buildings [25]. Manufacturers had stressed the fact that customers are used to purchasing a product made from very consistent raw materials. This would have implications for even the cheap precast blocks, as they tend to be consistent in terms of colour and surface finish. There was a worry that the cement paste would not completely mask the colour variations in the input raw material, especially the red colour of bricks, although this was dismissed after factory trials.

The factors that would affect the economic viability of using C&DW in the manufacturing of concrete building blocks include:

- The price of the finished block – the market suggests it needs to be cheaper than a conventional block manufactured with virgin aggregates. This is necessary to surmount “conservatism” by the marketplace.
- Positive financial factors such as Landfill tax and Aggregates Levy that will be avoided by using C&DW to manufacture a product.
- Negative financial factors, such as transportation costs, the requirements of legislation, the need for demolition contractors to invest in new equipment and the additional processing costs which may arise from variations in the raw material that increase maintenance costs, downtime, processing cost due to more product line change, etc.

The costs for crushing the C&DW, which was estimated to be approximately £7.20, was not recovered when it was sold as road subbase aggregate. The selling price depended heavily on the demand and could vary between £2.00 and £4.00 per tonne. The demolition contractors were still therefore required to cover the difference and thus meant that they had to pay the recycling plant to take away the C&DW. Operators of crushing plants would also welcome not only an increase in price per tonne but also a guaranteed constant/regular demand for the C&DW derived aggregate. Block making factories appeared to be interested in C&DW derived aggregate if the price was lower than that of quarried aggregate. A conservative value of £7.00 per tonne, including delivery, for 6 mm C&DW derived aggregates would have satisfied both the operators of crushing plants as well as the block making factories. There were other considerations to take into account such as (a) guaranteed supply over several years: this was to ensure that any competitive price advantage from the use of C&DW derived aggregate would not backfire for commitments to construction projects lasting several years, and (b) flow smoothing, supplying to meet demand and storage of material in case of downturn in the demand of building blocks. These were not considered to be insurmountable problems. There was therefore scope for investigating a high-end value market, such as concrete building blocks and concrete paving flags, for recycled demolition aggregate [27].



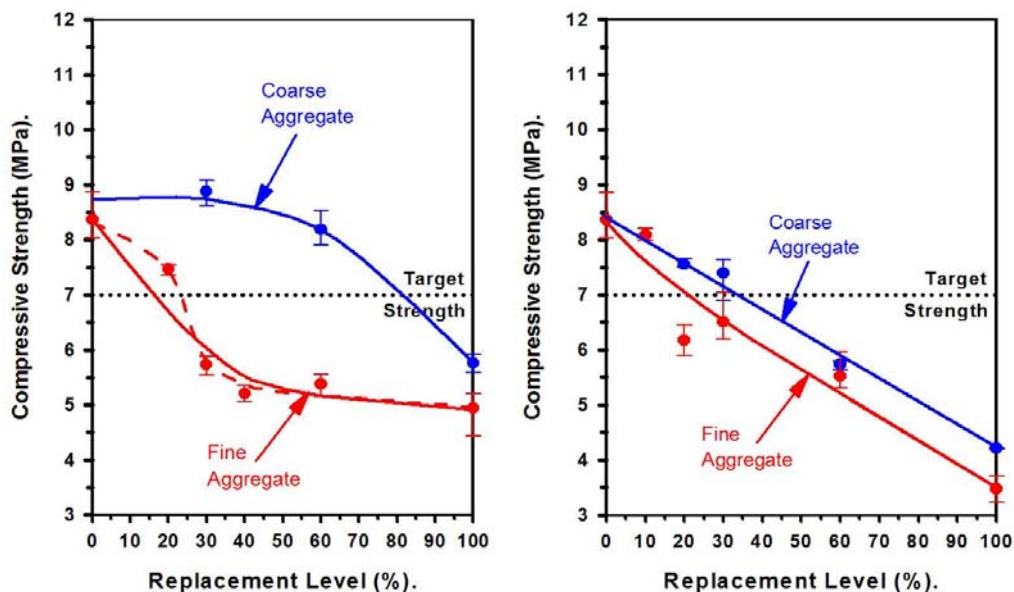
**Figure 1.** Implosion of Kenley Tower.

## 2.2. Laboratory study of precast concrete products made with recycled demolition aggregate (2003 – 2007)

Three types of aggregate had been obtained in 2003; quarried limestone aggregate was obtained from Forticrete's block making factory at Buxton, while recycled concrete and masonry derived aggregate were supplied by local demolition companies. Both the concrete and the masonry-derived recycled aggregates had very high water absorptions, which are similar to the behaviour of man-made lightweight aggregates. A mixing procedure adopted for making concrete using lightweight aggregate was thus trialled and found to be successful when using recycled concrete aggregate, i.e. pre-mixing of half the mix water with the aggregate and subsequently adding the cement and the remaining water.

Precast concrete factories are normally in operation round the clock. Stoppage in production costs a lot of money and therefore the investigation into the effect of replacing quarried aggregate with recycled demolition aggregate had to be done in the laboratory. The first objective was to replicate the industrial casting procedures using laboratory equipment. The technique used by industry for making building and paving blocks is based on applying simultaneous vibration and compaction. A heavy metal block is used to compress the concrete while it is vibrated. This procedure was replicated in the laboratory by the use of an electric hammer. After having successfully replicated the industrial block-making procedure in the laboratory, the replacement of quarried limestone with concrete-derived aggregates was investigated. The mix proportions of natural limestone aggregate used by a block making factory were converted to equivalent volumes, replaced by an equal volume of recycled demolition aggregate, and then converted back into weight. This ensured that the replacement was on a volumetric basis, required to take into account the different densities of the recycled aggregates compared with quarried limestone aggregates. Blocks made with recycled concrete aggregates had a marginally lower wet density than quarried limestone blocks, e.g., 1890 kg/m<sup>3</sup> for a block using 100% replacement of both 6 mm and 4 mm-to-dust limestone aggregate with concrete-derived aggregate, compared with 2125 kg/m<sup>3</sup> for a block using only limestone aggregate. Portland cement used was 100 kg/m<sup>3</sup>. All blocks were tested at 7-days using fibreboard end packing and, following factory procedure, a conversion factor of 1.06 was used to convert this strength to the equivalent 28-day strength.

Studies were then carried out with the objective of replacing either the coarse fraction or the fines fraction, but not both, in order to quantify the relative effects of each fraction, see Figure 2 (left). Promising results were obtained for a 60% replacement of the coarse fraction with concrete-derived aggregate, i.e. there was no significant detrimental effect on the compressive strength. Replacement of the fine aggregate fraction only with concrete-derived aggregate had a more significant detrimental



**Figure 2.** Compressive strength against replacement level (%) with recycled demolition aggregates for building blocks (a) concrete-derived aggregate - left; and (b) masonry-derived aggregate – right [27].

effect on strength than the coarse aggregate replacement. A replacement level of fine aggregate higher than 30% was not recommended. It was concluded that reasonable replacement levels would be 60% for the coarse fraction and no more than 30% for the fine fraction.

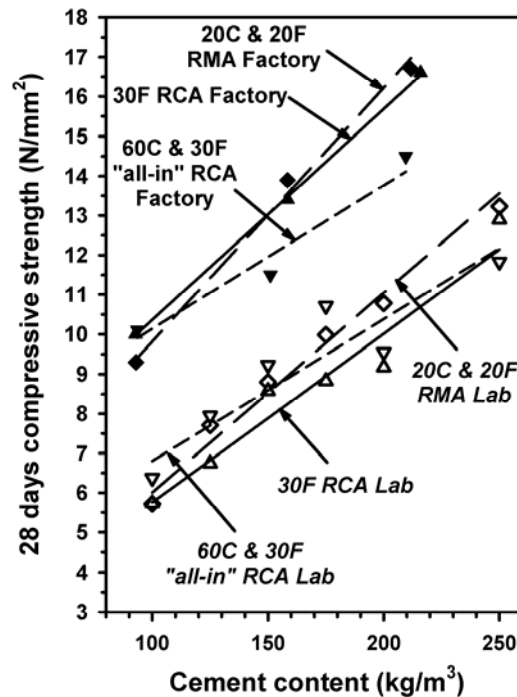
The effect of replacing newly quarried limestone with recycled masonry-derived aggregate is also shown in Figure 2 (right) and the detrimental effect was found to vary almost linearly with the percentage replacement level. 20% replacement level of coarse and fine aggregate was selected as it still produced blocks with a compressive strength above 7 MPa.

### 2.3. Factory trials of precast concrete products made with recycled demolition aggregate (May 2005)

The precast concrete manufacturer requested in 2005 that there should be enough aggregate crushed for several trials rather than just one. In total, 10 tonnes of recycled demolition aggregate were delivered to the Forticrete factory at Buxton. This comprised 2 tonnes of 6 mm and 2 tonnes of 5 mm to dust of Recycled Masonry Aggregate RMA and 4 tonnes of not “single-sized” but an “all-in” aggregate and 2 tonnes of 5mm to dust of Recycled Concrete Aggregate (RCA). Factory trial mixes therefore aimed at investigating the replacement of newly quarried aggregate with (a) RMA at replacement percentages of 20% for the coarse fraction and 20% for the fine fraction, (b) “all-in” RCA aggregate at replacement percentages of 60% for the coarse fraction and 30% for the fine fraction, and (c) RCA at the replacement percentage of 30% for only the fine fraction.

The cement contents investigated were approximately 100, 175 and 250 kg/m<sup>3</sup>. The blocks cast were labelled and one of the blocks from each batch was weighed. All blocks were cured for one day in the factory’s humidity chamber. Five or six blocks were tested for compressive strength at 7- and 28-days. The concrete strengths obtained are also shown graphically in Figure 3. It is seen that the industrial vibro-compaction technique was more efficient than the laboratory technique and produced higher compressive strengths throughout. As a result of this, the relationships between strength and cement contents were shifted upwards. The strengths obtained confirmed that the replacement levels recommended from the laboratory work did not cause significant strength reduction, i.e. there was no requirement to increase the cement content to maintain the required strength, and hence there would be no additional cost to the manufacturers if they were to use recycled aggregate. Overall, it was a very satisfactory factory trial [27].





**Figure 3.** The 28 day strengths of factory blocks made with recycled demolition aggregate[27].

#### 2.4. Developments in the use of recycled aggregate during the last decade

The use of recycled aggregate has been an integral part of the United Kingdom's minerals policies for a number of years. The UK Minerals Policy Statements [28] promote sustainable development, which is itself a requirement of the Planning and Compulsory Purchase Act of 2004. These initiatives are complemented by the government's sustainable development strategies which encourage waste minimisation and stress the importance of combining economic growth with an environmentally friendly approach for sustainable development. Over recent years the UK government has further demonstrated its commitment to sustainable development through financial backing of, for example: the Aggregates Levy Sustainability Fund [29], and the Waste & Resources Action Programme (WRAP). Government funded construction, demolition and excavation waste surveys carried out at two yearly intervals since 1999, have provided information on the arisings and use as aggregate, of construction, demolition and excavation waste as an alternative to the use of primary aggregates [30].

British Aggregates estimated that there was an increase of 420% in the use of recycled aggregates between 1990 and 2008 despite a steady overall reduction in the total quantity of aggregates used between these years [31], with recent figures from 2014 estimating that 28-29% were from recycled and secondary sources [32,33]. The report also notes that the introduction of the landfill tax resulted in a doubling of the recycling plants from 16 to 32 new plants per annum. It was also noted that these companies, which are generally small or medium sized enterprises (SMEs), operated over two thirds of all UK static aggregates recycling plants. The statistics do not, however, give the complete picture as waste is also reused on demolition sites. Although there is no data available, it is reasonable to believe that there has also been an increase in the volumes of waste reused at building sites. The consequence of the UK sustainability initiatives and in particular the landfill tax is that the UK is now the leading recycler of aggregates in the European Union. A report by the European Aggregates Association [34] stated that 216 million tonnes of aggregate materials were recycled in Europe in 2008. This, however, only represented 6% of the total European production as compared with a rate of 28% recycled aggregates in the supply mix of Great Britain [32].

### 2.5. Developments in the North West of England

Successive UK governments have been committed to creating the drivers and conditions that will encourage the reuse of C&DW as recycled aggregate, even during the economic downturn. This has had an impact on regional aggregate markets and in particular the demolition, excavation and recycled aggregate sectors.

Primary aggregate sales in the North West of England had been steadily declining with a 14% fall in 2008 and a further 25% drop in 2009 to the lowest level for 16 years, with a further 16% decline in 2011 and a slight increase to sub 2009 levels in 2012 [35,36]. Despite this, the market for recycled aggregates was still thriving. There were 58 registered fixed construction demolition and excavation waste sites in the North West of England in 2008, recycling 59% of C&DW arisings in the region. Revisions to the UK national guidelines for aggregates provision assume that 26% aggregates required in the North West of the UK between 2001 and 2016 will have come from secondary and recycled sources. This exceeds UK policy from 2003 stating that the government is working with the industry to achieve 25% aggregates to be from secondary or recycled sources by 2021.

It is generally considered that the use of recycled aggregate can only be considered a carbon footprint reducing option if transported by road and used within 10 miles (or 15 km) of their source [37]. Regional suppliers of recycled aggregate are therefore investing heavily in new plant in order to produce higher quality products for the construction industry which is keen to increase CEEQUAL [38] and BREEAM [39] credits. Such drivers have encouraged others to consider recycling, e.g., skip hire companies. One such company has invested in not only mobile but also static crushing equipment. The skips are no longer sent to landfill; they are tipped over inside a hangar and the waste is separated by hand. Only the waste that cannot be recycled is sent to landfill. Even waste collectors have to now recycle if they are to stay in business. Their profit margin would be eroded away if everything was to be landfilled.

Large stockpiles of mixed C&DW arisings (this included significant quantities of excavation waste much of which is actually natural material) from numerous demolition and excavation sites in Merseyside had been created at one demolition contractor's site which is just outside Liverpool. This arose because of: (a) an increasing amount of regeneration on Merseyside and (b) the productivity of dry sieving was being dramatically affected by wet conditions. As the site was limited to just 9.5 acres it became necessary to process the existing stockpiles efficiently and economically. The company invested £1.6 million on a new aggregate washing plant, upgrading from a dry crushing and screening process, see Figure 4. The primary motivation for this investment was a need to reduce costs of



**Figure 4.** The “urban” quarry.



landfilling which were escalating due to the UK's landfill tax. Customers' increasing acceptance of recycled aggregate as a replacement for quarried materials was also an important incentive for the investment as it demonstrated that there would be a market for the recycled products. The washing plant can be used in all weather conditions with the additional benefits of increasing the quality of the recycled aggregate. The washing plant is capable of processing up to 120 tonnes per hour, and typically operates at around 90 tonnes per hour. The C&DW is treated through various phases on the washing plant to produce a number of recycled products including sand and other sizes of aggregate.

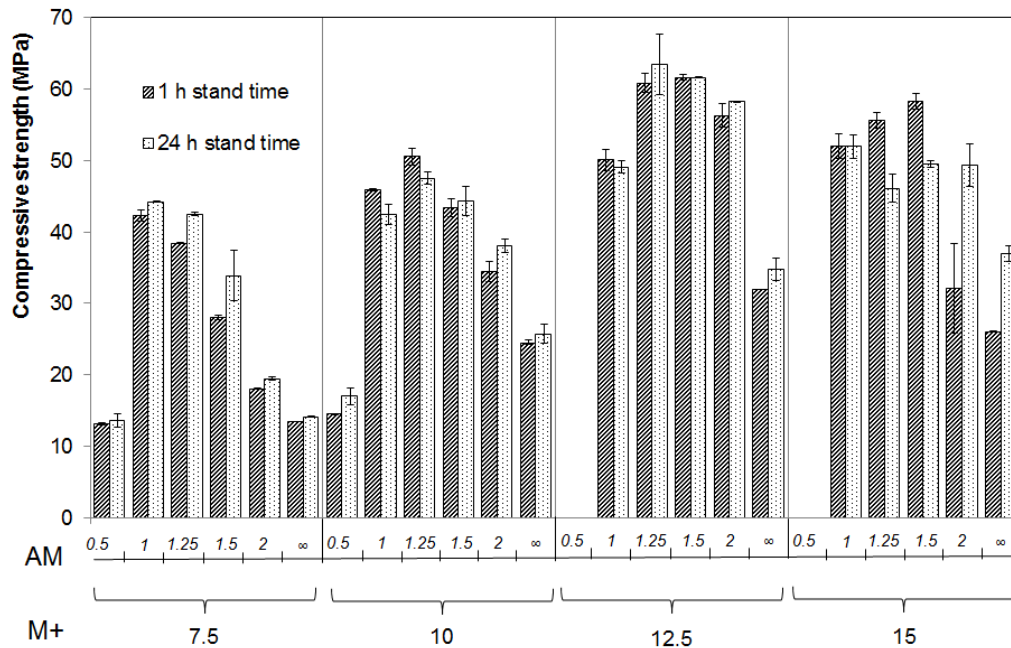
Prior to the installation of the washing plant, a 20 tonne load on a heavy goods vehicle would cost approximately £50 to send to landfill. It is now possible to charge on average £6 to £7 per tonne for the processed material after haulage. Removal of the clay looking fine material through the plant leaves around 16 tonnes of useful material per load which equates to around £112 in income. Taking previous disposal costs into account this is an improvement of £162 per vehicle. Processing on average around 900 tonnes per day (45 lorry loads) with running costs of approximately £1.5 per tonne gives a gross value of £5,940 per day for running the plant [30]. The product with the least demand is the 0-4 mm sand which occasionally is sold as soil for £4.50 per tonne in order to reduce the stock levels. This is still a marked improvement on previous landfill costs. The most popular product is the 6-10 mm, used for pipe bedding, which is normally sold immediately after processing, leaving no stockpile. A visit to the plant a year after it opened indicated that the stockpile of C&DW shown in the background of Figure 4 was still almost intact. The company is taking more C&DW through its front gates than ever before proving that there is enough resource material to keep the washing plant operating at its full capacity.

### **3. Alkali activated binders (AABs) and geopolymer concretes**

The carbon footprint of the concretes does not significantly reduce with the use of recycled demolition aggregate. Its use is highly encouraged because of the large volumes that arise from construction demolition and the fact that large volumes can be reused in concrete and thus avoiding landfilling them. The main reason for the high carbon footprint of concretes is that due to the binder which is normally Portland cement. Alternative binders have been developed that are based on aluminosilicate materials that arise from waste-streams or as by-product pozzolans, which are readily available from existing industries [18]. These include fly ash (FA) and ground granulated blast furnace slag (ggbs). Although ggbs has a relatively high demand from an existing market-base, and an associated relatively high value, perhaps equivalent to that of Portland cement, waste-stream pozzolans such as FA are not fully recycled into value added products, and excesses are stockpiled or landfilled. Geopolymers can provide a desirable alternative to Portland cement (PC) binders, not only for the environmental benefits arising from the avoidance of CO<sub>2</sub> emissions associated with PC production, but also in terms of their performance and durability, where such properties are not only equivalent, but often better than those achieved with PC.

The work on developing guidelines for the production of geopolymer concretes started more than ten years ago. The aim was to gain a better understanding of what affects their properties. Factors investigated included: (a) the effect of curing procedure and activator dosages on the strength development of FA-based mortar, (b) the influence of physical and chemical properties of 13 FA sources obtained from 8 UK power stations, (c) the effect of partial substitution with ggbs on the compressive strength development and microstructure of the reacted mortar. It became apparent that the main obstacle to commercialisation of these new alternative binders was the cost of the activating solutions, i.e. the sodium hydroxide and the sodium silicate. The latter is the most expensive one and results in geopolymer concretes that cannot compete on price with Portland cement concretes. Attempts therefore concentrated on developing a procedure for the production of sodium hydroxide from again waste streams, which in this case was ground glass cullet.

The alkali dosage (M<sup>+</sup>) used in the geopolymer concretes was defined as the percentage mass ratio of total sodium oxide (Na<sub>2</sub>O) in the activating solution to the binder. The alkali modulus (AM) was defined as the mass ratio of sodium oxide to silica in the activating solution.



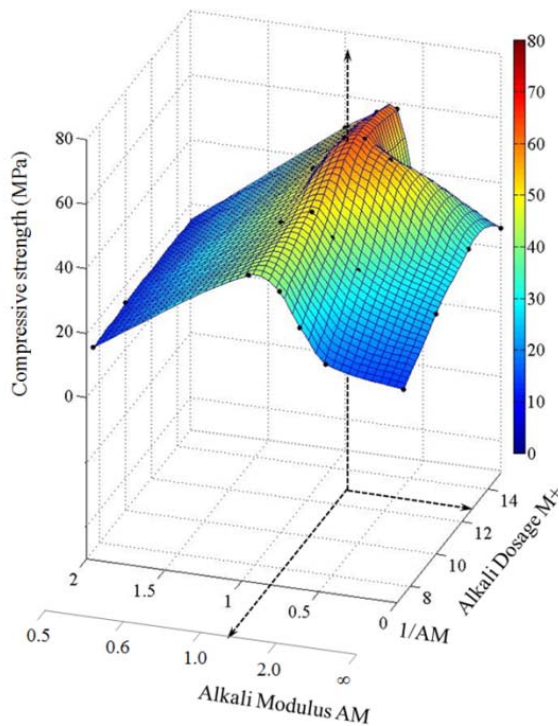
**Figure 5.** Compressive strengths at 28 days for 1 h and 24 h of stand time of 100% FA mortars (70°C curing temperature) for a range of alkali modulus (AM) and alkali dosage (M+) [40].

### 3.1. Effect of curing procedure and activator dosages on strength development

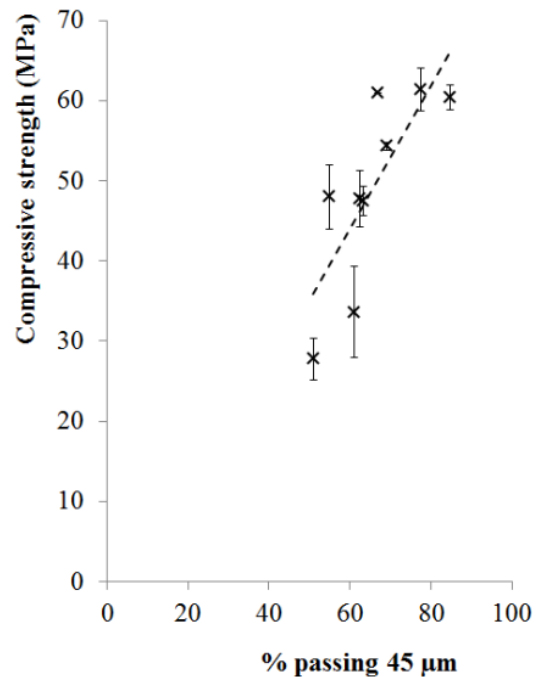
Twenty-four combinations of M+ and AM were investigated for each of the four curing regimes, for a total number of 96 different series of mixes. The effects of curing temperature, and activator dosage were investigated by determining the compressive strength development.

Figure 5 shows the effect of curing temperature on the 28-day strengths of all mixes [40]. It can be seen that in all cases, with the exception of those with the lowest AM (0.5), 70°C curing temperatures give significantly increased strengths compared to those cured at 50°C for the same time. The observed effect of curing temperature on the mechanical strength is well documented in the literature. Investigations on reactivity of FA under thermal curing are reported to having been carried out for temperatures in the range 30 °C to 85 °C [41]. Another study [42] found that increasing the curing temperature from 45 °C to 65 °C resulted in a 5-fold rise of mechanical strength, whereas a 10-fold rise was observed between 65 °C and 85 °C.

An increase in alkali dosage (M+) resulted in an increase of the strength up to an M+ of 12.5%. Beyond this ‘optimum’ value, the strengths decreased, which is attributed to saturation of the gel with alkali ions resulting in less free water to be available for speciation of silica and alumina oligomers from the dissolution of FA. An optimum range of values for the alkali modulus was identified, above and below which strengths decrease. With increasing alkali dosage, that ‘sweet spot’ broadens out towards higher alkali modulus. Again, results for M+ = 15% do not follow these trends. In general, alkali moduli between 1 and 1.25 give the highest strengths across the alkali dosages investigated. The drop-off in strength with increasing modulus is likely to be due to the reduced amount of available silica that can participate in the ‘reorganisation-gelation-polymerisation’ steps of the geopolymer formation and thus the development of a denser and more complete and long polymer chain. The reduction in strengths at low modulus (AM=0.5: all sodium silicate) can be attributed to the reduction of the pH in the system when only sodium silicate solution is used. The expansion of the cubes upon thermal curing could also have contributed. Figure 6 shows a 3-D plot identifying the combined effect of alkali dosage and modulus on compressive strength for curing temperature of 70°C. These curing conditions were selected because 70 °C curing temperature gave the highest compressive strengths. The ‘sweet spot’ of the



**Figure 6.** 3-D plot showing the combined effects of alkali dosage and modulus on the 28-day strength of 100% FA mortars (1 hour at 20 °C followed by 70 °C [40].



**Figure 7.** 28-day compressive strength of 9 FA sources cured at 70 °C vs. % volume passing 45 µm sieve. Error bars represent the range of obtained values [40].

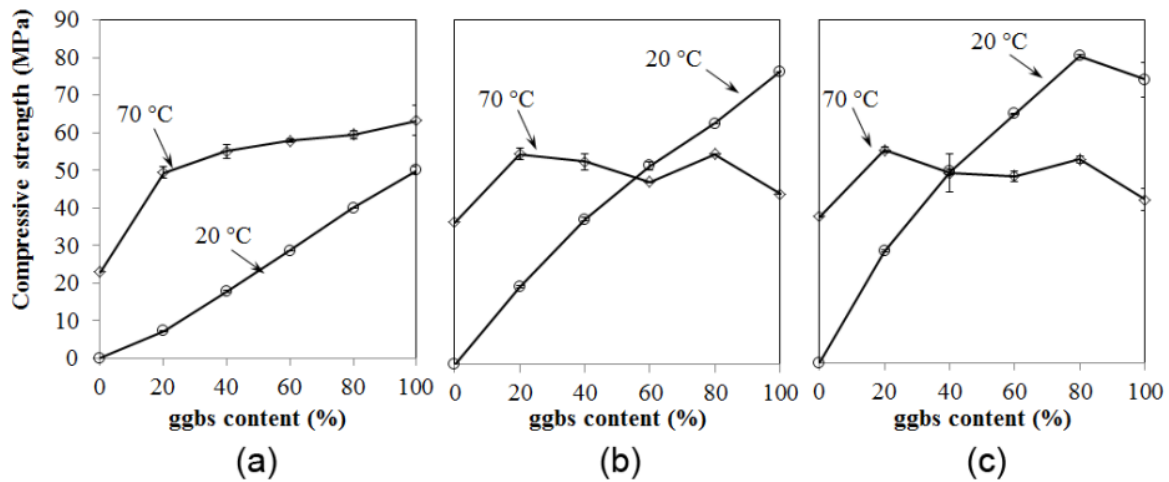
optimum alkali modulus and dosage combinations has a strength maximum of 70 MPa at around an alkali dosage of 12.5% and alkali modulus of 1.25.

### 3.2. Influence of physical and chemical properties of raw materials on compressive strength

A comprehensive characterisation of 13 different fly ashes from coal powered electricity generating stations was carried out in order to investigate the suitability of different FA sources in the UK. Chemical composition, mineralogical composition, grain size distribution and strengths after alkali activation were investigated. It was concluded that the most important factor to consider for achieving high compressive strengths is the grain size of the FA, see Figure 7. It must, however, be emphasised that ten out of thirteen of the tested FA samples are suitable for use in concretes to partially replace Portland cement and thus conform to EN-450. Attempts to examine fuel ash from lagoons did not prove possible. It may be that the chemical composition of lagoon ash has been altered over time and it is thus considerably different from all the sources investigated in this programme of work.

### 3.3. Effect of partial replacement of FA with ggbs

Mortar mixtures containing only FA did not develop any significant strength at room temperature. However, the addition of ggbs at any level gave significant strength enhancements even at room temperature. Figure 8 shows the strength of FA/ggbs based mortars with M+ 7.5% and AM 1.25. There is an almost linear relationship between the amount of ggbs in the binder and the strength at 1, 7 and 28 days where cubes were cured at room temperature (20°C). This seems to suggest that FA did not contribute much to the strength. There was a significant increase in the strength from ~20 MPa to ~50 MPa with the addition of only 20% ggbs when cured for 1 day at 70 °C. Higher levels of ggbs cured for 1 day resulted in smaller incremental increases up to ~60 MPa at 100% ggbs.



**Figure 8.** Effect of ggbs substitution rate on the strength of sodium silicate/sodium hydroxide-activated binders with M+ 7.5% and AM 1.25. (a) 1 day; (b) 7 days; (c) 28 days [40].

### 3.4. Production of sodium silicate powder from waste glass cullet

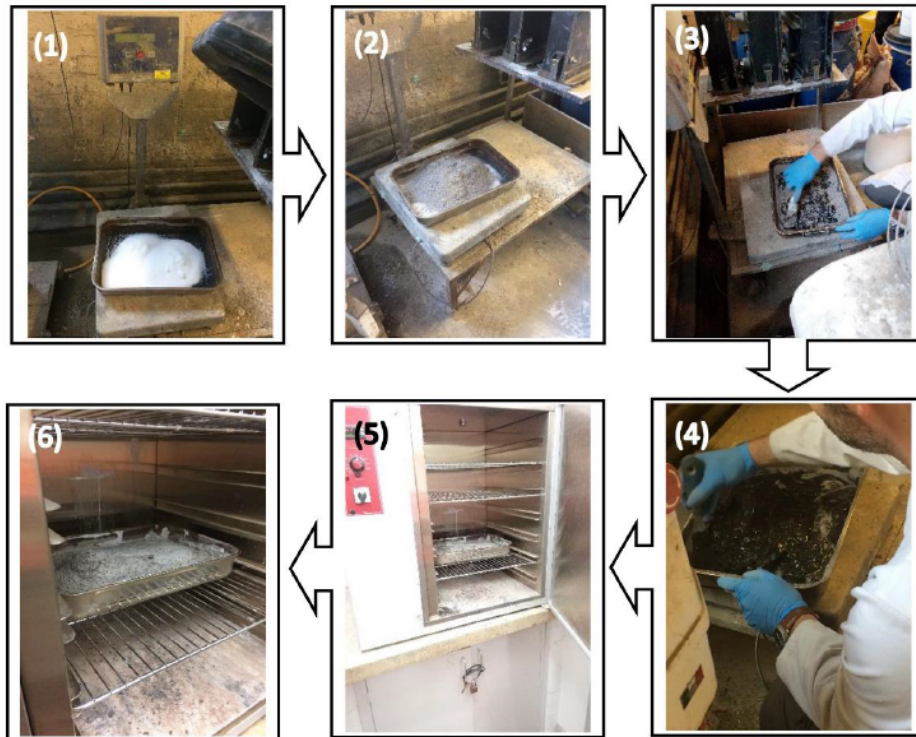
Alkali activated binders (AABs) may be an alternative for Portland cement in concrete applications, but the cost and the environmental footprint of commercially available chemical activators, such as sodium silicate, are currently hindering their commercialisation. The need to use highly alkaline liquid activators poses serious health and safety concerns. A simple and inexpensive process to produce solid sodium silicate powder at a low temperature with the use of glass cullet is highly desirable as it will be a “game changer”, i.e. the cost of AAB concretes may be such that they can commercially compete with Portland cement concretes. The procedure involves mixing sodium hydroxide with ground glass cullet and some water to form a paste and then heat treating it at relatively low temperature. Parameters, such as the glass cullet (providing the  $\text{SiO}_2$ ) and sodium hydroxide (providing the  $\text{Na}_2\text{O}$ ) ratio, the process temperature and duration, the inclusion of water in the mix and the fineness of NaOH were investigated to determine their effects on the resulting sodium silicate powder [43]. The activation potential of this powder for typical AAB precursors, such as fly ash or fly ash/GGBS blends was found to be comparable to commercially available sodium hydroxide/sodium silicate blended solutions. Compressive strengths of AAB mortars with the in-house produced powder were similar to or better than those obtained with control mixes prepared with commercially available sodium hydroxide/sodium silicate blended solutions. FT-IR tests indicated that the reactivity of the in-house prepared powder may be due to the silicate structure that has a high number of non-bridging oxygen atoms. Initial cost estimates, see Figure 10, indicate that normal strength AAB concrete (35 MPa nominal strength) can be produced at a similar cost to Portland cement concrete. The use of low cost in-house produced powder may result in AAB concretes with higher compressive strengths, e.g. nominal strengths of 50 and 70 MPa that have lower cost to produce than conventional Portland cement concretes.

## 4. Conclusions

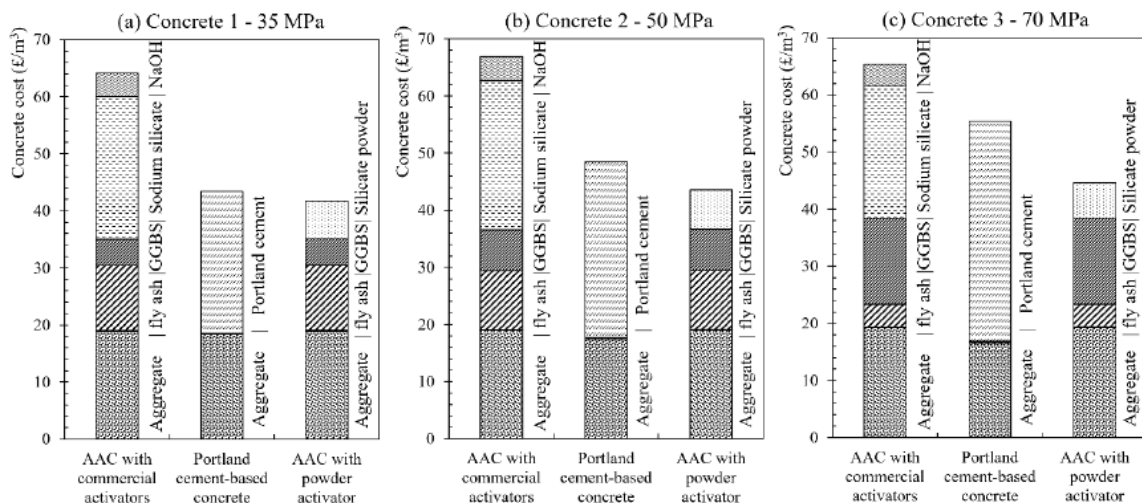
The studies described have demonstrated the potential for sustainable concrete construction through the use of (a) C&DW derived aggregate as a replacement for newly quarried aggregate in precast concrete building blocks, and (b) by-products for the production of alkali activated binders and geopolymer concretes.

In terms of recycled demolition aggregate:





**Figure 9.** Procedure steps for the production of the activating powder: (1) The NaOH (10 parts in mass) is weighted in a tray. (2) The glass cullet powder (11 parts in mass) is added. (3) Water is added. (4) Constituents are mixed until the required consistency is achieved. (5) Mix is put in oven at 150 to 330 °C for two hours. (6) The tray is removed and the powder is collected [43].



**Figure 10.** Comparison of the cost per cubic metre of different concrete classes [43].

- Replacement levels have been recommended for both fine and coarse recycled aggregate which will not require an increase in the cement content to maintain the required strength, and hence there would be no additional cost to the manufacturers if they were to use recycled aggregate.
- The market forces and the incentives/drivers for construction companies to adopt sustainable practices have encouraged investment of several million pounds to be made in new recycling plants and have resulted in “urban quarries”.



The developments in recycling of construction and demolition over the last decade, with particular reference to Merseyside, have shown that recycling is not only sustainable but also profitable.

Geopolymer and alkali activated binders can offer a possible alternative to Portland cement concrete. Guidelines for their production include:

- Curing temperature has a very significant effect on strength of FA based geopolymers: specimens cured at 70°C were considerably stronger than specimens cured at 50°C.
- The dosage of activators is very important for not only achieving the required early age properties but also for the effect on compressive strength. A ‘sweet spot’ of the optimum alkali modulus and dosage combinations, i.e. alkali dosage of 12.5% and alkali modulus of 1.25, gave compressive strength of ~70 MPa.
- Physical and chemical properties of potential FA sources should be investigated before selecting the most suitable one. Average grain size was found to be one of the important factors affecting the potential compressive strength. Coarse FA coupled with low amorphous content and high LOI needs to be avoided.
- Partial FA replacement with ggbs leads to increases in the compressive strength. Strengths of 80 MPa with only M+ 7.5% and AM 1.25 were obtained. The other benefit from such blends is that curing at room temperature only is sufficient and no elevated curing temperatures are needed.

The development of a low cost and with a low environmental carbon footprint powder activator has been described. This is an alternative to the currently commercially available ones. The cost of currently available commercial activators is hindering the commercialisation of AAB concretes. Commercially available activators are not only expensive but also come in liquid form which has health and safety implications in their handling on site.

The new procedure for producing a cheap activator makes it possible for geopolymer concretes to be competitively priced for them to be introduced into new construction. Their use together with recycled demolition aggregates makes it possible to produce a nearly all recycled concrete.

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