

Mechanical Recycling of Automotive Composites for Use as Reinforcement in Thermoset Composites

**Submitted by James Alexander Thomas Palmer,
to the University of Exeter as a thesis
for the degree of Doctor of Philosophy in Engineering
May 2009**

This thesis is available for Library use on the understanding that it is copyright material and that no quotation from the thesis may be published without proper acknowledgement.

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.

.....

Abstract

The aim of this research was to investigate the potential use of recycled glass fibre composite materials as a replacement for virgin reinforcing materials in new thermoset composites. Specifically the closed-loop mechanical recycling of composites used heavily in the automotive sector known as dough and sheet moulding composites, DMC and SMC respectively, are investigated. The recycling of glass reinforced thermoset polymer composite materials has been an area of investigation for many years and composites used in the automotive industry are of particular interest due to legislative and social pressures on the industry.

The mechanical recycling process and then collection of useful fibrous grades of recycled materials, recyclate, by a novel air separation technique were investigated first. The properties of these recyclate fibres were characterised and compared directly with the properties of virgin glass fibres they were to be used to replace. Single fibre tensile tests were employed to compare the strengths of the fibres and single fibre pull-out tests were used to investigate the strength of the interface between the fibres and a polyester matrix. These tests showed the recyclate fibres to be weaker and have a poorer interface with the polyester matrix than the virgin glass fibres. Understanding the properties of the recyclate materials meant their reformulation into new composites could be carefully considered for the production of new high performance materials.

Two grades of the collected recyclate materials were then reformulated in to new DMC and SMC composites, replacing percentages of the virgin glass fibre reinforcement. The mechanical properties of the resulting manufactured composites were characterised throughout for direct comparison against one another and an unmodified control material, using both three-point flexural tests and Charpy impact tests. Through the modification of existing manufacturing techniques and the development of novel production equipment it has been possible to successfully manufacture both DMC and SMC composites with the recyclate materials used to replace virgin glass fibres. Virgin glass fibres have successfully been replaced by recyclate materials without disrupting standard production techniques and with minimal reduction of the mechanical properties of the resulting composites. As the loadings of recyclate materials used were greatly increased both the flexural and impact strengths were significantly degraded and it was found that chemical modification of the composite could be used to improve these formulations. It has been shown that the recyclate materials should be considered and treated as a distinct reinforcing ingredient, separately from the remaining virgin glass fibres.

Publications

Some of the content of this thesis has been published during the course of the research:

J. Palmer, O.R. Ghita, L. Savage, K.E. Evans. *Successful closed-loop recycling of thermoset composites*. Composites Part A: Applied science and manufacturing, 2009. 40(4) p. 490-498.

J. Palmer, O.R. Ghita, L. Savage, K.E. Evans. *Recyclate fibres – matrix interface analysis for reuse in sheet moulding compounds (SMC)*. Proceedings of European Conference on Composite Materials (ECCM 13). 2008. Stockholm, Sweden.

J. Palmer, O.R. Ghita, L. Savage, K.E. Evans. *New automotive composites based on glass and carbon fibre recyclate*. Proceeding of International Conference for Composite Materials (ICCM 17). 2009. Edinburgh, UK.

Acknowledgments

I would like to express my sincere gratitude to my supervisors Dr Oana Ghita and Prof. Ken Evans. For firstly giving me the opportunity to undertake this research and then thanks to their continued support, patience and guidance I was able bring it all together to form this thesis. I would also like to thank Dr Luke Savage for giving me the opportunity to undertake this research and for his assistance and guidance throughout. This research has been part of the RECCOMP project funded by the DTi and several industrial partners. Of the many companies and people involved in the project, particular thanks must go to Ester Wegher, Richard Taylor and Steve Crowther at Menzolit UK for their assistance, for sharing their extensive technical knowledge and repeatedly allowing me to disrupt their place of work. Thanks also to Mike Hartland of Mitras Automotive and Dr Richard Hooper of Sims UK for their help and time. I would like to thank all of my colleagues at Exeter Advanced Technologies for their assistance, patients and friendship over the past three years. Special thanks must go to Dr Mark Beard and Dr Mike Sloan for their invaluable guidance, support and knowledge throughout. Also thanks to Peter Gerry for his incredible skill, hard work and technical expertise, without which most of this research would have been impossible.

Thanks to all of my family for their unquestioning support and encouragement which has enabled me to achieve all that I have. Finally, a very special thank you to my amazing girlfriend, Vicky, without her unwavering patience, support, understanding and love none of this would have ever have been possible.

Contents

1. Introduction.....	22
1.1. Thesis Outline.....	23
2. Literature Review	26
2.1. Composite Materials.....	26
2.2. Need to Recycle.....	27
2.2.1. General	27
2.2.2. End-of-Life Vehicle Directive	27
2.2.3. What does the ELV Directive Mean for Automotive Manufacturers?	28
2.3. Sheet and Dough Moulding Compounds	29
2.3.1. General	29
2.3.2. Material Properties	30
2.4. Raw Materials and Manufacturing	31
2.4.1. Introduction	31
2.4.2. SMC and DMC Material Ingredients.....	31
2.4.2.1. General.....	31
2.4.2.2. Thermosetting Resin	31
2.4.2.3. Styrene	33
2.4.2.4. Low-Profile Additive (LPA).....	33
2.4.2.5. Initiator	34
2.4.2.6. Inhibitor	34
2.4.2.7. Release Agent	34
2.4.2.8. Thickener	35
2.4.2.9. Reinforcing Fibres	35
2.4.2.10. Filler	36
2.4.2.11. Wetting and Dispersion Agents.....	36
2.4.2.12. Pigment.....	36
2.5. Sheet Moulding Compound.....	37
2.5.1. General	37

2.5.2.	Formulation	37
2.5.3.	Manufacturing	38
2.6.	Dough Moulding Compound	40
2.6.1.	General	40
2.6.2.	Formulation	40
2.6.3.	Manufacturing	41
2.7.	Previous Investigations into Recycling Thermoset Composites	42
2.7.1.	General	42
2.7.2.	Thermal Recycling Methods	43
2.7.2.1.	General	43
2.7.2.2.	Energy Recovery or Incineration	43
2.7.2.3.	Fluidised-Bed	44
2.7.2.4.	Pyrolysis	45
2.7.3.	Chemical Recycling	46
2.7.3.1.	General	46
2.7.3.2.	Solvolysis	46
2.7.3.3.	Hydrolysis	46
2.7.4.	Mechanical Recycling	47
2.7.4.1.	General	47
2.7.4.2.	Size Reduction	47
2.7.4.3.	Recyclate Classification	48
2.7.4.4.	Physical Characterisation of Recyclate	49
2.7.4.5.	Recyclate Material Composition	49
2.7.4.6.	Composite Reformulation	50
2.7.5.	Previous Research into Mechanical Recycling	50
2.7.5.1.	General	50
2.7.5.2.	Industrial Recyclate Production	50
2.7.5.3.	Scientific Investigation	51
2.7.6.	Discussion	56
3.	Experimental Techniques	60

3.1.	Introduction	60
3.2.	Recyclate Production.....	60
3.2.1.	Waste Materials.....	60
3.2.2.	Granulation.....	61
3.2.3.	Classification.....	61
3.3.	Recyclate Material Content	61
3.3.1.	Introduction	61
3.3.2.	Thermo-Gravimetric Analysis Method	62
3.3.3.	Burn Off and Acid Digestion Method.....	62
3.4.	Composite Manufacture	63
3.4.1.	Raw Materials	63
3.4.2.	DMC Manufacture	64
3.4.3.	SMC Manufacture.....	65
3.5.	Composite Moulding.....	65
3.5.1.	Introduction.....	65
3.5.2.	Moulding Method	66
3.5.3.	Apparatus	67
3.6.	Test Sample Preparation.....	67
3.6.1.	Introduction.....	67
3.6.2.	Method	68
3.7.	Mechanical Characterisation	69
3.7.1.	Introduction.....	69
3.7.2.	Flexural Testing	69
3.7.2.1.	Introduction.....	69
3.7.2.2.	Experimental Apparatus	70
3.7.2.3.	Experimental Technique.....	70
3.7.2.4.	Calculations	71
3.7.3.	Charpy Impact Tests	71
3.7.3.1.	Introduction.....	71
3.7.3.2.	Experimental Apparatus	72
3.7.3.3.	Experimental Technique.....	73
3.7.4.	Statistical Analysis	73

3.7.5.	Scanning Electron Microscopy	74
3.7.5.1.	General.....	74
3.7.5.2.	Apparatus.....	74
3.7.5.3.	Recyclate Powder	74
3.7.5.4.	Fibres	75
3.7.5.5.	Impact Specimens.....	75
4.	Recyclate Classification Results	76
4.1.	Introduction	76
4.2.	Granulation.....	76
4.2.1.	Introduction.....	76
4.2.2.	Method	76
4.2.3.	Experimental Technique	77
4.3.	Results: Granulation Trials.....	77
4.3.1.	Discussion	79
4.4.	Classification: Recyclate Grades.....	80
4.4.1.	Introduction.....	80
4.4.2.	Air Classification	80
4.4.2.1.	Introduction.....	80
4.4.2.2.	Zig-Zag Classification Method.....	81
4.4.3.	Results: Recyclate Classification.....	84
4.4.4.	Discussion	87
4.5.	Recyclate Material Content.....	87
4.5.1.	Thermo-Gravimetric Analysis Results.....	87
4.5.1.1.	Discussion.....	88
4.5.2.	Results: Recyclate Material Content.....	88
4.5.3.	Discussion	89
4.6.	Particle Shape Analysis	90
4.6.1.	Introduction.....	90
4.6.2.	Method	90
4.6.3.	Results: Particle Shape Analysis.....	93
4.6.3.1.	Particle Area	93

4.6.3.2.	Circularity	94
4.6.3.3.	Curve Length	95
4.6.3.4.	Curve Width.....	96
4.6.4.	Discussion	96
5.	Fibre Testing	98
5.1.	Introduction	98
5.2.	Literature Review	98
5.2.1.	Discussion	102
5.3.	Single Fibre Experimental Methods.....	103
5.3.1.	Fibre Diameter	103
5.3.1.1.	Results: Fibre Diameter	103
5.3.2.	Micro-Tensile Testing.....	104
5.3.2.1.	Apparatus.....	104
5.4.	Single Fibre Tensile Testing.....	105
5.4.1.	Introduction.....	105
5.4.2.	Analysis Method	106
5.4.3.	Experimental Method.....	108
5.4.4.	Results: Single Fibre Tensile Testing	110
5.4.5.	Results: Weibull Analysis.....	112
5.4.6.	Discussion	114
5.5.	Fibre – Matrix Interface Strength.....	116
5.5.1.	Introduction.....	116
5.5.2.	Analysis Method	117
5.5.2.1.	Single Fibre Pull-Out.....	118
5.5.2.2.	Pull-Out Data Analysis	119
5.5.3.	Experimental Method.....	125
5.5.3.1.	Stage 1	126
5.5.3.2.	Stage 2	126
5.5.3.3.	Stage 3	127
5.5.4.	Results: Pull-Out Test.....	129
5.5.5.	Results: Pull-Out Modelling	132

5.5.6.	Results: Scanning Electron Microscopy	133
5.5.7.	Discussion	134
6.	Dough Moulding Compound Trials	138
6.1.	Introduction	138
6.2.	DMC Composite Mixing Time	138
6.2.1.	Introduction	138
6.2.2.	Experimental Manufacturing Method	140
6.2.3.	Results and Discussion: Mixing Time	141
6.2.3.1.	Flexural Testing	141
6.2.3.2.	Impact Testing	144
6.2.4.	Results: Statistical Analysis of Mechanical Results	145
6.2.5.	Results: SEM Images	147
6.2.5.1.	Standard DMC	147
6.2.5.2.	Eight Minutes Mixing	147
6.2.5.3.	Four Minutes Mixing	148
6.2.5.4.	Two Minutes Mixing	149
6.2.6.	Discussion: Mixing Time	150
6.3.	DMC Composite Reformulation	151
6.3.1.	Introduction	151
6.3.2.	Method	152
6.3.3.	Results 10% Replacements	154
6.3.3.1.	Flexural Testing	154
6.3.3.2.	Impact Strength	155
6.3.4.	Results 20% Replacements	156
6.3.4.1.	Introduction	156
6.3.4.2.	Flexural Testing	156
6.3.4.3.	Impact Testing	158
6.3.4.4.	Statistical Analysis	159
6.3.5.	Discussion: Reformulation Method	160
6.4.	DMC Chemical Treatment	164
6.4.1.	Introduction	164

6.4.2.	Experimental Method.....	165
6.4.3.	Results Chemical Treatment	166
6.4.3.1.	Flexural Testing	166
6.4.3.2.	Impact Testing	167
6.4.4.	Statistical Analysis	168
6.4.5.	Discussion: Chemical Treatment	169
6.5.	Overall Discussion.....	169
7.	Sheet Moulding Compound Trials	171
7.1.	Introduction	171
7.2.	SMC Recyclate Distribution Unit	172
7.2.1.	Introduction.....	172
7.2.2.	Machine Design	173
7.3.	Apparatus.....	175
7.4.	SMC Manufacturing Method	176
7.5.	SMC Raw Material.....	178
7.5.1.	Moulding Charge Trials	179
7.6.	Results: Mechanical Characterisation	180
7.6.1.	Flexural Testing	181
7.6.2.	Flexural Modulus	181
7.6.3.	Impact Strength	182
7.6.4.	Statistical Analysis	183
7.6.5.	Discussion	183
7.7.	Automotive Component Moulding Trials	184
7.7.1.	Introduction.....	184
7.7.2.	Method	184
7.7.3.	Results.....	185
7.7.4.	Surface Defects	185
7.7.5.	Part Painting.....	187
7.7.6.	Discussion	188
8.	Overall Conclusions.....	189
9.	Future Work.....	191
10.	Appendix A – Mould Flow Analysis.....	192

11.	Appendix B – Composite Test Data.....	198
12.	Appendix C – Recyclate Distribution Line	213
13.	Bibliography	218

List of Figures

Figure 2.1, Material Break-Down for an Average Passenger Vehicle in 2000 [6].....	28
Figure 2.2, Examples of Automotive SMC Components: (a) Mercedes Tailgate [10], (b) Engine Cover [11].	29
Figure 2.3, Production of Unsaturated Polyester Molecules, (* Marks the Unsaturated Carbon Double Bonds) [16].	32
Figure 2.4, Chemical Structure of Cross-Linking Process During Curing of Polyester Resin [18].	33
Figure 2.5, Schematic Diagram of a Typical SMC Manufacture Production Line.....	39
Figure 2.6, Raw SMC Ply with Orange Thermoplastic Carrier Film.	40
Figure 2.7, The ‘Z’-Blade DMC Mixer Used for this Research.	41
Figure 2.8, Raw DMC Material.	42
Figure 2.9, Previously Investigated Composite Recycling Methods [1].	43
Figure 3.1, SMC Front Fender Section for Granulation.	60
Figure 3.2, Simple Compression Moulding Press [51]......	66
Figure 3.3, The Mould Tool Cavity and Press used for Moulding Test Panels.	67
Figure 3.4, Test Panel Cutting Stencil: F# - Specimen for Flexural Testing, C# - Specimen for Impact Testing.....	68
Figure 3.6, Three-Point Testing Equipment and Sample Set-up.	70
Figure 3.7, Charpy Impact Test Machine and Specimen Set-up.....	72
Figure 4.1, Diagram of a Rotating Hammer-Mill Type Granulator [64].	77
Figure 4.2, Recyclate Produced with a 5 mm Classifier Screen Aperture.	78
Figure 4.3, Recyclate Produced with an 8 mm Classifier Screen Aperture.	78
Figure 4.4, Recyclate Produced with a 10 mm Classifier Screen Aperture.....	79
Figure 4.5, Simple Force Balance Diagram for a Particle in an Airflow.....	81
Figure 4.6, Operating Principle of the Zig-Zag Classifier.	82
Figure 4.7, Illustration of the Zig-Zag Classifier.	82
Figure 4.8, The Three Stages of Zig-Zag Classification and the Resulting Recyclate Grades.....	85
Figure 4.9, SEM Image of the ‘Powder’ Grade of Recyclate.	86
Figure 4.10, TGA of Calcium Carbonate Filler, Polyester Resin and Glass Fibres.	88
Figure 4.11, Material Constituents in Different Recyclate Grades.....	89
Figure 4.12, Processing of Recyclate Images for Particle Analysis.	91

Figure 4.13, Dimensions Measured of Recyclate Particles.....	92
Figure 4.14, Validation of Recyclate Particles Measured by the Software.	93
Figure 4.15, Histogram of Area for the Fine and Coarse Recyclate Particles.	94
Figure 4.16, Histogram of Circularity for the Fine and Coarse Recyclate Particles.....	95
Figure 4.17, Histogram of Curve Length for the Fine and Coarse Recyclate Particles..	95
Figure 4.18, Histogram of Curve Width for the Fine and Coarse Recyclate Particles..	96
Figure 5.1, Schematic Diagram of a Unidirectional Reinforced Composite [13].....	99
Figure 5.2, Diagram of (a) Deformation Around a Short Fibre in a Matrix with Tensile Load Applied Parallel to Fibre (b) Variation of Tensile Stress in the Fibre and Shear Stress at Fibre-Matrix Interface [76].	101
Figure 5.3. SEM Image of (a) Recyclate and (b) Virgin Glass Fibres.....	103
Figure 5.4, Micro-Tensile Testing Rig: (a) Load Cell, (b) LDVT, (c) Microscope and (d) Adjustable Light Source.	105
Figure 5.5, Mounted Single Fibre Tensile Test Specimens.	109
Figure 5.6, Typical Single Fibre Tensile Test Load-Displacement Plot.....	111
Figure 5.7, Weibull Plot for Both Fibre Types, Recyclate (o) and Virgin (Δ) Glass, at Gauge Length 5 mm.	112
Figure 5.9, Weibull Plot for Both Fibre Types, Recyclate (o) and Virgin (Δ) Glass, at Gauge Length 15 mm.	113
Figure 5.10, Schematic Diagrams of Interfacial Test Methods; (a) Droplet Micro- debond, (b) Pull-out, (c) Fragmentation and (d) Indentation [93].....	118
Figure 5.11, Typical Load - Displacement Failure Mode Plots for Pull-Out Tests.....	120
Figure 5.12, Single Fibre Pull-Out Test Specimen Set-Up.....	125
Figure 5.13, Pull-Out Sample Preparation Stage 1: (a) Mould Tool and (b) Free Fibres in Epoxy Pucks.	126
Figure 5.14, Pull-Out Sample Preparation Stage 2: Schematic Diagram of Embedding Fibre in Polyester Resin and Image of Rig Used.....	127
Figure 5.15, Sample Holder for Pull-Out Specimens.	128
Figure 5.16, Image of Successful Single Fibre Pull-out Test Seen Through Microscope.	128
Figure 5.17, Maximum Debonding Load Versus Embedded Length for Virgin and Recyclate Fibres.	129
Figure 5.18, Load Displacement Plots for the Virgin Fibre Pull-out Tests and Different Failure Modes.....	130

Figure 5.19, Load Displacement Plots for the Recyclate Fibre Pull-out Tests and Different Failure Modes.	131
Figure 5.20, Histogram of Failure Modes for Pulled-out Virgin and Recyclate Fibres.	131
Figure 5.21, Average Shear Stress vs. Embedded Length for Pulled-Out Virgin Glass Fibres (Experimental Results o and Lawrence’s Model —).	132
Figure 5.22, Average Shear Stress vs. Embedded Length for Pulled-Out Recyclate Glass Fibres (Experimental Results o and Lawrence’s Model —).	133
Figure 5.23, Fibre Surface of Two Recyclate Fibres Embedded Length after Pull-Out Testing.	134
Figure 5.24, Either Side of a Recyclate Fibre after Pull-Out, (a) Free Length of Fibre not Embedded and (b) Embedded Section of Fibre.	134
Figure 5.25, Plot of Failure Mode against Embedded Length for Virgin (Δ) and Recyclate (o) Fibres.	135
Figure 6.1, Mixing Procedures for the Reinforcement in DMC Composites Containing the Recyclate Materials: (1) Increased Mixing, (2) Normal Mixing and (3) Reduced Mixing Process.	141
Figure 6.2, Typical Stress-Strain Curve for a Tested DMC Sample.	142
Figure 6.3, The Effect of Mixing Time on the DMC Flexural Strength.	143
Figure 6.4, The Effect of Mixing Time on the DMC Flexural Modulus.	144
Figure 6.5. The Effect of Mixing Time on the DMC Impact Strength.	145
Figure 6.6. Fracture Surfaces of Standard DMC after Charpy Impact Testing.	147
Figure 6.7, Fracture Surfaces of 10%wt Recyclate DMC, Mixed for 8 Minutes, after Charpy Impact Testing: (a) Fine Recyclate and (b) Coarse Recyclate.	148
Figure 6.8, Fracture Surfaces of 10%wt Recyclate DMC, Mixed for 4 Minutes, after Charpy Impact Testing: (a) Fine Recyclate and (b) Coarse Recyclate.	149
Figure 6.9, Fracture Surfaces of 10%wt Recyclate DMC, Mixed for 2 Minutes, after Charpy Impact Testing: (a) Fine Recyclate and (b) Coarse Recyclate.	149
Figure 6.10, The Effect of Reformulation Method on the DMC Flexural Strength at 10% Replacement.	154
Figure 6.11, The Effect of Reformulation Method on the DMC Flexural Modulus at 10% Replacement.	155
Figure 6.12, The Effect of Reformulation Method on the DMC Impact Strength at 10% Replacement.	156

Figure 6.13, The Effect of Reformulation Method on the DMC Flexural Strength at 20% Replacement.	157
Figure 6.14, The Effect of Reformulation Method on the DMC Flexural Modulus at 20% Replacement.	158
Figure 6.15, The Effect of Reformulation Method on the DMC Impact Strength at 20% Replacement.	159
Figure 6.16, Percentage Change and Trend Lines for DMC Composite's Flexural Strength with Increased Recyclate Content.	161
Figure 6.17, Percentage Change and Trend Lines for DMC Composite's Flexural Modulus with Increased Recyclate Content.	162
Figure 6.18, Percentage Change and Trend Lines for DMC Composite's Impact Strength with Increased Recyclate Content.	163
Figure 6.19, The Effect of Wetting Agent on the DMC Flexural Strength.	166
Figure 6.20, The Effect of Wetting Agent on the DMC Flexural Modulus.	167
Figure 6.21, The Effect of Wetting Agent on the DMC Impact Strength.	168
Figure 7.1, SMC Doctor Box Spreading Paste Layer on Carrier Film.	172
Figure 7.2, SMC Manufacturing Line Glass Fibre Feed System: (a) Fibre Rovings in Storage and (b) the Strands Fed through Pipes to the Chopping Unit above Production Line.	173
Figure 7.3, Design Images of the Recyclate Distribution Machine.	174
Figure 7.4, The SMC Pilot Production Line at Menzolit UK.	175
Figure 7.5, The SMC Distribution Machine In Place Over the SMC Pilot Plant.	176
Figure 7.6, Reinforcing Fibre Layer Effect in New SMC Raw Materials.	178
Figure 7.7, Raw SMC Sheet (a) Standard Material and (b) Containing Recyclate Materials.	179
Figure 7.8, Layering of Mould Charge to Position Recyclate Fibre Layer on (a) Outside or (b) Inside of Panel.	180
Figure 7.9, The Effect of Recyclate Reinforcement on the SMC Flexural Strength. ...	181
Figure 7.10, The Effect of Recyclate Reinforcement on the SMC Flexural Modulus. ...	182
Figure 7.11, The Effect of Recyclate Reinforcement on the SMC Impact Strength. ...	182
Figure 7.12, Automotive Rear Spoiler Sections Moulded from Fine Recyclate Reinforced SMC.	185
Figure 7.13, Surface Defects on SMC Moulding Viewed from Above (a) Before and (b) After Resin Burn Off.	186

Figure 7.14, Surface Defects on SMC Moulding Viewed from the Side (a) Before and (b) After Resin Burn Off.	186
Figure 7.15, SEM Image of Defect in SMC Caused by Clump of Recyclate Materials.	187
Figure 7.16, Painted SMC Mouldings and Bumps on the Surface.	188

List of Tables

Table 2.1, An Example of a Typical SMC Paste Formulation [14].....	38
Table 2.2, Example of a Basic DMC Formulation [14].....	41
Table 2.3, ERCOM Recyclate Grades [3].....	51
Table 3.4, Types of Raw Materials Used for SMC and DMC Composite Manufacture in this Investigation.....	64
Table 4.1, Statistical Results from Recyclate Particle Measurements.	96
Table 5.1, Results of Fibre Diameter Measurements.....	104
Table 5.2, Average Results from Tensile Testing of Virgin and Recyclate Fibres.	111
Table 5.3, Values of the Weibull Parameters from Single Fibre Tensile Tests at Each Gauge Length.	114
Table 6.1, Statistical Comparison of the Results from Mixing Time Investigation, significant P-Values are highlighted by ‘*’.....	146
Table 6.2, Between Group Comparison of Results from Mixing Time Investigations, significant P-Values are highlighted by ‘*’.....	146
Table 6.3, The Weights of Major Material Constituents in DMC for Different Reformulations.	153
Table 6.4, Statistical Comparison of the Results from Reformulation Investigation, significant P-Values are highlighted by ‘*’.....	160
Table 6.5, Between Group Comparisons of Results from Reformulation Investigations.	160
Table 6.6 Statistical Comparisons of the Results from Chemical Treatment Investigation, significant P-Values are highlighted by ‘*’.....	168
Table 6.7, Between Group Comparisons of Results from Chemical Treatment Investigations.....	169
Table 7.1, Calculation of the Production Settings for a 20% of Virgin Glass Fibres in a SMC Material.	177
Table 7.2, Statistical Comparison of the Results from SMC Investigations, Significant P-Values are highlighted by ‘*’.....	183

Nomenclature

Symbol	Dimension	Description
V	(mm s ⁻¹)	Cross head speed
ε'	(s ⁻¹)	Rate of applied strain
l_s	(m)	Sample span
h	(m)	Specimen thickness
σ_F	(Pa)	Flexural stress
F_{\max}	(N)	Maximum force
b	(m)	Specimen width
s	(m)	Deflection
E_F	(N m ⁻²)	Flexural modulus
a_{cU}	(kJ m ⁻²)	Charpy impact strength
W_b	J	Energy at break
W_f	J	Frictional energy losses
F_D	(N)	Drag force
F_L	(N)	Lift force
F_B	(N)	Buoyancy force
C_D	-	Drag coefficient
u	(m s ⁻¹)	Velocity of particle relative to fluid
A_p	(m ²)	Cross-sectional area of particle normal to the direction of the drag force
ρ	(Kg m ⁻³)	Fluid density
L_c	(N)	Load applied to composite
L_m	(N)	Load applied to matrix
L_f	(N)	Load applied to fibre
A_f	(m ²)	Fibre surface area
σ_c	(Pa)	Stress on composite
σ_f	(Pa)	Stress on fibre
σ_m	(Pa)	Stress on matrix

σ^*	(Pa)	Failure Stress
V_f	-	Fibre volume fraction
E_c	(N m ⁻²)	Composite Young's Modulus
E_f	(N m ⁻²)	Fibre Young's modulus
E_m	(N m ⁻²)	Matrix Young's modulus
ε_f^*	-	Fibre failure strain
σ_f^*	(Pa)	Fibre failure strength
ε	-	Strain
l	(m)	Fibre length
x	(m)	Distance from fibre end
r	(m)	Fibre radius
τ_{IF}	(Pa)	Interfacial shear stress
R	(m)	Radius of matrix
l_c	(m)	Critical fibre length
$P_f(\sigma_f)$	-	Probability of fibre failure
m	-	Weibull modulus or shape parameter
σ	(Pa)	Stress
σ_0	(Pa)	Weibull scale parameter
l_0	(m)	Largest fibre length that contains only one flaw
n	-	Number of data points
i	-	Rank of a data point
P_i	-	Probability of failure of i 'th data point
$\langle \sigma \rangle$	(Pa)	Average fracture stress
Γ	-	The gamma function
τ_d	(Pa)	Critical value of interfacial shear stress above which debonding occurs
L_d	(N)	Load at debonding
l_e	(m)	Embedded fibre length
μ_m	(Pa)	Matrix shear modulus

G_i	(J m ⁻²)	Interfacial fracture toughness
ν_m	-	Matrix Poission's ratio
ν_f	-	Fibre Poission's ratio
z	(m)	Debonded fibre length
q_o	(Pa)	Residual clamping stress
μ	-	Friction at interface
σ_d	(Pa)	Maximum debond stress
σ_i	(Pa)	Initiation of debonding stress
σ_{fr}	(Pa)	Frictional pull-out stress
l_{free}	(m)	Free fibre length
X	(m)	Extension
C	(m N ⁻¹)	True fibre compliance
C_a	(m N ⁻¹)	Recorded fibre compliance
C_s	(m N ⁻¹)	System compliance
d_f	(m)	Diameter of fibre