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Engineering**



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Nottingham**

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**INVESTIGATION ON THE USE OF
RECYCLED PLASTICS IN THE PRODUCTION
OF AUTOMOBILE PARTS**

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Abstract

It has been reported that the use of recycled plastics is economical and environmentally-friendly. However, despite studies suggesting that properties of recycled plastics can be improved upon, there is very limited research which focuses on the application of recycled plastics in demanding industrial applications. Disappointingly recycled plastics have been almost totally neglected in the automobile production industry.

This research investigates the use of recycled plastics in the production of automobile parts, starting by identifying of gap in knowledge between academic research and industrial practice. The only existing research into using recycled plastics in automobile production was focussed on closed-loop recycling. In this study, a review of current recycling practice was made with typical products analyzed in detail. It was found the mechanical, thermal and flammability properties of recycled plastics suffered noticeable deteriorations, while rheological properties were altered. Contaminants in recycled plastics were identified as elemental analysis was performed.

At first, three representative fillers, i.e., talcum powder (talc),

glass fibre (GF) and organically montmorillonite (OMMT), were selected to mix with recycled plastics to promote the desired properties. Their effects were compared. Experiments showed that GF was the most effective filler in improving most of the mechanical properties, and OMMT was the most effective in promoting flexural properties with the least loading. Talc and OMMT improved both the rheological and flammability performance of recycled plastics. For the first time, the recycled PP/talc composites were found to maintain better mechanical properties in ageing and reprocessing tests compared with virgin composites. At this initial stage, the effects of different coupling agents in compatilising recycled plastics and fillers were identified.

For the study, four data analysis techniques were selected and used to predict, optimise and evaluate the formulae and procedures of recycled plastics: grey model (GM), Taguchi method (TM), principal component analysis (PCA) and cluster analysis (CA). Among these techniques, GM was successfully applied in predicting the effect of adding recycled plastic to virgin plastic based limited trials. TM was successfully applied in optimising injection moulding conditions when using recycled

plastics. PCA and CA were successfully applied in analysis and evaluation of the performance of recycled plastics.

This research found that with the addition of certain additives and the application of mathematical methods, recycled plastics and their corresponding composites showed potential in industrial applications, since some properties of these composites were more favorable than those of industrial composites currently being used in automobile industry. The novel methodology developed in this research was successfully applied in the enhancement of mechanical properties of recycled plastics, an outcome which represented a crucial step towards large-scale utilization of recycled plastics in the production of automobile parts.

Affirmation

I hereby declared that all the work contained in this research is my own work (unless acknowledged otherwise) and has not been previously submitted for any other degree.

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Contents

Abstract	i
Affirmation	v
Acknowledgments	v
Contents	vii
List of Figures	xiii
List of Tables	xxi
List of Equations	xxiii
Abbreviations	xxv
Chapter 1 Introduction	1
1.1 Background	1
1.1.1 Introduction of Plastics	1
1.1.1.1 Definition of Plastics.....	1
1.1.1.2 Classification of Plastics.....	3
1.1.1.3 Development of Plastics	6
1.1.2 Plastics in Automobiles	7
1.1.2.1 Percentages of Plastics in Automobiles.....	8
1.1.2.2 Plastic Parts of Automobiles.....	11
1.1.3 Recycled Plastics and Recycling.....	14
1.1.3.1 Demand for Recycled Plastics.....	14
1.1.3.2 Current Recycling Practices.....	16
1.1.3.3 Separation of Plastics	24
1.1.4 Merits and Current Situation of using Recycled Plastics..	27
1.2 Aims and Objectives	31
1.3 Research Strategy	33
Chapter 2 Literature review	37
2.1 Ageing and Degradation of Plastics	37
2.1.1 Mechanisms of Thermal Degradation.....	40
2.1.2 Degradation during Extrusion	43
2.1.3 Degradation during Injection Moulding	44
2.1.4 Photo-oxidation.....	46
2.2 Modification and Improvement	49
2.2.1 Fillers for Plastics	50
2.2.1.1 Natural Fillers.....	50
2.2.1.2 Mineral Fillers.....	54
2.2.1.3 Nano-fillers	56
2.2.1.4 Fibres	64
2.2.2 Reactive Processes	65
2.2.3 Restabilisation and Compatibilisation.....	68

2.2.3.1 Restabilisation.....	68
2.2.3.2 Compatibilisation	71
2.2.4 Optimisation Tools.....	72
2.3 Close-looped Recycling of Automobile Plastic Parts	73
2.3.1 Collision Bumpers.....	74
2.3.2 Dashboard.....	78
2.3.3 Fuel Tank.....	79
2.3.4 Other Components.....	80
2.4 Other Properties of Plastic for Manufacturing	81
2.4.1 Reprocessing	81
2.4.2 Flammability.....	83
2.5 Summary of Current Study on Recycled Plastics	85
2.6 Knowledge Gap	87
2.7 Selected Fillers for Recycled Plastics	90
2.8 Selected Tools for Recycled Plastics	91
2.8.1 Prediction Tool for Recycled Plastics.....	92
2.8.1.1 Selection of Grey Model	92
2.8.1.2 Introduction to Grey Model.....	94
2.8.1.3 Grey Model Techniques	96
2.8.2 Optimisation Tool for Recycled Plastics.....	99
2.8.2.1 Selection of Taguchi Method.....	99
2.8.2.2 Introduction to Taguchi Method	101
2.8.2.3 Taguchi Method Procedure.....	103
2.8.3 Evaluation Tool	105
2.8.3.1 Selection of Principal Component Analysis and Cluster Analysis.....	105
2.8.3.2 Introduction of Principal Component Analysis and Cluster Analysis.....	107
2.8.3.3 Analysis Procedure.....	109
Chapter 3 Experimental	117
3.1 Introduction	117
3.2 Experimental Procedures.....	117
3.2.1 Experimental Analysis of Plastics	118
3.2.1.1 Mechanical Properties	120
3.2.1.2 Rheological Properties	129
3.2.1.3 Thermal Properties.....	131
3.2.1.4 Ash Content in Plastics.....	133
3.2.1.5 Flammability	134
3.2.2 Selection of Materials.....	136
3.2.2.1 Base Materials.....	136
3.2.2.1 Fillers and Additives	142
3.2.3 Sampling Procedure	145
3.2.3.1 Extrusion.....	145
3.2.3.2 Drying	149

3.2.3.3 Injection Moulding	149
3.2.3.4 Hot Pressing	155
3.3 Compositions of Materials	157
3.3.1 Initial Experimental Investigation.....	157
3.3.2 Compositions for Filler Addition.....	159
3.3.2.1 PP/Talc Compositions.....	159
3.3.2.2 PP/GF Compositions	161
3.3.2.3 PP/OMMT Compositions	164
3.3.3 Compositions for Ageing	165
3.3.4 Compositions for Reprocessing.....	166
3.3.5 Compositions for flammability	167
3.3.6 Compositions for Application of Tools.....	168
3.3.6.1 Compositions for Grey Model Application	168
3.3.6.2 Compositions for Taguchi Method Application.....	170
3.4 Summary	171
Chapter 4 Charateristation of Typical Recycled Plastics in	
Chinese Market	173
4.1 Introduction	173
4.2 Performance of Recycled Plastics	173
4.2.1 Mechanical Results.....	173
4.2.2 Rheological Results.....	177
4.2.3 Thermal Results.....	180
4.2.4 Ash Content Results.....	182
4.3 Assessments of Recycled Plastics	183
4.3.1 Merits of Recycled Plastics.....	183
4.3.2 Drawbacks of Recycled Plastics	185
4.3.3 Possible Solutions to Improve Recycled Plastics.....	187
Chapter 5 Fillers for Improving Recycled Plastics	189
5.1 Introduction	189
5.2 Addition of Talc in Recycled Plastics.....	190
5.2.1 Mechanical Results.....	191
5.2.2 Commentary	192
5.3 Addition of GF in Recycled Plastics	195
5.3.1 Machanical Tests Results	196
5.3.2 Commentary	198
5.4 Addition of OMMT in Recycled Plastics	200
5.4.1 Machanical Results and Discussion	201
5.4.2 Rheological Results and Discussion.....	204
5.5 Summary of Filler Addition Experiments	206
5.5.1 Improvement Assessment	207
5.5.2 Comparison with Virgin Material	210
5.6 Further Work	213
Chapter 6 Durability Tests.....	215

6.1 Introduction	215
6.2 Ageing Tests for Recycled Plastics.....	217
6.2.1 Room Condition Ageing Tests	217
6.2.1.1 Treatment	218
6.2.1.2 Results and Discussion.....	219
6.2.2 Accelerated Weathering for Recycled Plastics	228
6.2.2.1 Treatment	228
6.2.2.2 Results and Discussion.....	231
6.3 Effects of Reprocessing on Recycled Plastics.....	235
6.3.1 Reprocessing Cycles	235
6.3.1.1 Extrusion Cycles.....	235
6.3.1.2 Injection Moulding Cycles.....	235
6.3.2 Results and Discussion.....	236
6.3.2.1 Effects of Multiple Reprocessing	236
6.3.2.2 Comparison of Effects of Recycled Composites	244
6.4 Summary.....	246
Chapter 7 Flammability Tests for Recycled Plastics	249
7.1 Introduction	249
7.2 Results and Discussion.....	249
7.2.1 Effects of Recycled Content.....	249
7.2.2 Effects of Fillers.....	251
7.2.2.1 Influence of Talc Addition on Flammability.....	251
7.2.2.2 Influence of OMMT Addition on Flammability	254
7.3 Summary.....	257
Chapter 8 Application of Prediction, Optimisation and	
Evaluation Techniques of Recycled Plastics	259
8.1 Introduction	259
8.2 Application of Grey Model.....	260
8.2.1 Procedure of Application.....	261
8.2.2 Data Check Procedure	262
8.2.3 Results and Discussion.....	263
8.2.3.1 Curve Simulation by Grey Model.....	263
8.2.3.2 Curve Prediction by Grey Model.....	267
8.2.4 Verification of Grey Model on ABS	272
8.2.4.1 Simulation Set on ABS	272
8.2.4.1 Prediction Set on ABS.....	274
8.3 Utilisation of the Taguchi Method to Optimise Processing	
Parameters for Recycled PP.....	277
8.3.1 Selection of Processing Parameters	278
8.3.2 Results and Analysis.....	280
8.3.2.1 Verification of Selected Processing Parameters	280
8.3.2.2 Taguchi Optimisation.....	283
8.3.3 Verification of Taguchi Method	292

8.3.3.1 Verification of Optimal Chosen Processing Parameters	292
8.3.3.2 Verification of Tagchi Method on PP/talc Composites	295
8.4 Principal Component Analysis and Cluster Analysis.....	300
8.4.1 Classification by Cluster Analysis.....	300
8.4.2 Evaluation by Principal Component Analysis.....	305
8.4.2.1 Composite Evaluation.....	305
8.4.2.2 Procedure Evaluation.....	311
8.5 Summary.....	315
Chapter 9 Conclusion and Future Work	317
9.1 Conclusion	317
9.2 Future Work	322
References.....	326
Appendix	i

List of Figures

Figure 1-1 Main components of the global trade in recovered plastics	13
Figure 1-2 China consumption of recycled plastics	14
Figure 1-3 Plastic scarp distribution centre in a port of Taizhou	16
Figure 1-4 Plastic scraps sorting	16
Figure 1-5 Work flow of a small plastic recycling plant in Guangdong	20
Figure 1-6 Example of a mixed plastic recycling plant in Ningbo	23
Figure 1-7 Comparison of environmental load of material production between bumper material and splash-shield material (per 1 kg)	28
Figure 1-8 Comparison of the total effect of reductions in the environmental load among different recycling scenarios	28
Figure 1-9 Structure of this research	34
Figure 2-1 Impact strength of rPBT nanocomposites containing different nanoparticles	60
Figure 2-2 Mechanical properties of rPP/CNTs nanocomposites	64
Figure 2-3 Processes and technologies used to recycle bumper	76
Figure 2-4 Paint-coated PP bumpers modifying process	77
Figure 2-5 Schematic diagram of polymer burning	85
Figure 3-1 Typical stress/strain curves	124
Figure 3-2 Flexural test starting position	127
Figure 3-3 Typical curves of flexural stress σ_f , versus flexural strain ε_f , and deflection s	127
Figure 3-4 EPS30R (VPP1, left), PPB-MO2-V (VPP2, mid) and K8303 (VPP3, right) pellets	137
Figure 3-5 Grey recycled PP (RPP1, left) and black recycled PP (RPP2, right)	139
Figure 3-6 A5132TB12378L (Pret PP, left) and APO-4004HMB001 (Kinghfa PP, right) pellets	140
Figure 3-7 PA707K pellets	141
Figure 3-8 Recycled ABS pellets	142
Figure 3-9 Talc	142
Figure 3-10 Glass fibre	143
Figure 3-11 OMMT	144
Figure 3-12 MAPP	145
Figure 3-13 High-speed mixer	146
Figure 3-14 Kangrun KRSHJ-20 twin-screw extruder	146

Figure 3-15 Blended PP pellets	147
Figure 3-16 Haitian MA1200/370 injection moulding machine	150
Figure 3-17 Injection moulded test specimens, made from virgin (white, VPP1) and recycled PP (black, RPP2)	151
Figure 3-18 Dumbbell tensile specimens	151
Figure 3-19 Injection moulded PP/talc test specimens based on VPP1	152
Figure 3-20 Injection moulded PP/GF test specimens based on VPP1	153
Figure 3-21 Examples of injection moulded ABS specimens	155
Figure 3-22 Vulcanizing machine, model ZG-20T	156
Figure 3-23 Manual cutting sampler	157
Figure 3-24 Sample cutting procedure	157
Figure 4-1 Tensile Modulus (MPa) against percentage of VPP1	174
Figure 4-2 Tensile Strength (MPa) against percentage of VPP1	174
Figure 4-3 Yield Strength (MPa) against percentage of VPP1	174
Figure 4-4 Elongation at Break (%) against percentage of VPP1	175
Figure 4-5 Flexural Modulus (MPa) against percentage of VPP1	175
Figure 4-6 Flexural Strength (MPa) against percentage of VPP1	175
Figure 4-7 Charpy Impact Strength (kJ m^{-2}) against percentage of VPP1	176
Figure 4-8 MFI (measured by g 10 min^{-1} under load of 2.16 kg at 230°C) against percentage of VPP1	178
Figure 4-9 Shear Viscosity against Shear Rate	179
Figure 4-10 TGA plot: weight loss percentage (%) versus temperature ($^{\circ}\text{C}$) for the four PP materials recorded at a heating rate of $10^{\circ}\text{C min}^{-1}$ under room atmosphere	180
Figure 4-11 TDL ($^{\circ}\text{C}$) against percentage of VPP1	181
Figure 5-1 Shear Viscosity against Shear Rate of recycled PP based OMMT composites (effects of different OMMT content)	205
Figure 5-2 Shear Viscosity against Shear Rate of virgin PP based OMMT composites (effects of different MAPPs)	206
Figure 5-3 Shear Viscosity against Shear Rate of recycled PP based OMMT composites (effects of different MAPPs)	206
Figure 6-1 Tensile Modulus (MPa) of blends of VPP1 and	219

RPP2 under room condition	
Figure 6-2 Tensile Strength (MPa) of blends of VPP1 and RPP2 under room condition	220
Figure 6-3 Yield Strength (MPa) of blends of VPP1 and RPP2 under room condition	220
Figure 6-4 Flexural Modulus (MPa) of blends of VPP1 and RPP2 under room condition	220
Figure 6-5 Flexural Strength (MPa) of blends of VPP1 and RPP2 under room condition	221
Figure 6-6 Charpy Impact Strength (kJ m^{-2}) of blends of VPP1 and RPP2 under room condition	221
Figure 6-7 The moulds and the directions of their flow-passages as indicated by red arrows	224
Figure 6-8 Direction of flexural testing force applied on specimens	225
Figure 6-9 The moulds in injection moulding machine and the direction of packing pressure applied on specimens as indicated by blue arrows	226
Figure 6-10 Tensile Modulus (MPa) against days of ageing under room condition	226
Figure 6-11 Tensile Strength (MPa) against days of ageing under room condition	227
Figure 6-12 Yield Strength (MPa) against days of ageing under room condition	227
Figure 6-13 The freeze/thaw cycles used	230
Figure 6-14 Tensile Modulus (MPa) against percentage of VPP1 under accelerated weathering	231
Figure 6-15 Tensile Strength (MPa) against percentage of VPP1 under accelerated weathering	231
Figure 6-16 Yield Strength (MPa) against percentage of VPP1 under room accelerated weathering	232
Figure 6-17 Shredded plastics	236
Figure 6-18 Tensile Modulus (MPa) against number of extrusion cycles	237
Figure 6-19 Tensile Strength (MPa) against number of extrusion cycles	237
Figure 6-20 Yield Strength (MPa) against number of extrusion cycles	237
Figure 6-21 Elongation at Break (%) against number of extrusion cycles	238
Figure 6-22 Flexural Modulus (MPa) against number of extrusion cycles	238
Figure 6-23 Flexural Strength (MPa) against number of extrusion cycles	238

Figure 6-24 TDL ($^{\circ}\text{C}$) against number of extrusion cycles	239
Figure 6-25 Shear viscosity plot of multiple extrusions	243
Figure 6-26 Tensile Modulus (MPa) against number of reprocessing	244
Figure 6-27 Tensile Strength (MPa) against number of reprocessing	245
Figure 6-28 Yield Strength (MPa) against number of reprocessing	245
Figure 7-1 Flammability Properties against percentage of VPP2	250
Figure 7-2 Burning Rate (mm min^{-1}) against percentage of talc	252
Figure 7-3 Ignition Time (s) against percentage of talc	252
Figure 7-4 Burning Rate (mm min^{-1}) against percentage of OMMT	254
Figure 7-5 Ignition Time (s) against percentage of OMMT	254
Figure 8-1 Tensile Modulus (MPa) against percentage of VPP1 in simulation set	263
Figure 8-2 Tensile Strength (MPa) against percentage of VPP1 in simulation set	264
Figure 8-3 Yield Strength (MPa) against percentage of VPP1 in simulation set	264
Figure 8-4 Flexural Modulus (MPa) against percentage of VPP1 in simulation set	264
Figure 8-5 Flexural Strength (MPa) against percentage of VPP1 in simulation set	265
Figure 8-6 Charpy Impact Strength (kJ m^{-2}) against percentage of VPP1 in simulation set	265
Figure 8-7 Tensile Modulus (MPa) against percentage of VPP1 in prediction set	267
Figure 8-8 Tensile Strength (MPa) against percentage of VPP1 in prediction set	268
Figure 8-9 Yield Strength (MPa) against percentage of VPP1 in prediction set	268
Figure 8-10 Flexural Modulus (MPa) against percentage of VPP1 in prediction set	268
Figure 8-11 Flexural Strength (MPa) against percentage of VPP1 in prediction set	269
Figure 8-12 Charpy Impact Strength (kJ m^{-2}) against percentage of VPP1 in prediction set	269
Figure 8-13 Tensile Modulus (MPa) against percentage of virgin ABS in simulation set	272
Figure 8-14 Tensile Strength (MPa) against percentage of virgin ABS in simulation set	273

Figure 8-15 Flexural Modulus (MPa) against percentage of virgin ABS in simulation set	273
Figure 8-16 Flexural Strength (MPa) against percentage of virgin ABS in simulation set	273
Figure 8-17 Tensile Modulus (MPa) against percentage of virgin ABS in prediction set	275
Figure 8-18 Tensile Strength (MPa) against percentage of virgin ABS in prediction set	275
Figure 8-19 Flexural Modulus (MPa) against percentage of virgin ABS in prediction set	275
Figure 8-20 Flexural Strength (MPa) against percentage of virgin ABS in prediction set	276
Figure 8-21 Densities (g cm^{-3}) against percent of VPP3	280
Figure 8-22 TGA plot: weight loss percentage (%) versus temperature ($^{\circ}\text{C}$) for the four PP materials recorded at a heating rate of $10^{\circ}\text{C min}^{-1}$ under room atmosphere	281
Figure 8-23 S/N ratios against processing parameters for tensile strength	284
Figure 8-24 S/N ratios against processing parameters for yield strength	285
Figure 8-25 S/N ratios against processing parameters for flexural modulus	285
Figure 8-26 S/N ratios against processing parameters for flexural strength	285
Figure 8-27 S/N ratios against processing parameters for impact strength	286
Figure 8-28 S/N ratios against processing parameters for tensile strength	288
Figure 8-29 Clustering of the talc group	302
Figure 8-30 Clustering of the GF group	304
Figure 8-31 Clustering of the OMMT group	305

List of Tables

Table 1-1 Examples of plastics classified by crystallization behaviours	5
Table 1-2 Characteristics for classifications and examples	6
Table 1-3 Chinese automobile models' total mass, plastics mass and their percentage	10
Table 1-4 Common plastic auto parts, their requirements and types	12
Table 1-5 Identification codes	24
Table 1-6 PPs' price statistics in China's markets (measured in RMB per ton)	27
Table 2-1 Automobile parts those are recycled or reused from ELVs in common practices	73
Table 3-1 Dimension of Type 1B dumbbell specimen (mm)	151
Table 3-2 Composition (wt%) of PP materials	159
Table 3-3 Compositions of the talc/PP composites (wt%)	161
Table 3-4 Compositions of the GF/PP composites (wt%)	163
Table 3-5 Compositions of the OMMT/PP composites (wt%)	165
Table 3-6 Compositions of the PP blends and PP/talc composites for Ageing Tests (wt%)	166
Table 3-7 Compositions of the PP and talc/PP composites for Reprocessing Tests (wt%)	167
Table 3-8 Compositions of the Materials for Flammability Tests (wt%)	168
Table 3-9 Composition of the PP blends for Application of GM (wt%)	169
Table 3-10 Composition of ABS materials for Verification of GM (wt%)	170
Table 3-11 Composition of PP materials for Application of TM (wt%)	170
Table 3-12 Compositions of the talc/PP composites for Verification of TM (wt%)	171
Table 4-1 Selected mixture weight percentages (wt%) matrix for Shear Viscosity Test using RH2200 capillary rheometer	179
Table 4-2 Ash percentages	182
Table 4-3 Metal content in the ashes (wt%) obtained by ICP-MS and AAS	182
Table 4-4 Performance of recycled plastics, expressed in PR (%)	184
Table 4-5 Performances of industrial composites and comparison against recycled plastics	186
Table 5-1 Experimental results of PP/talc composites	192

Table 5-2 Experimental results of PP/GF composites	197
Table 5-3 Experimental results of PP/OMMT composites	202
Table 5-4 <i>IRs</i> of recycled PP by the addition of three fillers (%)	208
Table 5-5 Average <i>IRPLs</i> of recycled PP by the addition of three fillers (%)	210
Table 5-6 <i>PRs</i> of recycled PP by the addition of three fillers (%)	212
Table 6-1 <i>DRs</i> of tensile properties for blends based on VPP1 and talc-filled composites under room condition for 90 days (%)	228
Table 6-2 Average <i>DRs</i> of tensile properties for blends based on VPP1 (%)	232
Table 6-3 <i>DRs</i> of Strengths for blends based on VPP1 and talc-filled composites under accelerated weathering (%)	234
Table 6-4 <i>DRs</i> of some properties during extrusion cycles (% , comparing with the 1st process)	241
Table 7-1 <i>DRs</i> of ignition time compared with virgin PP (%)	251
Table 7-2 <i>IRs</i> of ignition time compared with original PP by talc (%)	253
Table 7-3 <i>IRs</i> of ignition time comparing to original PP by OMMT (%)	257
Table 8-1 <i>AERs</i> of each tested property in simulation	266
Table 8-2 <i>AERs</i> , <i>ASERs</i> and <i>APERs</i> of prediction	270
Table 8-3 <i>AERs</i> of simulation	274
Table 8-4 <i>AERs</i> , <i>ASERs</i> and <i>APERs</i> of prediction	276
Table 8-5 Processing parameters and levels	279
Table 8-6 L9 (3 ⁴) OA used in the experiment	280
Table 8-7 S/N responses of tensile strength (dB)	283
Table 8-8 Optimal conditions within the chosen levels	291
Table 8-9 S/N responses of verification test according to Table 8-8	293
Table 8-10 <i>IR</i> results (%)	294
Table 8-11 Processing parameters and levels	296
Table 8-12 L9 (3 ³) OA used in the experiment	297
Table 8-13 Optimal conditions of verification set	299
Table 8-14 Standardised data matrix	301
Table 8-15 Correlation coefficient matrix	302
Table 8-16 Final data of talc group	307
Table 8-17 Final data of GF group	308
Table 8-18 Final data of OMMT group	310
Table 8-19 Eigenvalues, <i>EVs</i> and <i>AEVs</i> of TM trials	314
Table 8-20 Optimal trials based on final data	315

Table 8-21 *CR* results (%)
Appendix Table 1

316
363

List of Equations

Equation 2-1 1 st Order Accumulating Generation Operaor	96
Equation 2-2 Mean Consecutive Neighbours Generation Operator	96
Equation 2-3 GM (1, 1)	97
Equation 2-4 Whitenization Equation of GM (1, 1)	97
Equation 2-5 Parameter Matrix of GM (1, 1)	97
Equation 2-6 Inverse Accumulating Generation Operator	97
Equation 2-7 Simulation Function of GM (1, 1)	98
Equation 2-8 First Datum Solution	98
Equation 2-9 Last Datum Solution	98
Equation 2-10 Least Square Solution	98
Equation 2-11 First Datum Simulation Function	98
Equation 2-12 Grey Verhulst Model	99
Equation 2-13 Whitenization Equation of Grey Verhulst Model	99
Equation 2-14 Simulation Function of GM Grey Verhulst Model	99
Equation 2-15 The S/N ratio with the lower the better characteristic	104
Equation 2-16 The S/N ratio with the nominal the better characteristic	104
Equation 2-17 The S/N ratio with the higher the better characteristic	105
Equation 2-18 Normalization with the higher the better characteristic	109
Equation 2-19 Normalization with the lower the better characteristic	110
Equation 2-20 Normalization with the target value	110
Equation 2-21 Normalization with the first value	110
Equation 2-22 Multiple Quality Characteristic Matrix	113
Equation 2-23 Standardised Matrix	113
Equation 2-24 Correlation Coefficient Matrix	113
Equation 2-25 Distance	113
Equation 2-26 Correlation Coefficient Array	114
Equation 2-27 Explained Variation	114
Equation 2-28 Accumulative Explained Variation	114
Equation 2-29 Final Data	114
Equation 3-1 Tensile Modulus	122
Equation 3-2 Tensile Stress	122
Equation 3-3 Tensile Strain	122
Equation 3-4 Flexural Modulus	125
Equation 3-5 Flexural Stress	125
Equation 3-6 Flexural Strain	126

Equation 3-7 Impact Strength	129
Equation 3-8 Shear Viscosity	131
Equation 4-1 Preservation Rate	183
Equation 5-1 Improvement Rate	207
Equation 5-2 Improvement Rate per Loading	209
Equation 6-1 Degradation Rate	219
Equation 8-1 Average Error Rate	262
Equation 8-2 Comparator Ratio	314

Abbreviations

AAS	atomic absorption spectrometer
ABS	acrylonitrile butadiene styrene
AER	average error rate
AES	acrylonitrile ethylene styrene
AEV	accumulative explained variation
AFM	atomic force microscope
ANOVA	analysis of variance
APER	average prediction error rate
AS	acrylonitrile styrene
ASA	acrylic styrene acrylonitrile
ASER	average simulation error rate
ASTM	American society for testing and materials
BPF	British plastics federation
BMC	bulk moulding compound
CA	cluster analysis
CCA	chromated copper arsenate
COC	cyclic olefin copolymer
CPS	China plastic survey
CNT	carbon nanotube
CR	comparator ratio
DoE	design of experiment
DR	deterioration rate
DSC	differential scanning calorimetry
EC	European commission
EIA	energy information administration (U.S.)
ELV	end-of-life vehicle
EPA	environmental protection agency
EPDM	ethylene propylene diene terpolymer
EV	explained variation
FEMA	federal emergency management agency
GF	glass fibre
GM	grey model
GMC	granular moulding compound
GPC	gel permeation chromatography
HAS	hindered amine stabiliser
HDPE	high-density polyethylene
HDT	heat distortion temperature
HPN	highperform nylon
ICP-MS	inductively coupled plasma mass spectrometry
IR	improvement rate
ISO	international standard organization
KMO	Kaiser-Meyer-Olkin Measure of Sampling
LCA	life cycle analysis

LCP	liquid crystal polymer
LDPE	low-density polyethylene
m or M	modified
MAPE	maleated polyethylene
MAPP	maleic anhydride grafted polypropylene
MDI	diphenylmethanediisocyanate
MFI	melt flow index
MoDiP	museum of design in plastics
MMA	methyl methacrylate
MMT	montmorillonite
MSW	municipal solid waste
MW	molecular weight
OA	orthogonal array
OICA	organisation internationale des constructeurs d'automobiles
OMMT	organic (modified) montmorillonite
ONP	old newspaper
PA	polyamide
PA-6	polyamide-6
PA-66	polyamide-66
PAI	polyamide-imide
PBO	phenylene benz obisoxazole
PBT	polybutylene terephthalate
PC	principal component
PC	polycarbonate
PCA	principal component analysis
PCN	polymer-clay nanocomposite
PE	polyethylene
PEEK	polyetheretherketone
PEI	polyetherimide
PESTUR	polyesterurethane
PESU	polyethersulfone
PET	polyethylene terephthalate
PEX	polyethylene
PFSA	perfluorosulfonic acid
PMDA	pyromellitic dianhydride
PMMA	polymethylmethacrylic
PO	polyolefin
POM	polyoxymethylene
PP	polypropylene
PPA	polyphthalamide
PPO	polypropylene oxide
PPSU	polyphenylsulfone
PR	preservation rate

PS	polystyrene
PTFE	polytetrafluoroethylene
PU	polyurethane
PUR	polyurethane
PVC	polyvinyl chloride
PVDC	polyvinylidene chloride
R or r	recycled (recovered)
R.H.	relative humidity
RIM	reaction injection moulding
RWF	rubber-wood flour
SEBS	styrene ethylene butylene styrene
SEM	scanning electron microscope
SMA	styrene-maleic anhydride copolymer
SMC	sheet moulding compound
S/N	signal-to-noise
Talc	talcum powder
TDL	temperatures of deflection under load
TGA	thermogravimetric analysis
TEM	transmission electron microscopy
TM	Taguchi method
TPI	thermoplastic polyimide
TPO	thermoplastic polyolefin
TPUR	thermoplastic polyurethane
UHMWPE	ultra high molecular weight polyethylene
USCAR	United States council for automotive research
U.S.F.A	United States fire administration
UV	ultraviolet
WAXS	wide-angle X-ray scattering
WRAP	waste reduction awards program
V or v	virgin
XRD	X-ray diffraction

Chapter 1 Introduction

1.1 Background

1.1.1 Introduction of Plastics

1.1.1.1 Definition of Plastics

The word plastic is derived from the Greek word πλαστικός, which means the capacity for being shaped or moulded.

Webster's Dictionary defines polymers as any of various complex organic compounds produced by polymerization; they are capable of being moulded, extruded, cast into various shapes and films or drawn into filaments and then used as textile fibres.

Plastic materials encompass a wide range of synthetic or semi-synthetic polymers with high molecular weight and long molecular chains and many of them may contain other organic/inorganic substances to improve performance and/or reduce production costs. These substances include wood fibre and talc, which is similar to natural resins found in plants. The vast majority of plastics are composed of polymers of carbon and hydrogen alone, or with oxygen, nitrogen, chlorine or sulfur in the backbone. The backbone is the part of the chain on the main "path" linking a large number of repeat units together. To customize the properties of a plastic, different molecular groups

"hang" from the backbone (usually they are "hung" as part of the monomers before linking monomers together to form the polymer chain). Due to their malleability or plasticity, relatively cheap cost and versatility, plastics have been used in the manufacture of industrial products for many years, from cups to spacecraft.

The use of plastics is limited by certain chemical and physical properties, such as low hardness and a high moisture absorption rate. They also demonstrate low resistance to heat, organic solvents, oxidation and ionizing radiation. Most plastics will melt or decompose when heated to a few hundred degrees Celsius. The electrical conductivity of plastics is only up to 80 kS cm^{-1} in case of stretch-oriented polyacetylene (Moore, 1996). Plastics generally have much lower conductivity than most metals which have conductivities of several hundreds of kS cm^{-1} (Heeger et al., 1988; Burroughes et al., 1990; Sariciftci et al., 1992; Sirringhaus, 2005). However, plastics are still too expensive as a replacement for wood, concrete or ceramic in bulky objects like conventional buildings, bridges, dams, pavement, and railroad ties.

The raw materials needed to make most plastics mainly come from petroleum and natural gas; others are fillers, and include wood fibre, talcum starch, and flax fibres.

1.1.1.2 Classification of Plastics

Generally, there are two types of plastics: thermoplastics and thermosetting polymers (or so-called thermosets) (Brooks, 2013).

Thermoplastics, also known as thermosoftening plastics, are plastics that will turn to a liquid when heated and solidify to a very glassy state when cooled sufficiently (Baeurle and Hotta, 2006). This allows them to be moulded through many cycles, and the common examples include polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polycarbonate (PC), polyurethane (PU), polyester terephthalate (PET) and acrylonitrile butadiene styrene (ABS). Most thermoplastics are high-molecular-weight polymers whose chains associate through weak Van der Waals forces (e.g. polyethylene), stronger dipole-dipole interactions and hydrogen bonding (e.g. nylon) (Karimi-Varzaneh et al., 2008).

Thermosets, also known as thermosetting plastics, are polymer materials that irreversibly cure. This means that they cannot be moulded again and again. The cure may occur through heating (generally above 200°C), through a chemical reaction (e.g. in the case of two-part epoxy resins), or through irradiation as with UV light and electron beam processing which involves using high-energy electrons at elevated temperatures in a nitrogen atmosphere. Thermoset materials are usually liquid or malleable prior to curing and designed to be moulded into their final form, or used as adhesives. Others are solids like the moulding compound used in semiconductors and integrated circuits (IC), i.e., phenolic and epoxy resins. Common thermoplastics range from 20,000 to 500,000 amu, while thermosets are assumed to have infinite molecular weight.

Another classification is based on the crystallization behaviours of plastics. So-called semi-crystalline (partially crystalline and partially amorphous) plastics have both a melting point (the temperature at which the attractive intermolecular forces are overcome) and one or more glass transition points (temperatures above which the extent of localized molecular flexibility is substantially increased), while the melting point

and glass transition point of so-called amorphous plastics are at the same temperature.

The semi-crystalline plastics include polyethylene, polypropylene, poly vinyl chloride, polyamides (nylons), polyesters and some types of polyurethanes. Amorphous plastics include polystyrene and its copolymers, poly (methyl methacrylate), and all thermosets. The examples are shown in Table 1-1.

Table 1-1 Examples of plastics classified by crystallization behaviours

Classification	Examples
Amorphous	ABS, COC, PAI, PC, PEI, PESU, PMMA, PPC, PPSU, PS, PVC, TPI, High-temperature sulfone
Semi-crystalline	HPN, LCP, PA, PBT, PE, PEEK, PET, PEX, PFSA, PP, PPA, PPS, POM, PVDC, UHMWPE

Furthermore, plastics can be classified according to their different characteristics, with examples are shown in Table 1-2.

Table 1-2 Characteristics for classifications and examples

Characteristics	Examples
Monomer – the repeating molecular unit which makes up the polymers' chain, backbone and side chains	Acrylics, polyesters, polyurethanes, and halogenated plastics
Synthesis processes	Addition, cross-linking composites
Purposes, usages and requirements	Elastomer, biodegradable PP
Physical properties	High-impact PS

1.1.1.3 Development of Plastics

The history of manufactured plastics stretches back more than 100 years. However, when compared to other materials, plastics are relatively modern. Their usage over the past century has enabled society to make huge technological advances. For example, in 1982, the first artificial heart made mainly of polyurethane was introduced and implanted in a human. The development of plastics has come from the use of natural plastic materials (e.g., couma macrocarpa and shellac) to the use of chemically modified natural materials (e.g., rubber, nitrocellulose, collagen, galalite) and finally to completely synthetic molecules (e.g., bakelite, epoxy, polyvinyl chloride, polyethylene).

Although plastics are thought as a modern invention, there have always been "natural polymers" such as amber, tortoise shells and animal horns. In 1284, first recorded mention of The Horners Company of London, with horn and tortoiseshell as the predominant early natural plastic (BPF, 2013). These materials behaved very much like today's manufactured plastics and were often used similar way to that for plastics are currently being used, as both natural and synthesised materials used in chewing gum.

The first man-made plastic was produced by Alexander Parkes who publicly demonstrated it at the 1862 Great International Exhibition in London (Meikle, 1995). This can be said to be when the era of modern plastics began.

1.1.2 Plastics in Automobiles

The practice of using plastics in automobile applications began in 1916 when Rolls Royce began to use phenol formaldehyde in its car interiors and subsequently boasted about the incorporation of this new material (Freinkel, 2011; BPF, 2013; MoDiP, 2013). In 1956, The Reliant Regal 111 went on sale. This was the first commercially successful all-glass and

reinforced-plastic bodied car (Freinkel, 2011; BPF, 2013; MoDiP, 2013). In 1966, blow moulding of fuel tanks was introduced and these have been used in automobiles up to present (Freinkel, 2011; BPF, 2013; MoDiP, 2013).

1.1.2.1 Percentages of Plastics in Automobiles

In automobile engineering, one of the most efficient and common solutions to increase fuel efficiency is to reduce the weight of vehicles. This helps mitigate the problems caused by increasing fuel prices and the emission of CO₂ and other green-house-gases. It is estimated that with every 10% reduction of automobile mass, fuel consumption can be reduced by 3% ~ 5% and CO₂ emissions are cut down by 25kg (CPS, 2011). According to the British Plastics Federation (BPF), "105kg of plastics, used as a replacement for metals in a car weighing 1,000kg could make possible a fuel saving of up to 7.5%". Thus, due to the high performance/density ratio, plastics are a perfect substitute for traditional metal materials. Ever since the development of thermoplastics on a large scale during the 1950s, the use of plastics in automotive components has undergone enormous growth. This is particularly true with the development of engineering thermoplastics and

technological advances from the blending of different plastics, to the alloying of newer materials with specific combinations of plastic.

Since 1978, the total weight of a typical passenger car has decreased by almost 140 kg. In that same period, the amount of regular steel and iron used in a typical car has decreased by almost 320 kg. The use of high-strength steel has increased by about 86 kg, the use of aluminium has increased by more than 45 kg, and the use of plastics has increased by almost 33 kg (Ward's, 2000). Statistics show that the consumption of plastics or composites used in US-built automobiles increased from 79.2 kg in 1978 to 109 kg in 1992, and by 2000 the average weight of an automobile was about 1350 kg of which 135 kg was comprised of plastics (Jenseit et al., 2003). The percentage of plastics in an average automobile in Western Europe has kept rising over past the four decades. The percentage had risen from 6 wt% in 1970 to about 10 wt% ~ 15 wt% in 2010 and could rise to more than 25 wt% by 2020 (Jenseit, et al., 2003; ICIS, 2010).

Table 1-3 shows total mass of specific automobile models, mass

of plastics content and percentage of total weight represented
by this content.

Table 1-3 Some automobile models' total mass, plastics mass and percentage of total comprised of plastics (Joyson, 2011)

Automobile Model	Total Mass (kg)	Plastics Mass (kg)	Plastics Percentage
BYD F3	1200	133	11.10%
Citroen "Fukang"	1050	82	7.76%
Chery QQ	1255	96	7.65%
Chery EASTAR	1440	158	10.97%
Faw-Volkswagen A4	1490	90	6.04%
Honda Accord	1422	131	9.21%
Honda Fit	1060	114	10.75%
Hongqi CA7220	1300	88	6.79%
Peugeot Citroen 2005	1210	157	12.97%
Peugeot 307	1239	130	10.49%
Steyr King SDRC	7120	121	1.69%
Toyota Camry	1480	130	8.78%
SVW Santana 2000	1140	67	5.89%
SVW Passat 2005	1429	201	14.07%

1.1.2.2 Plastic Parts of Automobiles

The automobile industry uses plastics and polymeric composites in a wide range of applications; it is the second most common class of automotive material after ferrous metals and alloys (cast iron, steel, and nickel).

In automobiles, plastics are used in exterior and interior components such as bumpers, doors, safety and windows, headlight and side view mirror housing, trunk lids, hoods, grilles and wheel covers (Minth, 2012). The plastic contents comprise about 50% of all interior components in automobiles, including safety subsystems, door, roof, and seat assemblies.

Some examples of the most common automobile components made of plastics are summarized and shown in Table 1-4 (for more detailed information see Table 1 in Appendix) (Joyson, 2011).

Table 1-4 Common plastic auto parts, their requirements and types (Joyson, 2011)

Components	Requirements	Types of Plastics
Dashboard	Thermal Stability, High Rigidity, Impact Resistance	ABS, ABS/PC, PC, PP, PP/EPDM, PPO, PU, PVC, PVC/ABS, SMA-GF15, TPO
Inner Door	Thermal Stability, High Rigidity, Impact Resistance	ABS, GFAS, PC/ABS, POM, PP/EPDM, PP-T20, PVC, PVC/ABS, TPO
Seat	Thermal Stability, High Rigidity, Impact Resistance	ABS, GMT, PP, PU, PVC
Ceiling and Rear wall	Thermal Stability, High Rigidity, Impact Resistance	PP, PVC, TPO, TPUR,
Sun Shade	High Rigidity, Thermal Stability	PP, PVC, TPO
Engine Bonnet and Ground Mat	Heat insulation, Impact Resistance	PP or PVC Foams
Glove Compartment and Ashtray	Thermal Stability, Impact Resistance	ABS, ABS/PC, PC, PP
Bumper	Thermal Stability, High Rigidity, Impact Resistance	ABS, PA, PC/PBT, PC/PET, TPO, POE, PP/EPDM, PPO/PBT, PU, PUR/RIM, SMC
Radiator Grille	Thermal Stability	ABS, PC/ABS, PE, PP
Light	Light Transmittance, Thermal Stability, High Rigidity, Impact Resistance	ABS, PBT, PC, PC/ABS, PMMA, PP-GF15, PP-T40, PPO/PS, PPS
Outside Door Handle and Locker	High Rigidity, Impact Resistance	ABS, PP, POM
Wiper	Thermal Stability, High Rigidity	PBT, POM
Band for Wheel Hub	Thermal Stability, High Rigidity, Impact Resistance	ABS, PA, PA/PPO, PC/ABS
Steering Wheel	Abrasion Resistance, Thermal Stability	ABS, PP, PU, PVC
Battery Slot	Electrical Insulativity	PP
Fuel Feeding System	Chemical Stability	PA, PBT, PBT/PC
Air Conditioning	Thermal Stability, High Rigidity	PE, PP
Body Structural Parts	Thermal Stability, High Rigidity	ABS, PP-GF10, PP-GF15, PP-T40, PC/PBT, PC/PET

Many types of plastics and polymeric composites are used in automobiles. Among them, PP is the plastic type which is used in greatest proportion in Chinese automobiles, with an average of 40 kg ~ 80 kg per car. Next come PU, ABS, PVC and PE and to give an illustratory example, the production of one SVW Passat 2005 incorporates 73 kg of PP, 27 kg of PU, 16 kg of PE, and 15 kg of ABS (Liao, 2009).

1.1.3 Recycled Plastics and Recycling

1.1.3.1 Demand for Recycled Plastics

The rapid growth of the Chinese economy has created an increasing demand for raw materials such as waste plastics, but has also created a large amount of plastic waste.

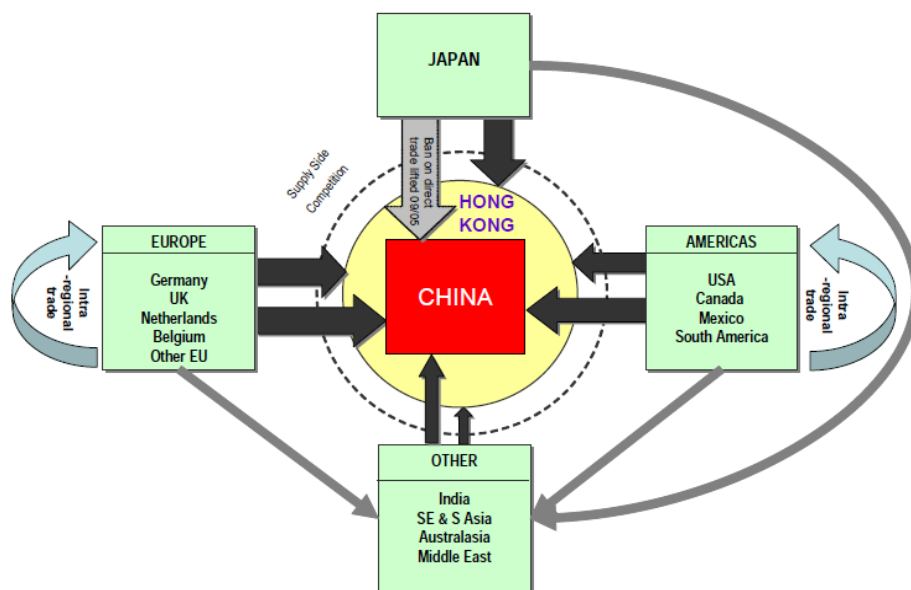


Figure 1-1 Main components of the global trade in recovered plastics (WRAP, 2006)

As shown in Figure 1-1, China has already become the world centre for recycled plastics. CBI China (2013) forecasts that China's demand for recovered (recycled) plastic could reach 29 million tonnes by 2015, 65% more than that in 2009 (as shown in Figure 1-2, the equivalent of compound average annual growth of 8.7%) (WRAP, 2011). Waste plastics for recycling in China generally come from two sources: the domestic market and imports.

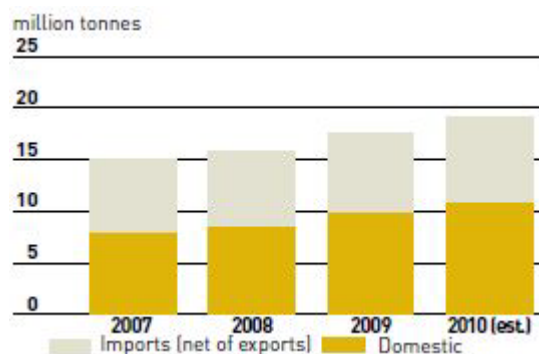


Figure 1-2 China consumption of recycled plastics (WRAP, 2011)

By April, 2011, the import total amount of waste plastics in 2011 had already reached 9,641,780 tonnes (CCS, 2011).

The domestic plastics recycling rate is estimated as being between 25% and 30% (Liao, 2007; Ma and Zhang, 2009) while 70% ~ 75% waste plastic is not recycled: it is burnt,

discarded, or buried.

1.1.3.2 Current Recycling Practices

Nearly all kinds of plastic products or components can be recycled, including appliances, packaging, bags, bottles, basins and buckets, covers, clothes, containers, pipelines, plates, toys and shoes.

Generally, there are two major routes of gathering waste plastics from end-of-life plastic products: single source recycling and mixed recycling, which are discussed in the following sections.

End-of-life plastic products are typically taken to salvage stations or plastic scrap distribution centres by householders or private collectors and then sold to recycling companies. Typical examples of such end-of-life plastic products accumulated in Chinese ports are used packages, post-consumer containers and waste electrical and electronic equipment (WEEE).

Figures 1-3 and figure 1-4 show a typical plastic scrap distribution centre at the port in Taizhou, Zhejiang Province. In that particular centre, plastic scrap is shipped from Europe

along with other wastes. The received scrap is roughly sorted by manual labourers into generic categories, such as steel, plastics, copper, and rubber, and then sold to different buyers. Most its customers are small recycling operations, which only practice recycling materials from a few sources.



Figure 1-3 Plastic scrap distribution centre in a port of Taizhou



Figure 1-4 Plastic scraps sorting

Due to competitive selection and market competition, there are dozens of recycled plastics trading markets and collection, manufacturing and distribution centres in China, each of which normally consists of hundreds of plastic recycling companies. Some larger scale recycled plastics markets and centres can even comprise thousands of such companies. Around each of those recycling centres, there are hundreds of plastic recycling companies. For some larger centres, there could be thousands of associated recycling companies. It was estimated that the economic value of those centres has risen from 2 billion yuan (approximately 200 million GBP) in 2000 to over 100 billion yuan (approximately 10 billion GBP) in 2007 (Ma and Zhang, 2009). Most of these centres are located in the eastern provinces of China, such as Guangdong, Zhejiang, Jiangsu, Fujian, Shandong, Henan, Hebei, Anhui and Liaoning. The towns in those provinces where the recycling centres are located are Yuyao, Ningbo, Cixi, Dongyang and Taizhou in Zhejiang; Xinghua, Changzhou, Taicang, Lianyungang and Xuzhou in Jiangsu; Wending, Baoding, Xiongqian and Yutian in Hebei; Laizhou, Zhangqiu and Linyin in Shandong; Anyang and Changge in Henan, Around major cities in China, in Beijing, Shanghai, Tianjing, Chongqing, Guangzhou, Wuhan, Chengdu,

Taiyuan, Kunming, and Urumqi, such kind of centres also exist

Rejected products from plastic manufacturing plants are directly taken by contracted recycling companies. Plastic product manufacturers rarely carry out recycling themselves. For example, a plastic package manufacturer in Taizhou, Zhejiang makes its products by pressing on hot plastic film. The products are inspected initially after being produced, and rejected products are collected. Then, rejected products are shipped to a contracted recycling plant for reprocessing.

Waste plastics gathered from the mixed recycling route tend to be of poorer quality as, in their initial life, they were exposed to a service environment for a certain period, where degradation and possible contamination might occur. In common practice, either householders or private collectors would only gather a small amount of mixed waste plastics. Recycling companies need to invest extra labour and equipment to classify those mixed waste plastics. Thus, those waste plastics have lower prices, and the prices are more sensitive to market demand.

Rejected plastic products have not been exposed to the service

environment, have far less contamination, are of similar type, and their supply is likely to be stable. Thus, the quality and supply of this type of waste plastics are relatively secure. Hence, the contracted prices would be stable also.

There are two types of companies recycling plastic in China:

1. Small recycling companies which are usually located in rural areas, owned by private citizens;
2. Large recycling companies which are usually located on the outskirts of cities, owned by local government or private enterprises.

Most existing recycling companies belong to the first type. They are typically very small, operating at low costs and expenses with low capacity of production and few environmental protection measurements. Usually a company operates on an area of land of no more than 200 m² in total. It hires no more than ten employees and has one or two processing lines (usually consisting of one extruder and one pelletizing machine only). With the exception of melting and pelletizing, labourers carry out all of the work. This includes sorting, washing and carrying the waste plastics. It is estimated that a small

recycling company investing less than 100,000 yuan (approximately 10,000 GBP) can produce the first batch within 5 days ~ 7 days (Cheng, 2007). The number of such small plastic recycling plants in China is estimated to be more than 20,000 (Ma and Zhang, 2009).

A visit to a typical small recycling company in Guangdong province (Figure 1-5) took place in July 2012. This enterprise recovers isotactic polypropylene from which bag fibres are produced.



Figure 1-5 Work flow of a small plastic recycling plant in Guangdong

This small company purchases post-consumer fertilizer bags from plastic scrap distribution centres or collects them from local farms. The bags are washed manually in the small river nearby, and dried naturally. The bags are then cut manually with scissors and fed into a twin-screw extruder for making plastic pellets. Those recycled plastic pellets are usually used for producing low-value products, such as trash bins or

flowerpots. Due to the low production capacity, the company will collaborate with recycling plants in neighbouring villages when seeking to obtain large orders.

While there are not many large recycling companies in China, these large recycling companies typically have stable sources of waste or end-of-life plastics and fixed markets. Typically they hire over 20 employees, utilise manual labour and sophisticated equipment to do sorting, reprocessing and shipping. They operate with comparatively high standards of environmental protection. These large companies produce more than 60% of domestic recycled plastics in China (Ma and Zhang, 2009). Most of them are owned by local government.

In China and elsewhere single source plastic recycling companies use plastics either from a single source or only recycle a single type of plastic. This type of recycling plant tends to be small and in most cases is operated without a license. Most small recycling companies, as shown in Figure 1-5, are doing single source recycling only. The main advantage of single source recycling is that it guarantees acceptable quality with minimum cost. Single source recycling avoids a lot of

sorting work, which requires expertise and extra labour cost.

Re-processing without removing other types of plastics would lower the quality of the desired recycled plastic, and single source recycling reduces the chance of introducing other plastics. The main disadvantage for the business is that it is very sensitive and fragile; a small change in supply and demand can have a decisive effect on those small plants.

The plants which deal with plastic scrap from different sources are generally larger than single source plants. The presentation of a plant of this type in Ningbo is shown in Figure 1-6. The plant collects plastic scrap from different sources, either foreign (EU mainly) or domestic, and the plastic scrap is then processed via manual sorting, shredding, and pelletizing.

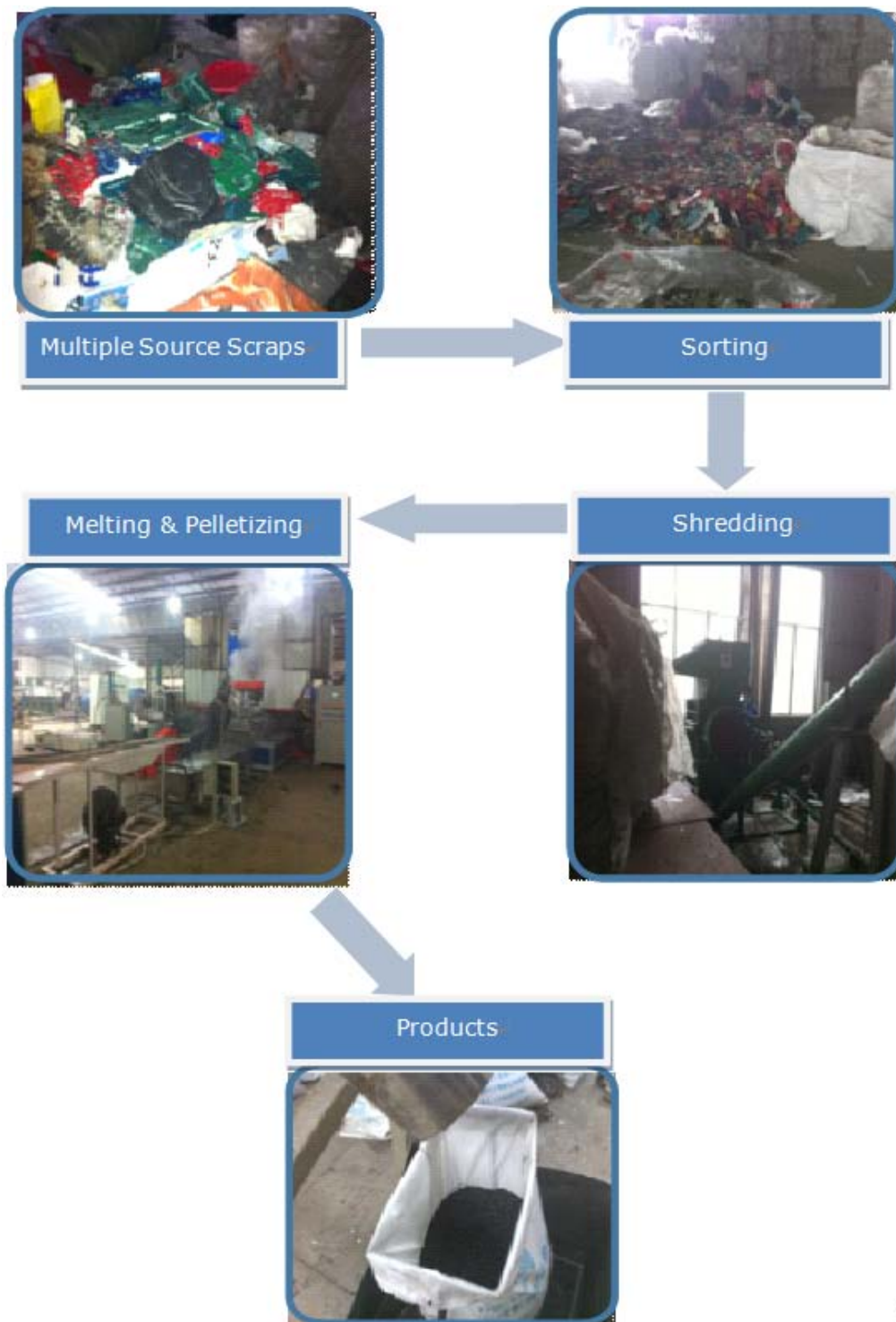


Figure 1-6 Example of a mixed plastic recycling plant in Ningbo

1.1.3.3 Separation of Plastics

Plastic separation has proved to be one of the major problems

for polymer recycling (Burat et al., 2009). For ease of separation, most manufacturers determine the type of plastics by the numerical coding system created by Society of Plastics Industry in 1980s (EPA, 2013). The identification codes can be found at the bottom of most plastic packaging. Table 1-5 shows the identification codes.

Table 1-5 Identification codes (EPA, 2013)

SPI Resin Identification Code	1	2	3	4	5	6	7
Type of Resin Content	PET	HDPE	Vinyl	LDPE	PP	PS	Other

However, there are many plastic products or parts cannot be categorised using this numbering system, and these include composited pipes, multiple-layered panels, and fibre-inserted mats. When working with these products, manual sorting is required.

Plastic separation techniques include flotation, water table separation, centrifuges, cyclones, air vibration tables, dissolution, optical sorting (include spectroscopic identification) and other advanced techniques (based on dielectric properties

or colour). Infrared sorting is quite common for the sorting of PE packaging, and piezoelectric methods and high frequency cameras can be used to separate PVC (EC, 2013). An example of automatic plastic separation line based on density separation can consist of the following stages (EC, 2013):

1. Air classifier, which is used to separate out less dense films and fragments from the main stream. This is achieved using jets of air to blow labels and fragments away from the denser body packaging.

2. Flotation, as the main different types of plastic all possess distinct densities ranging from PP ($0.85 \text{ g cm}^{-3} \sim 0.95 \text{ g cm}^{-3}$) to PET ($1.35 \text{ g cm}^{-3} \sim 1.38 \text{ g cm}^{-3}$). Note that plastic density can vary depending on the additive load and the density of the additive. In a flotation tank, plastic flakes pass and sink or float depending on the density of the material. Mechanical extractors collect either the sinking or floating fractions.

3. Centrifugal systems can also be used to separate plastics of differing densities.

4. Cyclone and hydro-cyclone. An air or water-based system which uses centrifugal and shearing effects to separate polymer particles based on size differences of those particles.

However, the cost of purchasing and maintaining a production line based on these separation machines is very expensive. Since current labour cost in China is low when compared with Europe, it is both economical and convenient to use man power to classify the plastic scraps. Manual sorting is based on the experience and expertise of the workers, who have been trained and may have worked in this profession for many years.

However, some studies have already shown that the quantity of foreign materials found in recycled polypropylene can be up to 10% despite being sorted centrally by trained personnel (Seiler, 1995).

1.1.4 Merits and Current Situation of using Recycled Plastics

Although the performance of recycled plastics does not match those of industrial polymers or composites according to many criteria, the low price of recycled plastic has a great advantage, since the prices of recycled plastic are about 10% ~ 50% cheaper than those of virgin plastics according to the state of the market. The prices of three common industrial virgin PP and three grades of recycled PP are shown in Table 1-6 for the years 2011 and 2012. The average prices and increments calculated

confirmed the economic advantage of recycled plastics.

**Table 1-6 PPs' price statistics in China's markets
(measured in RMB per ton)**

Plastics Type	Current Price	2012 Average	2011 Average	11/12 Increment
VPP1	16,500	15,600	13,700	13.87%
VPP2	13,800	13,000	11,000	18.18%
K8303	12,500	10,500	9,000	16.67%
3 rd Class rPP (Black)	4,600	4,400	4,150	6.02%
2 nd Class rPP (Grey)	5,900	5,120	4,800	6.67%
1 st Class rPP (White)	8,300	8,300	8,160	1.72%

Other than economic advantages, recent studies have shown that, recycled plastics still maintain some good performance (Khattab and El-Zoghby, 1998; Tarantili et al., 2010) and the original properties could be restored upon reprocessing (Boldizar and Möller, 2003). For certain types of plastics, some properties are even improved by multiple reprocesses (Su et al., 2007). However, many other plastics can only be recycled a limited number of times (Pérez et al., 2010). Furthermore, the use of recycled plastics in automobiles could have significant environmental impacts. As shown in Figure 1-7 and Figure 1-8 (Makuta et al., 2000), an analysis of the accumulated

environmental burden based on all steps, from excavation of raw materials to production, shows that the environmental impacts for recycled materials are lower.

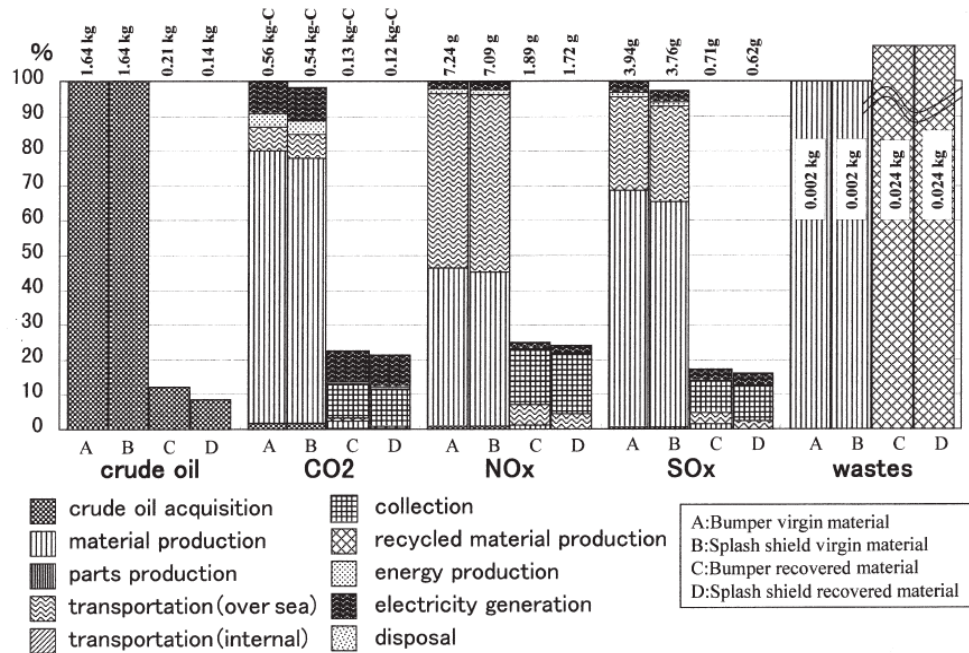


Figure 1-7 Comparison of environmental load of material production between bumper material and splash-shield material (per 1 kg) (Makuta, et al., 2000)

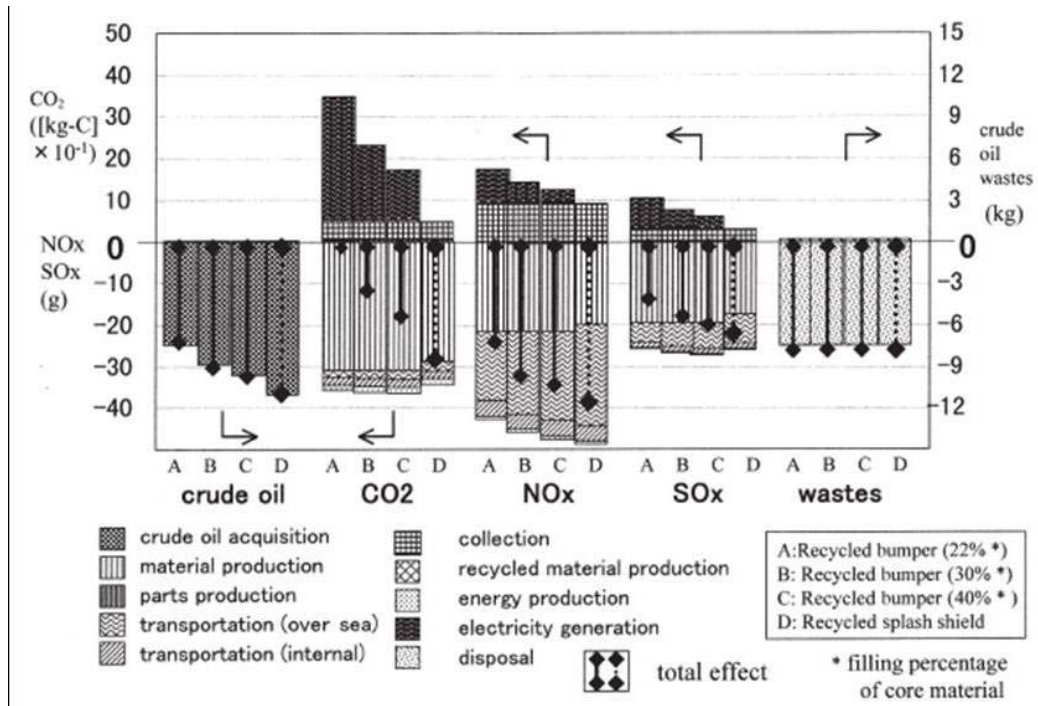


Figure 1-8 Comparison of the total effect of reductions in the environmental load among different recycling scenarios (Makuta et al., 2000)

Figure 1-7 and Figure 1-8 illustrate that, recycled material could achieve reductions in environmental impacts representing about 90% of the values for crude oil, and about 80% of atmospheric emissions (CO_2 , NO_x , SO_x).

However, currently less than 1% of plastic used in the automobile industry in China is recycled plastic (WRAP, 2010). This fact exists in a context where China is the largest automobile manufacturer and recovered plastic consumer in the world. Of the major automobile parts manufacturers that

were visited during this research, in Shanghai, Guangzhou and Ningbo, strict rules forbidding the use of recycled plastics in production were in place. Even the use of internally reprocessed plastics was limited, with an upper limit of to 30%.

1.2 Aims and Objectives

This research project aims to investigate the potential use of recycled plastics in new automobile production.

It is necessary to answer the question "why not use recycled plastics in automobile production?" This raises the following issues which needed to be identified:

1. The knowledge gap between academic research and industry practices, the quality issues and possibility of defects in parts made with recycled plastics.
2. The practical and economic possibility of using recycled plastics in automobile production.
3. The complicated and intertwining factors in the processing and reprocessing of recycled plastic.

The objectives of this research include the following:

1. Review past research on manufacturing recycled plastics,

including ageing mechanisms, modifications and automobile applications of recycled plastics;

2. To study typical examples of current recycled plastics in China;
3. To investigate the detailed mechanical performance and properties of recycled plastics utilising ISO standard tests;
4. To investigate the formulas for improving recycled plastics, and identify the effects of different proportions of fillers and compatibilisers on the end products;
5. To apply durability and flammability tests on manufactured parts using recycled plastics or recycled plastics based composites to check their potential for demanding industrial applications;
6. To identify and utilise mathematic and advanced experimental design methods to predict, optimise and evaluate the performance of end products produced from recycled plastics, identifying of key factors and relationships.

By linking these, it would be possible to understand the effects of virgin plastics, recycled plastics, fillers, processes and working conditions associated with plastic composites made from recycled plastics. This would then lead to the feasible

manufacturing approaches to enhance the use of recycled plastics in automobile production.

1.3 Research Strategy

To accomplish the objectives, it is necessary to identify the possible defects of recycled plastics in comparison to virgin plastics. Common and cheap recycled plastics in the current market will receive specific attention in this research. Recycled plastics could be required to improve performance by countering certain defects. This could include the addition of fillers or modification of procedure. In addition, durability and flammability tests will be conducted on improved recycled composites to verify the applicability of those polymers when exposed to hostile working conditions. Last, the recycled composites will be assessed from different perspectives with the aim of assessing their economic viability.

The structure of this research is as follows, Figure 1-9:

1. Chapter 2 provides an in-depth review of current published literature and routes of improving recycled plastics are proposed: by means of fillers and mathematical tools;
2. Chapter 3 describes selections of plastic materials, sample

preparation, standard tests and compositions for use in the subsequent chapters;

3. Chapter 4 describes an initial characterisation set identifying the characteristics of typical available recycled plastics;

4. Chapter 5 describes an investigation into the effect of adding typical and representative fillers into recycled plastics in term of mechanical, thermal and rheological properties, and the compounding effect of coupling agents were also tested;

5. Chapter 6 describes durability of recycled plastics under ageing and reprocessing, for verifying the feasibility of using recycled plastics in long term service under hostile environments and manufacturing industry;

6. Chapter 7 describes a flammability of recycled plastics adapting UL94 standards;

7. Chapter 8 describes the techniques to predict, optimise and evaluate recycled plastic, and then these techniques were applied and verified in Chapter 8;

8. Chapter 9 provides the conclusion of the research, and possible future work is put forward.

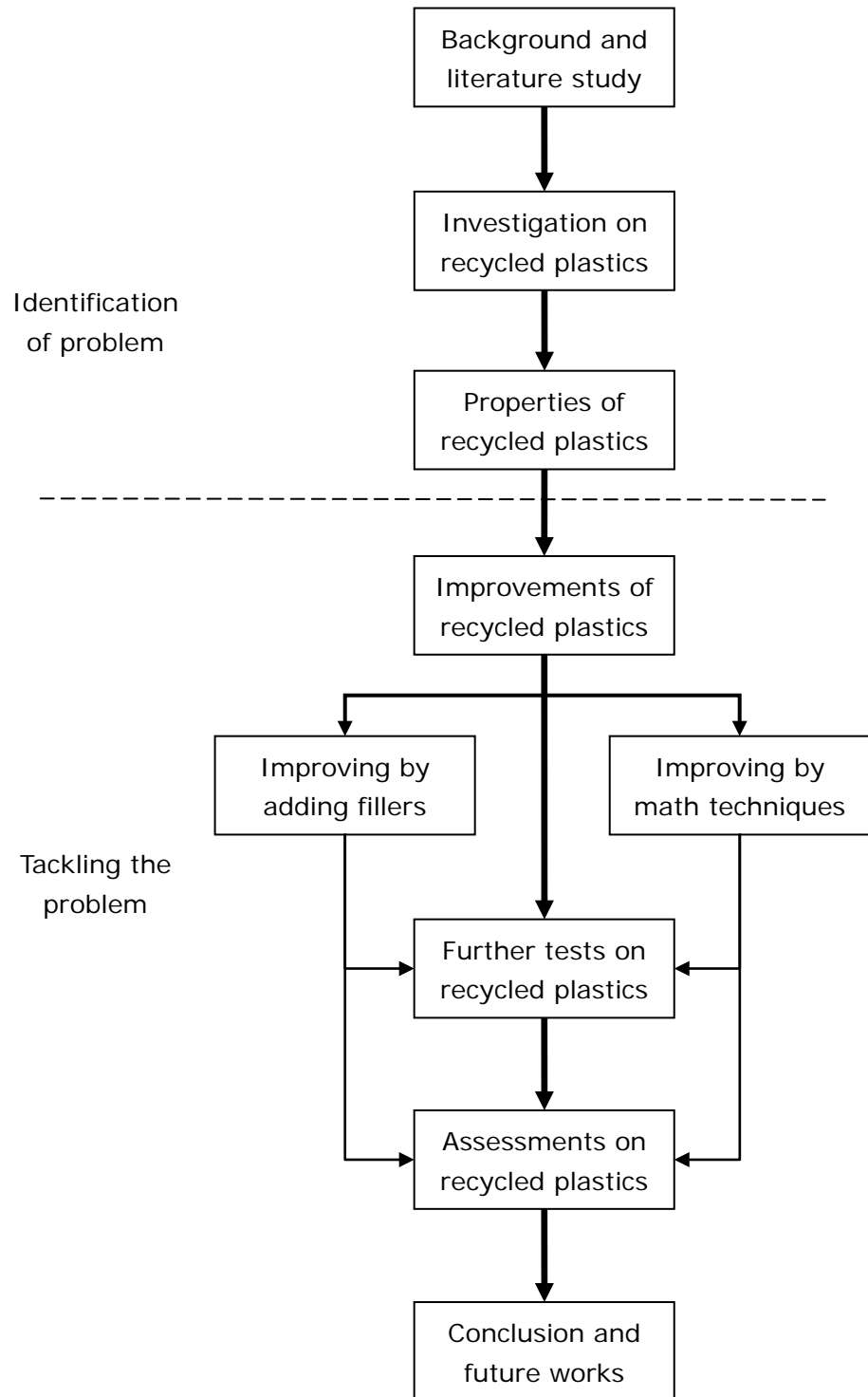


Figure 1-9 Structure of this research

Since PP takes a leading role in automobile plastics, it is used as a primary polymer material throughout this study, in investigations and tests conducted on PP and PP based

composites. A commentary on these results will be presented.

Chapter 2 Literature review

2.1 Ageing and Degradation of Plastics

Recycled plastics usually have less desirable properties compared to virgin materials (Ehrig, 1992). Ageing and degradation are given as two major reasons for reduction in performance. Ageing is known to be reversible, and is caused by a continuous progress towards the thermodynamic equilibrium of the molecular structures (Komitov et al., 1989). Degradation, on the other hand, stems from permanent chemical and physical changes of the molecular structures, and is irreversible.

Ageing and degradation of polymeric composites can occur within a few hours of exposure to harsh conditions of the working environment, such as high temperature and high humidity. Common ageing and degradation causes are summarized and shown below (Wright, 2001; Wypych, 2003; Maxwell et al., 2006):

1. Thermal - static heat ageing, exposure to low temperatures or thermal cycling;
2. Humidity (heat and damp) exposure;
3. Complete immersion in water at ambient and/or elevated temperatures;

4. Freeze/thaw and dry/wet cyclic conditions;
5. Continuous or intermittent saltwater immersion or spray;
6. Weathering (including rain and sand erosion);
7. Combined load (stress) and environmental exposures (temperature);
8. Chemical (water, fuel, acids, alkalis, solvents and oxygen)
9. Ultraviolet and other high-energy radiation;
10. Electrical stress (lightning stress and galvanic reactions);
11. Micro-organisms (fungi or bacteria).

Under many circumstances, a combination of more than one of the above factors affects the plastic parts, and results in complex degradation of the materials. The effect of one agent can also reduce resistance to other agents, similar to biological systems (Maxwell et al. 2006).

The physico-chemical deterioration of polymers occurs at elevated temperatures during initial processing (Glockner, 1968; Long and Sokol, 1974; Kirilova and Shulgina, 1988; Hinsken et al., 1991; Samperi et al., 2004; Rex and Graham, 2005), reprocessing (Abbas, 1980; Boldizar, et al., 1995; Chrysostomou and Hashemi, 1996; Eguiazabal and Nazabal,

1989; Eguiazabal and Nazabal, 1990; Sánchez et al., 1992) and service life (Ranby and Rabek, 1975; Bair et al., 1980; Severini, et al., Ricca, G., 1993; Rabek, 1996; Shimada and Kabuki, 1968), which results in the loss of performance. The deteriorations in rheological and mechanical properties for polymers are attributed to the macromolecular chain scissions, which result in decreasing molecular weight (Abbas, 1980; Abbas, 1981; González-González et al., 1998; Valenza and La Mantia, 1988), especially when plastics are recycled at high temperatures and shear stresses (Abbas, 1980; Billiana and Fleischmann, 1990; Eguiazabal and Nazabal, 1989).

Recent studies suggest that recycled plastics continue to maintain some good performance, as some waste plastics are similar to those made from virgin materials. Tests indicated only a minor drop-off in mechanical properties is observed (Khattab and El-Zoghby, 1998; Tarantili et al., 2010). Some original properties can be restored upon reprocessing (Boldizar and Möller, 2003). For certain types of plastics, certain properties, such as tensile yield stress, flexural strength and modulus of elasticity even improve during multiple reprocessing (Su et al., 2007). However, for most plastics, they

can only be recycled a limited number of times unless they are enhanced by specific additives (Pérez et al., 2010).

2.1.1 Mechanisms of Thermal Degradation

Plastics' recycling is carried out mainly by reprocessing (Abbas et al., 1978; Leidner, 1981). This process involves several high temperature shearing cycles that lead to the following sequence (Abbas et al., 1977; Abbas et al., 1978; Santos et al., 2002):

1. The occurrence of thermal and/or mechanical degradation;
2. Chemical and physical changes;
3. Detrimental effect on properties of final product.

Thermal degradation refers to the chemical and physical changes in polymers that take place at elevated temperatures. Temperature accelerates thermal degradation processes such as oxidation, chemical attack and mechanical creep (Maxwell et al., 2006).

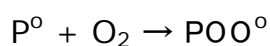
Thermal degradation of polymers usually occurs during their first processing (Kirilova and Shulgina, 1988; Ranzi et al., 1997; Gao et al., 2003; Capone et al., 2007; Lu et al., 2009; Grassie, 1956; Grassie and McNeill, 1958), during the coloration

reactions initiated by other substances (Grassie and McNeill, 1959), and the random, progressive scission of polymer chains in time (Simha and Wall, 1952; Westerhout, et al., 1997; Caceres and Canevarolo, 2008).

The reprocessing effects on properties and their mechanisms have been conducted on a large number of polymers, e.g. polyethylene (Moss and Zweifel, 1989; Zahavich et al., 1997; Scaffaro, 2009; Mendes et al., 2011), polypropylene (Schott and Kaghan, 1963; Guerrica-Echevarría et al., 1996), polyolefins (Mitterhofer, 1980; Kostadinova et al., 1997; Ahmed et al., 1999), polycarbonate (PC) (Shea et al., 1975; Shea et al., 1977; Abbas, 1980; Liu et al., 2000; Pérez et al., 2010), poly(alkylene terephthalates) (Silva Spinacé and De Paoli, 2001), polyamides (PAs) (Lozano-Gonzalez et al., 2000; La Mantia et al., 2002; Scaffaro and La Mantia, 2002; Groning and Hakkarainen, 2002; Su et al., 2007), and bisphenol-a polycarbonate (Eguiazabal and Nazabal, 1989). Reprocessing reduces the impact resistance and worsens the tensile properties at fracture, but exerts no influence on the modulus of elasticity or on the yield stress observed in bisphenol-a polycarbonate (Eguiazabal and Nazabal, 1989).

Reprocessing of polymer blends such as PA6/polypropylene (PP) (La Mantia and Capizzi, 2001) and polypropylene-(ethylene-propylene) copolymer (PP-EP)/poly(ethylene-co-vinyl acetate) (EVA) (Ramírez-Vargas and Navarro-Rodríguez, 2004) has been studied as well as that of reinforced materials (Balatinecz and Sain, 1998; Chrysostomou and Hashemi, 2000; Maspoch et al., 2003). PE undergoes chain scission, branching and cross-linking, which occur as competing reactions in processing at elevated temperatures (Tidjani and Arnaud, 1993; Tidjani et al., 1993; Barkhudaryan, 2000), whereas PP predominantly undergoes chain scission (Vaillant et al., 1994; Commereuc et al., 1997).

Oxidation is the most serious problem when using polymers at high processing temperatures (Wright, 2001). The influence of temperature on the oxidation process depends on chemical structure of the polymer. Thermo-oxidation is initiated by the reaction of polymer free radicals (P°) with oxygen to form peroxide radicals (Maxwell et al., 2006):



Thermal expansion can occur in polymers at elevated temperatures (Brown et al., 1995). Thermal expansion is reversible and generally does not significantly affect the life expectancy of a polymer. However, in polymer composites the mismatch between the different thermal expansions of the polymers and the fibres may cause thermo-mechanical degradation during processing and reprocessing. Similar mechanisms may also occur in adhesive joints (Brown et al., 1995).

2.1.2 Degradation during Extrusion

Plastic extrusion is a hot working process achieved by heating the material above its recrystallization temperature to avoid hardening and to make it easier to push the material through the die. During extrusion, raw plastic material is melted and formed into a continuous profile.

Extrusion is considered to be a primary polymer processing technique since all commercial polymeric materials are extruded at least once in their life cycle. This occurs either when they are pelletized at the end of the polymerization process, or

when additives are introduced (Capone et al., 2007). After several extrusion cycles, the high temperature shearing degrades the structure of polymer resulting in poorer thermal and/or mechanical properties (Oromiehie and Mamizadeh, 2004; Goto et al., 2006; Goitisoló et al., 2008).

The chain scission takes place during multiple extrusions and reduces the molecular weight, and can cause degradation (Canevarolo, 2000; Hermanová et al. 2009). Some improvements in melt flow index (MFI) and impact strength were observed during multiple extrusions of modified PP co-polymers (Tocháček et al. 2011). The yield strength was stable for PP/talc 80/20 (20 wt% talc) but increased for PP/talc 90/10 (10 wt% talc) with re-extrusion cycles, and the yield strength of neat PP increased for the first re-extrusion and then decreased for higher number of re-extrusions (Wang et al., 2013). Hence, talc has a positive effect on the mechanical properties of PP/talc composites during the initial extrusion cycles.

2.1.3 Degradation during Injection Moulding

Injection moulding is a manufacturing process for producing

parts from an array of different types of materials, including metals, glasses, elastomers, confections, and most commonly used thermoplastics. Material for producing the part is fed into a heated barrel, mixed, and forced into a mould cavity where it cools and hardens to the configuration of the cavity (Todd et al., 1994). It is a process which involves both heat and sheer force.

Virgin polyamide 6 (PA6) via multiple injection moulding cycles showed that the crystallization rate increased with increasing reprocessing cycles, resulting in an increase in tensile yield strength, flexural strength and modulus. However, impact strength decreased after each processing cycle (Su et al., 2007).

It was found that the viscosity of the low viscosity grade ABS reduced and the high viscosity grade ABS had an increase in melt viscosity as the number of injection moulding cycles increased (Boronat et al., 2009). The tensile modulus and the tensile strength of polycarbonates remained almost same during each of the multiple injection moulding cycles, while the impact strength decreased sharply (Pérez et al., 2010).

Mendes et al. (2011) evaluated both HDPE and LDPE during injection moulding cycles and confirmed the coexistence of two distinct degradation mechanisms, cross-linking and chain scission, which occurred due to thermo-oxidative reactions in reprocessing. Further, it was found that PE can be recycled with only minor material property losses under controlled conditions.

2.1.4 Photo-oxidation

All polymers contain free radicals due to their polymerisation and processing, and the concentration of free radicals can be significantly increased through interaction with light. This effect is called photo-oxidation. By definition, photo-oxidation of polymers refers to the chemical and physical changes that occur when radiation is absorbed by polymeric materials (White and Turnbull, 1994; Brown et al., 1995; Greenwood, 1997; Wypych, 2003).

The effects and mechanisms of polymer photo-oxidative degradation have been studied extensively (Amin et al., 1975; Ranby and Rabek, 1975; Slobodetskaya et al., 1982; Billingham et al., 1983; Rabek, 1995; Scott, 1999; Stevens, 1999).

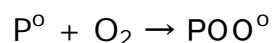
Degradation mechanisms caused by oxidation reactions are fairly well-established and include the following (Ranby, 1989; Wypych, 2003):

1. Extraneous groups and/or impurities in the polymer absorb light quanta and form excited states through the dissociation of the C-H bonds in the polymer chains. Initially singlet excited states (shortly-lived) which are transformed to triplet excited states (long-lived and reactive).



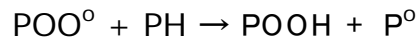
2. Excited triplet states may cleave the polymer chains and form radical pairs (Norrish Type I reaction) or form pairs of saturated and unsaturated chain ends by hydrogen transfer (Norrish Type II reaction).

3. The polymer radicals formed react with atmospheric molecular oxygen (in triplet ground state) to form peroxy radicals which abstract hydrogen and form hydro-peroxide groups.



4. The hydro-peroxide groups absorb UV light or become excited by energy transfer, the weak O-O bonds break and pairs of alkoxy and hydroxyl radicals are formed which may react in

various ways, e.g. by hydrogen abstraction, chain scission, rearrangement, etc. This is known as accelerated photo degradation.



5. Double bonds may add singlet excited oxygen molecules. In this reaction the double bond is shifted to an adjacent C-C bond and a hydro-peroxide group is formed.



The formation and propagation of free radicals in itself does not have a serious effect on the mechanical properties of the polymer, as they do not significantly alter the long-chain nature of the polymer molecules. Degradation of the mechanical properties occurs because the free radicals produced are highly unstable and readily undergo chain scission reactions. The chain scission reactions result in the formation of two smaller polymer chains, one of which is a free radical and capable of further reactions, for example:

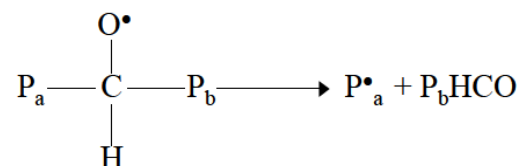


Photo oxidation and degradation are mainly initiated by the

absorption of UV wavelengths of light in solar radiation by chromophores and in the activation of excited states in macromolecules. Oxidation reactions without UV involvement are much slower than UV-initiated photo-oxidation. In almost all polymers photo-oxidative degradation occurs via a free-radical chain mechanism, and the starting reaction is initiated by the absorption of UV radiation by chromospheres within the polymer, which always result in bond scission in the polymer chain or in other molecule initiating degradation as procedure described previously (Vasile, 1993). Subsequent reactions include cross-linking and the formation of double bonds, acid and vinyl groups generated during reactions form from hydro-peroxide groups (Amin et al., 1975; Tidjani and Arnaud, 1993). Factors influencing polymer degradation caused by photo-oxidation include molecular structure, polymer morphology (degree of tacticity and crystallinity), internal impurities, specimen thickness, temperature, irradiation intensity and other climatic conditions (Vasile, 1993). Moreover, as Giesse and De Paoli (1988) point out, UV-irradiation could cause degradation of the surface layer of polymers.

2.2 Modification and Improvement

Once the problems associated with the manufacturing of

recycled plastics are identified, there is a need to improve recycled plastics through the use of fillers and experimental design tools.

2.2.1 Fillers for Plastics

One of the most common practices for improving the improvementally desired properties of recycled plastics is to blend recycled plastics with different substances or additives. Simple fillers are additives such as antioxidants, inert fillers and impact modifiers. These can improve mechanical properties of recycled plastics so that they are similar to those of virgin materials (Dintcheva et al., 1997).

2.2.1.1 Natural Fillers

Natural fillers come from renewable resources such as sawdust and starch and are relatively inexpensive (Ashori, 2008). They are also now well recognized as additives capable of reinforcing the capacity of composites. Those biodegradable composites not only exhibit good performance, but are also environmentally friendly.

1. Wood Fillers

Plastics-wood composite is a popular choice when considering

natural fillers (Youngquist et al., 1994; Sellers et al., 2000; Foulk et al., 2004; Kamdem et al., 2004; Chen et al., 2006; Adhikary et al., 2008). The tensile strength and modulus of plastic-wood composites are generally inferior compared to those of polymeric fibres such as PET fibre and they often exhibit significantly larger elongation giving them better damage tolerance (Mukherjee and Sathyanarayana, 1986; Chand et al., 1988; Groom et al., 1995). There has been a large amount of research on the reinforcement of virgin plastics with wood fibres particularly regarding the resulting mechanical properties, dimensional stability, interfacial bonding and durability (Raj and Kokta, 1991; Razi et al., 1997; Starka and Mautana, 2004; Lu et al., 2005).

Yam et al. (1990) and Selke and Wichman (2004) have studied recycled HDPE (rHDPE) and wood fibre composites using extrusion moulding and reported that the performance of those composites are as good as the composites based on virgin plastics. Chtourou et al. (1992) have studied injection moulded recycled polyolefins composed of 95% PE and 5% PP, reinforced with chemical and thermo-mechanical pulp fibre, and observed that tensile properties can be increased up to 150%. The

composites made by thermoforming of wood waste and recycled plastics from post-consumer milk bottles exhibits a broad range of properties similar to those made of virgin materials (Youngquist et al., 1994). Wood fibre-reinforced composite made from the waste stream have some good mechanical properties such as tensile strength and modulus, when compared with virgin materials (Miller et al., 1998). Hot-pressed composites of recycled pine wood fibres and recycled polyethylene have mechanical properties that are adequate for use in construction (Sellers et al., 2000). Jayaraman and Bhattacharya (2004) studied the performance of melt blending and injection-moulding composites made from Monterey pine (*pinus radiata*) fibres and rHDPE, and found that the tensile strength was 25% higher than those of composites using virgin HDPE (vHDPE). The rHDPE, recycled PP (rPP) and old newspaper (rONP) fibre used to manufacture experimental composite panels, without incurring any significant loss on properties, and even leading to relatively superior performance (Ashori and Nourbakhsh, 2009). In each of these studies, the performance of recycled plastics, especially of tensile properties, was improved by the addition of wood fillers.

Furthermore studies have shown that the performance of wood-plastic composites is strongly associated with the properties of fillers themselves such as particle size, treatment and additives used. The initial particle geometry of HDPE plays an important role in the quality of the combination of vHDPE and rHDPE and pine wood flakes (Rongzhi et al., 1997). The compression-moulded composites made of rHDPE and wood flour from chromated copper arsenate (CCA) treated pine wood exhibit higher flexural strength compared to composite from untreated pine wood (Kamdem et al., 2004). It was found that smaller sized wood particles improved water absorption and thickness swelling behaviour of hot-pressed composites based on construction wood waste and rHDPE (Chen et al. 2006). Adhikary et al. (2008) investigated the stability, mechanical properties, and the microstructure of wood-plastic composites made from recycled or virgin HDPE with wood flour obtained from *Pinusradiata* as the major filler, and maleated polypropylene (MAPP) as coupling agent. It was found that dimensional stability and strength of the composites can be improved by increasing the polymer content or through the addition of coupling agent. However, additional requirements or procedures associated with the use of wood fillers increase

production costs, thus limiting the potential use of these fillers.

2. Starch

Starch has also been used as natural filler in composites.

Studies have been carried out which focus on the effects and characterisation of adding starch to virgin or recycled plastics (Jane et al., 1992; St-Pierre et al. 1997; Jang et al., 2001; Pedroso and Rosa, 2005; Garg and Jana, 2007).

It was found that the addition of starch reduces the MFI, the tensile strength and the elongation at break of extruded recycled LDPE/starch blends, but increases the Young's modulus (Pedroso et al., 2005). This is similar to the starch–LDPE blends made by Garg and Jana (2007).

2.2.1.2 Mineral Fillers

Another type of common filler used to improve recycled plastics is mineral fillers such as the talcum powder (talc). It has been reported that mineral fillers have following effects (Lazzeri et al., 2005; Brachet, et al., 2008):

1. They improve mechanical performance;
2. They improve dimensional stability;

3. They improve flame retardancy;
4. They reduce viscosity;
5. They reduce cost.

Talc is a type of common mineral filler which has been widely applied in polymer field, especially industrial applications for improving the quality of plastics, such as PP (Aasetre et al., 1998; Karian, 2003; Liu and Li, 2006; Lederer et al., 2010). Talc has been applied in improving the performance of recycled PP (Long et al., 1995; Tall et al., 2001; Bahlouli et al., 2006). Talc was used as a filler in a compound consisting of recycled PP and elastomeric rubber - Ethylene Propylene Diene Monomer (EPDM), and compared the performance with virgin specimens (Tall et al. 2001). The testing results showed talc-filled recycled PP yielded mechanical properties similar to those of a commercial PP composite used for demanding engineering applications (Tall et al. 2001). Bahlouli et al. (2006) tested recycled PP by compounding with talc and/or a specific virgin high-crystallinity PP, and the results indicated that the composites can be used for demanding engineering applications, such as automobile parts.

Brachet et al. (2008) modified the mechanical properties of recycled PP from post-consumer containers with the addition of stabilisers, elastomer (ethylene–octene rubber, EOR) and calcium carbonate (CaCO₃). The results showed limited improvements with the addition of those fillers, and differential scanning calorimetry (DSC) analysis confirmed the presence of PE in the recycled PP. The impurity and the presence of many different qualities of PP in the recycled material may have prevented any possible improvement seen in previous studies on virgin polymers (Yang et al., 2006; Brachet et al., 2008).

2.2.1.3 Nano-fillers

Composites have been made from polymers filled with small particles in order to improve the properties or to reduce the cost of the final product. It has been previously reported that the addition of conventional fillers, such as mineral particles and fibres, leads to weight increase, brittleness and opacity of the composites, thus limiting their potential use (Alexandre and Dubois, 2000; Fischer, 2003).

Nanotechnology is one of the key technologies in the recent century, and it already been applied in the material engineering

field for making new composites used in demanding industrial applications (Shabani et al., 2012). Nanofiller is a doping agent distributed in the matrix of a composite. Nanocomposites, a new class of composite, are particle-filled polymers for which at least one dimension of the dispersed particles is in the nano-meter range (Alexandre and Dubois, 2000). While nanofiller particles are usually sized below 100 nm, their higher specific surface area than that of fillers with larger particles allows one to substantially reduce the composite's degree of filler loading. Transitions to the nanoscale of conventional fillers alongside the optimised combination of processing parameters helps to not only reduce specific consumption of the filler, but also to produce higher performance materials at low filler loading.

Nanocomposites have relatively low loading - approximately 5% of composites' weight of nano-fillers were sufficient to achieve the improvement of overall performance, including mechanical and thermal properties, and without increasing the density and cost or reducing the light transmission (optical) or other mechanical properties of the base polymer (Yoo et al., 2004; Andričić et al., 2008; Gao et al., 2011; Shi et al., 2011; Jafari et

al., 2012; Shahabadi and Garmabi, 2012; Zare and Garmabi, 2012a; Zare and Garmabi, 2012b).

1. Nanoclay

Nanoclays are nanoparticles of layered mineral silicates, i.e. mineral silicates whose critical dimensions are less than 100 nm. Montmorillonite, bentonite, and halloysite nanoclays and organoclays are the most common nanoclays used in polymer-clay nanocomposites. Polymer-clay nanocomposites (PCNs) have received special attention in recent years because they exhibit dramatic improvement in properties such as Young's modulus, tensile strength and thermal stability at very low content compared with conventional fillers (Ray and Okamoto, 2003; Yu et al., 2004; Pavlidou and Papaspyrides, 2008). These improvements in properties are attributed to the strong synergistic effects between the polymer and the silicate platelets on both the molecular and the nanometric scale (Ray and Okamoto, 2003; Zhang et al., 2004).

Good dispersion of nanoclay layers gave the PCNs greater thermal stability and improved their mechanical properties, indicating a reinforcing effect of the clay in the polymer matrix.

The performance of the nanocomposites was found to be strongly dependent on clay percentage (Alexandre and Dubois, 2000; Gorrasi et al., 2002; Zhang et al., 2004; Liu and Xu, 2011; Zhu et al., 2011). The mechanical and thermal properties of the recycled PVC (rPVC)/clay nanocomposite increased simultaneously for various clay loadings, (1 wt%, 3 wt%, 5 wt% and 10 wt%), and the tensile storage modulus of nanocomposite composed of 10 wt% of nanoclay was 11 times higher than that of original rPVC (Yoo et al. 2004). Hamzehlou and Katbab (2007) have found the optimal DK2 (a type of nanoclay) content to be 3 wt% for tensile strength of both recycled and virgin PET nanocomposites. Higher contents of nanoclay in nanocomposites based on rPMMA with both natural and organically modified silicate exhibit worse light transmittance capacity but have higher tensile modulus (Martin et al., 2008). According to Zhang et al. (2009a), the mechanical properties of recycled glass fibre reinforced flame retardant PBT were improved using three types of nanoparticles including SiO₂, montmorillonite (MMT) and mica. Figure 2-1 showed the impact strength of prepared samples with different nanoparticles.

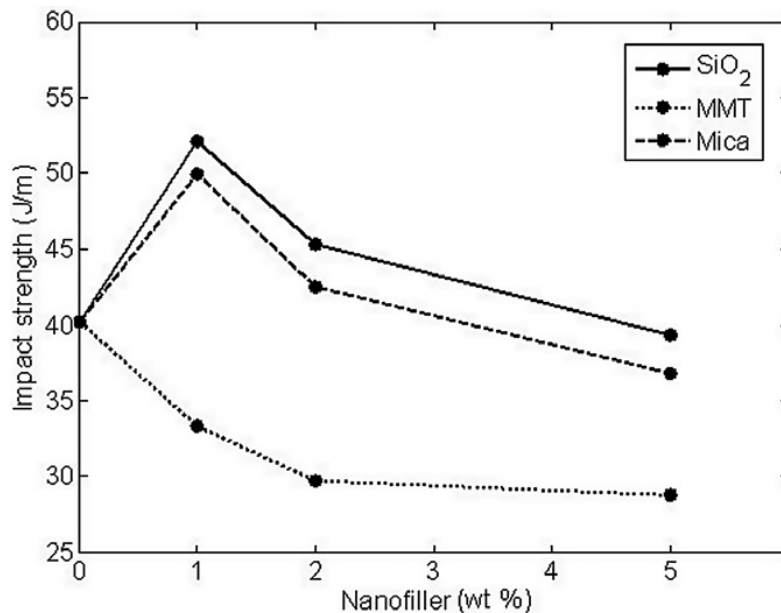


Figure 2-1 Impact strength of rPBT nanocomposites containing different nanoparticles (Zhang et al., 2009)

It was shown that the samples containing SiO₂ and mica demonstrated the largest improvement in impact strength at 1 wt% concentration. The MMT inversely caused a reduction in impact strength due to reduction in chain mobility, and the tensile/flexural strength was shown to have the same trend. But the heat distortion temperature (HDT) increased with addition of SiO₂ and mica, and the addition of further nanoparticles did not significantly affect the electrical and flame retardancy. It was found that the Young's modulus increased significantly when the polycarbonate (PC) composite contained 5 wt% organoclay (Labidi et al., 2010). The tensile strength and impact strength of rPET/ABS/AES nanocomposites improved as the content of nano-SiO₂ increased (Shiet et al., 2011). Also,

the dispersion of nano-SiO₂ fillers in the composite facilitates the dispersion of the two-continuous phases of rPET/ABS (Shiet et al., 2011). Nanocomposites with 5 wt% of organoclay have a slightly higher tensile modulus and tensile strength than base materials (Szustakiewicz et al., 2011).

Some research focused on the enhancement mechanisms of nanoclay. Mechanical tests demonstrated that rPET/organoclay nanocomposite properties were superior to the recycled PET in terms of strength and elasticity modulus (Bizarria et al., 2007). This improvement is attributed to nano-scale effects and strong interaction between the rPET matrix and the clay interface, as revealed by wide-angle X-ray scattering (WAXS) and transmission electron microscopy (TEM) (Bizarria et al., 2007). With the addition of 2 wt% of nanoclay, the morphology of the blend changed significantly (Kerboua et al., 2010). Increments in nanoclay loading from 2 wt% ~ 5 wt% led to a reduction in particle size (Kerboua et al., 2010). These results indicated the strong interfacial activity of nanoclays occurring in this polymer blend.

Other research focused on identifying the compatibilisation

effect of coupling agents in recycled nanocomposites. Lei et al. (2007) used both maleated polyethylene (MAPE) and titanate for compatibilisation of rHDPE with nanoclay. Both compatibilisers could improve the compatibilisation of components, as the impact strength of rHDPE/clay composite containing 5% MAPE increased by 44% compared with that of the hybrid containing no MAPE. Furthermore, the storage and loss moduli increased with up to 5 wt% of clay in hybrids. MAPP grafted nanocomposites with 3 wt% ~ 5 wt% have optimal mechanical performance (Liu and Liang, 2011), and the composites grafted with the MAPP have the best tensile results when the MMT weight percentage is 3 wt% (Liu and Xu, 2011). Despite the significant improvements in the properties mentioned before, a major drawback of PCNs which limits their range of potential engineering applications is reduced toughness, especially when the organoclay content is above 5 wt% (Yu et al., 2004).

2. CaCO₃ Nanoparticles

CaCO₃ is common mineral filler, and can be used as nano filler if it has a particle size within the nano range (<100 nm).

Andričić et al. (2008) added virgin PVC (vPVC) and CaCO₃ nanoparticles to a waste laminate containing PVC, CaCO₃ and PP in the following amounts - 40 wt%, 25 wt%, and 10 wt%, respectively. The tensile strength and elongation at breakage of PVC compounded sheets containing 10 wt%, 20 wt% and 30 wt% of waste laminate (1 wt%, 2 wt% and 3 wt% of PP) decreased as PP content increased. In the samples with lower PP content, mechanical properties improved as the filler content increased, while with higher PP content, mechanical properties peaked at about 6 wt% of CaCO₃ content. The yield strength and strain of virgin PP decreased gradually with the CaCO₃ nanoparticle content, while its Young's modulus increased slightly with increasing CaCO₃ loading (Elloumi et al., 2011). These phenomena were less pronounced for the recycled matrix, where only a little increment was observed in the yield strength.

3. Carbon Nanotubes

With increasing carbon nanotubes (CNTs) content, tensile strength and elongation at break of rPP based composites initially increased and then decreased as shown in Figure 2-2 (Gao et al., 2011). The later decrease was probably attributed

to interface compatibilisation, as a unique tensile rupture characteristic was observed by SEM (Gao et al., 2011).

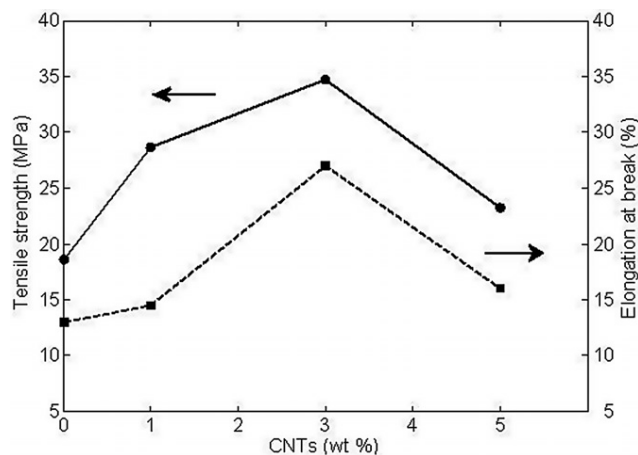


Figure 2-2 Mechanical properties of rPP/CNTs nanocomposites (Gao et al., 2011).

2.2.1.4 Fibres

The practice of adding of various fibres to polymers to improve performance has been carried out for more than half a century (Marsh, 2006). Glass fibre (GF) has been commonly used as a reinforcing agent for polymers since it was developed (Marsh, 2006). By adding glass fibre to polymers, their compressive strength, tensile and flexural strength, notched and unnotched impact strengths increased significantly (Rijsdijk et al., 1993; Thomason and Schoolenberg, 1994; Lee and Jang, 1999; Thomason, 2002; Valente et al., 2011). Glass fibre has comparable properties to other fibres such as natural fibres or carbon fibre (Summerscales and Short, 1978; Manders and

Bader, 1981; Corbière-Nicollier et al., 2001; Wambua et al., 2003). When compared with carbon fibre, it is much cheaper and significantly less brittle though it is not as strong as carbon fibre (Fu et al., 2000).

Research has been carried out into the area of blending recycled plastics with glass fibre. Glass fibre was added to recycled poly ethylene terephthalate (PET), and the results showed improvements in mechanical properties such as Young's modulus and impact strength (Giraldi et al., 2005). Glass fibre was added to rPP/palm wood flour composites, and an extruder and an injection moulding machine was used to mix and prepare samples. The results showed that the tensile strength and Young's modulus of wood flour reinforced rPP increased further by adding glass fibre (Al Maadeed et al., 2012). Addition of as little as 5 wt% glass fibre to wood flour reinforced RPP increases the tensile strength by about 18% relative to wood flour reinforcement alone (Al Maadeed et al., 2012).

2.2.2 Reactive Processes

Other methods for improving properties of recycled plastics are adding additives during reprocessing, or so-called reactive

extrusion. During reactive extrusion, individual components are first bonded by chemical reactions. Various additives are added to trigger those chemical reactions. Different chain extenders such as bis cyclic-imino-ethers and 2, 2'-bis(2-oxazoline) can be used to increase the molecular weight and reduce carboxyl contents, providing a relatively simpler and cheaper method to obtain high-molecular-weight polymer (Guo and Chan, 1999; Awaj, et al., 2004; Awaja and Pavel, 2005a; Tang et al., 2007). The molecularweight improving effects of certain chain extenders have long been established (Inata and Matsumura, 1987; Cardi et al., 1993; Karayannidis et al., 1995; Bikiaris and Karayannidis, 1995; Bikiaris and Karayannidis, 1996; Loontjens et al., 1997; Haralabakopoulos et al., 1999; Rosales et al., 1999).

By extending the chains in polymer, the performance of the material is improved, expanding its usage. The molecular weight of rPET could be improved by chain extension processes using 2,2'-(1,4-phenylene)bis(2-oxazoline) (PBO) as the chain extender (Karayannidis and Psalida, 2000).

Pyromelliticdianhydride (PMDA) was used as a chain extender to increase the molecular weight of rPET and thus made this

recycled polymer suitable for film blowing and blow moulding processes (Incarnato et al., 2000).

Many researchers found that by adding chain extenders into recycled polymer materials the performance of those materials improved. Guo and Chan (1999) used a high-reactivity diepoxy-diglycidyl-tetrahydrophthalate as a chain extender which can react with the hydroxyl and carboxyl end groups of polybutylene terephthalate (PBT) at a very fast rate and a relatively high temperature. They found that the melt flow index (MFI) dramatically decreased as the diepoxy-diglycidyl-tetrahydrophthalate was added. The notched Izod impact strength and elongation-at-break of the chain-extended increased and the polymer showed increased thermal stability. Polymeric methylene diphenyldiisocyanate (PMDI) was used as a chain extender in a blend of rPET and linear low density polyethylene (LLDPE) and the results demonstrated that the impact strength of the blend with 1.1 wt% PMDI increased by 120% relative to the blend without PMDI, while the tensile strength decreased by 8% (Zhang et al., 1999). Awaja and Pavel (2005a) studied the effects of extruded rPET blended with vPET, and found that bottles made from rPET and

virgin PET blends displayed similar or enhanced mechanical and barrier properties at certain compositions to those made from vPET. Furthermore, Awaja and Pavel (2005b) used experimental results in an optimisation process aiming to identify the composition that produces best bottle properties. The rPET with pyromellitic dianhydride (PMDA) exhibited higher complex viscosity and higher storage modulus compared to unmodified rPET samples (Daver et al., 2008).

2.2.3 Restabilisation and Compatibilisation

Restabilisation is a procedure that protects polymers from chain scission and other thermal or photo degradation, while compatibilisation procedure modifies the interfacial character of polymers and stabilises their morphology. Both procedures are triggered by the addition of specific additives, such as UV stabilisers, compatibilisers, and chain-extendors.

The practice of upgrading the recycled post-consumer plastics via restabilisation and compatibilisation was recommended for high-value products (Pospíšil et al., 1995).

2.2.3.1 Restabilisation

The purpose of stabilisers is to prevent plastics from chemical damage that occur during processing, reprocessing and first-life application and to reduce structural inhomogeneity (polymeric impurities) formed in the polymers during processing and ageing (Pospíšil et al., 1997). Furthermore, they reduce non-polymeric impurities admixed or generated during the first lifetime of the plastic, and increase the resistance to degradation (Pospíšil et al., 1997). Studies have shown the protecting effects of stabilisers against chain scission and other thermal or photo degradation on processes (Drake et al., 1990; Pospíšil, 1993). Some restabilisation procedures were applied to recycled plastics (Holmström and Sörvik, 1977; Mitterhofer, 1978; Allen and McKellar, 1980; Klemchuk and Thompson, 1992). The recovery effects on physical properties of the stabilisers can make recycled plastics suitable for demanding applications (Pospíšil et al., 1997; Pfaendner et al., 1998).

PVC and CPE in LDPE recovered from PE film wastes adversely affected the thermo-oxidative stability of LDPE (Holmström and Sörvik, 1977). Based on the examination of PVC and CPE, It was found that HCl was produced during processing, and

stabilisation of the LDPE is proved to be best achieved by phenolic antioxidants (Holmström and Sörvik, 1977). Mitterhofer (1978) used Sandostab P-EPQ, an organic phosphonite compound as a stabiliser, which retards or prevents the degradation. They also discussed the recycling of PP, HDPE, LDPE and PC from used materials which have or have not been exposed to service conditions in order to prove the protection effects of stabilisers.

Gugumus (1994) studied the stabilisation effects and mechanisms of hindered amine stabilisers (HAVE) added into PP against thermo-oxidation, compared with stabilisation with phenolic antioxidants. The results showed the experimental results matched the theoretical dependence of the lifetime of hindered amine stabiliser (HAS) stabilised PP on HAS concentration. Recycled post-consumer films with an antioxidant were compared to an UV stabiliser with untreated films, and it was reported that the film with stabiliser can withstand longer UV exposure without becoming brittle and that the protective action of the antioxidant avoids the formation of oxygenated compounds during the processing (Dintcheva and La Mantia, 2004). Recycled LDPE blended with

high-impact polystyrene (HIPS), styrene–butadiene copolymer (SB) and ethylene–propylene–diene monomer (EPDM), then restabilised with N,N′-disubstituted 1,4-phenylenediamine (PD), and it was found that the impact tensile strength was improved (Pospíšil et al., 2005).

2.2.3.2 Compatibilisation

The compatibilisation procedure has three objectives (Utracki, 2002):

1. Optimisation of the interfacial tension;
2. Stabilise the morphology against high stresses during formation;
3. Enhance adhesion between the phases in the solid state.

A mixture of commercial copolymers (EPDM – ethylene-propylene-diene statistical terpolymer and SBS – styrene-butadiene-block copolymer) was established as an efficient compatibiliser for polyethylene/polypropylene/polystyrene blends and for application on municipal plastics waste, and performance was improved after the addition (Fortelný et al., 2002).

Polystyrene-ethylene/butyldiene-styrene (SEBS) and maleic anhydride-grafted polystyrene-ethylene/butyldiene-styrene (SEBS-g-MA) were used to compatibilise the blends of rPET and LLDPE. It was found that elongation at break and Charpy impact strength of the blends increased with the increasing content of compatilizer, and higher SEBS-g-MA content can induce the formation of a salami microstructure (Zhang et al., 2007).

2.2.4 Optimisation Tools

Significantly less research has been conducted on the use of optimisation methods to improve recycled plastics.

Mehat and Kamaruddin (2011) looked to improve the mechanical properties of products made from recycled plastic by utilising the Taguchi method to optimise the parameters in the injection moulding procedure. Four controllable factors (melt temperature, packing pressure, injection time, and packing time), each at three levels, were tested to determine the optimal combination of factors and levels in the manufacturing process. The results revealed that the product made of 25% recycled PP and 75% virgin PP exhibited a better flexural modulus compared to the virgin PP.

Homkhiew et al. (2014) utilised a mixture design to determine the optimal mixture for composites of rubber-wood flour (RWF) and reinforced recycled PP. The optimal formulation found was 50.3 wt% rPP, 44.5 wt% RWF, 3.9 wt% MAPP, 0.2 wt% UV stabiliser, and 1.0 wt% lubricant. This composite has desirable mechanical properties that closely matched model predictions.

2.3 Close-looped Recycling of Automobile Plastic Parts

Research on the use of recycled plastics in automobile production is limited. Existing studies have mainly focused on the close-looped recycling of end-of-life vehicles (ELVs) but generally of metal parts. Table 2-1 lists parts of an ELV that are recycled and reused in common practices, with indication of possible end products (Zameri and Saman, 2006). As shown in Table 2-1, among them, seats and bumpers are the only parts made of plastics that were recycled or reused in automobile production.

Table 2-1 Automobile parts those are recycled or reused from ELVs in common practices (Zameri and Saman, 2006)

Part	Material	Recycled as
Window	Glass	Tiles
Seat	Foam and fibre	Soundproofing materials for vehicles
Body, trunk, hood and door	Steel	Car parts and general steel products
Wire harness	Cu	Cu and engine products (cast Al reinforcement)
Bumper	Resin	Bumper, interior parts, toolbox, etc.
Radiators	Cu and Al	Gun metal ingots and Al products
Coolant, engine and gear oil	Oil	Alternative fuel for boilers and incinerators
Engine transmission, suspension and wheel	Steel and Al	General steel and Al products
Catalytic converter	Precious metals	Catalytic converters or precious metal (e.g. platinum) recycling
Tire	Rubber	Raw material and energy recovery (e.g. cement kilns)

2.3.1 Collision Bumpers

Collision bumpers are one of the largest automobile parts which are made from plastics, as a safety measure and for aesthetic

decoration. Bumpers from ELVs are usually of good quality, as the impact strength of thermoplastic olefin (TPO) material recovered from end-of-life bumpers is over 25.59 kJ m^{-2} , about 10 times higher than normal PP+EPDM+HDPE plastic composite. This recycled material could be a useful material for several applications in the automotive industry (Martins et al., 2000).

According to a life cycle analysis (LCA), Makuta et al. (2000) pointed out that compared with bumper-to-bumper recycling, the materials recovered from end-of-life bumpers are more suitable and more environmentally friendly for the production of other low quality automobile parts, such as splash shields.

However, metal inserts (Iron, Aluminium) within the bumper should be removed. PVC, PE or certain sheet moulding compounds (SMC), which are not compatible with PP, should be separated and classified. Any paint on the surface must also be removed, in order to recover the materials while retaining their value. Recyclers in Europe have developed the following procedure (see Figure 2-3) (Froelich and Maris, 2007).

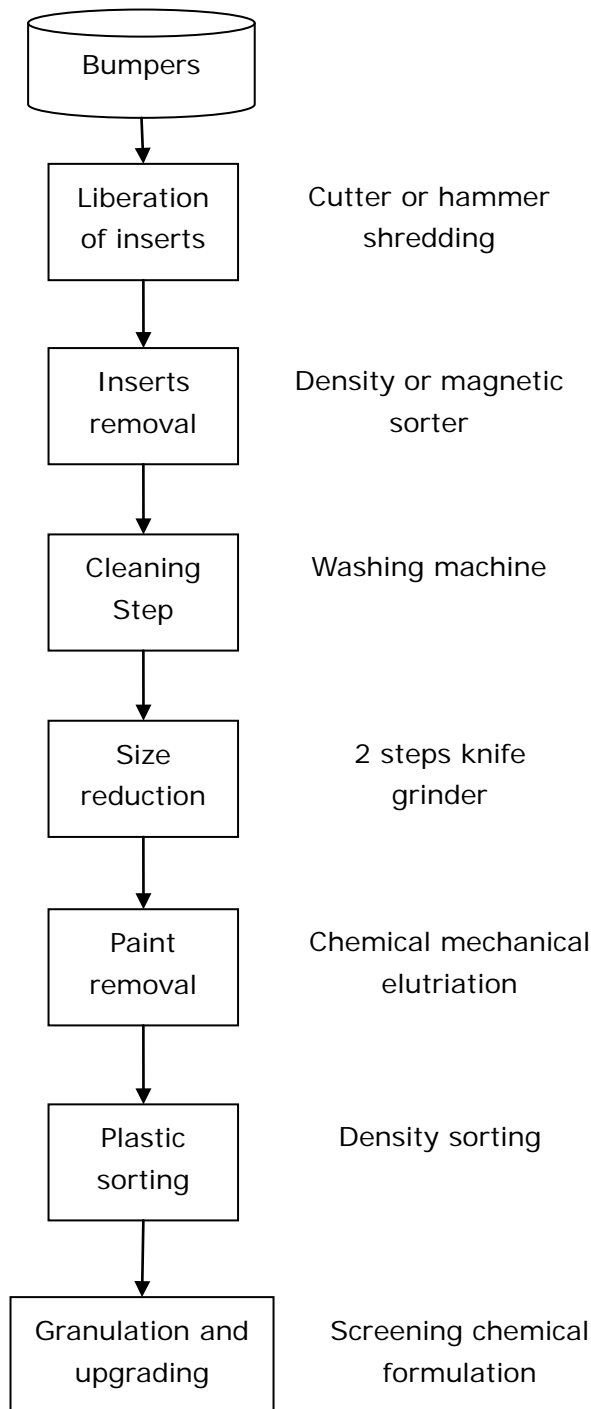


Figure 2-3 Processes and technologies used to recycle bumper (Froelich and Maris, 2007)

Ohori et al. (1996) have used a modifier which allows the ether linkage in the paint film to be cleaved and its molecular structure changed, which results in improved compatibility

between the paint and the material. They also studied extrusion and moulding technologies in order to make the modified recycled material meet certain requirements of automobile production. Furthermore, they pointed out that the continuous procedure of modification and pelletization can reduce the number of process steps and total processing time. The procedure is proved to be productive and economic, as shown in Figure 2-4 (Ohori et al., 1996).

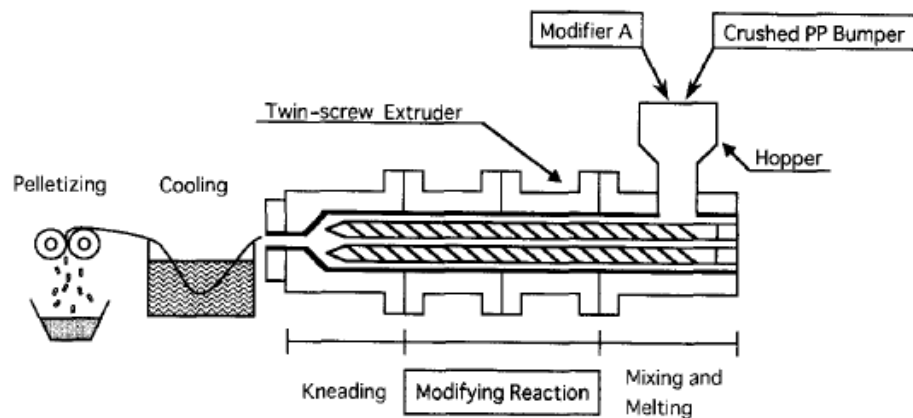


Figure 2-4 Paint-coated PP bumpers modifying process (Ohori et al., 1996)

With the purpose of successfully restoring and enhancing the mechanical properties of recycled materials from end-of-life bumpers, Luda et al. (2003) designed an additive which contained a regenerative agent and an antioxidant system. This re-established the compatibility while the antioxidants inhibit oxidation. It was shown that the product could be used in

automobile production again.

2.3.2 Dashboard

The dashboard or instrument panel is an important plastic component used in automobiles for installing electrical equipment and control instruments.

Two kinds of dashboard are commonly employed:

1. Rigid dashboard (uncovered) made by a rigid body in polypropylene with a number of parts in ABS based materials;
2. Covered dashboards, which can be classified into two different types: the first consists of a rigid support in polycarbonate/ABS and a leather-like covering in foamed PVC.

The second type of covered dashboard is made from a rigid support in ABS reinforced with glass fibre, an intermediate layer of foamed polyurethane and a final leather-like covering in PVC/ABS.

Toshino et al. (2000) developed a set of manufacturing processes to achieve dashboard-to-dashboard recycling, to produce materials which have sufficient mechanical strength and thermal stability. Ragosta et al. (2000) developed

technology for recycling multilayer automobile dashboards based on polypropylene. They observed that the recycled material showed a strong reduction in the mechanical and impact properties due to the occurrence of thermo-oxidative and thermo-mechanical degradation phenomena taking place during processing and reprocessing. With a suitable antioxidant and stabiliser additive, only a limited degradation in the overall mechanical behaviour occurs during the recycling. A more significant enhancement has been achieved in terms of deformation at break - impact toughness and overall morphology when an ethylene-propylene copolymer and virgin polypropylene were added to the formulation during the recycling process. By means of this procedure materials with properties suitable for reuse within the car have been identified.

2.3.3 Fuel Tank

A fuel tank designed to hold flammable automobile fuel can be constructed from high-density polyethylene (HDPE). While viable for recycling when used in the short term, in the long term HDPE can be permeated with fuels such as diesel and gasoline.

Polyethylene (PE) from post-customer automotive fuel tanks is considered a valuable material for recycling: mechanical properties of the regenerated material are similar to mechanical properties of vHDPE (Graham et al., 2000). Gorrasi et al. (2002) studied HDPE scraps from used fuel tanks with rheological analysis (rotational rheometry) of the molten materials and their processability. He concluded that HDPE recovered from post-use fuel tanks can be used in producing new automobile fuel tanks. Hunter et al. (2003) demonstrated the feasibility of utilising high-density polyethylene (HDPE) recovered from post-consumer automotive fuel tanks using an explosion process in combination with wood fibre to create a new material suitable for use in an automotive substrate, such as a mat in an automotive interior door panel.

2.3.4 Other Components

Due to the pressure from legislation on recycling post-customer automobiles, Sims and Angus (1996) have incorporated polyester polyurethane foam and foam/fabric laminates recycled from automotive seat covers into re-bonded foam using a prepolymer based on diphenylmethanediisocyanate (MDI). It was shown that composite could be used in

manufacturing automobile parts. Up to 25% foam by weight could be replaced by laminate without adversely affecting compression or fatigue properties, thereby providing a potentially useful route for the recycling of automotive laminates.

Carlson et al. (2003) developed a new recycling technology for polyamide which is referred to as "Nylon Composite Recycle", which allows for the recovery of the base resin that is then recycled into a radiator end tank with performance equivalent of the one made of virgin resin.

Kang et al. (2008) studied the recovery methyl methacrylate (MMA) from lenses of exterior lights of end-of-life automobiles. The MMA recovered from the experiments can be used as feedstock for the polymerization of polymethyl methacrylate (PMMA).

2.4 Other Properties of Plastic for Manufacturing

2.4.1 Reprocessing

It is important to study the effect of repeated processing cycles on the properties of polymer composites (Kalfoglou and Chaffey, 1979). Moreover it is economical for manufacturers to reuse

rejected parts in the production, which involves the procedure of reprocessing (Hamskog et al., 2004; Nunes dos Santos et al., 2007). In industrial practice, the rejected parts are collected, shredded and fed into the injection moulding machine in order to produce new parts (Joyson, 2011).

Currently, there are some existing studies which have been conducted on reprocessing of PP/talc composites. The molecular weight of PP/talc composites decreased after multiple injection moulding cycles and break properties (such as Elongation at break) were related to the filler content and processing conditions (Guerrica-Echevarría et al., 1996). A better thermal and structural stability for talc-filled high impact polypropylenes (HiPP) was found on recycling of two HiPPs (Bahlouli et al., 2012). Wang et al. (2013) pointed out that during the repeated extrusion cycles, talc in PP slightly increased the Young's modulus and the yield strength.

Yet, most current studies have only focused on reprocessing effect on virgin composites, e.g. virgin PP/talc composites, or the recycling of waste plastics from different sources. The influence of the filler content and reprocessing cycle numbers

on the properties of recycled PP-based composites has received little or no attention. Lack of research on recycled plastic based materials would certainly limit their use. Further, there is no research comparing the effects of two major reprocessing routes (extrusion and injection moulding) despite the fact that, in an industrial context, mechanical recycling usually involves both procedures (Minth, 2012; Lindahla et al., 2014).

2.4.2 Flammability

Like the majority of organic materials, most polymers burn readily in air or oxygen. The flammability of polymers is an important issue and severely limits their applications (Troitzsch, 1983; Brossas, 1989). In industrial applications, such as electronic enclosures, ships, airplanes and automobile, there is a noticeable need for fire-resistance in polymers (Gann et al., 1987; Zhang, 2004). High strength/density ratio of polymeric materials offers more advantages than conventional materials, but they greatly increase the likelihood of fire hazard because of their flammability and possible release of toxic by-products (Zhang, 2004). In general, non-polymeric materials (e.g., matches, cigarettes, torches, or electric arcs) are the main sources of ignition, but polymers are most frequently

responsible for the propagation of a fire (Zhang, 2004). Under some circumstances, polymers undergo self-sustained combustion in air or oxygen (Landrock, 1983).

Of the 1.6 million fires reported each year in the USA, one out of five (300,000) are vehicle fires, causing approximately 3,000 injuries and claiming approximately 500 lives per year on average (U.S.F.A., 2002; F.E.M.A., 2003; Ahrens, 2005, 2006).

The rapid progression of fire is one of the major contributing factors in two thirds of vehicle fire deaths (F.E.M.A., 2003).

Thus, promoting the flame retardance of plastic materials used in automobile components is of critical importance, especially when considering automobile manufacturers continue to replace metal with combustible plastic for lighter and more fuel-efficient cars.

Polymer combustion occurs as a cycle of coupled events (Cullis and Hirschler, 1981): (1) heating of the polymer, (2) decomposition, (3) ignition, and (4) combustion. The polymer is first heated to a temperature at which it starts to decompose and gives out gaseous products that are usually combustible.

These products then diffuse into the flame zone above the

burning polymer. If there is an ignition source, they will undergo combustion in the gas phase and liberate more heat. Under steady-state burning conditions, some heat is transferred back to the polymer surface, producing more volatile polymer fragments to sustain the combustion cycle. This process is shown in Figure 2-5.

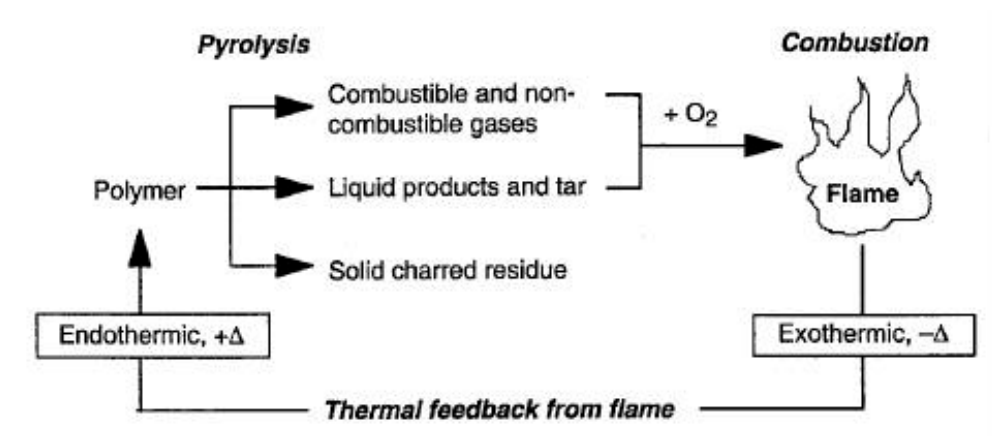


Figure 2-5 Schematic diagram of polymer burning (Zhang, 2004)

Although flammability of plastic composites have been studied intensively in the past (Lu and Hamerton, 2002; Zhang and Horrocks, 2003; Kiliaris and Papaspyrides, 2010; Mngomezulu et al., 2014), there is no research on flammability of recycled plastic based composites.

2.5 Summary of Current Study on Recycled Plastics

The properties of recycled plastics deteriorate under the

influence of many factors. Degradation of the mechanical performance of polymers takes place during their processing and reprocessing in elevated temperatures. Photo-oxidation occurs during their life cycle and under the influence of multiple effective degradation agents. Deterioration in polymer performance is attributed to macromolecular chain scissions, which can result from shearing under high temperature or oxidation reactions.

The strengthening effects of various fillers have been studied thoroughly, from traditional mineral fillers, biodegradable fillers to nano-fillers. Many researchers have shown that with the additions of those fillers, the performance of recycled plastics was in some respects close or even superior to those of virgin plastics. Chain extenders were added into recycled plastics to extend the macromolecular chain, improving the rheological and mechanical properties during these reactive processes. A Stabiliser and compatibiliser were added, and an increase in mechanical properties, e.g. tensile impact strength, was observed.

However, new formulas or processes which produce new

composite materials from recycled plastics are introduced each year. Limited research is reported on combining new formulas and new processing procedures with the use of recycled plastics and there is little application of the above in automobile manufacture. Limited research based on optimisation methods, which include experimental design and mathematical modelling tools was found to exist currently.

Some research has been conducted in adopting recycled plastics into manufacturing, and most studies focused on close-looped recycling of major components, such as bumpers, dashboards and fuel tanks. Thus far no studies have investigated the reprocessing and flammability of recycled plastics even though these two properties are of critical importance for polymeric materials used in manufacturing.

2.6 Knowledge Gap

Much of the research into recycled plastics has focused on their properties, ageing or degradation mechanisms, and enhancement methods. Yet the question "why is there so little recycled plastics in automobile production?" still remains unanswered. There is scarce research into the use of recycled

plastics in automobile production, and no application of new formulas or innovative processing procedures in manufacturing are reported. The use of recycled plastic is seen as troublesome in production terms because of possible variances in the recycled plastics properties.

There is a necessity to use common recycled plastics in the current market because they are abundant and inexpensive when compared with specialised recycling of specific ELV plastics. A knowledge gap in this area exists, possibly because of the high standards required for plastics used in automobile production. Current research tends to focus on using recycled plastic for lower value products with technical specifications.

The high specifications for automobile plastics at times ignore what is actually needed for specific parts. Specifications err on the side of caution, setting up false barriers to entry for the use of recycled plastic in automobile production.

The challenge of this research is to examine the feasibility of using recycled plastics in automobile production. The properties of recycled plastics, such as mechanical performance and flammability, will be looked into to assess their performance

during manufacture and post-manufacturing. However, improving mechanical properties is an insufficient means of proving the feasibility of using recycled plastics in automobile production. A suitable plastic should exhibit good mechanical, rheological, thermal and flammability properties, be economically viable and have a long life expectancy when exposed to hostile service environments.

To address this challenge, the following steps have been identified:

1. To review current plastic recycling products on the market with the purpose of identifying potential problems;
2. To identify the appropriate fillers and processing procedures for improving the performance of these recycled plastics;
3. To investigate the performance of modified recycled materials in hostile service environments by means of durability and flammability tests;
4. To assess recycled plastics using various criteria, such as performance, procedure and cost, to create a better understanding of the potential of recycled plastics.

This research aims to understand why there is no recycled

plastic in automobile production, with a view of promoting recycled plastics which meet the specifications for automobile parts. In the following sections, a selection of fillers and tools for promoting recycled plastic are discussed.

2.7 Selected Fillers for Recycled Plastics

Addition of fillers into recycled plastics may get certain properties closer to the performance of industrial virgin PP or other industrial composites, or help meet some standards.

In practice, carbon fibre is too expensive to reinforce recycled plastics. Natural fillers are renewable and relatively inexpensive (Ashori, 2008). However, the temperatures during processing of the virgin and recycled PP are beyond 180°C, which would cause decomposition and carbonization of almost all natural fillers, such as flax fibre, wood flour or starch. The natural fillers were not tested in this research.

Fillers representing the three common types were selected: talcum powder (talc) which represents a mineral filler, glass fibre (GF) which represents a fibre, and organically modified

montmorillonite (OMMT) which represents a nanoclay.

Although these three fillers are widely used in industrial applications, limited research on their use with recycled plastics has been reported. For example, OMMT is an example of nanoclay, which has been widely studied (Zhang et al., 2004; Liu and Xu, 2011; Zhu et al., 2011). Although OMMT has become intensively studied, only a handful of researchers have looked at recycled plastic nanocomposites filled with OMMT.

2.8 Selected Tools for Recycled Plastics

In order to use using recycled plastics in the manufacturing industry, the following questions should be answered:

1. What is the suitable proportion for adding recycled plastics to the blends (with virgin materials)?
2. What is the suitable manufacturing procedure for recycled plastics?
3. How to evaluate the materials which could be used based on the consideration of a range of properties?

To answer those questions, suitable tools need to be identified.

These tools should meet the following requirements:

1. Solving the questions without the need for acquiring large amounts of experimental data, which is costly and environmentally damaging;
2. Solving the questions without subjective input, e.g. criteria, rules or guidelines, for subject input would vary from person to person, and further limit the use of recycled plastics;
3. Solving the questions without too much computation complexity, i.e. a requirement for a quick solution.

In this section, different tools are identified and evaluated to answer each of these three questions. This could reduce both the cost and emission caused by repeated tests on each possible group.

2.8.1 Prediction Tool for Recycled Plastics

2.8.1.1 Selection of Grey Model

A number of studies have looked into improving recycled plastics, to make their performance close to, equivalent or better than that of virgin plastics, as previously cited. However, these have focused on the more expensive process conditions and specialist equipment required using fillers, rather than the simpler and commonly practiced method for improving the quality of recycled plastics, which is blending with virgin plastics

(Ehrig, 1992).

The key factor in blending recycled with virgin plastics is determining the optimal proportion. Due to uncertainty in the nature of recycled plastics, variation in process procedures and differences in purity of materials from plant to plant, it is always necessary to conduct tests with blended composites based on every possible composition formula, even within the same batch. Therefore there is a need for a quick decision support system to determine the optimal proportion of recycled plastics by predicting possible performance without conducting costly, detailed testing on each possible group. It is proposed that this system take the form of a modelling tool utilising data provided by a limited number of quick and affordable material property tests.

Many predicting or forecasting models are applied in solving engineering problems, such as a statistical model, regression analysis (RA), time series analysis, artificial neural network, semi-parametric approach and non-parametric method (McMeekin et al., 2002; Tao and Yau, 2007; Kumar and Jain, 2010; Cheong, 2011; Wesseh and Zoumara, 2012; Haghdadati et

al., 2013; Ardestani et al., 2014; Ju et al., 2014; Thorson and Taylor, 2014; Gosukonda et al., 2015).

However, these models typically require large numbers of observed data and complicated input factors in order to make sensible predictions (Xie et al., 2015). Therefore, they are not convenient as tools for use in decision making. When considering cost, time, energy consumption, emission and other environmental impacts, it is extremely difficult to gather sufficient observation data to satisfy the requirements of these models for making predictions. To forecast the trends with limited data sequence, a model that works well with small data sets is necessary to overcome limited data availability.

Commonly used methods, such as time series analysis and artificial neural network, make predictions based on large amounts of data, and thus fail to meet this requirement. The Grey model is introduced as a mathematical technique based on limited observed data (Deng, 1989).

2.8.1.2 Introduction to Grey Model

The grey model was first introduced in the early 1980s by Deng (1982) to deal with grey systems. Grey systems, are

characterised by having partially known, and partially unknown information, and their applications have been reported in social, economic, industrial and environmental studies (Deng, 1985; Mao and Chirwa, 2006; Chen et al., 2008; Kung and Yu, 2008; Hsu and Wang, 2009; Chen et al., 2010; Kang and Zhao, 2012).

A grey model is usually presented as GM (m, n), where m equals the order of the grey model equation and n the number of variables. Generally three types of grey models are most frequently used (Deng, 1989):

1. GM (1, 1) which is suitable for observed data with an exponential distribution;
2. Grey Verhulst model which is suitable for observed data with an "S" type distribution (i.e., saturated distribution) (Deng, 1989; Liu, et al., 2004; Xiao, et al, 2005).

Parameters of grey models can be obtained through solving their whitenization equations with the initial values.

Whitenization equations are differential equations deduced from the grey models' definition equations, and the initial values are taken from the original data set (Deng, 1989).

In this research, each of the two grey models mentioned above are tested to verify their feasibility in simulating and predicting the properties of ABS blends.

2.8.1.3 Grey Model Techniques

2.8.1.3.1 GM (1, 1)

GM (1, 1) is used in data series with exponential characteristics and monotonic transformation, encompassing a group of differential equations adapted for parameter variance, rather than a first order differential equation (Deng, 1985, 1989; Xiao et al., 2005). Although it is not necessary to employ all the data from the original series to construct the GM (1, 1) model, the potency of the series data must be more than four (Deng, 1985).

Suppose the primitive data sequence to be

$$x^{(0)} = (x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(n))$$

If all grade ratios λ of $X^{(0)}$, which are defined as

$$\lambda(k) = \frac{x^{(0)}(k-1)}{x^{(0)}(k)}, k = 2, 3, \dots, n \quad \text{within the range of } (e^{-\frac{2}{n+1}}, e^{\frac{2}{n+1}}), \text{ where}$$

n is the length of data, then GM (1, 1) can be applied.

According to grey systems theory (Deng, 1985; Liu et al., 2003;

Liu et al., 2004), it will have equations as follows,

$$1-AGOx^{(0)} : x^{(1)} = (x^{(1)}(1), x^{(1)}(2), \dots, x^{(1)}(n)) \quad \text{(Equation 2-1)}$$

and

$$MEANx^{(1)} : z^{(1)} = (z^{(1)}(2), z^{(1)}(3), \dots, z^{(1)}(n)) \quad \text{(Equation 2-2)}$$

in which, the symbol $1-AGOx^{(0)}$, denotes the first order accumulating generation operator for $X^{(0)}$, defined as

$$x^{(1)}(k) = \sum_{i=1}^k x^{(0)}(i), k = 1, 2, \dots, n, n \geq 4 ;$$

Symbol $MEANx^{(1)}$ denotes the mean consecutive neighbours generation operator for $x^{(1)}$, which defined and calculated as

$$z^{(1)}(k) = 0.5x^{(1)}(k) + 0.5x^{(1)}(k-1), k = 2, 3, \dots, n, n \geq 4 .$$

The GM (1, 1) could be defined as (Deng, 1985):

$$x^{(0)}(k) + ax^{(1)}(k) = b \quad \text{(Equation 2-3)}$$

and its whitenization equation is

$$\frac{dx^{(1)}}{dk} + ax^{(1)} = b \quad \text{(Equation 2-4)}$$

in which, a and b are the interim parameters, and the

parameter matrix is

$$\hat{a} = \begin{bmatrix} a \\ b \end{bmatrix} = (B^T B)^{-1} B^T Y \quad \text{(Equation 2-5)}$$

in which,

$$B = \begin{pmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \dots & \dots \\ -z^{(1)}(n) & 1 \end{pmatrix}, \quad Y = \begin{bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \dots \\ x^{(0)}(n) \end{bmatrix}.$$

The solution of Equation 7-4, i.e., the time response functions,

is

$$\hat{x}^{(1)}(k) = ce^{-ak} + \frac{b}{a}, k = 1, 2, \dots, n \quad \text{(Equation 2-6)}$$

in which, c is the undetermined integration constant. The simulation function of $X^{(0)}$ may be obtained as follows:

$$\hat{x}^{(0)}(k+1) = \hat{x}^{(1)}(k+1) - \hat{x}^{(1)}(k) = c(e^{-a} - 1)e^{-ak} \quad \text{(Equation 2-7)}$$

There are three existing approximations available for solving grey model, and the computing formulas of c are, respectively:

1. Taking the first datum in observed data sequence as the initial condition (Deng, 1985; Xiao et al., 2005)

$$c = (x^{(1)}(1) - \frac{b}{a})e^a \quad \text{(Equation 2-8)}$$

2. Taking the last datum (Li et al., 1992; Dang et al., 2005)

$$c = (x^{(1)}(n) - \frac{b}{a})e^{an} \quad \text{(Equation 2-9)}$$

3. Using least squares (Shen and Zhao, 2001; Liu et al., 2003)

$$c = \frac{\sum_{k=1}^n \left[x^{(1)}(k) - \frac{b}{a} \right] e^{-ak}}{\sum_{k=1}^n e^{-2ak}} \quad \text{(Equation 2-10)}$$

Use (Equation 7-8), the simulation function of $X^{(0)}$ can be obtained as follows,

$$\hat{x}^{(0)}(k) = (x^{(1)}(1) - \frac{b}{a})e^{-ak} + \frac{b}{a}, k = 1, 2, \dots, n \quad \text{(Equation 2-11)}$$

2.8.1.3.2 Grey Verhulst model

The Grey Verhulst model was first proposed by German biologist Pierre Francois Verhulst to describe increasing processes with an S-curve which have a saturation region. Later its usage was extended to numerous applications in various fields, for example, in explaining the phenomena of population increase, animal breeding and individual growth (Kayacan et.al, 2010).

The Grey Verhulst model could be defined as (Deng, 1985; Xu et al., 2011):

$$x^{(0)}(k) + az^{(1)}(k) = b(z^{(1)}(k))^2 \quad (\text{Equation 2-12})$$

and its whitenization equation is

$$\frac{dx^{(1)}}{dk} + ax^{(1)} = b[x^{(1)}]^2 \quad (\text{Equation 2-13})$$

Taking $x^{(1)}(1)$ as the initial conditions in this research, the simulation function of $X^{(0)}$ can be obtained by following equation,

$$\hat{x}^{(0)}(k+1) = \hat{x}^{(1)}(k+1) - \hat{x}^{(1)}(k) \quad (\text{Equation 2-14})$$

2.8.2 Optimisation Tool for Recycled Plastics

2.8.2.1 Selection of Taguchi Method

Although the introduction of fillers improves certain desirable properties of recycled materials it may increase the overall cost (Ramirez-Vargas and Sandoval-Arellano, 2006).

Utilising new material requires the design of a suitable manufacturing process, and to design the manufacturing process, the effect of various processing parameters must be identified. The conventional approach to studying the effect of various parameters on a particular phenomenon involves variation of one parameter at a time while keeping other parameters constant. Such a cumbersome approach does not provide any information related to interactive effects among various process parameters (Aslan and Unal, 2009). Moreover, the intricate nature of interrelated processing parameters in manufacturing procedure might involve the repetition of numerous detailed experiments, which would lead the procedure design process to be costly, time-consuming and environmentally damaging.

The Taguchi method is one of the most effective and most popular optimisation methods in science and engineering. For one set of experiments with four factors and each factor at

three levels, the traditional full factorial design requires $3^4 = 81$ possible combinations of trials, Box–Behnken Design requires 29 trials (Grosso et al., 2014), Box-Wilson experimental design requires 28 trials (Cebeci and Sönmez, 2006), when Taguchi OA only requires the L9 (3^4) OA for 9 trials, which significantly reduces the number of experiments under permissive reliability. By comparing the number of trials for each common method, Taguchi method is proved to be highly effective in targeting quality improvement in product or procedure development. Besides, the computation procedure for optimisation of Taguchi method is much simpler when compared to other optimisation tools, such as Box–Behnken Design or Box-Wilson experimental design. Thus, the Taguchi method was selected as a tool to optimise manufacturing procedure using recycled plastics.

2.8.2.2 Introduction to Taguchi Method

The Taguchi method was developed by Taguchi and Konishi (1987), and has been widely used in engineering to optimise the performance characteristics within a combination of design parameters, and in the design of quality systems. Several studies were made with the purpose of optimising the processing parameters to tackle the warpage or shrinkage

problems in injection moulding of thin-shell part. These have proved the efficiency and feasibility of using the Taguchi method in experimental design (Liao et al., 2004; Ozcelik and Erzurumlu, 2006; Oktem et.al, 2007; Ozcelik and Sonat, 2009).

The Taguchi method contains system design, parameter design, and tolerance design procedures to achieve a robust process and result for the best product quality. The system design procedure is to determine the suitable working levels of the design factors. The parameter design procedure determines the factor levels that can generate the best performance of the product or process under study. The tolerance design procedure is used to fine-tune the results of parameter design by tightening the tolerance levels of factors that have significant effects on the product or process.

During Taguchi parameter design, the desired quality output (organic matter recovery) is obtained by finding the optimum values of the controllable factors and simultaneously minimising the variation in the quality output due to uncontrollable factors (Tjantelé, 1991). The parameters are

determined such that the product's functional characteristics are optimised, with minimal sensitivity to noise (Bedworth et.al, 1991). An integrated approach that is simple and efficient is introduced in order to find the best range of designs based on quality, performance, and computational cost (Taguchi, 1990).

2.8.2.3 Taguchi Method Procedure

The Taguchi method consists of three-stages (Yong and Tarng, 1998):

1. System design, which consists of information and knowledge required for producing an end product;
2. Parameter design, which is aimed at determining the relationships between the processing parameters and performance of the end product, and obtaining the optimum levels of processing parameters for the desirable characteristics;
3. Tolerance design, which is employed to determine and to analyze tolerances for the optimum combinations suggested by parameter design.

By utilising the Taguchi OA, the number of trials in experiments can be significantly reduced, thus the time and cost incurred by

multiple trials are also reduced.

Taguchi introduced the use of the signal-to-noise (S/N) ratio to determine the quality of the characteristics. The S/N ratio is a measure of performance aimed at developing products and processes that are insensitive to noise factors. A higher S/N ratio would imply that the signal is higher than the random effects generated by the noise factors, and that the relative operation is fairly consistent and yields optimal quality characteristics of minimum variance (Taguchi, 1990; Oktem and Erzurumlu, 2007).

Using the Taguchi method, quality characteristics can be categorised into three types: the lower the better, the nominal the better and the higher the better (Wu and Wu, 2000). The S/N ratio with the lower the better characteristic that can be expressed as:

$$S / N = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n y_i^2 \right) \quad \text{(Equation 2-15)}$$

The S/N ratio with the nominal the better characteristic can be expressed as:

$$S / N = -10 \log_{10} \left(\frac{1}{ns} \sum_{i=1}^n y_i^2 \right) \quad (\text{Equation 2-16})$$

The S/N ratio with the higher the better characteristic can be expressed as:

$$S / N = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right) \quad (\text{Equation 2-17})$$

in which y_i is the i th experiment at the test, n is the total number of trials in the test, and s is the standard deviation of y_i .

In the research, the higher the better equation (Equation 2-17) was used since enhanced performance of the materials were expected.

2.8.3 Evaluation Tool

2.8.3.1 Selection of Principal Component Analysis and Cluster Analysis

Based on literatures mentioned in previous sections, it is shown that some fillers have improved recycled plastic in tensile/flexural moduli and strength, such as talc and GF.

However, according to experimental results previously reported, those materials showed different patterns in their properties, some properties have improved via the addition of fillers compared to the base materials while others deteriorated.

Further, it is found that there were certain trade-offs or adhesions between multiple properties of those materials, such as trade-off between modulus and impact strength of talc or MMT-filled recycled composites. To utilise those materials in industrial applications, it is necessary to evaluate the materials based on multiple criteria and to classify the interrelationships between properties for selection or in order to further improve the materials. Thus, multiple criteria evaluation and classification tools are required.

Traditional multiple criteria evaluation involves determining the priority and the utility degree of alternatives using subjective opinions (Zavadskas and Kaklauskas, 1996; Vilutiene and Zavadskas, 2003). In recent years, fuzzy sets have drawn a lot of attention in modelling multiple criteria decision making.

These include Hesitant Fuzzy Linguistic Term Set (Rodriguez et al., 2012), Interval-Valued Fuzzy Set (Chen, 2014), Dual Hesitant Fuzzy Set (Ye, 2014), Higher Order Hesitant Fuzzy Set (Farhadinia, 2014), and Hierarchical Hesitant Fuzzy Linguistic Set (Yavuz et al., 2014). However, these systems are mainly designed for quantifying the ambiguous nature of subjective judgements (Chen, 2014), and will not satisfy the requirements

of the evaluation of plastics, which is based on unambiguous experimental data.

Thus, exploratory factor analysis (EFA) is under consideration, for it is a statistical method used to uncover the structure of multivariate statistics (Spearman, 1904), which have been widely used in social, health, biological, and physical sciences (Cudeck and MacCallum, 2007). In EFA, it assumes that any measured variable may be associated with any factor. A factor might influence two or more measured variables (Norris and Lecavalier, 2009). Among common EFA methods, PCA and CA were selected for evaluation and classification of recycled plastic composites based on a relatively large experimental data set, since PCA and CA are methods which directly deal with the data set without any presumption or subjective judgement.

2.8.3.2 Introduction of Principal Component Analysis and Cluster Analysis

As statistical methods in exploratory data analysis and for making predictive models, Principal Component Analysis (PCA) and Cluster Analysis (CA) have been applied in many fields. To cite some examples, applications of PCA and CA were found in environmental science (Mendiguchía et al., 2004; Singh et al.,

2005; Gramsch et al., 2006; Shrestha and Kazama, 2007), geochemical study (Yunker et al., 2005; Bellanti et al., 2008; Panero and da Silva, 2008; Fadigas et al., 2010; dos Santos and Simões, 2010), the petroleum industry (Peters et al., 2007), analytic chemistry (Cecere et al., 2008; Pontes et al., 2009) and polymer science (Zhao et al., 2009a; Zhao et al., 2009b).

PCA was first developed by Pearson (Pearson, 1901; Hotelling, 1933; Malinowski, 1991) as an exploratory methodology (a kind of EFA method) that aims to find similarities or differences among the samples in a dataset (Panero and da Silva, 2008).

After proper data preprocessing (e.g. mean centering, normalizing or using Z-scores), the original data matrix (Kemsley, 1996; Abdi and Williams, 2010), PCA can be carried out by eigenvalue decomposition of a data covariance (or correlation) matrix or singular value decomposition of a data matrix.

CA characterises similarities among samples by examining inter-point distances representing all possible sample pairs in high dimensional space, and yields two dimensional diagrams presenting similarities of samples called dendrograms (Sharaf

et al., 1986).

Although few PCA and CA applications are found in polymer field, no application of using PCA and CA on recycled plastics has been reported. In this section, PCA is selected as an analysis tool for evaluating composites based on recycled plastics for the first time, and CA is selected for classifying the properties of recycled composites originally.

2.8.3.3 Analysis Procedure

2.8.3.3.1 Data Preprocessing

Data preprocessing is a procedure which aims to transfer the original data into a comparable range (e.g. 0 to 1), providing a basis for weighting all observations equally (Tosun, 2006).

For this research, the experimental results were normalized in a range of (0,1). Normalization can be done using several different approaches (Deng, 1992; Fung, 2003; Tosun, 2006; Huang and Lin, 2008). If the expected value of original data sequence has the characteristic of "the higher the better", then the normalization approach shown below is taken (Fung, 2003; Çaydaş and Haşçalık, 2008; Aslan, 2012):

$$\tilde{x}_{ij} = \frac{x_{ij} - \min x_j}{\max x_j - \min x_j} \quad (\text{Equation 2-18})$$

When the “the lower the better” characteristic of the original sequence is considered, then the original sequence should be normalized as follows:

$$\tilde{x}_{ij} = \frac{\max x_j - x_{ij}}{\max x_j - \min x_j} \quad (\text{Equation 2-19})$$

However, if there is a definite target value to be achieved, the original sequence will be normalized as:

$$\tilde{x}_{ij} = 1 - \frac{|x_{ij} - x_0|}{\max x_j - x_0} \quad (\text{Equation 2-20})$$

Moreover, the original sequence can be simply normalized using the most basic methodology, i.e. the values of original sequence being divided by the first value of the sequence:

$$\tilde{x}_{ij} = \frac{x_{ij}}{x_{1j}} \quad (\text{Equation 2-21})$$

where x_{ij} denotes the original sequence, \tilde{x}_{ij} is the sequence after the data preprocessing, $\max x_j$ is the largest value of x_j , $\min x_j$ is the smallest value of x_j , x_{1j} is the initial value of x_j , and x_0 is the desired value.

In the study, the higher the better equation (Equation 2-18) was used since enhanced performance of the materials was expected.

2.8.3.3.2 Cluster Analysis

CA is a set of techniques designed to classify observations based on the similarities between them: members of resulting groups are similar to each other and distinct from other groups (Manly, 1994).

Clustering algorithms can be classified as hierarchical, partitional, density-based or grid-based (Jain et al, 1999).

Among them, hierarchical and partitional clustering are the two most widely used approaches (Davis, 1986; Suk and Lee, 1999; Kovács et al., 2006). Hierarchical clustering algorithms create clusters recursively, by merging smaller cluster into larger ones or splitting larger clusters into smaller ones. The ideal number of clusters may be determined graphically by means of a dendrogram, a tree-like structure diagram, representing the groups of patterns and the similarity level at which groupings change (Manly, 1994; McKenna, 2003). In contrast, partitional clustering does not involve this tree-like construction process.

Partitional clustering algorithms directly decompose the data set into a set of disjoint clusters. They attempt to determine the desired partitions that optimise a certain criterion function (Mok, et al., 2012).

In this research, a hierarchical agglomeration algorithm for clustering was applied. Hierarchical clustering algorithms create clusters recursively, by merging smaller clusters into larger ones or splitting larger clusters into smaller ones. The ideal number of clusters may be determined graphically through a dendrogram, a tree-like structure diagram, representing the groups of patterns and the similarity level at which groupings change (Manly, 1994).

2.8.3.3.3 Principal Component Analysis

PCA is one of the most frequently used multivariate techniques. It can reduce the dimensionality of a data set consisting of a number of interrelated variables while retaining as much as possible of the variation present in the data set. It is achieved by transforming the data into a new set of variables, the Principal Components (PCs), which are uncorrelated, orthogonal and ordered so that the first few retain most the

variation present in all of the data set (Doukas et al., 2012). The PCs are ordered in such a way that the first explains most the variance in the data, and each subsequent one accounts for the largest proportion of variability that has not been accounted for by its predecessors (Abdul-Wahab et al., 2005; Škrbić and Đurišić-Mladenović, 2007; Sousa et al., 2007). The PCA procedure is described as follows (Fung and Kang, 2005):

1. The original multiple quality characteristic matrix,

$$X^0 = \begin{pmatrix} x_{11} & \dots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \dots & x_{mn} \end{pmatrix} \quad \text{(Equation 2-22)}$$

where m is the number of trials and n is the number of the quality characteristic.

2. Data standardisation

Using Equation 7-21, thus the standardised matrix is:

$$X = \begin{pmatrix} \tilde{x}_{11} & \dots & \tilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \dots & \tilde{x}_{mn} \end{pmatrix} \quad \text{(Equation 2-23)}$$

3. Correlation coefficient matrix

$$R = \begin{pmatrix} r_{11} & \dots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \dots & r_{mn} \end{pmatrix} \quad \text{(Equation 2-24)}$$

in which,

$$r_{jk} = \frac{\sum_{i=1}^n (x_{ij} - \bar{x}_j)(x_{ik} - \bar{x}_k)}{\sqrt{\sum_{i=1}^n (x_{ij} - \bar{x}_j)^2 \sum_{i=1}^n (x_{ik} - \bar{x}_k)^2}} \quad \text{(Equation 2-25)}$$

where \bar{x}_j and \bar{x}_k are the mean values of x_j and x_k respectively.

4. Determining the eigenvalues and eigenvectors

The eigenvalues and eigenvectors are determined from the correlation coefficient array,

$$(R - \lambda_j)V_j = 0 \quad \text{(Equation 2-26)}$$

in which, λ_j eigenvalues, $\sum_{j=1}^n \lambda_j = n$, $j = 1, 2, \dots, m$; $V_j = (a_{j1}, a_{j2}, \dots, a_{jn})^T$ are the eigenvectors corresponding to the eigenvalues.

5. Explained variations (EV)

$$b_j = \frac{\lambda_j}{\sum_{i=1}^n \lambda_i} \quad \text{(Equation 2-27)}$$

6. Accumulative explained variations (AEV)

$$a_p = \frac{\sum_{j=1}^p \lambda_j}{\sum_{i=1}^n \lambda_i} \quad \text{(Equation 2-28)}$$

in which, b_j represents the explained variations (EV) of the j^{th} eigenvalue, and a_p represents the accumulative explained variations (AEV) of the p^{th} eigenvalue. Each eigenvalue has an associated eigenvector.

7. Final data

The final data is formulated as follows:

$$Y_{mj} = \sum_{i=1}^n x_m(i)V_{ij} \quad \text{(Equation 2-29)}$$

in which Y_{mj} is the j^{th} final data formulated from eigenvector V_{ij} of principal components in the analysis.

PCA is a variable reduction technique that can be used when variables are highly correlated; it reduces the number of observed variables to a smaller number of PCs that account for most of the variation in the observed variables and is a large sample procedure (Jolliffe, 2002). Before applying the PCA procedure, Kaiser-Meyer-Olkin Measure of Sampling Adequacy (KMO) and Bartlett's Test of Sphericity (p-value) on the original experimental data were performed to test partial correlation and dependence for excluding the potential non-independence of the original data which can affect the result of PCA. For applicable data, KMO should demonstrate a value >0.6 . Bartlett's test of sphericity should be significant ($p < 0.05$).

To sum up, mathematical analysis and design techniques used in this research include: grey model (GM), Taguchi method (TM), principal component analysis (PCA) and cluster analysis (CA).

The GM is used as a quick decision support system to predict

the performance of recycled plastic blends based on the results from a limited number of quick and affordable material property tests. The Taguchi method is used to optimise the performance characteristics within a combination of processing parameters, as described via a reduced number of trials. PCA is used for the evaluation and optimisation of composition formulas, while CA was used to study the inter-relationships between properties of those composites.

Although some of these techniques are previously applied to polymers, only very few applications in plastic manufacturing area or in the field of recycled plastics are found in existing literature. For GM and CA, no report on polymer field application has been found. Therefore, the application of these optimisation techniques' application in this research is original and novel.

Chapter 3 Experimental

3.1 Introduction

All processing and testing parameters remained constant during single experimentation and recognized standards are used for yielding reliable and comparable results. Thus, to investigate the properties of recycled plastics, proper experimental methodology should be established in the first place. The purpose of the preceding chapter is setting up a baseline for the study, since the experimental procedures and the compositions are described in subsequent chapters.

Standard characterisation tests (including standards, equipment and testing parameters), selection of materials (included plastics, fillers and additives), sampling procedure and compositions for all the following trials (included filler addition and for application of mathematic tools) are introduced in this chapter, and experimental parts in the subsequent chapters will refer back to this chapter.

3.2 Experimental Procedures

For recycled plastics, it is necessary to know the properties of the materials before making a decision whether to utilise them or not, what area they can be used in and in what capacity that

can be used. Through characterisation, the strength and weakness of recycled plastics can be revealed, especially when comparing these with virgin materials under the same conditions.

3.2.1 Experimental Analysis of Plastics

To utilise recycled plastics in automobile production, various properties of the materials need to be identified to establish whether they meet the requirements for automobile parts. The desirable materials should have the strength to withstand a specific physical load or impact, and are able to function normally under specific temperature ranges. The production rate of parts using the materials is also under scrutiny . Furthermore, possible contaminants within the recycled materials need to be identified, and some specific requirements need to be satisfied.

For this research, mechanical, rheological, thermal, ash content and flammability as five essential features of the recycled materials were selected and measured:

1. The mechanical properties indicated the strength or easiness to deform under certain types of physical load, which are

crucial characteristics for certain applications;

2. The rheological properties indicated the flowability of the materials under processing temperatures, which are linked with production rate;
3. The thermal properties indicated the thermal stability of the materials at elevated temperatures;
4. The ash content tests examine the possible ingredients in the first life of the materials or contaminants contained within, which would be helpful in understanding behaviours of the recycled materials;
5. The flammability indicateds the resistance to fire, which is linked with safty requirements of industrial applications.

To compare those measured properties and performance using a common framework, designers, producers and end users of materials utilise standardised testing methods, such as those developed by the American Society for Testing and Materials (ASTM) and the International Organisation for Standardisation (ISO). These standards prescribe the method by which the test specimens will be prepared and tested, as well as how the test results will be analyzed and reported. Standards also exist which define terminology and nomenclature as well as

classification and specification schemes.

3.2.1.1 Mechanical Properties

Almost all applications require a plastic to have certain mechanical strength as the material is subject to forces (loads) when used. For example, a car bumper needs to be able to absorb a certain amount of impact energy. The mechanical properties of a material determine how it will react to physical forces. Designers and engineers need to calculate these forces based on data relating to mechanical properties.

Mechanical properties occur as a result of the physical properties inherent in each material, and are determined through a series of standardised mechanical tests. Mechanical properties are often measured with machines and devices. This not only helps ensure accurate measurements to the slightest degree, but also helps to ensure the accuracy and consistency of the forces and stresses that are applied.

In this research, the mechanical properties of the tested polymeric materials were evaluated in terms of tensile, flexural, and impact properties, and all specimens were conditioned at a

room temperature of 23°C and 50% R.H. (relative humidity) for 88 h before testing in accordance with ISO291 specifications (ISO 291:2008).

1. Tensile Properties

Tensile properties including tensile modulus (Young's modulus obtained by tensile test)/strength, yield strength, and elongation at break indicated how the material reacts when subjected to tensile forces. A prepared specimen is loaded in a very controlled manner while measuring the applied load and the elongation of the specimen. In this research, the tensile properties gained in accordance to ISO527 specifications (ISO 527-2:2012).

The tensile modulus, or so-called Young's modulus or elastic modulus, expresses of the stiffness of an elastic material and is defined as the ratio of the stress (force per unit area, denoted by σ) along an axis of strain (ratio of deformation over initial length, denoted by ϵ) in the range of stress in which Hooke's law holds (Moore, 1996). ISO 527-1 (2012) states, the tensile modulus can be calculated by Equation 3-1,

$$E_t = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \quad \text{(Equation 3-1)}$$

where E_t is the tensile modulus, expressed in MPa; σ_1 is the stress, expressed in MPa, measured at the strain value $\varepsilon_1 = 0.0005$ (0.05%) and σ_2 is the stress, expressed in MPa, measured at the strain value $\varepsilon_2 = 0.0025$ (0.25%).

The tensile stress σ is defined as the normal force per unit area of the original cross-section within the gauge length, and is calculated by Equation 3-2,

$$\sigma = \frac{F}{A} \quad \text{(Equation 3-2)}$$

where σ is the stress value, expressed in MPa;

F is the measured force concerned, expressed in N;

A is the initial cross-sectional area of the specimen, expressed in mm^2 .

The tensile strain ε is defined as the increase rate in length per unit original length of the gauge, and is calculated by Equation 3-3,

$$\varepsilon = \frac{\Delta L_0}{L_0} \quad \text{(Equation 3-3)}$$

where ε is the strain value in question, expressed as a dimensionless ratio, or as a percentage;

L_0 is the gauge length of the test specimen, expressed in mm;
 ΔL_0 is the increase of the specimen length between the gauge marks, expressed in mm.

In ISO 527-1 (2012), typical tensile – stress/strain curves of plastic materials are plotted in Figure 3-1, in which Curve (a) represents a brittle material, breaking without yielding at low strains, Curve (d) represents a very soft rubber-like material breaking at larger strains (normally >50%), Curve (b) and Curve (c) represent materials whose elastic properties are within the range of (a) and (d). In Figure 3-1 and ISO 527-1's (2012) definitions, σ_m is the tensile strength, which represents the maximum stress applied; σ_y is the yield strength, which represents the stress at yield point, and strain at yield is determined by drawing a horizontal tangent to a continuously recorded stress/strain curve; ϵ_m or ϵ_b is the elongation at break, which represents the strain at failure.

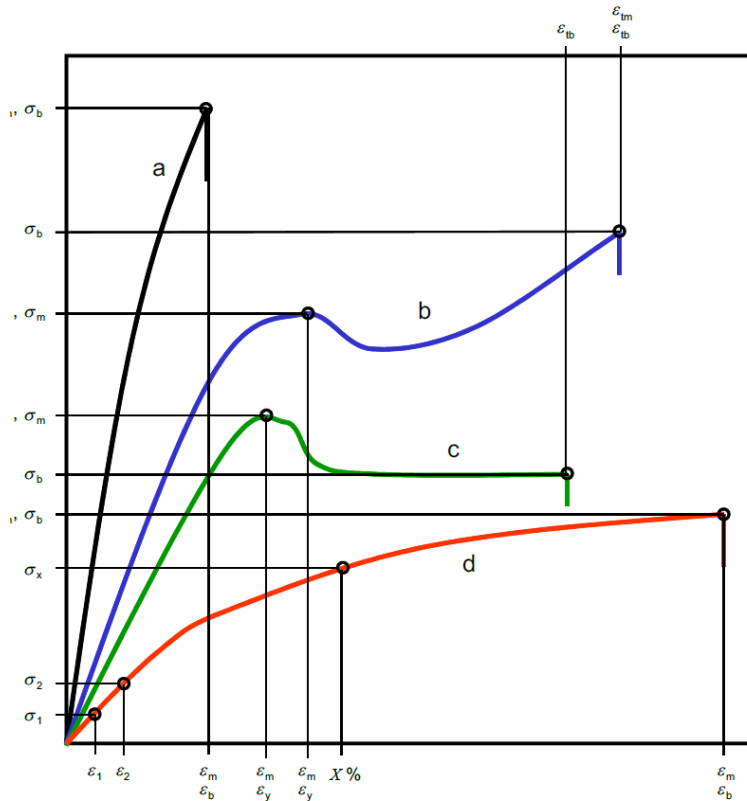


Figure 3-1 Typical stress/strain curves (ISO 527-2:2012)

The tensile tests in this research were conducted using a Gotech Universal Testing Machine (model TCS-2000NE) at a room temperature of 23°C and at 50% R.H, with a gauge of 50mm at a fixed speed of 50 mm min⁻¹, a sampling rate of 200 pts s⁻¹, and full-scale load range of 20 kN.

2. Flexural Properties

Flexural test measures the force required to bend a beam under three point loading conditions and the main advantage of a three point flexural test is the ease of the specimen preparation

and testing. During experimentation, the flexural properties include flexural modulus (Young's modulus obtained by flexural test)/strength, gained in accordance with ISO178 specifications (ISO 178:2010).

The flexural modulus, or so-called bending modulus, is the ratio of stress to strain in flexural deformation, or the tendency for a material to bend, which is determined from the slope of a stress-strain curve (as shown in Figure 3-12) produced by a flexural test (Moore, 1996). ISO 178 (2010) states that the flexural modulus is calculated by Equation 3-4:

$$E_f = \frac{\sigma_{f2} - \sigma_{f1}}{\varepsilon_{f2} - \varepsilon_{f1}} \quad \text{(Equation 3-4)}$$

where E_f is the flexural modulus, expressed in MPa; σ_{f1} is the flexural stress, in MPa, measured at deflection s_1 ; σ_{f2} is the flexural stress, in MPa, measured at deflection s_2 ; $\varepsilon_{f1} = 0.0005$ and $\varepsilon_{f2} = 0.0025$.

The flexural stress σ_f is defined as the tensile stress at the outer surface of the test specimen at midspan, and is calculated using following equation,

$$\sigma_f = \frac{3FL}{2bh^2} \quad \text{(Equation 3-5)}$$

where σ_f is the flexural stress; F is the applied force, in N; L is the span, in mm; b is the width of the specimen, in mm; h is the thickness of the specimen, in mm.

To calculate the deflections s_1 and s_2 corresponding to the given values of the flexural strain $\epsilon_{f1} = 0.0005$ and $\epsilon_{f2} = 0.0025$, the following equation is used,

$$S_i = \frac{\epsilon_{fi} L^2}{6h} \quad (i = 1 \text{ or } 2), \quad \text{(Equation 3-6)}$$

where s_i is one of the deflections, in mm; ϵ_{fi} is the corresponding flexural strain, whose values ϵ_{f1} and ϵ_{f2} are given above; L is the span, in mm; h is the thickness of the specimen, in mm.

An illustration of a standard flexural test is shown in Figure 3-2 (ISO 178:2010), where 1 is the test specimen, F is the applied force, L is the span length, h is the thickness of specimen, l is the length of specimen, R_1 and R_2 are radius of loading edge and radius of supports respectively.

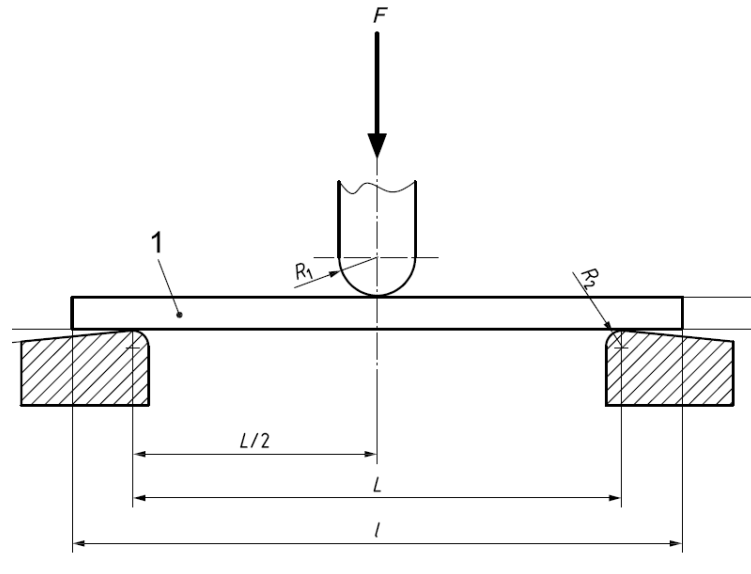


Figure 3-2 Flexural test starting position (ISO 178:2010)

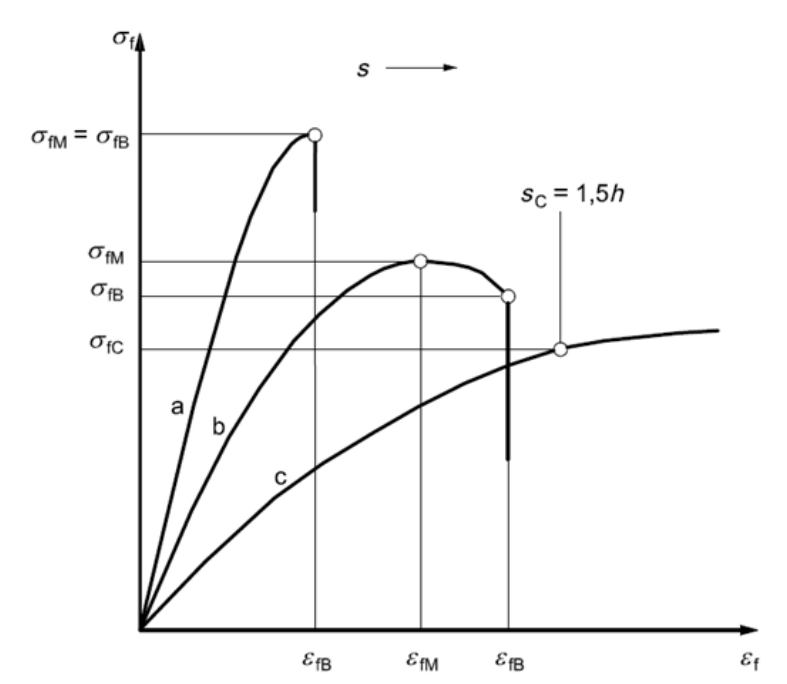


Figure 3-3 Typical curves of flexural stress σ_{f_i} versus flexural strain ϵ_{f_i} and deflection s (ISO 178:2010)

The typical flexural - stress/strain/deflection curves of plastic materials are shown in Figure 3-3. Curve (a) represents a specimen that breaks before yielding; curve (b) represents a

specimen that gives a maximum and then breaks before the conventional deflection, s_c ; curve (c) represents specimen that neither gives a maximum nor breaks before s_c . In Figure 3-3 and ISO 178 specification (2010) definitions, σ_{TM} is the flexural strength, which represents the maximum stress applied.

The tests in this research were conducted using a Gotech Universal Testing Machine (model TCS-2000NE) at a room temperature of 23°C and at 50% R.H, with a span of 64 mm at a crosshead moving speed of 10 mm min⁻¹, a sampling rate of 200 pts s⁻¹, and a full-scale load range of 20 kN.

3. Impact Properties

Impact property is a measurement of how well a material holds up when struck, dropped, or subjected to other sharp impacts. Impact happens quickly and can cause considerable strain on a material. The material does not have time to adapt and distribute the pressure because the incident happens so quickly. Resistance to impact can be a critical trait since shock loads may occur in emergencies or other real-life conditions, and material failures could be catastrophic in these contexts.

For this research, the impact property is the impact strength, gained in accordance to ISO178 Charpy Impact specifications, which is calculated using following equation (ISO 179-2: 2010):

$$a_{cU} = \frac{E_C}{hb} \times 10^3 \quad \text{(Equation 3-7)}$$

where a_{cU} is the Charpy impact strength, in kilo joules per square meter (kJ m^{-2}); E_C is the corrected energy, in joules (J), absorbed by breaking the test specimen and measured by hammer's angles; h is the thickness of the test specimen, in mm; b is the width the test specimen, in mm.

The tests in this research were conducted using a Gotech Impact Tester (model GT-7045-NHR) at room temperature of 23°C and at 50% R.H. It has a span of 62 mm and hammers impact of 5 J, 7.5 J and 15 J at a speed of 3.8 m s^{-1} .

10 sample pieces were tested in each group of each mechanical property, and the average values were recorded if the coefficient of variance of tested results met the required limits (5% in accordance with ISO2602 specifications) (ISO2602: 1980).

3.2.1.2 Rheological Properties

Plastic materials are processed at elevated temperatures, such as extrusion and injection moulding. The melt flow speed would largely affect the production rate, and viscosity is one of the key properties in rheological performance. Rheology is the study of flow and deformation of materials under applied forces or temperatures. The measurement of rheological properties is applicable to all materials, and rheological properties impact at all stages of material utilisation across multiple industries - from formulation development and stability to processing to product performance. For this research, the following two tests were selected.

Melt flow index (MFI) is a measure for the flowability of a thermoplastic polymer melt. It is defined as the mass of polymer (measured in grams) flowing through a capillary of a specified diameter for ten minutes while pressure is applied via prescribed alternative gravimetric weights at a certain temperature. The MFI test was conducted to determine if the basic rheological behaviour of the blends is in accordance with ISO1133 Melt Mass-flow Rate specifications (ISO 1133-1:2011), measured in $\text{g } 10 \text{ min}^{-1}$ under a load of 2.16 kg at 230°C, using a Gotech melt flow indexer (model GT-7200-MIBH), at room

temperature of 23°C and at 50% R.H. Samples were pre-heated to 230°C for 4 min.

The flow behaviour of the blends was assessed using steady and dynamic shear rheology. The tests were conducted using a dual-bore capillary rheometer (Rosand RH2200, Malvern Instruments) with 1 mm capillary die, using two capillaries with the same radius but different length/radius ratios. Samples were pre-heated in the dual barrels to 190°C for 2 min, and measurements were carried out at 190°C under a shear rate ranging from 10 to 5000 s⁻¹, at room temperature of 23°C and at 50% R.H. Viscosity is plotted against shear rate, and the power law model was used to describe relationship between viscosity (η) and shear rate (γ) as described in Equation 3-8:

$$\eta = K\gamma^{n-1} \quad \text{(Equation 3-8)}$$

in which the consistency K corresponds to the viscosity value for a shear rate γ of 1 s⁻¹ and the power-law index n characterises the deviation from the Newtonian behaviour.

3.2.1.3 Thermal Properties

In some circumstances, plastic parts are exposed to high temperatures where degradation and decomposition

(thermolysis) occur. Good thermal stability is required, to limit the decay rate of organic materials. Materials with a greater thermal stability will retain their properties and structural integrity for a longer time at elevated temperatures.

Thermal Gravimetric Analysis (TGA) is a method of thermal analysis in which changes in mass of materials are measured against time and a constant rate of temperature increase. TGA is used to determine certain characteristics of materials under elevated temperature by measuring the mass loss resulting from decomposition, oxidation, or loss of volatile content. The TGA experiments were conducted using a NETZSCH STA 449 F3 Jupiter[®] thermal analyzer using a scanning rate of $10^{\circ}\text{C min}^{-1}$ at room atmosphere. The temperature range started from 100°C and ended at 700°C . Samples averaging about 15 mg were prepared and tested at a room temperature of 23°C and at 50% R.H. Samples were weighted with a four-figure Mettler Toledo analytical balance (model XP204S).

Tests determining the Temperatures of Deflection under Load (TDL) which used to determine the short-term heat resistance of flexural strength were conducted using an HDT-VICAT test

processor (CEAST model 6911.000) according to ISO75 (ISO 75-2: 2004), with a constant heating rate of $50^{\circ}\text{C h}^{-1}$ and a load of 0.45 MPa. The samples were immersed in silicon oil and preheated for 4 min at 40°C .

3 samples were prepared and tested in each group of each rheological property, and the average values were recorded.

3.2.1.4 Ash Content in Plastics

The incorporation of fillers, reinforcements, additives or contaminants accumulated in polymers plays an important role in modifying the properties. The amount and type of filler and containment has a significant influence on the material properties. Consequently, measuring that content is an important aspect of quality control monitoring. The ash content tests were designed to determine the content of potential inorganic fillers or contaminants of plastics, especially those in recycled plastics. The mass of non-volatile inorganic matter which remains after subjecting it to a high decomposition temperature is measured, and is compared to the total mass of tested material.

The tests were set according to ISO3451 (ISO 3451-1:2008), and an average of 2 g samples of those plastic materials were fed into muffle furnace in quartz crucibles. The furnace was set to 250°C for 1 h, then heated to 400°C for 1h and finally to 800°C for 2 h, and then stopped. After that, cooling in the furnace was carried out for a 2 h period, and the ash was carefully collected and its weight was measured by a four-figure Mettler Toledo analytical balance (model XP204S).

10% nitrohydrochloric acid solution was used to dissolve the ash. The ash and acid were digested using a CEM Mars microwave digester to make the solution for element analysis. A PerkinElmer NexION 300x Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and a ThermoFisher iCE3500 Atomic Absorption Spectrometer (AAS) were utilised to conduct element analysis.

3 samples were prepared and tested in each group of each thermal property.

3.2.1.5 Flammability

In this research, flammability properties of recycled plastics

and virgin plastics were compared in accordance with UL94 horizontal burning test standard (UL-94).

All specimens were conditioned at a room temperature of 23°C and 50% R.H. for 48 h before testing in accordance with UL94 standard (UL94).

Horizontal burning tests were conducted according to UL94 standard, and carried out in a FTT horizontal/vertical flame chamber (Fire Testing Technology Ltd., UK). The specimens were marked at 25 mm and 100 mm, placed on clamps and ignited for 30 s before the ignition device was removed. If the flame reached the 25 mm mark within 30 s, the ignition device was removed. The burning rate of 25 mm mark to 100 mm mark was measured. For the specimens' thickness of 3 to 13 mm, the material can be classified into 94 HB degree (the minimum flame retardant degree proposed by UL94 standard) if the burning rate does not exceed 40 mm m⁻¹.

For this research, the time taken for the arrival of flame on 25 mm (measured by s, denoted by ignition time) and 100 mm (measured by s, denoted by end time) marks were recorded,

and the burning rate (mm min^{-1}) between the marks was measured.

5 sample pieces were tested in each group, and their average values were used if the coefficient of variance of tested results met the required limits (5% in accordance with ISO2602 specifications) (ISO2602:1980).

3.2.2 Selection of Materials

3.2.2.1 Base Materials

To begin the characterisation, material selection was a crucial step: materials selected should be particularly suitable for in automobile production". PP is one of the most important polymers in automobile production, representing the largest proportion (32%) in automobile plastics (Szeteiová, 2010). It was used as a primary material, while ABS was used as secondary material.

Firstly, three types of virgin PP were selected as comparators, and were used to blend with recycled PP. The first virgin PP, denoted by VPP1, was a high-grade high-impact, homo-polymer mainly being used for producing automobile structural components, household applications or vessels, with

a trade-name of EPS30R and produced by Dushanzi Sinopec. It has low melt index, good processing properties, melt stability, good rigidity and low volatility. VPP1 has been widely used in automobile production, such as in dashboards and bumpers. The second virgin PP material (denoted by VPP2) was a block co-polymer mainly used for manufacturing automobile parts, electric and electronic devices or pipelines, with a trade-name of PPB-MO2-V and manufactured by Yangzi Petrochemical Co., Ltd. These materials were used as received, and have an average of particle size of 3.0 mm, density of 0.9 g cm^{-3} , as shown in Figure 3-16. A third virgin PP used in this work was a high-impact co-polymer, with a trade name of K8303 (denoted by VPP3) and produced by Yanshan Sinopec, commonly used for high-impact parts and devices, such as automotive parts. The average pellet size was 3 mm, a density of 0.9 g cm^{-3} , as shown in Figure 3-4. The materials were used as received.



Figure 3-4 EPS30R (VPP1, left), PPB-MO2-V (VPP2, mid) and K8303 (VPP3, right) pellets

Particle sizes were measured using a laser sizer, model Malvern Mastersizer 3000. The densities were obtained by a pycnometer, model Quantachrome Ultra PYC 1200e, using small sample cell of 5 ml, and 99.99% N₂ as purge gas in accordance with ISO1183 at a room temperature of 23°C and at 50% R.H (ISO 1183-3:1999). The purpose of measuring was to ensure the sizes and densities of those pellets were within reasonable ranges, thus proving materials suitable for thermal processing (Joyson, 2011).

Two kinds of recycled PP materials were used in this initial test set: grey recycled PP denoted by RPP1, was recovered from white post-customer storage boxes (as an example of single source recycling); black recycled PP denoted by RPP2, recovered from common municipal solid waste (MSW), such as post-consumer packages, cases and shells of household devices (as an example of mixed recycling). The average size of RPP1 and RPP2 pellets was approximately 3.0 mm, as shown in Figure 3-5. Their densities were 1.0 g cm⁻³ and 1.1 g cm⁻³ respectively. Particle size and density were measured in the same manner as mentioned before, using the laser sizer and

the pycnometer. Both recycled plastics were acquired from recycling plants around Hangzhou Bay area (near Ningbo and Shanghai): RPP1 from the large mixed recycling plant; RPP2 from a small single source recycling plant, with a procedure as shown in Figure 1-5. Both materials were used as received and treated in the same way as each of the virgin-recycled PP blends.

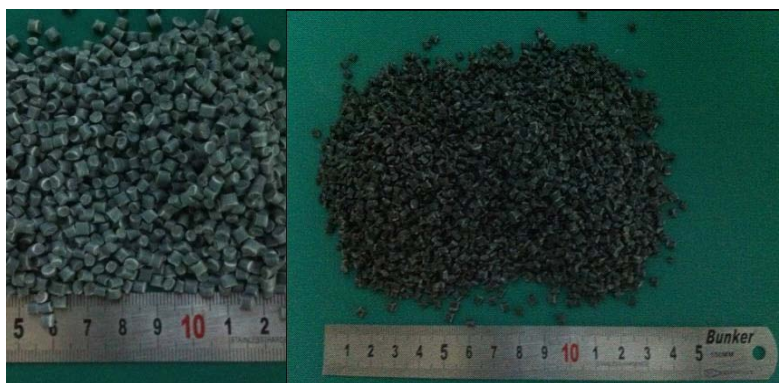


Figure 3-5 Grey recycled PP (RPP1, left) and black recycled PP (RPP2, right)

Two types of industrial talc-filled PP were used in this work, each specifically designed by the automobile production industry for use in the production of dashboards, bumpers and other interior trims. A5132TB12378L (denoted by Pret PP) is manufactured by Shanghai Pret Composites Co., Ltd, and is a type of PP copolymer with 20 wt% talc as filler. It has average particle size of 3.0 mm and a density of 1.2 g cm^{-3} .

APO-4004HMB001 (denoted by Kinghfa PP) is manufactured by Shanghai Kingfa Science & Technology Co., Ltd, a type of PP copolymer with 40 wt% talc as filler, with an average particle size of 3.0 mm, and a density of 1.5 g cm^{-3} . Particle size and density were measured in the same manner as mentioned before. Both materials were bought directly from automobile parts manufacturing factory, and were used as received, as shown in Figure 3-6.

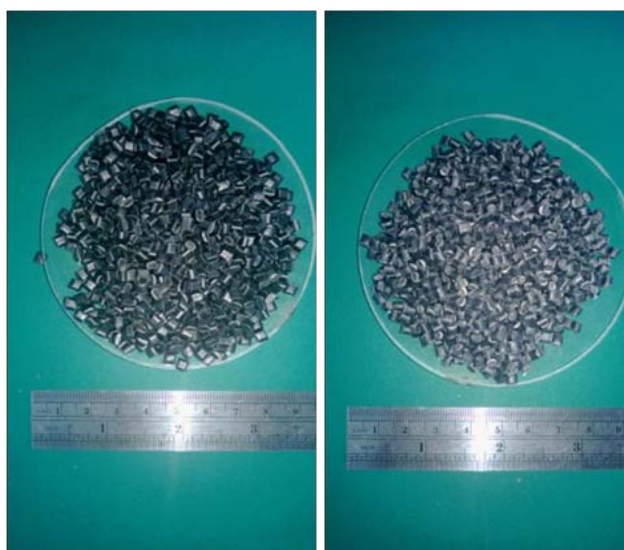


Figure 3-6 A5132TB12378L (Pret PP, left) and APO-4004HMB001 (Kinghfa PP, right) pellets

Virgin ABS used in the research was a commercial general purpose grade, denoted by PA707K, produced by CHIMEI Taiwan. It is widely used in automotive parts (Joyson, 2011). The melt flow index of this material is $23 \text{ g } 10 \text{ min}^{-1}$ under a load

of 10kg at a temperature of 200°C in accordance with ISO1133 (ISO 1133-1:2011; Hechang, 2011). The material was used as received (see Figure 3-7), and has an average particle size of 4 mm and a density of 1.1 g cm⁻³. Particle size and density were measured in the same manner as previously.



Figure 3-7 PA707K pellets

Recycled ABS used in this research was a high-grade single-source recycled ivory coloured ABS recovered from post-consumer furniture, denoted by RABS. The average pellet size and density are similar to the virgin ABS material. The material was used as received (see Figure 3-8), and Particle size and density were measured in the same manner as previously.



Figure 3-8 Recycled ABS pellets

3.2.2.1 Fillers and Additives

Talc used in this research shown in Figure 3-9 was acquired from a Ningbo factory, which has an average particle size of 12.5 μm , a density of 2.7 g cm^{-3} , and was used as received.

Particle size and density were measured in the same manner as in the previous section.



Figure 3-9 Talc

GF used in this research shown in Figure 3-10, was acquired from a Ningbo factory, which has an average of length of 6 mm, a density of 2.5 g cm^{-3} , and was used as received. Particle size

and density were measured in the same manner as the previous section.



Figure 3-10 Glass fibre

OMMT used in this research shown in Figure 3-11, was acquired from Yoshida Chemical co.ltd., Shenzhen, Guangdong and has an average of size of 37.5 μm and a density of 1.7 g cm^{-3} . The material was used as received. Particle size and density were measured in the same manner as in the previous section.



Figure 3-11 OMMT

Coupling agent (compatibiliser) used in this research was maleic anhydride grafted polypropylene (MAPP), as the effect of polypropylene-g-maleic anhydride to enhance dispersibility of clay in PP matrix has been proven (Tang et al., 2004; Hong et al., 2008). There were two kinds of MAPPs used, both of them were acquired from Nanjing Deba Chemical Co.Ltd, and were used as received. The two compatibilisers have the same average particle size of 2.5 μm , the same density of 0.9 g cm^{-3} , but with different grafted rate of 0.8% and 0.9%, denoted by MAPP1 and MAPP2 respectively. They have a similar appearance to that shown in Figure 3-12.



Figure 3-12 MAPP

3.2.3 Sampling Procedure

3.2.3.1 Extrusion

After mixing in a high-speed mixer (Figure 3-13) for 3 min, all PP blends in this research were processed by a Kangrun KRSJ-20 twin-screw, co-rotating, intermeshing extruder with six heating barrels, with a screw diameter of 20 mm and L/D = 44 (Figure 3-14). A single-screw feeder attached to the hopper carried all materials into the heating barrels. The processing temperatures were allowed to increase from 190°C to 200°C from the hopper to the 3rd barrel. The temperatures of the last three barrels were maintained at 200°C, while the die temperature was also set at 200°C. The rotation speed of the screws was 180 rpm, and the estimated mass flow rate was 4 kg h⁻¹ which was measured by a balance. Blended strands were

extruded into a water bath for cooling, and then pelletized. The average blended pellet size was 2.8 mm, and its density depended on blending formula, see Figure 3-15.



Figure 3-13 High-speed mixer



Figure 3-14 Kangrun KRSJ-20 twin-screw extruder



Figure 3-15 Blended PP pellets

For adapting filler additions in plastics, some of the processing parameters were modified accordingly.

For PP/talc composites, the processing temperatures of the twin screw extruder were allowed to increase from 195°C to 210°C from the hopper to the 3rd barrel, and the temperatures of the last three barrels maintained at 210°C, while the die temperature was set at 205°C. The screw rotation speed was kept 150 rpm and the total mass flow rate was 6 kg h⁻¹.

For PP/GF composites, the processing temperatures of the twin screw extruder were allowed to increase from 190°C to 210°C going from the hopper to the 3rd barrel, and the temperatures of the last three barrels maintained at 210°C, while the die temperature was set at 205°C. The screw rotation speed was

kept at 120 rpm and the total mass flow rate was 5 kg h⁻¹.

For PP/OMMT composites, the processing temperatures of the twin screw extruder were allowed to increase from 180°C to 200°C going from the hopper to the 4th barrel, the temperatures of the last two barrels were maintained at 200°C, while the die temperature was set at 195 °C. The rotation speed of the screws was kept at 180 rpm and the estimated mass flow rate was 4 kg h⁻¹.

All ABS blends were processed using a Jieya SHJ-40 extruder after mixing, which is different from the previous method. This is a co-rotating, intermeshing, twin-screw extruder with 10 heating barrels and a screw diameter of 44 mm with L/D = 44. A twin-screw feeder was used to produce pellets. The processing temperature was allowed to increase from 220 °C to 240°C from the hopper to the 6th barrel; the temperatures in the last four barrels was kept constant at 240°C, whilst the die temperature was set to 235°C. The screw rotation speed was 150 rpm, and the total mass flow rate was 15 kg h⁻¹. Blended strands were extruded into a water bath and then pelletized. The blended pellets' average size was a slightly smaller than

virgin or recycled ones, averaging around 3 mm, which was similar to the previous set.

3.2.3.2 Drying

Extruded PP pellets were dried in an oven at 85°C for 12 h with constant air flow to ensure a moisture content of below 1% before being subjected to injection moulding. This step was taken because moisture content in plastic materials would cause a series of defects, such as the formation of bubbles or shrinkage, rendering the testing results unreliable (Karian, 2003).

Extruded ABS pellets were dried in a vacuum dry oven that 75°C for 4 hours with a protection nitrogen gas (purity, 99.999%) to ensure the moisture content of pellets was less than 1% by weight.

3.2.3.3 Injection Moulding

The extruded pellets were moulded into test specimens in accordance to ISO standards (such as ISO75, ISO178, ISO179, ISO527), by utilising a Haitian MA1200/370 injection moulding machine (Figure 3-16). Two (dumbbell pieces for tensile tests) or four (cuboid pieces for flexural or impact) test specimens

being produced per single injection moulding cycle. The temperatures of the five heating barrels were set at 190°C, 195°C, 200°C, 200°C, 200°C respectively, and the mould was pre-heated to 50°C. The other processing parameters were:

1. an injection speed at 50 g per second with a pressure of 50 MPa;
2. a packing pressure of 40 MPa;
3. a holding time of 15 s;
4. a mould cooling time is 10 s.

The processing parameters were based on ISO1873-2 trials (ISO 1873-2:2007) and recommendations from automobile parts manufacturers (Joyson, 2011).



Figure 3-16 Haitian MA1200/370 injection moulding machine

Examples of specimens produced are shown in Figure 3-17.

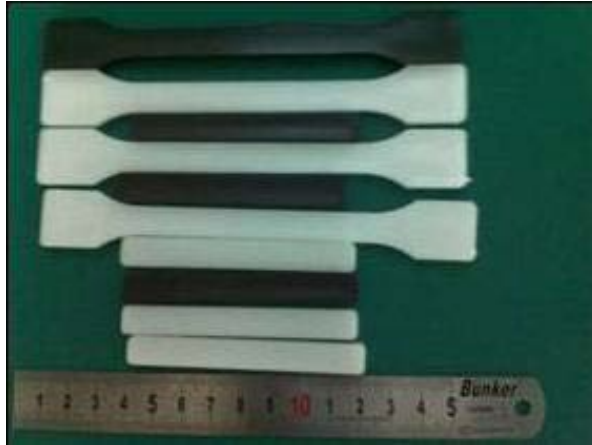


Figure 3-17 Injection moulded test specimens, made from virgin (white, VPP1) and recycled PP (black, RPP2)

The dimension of Type 1B dumbbell specimens defined in ISO 527-2 (2012) for tensile test is shown in Figure 3-18 and Table 3-1.

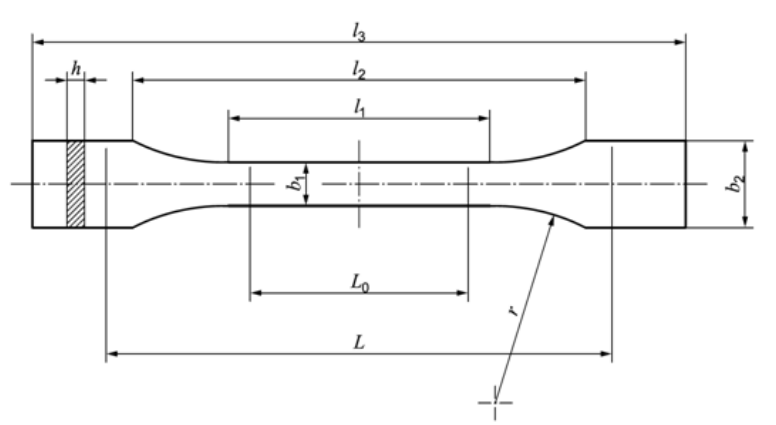


Figure 3-18 Dumbbell tensile specimens (ISO527-2:2012)

Table 3-1 Dimension of Type 1B dumbbell specimen (mm)

l_1	l_2	l_3	b_1	b_2	L	L_0	r	h
60	108	150	10	20	115	50	60	4

For flexural, impact and TDL specimens, length $l = 80$ mm, width $b = 10$ mm, thickness $h = 4$ mm.

For adapting filler additions in plastics, some of the processing parameters were modified accordingly.

For PP/talc composites, the temperatures of five heating barrels of the injection moulding machine were set at 195°C, 205°C, 210°C, 210°C, 210°C respectively. The other processing parameters were: 1. an injection pressure of 55 MPa; 2. an injection speed of 50 g s⁻¹; 3. a packing pressure of 45 MPa for 5 s; 4. cooling in moulds was allowed for 15 s; 5. the mould was pre-heated to 45°C. The PP/talc samples are shown in Figure 3-19.



Figure 3-19 Injection moulded PP/talc test specimens based on VPP1

For PP/GF composites, the temperatures of five heating barrels of the injection moulding machine were set at 195°C, 205°C, 210°C, 210°C, 210°C respectively. The other processing parameters were: 1. an injection pressure of 60 MPa; 2. an injection speed of 50 g s⁻¹; 3. a packing pressure of 40 MPa for 10 s; 4. cooling in moulds was allowed for 15 s; 5. the mould was pre-heated to 45°C. The PP/GF samples are shown in Figure 3-20.



Figure 3-20 Injection moulded PP/GF test specimens based on VPP1

For PP/OMMT composites, the temperatures of five heating barrels of the injection moulding machine were set at 190°C, 195°C, 200°C, 200°C, 200°C respectively. The other processing parameters were: 1. a injection pressure of 50 MPa; 2. an injection speed at 50 g s⁻¹; 3. a packing pressure of 20

MPa for 15 s; 4. cooling in moulds was allowed for 10 s; 5. the mould was pre-heated to 50°C. The processing parameters were determined by ISO1873-2 trials (ISO1873-2:2007) and previous literature (Lertwimolnun and Vergnes, 2006).

For ABS, the temperatures of the five heating barrels of the injection moulding machine were set at 225°C, 230°C, 235°C, 235°C, 235°C respectively, based on the melt flow index data in the supplier's specification (Hechang, 2011). The other processing parameters: 1. an injection pressure was set at 65 MPa; 2. an injection speed at 80 g s⁻¹; 3. a packing pressure of 50 MPa for 25 s in accordance with ISO2580-2. A Xinyi oil-media mould heater was used to improve the dimensional consistency of sample pieces and to avoid production problems such as shrinkage or bubble formation. A heating temperature was set at 50°C. The processing parameters were determined by ISO1873-2 trials (ISO1873-2:2007) and advice from automobile parts manufacturers (Joyson, 2011). Examples of sample pieces produced are shown in Figure 3-21.



Figure 3-21 Examples of injection moulded ABS specimens

3.2.3.4 Hot Pressing

For UL94 flammability test, hot pressing procedure was used to produce required samples. A vulcanizing machine (or so-called hot compressor) model ZG-20T was used, with inner pressing space of 300 mm * 300 mm, and a maximum pressure of 20 tones, as shown in Figure 3-22. The pellets were placed in a stainless steel mould whose size of 250 mm * 250 mm * 3 mm, then covered with two pieces of stainless steel plate and polyimide films. The three pieces of steel were put into the machine. The pressing procedure was divided into two processes, hot process and cold process. The temperature of the hot process was set and maintained at 180°C, and it consisted of the following three phrases:

1. 70 MPa, kept for 200 s;
2. 75 MPa, kept for 100 s;

3. 80 MPa, kept for 60 s.

After the hot process, the plates were taken out for the cold process: 80 MPa, kept for 300 s. The processing parameters were determined by ISO1873-2 trials (ISO1873-2:2007) and advice from automobile parts manufacturers (Minth, 2012).



Figure 3-22 Vulcanizing machine, model ZG-20T

The pressed plastic plate was taken out from the mould, and cut into 125 mm * 13 mm * 3 mm specimens in accordance with UL94 standard by a manual pressing cutter (Figure 3-23 and Figure 3-24).



Figure 3-23 Manual cutting sampler

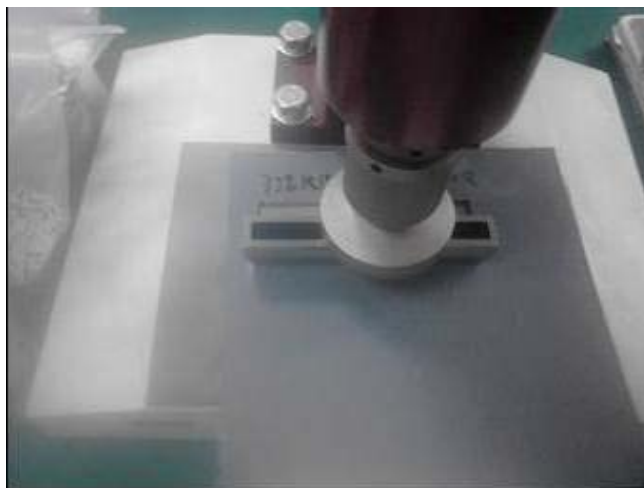


Figure 3-24 Sample cutting procedure

3.3 Compositions of Materials

3.3.1 Initial Experimental Investigation

An initial experimental investigation was purposed to understand the characteristics of typical recycled plastics acquired in China, and comparisons were made between various properties of virgin plastics and virgin plastic-based

composites which are used in automobile manufacturing. This reveals any possible problems associated with the reuse of recycled plastics and creates a platform for finding solutions.

During this initial experimental investigation, VPP1 was used as base material, with VPP2 and recycled materials added in. The detailed groups of various proportions of the materials are shown in Table 3-1, measured by percentage of weight. V denoted VPP2 was adding into the blends, G denoted RPP1 and B denoted RPP2 repectively.

Table 3-2 Composition (wt%) of PP materials

Designation	VPP1	VPP2	RPP1	RPP2	Pret PP	Kinghfa PP
PP100	100					
PP75V	75	25				
PP50V	50	50				
PP25V	25	75				
PP0V		100				
PP75G	75		25			
PP50G	50		50			
PP25G	25		75			
PP0G			100			
PP75B	75			25		
PP50B	50			50		
PP25B	25			75		
PP0B				100		
PP-T20					100	
PP-T40						100

3.3.2 Compositions for Filler Addition

3.3.2.1 PP/Talc Compositions

The detailed groups of PP/talc compositions are shown in Table 3-3. The amount of MAPP to talc was kept 1:4 based on previous literatures (Karian, 2003; Liu and Li, 2006; Lederer, et al., 2010). In some groups, PP and talc were blended without

addition of any MAPP (untreated, denoted by "-U"), which to be used as control groups to show the effect of coupling agent in compatibilisation of polymer and filler. The added talc content was starting from 0 wt% (100 wt% virgin or recycled PP), then increasing by 10 wt% per group and up to 40%.

**Table 3-3 Compositions of the talc/PP composites
(wt%)**

Designation	VPP1	RPP2	Talc	MAPP	Pret PP	Kingfa PP
VPP	100	0	0	0	0	0
RPP	0	100	0	0	0	0
VPP-T10	87.5	0	10	2.5	0	0
VPP-T20	75	0	20	5	0	0
VPP-T30	62.5	0	30	7.5	0	0
VPP-T40	50	0	40	10	0	0
RPP-T10	0	87.5	10	2.5	0	0
RPP-T20	0	75	20	5	0	0
RPP-T30	0	62.5	30	7.5	0	0
RPP-T40	0	50	40	10	0	0
RPP-T10-U	0	90	10	0	0	0
RPP-T20-U	0	80	20	0	0	0
RPP-T30-U	0	70	30	0	0	0
RPP-T40-U	0	60	40	0	0	0
PP-T20	0	0	(20)	0	100	0
PP-T40	0	0	(40)	0	0	100

3.3.2.2 PP/GF Compositions

The detailed groups of PP/GF compositions are shown in Table 3-4. The amount of MAPP to GF was kept 1:2 based on previous literatures (Rijsdijk et al., 1993; Thomason and Schoolenberg,

1994; Thomason, 2002), while some other groups were without any MAPP used as control groups (denoted by "-U") to verify the effects of compounding recycled plastics and GF.

Table 3-4 Compositions of the GF/PP composites (wt%)

Designation	VPP1	RPP2	GF	MAPP	Pret PP	Kingfa PP
VPP	100	0	0	0	0	0
RPP	0	100	0	0	0	0
VPP-GF5	92.5	0	5	2.5	0	0
VPP-GF10	85	0	10	5	0	0
VPP-GF15	77.5	0	15	7.5	0	0
VPP-GF20	70	0	20	10	0	0
RPP-GF5	0	92.5	5	2.5	0	0
RPP-GF10	0	85	10	5	0	0
RPP-GF15	0	77.5	15	7.5	0	0
RPP-GF20	0	70	20	10	0	0
VPP-GF5-U	95	0	5	0	0	0
VPP-GF10-U	90	0	10	0	0	0
VPP-GF15-U	85	0	15	0	0	0
VPP-GF20-U	80	0	20	0	0	0
RPP-GF5-U	0	95	5	0	0	0
RPP-GF10-U	0	90	10	0	0	0
RPP-GF15-U	0	85	15	0	0	0
RPP-GF20-U	0	80	20	0	0	0
PP-T20	0	0	0	0	100	0
PP-T40	0	0	0	0	0	100

3.3.2.3 PP/OMMT Compositions

Tri Phuong et al. (2008) prepared the rPP/nanoclay nanocomposite at different loadings of nanoclay and MAPP as the compatibiliser. They found that the nanoclay loading of 4 wt% and MAPP content of 20 wt% (1:5 ratio) created the best results of impact and tensile strength. The results were superior to those of virgin PP, and further addition of MAPP did not improve the performance of nanocomposite. Zahedi et al. (2013) investigated the mechanical properties of nanocomposites based on OMMT, wood flour recycled PP, compatibilised by MAPP. It was found that the highest improvement of mechanical properties was achieved at 3 wt% organo-clay loading and 6 wt% MAPP (1:2 ratio).

Based on previous studies, the proportions of blended composites were decided as shown in Table 3-5. The ratio of the amount of OMMT to MAPP was selected as 1:3 (between 1:2 and 1:5). This ratio was kept constant for both kinds of MAPP, for both virgin and recycled PP and for PP/talc composites.

Table 3-5 Compositions of the OMMT/PP composites (wt%)

Designation	VPP2	RPP1	OMMT	MAP P1	MA PP2	Talc
VPP	100	0	0	0	0	0
RPP	0	100	0	0	0	0
V1-MAPP1	96	0	1	3	0	0
V2-MAPP1	92	0	2	6	0	0
V3-MAPP1	88	0	3	9	0	0
V4-MAPP1	84	0	4	12	0	0
V5-MAPP1	80	0	5	15	0	0
V1-MAPP2	96	0	1	0	3	0
V2-MAPP2	92	0	2	0	6	0
V3-MAPP2	88	0	3	0	9	0
V4-MAPP2	84	0	4	0	12	0
V5-MAPP2	80	0	5	0	15	0
R1-MAPP1	0	96	1	3	0	0
R2-MAPP1	0	92	2	6	0	0
R3-MAPP1	0	88	3	9	0	0
R4-MAPP1	0	84	4	12	0	0
R5-MAPP1	0	80	5	15	0	0
R1-MAPP2	0	96	1	0	3	0
R2-MAPP2	0	92	2	0	6	0
R3-MAPP2	0	88	3	0	9	0
R4-MAPP2	0	84	4	0	12	0
R5-MAPP2	0	80	5	0	15	0

3.3.3 Compositions for Ageing

The detailed groups of various proportions for the ageing experiment are shown in Table 3-6.

Table 3-6 Compositions of the PP blends and PP/talc composites for Ageing Tests (wt%)

Designation	VPP1	RPP2	Talc	MAPP	Pret PP	Kingfa PP
PP100	100	0	0	0	0	0
PP90	90	10	0	0	0	0
PP70	70	30	0	0	0	0
PP50	50	50	0	0	0	0
PP30	30	70	0	0	0	0
PP10	10	90	0	0	0	0
RPP	0	100	0	0	0	0
RPP-T20	0	75	20	5	0	0
RPP-T40	0	50	40	10	0	0
PP-T20	0	0	(20)	0	100	0
PP-T40	0	0	(40)	0	0	100

3.3.4 Compositions for Reprocessing

The detailed groups of various proportions for reprocessing experiment are shown in Table 3-7.

Table 3-7 Compositions of the PP and talc/PP composites for Reprocessing Tests (wt%)

Designation	VPP2	RPP1	Talc	MAPP
VPP	100	0	0	0
RPP	0	100	0	0
RPP-T20	0	75	20	5
RPP-T40	0	50	40	10

3.3.5 Compositions for flammability

The detailed groups of various proportions for flammability tests are shown in Table 3-8. The ratio of MAPP to talc was 1:4, and the ratio of MAPP to OMMT was 3:1 according to previous studies.

Table 3-8 Compositions of the Materials for Flammability Tests (wt%)

Designation	VPP2	RPP1	OMMT	MAPP1	MAPP2	Talc
PP100	100	0	0	0	0	0
PP75	75	25	0	0	0	0
PP50	50	50	0	0	0	0
PP25	25	75	0	0	0	0
PPO	0	100	0	0	0	0
V1-MAPP1	96	0	1	3	0	0
V2-MAPP1	92	0	2	6	0	0
V3-MAPP1	88	0	3	9	0	0
V4-MAPP1	84	0	4	12	0	0
V5-MAPP1	80	0	5	15	0	0
V1-MAPP2	96	0	1	0	3	0
V2-MAPP2	92	0	2	0	6	0
V3-MAPP2	88	0	3	0	9	0
V4-MAPP2	84	0	4	0	12	0
V5-MAPP2	80	0	5	0	15	0
R1-MAPP1	0	96	1	3	0	0
R2-MAPP1	0	92	2	6	0	0
R3-MAPP1	0	88	3	9	0	0
R4-MAPP1	0	84	4	12	0	0
R5-MAPP1	0	80	5	15	0	0
R1-MAPP2	0	96	1	0	3	0
R2-MAPP2	0	92	2	0	6	0
R3-MAPP2	0	88	3	0	9	0
R4-MAPP2	0	84	4	0	12	0
R5-MAPP2	0	80	5	0	15	0
VPP-T20	75	0	0	5	0	20
VPP-T40	50	0	0	10	0	40
RPP-T20	0	75	0	5	0	20
RPP-T40	0	50	0	10	0	40

3.3.6 Compositions for Application of Tools

3.3.6.1 Compositions for Grey Model Application

For application of GM, the initial mass proportion of virgin PP in the blends was 100 wt%, decreasing by 10 wt% in every group that followed (making the data set equidistant), as shown in Table 3-9.

Table 3-9 Composition of the PP blends for Application of GM (wt%)

Designation	VPP1	RPP1
PP100	100	0
PP90	90	10
PP80	80	20
PP70	70	30
PP60	60	40
PP50	50	50
PP40	40	60
PP30	30	70
PP20	20	80
PP10	10	90
PP0	0	100

For verification of GM, the initial mass proportion of virgin ABS in the blends was 100 wt%, decreasing by 10 wt% in every group that followed; making the blending proportions equidistant, as shown in Table 3-10.

Table 3-10 Composition of ABS materials for Verification of GM (wt%)

Designation	PA707K	RABS
ABS100	100	0
ABS90	90	10
ABS80	80	20
ABS70	70	30
ABS60	60	40
ABS50	50	50
ABS40	40	60
ABS30	30	70
ABS20	20	80
ABS10	10	90
ABS0	0	100

3.3.6.2 Compositions for Taguchi Method Application

For application of TM, the mass proportion of virgin PP in the blends started at 100 wt%, with a variety of equidistance lower proportions as shown in Table 3-11.

Table 3-11 Composition of PP materials for Application of TM (wt%)

Designation	VPP3	RPP2
PP100	100	0
PP90	90	10
PP70	70	30
PP50	50	50
PP30	30	70
PP10	10	90
PP0	0	100

For verification of TM, the detailed groups of various compositions are shown in Table 3-12.

Table 3-12 Compositions of the talc/PP composites for Verification of TM (wt%)

Designation	VPP2	RPP1	Talc	MAPP
PP100	100	0	0	0
PP75	75	25	0	0
PP50	50	50	0	0
PP25	25	75	0	0
PP0	0	100	0	0
RPP-T20	0	70	20	10
RPP-T40	0	55	40	5

3.4 Summary

In this chapter, the selection of plastic materials, the sample preparation, the standard tests used and the compositions are introduced in detail, which provided a basis for further investigation on recycled plastics.

Chapter 4 Characterisation of Typical Recycled Plastics in Chinese Market

4.1 Introduction

In this chapter, quality of recycled plastics acquired from China, the largest recycled plastics consumer and the largest automobile manufacturer in the world, was investigated.

A series of experiments were conducted on recycled plastics bought in China, and comparisons were made between various properties of virgin plastics and virgin plastic-based composites which are used in automobile manufacturing. This would reveal any possible problems associated with the reuse of recycled plastics and would create a platform for finding solutions.

The compositions for initial experimental investigation are shown in Table 3-2, and the experimental procedure was shown in Section 3.2

4.2 Performance of Recycled Plastics

4.2.1 Mechanical Results

The mechanical tests' results obtained for mechanical tests are presented in Figure 4-1 to Figure 4-7, respectively.

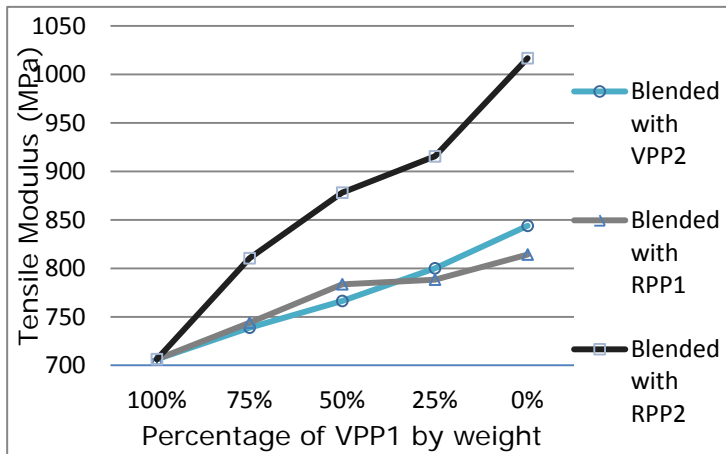


Figure 4-1 Tensile Modulus (MPa) against percentage of VPP1

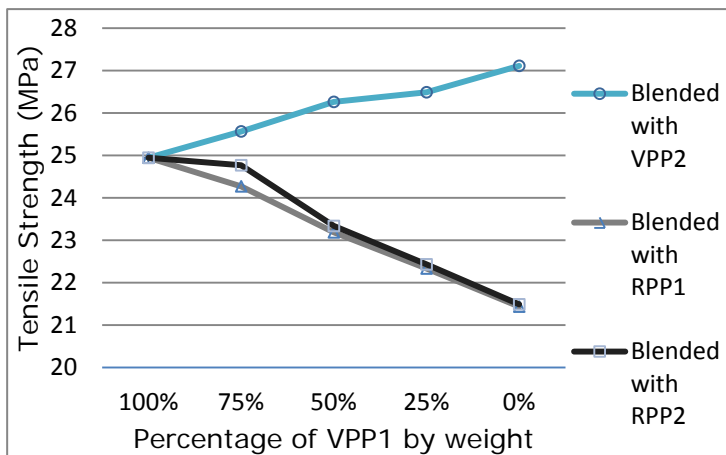


Figure 4-2 Tensile Strength (MPa) against percentage of VPP1

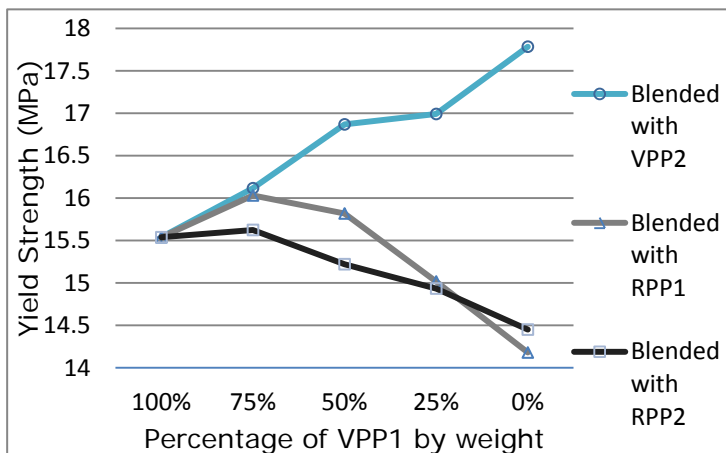


Figure 4-3 Yield Strength (MPa) against percentage of VPP1

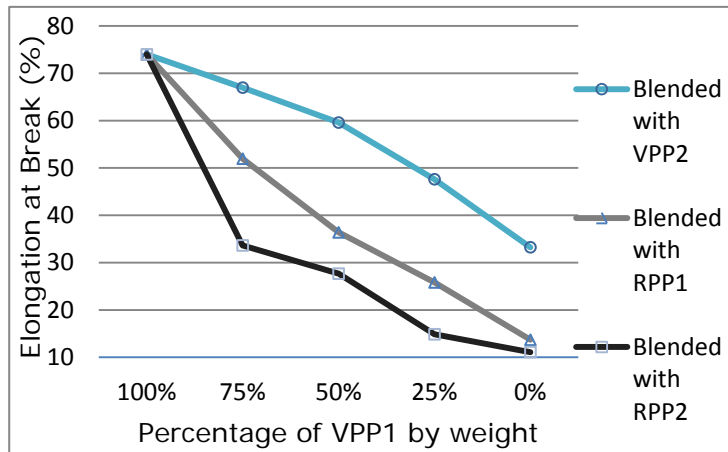


Figure 4-4 Elongation at Break (%) against percentage of VPP1

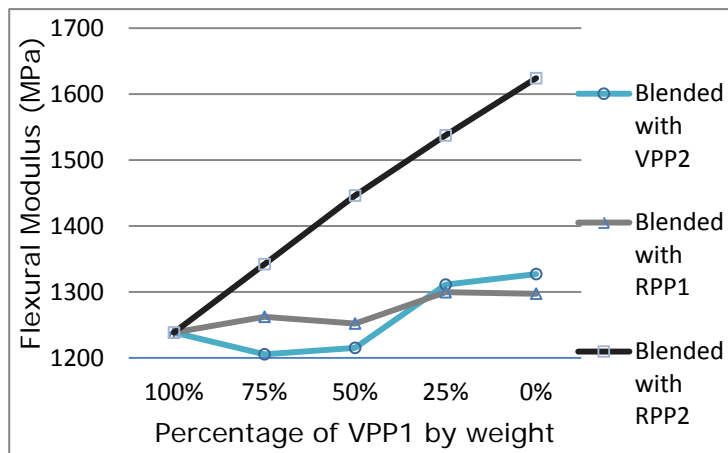


Figure 4-5 Flexural Modulus (MPa) against percentage of VPP1

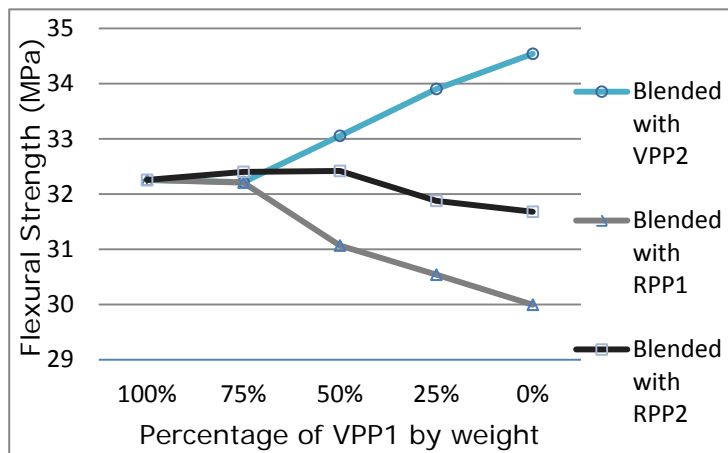


Figure 4-6 Flexural Strength (MPa) against percentage of VPP1

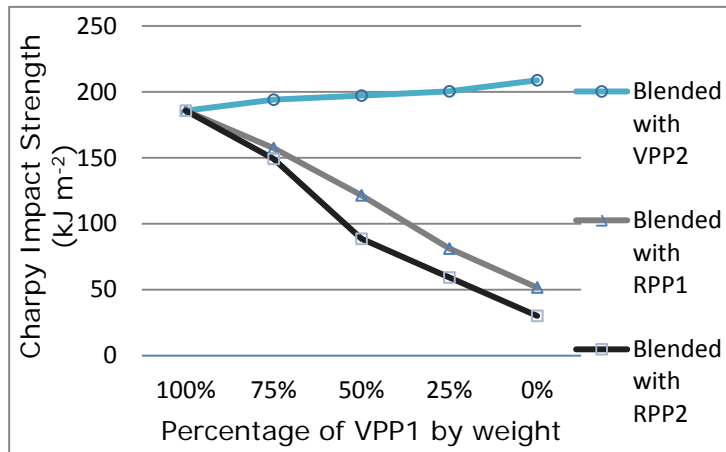


Figure 4-7 Charpy Impact Strength (kJ m^{-2}) against percentage of VPP1

The figures showed that both tensile and flexural moduli increased with the addition of recycled plastics, while the remaining properties of the blends decreased incrementally with addition of recycled plastics. Increased recycled content has the effect of causing deterioration in the mechanical performance of the blends, which could indicate one of the major weaknesses of recycled plastics, i.e. mechanical performance. Among those tested mechanical properties, impact strength suffered the most serious deterioration, possibly because contamination content could facilitate the crystallization of the materials (Wang et al., 2013; Wang et al., 2014). It is verified by further tests in the following chapters.

RPP2 pellets were recovered from MSW, and MSW contains much used packaging material, such as bags and bonds.

Packaging materials are generally made from isotactic polypropylene which is a random copolymer characterised by higher moduli and lower strength (Moore, 1996). The results of mechanical tests confirmed these patterns, as higher moduli are observed.

Other virgin material, VPP2, was added into VPP1 and caused increments in most mechanical properties of the blends, except for elongation at break. It showed that the performance of VPP1 is inferior to that of VPP2 in these experiments.

Using VPP2 as a base material for recycled plastics addition is not carried out in this research, since a similar effect to VPP1 is expected.

4.2.2 Rheological Results

The results obtained for MFI are presented in Figure 4-8.

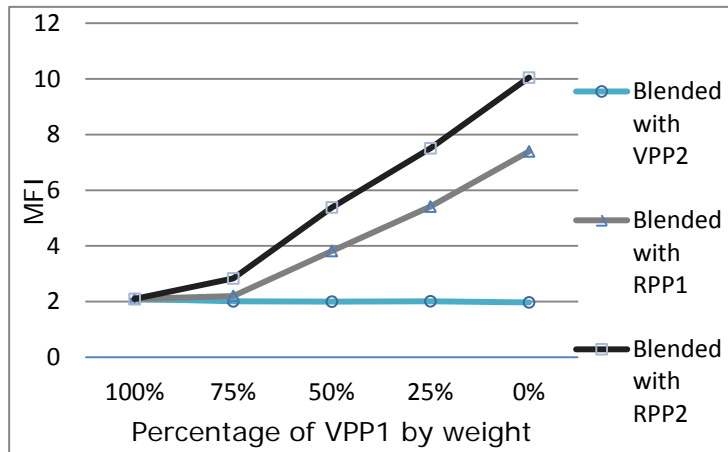


Figure 4-8 MFI (measured by $\text{g } 10 \text{ min}^{-1}$ under load of 2.16 kg at 230°C) against percentage of VPP1

An increase in the percentage of recycled PP in the blends resulted in incremental increase in MFI values. Again this is possibly a result of contamination of the recycled plastic and the thermodynamic immiscibility phenomenon which is caused by a loss in molecular weight of the polymers (Abbas, 1980; Eguiazabal and Nazabal, 1989; Billiana and Fleischmann, 1990; González-González et al., 1998). Both contaminants and chain-scissions which reduce molecular weight could have a significant impact on the process abilities and performances of products made from those composites, especially their mechanical properties.

Five groups selected for shear viscosity testing using capillary rheometer are shown in Table 4-1.

Table 4-1 Selected mixture weight percentages (wt%) matrix for Shear Viscosity Test using RH2200 capillary rheometer

Designation	VPP1	RPP1
PP100	100	0
PP75	75	25
PP50	50	50
PP25	25	75
PP0	0	100

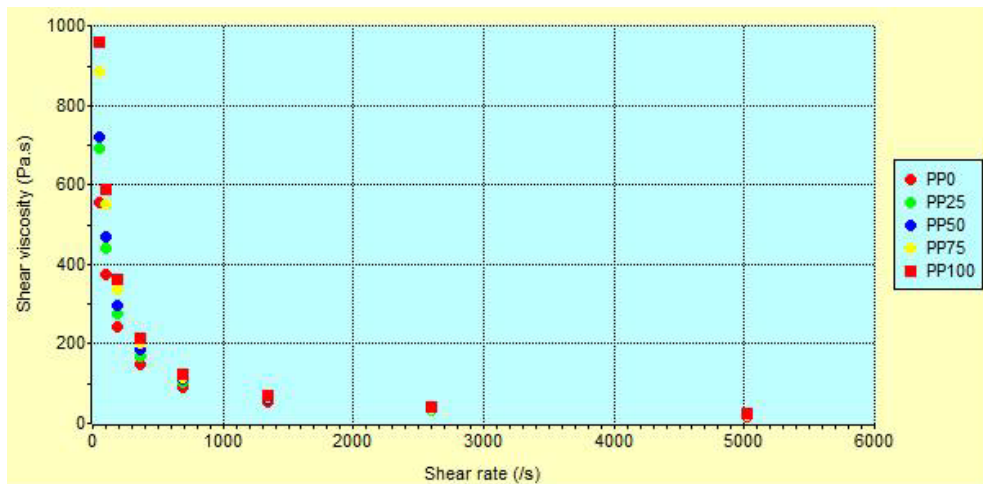


Figure 4-9 Shear Viscosity against Shear Rate

Figure 4-9 shows that the more recycled content, the lower the shear viscosities are. This is also implied by the MFI results implied and previous literature (Fernandez et al., 2014). The causes of this phenomenon could be macromolecular chain scissions during recycling (Abbas, 1980; Valenza and La Mantia, 1988; González-González et al., 1998; Feller and Bourmaud, 2003). This implies that the reduced melt strength of recycled

polymers in extrusion process could cause the inconsistency of material after leaving the die. This makes the production more difficult, as Hamzehlou and Katbab (2007) found during twin screw recycling of PET.

4.2.3 Thermal Results

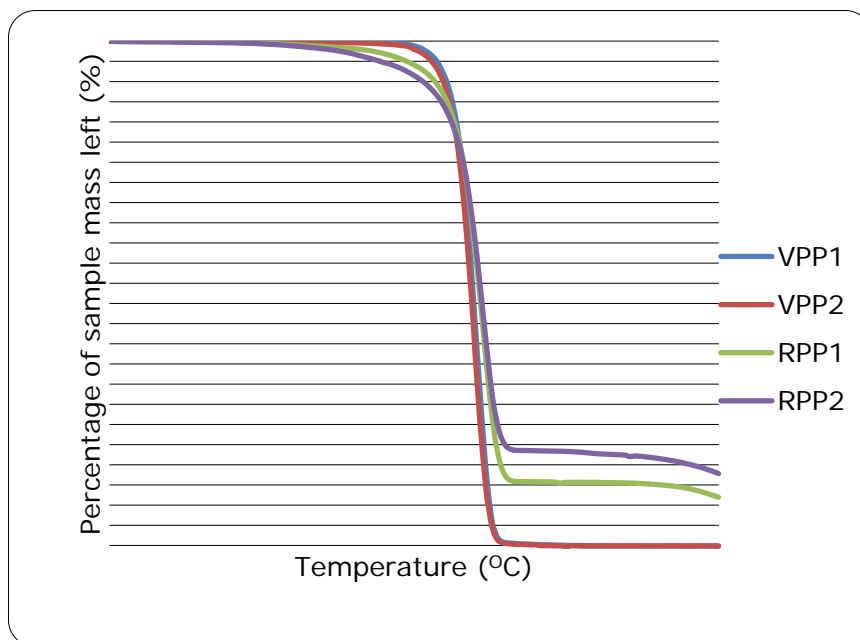


Figure 4-10 TGA plot: weight loss percentage (%) versus temperature (°C) for the four PP materials recorded at a heating rate of $10^{\circ}\text{C min}^{-1}$ under room atmosphere

TGA data indicated that the four polymers lost less than 2% of their weight under 250°C (VPP1: 99.93% at 250°C , VPP2: 99.83% at 250°C , RPP1: 99.59% at 250°C , and RPP2: 99.46% at 250°C), and began to decompose at temperatures above 300°C . Neither of the virgin PP materials were present after the

TGA test, while each of the two recycled PP materials left some residues. These could be the additives in original PP composites or contaminants accumulated during the life-cycle. According to industrial practises, the usual filler loadings are within the range of 10-20%, e.g. 10% CaCO₃ or Al(OH)₃ in PP composites used in automobile parts (Joyson, 2011; Minth, 2012), which closely matches the TGA results.

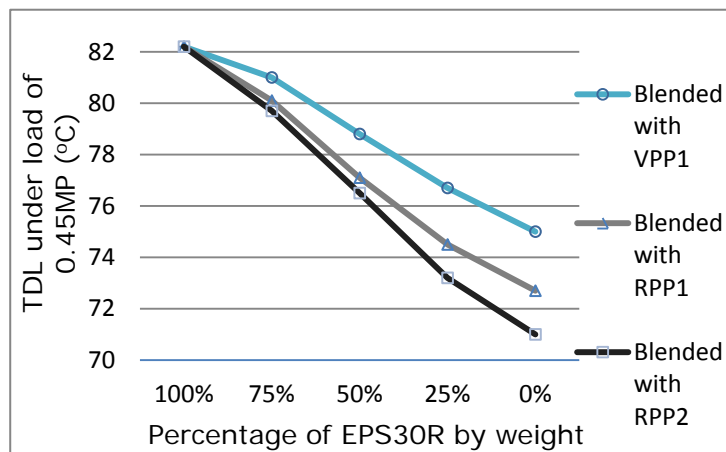


Figure 4-11 TDL (°C) against percentage of VPP1

TDL test results of 0.45 MPa load are shown in Figure 4-11. The results imply that the thermal stability of the blends was strongly influenced by the addition of other polymers, especially of recycled polymers. This may have resulted from the thermal properties of those materials, for the TDL values of VPP2 and the original materials of the recycled plastics are lower than that of VPP1. Contaminants contained in recycled

plastics could also affect the microstructures. These made the recycled plastics more fragile, leading to more deformation at elevated temperatures. This would certainly constrain the applications of recycled materials.

4.2.4 Ash Content Results

The results of ash content tests are shown in Table 4-2 and Table 4-3.

Table 4-2 Ash percentages

	VPP1	VPP2	RPP1	RPP2
Sample Weight (g)	2.0005	1.9991	1.9982	2.0012
Ash Weight (g)	0.0040	0.0037	0.1789	0.2024
Ash Percentage (%)	0.2	0.19	8.95	10.11

Table 4-3 Metal content in the ashes (wt%) obtained by ICP-MS and AAS

Element/Percentage	RPP1	RPP2
Al	12.06	42.92
V	0.16	0.35
Mn	0.26	0.43
Fe	9.12	31.11
Co	0.01	0.04
Ni	0.14	0.34
Cu	3.66	6.01
Zn	2.94	2.45
As	0.21	0.33
Se	0.04	0.11
Mo	0.01	0.05
Ag	0.01	0.06
Cd	0.01	0.16
Sn	0.14	0.44
Sb	7.57	2.77
Ba	63.35	11.66
Pb	0.31	0.78

Both recycled PP materials contained more ash than that of virgin PP. As previously stated, these could be the fillers in original PP composites or contaminants accumulated during the lifecycle.

BaSO₄ is a basic ingredient of white paint or dye and since RPP1 was recovered from post-consumer white furniture, this could explain the presence of a large content of Ba in the ash. Since RPP2 was recovered from MSW, Al, Fe contents were significantly higher than in RPP1, which probably resulted from the existence of contaminants during their lifecycle.

4.3 Assessments of Recycled Plastics

4.3.1 Merits of Recycled Plastics

As shown in the plots of experimental results, the recycled plastics preserve some desirable characteristics. The preservation rate (*PR*) was used to calculate the proportional ratio of performances of recycled plastics compared to those of virgin plastics and industrial composites, shown in Equation 4-1,

$$PR = \frac{P_R}{P_V} \times 100\% \quad \text{(Equation 4-1)}$$

in which, P_R represents the performance of recycled plastics P_V represents the performance of virgin plastics or industrial composites, both presented by experimental results. The PR results were calculated and shown in Table 4-4.

Table 4-4 Performance of recycled plastics, expressed in PR (%)

Comparator	RPP	Tensile Modulus	Tensile Strength	Flexural Modulus	Flexural Strength	Impact Strength	MFI	TDL
VPP1	RPP1	115.28	85.93	104.75	92.99	27.82	352.79	88.44
	RPP2	143.95	86.15	131.15	98.21	16.23	479.33	86.37
VPP2	RPP1	96.49	79.07	97.75	86.84	24.74	375.31	96.93
	RPP2	120.48	79.26	122.38	91.72	14.43	509.93	94.67
Pret PP	RPP1	52.98	73.87	46.72	66.57	105.42	71.24	83.37
	RPP2	66.16	74.05	58.49	70.31	61.49	96.79	81.42
Kinfa PP	RPP1	41.73	92.40	31.83	79.27	152.99	53.35	81.05
	RPP2	52.11	92.63	39.86	83.72	89.24	72.49	79.15

While recycled plastics cannot match virgin plastics or industrial composites, Table 4-4 suggests that some properties of recycled plastics are at a relatively high level (PR s of RPP1 and RPP2 are over 90%). Some of the properties even exceed those of virgin plastics or industrial composites: the tensile and flexural moduli of recycled plastics are superior when compared

with VPP1.

4.3.2 Drawbacks of Recycled Plastics

With the exception of tensile modulus and flexural modulus, the mechanical or thermal properties of the virgin-recycled blends decreased with the addition of recycled contents. This could be the result of ageing, degradation, contamination, or the existence of heterogeneous materials during life span. It is also a possibility that the original materials of those recycled PP were not as good as those used for automobile parts, especially when considering the materials were recovered from packages.

An additional determination of average molecular weights (MW) of VPP1 and RPP2 used in this section was conducted, with results obtained via gel permeation chromatography (GPC) in accordance with ASTM: D 6474-12. The PP pellets were dissolved in 1,2,4-trichlorobenzene under 150°C for 3 h, the concentration of PP was kept at around 2.0 mg cm⁻³ and the sampling size was 200 µL. The tests were carried out using PL-GPC220 machine, with PL gel 10 um MIXED-B 300 mm × 7.5 mm chromatographic columns and 0.45 um filter. Standard polystyrene pellets of 10 different average molecular weights

were provided by the equipment manufacturer and used for calibration before testing. Calibration parameters were set at $K_{PP} = 19 \times 10^{-3} \text{ ml g}^{-1}$ and $a_{PP} = 0.725$. The results were expressed in form of weight average MW. The results have confirmed that the chain length of recycled plastics is shortened, since MW of virgin material was 489, 560 and MW of recycled material was 77,526.

The testing results of the two industrial PP composites are shown in Table 4-5.

Table 4-5 Performances of industrial composites and comparison against recycled plastics

Property	Pret PP	Kingfa PP	RPP1	RPP2
Tensile Modulus (MPa)	1536.9	1951.1	814.3	1016.8
Tensile Strength (MPa)	29.02	23.2	21.4	21.5
Elongation at Break (%)	11.9	4.3	13.7	11.1
Flexural Modulus (MPa)	2776.8	4075.0	1297.3	1624.1
Flexural Strength (MPa)	45.1	37.8	30.0	31.7
Charpy Impact Strength (kJ m ⁻²)	49.0	33.8	51.7	30.1
MFI (g 10 min ⁻¹)	10.4	13.9	8.4	10.1
TDL (°C)	87.2	89.7	72.7	71.0

The two industrial PP composites' performances surpass the

recycled PP in almost every single property, while the two virgin industrial PP materials are superior to recycled PP in relation to most properties. The quality issue proved to be one of the major reasons that back up the policy of “never use recycled plastics in automobile production”, since the performance of recycled plastics is still not as good as virgin industrial composites.

Due to the uncertainty in the composition and contamination in recycled plastics, it is always necessary to adjust procedure when using recycled plastics, which leads to a series of costly, time-consuming and environmentally damaging trials on different batches or different formulas for producing the same product. This could make recycled plastics economically unviable in industrial-level production.

Although it is more environmentally-friendly to use recycled plastics in automobile applications, the inferior performance of recycled plastics has become a major stumbling block.

4.3.3 Possible Solutions to Improve Recycled Plastics

There were two possible routes to improve the performance of

recycled plastics for potential application in the production of automobile parts: the use of fillers and production optimization, as mentioned in Section 2.7 and Section 2.8 respectively.

Chapter 5 Fillers for Improving Recycled Plastics

5.1 Introduction

In Chapter 4, problems associated with the use of recycled plastics in industrial applications are identified by investigating various physical properties. This chapter focuses on how the physical properties of recycled plastics could be improved through the addition of fillers.

In Section 2.7, three categories of polymeric fillers are identified which are used to promote the performance of recycled plastics in order to match or get close to the performance of virgin plastics or industrial composites. However, no comparison against industrial composites has been reported. Also, limited research investigating their beneficial effect on recycled plastics is found. Usually fillers like talc or GF are added to recycled plastics along with other fillers, such as rubber, wood flour or virgin plastics.

In this chapter, the effect of adding those fillers to recycled plastics was studied and compared to virgin plastics or industrial composites. Compatibilisation effects of coupling agents were also studied against control groups without coupling agents. Talc and GF were used as the primary fillers to

improve recycled plastics without the addition of other fillers. Original research on the compatibilisation effects of coupling agents with different grafted rate (percentage of mass of grafted monomers in the polymer) for compounding recycled plastics and OMMT was conducted.

The experimental data and compounding formulas obtained from this chapter are used for evaluation, optimisation and further tests or assessments in the following chapters.

5.2 Addition of Talc in Recycled Plastics

In this study, talc is added to both recycled and virgin plastics to verify its effect on strengthening the mechanical performance of the composited polymers, in term of tensile modulus, tensile strength, yield strength, flexural modulus, flexural strength and impact strength. The compatibilisation effect of coupling agent (or so-called compatibiliser) was also examined by comparing the results of composites with or without coupling agent addition.

The compositions for PP/talc composites are shown in Table 3-3, and the experimental procedure is shown in Section 3.2

5.2.1 Mechanical Results

Experimental results of mechanical tests are shown in Table 5-1, including tensile/flexural modulus, tensile/flexural strength, yield strength and impact strength.

Table 5-1 Experimental results of PP/talc composites

Designation	Tensile Modulus	Tensile Strength	Yield Strength	Flexural Modulus	Flexural Strength	Impact Strength
VPP	1053	23.6	16.4	850	25.6	137.2
RPP	1236	20.1	14.7	1108	27.7	37.9
VPP-T10	1256	23.6	17.1	1195	29.8	165.1
VPP-T20	1552	24.2	17.4	1500	32.2	183.7
VPP-T30	1934	26.1	18.7	1909	36.5	217.4
VPP-T40	2533	27.8	20.8	2417	39.2	129.1
RPP-T10	1524	20.9	16.1	1328	29.2	33.9
RPP-T20	1959	21.8	16.3	1649	31.7	27.4
RPP-T30	2432	23.8	18.3	2085	35.2	35.6
RPP-T40	2954	25.4	20.3	2831	37.5	22.4
RPP-T10-U	1457	20.2	15.1	1296	29.1	35.6
RPP-T20-U	1741	20.8	15.5	1566	30.3	31.8
RPP-T30-U	2175	20.3	15.3	1943	30.6	24.1
RPP-T40-U	2672	19.1	15	2463	30.1	16.3
PP-T20	2116	26.5	19.0	2014	36.3	46.1
PP-T40	2716	20.5	16.5	3186	32.7	32.5

5.2.2 Commentary

As shown in Table 5-1, with the addition of talc, the tensile modulus, flexural modulus, tensile strength and flexural strength of both VPP1 and RPP1 based composites with

coupling agent increased. As previous research (Long et al., 1995; Tall et al., 2001; Bahlouli et al., 2006) has pointed out, the introduction of talc acts as crystal forming core and increases crystallinity of PP based composites, thus the moduli and strength of PP/talc composites are improved.

However, some properties of recycled PP based composite without coupling agent suggest otherwise. Tensile and flexural strength initially increased slowly and insignificantly with the introduction of talc, and then declined with further talc addition. Although both tensile and flexural moduli of recycled PP/talc composites without coupling agent increased with the addition of talc content, the increase rates are noticeably lower than those of virgin and recycled PP/talc composites with coupling agent. This could verify the effect of coupling agent in compatibilisation of polymer and filler, especially with respect to recycled PP.

The impact strength of all PP/talc composites shows a distinguishable difference from moduli and strength figures. Impact strength of virgin PP/talc composites increased with the initial introduction of talc, and then the impact strength of

VPP-T40 declined and registered as even lower than that of virgin PP. This decline has several possible reasons, one of which could be that the amount of coupling agent in VPP-T40 was not sufficient to compatibilise talc and PP, i.e. the 1:4 ratio did not work on this formula. Another reason might be, as previous research has suggested, impact property is influenced by the interactions between talc and polymer, since high crystallinity leads to high brittleness. For that reason, rubber can be added to counter the brittleness (Tall et al., 2001). However, rubber addition would largely constrain the recyclability of the composites, since rubber and polymer cannot be readily separated.

The impact strength of recycled PP/talc composites decreased with the addition of talc, whether with coupling agent or not. This could result from multiple causes, such as the fillers which already existed in the recycled plastics during their first life having had contamination introduced, or the compatibility problem mentioned above.

As the results indicated, some mechanical performance indicators of certain recycled PP/talc composites with coupling

agent are superior to those of industrial composites, e.g. RPP-T40 is superior to PP-T40 in every tested property except for flexural modulus and impact strength. The performance of virgin PP/talc composites are superior to those based on recycled PP and industrial composites with same talc loadings, except for both tensile and flexural moduli. From these experimental results, the recycled plastics demonstrate their potential through the addition of talc and MAPP. With proper formulation and treatment, it is proven that recycled PP/talc composites can match the performance of industrial composites with same talc loading. Therefore, these materials could be used in demanding industrial applications such as manufacturing automobile parts.

5.3 Addition of GF in Recycled Plastics

In this section, the study of glass fibre (GF) addition was carried out in a similar manner to that of the talc group. GF was added into recycled or virgin plastics to verify its effect on strengthening the mechanical performance of the composited polymers as the sole filler, the mechanical performance was measured in terms of tensile modulus, tensile strength, yield strength, flexural modulus, flexural strength and impact

strength. And the effects of coupling agent were also examined by comparing results obtained from coupling agent added groups and control groups.

As there is little research on the addition of GF into recycled plastics, the compounding procedure also posed a challenge for this research.

The compositions for PP/GF composites are shown in Table 3-4, and the experimental procedure is shown in Section 3.2

5.3.1 Mechanical Tests Results

Experimental results of mechanical tests are shown in Table 5-2, including tensile/flexural modulus, tensile/flexural strength, yield strength and impact strength.

Table 5-2 Experimental results of PP/GF composites

Designation	Tensile Modulus	Tensile Strength	Yield Strength	Flexural Modulus	Flexural Strength	Impact Strength
VPP	981	23.1	18.1	859	24.9	138.2
RPP	1241	20.1	16.2	1057	27.4	43.9
VPP-GF5	1589	24.0	18.9	1157	27.6	187.9
VPP-GF10	2201	25.2	19.6	1545	29.6	226.3
VPP-GF15	2933	27.0	21.5	1873	33.0	246.0
VPP-GF20	3544	28.7	23.0	2390	36.1	149.7
RPP-GF5	1848	21.0	17.2	1374	29.5	57.2
RPP-GF10	2405	22.4	18.3	1779	32.8	53.6
RPP-GF15	3120	24.3	20.1	2084	36.9	37.1
RPP-GF20	3699	25.6	21.5	2567	40.4	44.9
VPP-GF5-U	1546	23.4	18.9	1082	27.3	183.7
VPP-GF10-U	1935	24.3	19.5	1465	29.0	204.1
VPP-GF15-U	2534	25.4	20.8	1750	31.7	83.1
VPP-GF20-U	3024	26.6	21.6	2059	33.6	69.8
RPP-GF5-U	1757	20.8	17.1	1355	27.9	44.4
RPP-GF10-U	2259	21.9	18.2	1699	29.3	41.5
RPP-GF15-U	2891	22.9	19.1	1883	32.2	37.3
RPP-GF20-U	3371	23.7	20.3	2225	34.4	33.7
PP-T20	2167	26.3	21.8	1949	34.8	44.8
PP-T40	2711	20.1	13.4	3024	30.0	26.4

5.3.2 Commentary

Unlike the talc composites, Table 5-2 above illustrates that the tensile and flexural moduli, tensile and flexural strength of all PP/GF composites increased with the introduction of GF content, whether coupling agent was presented or not. It confirms the reinforcement effect of adding GF into PP (Rijsdijk et al., 1993; Thomason and Schoolenberg, 1994; Thomason, 2002).

However, PP/GF composites without coupling agent show slower growth rates in these properties whether based on virgin or recycled PP, results which could verify the effects of coupling agent in compatibilisation of polymer and fibre.

The pattern of impact strength of PP/GF composites is similar in some respects to those of PP/talc composites and brittleness of PP/GF composites was yet again observed in the results.

The impact strength of virgin PP based-composites increased with the initial introduction of GF, but decreased with further addition of GF. This can be seen when the addition of 15 wt% GF precipitated a reduction for the composites with coupling agent, and it can be seen that the addition of 10 wt% GF was the stage at which a reduction for the composites without coupling agent

occurred. The delay of impact strength turning points is possibly attributed to compatibilising effect of coupling agent, as MAPP content modify the interfacial behaviours of fibres and polymers, as outlined in previous literature (Thomason, 2002; Marsh, 2006; Valente et al., 2011).

The impact strength of recycled PP/GF composites did not increase with the addition of GF, whether in conjunction with coupling agent or not. Further, the impact strength of those composites without coupling agent decreased with GF loadings. This could most likely result from either the fillers or heterogeneous polymers which already existed in the original plastic parts or contamination during their life cycle.

As the results indicated, some mechanical performance of some composites based on recycled PP are superior to those of industrial composites, even those without coupling agent, e.g. PP-GF20 and PP-GF20-U are superior to PP-T40 in every tested property except for flexural modulus. Also, the virgin PP/GF composites are found to be superior to those based on recycled PP with same glass fibre loading, except for both tensile and flexural moduli, which is as similar as the PP/talc composites.

From the results shown above, the recycled plastic yet again demonstrates its potential for blending with GF; with proper formula and treatment, these materials could be used in demanding industrial applications, such as automobile parts.

5.4 Addition of OMMT in Recycled Plastics

In this study, the OMMT group was tried in a similar manner to previous groups; OMMT was added into recycled and virgin plastics to verify its effect on mechanical performance. The compositions for PP/OMMT composites are shown in Table 3-5, and the experimental procedure was shown in Section 3.2.

Two types of MAPP with different grafted rates were introduced as coupling agents and their compatibilisation effect in compounding recycled plastics and OMMT were evaluated and compared. Because the low compatibility and interfacial adhesion of composites leads to poorer mechanical and thermal properties of the final products (Aziz et al., 2005; Wu, 2005), there are only few researchers have looked at identification of compatibilising effect of different types of MAPPs (Kim et al., 2007). For the first time, an experimental work on identifying

the compatibilisation effect on recycled plastics of different CA has been reported.

Additionally, rheological and thermal stability tests were also performed with the aim of further verifying the effect of nanoclay in recycled polymer, following the work of other researchers (Zhu et al., 2009; Liu and Liang, 2011).

5.4.1 Mechanical Results and Discussion

Experimental results of mechanical tests are shown in Table 5-3.

Table 5-3 Experimental results of PP/OMMT composites

Designation	Flexural Modulus	Flexural Strength	Impact Strength	TDL
VPP	1307	33.4	185.1	76.2
RPP	1397	30.6	42.3	72.5
V1-MAPP1	1325	33.8	154.7	81.6
V2-MAPP1	1357	34.9	141.8	81.9
V3-MAPP1	1381	35.2	142.5	83.4
V4-MAPP1	1416	35.3	138.0	87.6
V5-MAPP1	1424	35.7	144.2	88.3
V1-MAPP2	1307	33.4	134.2	81.4
V2-MAPP2	1324	33.9	136.2	83
V3-MAPP2	1329	34.2	134.6	84.1
V4-MAPP2	1373	34.9	138.5	85.4
V5-MAPP2	1431	35.5	141.6	87.6
R1-MAPP1	1407	32.3	27.9	81.2
R2-MAPP1	1529	34.0	29.9	83.1
R3-MAPP1	1580	35.3	33.1	83.3
R4-MAPP1	1581	35.8	32.9	84.3
R5-MAPP1	1663	36.5	31.7	86
R1-MAPP2	1430	32.5	38.4	81.1
R2-MAPP2	1475	33.6	31.3	81.7
R3-MAPP2	1496	33.8	29.4	82.6
R4-MAPP2	1563	35.1	32.0	83.6
R5-MAPP2	1646	35.7	30.0	85.4

As shown in Table 5-3, the flexural modulus and flexural strength of all virgin and recycled PP/OMMT composites increased with the introduction of OMMT. Judging from the figures, it was seen that the reinforcement effect of OMMT

content in recycled PP is more significant than that in virgin PP. For example, the flexural strength of R5-MAPP1 increased by almost 20% compared to RPP1, while the flexural strength of V5-MAPP1 increased no more than 10% compared to VPP2 at same OMMT loading (5 wt%).

The growth rates of flexural modulus and strength of all the PP/OMMT composites when coupled with MAPP1 are noticeably higher than those which using MAPP2. It is demonstrated that the effect of MAPP1 is more pronounced than MAPP2 in compatibilising OMMT and PP whether recycled or not.

The impact strength of PP/OMMT composites has shown a different pattern compared to those of PP/talc or PP/GF composites: the value decreased with the initial introduction of OMMT, and then either increased slowly with further addition (virgin PP based compatibilising with MAPP2) or maintained the same level (recycled PP based). This phenomenon occurred with all PP/OMMT composites which could exclude the effects brought by contamination or heterogeneous materials which exist during their first life. Then, the possible cause could be the processing parameters, blending ratio or pre-treatments of

OMMT, or PP-OMMT interfacial structure, as polybutylene terephthalate (PBT) (Zhang et al., 2009a).

It can be found from the comparison of data in Table 5-3 and Table 4-5 that some properties of recycled PP/OMMT composites were closer to those of industrial composites, accordingly the impact strength of R3-MAPP1 is almost as same as the impact strength of Kingfa PP, TDLs of R5-MAPP1 and R5-MAPP2 were close to that of Pret PP. Considering the loading of OMMT and MAPP was quite low compared to talc or GF, these improvements were indeed quite significant. Moreover, because of low filler loading, the change in density of PP/OMMT composites is much less significant than those PP/talc or PP/GF composites. Thus, recycled PP/OMMT composites demonstrate a potential for being used in certain demanding industrial applications with specific requirements regarding weight or density.

5.4.2 Rheological Results and Discussion

Selected shear viscosities of recycled PP/OMMT composites are plotted in Figure 5-1. The shear viscosities of recycled PP/OMMT composites decreased with the addition of OMMT, which verifies

the lubricating effect of OMMT on recycled plastic as was demonstrated in conjunction with virgin plastic (Shahabadi and Garmabi, 2012; Zare and Garmabi, 2012b).

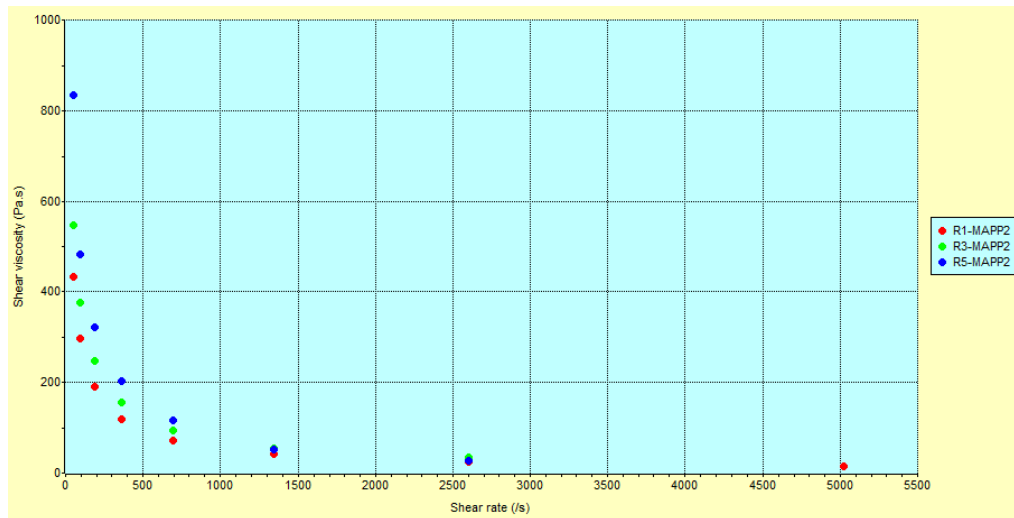


Figure 5-1 Shear Viscosity against Shear Rate of recycled PP based OMMT composites (effects of different OMMT content)

In Figure 5-2 and Figure 5-3, the two types of CA show different effects on rheological property: MAPP1 has a better compatibilisation effect in compatibilising both virgin and recycled PP/OMMT composites than MAPP2 as smaller shear viscosity values are observed in the figures.

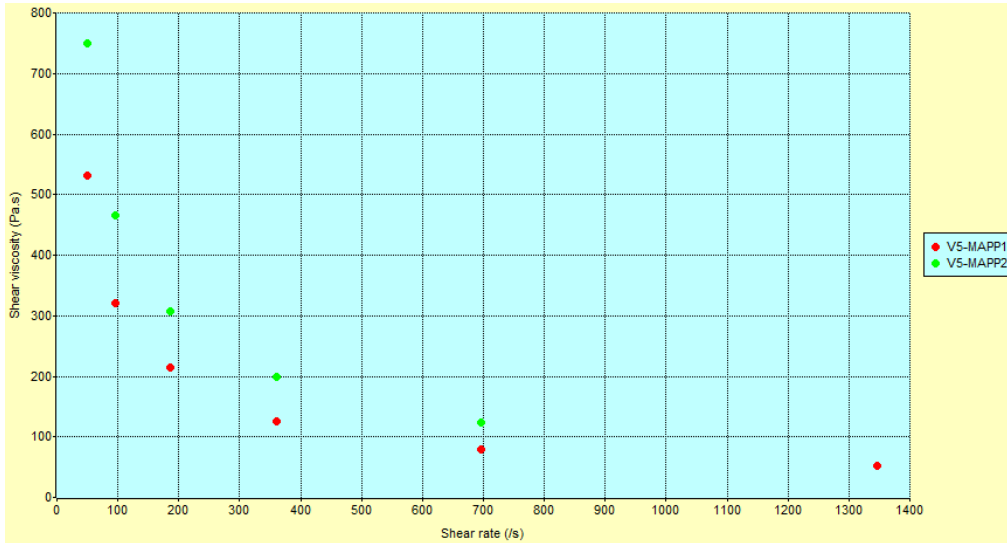


Figure 5-2 Shear Viscosity against Shear Rate of virgin PP based OMMT composites (effects of different MAPPs)

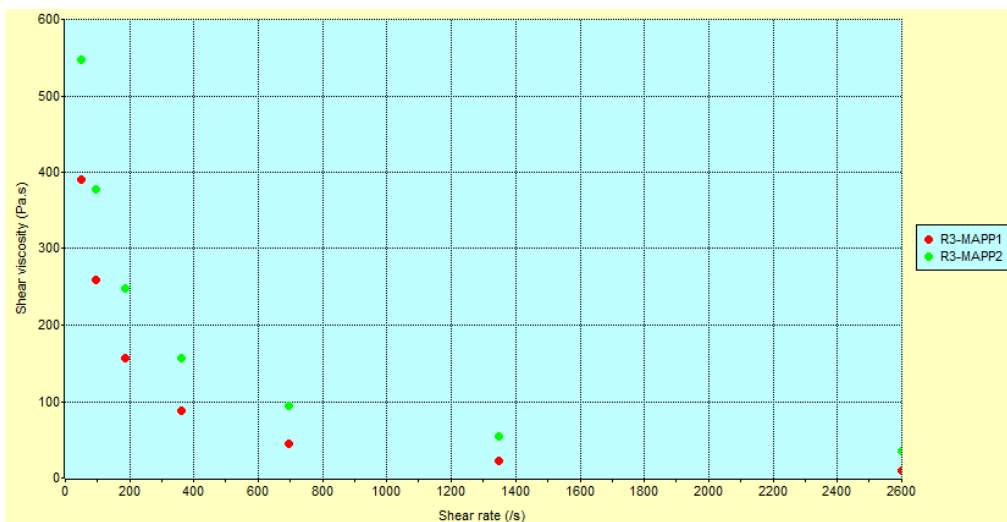


Figure 5-3 Shear Viscosity against Shear Rate of recycled PP based OMMT composites (effects of different MAPPs)

5.5 Summary of Filler Addition Experiments

Recycled plastic improved with the addition of all three fillers in terms of mechanical, thermal and rheological properties.

Besides, the compatibilisation effect of MAPP was identified, and the effects different MAPPs in compatibilising PP/OMMT

composites were compared.

5.5.1 Improvement Assessment

The improvement rate (IR) was used to calculate the proportional ratio of improvements in performance of recycled composites comparing to the original performance of recycled plastics, shown in Equation 5-1.

$$IR = \left(\frac{P'_R}{P_R} - 1 \right) \times 100\% \quad \text{(Equation 5-1)}$$

in which, P'_R represents the performance of filled recycled composites; P_R represents the original performance of recycled plastics. IR s of recycled PP by the additions of three fillers were calculated and summarized in Table 5-4 using Equation 5-1.

Table 5-4 IRs of recycled PP by the addition of three fillers (%)

Designation	Tensile Modulus	Tensile Strength	Yield Strength	Flexural Modulus	Flexural Strength	Impact Strength	TDL
RPP-T10	23.30	3.98	9.52	19.86	5.42	-10.55	N/A
RPP-T20	58.50	8.46	10.88	48.83	14.44	-27.70	N/A
RPP-T30	96.76	18.41	24.49	88.18	27.08	-6.07	N/A
RPP-T40	139	26.37	38.1	155.51	35.38	-40.9	N/A
RPP-GF5	48.91	4.48	6.17	29.99	7.66	30.3	N/A
RPP-GF10	93.8	11.44	12.96	68.31	19.71	22.1	N/A
RPP-GF15	151.41	20.9	24.07	97.16	34.67	-15.49	N/A
RPP-GF20	198.07	27.36	32.72	142.86	47.45	2.28	N/A
R1-MAPP1	N/A	N/A	N/A	0.72	5.56	-34.04	12
R2-MAPP1	N/A	N/A	N/A	9.45	11.11	-29.31	14.62
R3-MAPP1	N/A	N/A	N/A	13.1	15.36	-21.75	14.9
R4-MAPP1	N/A	N/A	N/A	13.17	16.99	-22.22	16.28
R5-MAPP1	N/A	N/A	N/A	19.04	19.28	-25.06	18.62
R1-MAPP2	N/A	N/A	N/A	2.36	6.21	-9.22	11.86
R2-MAPP2	N/A	N/A	N/A	5.58	9.80	-26.00	12.69
R3-MAPP2	N/A	N/A	N/A	7.09	10.46	-30.50	13.93
R4-MAPP2	N/A	N/A	N/A	11.88	14.71	-24.35	15.31
R5-MAPP2	N/A	N/A	N/A	17.82	16.67	-29.08	17.79
Average	101.22	15.18	19.86	41.72	17.66	-16.53	14.8

As shown in Table 5-4, almost all three fillers have improved the recycled plastics dramatically, except in terms of impact strength, as impact strength of most composited materials showed some decrease with the addition of filler contents. For both tensile and flexural moduli of filled recycled PP composites, the improvements are the most significant, followed by yield strength.

Further, the improvement rate per loading (*IRPL*) was used to calculate the proportional ratio of improvements in performance of recycled composites compared to the original performance of recycled plastics per 1% added filler loading, with the purpose of checking the effectiveness of each filler, shown in Equation 5-2.

$$IRPL = \frac{\left(\frac{P_R'}{P_R} - 1\right) \times 100\%}{FillerLoading} \quad \text{(Equation 5-2)}$$

in which, P_R' represents the performance of filled recycled composites, P_R represents the original performance of recycled plastics, *FillerLoading* refers to the percentage of filler in the composite, e.g. 20% talc is 20.

Average *IRPL* values of recycled PP composites with all the

three fillers were calculated and presented in Table 5-5 using Equation 5-2.

Table 5-5 Average *IRPLs* of recycled PP by the addition of three fillers (%)

Filler	Tensile Modulus	Tensile Strength	Yield Strength	Flexural Modulus	Flexural Strength	Impact Strength	TDL
Talc	3.18	0.57	0.83	3.12	0.82	-0.85	N/A
GF	8.20	1.07	1.27	5.64	1.82	0.65	N/A
OMMT-MAPP1	N/A	N/A	N/A	3.7	4.55	-8.83	5.09
OMMT-MAPP2	N/A	N/A	N/A	2.98	3.86	-7.94	4.77

As shown in Table 5-5, GF is the most effective filler in improving the widest range of mechanical properties, with the expectations of flexural strength and TDL (no testing data). Further, OMMT is the most effective filler in promoting flexural strength.

The average *IRPL* results proved that MAPP1 is a better compatibiliser when compared to MAPP2, since OMMT composites coupled with MAPP1 showed a greater improvement than those composites with MAPP2.

5.5.2 Comparison with Virgin Material

The comparisons with virgin PP (compared to the performance of the virgin PP used in the same group) are expressed in the form of *PRs*, which were calculated and summarized in Table 5-6 using definitions in Section 4.3.1 and Equation 4-1. The *PRs* results showed similar patterns to the *IRs*, all three fillers promoted the recycled plastics to approach or even surpass the property qualities virgin plastics ($PR > 100$), except with respect to impact strength.

Table 5-6 PRs of recycled PP by the addition of three fillers (%)

Designation	Tensile Modulus	Tensile Strength	Yield Strength	Flexural Modulus	Flexural Strength	Impact Strength	TDL
RPP-T10	144.73	88.56	98.17	156.24	114.06	24.71	N/A
RPP-T20	158.50	92.37	99.39	194.00	123.83	19.97	N/A
RPP-T30	196.76	100.85	111.59	245.29	137.50	25.95	N/A
RPP-T40	239.00	107.63	123.78	333.06	146.48	16.33	N/A
RPP-GF5	188.38	90.91	95.03	159.95	118.47	41.39	N/A
RPP-GF10	193.8	96.97	101.1	207.1	131.73	38.78	N/A
RPP-GF15	251.41	105.19	111.05	242.61	148.19	26.85	N/A
RPP-GF20	298.07	110.82	118.78	298.84	162.25	32.49	N/A
R1-MAPP1	N/A	N/A	N/A	107.65	96.71	15.07	106.56
R2-MAPP1	N/A	N/A	N/A	116.99	101.8	16.15	109.06
R3-MAPP1	N/A	N/A	N/A	120.89	105.69	17.88	109.32
R4-MAPP1	N/A	N/A	N/A	120.96	107.19	17.77	110.63
R5-MAPP1	N/A	N/A	N/A	127.24	109.28	17.13	112.86
R1-MAPP2	N/A	N/A	N/A	109.41	97.31	20.75	106.43
R2-MAPP2	N/A	N/A	N/A	112.85	100.6	16.91	107.22
R3-MAPP2	N/A	N/A	N/A	114.46	101.2	15.88	108.4
R4-MAPP2	N/A	N/A	N/A	119.59	105.09	17.29	109.71
R5-MAPP2	N/A	N/A	N/A	125.94	106.89	16.21	112.07
Average	208.83	99.16	107.36	167.39	117.46	22.08	109.23

Successful applications of the three fillers in this chapter showed the potentials of recycled plastics, as many of the properties of filled recycled composites were superior to those of virgin plastics or industrial composites. And with the identification of the compatibilisation effect of coupling agent, the suitable composition formulas can be readily obtained.

5.6 Further Work

It is shown for the first time that talc, GF and OMMT can be used as the primary fillers improve low quality recycled plastics recovered from MSW. MAPP with grafted rate of 0.8% (MAPP1) is proved to be a better compatibiliser in compounding recycled PP with OMMT than MAPP with grafted rate of 0.9% (MAPP2).

The procedures, formulas and results obtained in this chapter provide a valid basis for further experiments, assessments and discussions explored in the following chapters. The formulas and processing conditions of these filled PP composites are used in the following chapters to complement an exploration of areas for further study.

From tests and their results presented above, it can be

determined that the mechanical performance of recycled plastics (based) composites can match those of virgin plastics or industrial composites. Under certain conditions, recycled plastic composites possess superior qualities to virgin ones.

Chapter 6 Durability Tests

6.1 Introduction

Polymer and polymer composites are increasingly applied in a wide range of applications. In many cases, long-term life expectancy in hostile environments is required, which could entail up to 50 years' exposure. Durability problems of plastic parts are linked with their service environments and processing procedures (including maintenance, repair and modifications). Durability is a serious issue that concerns economic costs, and health and safety. The repair or replacement of a deteriorated part is both labour and capital intensive, especially for those large structural applications or clustered parts caused by "parts integration". As a consequence, there is growing demand for manufacturers to guarantee the life expectancy of their products, particularly where inspection can be difficult or catastrophic failure may occur in high risk contexts involving infrastructure and equipment such as gas pipelines, chemical storage tanks, underground cabling, aerospace components, personnel safety equipment and medical implants (Maxwell et al., 2006).

Even though much research has been reported on the durability of virgin materials, not much work has been done to investigate

the durability of recycled materials, and most reported work is concerned with construction materials, such as recycled plastics in concrete and fencing (Bajracharya et al., 2014). In this study, durability tests were conducted on recycled plastics and composites based on recycled plastics. Although the methodology of those tests is quite old-fashioned, it is original in terms of conducting experimental trials with recycled plastics or recycled composites. The durability study was classified into two categories:

1. Ageing: plastic parts work under controlled temperatures and humidity, for samples endure either constant condition or freeze/thaw cycles;
2. Reprocessing cycles: composites were processed in multiple reprocessing cycles with elevated temperatures.

For the first time, accelerated ageing tests, such as freeze/thaw cycles and hot, damp conditions, were conducted on recycled plastics, and compared against ageing results in room conditions. Reprocessing cycles were performed on recycled plastics originally, repeated extrusion and injection moulding. This chapter examined the effects of some degradation factors, such as temperature, humidity and shear forces, cast on

recycled plastics and recycled plastics based composites via tests performed on their mechanical properties.

6.2 Ageing Tests for Recycled Plastics

Since UV ageing (effect and its mechanism) has been studied intensively, as mentioned in the literature review, UV ageing tests were conducted during this study. Besides UV light (photo-oxidation), there are two predominant degradation agents (factors) causing environmental ageing - humidity and temperature. Therefore these two factors were the major elements in the ageing tests section, and a series of tests was conducted by controlling the two aforementioned factors.

For this study, the ageing tests are divided into two classes:

1. Long-term room condition ageing;
2. Accelerated weathering, which consists of both freeze/thaw cycles and constant high-temperature-humidity.

The compositions for ageing tests are shown in Table 3-6, and the experimental procedure is shown in Section 3.2.

6.2.1 Room Condition Ageing Tests

Room condition ageing behaviours and mechanisms of virgin

plastics have been studied for a considerable time (Read et al., 1988; Vittoria, 1988; Fiebig et al., 1999), but no report on recycled plastics has yet been published.

6.2.1.1 Treatment

In this research, the room condition was set at a temperature of 23°C and 50% Relative Humidity (R.H.) as previous literatures (Fiebig et al., 1999). The purpose was to establish a basic ageing performance data for recycled plastics.

Changes caused by physical ageing occur for extended periods of time and can be detected after months and even years using sophisticated methods, especially in the cases of modulus and strength (Fiebig et al., 1999). However, years or decades of continuous ageing tests are not feasible in academic research. Thus, the sampling timeline in this research was a simplified schedule based on the modification of previous literature relating to room ageing studies (Vittoria, 1988; Fiebig et al., 1999). The second set of tests was performed 30 days after the specimens were produced, and the third set was performed at 90 days after initial sampling.

This research used the following equation to calculate the degradation rate (DR) of the composites' performance which was applied for all properties:

$$DR = \frac{P_o - P_A}{P_o} \times 100\% \quad \text{(Equation 6-1)}$$

in which, the symbol P_o denotes the original performance obtained from initial tests once the specimens were made, the symbol P_A denotes the performance obtained after the ageing procedures were performed.

6.2.1.2 Results and Discussion

The experimental results obtained are plotted in Figure 6-1 to Figure 6-6.

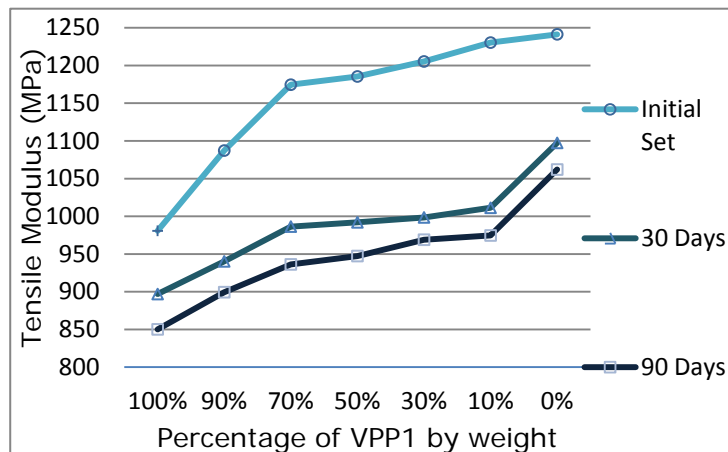


Figure 6-1 Tensile Modulus (MPa) of blends of VPP1 and RPP2 under room condition

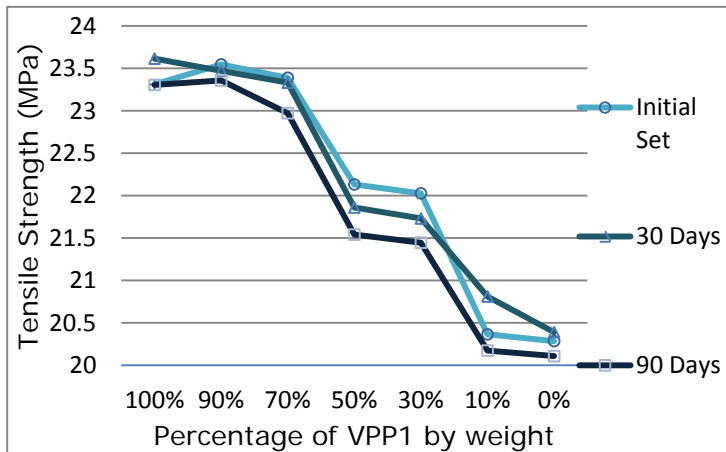


Figure 6-2 Tensile Strength (MPa) of blends of VPP1 and RPP2 under room condition

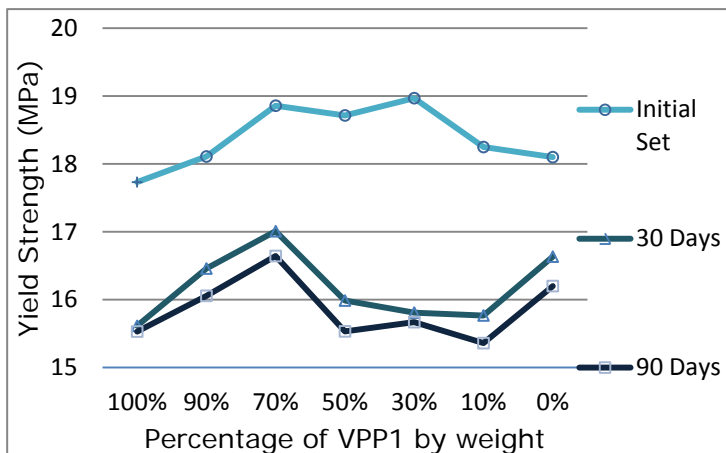


Figure 6-3 Yield Strength (MPa) of blends of VPP1 and RPP2 under room condition

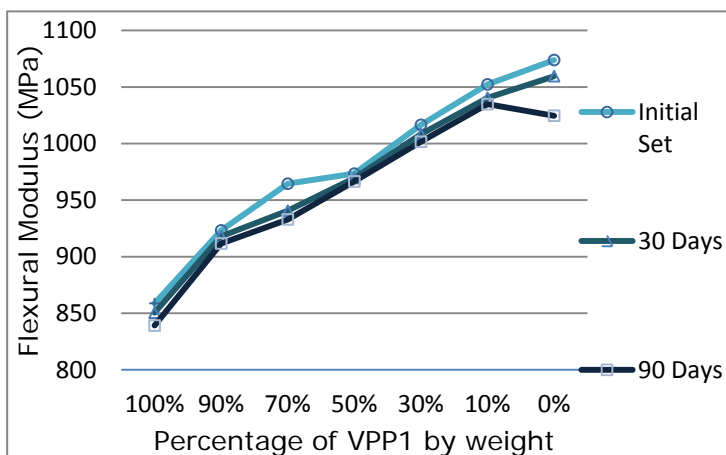


Figure 6-4 Flexural Modulus (MPa) of blends of VPP1 and RPP2 under room condition

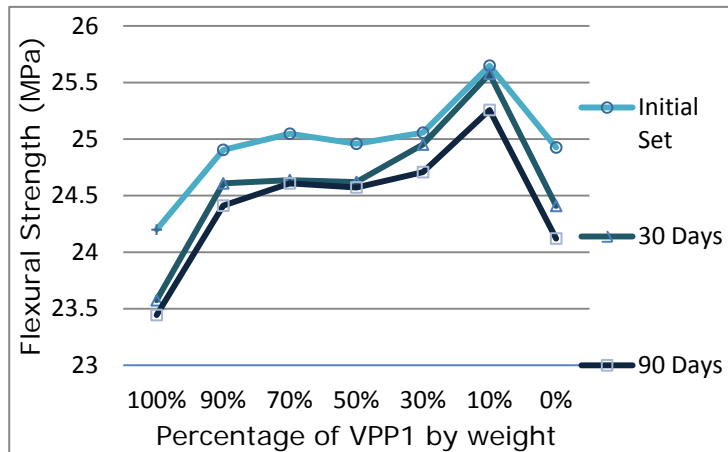


Figure 6-5 Flexural Strength (MPa) of blends of VPP1 and RPP2 under room condition

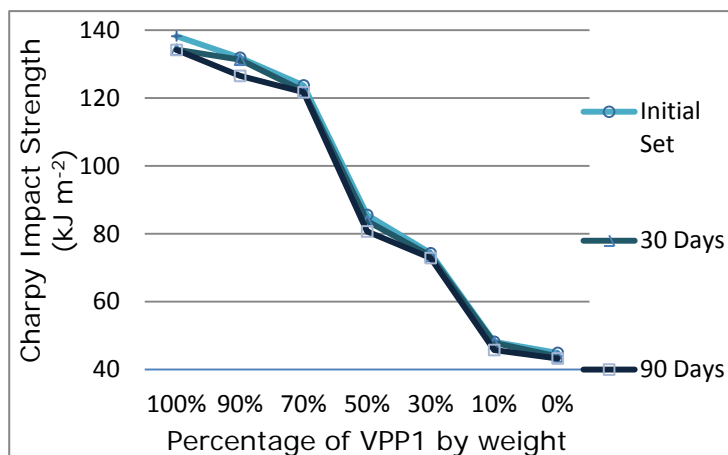


Figure 6-6 Charpy Impact Strength (kJ m⁻²) of blends of VPP1 and RPP2 under room condition

The results demonstrated that the degradation of mechanical properties occurred during 30 days after specimens were produced. The tensile properties declined during the 30 days, most notably tensile modulus and yield strength. After this period the speed of decline in performance slowed down, as shown in Figure 6-1 to Figure 6-3. For both flexural and impact properties, the degradation was observed but quite insignificant

compared to the deteriorations in tensile properties which are shown in Figure 6-4 to Figure 6-6, as the performance decreased less than 5% of original figure.

As Mitsuyoshi and Tetsuo (1991) stated, the properties of semicrystalline polymers, such as PP, are mainly determined by the crystalline morphology developed during mouldings. The main factors influencing the morphology are the combination of processing conditions and crystallization dynamics, as well as polymer's characteristics, such as average molecular weight, molecular mass distribution and chain regularity (Gahleitner et al., 1996).

However, property changes at room condition cannot be fully explained by crystallization theory because the temperature is far below the crystalline melting point. Fiebig et al. (1999) proposed that the properties are influenced by the partially highly mobile amorphous fractions. These fractions act as links between the crystalline segments and strongly influence the mechanical properties.

According to the results, it was clear that the design of moulds

and injection moulding procedure could affect the distribution of amorphous fractions in the specimens. The moulds used for making sample pieces and flow directions are shown in Figure 6-7. Melted plastic flow is directed by the flow passages in the mould. And in tensile tests, the pulling force exerted by the testing machine is in the same direction as the flow passages. Along these directions, there is no applied packing pressure. Thus, the specimens are likely to be relaxed or creep under the external force applied on those directions due to lack of sufficient external pressure to hold the shapes to assist crystallization procedure. This is a likely explanation as to why the ageing effect was quite significant in respect to tensile properties.



Figure 6-7 The moulds and the directions of their flow-passages as indicated by red arrows

For flexural and impact properties, the testing forces (flexural force, for example, was shown in Figure 6-8) were exerted on the specimens in exact by the same direction where the packing pressure applied on, as shown in Figure 6-9. The pressure has held the specimens to maintain their forms and strengthen internal structure in this direction (improved crystallization), rendering them more resistant to blending or impacting forces which are applied in the same direction. This could explain the patterns in Figure 6-4 to Figure 6-6, since the ageing in flexural

and impact properties observed was insignificant.

The crystallization differences in different directions of virgin and recycled polymers were observed by Wang et al. (2012; 2013) via wide-angle X-ray scattering tests, which confirmed the pattern observed in this research.



Figure 6-8 Direction of flexural testing force applied on specimens

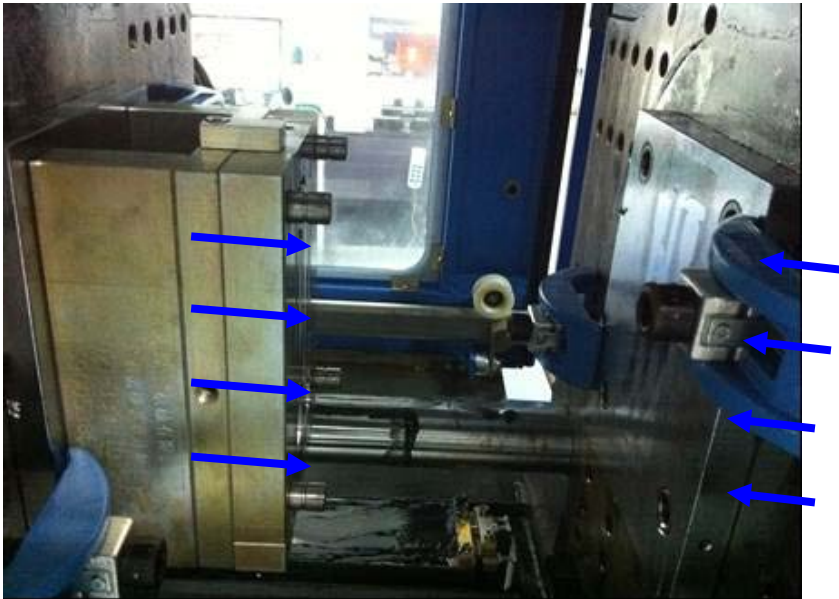


Figure 6-9 The moulds in injection moulding machine and the direction of packing pressure applied on specimens as indicated by blue arrows

The tensile properties of recycled PP based PP/talc composites and industrial composites are plotted in Figure 6-10 to Figure 6-12.

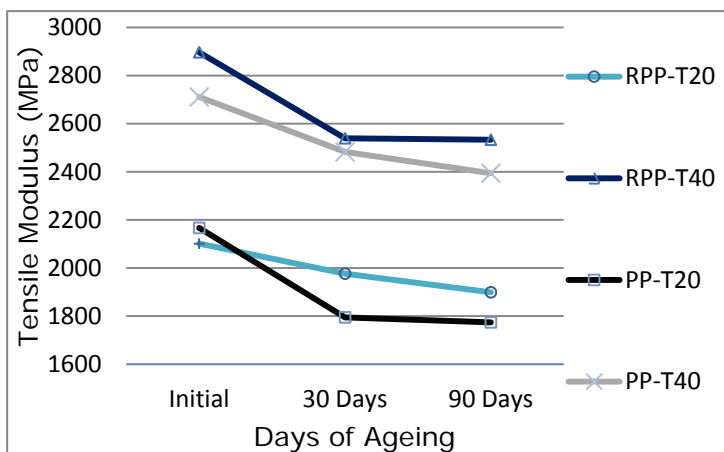


Figure 6-10 Tensile Modulus (MPa) against days of ageing under room condition

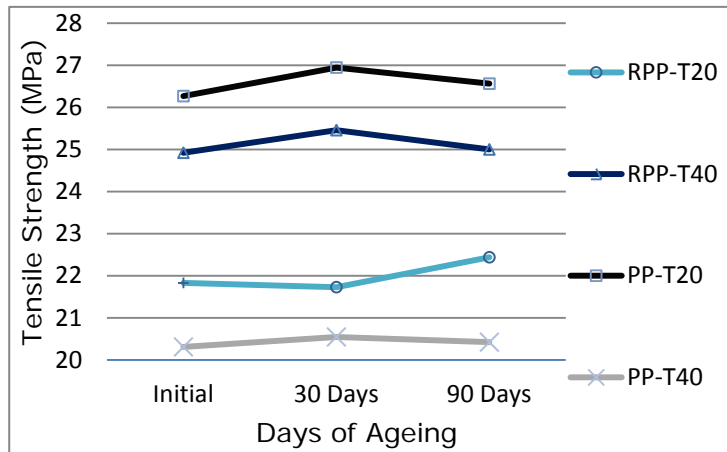


Figure 6-11 Tensile Strength (MPa) against days of ageing under room condition

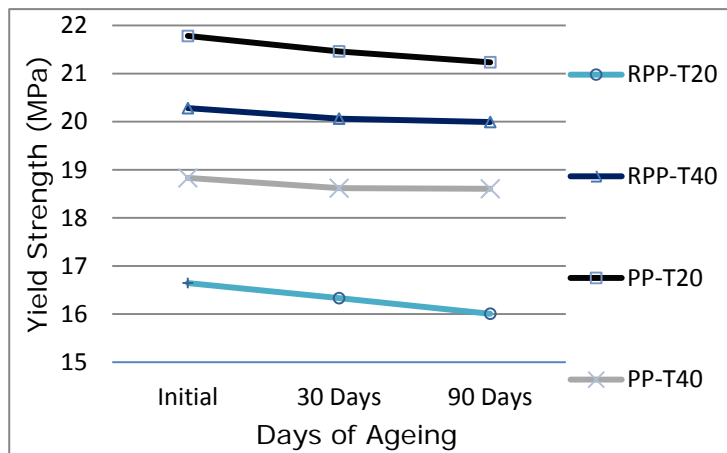


Figure 6-12 Yield Strength (MPa) against days of ageing under room condition

As shown in the figures above, PP/talc composites showed a slower degradation in tensile modulus and yield strength with ageing time, while tensile strength seemed to remain at the same level as the initial test set. The *DRs* of PP/talc composites were much smaller than those of unfilled PP blends, and even slightly less than those of industrial composites as shown in Table 6-1 obtained using Equation 6-1.

Table 6-1 DRs of tensile properties for blends based on VPP1 and talc-filled composites under room condition for 90 days (%)

Composites	Tensile Modulus	Tensile Strength	Yield Strength	Average
Average VPP1 based blends	17.97	1.39	13.74	11.03
RPP-T20	9.63	-2.79	3.84	3.56
RPP-T40	12.55	-0.32	1.42	4.55
PP-T20	18.13	-1.12	2.51	6.51
PP-T40	11.7	-0.55	1.19	4.11

6.2.2 Accelerated Weathering for Recycled Plastics

Accelerated ageing studies in environments with controlled temperature and humidity have been reported frequently during recent decades (Shah and Patni, 1994; Chin et al., 2007; Lv et al., 2011; Jiang et al., 2012).

6.2.2.1 Treatment

In this research, the accelerated weathering tests were divided into two categories adapted from existing literature (Haghighi-Yazdi et.al, 2011; Lv et al., 2011):

1. Freeze/thaw cycles, in which specimens undergo cyclical ageing procedure;
2. Hot and damp, which temperature and humidity remain

constant during ageing.

The accelerated weathering tests in this research were conducted in a programmable temperature and humidity ageing chamber, model CLMWS-170. Its temperature range is -70°C to 150°C while the humidity range is 20% R.H. to 98% R.H.

The specimens were put into sample trays made from stainless steel immediately after being produced.

1. Freeze/thaw Cycles Ageing

In a single freeze/thaw cycle, the temperature and humidity were set at 60°C and 90% R.H. initially, and kept for 4 h. Then the chamber temperature decreased to -60°C in 4 h while the humidity decreased to 0% in 2 h and this condition was kept for 4 h (0% R.H. was kept for 8 h), and the temperature raise back to the initial level in 4 h while the humidity increased to the initial level in 2 h, as shown in Figure 6-13.

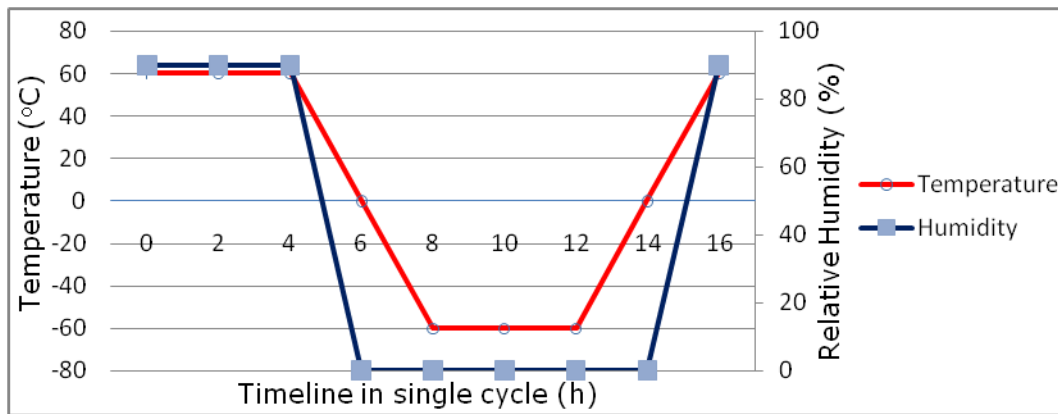


Figure 6-13 The freeze/thaw cycles used

This experimentation was designed to simulate the extreme weather, and each cycle was supposed to represent thermal impact of 8 ordinary days. The specimens were aged in chamber for 14 days, which equals 21 cycles, a period considered the equivalent of over 5 months under ordinary weather conditions. The specimens were conditioned at a room temperature of 23°C and 50% R.H. for 4 h before testing in order to drive out volatile moisture content, which concentrates at the surfaces of specimens.

2. Hot and Damp Ageing

In hot and damp test, the temperature and humidity were set at 50°C and 98% R.H. And the specimens were aged in the chamber under this condition for 60 days. The specimens were conditioned at a room temperature of 23°C and 50% R.H. for 4 h before testing, with the same purpose as the previous

section.

6.2.2.2 Results and Discussion

The experimental results of tensile properties of composites based on VPP1 are plotted in Figure 6-14 to Figure 6-16.

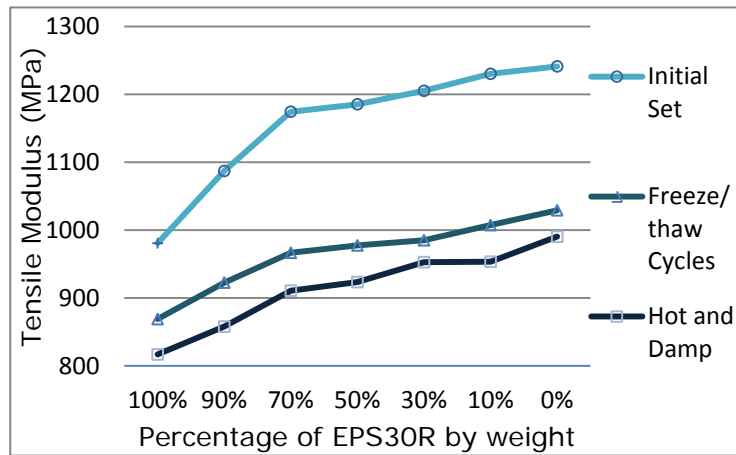


Figure 6-14 Tensile Modulus (MPa) against percentage of VPP1 under accelerated weathering

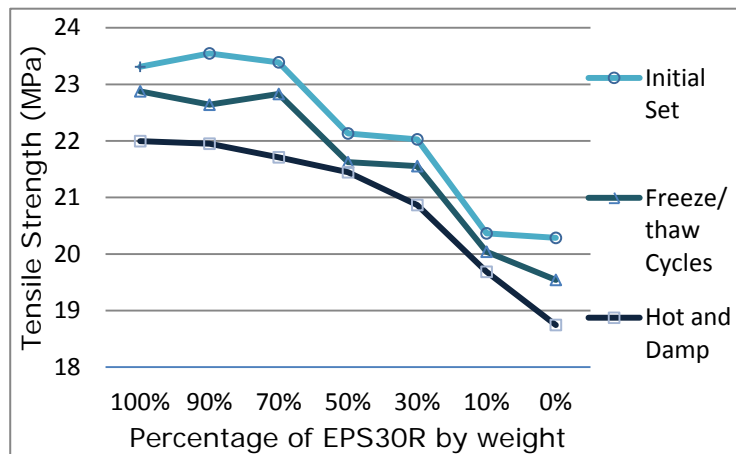


Figure 6-15 Tensile Strength (MPa) against percentage of VPP1 under accelerated weathering

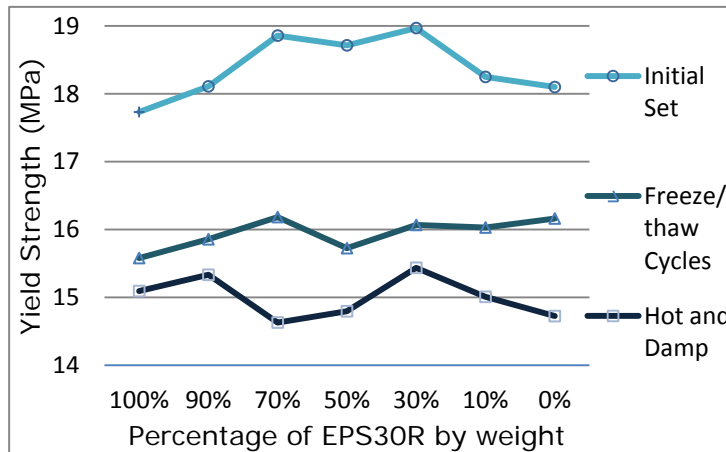


Figure 6-16 Yield Strength (MPa) against percentage of VPP1 under room accelerated weathering

As shown in Figure 6-14 to Figure 6-16 above, the polymeric degradation brought on by both accelerated weathering test sets is quite distinguishable. When comparing accelerated weathering test sets with ageing under room, the hot and damp ageing exhibited the most serious degradation, followed by freeze/thaw cycles and 90 days under room condition, as shown in Table 6-2, which were calculated using Equation 6-1.

Table 6-2 Average DRs of tensile properties for blends based on VPP1 (%)

Ageing Condition	Tensile Modulus	Tensile Strength	Yield Strength	Average
30 Days under Room Condition	14.42	-0.12	11.97	8.76
90 Days under Room Condition	17.97	1.38	13.74	11.03
Freeze/thaw Cycles	16.46	2.54	13.27	10.76
Hot and Damp	20.85	5.56	18.37	14.93

The other properties were similar to the tensile properties. The degradation was obvious and was relatively more serious than ageing under room condition. Further, in accelerated weathering tests, ageing effects caused by hot and damp condition are more serious than ageing under freeze/thaw cycles.

The PP/talc composites displayed the same pattern of behaviours as the room ageing tests set: only slight deterioration was observed, as calculated *DRs* in the four tested strengths were less than 10%, as presented in Table 6-4. Talc-filled composites appeared to be more stable than pure polymers, whether they were of virgin or recycled origin.

Table 6-3 DRs of Strengths for blends based on VPP1 and talc-filled composites under accelerated weathering (%)

Conditions	Composites	Tensile Strength	Yield Strength	Flexural Strength	Impact Strength	Average
Freeze/thaw Cycles	RPP-T20	0.71	4.87	2.39	-1.41	1.64
	RPP-T40	1.28	8.35	1.88	-0.17	2.84
	PP-T20	0.93	5.07	2.77	6.52	3.82
	PP-T40	1.16	6.44	1.6	5.92	3.78
Hot and Damp	RPP-T20	3.96	5.55	4.47	9.97	5.99
	RPP-T40	4.45	6.7	5.61	7.58	6.09
	PP-T20	3.62	4.95	8.13	8.8	6.38
	PP-T40	4.89	9.04	7.09	3.94	6.24

In Table 6-3, deterioration in flexural strength is much more significant than ageing of room condition represented in Section 6.2.1. This possibly resulted from structural relaxation and the creation of micro-cracks on the materials' surface due to saturated moisture absorption and thermal oxidation (Lv et al., 2011).

The results in Table 6-3 indicated that talc was acting as a stabilising filler in polymers, which could help to preserve mechanical performance. For recycled plastics, the talc content within was relatively effective, as smaller average *DRs* were

observed.

6.3 Effects of Reprocessing on Recycled Plastics

With the aim of promoting the understanding and use of composites based on recycled plastics, the effects from both extrusion and injection moulding cycles on the properties of recycled PP/talc composites were investigated experimentally. The compositions for reprocessing tests are shown in Table 3-7, and the experimental procedure was outlined in Section 3.2. The results were discussed and correlated with previous literatures.

6.3.1 Reprocessing Cycles

6.3.1.1 Extrusion Cycles

The extrusion process was repeated 5 times under the same operating conditions (as the same as Section 3.2), so the grinded material of each cycle was the starting material for the following reprocessing cycles. Samples were taken in every extrusion cycle and fed into injection moulding machine to make test specimens.

6.3.1.2 Injection Moulding Cycles

The injection process was repeated 5 times under the same

operating conditions. In each injection cycle, parts of the specimens were used for characterisation purposes, while the remainders were grinded by a cutting mill (Retsch, Germany, model SM 200) in order to be reprocessed, and 4 mm sieve was used. The shredded plastic pellets are shown in Figure 6-17, with an average of particle size of 3 mm.



Figure 6-17 Shredded plastics

6.3.2 Results and Discussion

6.3.2.1 Effects of Multiple Reprocessing

The experimental results from repeated extrusion cycles set are plotted in Figure 6-18 to Figure 6-24.

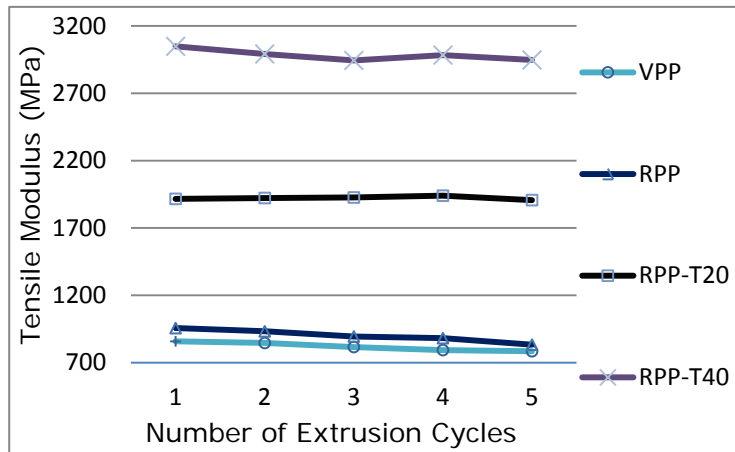


Figure 6-18 Tensile Modulus (MPa) against number of extrusion cycles

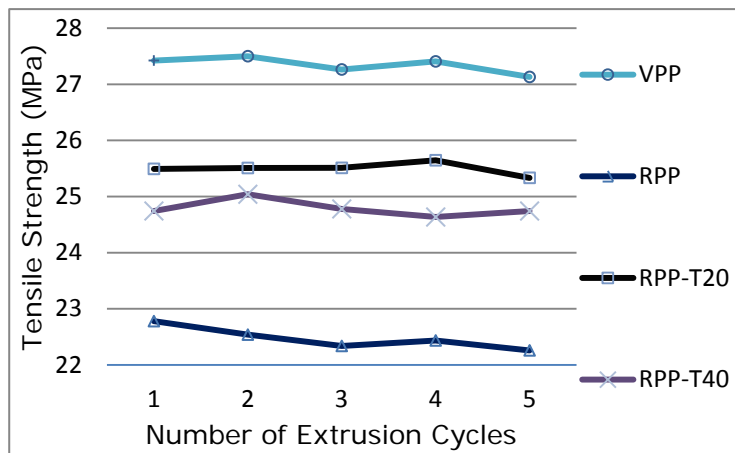


Figure 6-19 Tensile Strength (MPa) against number of extrusion cycles

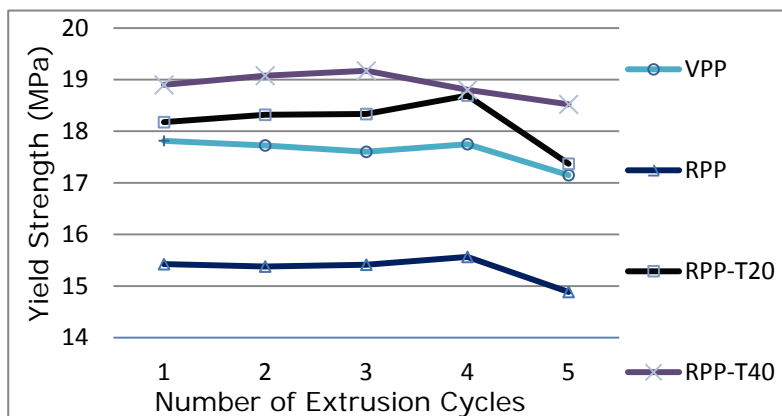


Figure 6-20 Yield Strength (MPa) against number of extrusion cycles

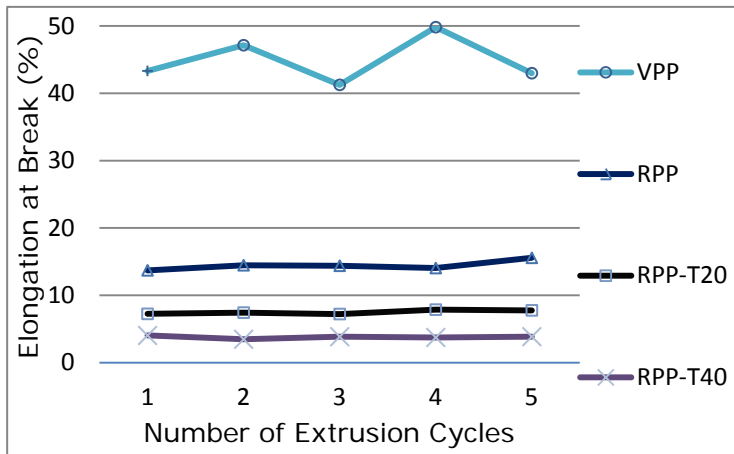


Figure 6-21 Elongation at Break (%) against number of extrusion cycles

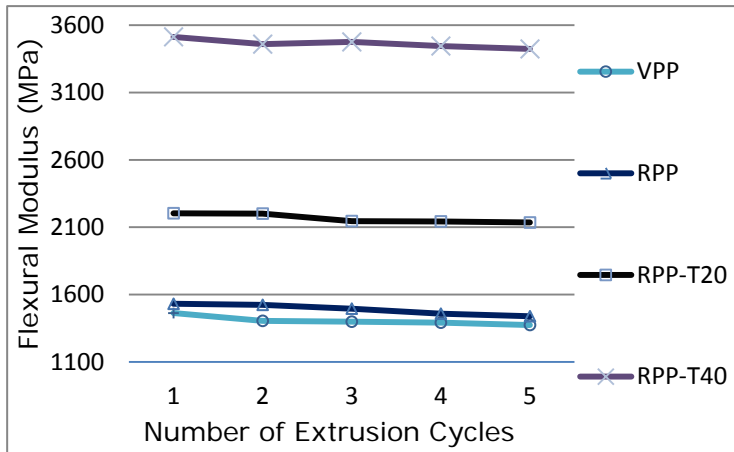


Figure 6-22 Flexural Modulus (MPa) against number of extrusion cycles

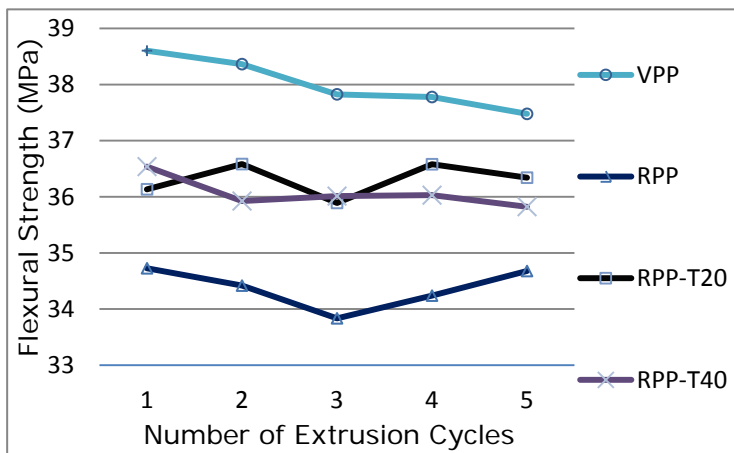


Figure 6-23 Flexural Strength (MPa) against number of extrusion cycles

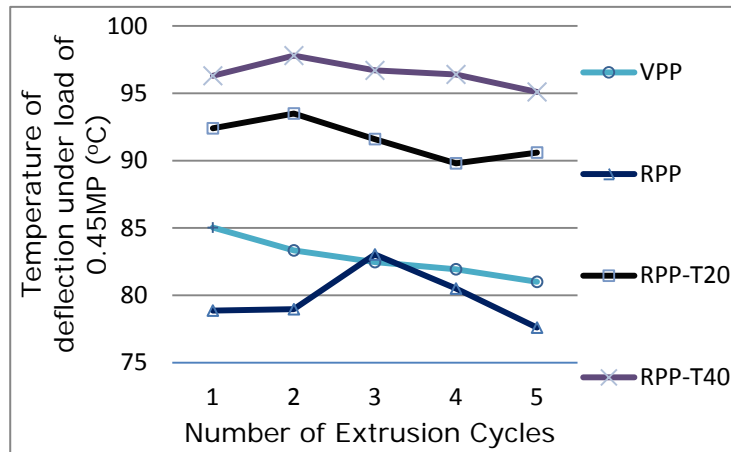


Figure 6-24 TDL (°C) against number of extrusion cycles

From Figure 6-18 to Figure 6-24 shown above, it is seen that the performance of the virgin PP decreased slowly with the number of extrusion cycles, except for elongation at break. These results were probably due to chain-scissions in polymers occurring at elevated temperatures as well as the effects of rotating shear forces as outlined in previous literature (La Mantia, 1996; González-González et al., 1998; Samperi et al., 2004).

For recycled PP and recycled PP/talc composites, some properties, such as yield strength and TDL, exhibited a minor improvement with reprocessing cycles initially and decreased with further extrusion. Other properties are shown to deteriorate slightly with reprocessing cycles. The elongation at break and flexural strength of recycled PP remained stable and

slightly enhanced at the 5th cycle. For recycled PP/talc composites, their performances were relatively more stable during repeated extrusions except for elongation at break. The talc content improves the mechanical and thermal properties of recycled PP as predicted (Denac et al., 2003; Wang et al., 2013).

For recycled PP/talc composites, their performance was relatively stable during repeated extrusions except for elongation at break, as their *DR* values were summarised in Table 6-4 using Equation 6-1. In Table 6-4, virgin PP showed the largest DR values, because at low MW, the chain scission is random, but at higher MW it becomes MW-dependent which is increasing with MW (Canevarolo, 2000), and MW of virgin PP is larger than recycled PP as shown in Section 4.3.2.

**Table 6-4 DRs of some properties during extrusion cycles
(%, comparing with the 1st process)**

	Number of Cycles	VPP	RPP	RPP-T20	RPP-T40
	2nd	1.42	2.49	-0.33	1.85
Tensile	3rd	4.89	6.50	-0.54	3.43
Modulus	4th	7.54	7.79	-1.23	2.14
	5th	8.53	12.86	0.48	3.31
	2nd	-0.28	1.06	-0.06	-1.21
Tensile	3rd	0.58	1.94	-0.07	-0.15
Strength	4th	0.06	1.51	-0.60	0.43
	5th	1.07	2.29	0.63	0.00
	2nd	0.50	0.30	-0.79	-0.95
Yield	3rd	1.19	0.07	-0.87	-1.44
Strength	4th	0.36	-0.91	-2.84	0.51
	5th	3.73	3.49	4.44	2.00
	2nd	3.95	0.50	0.12	1.54
Flexural	3rd	4.37	2.35	2.65	1.07
Modulus	4th	4.87	4.79	2.76	1.94
	5th	6.04	6.03	3.13	2.55
	2nd	0.62	0.89	-1.24	1.68
Flexural	3rd	2.01	2.57	0.67	1.44
Strength	4th	2.14	1.40	-1.23	1.39
	5th	2.92	0.14	-0.57	1.96
	2nd	2.00	-0.13	-1.19	-1.56
TDL	3rd	3.02	-5.28	0.87	-0.42
	4th	3.65	-2.07	2.81	-0.10
	5th	4.74	1.61	1.95	1.25
Average		2.91	2.17	0.37	0.94

In repeated heat and shear cycles, polymeric chain lengths become more identical than original lengths and molecular weight (MW), as shown in previous literature (Canevarolo, 2000). The mobility of the amorphous phase between the lamellae is increasing with the number of reprocesses (Mnif et al., 2010). This could give those polymers a better elongation at break. On the other hand, the presence of talc and contaminants within PP matrix resulted in an increase in crystallinity (Díez-Gutiérrez et al., 1999; Wang et al., 2013; Wang et al., 2014), which would improve tensile properties, and reduce elongation at break. Thus, it is difficult to fully understand the pattern of recycled PP/talc composites, as shown in figures and Table 6-4, and requires further study. Still, the stabilising effect of talc content is observed in recycled composites, as it has a similar effect on reprocessing of virgin PP/talc composites (Bahlouli et al., 2012; Wang et al., 2013; Wang et al., 2014).

For some rheological behaviour in the form of shear viscosity plot of the composites shown in Figure 5-28, reprocessing decreased the shear viscosity of virgin material, which may have contributed to chain-scission actions taking place in

elevated temperatures during reprocessing. However, recycled PP/talc composites (such as RPP-T20) are relatively more stable during repeated heat-involving procedures, as shown in Figure 6-25. The results from repeated injection moulding cycles have showed the same pattern.

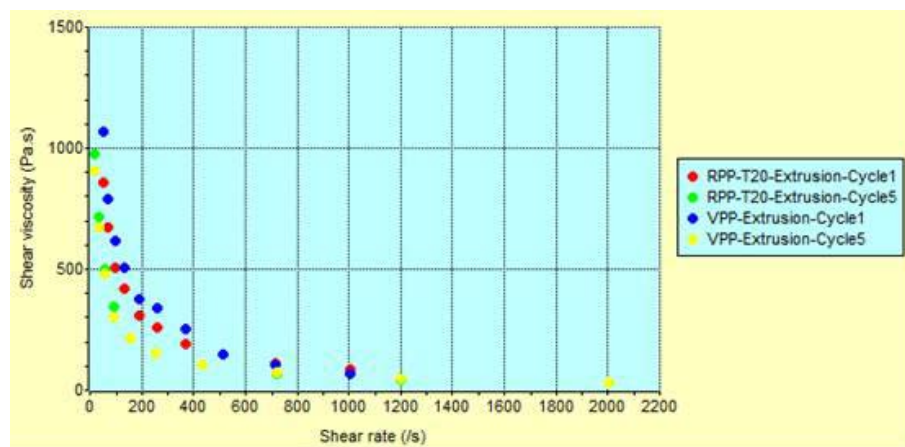


Figure 6-25 Shear viscosity plot of multiple extrusions

Results from repeated injection moulding cycles demonstrate the same pattern. It is assumed that the presence of talc does not have a significant influence on the degradation mechanisms of the material matrix (Guerrica-Echevarría et al., 1996).

Furthermore, the stability of recycled PP/talc composites might increase due to a gradual increase of delamination and dispersion of talc particles or agglomerates during successive reprocessing, resulting in an increased number of particles and a decreased particle size (Wang et al., 2013). The consistency

of flow properties of recycled PP/talc composites could lead to a more stable production rate, which would facilitate the use of such composites.

6.3.2.2 Comparison of Effects of Recycled Composites

The tensile results of recycled PP/talc composites from repeated injection moulding cycles set are plotted in Figure 6-26 to Figure 6-28 and compared with extrusion results, since the tensile properties are critical properties in reprocessing (Bernardo et al., 1996).

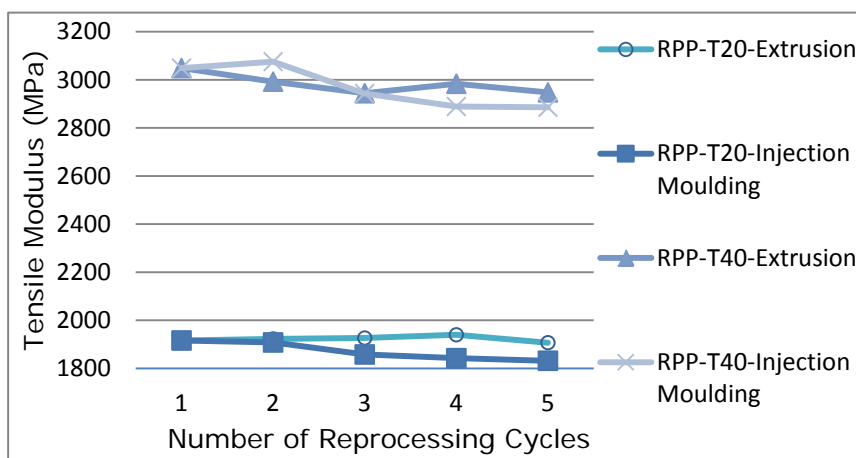


Figure 6-26 Tensile Modulus (MPa) against number of reprocessing

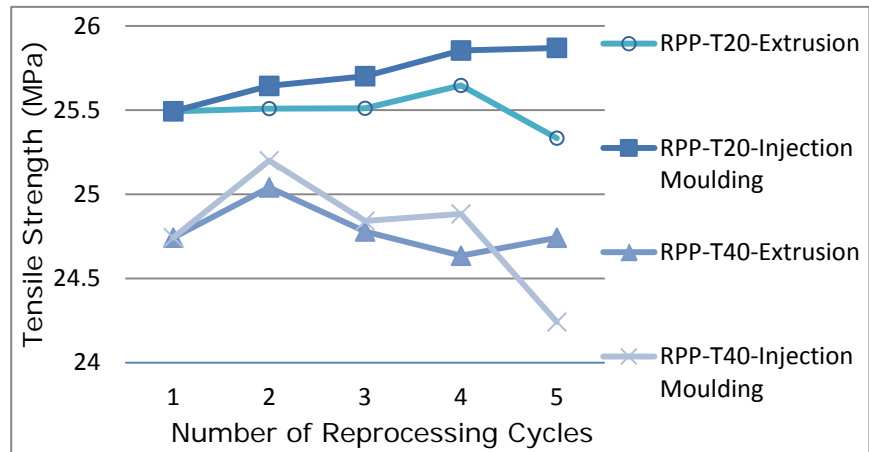


Figure 6-27 Tensile Strength (MPa) against number of reprocessing

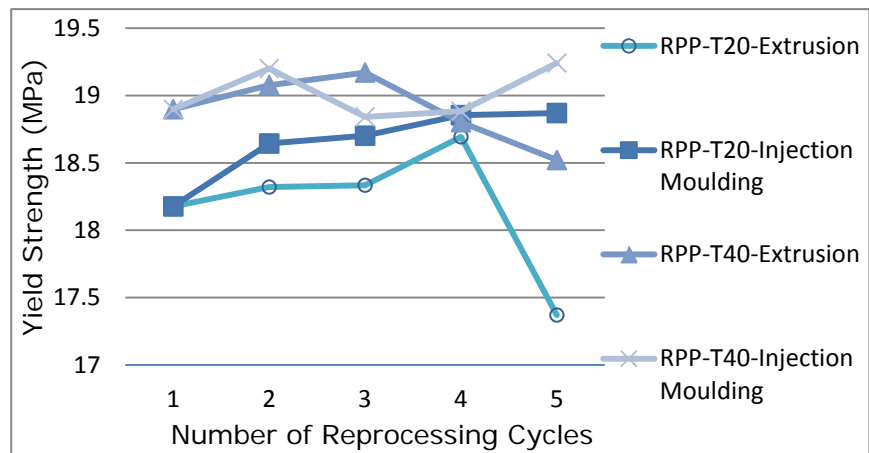


Figure 6-28 Yield Strength (MPa) against number of reprocessing

As shown in Figure 6-26 to Figure 6-28, the materials processed by multiple injection moulding cycles preserve the same desirable characteristics as those which are processed by multiple extrusion cycles. The tensile strength and yield strength increased with the number of injection moulding cycles, which would imply the increase of crystallinity as mentioned before. All tensile properties of RPP-T40 increased

initially, and then decreased with further re-injection moulding. It is possible that crystallinity degree of RPP-T40 has reached a certain limit, and the amorphous phase increased with further reprocessing.

The injection moulding cycles involve a shredding procedure, which also could be considered as an elevated temperature and high shear rate treatment. The materials endured twice such processes when compared to the extrusion set. The chain-scission effect took the ruling place in material matrix, and it would explain the lower tensile modulus than extrusion set.

To sum up, the recycled PP/talc composites maintain a high level of performance after reprocessing, and they are more stable when compared with both virgin and recycled PP with respect to most properties, as shown in Table 6-4. Thus, reuse of rejected parts made from the recycled PP/talc composites could be feasible.

6.4 Summary

This chapter investigated the durability of recycled materials,

fulfilling the gap in knowledge resulting from lack of such research, and promoting the use of recycled plastic. Using recycled plastics has already proved to be both economically-viable and environmentally-friendly. The experimental part of this chapter reported the testing on mechanical, rheological and thermal properties.

Generally speaking, composites based on recycled plastics have reasonable properties during durability tests when compared to virgin materials current being used in automobile production. Especially with regard to recycled PP/talc composites which are relatively more stable and preserve larger proportions of their original properties in both ageing and reprocessing experiments. The stabilising effect brought by talc as the major filler was identified during durability tests.

In ageing tests, creep behaviour in different directions was observed. This phenomenon could be attributed to injection moulding procedure, as confirmed in previous studies. The creep behaviour and internal relaxation were highly related to directions in which packing pressure was applied.

For the first time, recycled PP was compounded with talc and coupling agent using different concentrations. Using virgin and recycled PP as comparators, the materials were subjected to five reprocessing cycles through two different routes: extrusion and injection moulding. The results showed that the talc content has a similar performance enhancing and stabilisation effect on recycled PP as on virgin PP. Most properties of recycled PP/talc composites were superior to virgin PP after reprocessing. Their behaviour was more stable after multiple reprocessing cycles than that of virgin and recycled PP. For both reprocessing routes, the performance of the recycled PP/talc composites was similar, highlighting the potential of using recycled materials.

It is still not fully understood how reaction mechanisms within recycled polymer composites compete under ageing or reprocessing. Also the stabilisation mechanism of talc in the recycled materials requires further study.

Chapter 7 Flammability Tests for Recycled Plastics

7.1 Introduction

Both virgin and recycled PP was used as base materials to investigate the effect of recycled polymer on flammability. In this research, UL94 testing specimens were made by hot compression via a vulcanizing machine, as described in Section 3.2. Due to the sampling procedure, lower viscosities of the tested materials were expected. Thus, based on previous experiments and reports, talc and OMMT were selected for addition into virgin and recycled PP due to the convenience of sampling, as particle fillers have proved their effect on reducing the melt strength (viscosity) and facilitating production rate. Two MAPPs with different grafted rates were also used for further investigating their compatibilisation effect. The effects of recycled polymer content and fillers were studied. The compositions for flammability tests are shown in Table 3-8, and the experimental procedure was outlined in Section 3.2.

7.2 Results and Discussion

7.2.1 Effects of Recycled Content

The experimental results of PP100, PP75, PP50, PP25 and PP0 were selected and plotted in Figure 7-1 to show the effect of adding recycled polymer into virgin plastic.

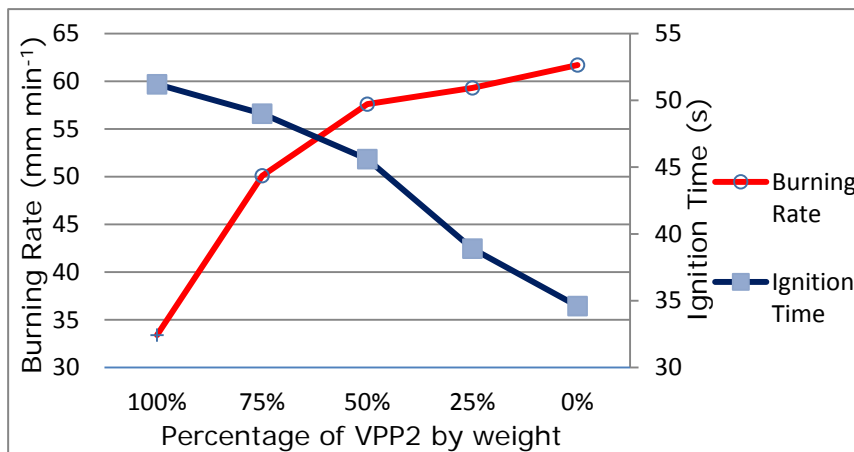


Figure 7-1 Flammability Properties against percentage of VPP2

Figure 7-1 shows that with the addition of recycled PP deteriorated the flammability properties significantly: a higher burning rate and shorter ignition time are observed. *DRs* of ignition time were calculated using Equation 6-1 and shown in Table 7-1. The blends with more recycled content tend to be more easily ignited, and the flame propagation rates tend to be noticeable higher. This likely results from the characteristics of original polymers which are recovered from or are heterogeneous materials contained in materials, which could be fillers in their initial life cycles or contaminations. More recent research confirms this result (Gug et al., 2015), as recycled PP recovered from household application tends to be much more combustible as higher heat release rate (HRR) was detected, and recycled PP could be used as coal replacement which would

offer a similar energy value to sub-bituminous coal resource (20.5 - 27.2 MJ kg⁻¹).

Table 7-1 DRs of ignition time comparing to virgin PP (%)

Designation	Ignition Time
PP75	4.3
PP50	10.94
PP25	24.02
PP0	32.42

From these blends, only PP100 can be classified into 94 HB degree. In other word, recycled materials cannot be used in industrial applications with fire resistance requirement, as each of these recycled materials failed to meet the minium requirements of UL94 standard, even when blended with virgin materials. Low flame retardance of recycled plastic (i.e. easy to burn) could be considered as a major weakness which prevents these materials from being applied in demanding industrial applications.

7.2.2 Effects of Fillers

7.2.2.1 Influence of Talc Addition on Flammability

The experimental results of PP100, PP0, VPP-T20, VPP-T40,

RPP-T20 and RPP-T40 are plotted in Figure 7-2 and Figure 7-3 to illustrate the effect of adding talc.

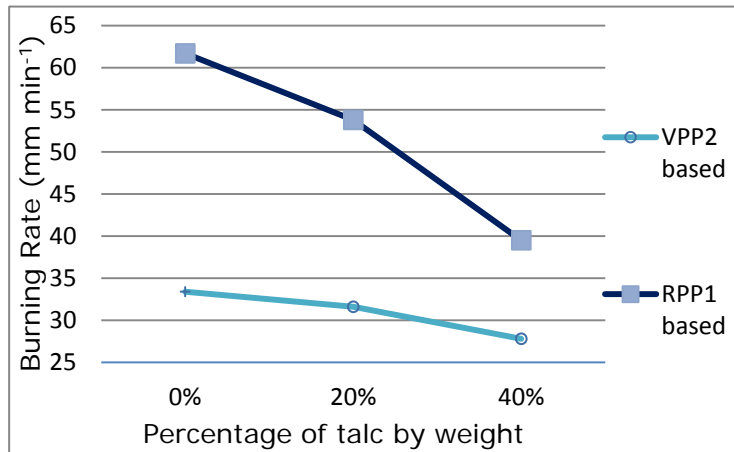


Figure 7-2 Burning Rate (mm min⁻¹) against percentage of talc

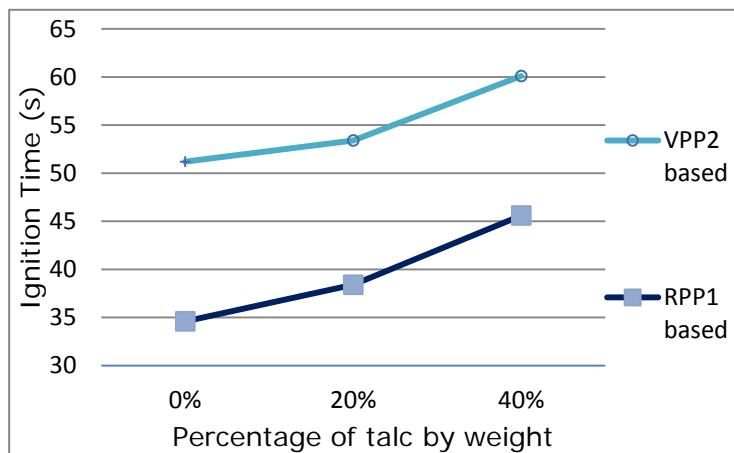


Figure 7-3 Ignition Time (s) against percentage of talc

As shown in Figure 7-2 and Figure 7-3, the flammability properties of composites improved with the addition of talc content, especially for recycled plastics, as they were becoming more resistance to ignition and were burning at a much slower speed. The flame retardance effect of talc has been studied via

combined DTA (Differential Thermal Analysis)/TGA-FTIR (Fourier Transform infrared spectroscopy) (Gibert et al., 2000), the bonded water in talc ($\text{Mg}_3[\text{Si}_4\text{O}_{10}](\text{OH})_2$) especially in $\text{Mg}(\text{OH})_2$ served as a flame retardant, and once water vaporized, the burning rate of the polymer increases dramatically with a strong exothermic effect due to the ignition of combustible vapors.

The improvements of recycled plastics with talc filler are more significant than those of virgin plastics, as Table 7-2 shown which were calculated using Equation 5-1.

Table 7-2 IRs of ignition time compared with original PP by talc (%)

Designation	IR of Ignition Time
VPP-T20	4.3
VPP-T40	17.38
RPP-T20	10.98
RPP-T40	31.79

Among these materials, RPP-T40 can be classified into 94 HB degree with talc/PP composites based on virgin PP, which indicated that RPP-T40 could be used in parts which have highest levels of flame retardance.

7.2.2.2 Influence of OMMT Addition on Flammability

The experimental results of PP/OMMT composites are plotted in Figure 7-4 and Figure 7-5 for illustrating the effect of adding OMMT.

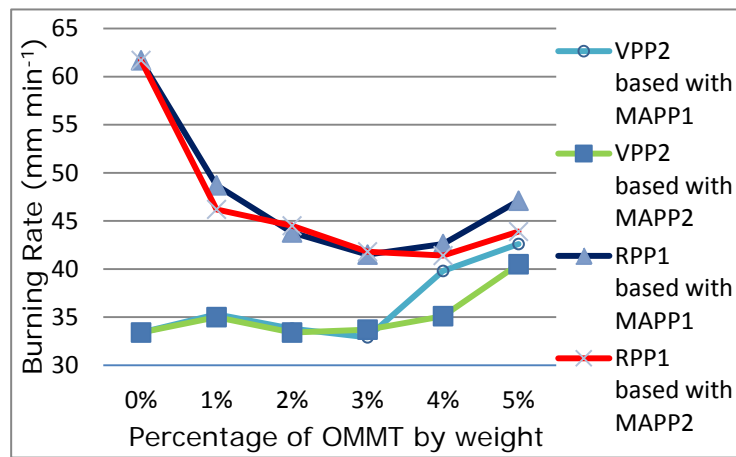


Figure 7-4 Burning Rate (mm min⁻¹) against percentage of OMMT

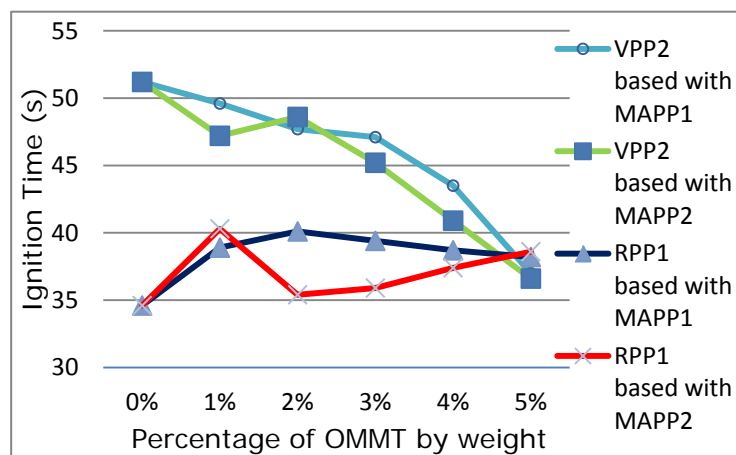


Figure 7-5 Ignition Time (s) against percentage of OMMT

Figure 7-4 and Figure 7-5 show that the burning rates of virgin PP based OMMT composites increased with OMMT content,

while the burning rates of recycled PP based OMMT composites decreased with addition of OMMT and increased with further addition of OMMT. The ignition time of virgin PP based OMMT composites decreased with OMMT content. The results demonstrated that the addition of OMMT in virgin PP reduced flammability, confirming previous findings (Szustakiewicz et al., 2011). The reduction in flammability of OMMT is found to be related to the type of layered silicate, filler dispersion, and blending processing conditions (Gilman et al., 2000).

The ignition time of recycled PP/OMMT composites coupled with two types of MAPPs displayed different patterns: the composites coupling with MAPP1 increased with addition of OMMT initially and then decreased with further addition of OMMT; the composites coupling with MAPP2 increased with addition of OMMT initially, then decreased, and increased with further addition of OMMT. The fire induction of PP/OMMT composites is influenced by filler dispersion (Gilman et al., 2000; Golebiewski and Galeski, 2007), and coupling agents have different impacts on filler dispersion (Garcia-Lopez et al., 2002).

In term of burning rates, the addition of OMMT and coupling agents into virgin PP somewhat deteriorates the flammability properties of the composites without any additional flame retardance agents, while OMMT gave a small increment for recycled PP based OMMT composites. The results derived from the use of virgin PP confirmed what previous literature proposed (Gilman et al., 2000; Yin et al., 2013). The flammability reduction effect of OMMT in recycled PP could result from the interaction between OMMT and flame retardance agents pre-existing in the materials' initial life cycle. One such example is the interaction between OMMT and alumina trihydrate (Chang et al., 2014). As shown in Table 3-7, the aluminium content suggests the possibility of existence of aluminium based flame retardance agents.

However, OMMT filled recycled composites do not meet the standard for 94 HB degrees. Thus, flammability should be considered as a major drawback of recycled PP/OMMT composites.

Table 7-3 IRs of ignition time compared with original PP by OMMT (%)

OMMT Loading	VPP2 with MAPP1	VPP2 with MAPP2	RPP1 with MAPP1	RPP1 with MAPP2
1%	-3.13	-7.81	12.43	16.47
2%	-6.84	-5.08	15.9	2.31
3%	-8.01	-11.72	13.87	3.76
4%	-15.04	-20.12	11.85	8.09
5%	-27.73	-28.52	10.4	11.56
Average	-12.15	-14.65	12.89	8.44

As calculated using Equation 5-1 and shown in Table 7-3, the MAPP1 is a better coupling agent in compounding plastics and OMMT. For recycled PP, the initial increase brought by adding OMMT is quite significant. The reasons could be the absorbed water on the surface and between of OMMT layers and the existence of the organic agent, which absorb a large amount of heat and decomposes slowing the burning of those materials (Yin et al., 2013).

7.3 Summary

Flammability tests were conducted to investigate the behaviour of recycled plastics, a feature rarely reported in literature until now.

Recycled plastics' weakness in resisting fire was identified. Two commonly used fillers, talc and OMMT, both increased the flame retardance of recycled plastics, but only the talc-filled composite - RPP-T40, can be classified as 94 HB degree, while the PP/OMMT composites failed to meet the standard. Furthermore, the effects of different MAPPs in compounding OMMT were compared based on flammability experiments in this research.

The flame retardant test results indicated that recycled PP/talc composites are viable in applications where there is a potential fire hazard.

Further work is needed, such as the identification of suitable formulas and processing parameters. Mathematical analysis and experimental design techniques are applied in the following chapters, for evaluation and optimisation of the formulas or the procedures of composites.

Chapter 8 Application of Prediction, Optimisation and Evaluation Techniques of Recycled Plastics

8.1 Introduction

In this chapter, grey model (GM), Taguchi method (TM), principal component analysis (PCA) and cluster analysis (CA) are applied to predict, evaluate and optimise the formulas and procedures for improving recycled composites. Based on blending formulas, procedures and experimental data obtained from previous chapters, these techniques are applied to improve the understanding and performance of recycled plastics.

These techniques allow quick and cost-effective prediction, evaluation and optimisation based on a limited number of experimental trials. When considering the use of recycled plastics in demanding industrial applications, such as automobile parts, they serve as decision support tools.

Among these techniques, GM was used for the first time to predict the effect of adding recycled plastic to virgin plastic. TM was used for optimising manufacturing conditions when using recycled plastics. PCA and CA were utilised to analyse and evaluate the performance of recycled composites.

8.2 Application of Grey Model

A number of studies aim to improve recycled plastics and make their performance either close to, equivalent or superior to that of virgin plastics. The simplest method to improve recycled plastic is to blend it with virgin plastic. One of the key factors in blending recycled plastic with virgin plastic is determining the proportion of recycled plastic in the blend. Due to uncertainty in the nature of recycled plastics, variation in process procedures, and differences in purity of materials from plant to plant, it is always necessary to conduct tests with blended composites based on every possible composition formula, even within the same batch. Therefore there is a need for a quick decision support system to determine the optimum proportion of recycled plastics in blends, without conducting costly, detailed testing on each possible group. It is proposed that this system would take the form of a modelling tool utilising data, provided by a limited number of quick and affordable material property tests.

Grey model is a mathematical technique based on limited observed data and poor information (Deng, 1989). The other

major benefit from the use of grey forecasting models is: the computation is very convenient in MATLAB environment.

Although the grey model has been practiced in many fields for a long period, no application of the grey model has been reported in the field of polymer science and engineering.

8.2.1 Procedure of Application

For the purpose of verifying the feasibility of applying grey model in polymer field, virgin and recycled plastics were blended in proportional equidistant series, and experiments were carried out for obtaining data used for both initial observed data and comparator values.

The application of grey model was classified into two categories:

1. Simulation set, as all groups of experimental data were used as initial observed data in modelling;
2. Prediction set, as some groups of experimental data were used as initial observed data, while the other groups used were used as comparator values.

Both simulation and prediction results were compared to the

experimental data to verify the feasibility of the grey model.

Additionally, verification test set was conducted in the same manner using other types of plastic.

The compositions for application of GM are shown in Table 3-9, and the experimental procedure was shown in Section 3.2.

8.2.2 Data Check Procedure

Before applying GM (1, 1), all data sets were checked to ensure

grade ratios $\lambda(k) = \frac{x^{(0)}(k-1)}{x^{(0)}(k)}, k = 2, 3, \dots, n$ were within the range $(e^{-\frac{2}{n+1}}, e^{\frac{2}{n+1}})$, in which n is the size of data set. All data sets here were checked and were within the required range.

The average error rate (*AER*) was used to represent the difference between the experimental results and the simulated grey model results. The *AER* is defined as follows,

$$\bar{\Delta} = \frac{1}{n} \sum_{k=1}^n \frac{|\hat{x}^{(0)}(k) - x^{(0)}(k)|}{x^{(0)}(k)}, k = 1, 2, \dots, n, n > 4 \quad \text{(Equation 8-1)}$$

in which $\hat{x}^{(0)}(k)$ is the grey model simulated result and $x^{(0)}(k)$ the experimental result.

A smaller *AER* implies a close match of the experimental with

simulated results indicating the appropriateness of the grey model in this application.

8.2.3 Results and Discussion

8.2.3.1 Curve Simulation by Grey Model

In the simulation set, all of the eleven groups of experimental data were used as initial observed data in modeling and both experimental results and simulation results are presented in the same plots drawn below; see Figure 8-1 to Figure 8-6. As shown in the figures below, all mechanical properties expect for tensile and flexural moduli deteriorated with the addition of recycled plastics in the blends. The more recycled content contained in the blend, the poorer performance was.

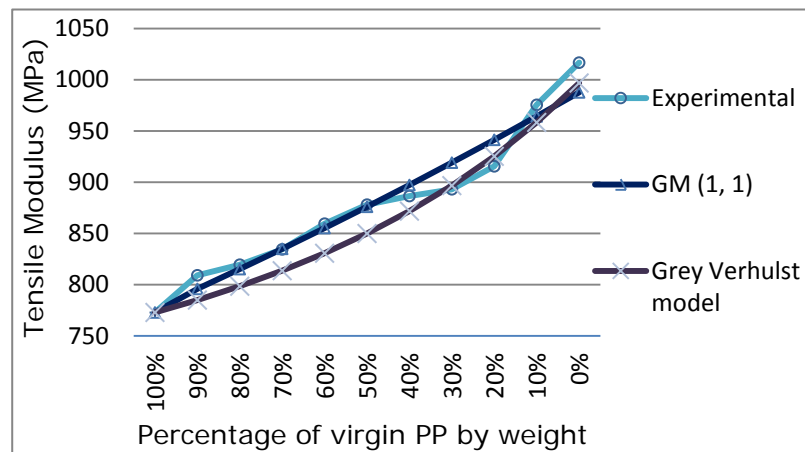


Figure 8-1 Tensile Modulus (MPa) against percentage of VPP1 in simulation set

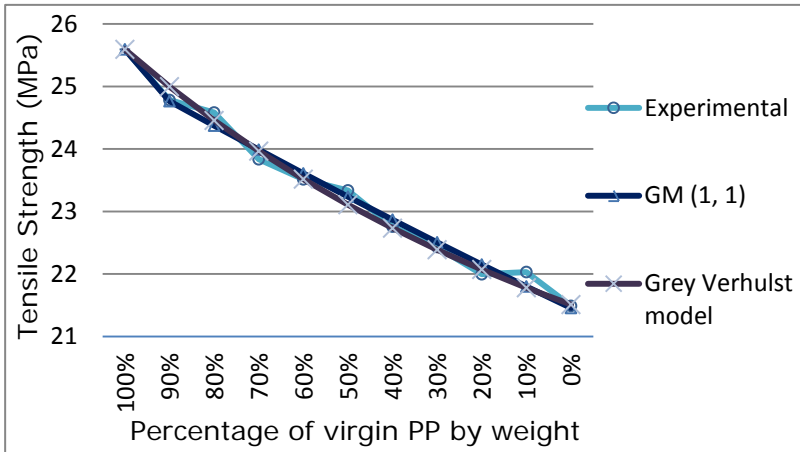


Figure 8-2 Tensile Strength (MPa) against percentage of VPP1 in simulation set

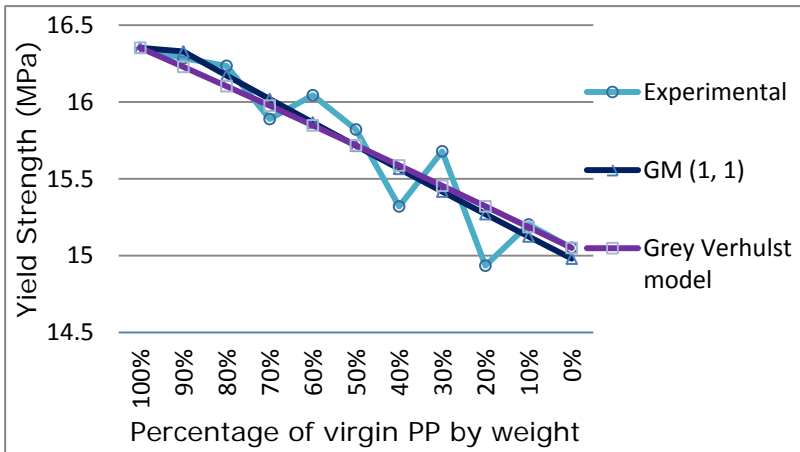


Figure 8-3 Yield Strength (MPa) against percentage of VPP1 in simulation set

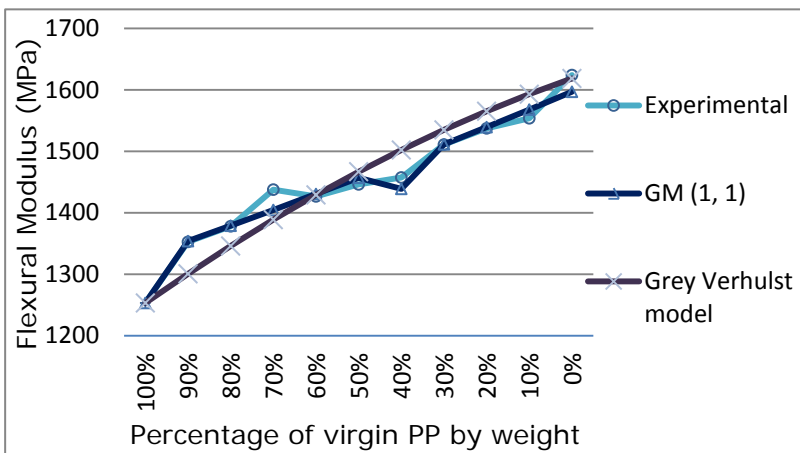


Figure 8-4 Flexural Modulus (MPa) against percentage of VPP1 in simulation set

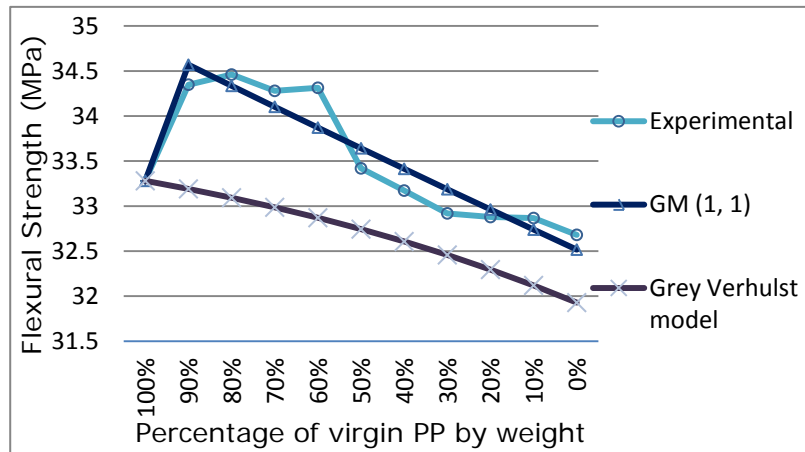


Figure 8-5 Flexural Strength (MPa) against percentage of VPP1 in simulation set

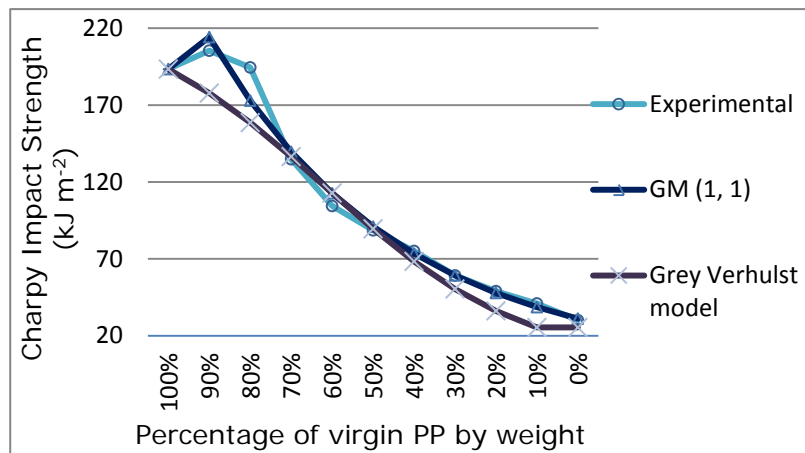


Figure 8-6 Charpy Impact Strength (kJ m⁻²) against percentage of VPP1 in simulation set

AERs were calculated using Equation 8-1 to evaluate the feasibility of the application of grey model in modelling the blends' mechanical properties, as shown in Table 8-1.

Table 8-1 AERs of each tested property in simulation

	GM (1, 1)	Grey Verhulst model
Tensile Modulus	0.0286	0.0195
Tensile Strength	0.0046	0.0044
Yield Strength	0.0047	0.0086
Flexural Modulus	0.0068	0.0186
Flexural Strength	0.0056	0.0247
Charpy Impact Strength	0.0395	0.1326
Average	0.015	0.0347

From the table shown above, especially the small *AER* range calculated in Table 8-1 (less than 0.2), the results correlate well with the experimental results according to the trusted range of 0.2 proposed by Deng (1985). This indicateds the feasibility of all three grey models' applications in simulation of the mechanical properties of those PP materials.

Between both techniques, GM (1, 1) displayed a better performance in simulation set among the three GMs, given it had the smallest average *AER*.

GM is feasible, reliable and highly efficient in modeling the behaviours of virgin-recycled PP blends. This model does not

require any assumptions to be made. and uses the intrinsic regularity of the original data, which proves a useful tool to support decision-making.

8.2.3.2 Curve Prediction by Grey Model

In the prediction set, only eight groups of data were used as initial observed data, while the last three groups used were used as comparator results against predicted values. The experimental results and prediction results are presented in the same plots (see Figure 8-7 to Figure 8-12).

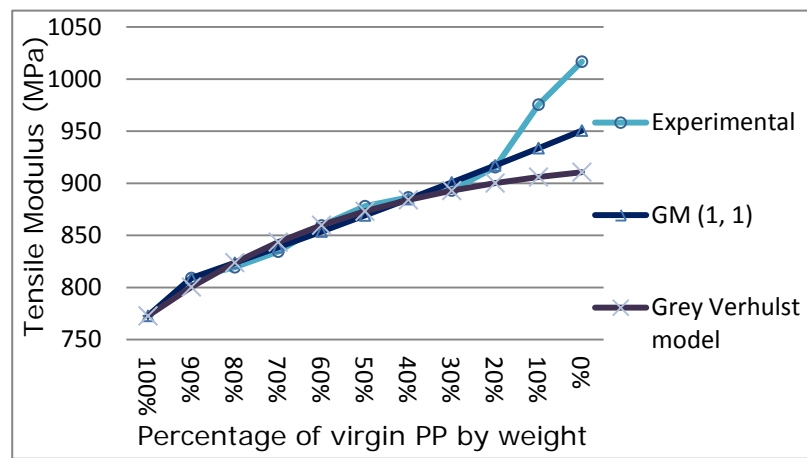


Figure 8-7 Tensile Modulus (MPa) against percentage of VPP1 in prediction set

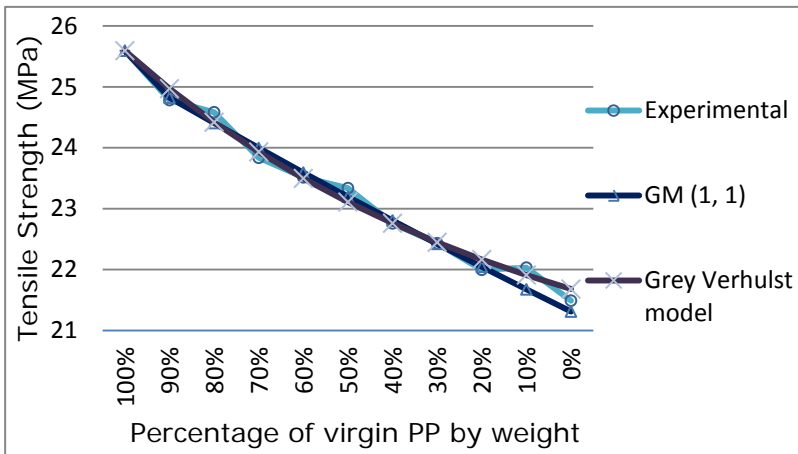


Figure 8-8 Tensile Strength (MPa) against percentage of VPP1 in prediction set

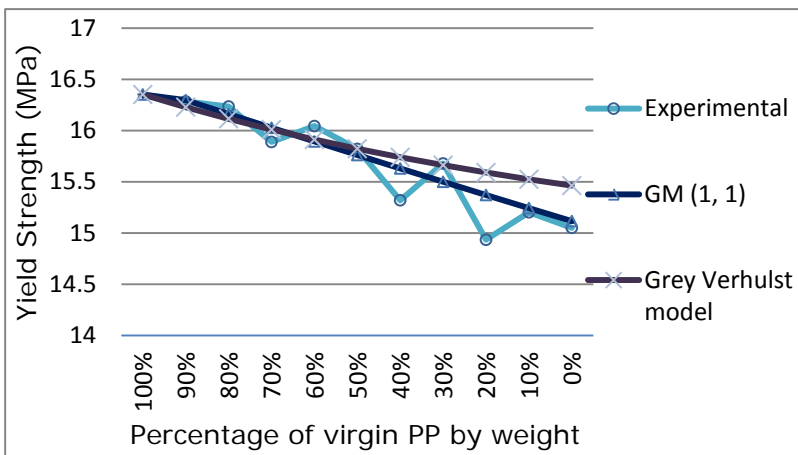


Figure 8-9 Yield Strength (MPa) against percentage of VPP1 in prediction set

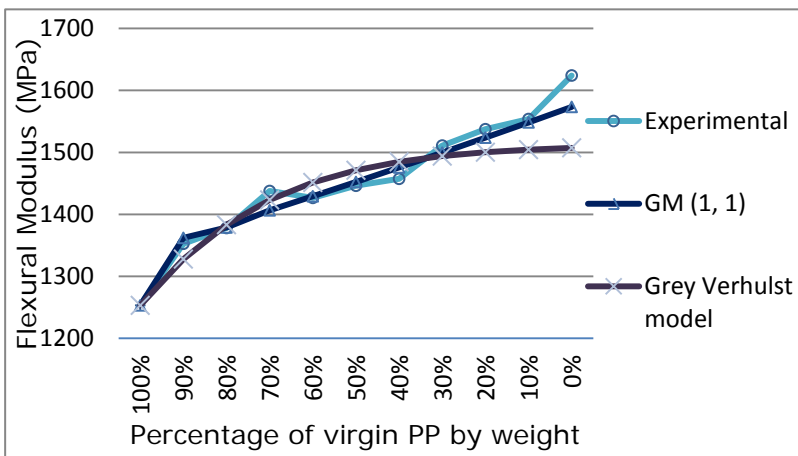


Figure 8-10 Flexural Modulus (MPa) against percentage of VPP1 in prediction set

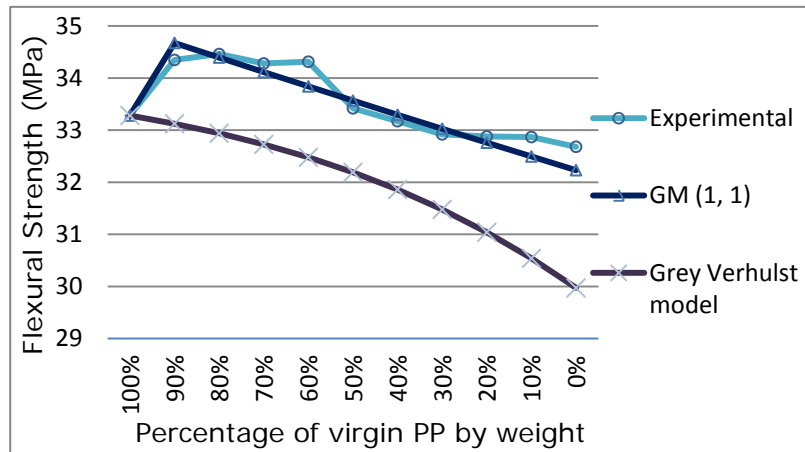


Figure 8-11 Flexural Strength (MPa) against percentage of VPP1 in prediction set

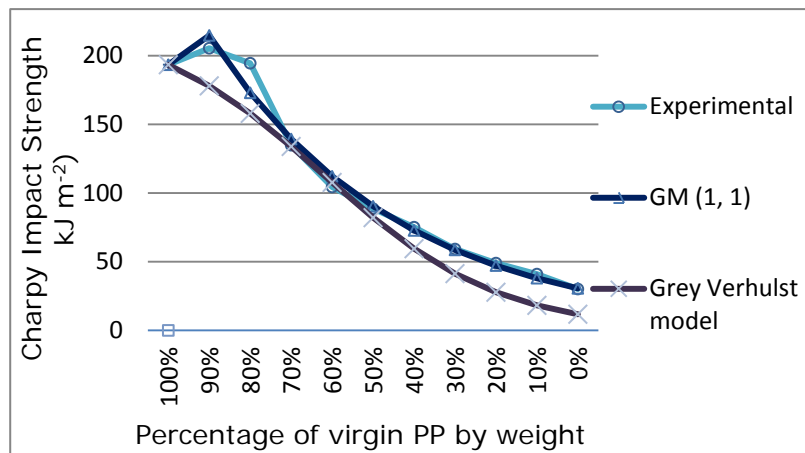


Figure 8-12 Charpy Impact Strength (kJ m⁻²) against percentage of VPP1 in prediction set

AERs were further separated into two categories: average simulation error rate (ASER, measuring the AERs of initial eight points, to measure the accuracy of simulated results) and average prediction error rate (APER, measuring the AERs of the last three points, to measure the accuracy of predicted results). These were calculated respectively to evaluate the applicability of the application of the grey model in predicting the PP blends'

mechanical properties, using Equation 8-1. The results are shown in Table 8-2.

Table 8-2 AERs, ASERs and APERs of prediction

Properties		GM (1, 1)	Grey Verhulst model
Tensile Modulus	AER	0.0134	0.0207
	ASER	0.0047	0.0045
	APER	0.0366	0.064
Tensile Strength	AER	0.0049	0.0047
	ASER	0.0034	0.0037
	APER	0.0089	0.0073
Yield Strength	AER	0.0087	0.0134
	ASER	0.0074	0.0069
	APER	0.0121	0.0308
Flexural Modulus	AER	0.009	0.0204
	ASER	0.0069	0.0121
	APER	0.0145	0.0426
Flexural Strength	AER	0.0064	0.0466
	ASER	0.0052	0.0378
	APER	0.0095	0.0699
Charpy Impact Strength	AER	0.041	0.231
	ASER	0.0407	0.118
	APER	0.0417	0.5322

Based on the experimental data and GM results shown in Table 8-2, the GM (1, 1) and Grey Verhulst model are shown to be applicable in predicting the performance of the blends whose tendencies are monotonic, e.g. tensile modulus, tensile strength, yield strength flexural modulus and flexural strength. The small APERs range which was less than 0.1 verified the feasibility of using the two techniques.

GM (1, 1) showed a higher forecasting accuracy in prediction of monotonic trends, as it has smaller APERs. GM (1, 1) has successfully predicted Charpy impact strength while Grey Verhulst model failed in this prediction.

The successful application of GM (1, 1) and grey Verhulst model in prediction selection would provide a new approach of decision making support in identifying suitable formulas of blending plastic material based on a limited number of tests in swift manner. This could allow a decision pertaining to an optimum blending formula to be made without conducting detailed, time-consuming, costly and environmentally harmful tests based on each possible proportion.

8.2.4 Verification of Grey Model on ABS

GM was tested on certain types of PP. In order to assess its applicability to other basic plastics types, the procedure was repeated using ABS. The compositions for verification of GM are shown in Table 3-10, and the experimental procedure was outlined in Section 3.2.

8.2.4.1 Simulation Set on ABS

In the simulation set, all eleven groups of data were used as initial observed data in modelling. Simulation and experimental results were presented in the same plots in Figure 8-13 to Figure 8-16, and AERs were calculated as illustrated in Table 8-3.

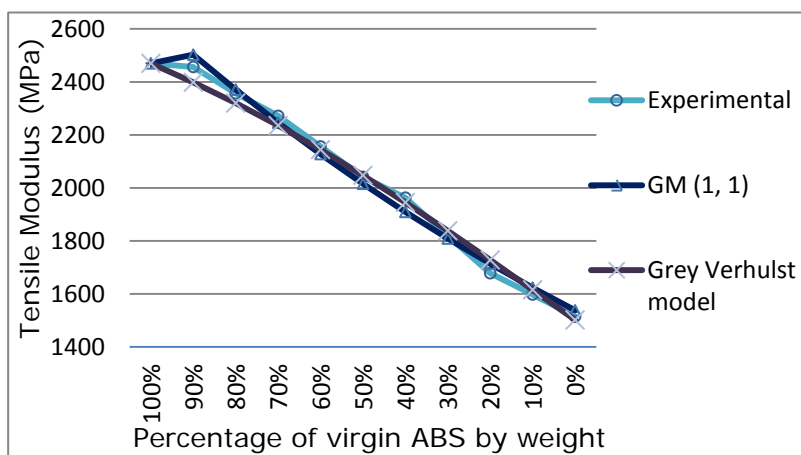


Figure 8-13 Tensile Modulus (MPa) against percentage of virgin ABS in simulation set

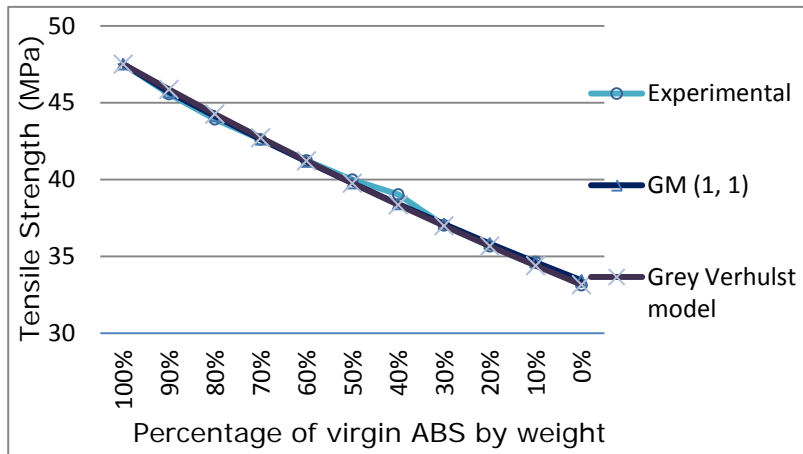


Figure 8-14 Tensile Strength (MPa) against percentage of virgin ABS in simulation set

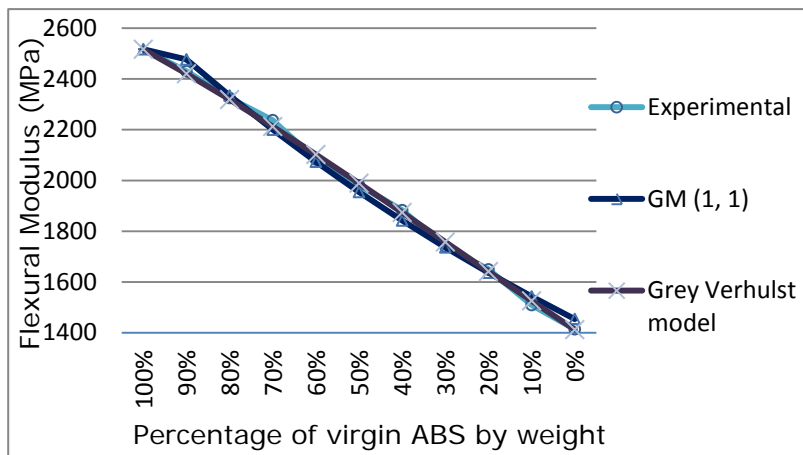


Figure 8-15 Flexural Modulus (MPa) against percentage of virgin ABS in simulation set

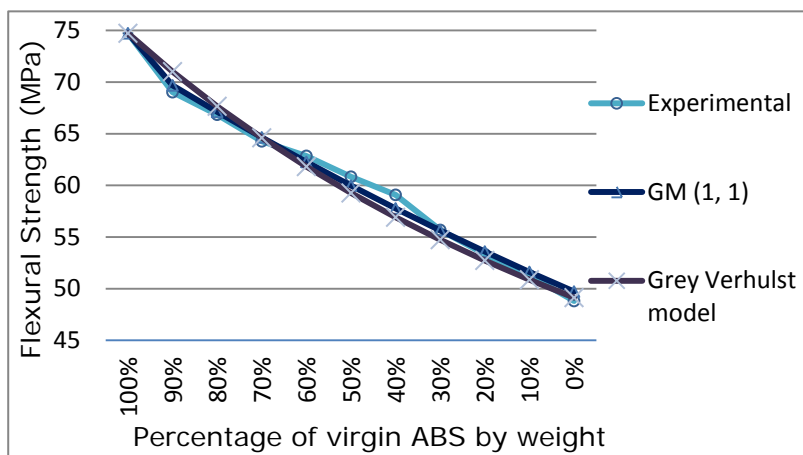


Figure 8-16 Flexural Strength (MPa) against percentage of virgin ABS in simulation set

Table 8-3 AERs of simulation

	GM (1, 1)	Grey Verhulst model
Tensile Modulus	0.0134	0.0121
Tensile Strength	0.0043	0.0045
Flexural Modulus	0.0126	0.0076
Flexural Strength	0.0087	0.0153
Average	0.0098	0.0099

The small *AER* range calculated in Table 8-5 (less than 0.2) indicated that the results correlate well with experimental results, proving the feasibility of applying grey model techniques in simulation of the mechanical properties of virgin-recycled ABS materials.

8.2.4.1 Prediction Set on ABS

In the prediction set, only eight groups of data were used as initial observed data, while the last three groups used were used as comparator results against predicted values, as in the previous experimentation. Prediction results and all eleven groups of experimental results were presented in the same plots, as shown in Figure 8-17 to Figure 8-20. *AERs* were separated into *ASER* and *APER*, as in the previous experimentation, and are displayed in Table 8-4.

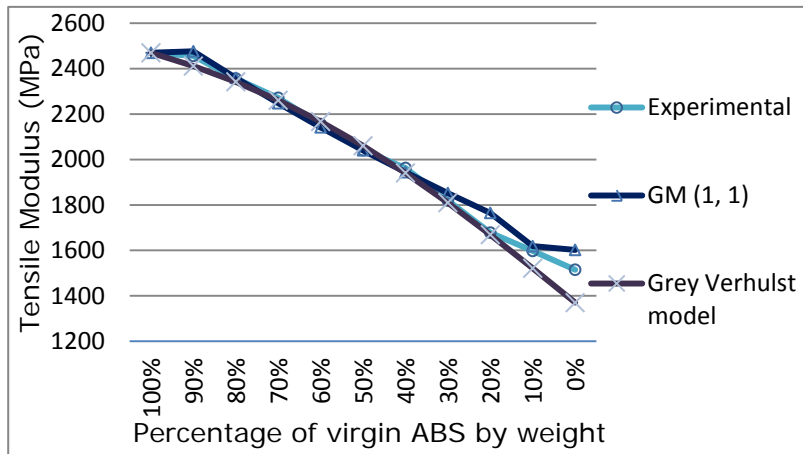


Figure 8-17 Tensile Modulus (MPa) against percentage of virgin ABS in prediction set

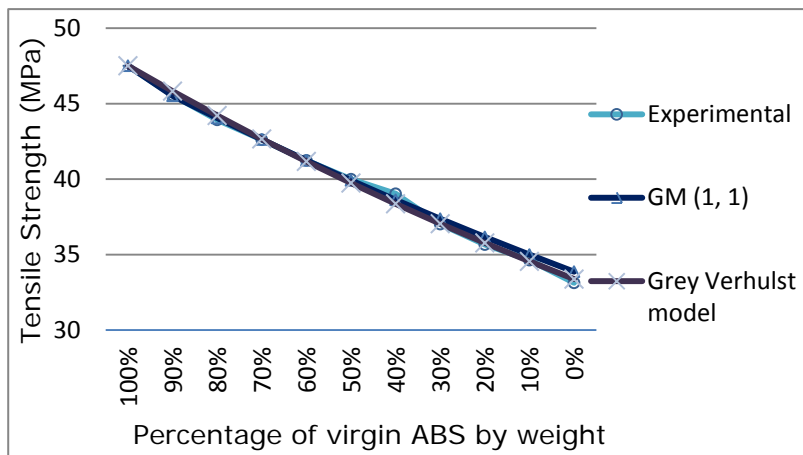


Figure 8-18 Tensile Strength (MPa) against percentage of virgin ABS in prediction set

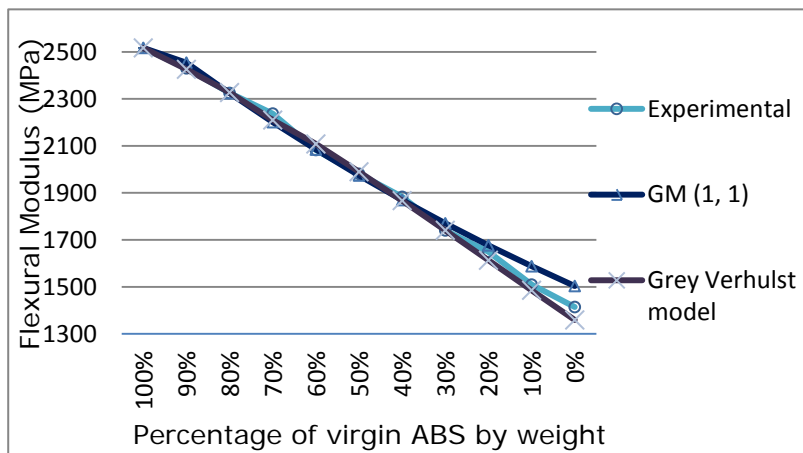


Figure 8-19 Flexural Modulus (MPa) against percentage of virgin ABS in prediction set

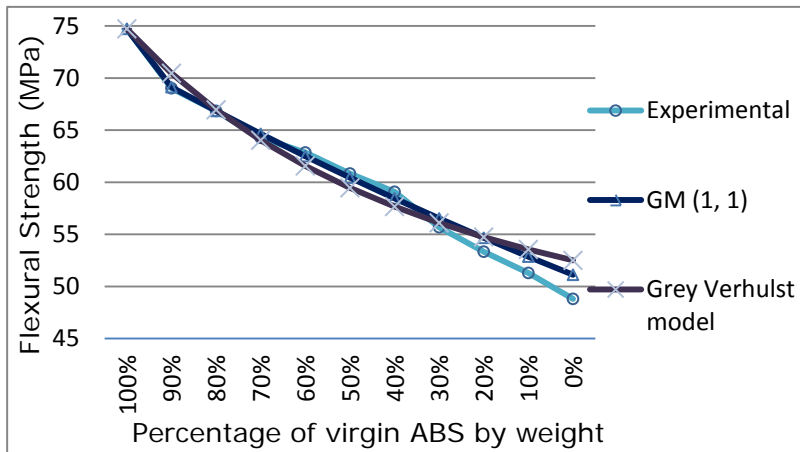


Figure 8-20 Flexural Strength (MPa) against percentage of virgin ABS in prediction set

Table 8-4 AERs, ASERs and APERs of prediction

		GM(1, 1)	Grey Verhulst model
Tensile Modulus	<i>AER</i>	0.0197	0.0190
	<i>ASER</i>	0.0068	0.0075
	<i>APER</i>	0.0540	0.0496
Tensile Strength	<i>AER</i>	0.0067	0.0047
	<i>ASER</i>	0.0033	0.0049
	<i>APER</i>	0.0157	0.0043
Flexural Modulus	<i>AER</i>	0.0170	0.0102
	<i>ASER</i>	0.0069	0.0045
	<i>APER</i>	0.0439	0.0256
Flexural Strength	<i>AER</i>	0.0134	0.0224
	<i>ASER</i>	0.0056	0.0126
	<i>APER</i>	0.0343	0.0486
Average		0.036	0.0373

The results were similar to the previous ones for the use of GM in conjunction with PP. Based on the experimental and grey model predictions shown in Figure 8-17 to Figure 8-20 and Table 8-4, the GM (1, 1) and Grey Verhulst model has been proved the most applicable GM in predicting the experimental performance of the blends whose tendencies are monotonic. Among the three models, the Grey Verhulst model showed a higher forecasting accuracy in prediction of monotonic trends, as it has the smallest *APER* values in tensile modulus, tensile strength and flexural modulus.

8.3 Utilisation of the Taguchi Method to Optimise Processing Parameters for Recycled PP

Although the introduction of fillers improves certain desirable properties of recycled materials, as the literature review and previous experiments indicated, it does increase the overall cost (Ramirez-Vargas and Sandoval-Arellano, 2006).

Furthermore, the intricate nature of inter-relative processing parameters might involve numerous repeated and detailed experiments, for example, to optimise 4 processing parameters and each parameter has 3 levels require $3^4=81$ trials. It was costly, time-consuming and environmentally unfriendly. Thus,

the Taguchi method was introduced to reduce the number of trials in experiment sets (Park, 1996; Ross, 1996).

The compositions for application of TM are shown in Table 3-11, and the experimental procedure was outlined in Section 3.2.

The selection of the processing parameters is described in the following section.

8.3.1 Selection of Processing Parameters

The experimental optimisation was conducted with four controllable processing parameters: melt temperature, mould temperature, an injection speed and packing pressure. Each of these parameters has three different levels. The other processing parameters involved, for example injection pressure (40 MPa), pressure packing time (5 s), and cooling time (20 s) were kept constant for the duration of the experiment. The selected processing parameters and their levels are shown in Table 8-5.

Table 8-5 Processing parameters and levels chosen

Column	Factor	Level 1	Level 2	Level 3
A	Melt temperature (°C)	200	220	240
B	Mould temperature (°C)	40	50	60
C	Injection speed (g s ⁻¹)	40	50	60
D	Packing pressure (MPa)	50	60	70

With four factors, each with three levels, the traditional full factorial design requires $3^4 = 81$ possible combinations of trials. Carrying out such a large number of experiments for all the combinations was not economically feasible or practical. The Taguchi method uses an Orthogonal Array (OA) to reduce the large number of experiments, by selecting a smaller number of trials for the experiment. In this case, the L9 (3^4) OA experiment, which is designed for an experiment which has 4 factors (each factor has 3 levels, Table 8-6). Nine trials of toolbox trays with five repetitions of various compositions were produced using the L9 Taguchi OA.

Table 8-6 L9 (3⁴) OA used in the experiment

Trial No.	A	B	C	D
1	Level 1	Level 1	Level 1	Level 1
2	Level 1	Level 2	Level 2	Level 2
3	Level 1	Level 3	Level 3	Level 3
4	Level 2	Level 1	Level 2	Level 3
5	Level 2	Level 2	Level 3	Level 1
6	Level 2	Level 3	Level 1	Level 2
7	Level 3	Level 1	Level 3	Level 2
8	Level 3	Level 2	Level 1	Level 3
9	Level 3	Level 3	Level 2	Level 1

8.3.2 Results and Analysis

8.3.2.1 Verification of Selected Processing Parameters

The results obtained for density test were presented in Figure 8-21.

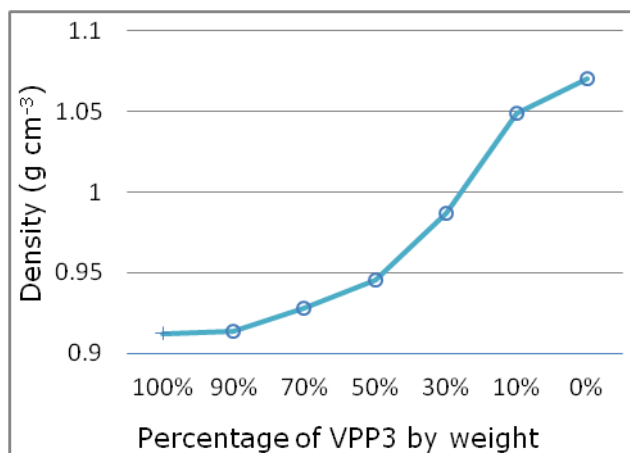


Figure 8-21 Densities (g cm⁻³) against percent of VPP3

An increase in the percentage of recycled PP in the composites resulted in an incremental change in densities. This was possibly a result of contamination and/or impurity of the recycled plastic. Contaminants and heterogeneous substances could have a very significant impact on the process ability and performance of products made from composites, especially their mechanical properties.

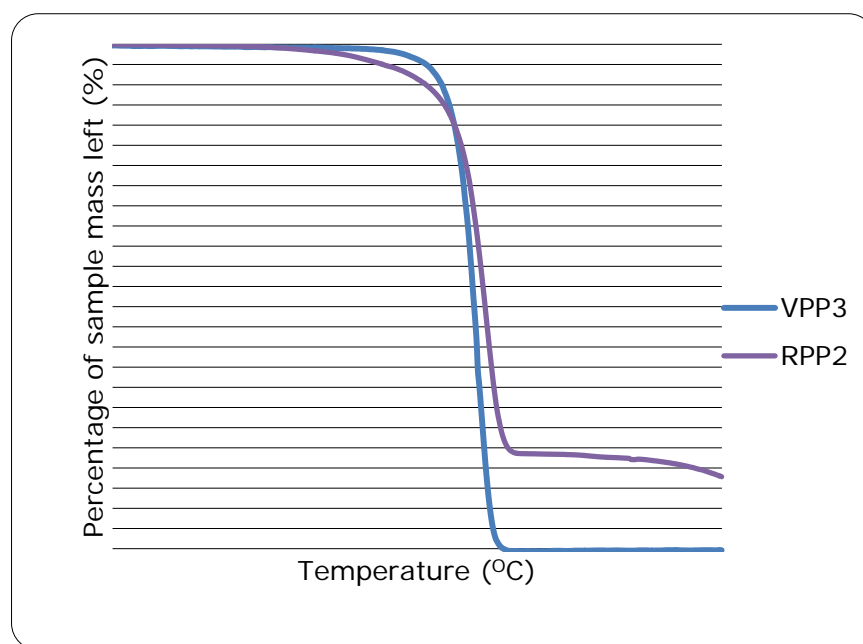


Figure 8-22 TGA plot: weight loss percentage (%) versus temperature (°C) for the four PP materials recorded at a heating rate of 10°C min⁻¹ under room atmosphere

TGA data indicated that the four polymers lost less than 2% of their weight under 250°C (VPP3: 99.87% at 250°C and RPP2: 98.72% at 250°C), and began to decompose at temperatures above 300°C. They began to decompose at temperatures above

300°C, which suggested that the highest level of melt temperature in this set (i.e. 240°C) was within the thermal stability range of both virgin and recycled PP. It was implied that the selection of melt temperature would not cause decomposition of the materials.

8.3.2.1.2 Mechanical Tests Results

The mechanical properties obtained from each trial were statistically analyzed by calculating S/N ratios. Since higher performance was expected, the S/N ratios were computed based on the higher the better characteristic (Equation 2-18). The S/N represented tensile strength as specified in Table 8-7.

Table 8-7 S/N responses of tensile strength (dB)

Trial No.	PP100	PP90	PP70	PP50	PP30	PP10	PP0
1	26.56	26.70	26.23	25.92	26.21	25.29	25.40
2	26.07	26.90	26.14	25.67	25.95	25.23	25.50
3	26.36	26.76	26.11	25.73	25.75	24.92	25.12
4	26.44	26.62	25.92	25.45	25.41	24.66	24.78
5	26.66	26.73	25.90	25.68	25.48	25.08	24.76
6	26.66	26.55	26.03	25.76	25.21	25.16	24.81
7	26.42	26.22	25.76	25.68	24.95	24.93	24.32
8	26.48	26.32	25.72	25.58	24.97	24.56	24.31
9	26.48	26.33	25.79	26.15	24.85	24.76	24.77

The data matrix shows the S/N ratios reduced with the addition of recycled plastic in the blends. A Taguchi analysis was performed with the purpose of identifying the effect of each controllable factor on every tested property of each blend.

8.3.2.2 Taguchi Optimisation

8.3.2.2.1 Analysis of S/N ratio

Taguchi analysis is performed in order to find the optimum levels of the four selected factors within the chosen levels, i.e. melt temperature, mould temperature, injection speed and packing pressure for PP100, PP90, PP70, PP50, PP30, PP10 and

PP0. The first step of Taguchi analysis is to calculate the average S/N response influenced by each level of every one of the four controllable factors. By comparing the averaged value (usually in plots), one can easily identify the impact difference. Figure 8-23 to Figure 8-27 are plotted by exploiting average S/N responses of each controllable factor based on the data presented in form of Table 8-7. In horizontal axis of Figure 8-23 to Figure 8-27, letter represented the processing parameter and number represented the level, for example, A1 represented melt temperature of 200°C.

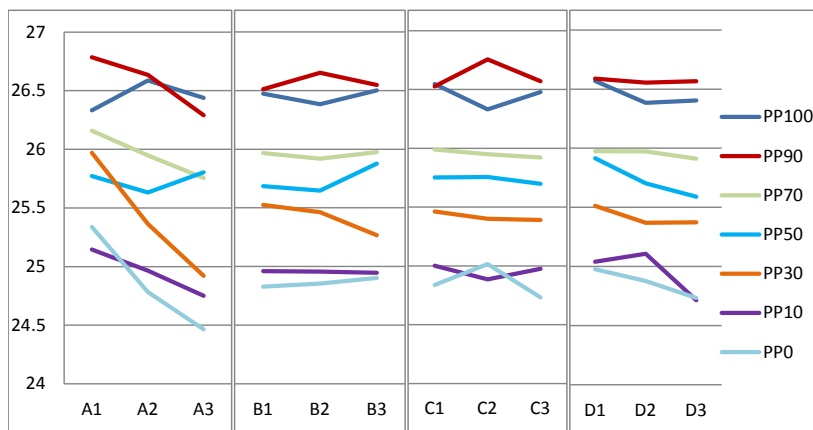


Figure 8-23 S/N ratios against processing parameters for tensile strength

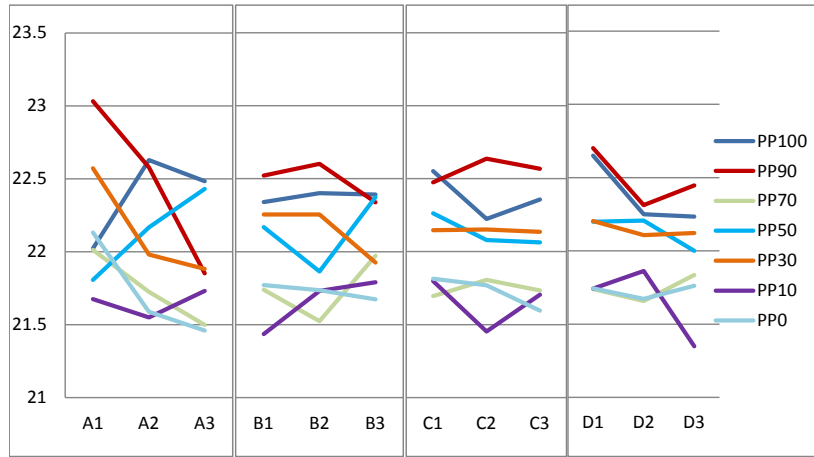


Figure 8-24 S/N ratios against processing parameters for yield strength

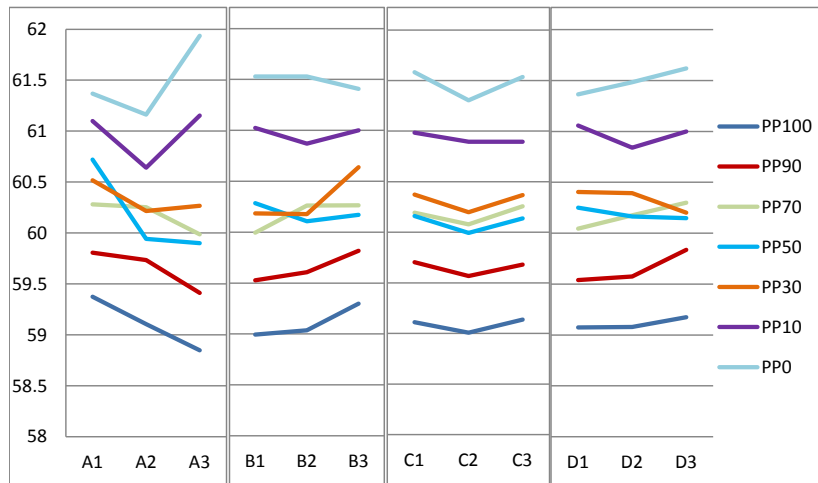


Figure 8-25 S/N ratios against processing parameters for flexural modulus

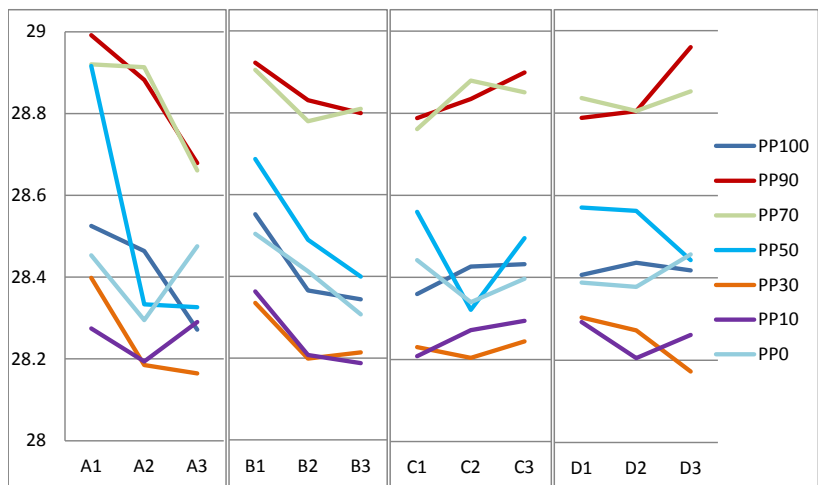


Figure 8-26 S/N ratios against processing parameters for flexural strength

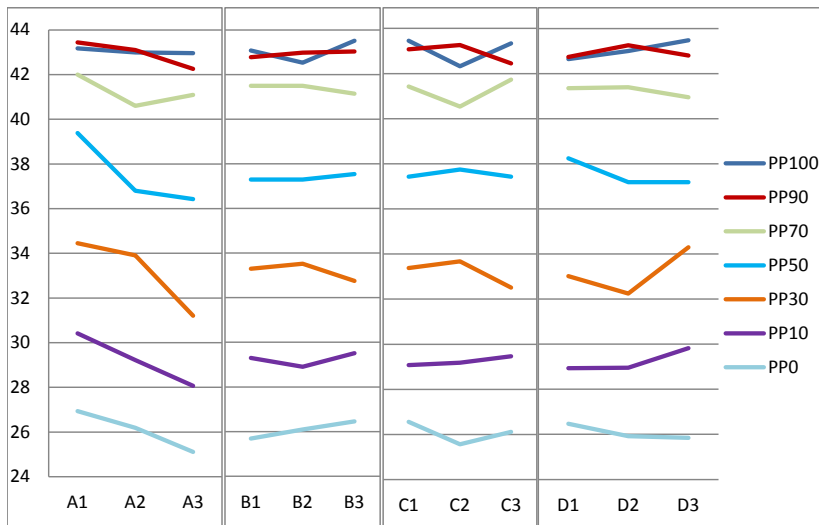


Figure 8-27 S/N ratios against processing parameters for impact strength

Figures 8-23 to Figure 8-27 suggest that any change in the four controllable factors (melt temperature, mould temperature, an injection speed and packing pressure) would lead to either improvement or degradation of mechanical properties. Four generic patterns of S/N ratios can be observed:

1. The flexural strength of PP90 and the impact strength of PP10 increased with the increase of injection speed and packing pressure; the impact strength of PP100 increased with the increase of packing pressure.
2. The yield strength of PP100 decreased with the increase of packing pressure; the yield strength of PP90, PP70, PP30 and PPO decreased with the increase of melt temperature; the tensile strength of PP90, PP70, PP30, PP10 and PPO decreased

with the increase of melt temperature; the flexural modulus of PP100, PP90, PP70 and PP50 decreased with the increase of melt temperature; the impact strength of PP100, PP90, PP50, PP30, PP10 and PP0 decreased with the increase of melt temperature.

3. The tensile strength of PP100 increased initially with the increase of melt temperature, and then decreased with the further increase of melt temperature; the yield strength of PP100 increased initially with the increase of injection speed, and then decreased with the further increase of injection speed; the flexural strength of PP70 increased initially with the increase of an injection speed, and then decreased with the further increase of injection speed; the impact strength of PP90 increased initially with the increase of injection speed, and then decreased with the further increase of injection speed.

4. The yield strength of PP100 decreased initially with the increase of packing pressure, and then increased with the further increase of packing pressure; the tensile strength of PP50 and the yield strength of PP10 decreased initially with the increase of melt temperature, and then increased with the further increase of under melt temperature.

Four selected controllable processing parameters each had different effects on the mechanical properties of the plastic blends:

1. Factor A - the melt temperature. The plastic blends which were processed under lower melt temperature tended to have better mechanical performance. For example, each of the highest impact strengths were obtained under the lowest temperature (A1). A possible explanation could be that lower melt temperature prevents materials from thermal degradation during injection moulding procedure.
2. Factor B - the mould temperature. The higher mould temperatures, such as B2 and B3, yielded better mechanical performance in the plastic blends, except in regard to all results based on flexural strengths. Higher mould temperatures could give samples a better cooling to increase the crystallinity, thus almost all properties improved.
3. Factor C - the injection speed. The experiments showed that the better results of tensile strength, yield strength and flexural modulus were obtained under a slower injection speed (C1). For flexural strength and impact strength, a higher injection speed (C3) yielded better results. Performance of many blends showed a distinguishable decline in median injection speed (C2),

especially of flexural modulus. Lower injection speed means a steadier melt flow into the mould which implies a more stable cooling, and the molecular chains could possibly generate a more evenly distributed pattern or a better crystallinity along the flow direction (which is as same as tensile test) in the samples, see Figure 6-7. Plastic filled the mould more quickly when being injected at a higher speed would reduce the crystallinity, thus would perform better under load in other directions, such as flexural and impact.

4. Factor D - the packing pressure. Better tensile results were obtained with lowest packing pressure (D1), while better flexural and impact results were obtained with highest packing pressure (D3). This phenomenon was related to what discovered in Section 6.2, as the direction of packing pressure has a significant impact on the flexural and impact properties, see Figure 6-9.

Generally, lower melt temperatures yield better flexural performance, which confirmed the results attained by Mehat and Kamaruddin (2011). The effects of packing pressure also confirmed their previous findings. Further, it is found that a lower melt temperature yielded better results for most

mechanical performance indicators, and higher packing pressure also yielded better impact results. However, for tensile properties, the lower packing pressure tended to yield better results.

8.3.2.2.2 Obtaining Optimal Chosen Levels

The levels of the processing parameters with the highest S/N ratios always yield the optimal quality with minimum variance (Roy, 1990). Hence, the processing parameter levels with the highest S/N ratios indicated a higher value of mechanical properties. All optimal processing parameters within the chosen levels for each property on each tested formula were presented in Table 8-8 based on the curves shown in Figure 8-23 to Figure 8-27, with the highest points representing the best levels of processing parameters within the chosen levels in Table 8-5. For example, the optimal condition within the chose levels for tensile strength of PP70 was A1B3C1D1, i.e. for getting optimum tensile strength results for PP70 within the chose levels, specimens should be injection moulded under a melt temperature of 200°C, mould temperature of 60°C, an injection speed of 40 g s⁻¹ and a packing pressure of 50 MPa.

8.3.3 Verification of Taguchi Method

8.3.3.1 Verification of Optimal Chosen Processing Parameters

With the purpose of investigating the effects of the proportion of recycled PP on the mechanical properties, a verification test was carried out using the optimal chosen processing parameters listed in Table 8-9 and referred to in Table 8-6, other processing parameters, plastic materials and blending formulas were the same as in previous experiments.

The materials were extruded, dried, conditioned, injection moulded and tested under constant processing parameters as for the previous tests, and the four controllable factors referred to in specimens in Table 8-8. 5 sample pieces were tested in each group, with the average results of the verification test summarized in Table 8-9.

Table 8-9 S/N responses of verification test according to Table 8-8

	Tensile strength	Yield strength	Flexural modulus	Flexural strength	Impact strength
PP100	26.77	23.06	59.60	28.52	43.62
PP90	26.85	23.17	59.76	28.92	43.23
PP70	26.30	22.14	60.18	28.90	42.60
PP50	26.23	22.52	60.50	28.68	38.98
PP30	26.22	22.64	60.46	28.28	35.51
PP10	26.11	22.07	61.16	28.27	31.83
PP0	25.97	22.34	61.98	28.47	28.58

As shown in Table 8-9, the samples made of PP90 demonstrated the highest tensile strength, yield strength and flexural strength in these tests; even slightly better than the properties of samples made of PP100 (pure virgin plastic, VPP3). The impact strength declined with the addition of recycled PP. The flexural modulus displayed the opposing characteristics of an increase in the flexural modulus with an increase in the recycled material percentage. This result can be explained by the fact that the recycled PP pellets in this experiment were recovered from MSW. It is therefore highly likely that this material contained package waste made from isotactic polypropylene which is a random co-polymer characterised by higher moduli

and lower strength (Moore, 1996). These characteristics were quite distinguishable especially when the material was added to a virgin high-impact PP co-polymer - K8303 – VPP3.

The *IR* results were calculated using Equation 5-1

$$IR = \left(\frac{P'_R}{P_R} - 1 \right) \times 100\%$$

() and shown in Table 8-10, in which P_R

represents the average performance under different combination of processing parameters in Table 8-8.

Table 8-10 *IR* results (%)

	Tensile strength	Yield strength	Flexural modulus	Flexural strength	Impact strength
PP100	1.22	3.04	0.83	0.37	1.34
PP90	1.07	3.02	0.29	0.23	0.69
PP70	1.34	2.77	0.19	0.25	3.32
PP50	1.91	2.22	0.51	2.06	3.84
PP30	3.14	2.83	0.29	1.69	6.99
PP10	4.63	1.92	0.32	0.06	8.86
PP0	4.44	2.8	0.81	0.23	9.58
Average	2.54	2.66	0.46	0.71	4.95

According to the data presented in Table 8-10, Taguchi optimisation method promoted all mechanical performance of

recycled plastic blends as no negative *IR* was found. The improvements in tensile and impact properties were more significant, while only slight improvements in flexural properties are observed.

As observed in Table 8-10, *IRs* of tensile strength and impact strength increased with the addition of recycled content. The largest *IR* was 9.58% which took place in the impact strength of PPO (pure recycled plastic, RPP2). It implied that TM is more effective in optimising some mechanical performance indicators of recycled materials, such as tensile and impact strength.

8.3.3.2 Verification of Tagchi Method on PP/talc Composites

In this study, TM was applied on PP composites to verify its performance-enhancing effect.

The compositions for application of GM are shown in Table 3-10. The experiment was conducted with three controllable processing parameters related to injection moulding: injection pressure, packing time and cooling time. Each of these had three levels, while the other processing parameters, such as melt temperature (200°C), mould temperature (50°C),

injection speed (50 g s^{-1}) and packing pressure (50 MPa) were kept constant during the experiment. The selected processing parameters and their levels are shown in Table 8-11.

Table 8-11 Processing parameters and levels chosen

Column	Factor	Level 1	Level 2	Level 3
A	Injection pressure (MPa)	40	50	60
B	Packing time (s)	5	10	15
C	Cooling time (s)	5	10	15

Taking into account three factors, each with three levels, the full factorial design requires $3^3 = 27$ possible combinations of trials. Taguchi L9 (3^3) OA experiment, as shown in Table 8-13, was conducted to study the four processing parameters, and reduced the number of trials. Nine trials of toolbox trays with five repetitions of various compositions were produced using the L9 Taguchi OA.

Table 8-12 L9 (3³) OA used in the experiment

Trial No.	A	B	C
1	Level 1	Level 1	Level 1
2	Level 1	Level 2	Level 2
3	Level 1	Level 3	Level 3
4	Level 2	Level 1	Level 2
5	Level 2	Level 2	Level 3
6	Level 2	Level 3	Level 1
7	Level 3	Level 1	Level 3
8	Level 3	Level 2	Level 1
9	Level 3	Level 3	Level 2

The additional processing parameters are shown in Section 3.2.

5 sample pieces were tested in each group; the average values were recorded and treated as previous section. The S/N ratios for each group tested over the nine trials were calculated and sorted in decibel (dB) units and plotted in exploiting average S/N responses of each controllable factor based on the data, an example of tensile strength in S/N was shown in Figure 8-28.

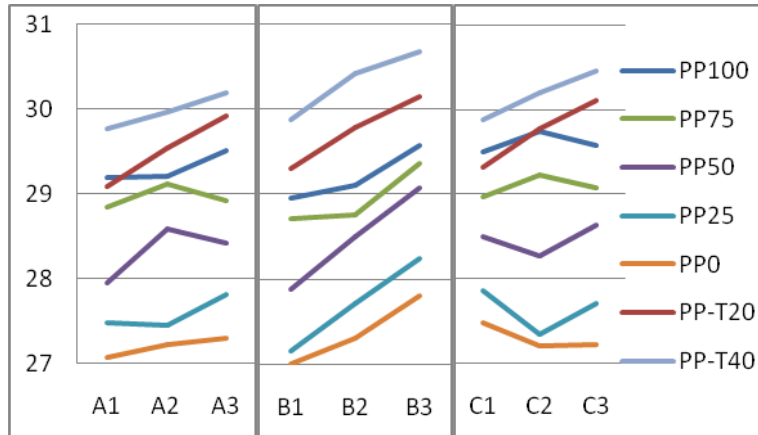


Figure 8-28 S/N ratios against processing parameters for tensile strength

Each of the optimal processing parameters within the chose levels are presented in Table 8-14. Generally, as observed in the plots and Table 8-14, the higher packing pressure, longer packing time and cooling time could improve the mechanical performance of the materials.

Table 8-13 Optimal conditions within the chosen levels of verification set

	Tensile strength	Yield strength	Flexural modulus	Flexural strength	Impact strength
PP100	A3B3C2: Injection pressure of 60 Mpa, packing time of 15 s, cooling time of 10 s	A3B3C1: Injection pressure of 60 Mpa, packing time of 15 s, cooling time of 5 s	A2B3C3: Injection pressure of 50 Mpa, packing time of 15 s, cooling time of 15 s	A2B3C3: Injection pressure of 50 Mpa, packing time of 15 s, cooling time of 15 s	A1B3C3: Injection pressure of 40 Mpa, packing time of 15 s, cooling time of 15 s
PP75	A2B3C2: Injection pressure of 50 Mpa, packing time of 15 s, cooling time of 10 s	A2B3C2: Injection pressure of 50 Mpa, packing time of 15 s, cooling time of 10 s	A3B3C3: Injection pressure of 60 Mpa, packing time of 15 s, cooling time of 10 s	A2B3C3: Injection pressure of 50 Mpa, packing time of 15 s, cooling time of 15 s	A2B2C2: Injection pressure of 50 Mpa, packing time of 10 s, cooling time of 10 s
PP50	A2B3C3: Injection pressure of 50 Mpa, packing time of 15 s, cooling time of 15 s	A1B3C3: Injection pressure of 40 Mpa, packing time of 15 s, cooling time of 15 s	A1B2C1: Injection pressure of 40 Mpa, packing time of 10 s, cooling time of 5 s	A3B3C2: Injection pressure of 60 Mpa, packing time of 15 s, cooling time of 10 s	A3B3C3: Injection pressure of 60 Mpa, packing time of 15 s, cooling time of 15 s
PP25	A1B3C1: Injection pressure of 40 Mpa, packing time of 15 s, cooling time of 5 s	A2B3C1: Injection pressure of 50 Mpa, packing time of 15 s, cooling time of 5 s	A1B3C3: Injection pressure of 40 Mpa, packing time of 15 s, cooling time of 10 s	A2B3C1: Injection pressure of 50 Mpa, packing time of 15 s, cooling time of 5 s	A3B3C3: Injection pressure of 60 Mpa, packing time of 15 s, cooling time of 15 s
PP0	A3B3C1: Injection pressure of 60 Mpa, packing time of 15 s, cooling time of 5 s	A1B3C1: Injection pressure of 40 Mpa, packing time of 15 s, cooling time of 10 s	A2B3C2: Injection pressure of 50 Mpa, packing time of 15 s, cooling time of 10 s	A2B3C3: Injection pressure of 50 Mpa, packing time of 15 s, cooling time of 15 s	A2B2C2: Injection pressure of 50 Mpa, packing time of 10 s, cooling time of 10 s
RPP-T20	A3B3C3: Injection pressure of 60 Mpa, packing time of 15 s, cooling time of 15 s	A3B3C3: Injection pressure of 60 Mpa, packing time of 15 s, cooling time of 15 s	A3B3C3: Injection pressure of 60 Mpa, packing time of 15 s, cooling time of 15 s	A3B3C3: Injection pressure of 60 Mpa, packing time of 15 s, cooling time of 15 s	A3B3C3: Injection pressure of 60 Mpa, packing time of 10 s, cooling time of 15 s
RPP-T40	A3B3C3: Injection pressure of 60 Mpa, packing time of 15 s, cooling time of 15 s	A2B3C3: Injection pressure of 50 Mpa, packing time of 15 s, cooling time of 15 s	A3B3C3: Injection pressure of 60 Mpa, packing time of 15 s, cooling time of 15 s	A3B3C1: Injection pressure of 60 Mpa, packing time of 15 s, cooling time of 5 s	A2B3C1: Injection pressure of 50 Mpa, packing time of 15 s, cooling time of 5 s

A verification test was carried out using the optimal processing parameters within the chosen levels which listed in Table 8-13, while the composites were extruded, dried, conditioned, injection moulded and tested under constant processing parameters as in the previous tests. The results showed some improvements compared to the trial experimental data, which verified the effectiveness of TM.

8.4 Principal Component Analysis and Cluster Analysis

8.4.1 Classification by Cluster Analysis

For this research, CA was utilised to classify the multiple properties of composites based on previous experimental data. The purpose of this classification was to promote the understanding of the nature of PP composites by identifying the interrelationships of multiple properties.

Based on the procedure described previously, the standardised data matrix and correlation coefficient matrix of the talc experimental results data set (Table 5-1) are shown in Table 8-14 and Table 8-15. All experimental data were transformed to the standardised data matrix within the range of [0, 1] as a valid basis for comparison and evaluation. The correlation

coefficient matrix showed relationships between each pair of tested properties, with a larger value denoting a closer relationship between the two properties.

Table 8-14 Standardised data matrix

Designation	Tensile Modulus	Tensile Strength	Yield Strength	Flexural Modulus	Flexural Strength	Impact Strength
VPP	0	0.5172	0.2787	0	0	0.6012
RPP	0.0963	0.1149	0	0.1104	0.1544	0.1074
VPP-T10	0.1068	0.5172	0.3934	0.1477	0.3088	0.7399
VPP-T20	0.2625	0.5862	0.4426	0.2783	0.4853	0.8324
VPP-T30	0.4634	0.8046	0.6557	0.4533	0.8015	1.0000
VPP-T40	0.7785	1.0000	1.0000	0.6708	1.0000	0.5609
RPP-T10	0.2478	0.2069	0.2295	0.2046	0.2647	0.0875
RPP-T20	0.4766	0.3103	0.2623	0.3420	0.4485	0.0552
RPP-T30	0.7254	0.5402	0.5902	0.5287	0.7059	0.0960
RPP-T40	1.0000	0.7241	0.9180	0.8480	0.8750	0.0303
RPP-T10-U	0.2125	0.1264	0.0656	0.1909	0.2574	0.0960
RPP-T20-U	0.3619	0.1954	0.1311	0.3065	0.3456	0.0771
RPP-T30-U	0.5902	0.1379	0.0984	0.4679	0.3676	0.0388
RPP-T40-U	0.8517	0	0.0492	0.6905	0.3309	0
PP-T20	0.5592	0.8506	0.7049	0.4983	0.7868	0.1482
PP-T40	0.8748	0.1609	0.2951	1.0000	0.5221	0.0806

Table 8-15 Correlation coefficient matrix

	Tensile Modulus	Tensile Strength	Yield Strength	Flexural Modulus	Flexural Strength	Impact Strength
Tensile Modulus	1.0000					
Tensile Strength	0.1758	1.0000				
Yield Strength	0.4675	0.9330	1.0000			
Flexural Modulus	0.9622	0.1616	0.4471	1.0000		
Flexural Strength	0.7088	0.7420	0.8803	0.6806	1.0000	
Impact Strength	-0.3737	0.5817	0.3641	-0.2895	0.1408	1.0000

The clustered mechanical properties are shown in Figure 8-29.

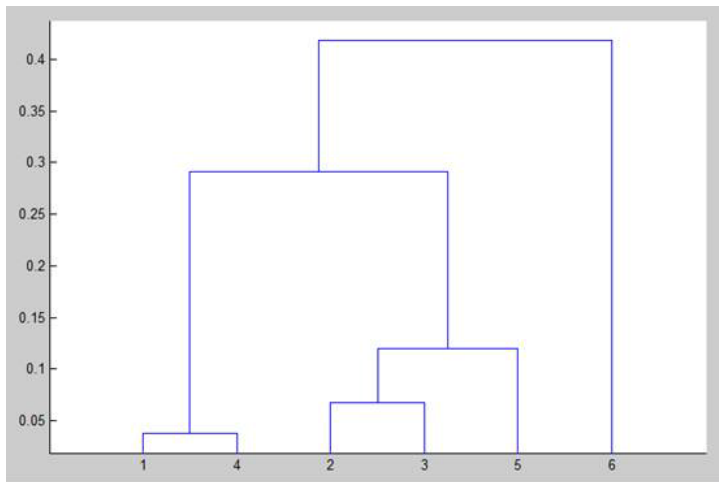


Figure 8-29 Clustering of the talc group

In Figure 8-29, elements 1 to 6 on the horizontal axis represent a range of mechanical properties:

1. No 1 represents tensile modulus;
2. No 2 represents tensile strength;
3. No 3 represents yield strength;
4. No 4 represents flexural modulus;
5. No 5 represents flexural strength;
6. No 6 represents Charpy impact strength.

The values on the y axis represent the distances between linked properties, e.g. the distance value of tensile modulus and flexural modulus is 0.05 as shown in the diagram.

As indicated in Figure 8-29, the six mechanical properties can be classified into three general categories:

1. Tensile modulus and flexural modulus;
2. Tensile strength and yield strength are closely connected, and flexural strength is related to them;
3. Charpy impact strength.

The classification results for the glass fibre group are shown in Figure 8-30. Here, a similar pattern to the classification result of

the talc group.was observed.

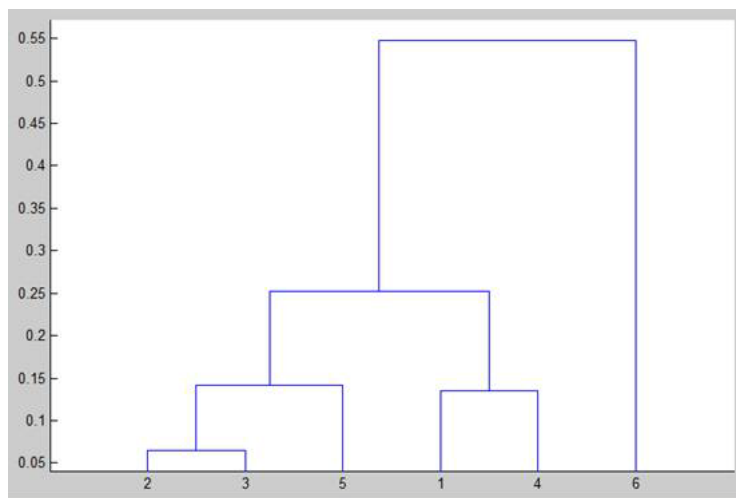


Figure 8-30 Clustering of the GF group

The classification result of the OMMT group was shown in Figure 8-31. In Figure 8-31, elements 1 to 4 on the horizontal axis represented different mechanical or thermal properties:

1. No 1 represents flexural modulus;
2. No 2 represents flexural strength;
3. No 3 represents Charpy impact strength;
4. No 4 represents TDL.

As illustrated in the figure, flexural strength and TDL are closely related, and flexural modulus is distantly related.

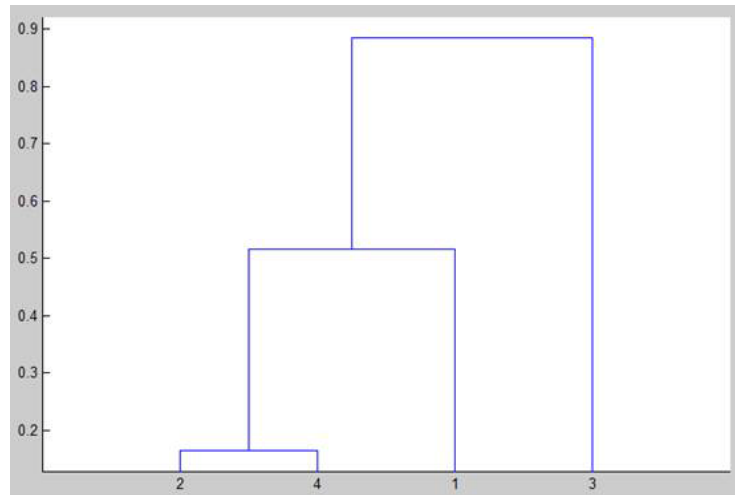


Figure 8-31 Clustering of the OMMT group

The clustered results could be used as a guideline for designing or modifying PP composites, e.g. one cannot expect a PP composite to have both low elongation value and high impact strength or flexural strength correlating with TDL value. This would be useful at the composite formula design phase, and could improve the understanding the nature of PP composites. CA reduces the constraints and contradicting goals, such as low elongation value and high impact strength.

8.4.2 Evaluation by Principal Component Analysis

8.4.2.1 Composite Evaluation

Based on the multiple performance data tables, PCA can be applied to evaluate the composites in a swift manner. The PCA evaluation is made by direct computation of the target data without making any subjective assumptions or introducing

additional systems based on multiple criteria. In composite evaluation, PCA was applied in the sorting and evaluation of three groups of experimental data- the talc group (Table 5-1), the GF group (Table 5-2), and the OMMT group (Table 5-3). KMO results of each of these three data sets were larger than 0.6 and Bartlett's $p=0 < 0.05$, which meant these data sets were middling acceptable for PCA application and suitable for PCA application (Joliffe, 2002).

With respect to the talc group (using data in Table 5-1), according to Equation 2-27 to Equation 2-28, the first four principal components of the talc group calculated explained most variations (4th $AEV = 0.9929$), whose EVs were 0.5864, 0.3352, 0.0583 and 0.0131. Thus, they were selected to determine the optimal combination of blended composites in the existing trials. The eigenvalues of the first four are 3.5187, 2.0109, 0.3495, and 0.0786. According to Equation 2-29, the final data of the talc group was calculated and presented in Table 8-16. As shown in the table, VPP-T40 is with the largest value in the set, and is considered to be the optimal combination of composites in this group, followed by VPP-T30 and RPP-T40.

Table 8-16 Final data of the talc group

<u>Designation</u>	<u>Final Data</u>
VPP	0.4722
RPP	0.1424
VPP-T10	0.6714
VPP-T20	0.8243
VPP-T30	1.1631
VPP-T40	1.3386
RPP-T10	0.3095
RPP-T20	0.4422
RPP-T30	0.7765
RPP-T40	1.0545
RPP-T10-U	0.2172
RPP-T20-U	0.3145
RPP-T30-U	0.3189
RPP-T40-U	0.2813
PP-T20	0.9504
PP-T40	0.5453

Using the repeated procedure, VPP-GF20 was found to be the best combination of composites in the PCA evaluation of the GF group (using data in Table 5-2, presented in Table 8-17), which

was followed by VPP-GF15 and RPP-GF20.

Table 8-17 Final data of the GF group

<u>Designation</u>	<u>Final Data</u>
VPP	0.4068
RPP	0.1916
VPP-GF5	0.6451
VPP-GF10	0.8764
VPP-GF15	1.1833
VPP-GF20	1.3464
RPP-GF5	0.3897
RPP-GF10	0.6154
RPP-GF15	0.8925
RPP-GF20	1.147
VPP-GF5-U	0.601
VPP-GF10-U	0.7714
VPP-GF15-U	0.852
VPP-GF20-U	1.0133
RPP-GF5-U	0.329
RPP-GF10-U	0.503
RPP-GF15-U	0.6889
RPP-GF20-U	0.8634
PP-T20	0.9135
PP-T40	0.3937

And V5-MAPP1 was found to be the optimum combination of composites in the PCA evaluation of the OMMT group (using data in Table 5-3, presented in Table 8-18), which was followed by R5-MAPP1 and V4-MAPP1.

Table 8-18 Final data of the OMMT group

Designation	Final Data
VPP	0.4892
RPP	0.0543
V1-MAPP1	0.6412
V2-MAPP1	0.7401
V3-MAPP1	0.8156
V4-MAPP1	0.9454
V5-MAPP1	1.0065
V1-MAPP2	0.5741
V2-MAPP2	0.6668
V3-MAPP2	0.721
V4-MAPP2	0.8361
V5-MAPP2	0.9721
R1-MAPP1	0.413
R2-MAPP1	0.6582
R3-MAPP1	0.7958
R4-MAPP1	0.8635
R5-MAPP1	1.0005
R1-MAPP2	0.4477
R2-MAPP2	0.5662
R3-MAPP2	0.6136
R4-MAPP2	0.7788
R5-MAPP2	0.9099

According to the PCA analysis, the virgin PP composites with the largest proportion of fillers were the optimum combinations in each filler group, and the composites with the second largest proportion of fillers took second place, followed by recycled PP

which had the largest proportion of fillers. These filled composites demonstrated more favourable qualities than the industrial composites, such as Pret PP and Kingfa PP used in each group.

8.4.2.2 Procedure Evaluation

It was established that PCA can be used in procedure evaluation and this approach is a novel one. The experimental data set from Taguchi method (Section 8.3.2) were used in procedure evaluation by PCA.

The experimental data sets were standardised, then used to evaluate the correlation coefficient matrix, and to determine the corresponding final data. The eigenvalues gained from each set of results are shown in Table 8-19, in descending order, together with their calculated and presented *EVs* and *AEVs*.

Table 8-19 Eigenvalues, EVs and AEVs of TM trials

No	1	2	3	4	5	
	2.3780	1.4562	0.7829	0.3815	0.0014	<i>Eigenvalue</i>
PP100	0.4756	0.2912	0.1566	0.0763	0.0003	<i>EV</i>
	0.4756	0.7668	0.9234	0.9997	1.0000	<i>AEV</i>
	2.9545	1.0313	0.6245	0.3340	0.0556	<i>Eigenvalue</i>
PP90	0.5909	0.2063	0.1249	0.0668	0.0111	<i>EV</i>
	0.5909	0.7972	0.9221	0.9889	1.0000	<i>AEV</i>
	2.7300	0.9911	0.7877	0.3155	0.1757	<i>Eigenvalue</i>
PP70	0.5460	0.1982	0.1575	0.0632	0.0351	<i>EV</i>
	0.5460	0.7342	0.8917	0.9649	1.0000	<i>AEV</i>
	3.2620	1.3921	0.2912	0.0434	0.0112	<i>Eigenvalue</i>
PP50	0.6524	0.2784	0.0582	0.0088	0.0022	<i>EV</i>
	0.6524	0.9308	0.9890	0.9978	1.0000	<i>AEV</i>
	3.1561	1.1830	0.5282	0.1131	0.0196	<i>Eigenvalue</i>
PP30	0.6312	0.2366	0.1056	0.0226	0.0040	<i>EV</i>
	0.6312	0.8578	0.9634	0.9960	1.0000	<i>AEV</i>
	1.9448	1.2821	1.1633	0.5164	0.0933	<i>Eigenvalue</i>
PP10	0.3890	0.2564	0.2327	0.1033	0.0186	<i>EV</i>
	0.3890	0.6454	0.8781	0.9814	1.0000	<i>AEV</i>
	2.7265	1.5781	0.5556	0.1078	0.0321	<i>Eigenvalue</i>
PP0	0.5453	0.3156	0.1111	0.0216	0.0064	<i>EV</i>
	0.5453	0.8609	0.9720	0.9936	1.0000	<i>AEV</i>

As shown in Table 8-19, the first four principal components would explain most variation, the average *AEV* of the 4th principal component was 0.9889. Thus, the first four principal components were selected to determine the optimal combination of the four processing parameters in the existing trials.

The largest values of final data set can be considered to be the highest performing materials, which corresponds to the optimal trials. The numbers of the optimal trials for each blend are shown in Table 8-20, according to Equation 2-30. Based on this the optimal processing parameters were gained.

Table 8-20 Optimal trials based on final data

	Final Data	Optimal trial No	Optimal condition
PP100	0.9926	6	A2B3C1D2
PP90	1.4145	3	A1B3C3D3
PP70	1.5811	3	A1B3C3D3
PP50	2.1604	1	A1B1C1D1
PP30	1.9922	1	A1B1C1D1
PP10	0.8417	1	A1B1C1D1
PP0	1.5709	1	A1B1C1D1

The PCA analysis converted optimisation of S/N ratios gained from Taguchi method set into evaluation of a single performance characteristic called final data, and optimisation of complicated multiple-performance characteristics can be greatly simplified by means of this approach, and from which the optimal trial for each proportion was obtained.

The comparator ratio (*CR*) was used to compare Taguchi optimisation results in Table 8-10 with the performance of optimal trials via PCA evaluation which shown in Table 8-21, shown in Equation 8-2:

$$CR = \frac{P_{Taguchi} - P_{PCA}}{P_{PCA}} \times 100\% \quad \text{(Equation 8-2)}$$

The *CR* results were calculated and are shown in Table 8-21.

Table 8-21 CR results (%)

	Tensile strength	Yield strength	Flexural modulus	Flexural strength	Impact strength
PP100	0.42	1.63	0.56	0.64	-0.5
PP90	0.36	1.06	-0.71	-0.62	0.69
PP70	0.75	-0.79	-0.66	-0.12	1.12
PP50	1.19	2.24	-0.59	-1.64	-1.91
PP30	0.01	-0.47	-0.02	-0.84	2.67
PP10	3.27	1.72	-0.19	-0.39	6.05
PP0	2.25	0.25	0.99	-0.32	4.94
Average	1.18	0.81	-0.09	-0.47	1.88

According to Table 8-21, Taguchi method allowed for improvement of tensile and impact properties of recycled plastic, as the largest *CR* value is as much as 6.05%. However, PCA evaluation showed high efficiency in calculation and evaluation, as the flexural properties of PCA evaluated results were more favourable than Taguchi optimised results.

8.5 Summary

The application of three selected mathematical tools proved to be quite successful, as four following marks were reached:

1. The application of both GM techniques was successful in test set, and among the two techniques, GM (1, 1) was a better technique as the smallest average AER value indicated. It could provide a new approach to support decision-making in identifying suitable formulas of blending plastic material based on a limited number of short tests in swift manner. Thus, the optimum blending formula can be made without conducting detailed, time-consuming, costly and environmentally harmful tests based on each possible proportion.
2. The TM was useful for identifying optimal levels of processing parameters for each blending proportion.

3. The optimal combined composites and processing procedures could be easily and quickly determined by the utilisation of PCA without conducting time-consuming repeated tests. PCA deals directly with the experimental data, and it can be used as a decision-making support tool to evaluate composites without introducing multiple complicated and subjective criteria.

4. CA was proved to be a useful tool in classifying the multiple properties of recycled composites. It aids in the study of recycled plastics, and facilitates the production of composites with certain desirable properties.

The combined use of fillers and mathematic techniques is efficient and effective in improving the overall performance of recycled plastics. The improvement of recycled plastics performance was sometimes significant. Some recycled composites performed at similar levels to virgin plastics or industrial composites and some demonstrated even higher performance levels.

Chapter 9 Conclusion and Future Work

9.1 Conclusion

Current plastic recycling practices in China follow two major routes: single source recycling and mixed recycling.

Representative products from both routes are bought and characterised via detailed standard tests. The following types of properties are measured:

1. Mechanical properties (Chapter 4): recycled content which has deteriorated could display mechanical properties indicating that mechanical performance is a major weakness of recycled plastics. Among all tested mechanical properties, impact strength suffer the most serious deterioration, most likely caused by contamination content that facilitated crystallization in the materials.
2. Rheological properties (Chapter 4): Higher MFI values and lesser shear viscosities are observed. These results verify the effects caused by reduced molecular weight and contaminants in recycled plastics.
3. Thermal properties (Chapter 4): TGA tests show recycled plastics started to decompose at lower temperatures, and TDL values of recycled plastics were significantly lower than those of virgin plastics. The deterioration in thermal stability could result from the changes in the micro-structure of the

materials, thereby limiting the use of the materials.

4. Durability properties (Chapter 6): recycled plastics displayed similar behaviour to virgin materials and demonstrate even better performance under multiple reprocess cycles.

Resistance against ageing and reprocessing could be a merit of recycled plastics.

5. Flammability properties (Chapter 7): recycled plastics are much easier to burn and have a faster burning rate when compared to virgin materials. The fire resistance of recycled plastics can be considered as another major weakness.

As shown in the experimental results mentioned above, the performance of recycled plastics is noticeably poorer than that of virgin materials, especially with respect to mechanical, thermal and flammability properties. Without proper treatment, recycled plastics cannot be used in any demanding industrial application, such as the manufacturing of automobile parts. Via a series of experiments in Chapter 4, it is verified that the performance of recycled plastics is largely affected by the original materials which derived from the degradation and contamination in the initial life cycle.

For this research, three commonly used fillers are selected to add into recycled plastics to promote certain desirable properties. They are talcum powder (talc) which represents common mineral filler, glass fibre (GF) which represents a fibre, and organically modified montmorillonite (OMMT) which represents a nanoclay. Experimental results in Chapter 5 indicated that all three fillers noticeably improve the performance of recycled plastics. Among them, GF is the most effective filler in improving most of the mechanical properties. When comparing the effects of these three fillers at the same loading level OMMT is the most effective filler in promoting flexural properties. The thermal, rheological and flammability properties showed improvements when adding talc and OMMT into the recycled plastics. Additionally, the recycled PP/talc composites maintain better mechanical properties in ageing and reprocessing tests than both virgin and recycled plastics. As mechanical, rheological and flammability results in Chapter 5 showed, the MAPP with grafted rate of 0.8% is proved to be a better compatibiliser when compared to MAPP with grafted rate of 0.9%.

In Section 2.8, four techniques were select to predict, evaluate

and optimise the formulas and procedures for improving recycled composites: grey model (GM), Taguchi method (TM), principal component analysis (PCA) and cluster analysis (CA). Among these techniques, GM was used to predict the effect of adding recycled plastic to virgin plastic based limited number of trials. TM was used for optimising processing conditions when using recycled plastics. PCA and CA were utilised to analyse and evaluate the performance of recycled composites. The conclusive remarks of application of these techniques in Chapter 8 are shown as follow:

1. GM techniques allow simulation of experimental curves. GM (1, 1) and grey Verhulst model were useful for predicting the behaviours of blends as a function of recycled content.
2. TM is very useful and effective in improving the mechanical properties of composites based on recycled plastics by optimising the processing parameters in injection moulding procedure. By obtaining and adapting the optimal combination within the chosen levels of processing parameters, the mechanical performance of recycled plastics can be improved by up to nearly 10%. During the TM optimisation procedure, melt temperature and packing pressure were identified as key factors influencing the

performance of end product in injection moulding.

3. PCA is a useful decision-making support tool to evaluate recycled plastics and composites based on multiple properties without making any subjective assumptions. PCA can be used as a quick evaluation tool in comparing materials.
4. CA is a useful tool in classification of the multiple properties of recycled composites by analysis the numeric relationships of the properties. This improves understanding of recycled plastics, and is useful for designing plastic composite for certain application without introducing self-contradicting objects.

In this research, the weaknesses in recycled plastics in some major criteria, such as mechanical properties, thermal properties and flammability, are identified in Chapter 4 and Chapter 7. With addition of additives (Chapter 5) and application of tools (Chapter 8), a noticeable improvement in performance of the recycled plastics and related composites is observed. Some of the tested properties, such as tensile and flexural properties of recycled PP/GF composites, are even more favourable than those of industrial composites as shown

in Section 5.2. While the combined methodology developed for improving recycled plastics is successful, recommendations for future work are presented in the next section.

9.2 Future Work

To utilise the recycled plastics in automobile production, there is still a lot work which needs to be done. Generally, future works addressing this gap in knowledge can be categorised according to the following five aims:

1. Better understanding of recycled plastics and related composites in microstructure;
2. Better understanding of automobile production;
3. Promote recycled plastics to meet the complicated industrial standards, such as flammability and impact strength;
4. Production trial using composites based on recycled plastics for manufacturing real automobile parts;
5. Marketing the composites based on recycled plastics.

As the characteristics of original materials and contamination in the initial life cycle are identified as the key factors that affect the performance of recycled plastics. It is necessary to identify the detailed waste management of scrap plastics, such as the

origins of recycled plastics, recycling methods and their consumers.

For this research, recycled plastics and composites were compared with virgin materials and industrial composites which are used in automobile production. However, full detailed requirements for specific automobile components should be used to inform further research.

PP was used as primary material for investigation as it constitutes the largest proportion among the plastics used in automobile production. In future, the research subject could be extended to other types of polymers, especially those engineering plastics which are commonly used in automobile production, such as ABS, POM, PS and PA. Existing formulas, procedures and methods could be applied to those materials.

Further, it is necessary to address the brittleness resulting from the addition of talc and which deteriorates the impact strength. A common practice is to combine different fillers, such as talc and elastomers, into recycled plastics to counter side effect (brittleness) and gain a more balanced performance. While this

has never been applied in recycled materials, this perspective merits further attention. Flame retardant agents can be added to recycled plastics and the effects on flammability and overall properties need to be identified. More detailed characterisation experiments can be performed, to include transmission electron microscope (TEM), atomic force microscope (AFM), X-ray diffraction (XRD) and thermal dynamic mechanical tests.

Durability tests performed in this research were not sufficiently conclusive to prove the feasibility of applying recycled plastics in automobiles. It is necessary to perform tests on recycled composites under certain loads and combined UV conditions for simulating the real working environment of automobile components. Research should focus on the degradation mechanism, in order to identify the effect of the potential use of an anti-oxidant agent. Creep behaviour of recycled plastics and composites will also receive attention, establishing long term data for structural application in automobiles.

While the application of mathematical tools was successful, they were applied in their basic forms with limited functionalities. For further study, GM with improved solutions

will be used for predicting the behaviour of complex formulas. All processing parameters in the whole recycling procedure (sorting, extrusion and injection moulding) should be included in TM for a well-structured full-scale optimisation with the aid of analysis tools (such as analysis of variance, ANOVA). PCA and CA can be used for designing and optimising certain composition formula with the purpose of improving specified properties.

While this research was conducted on a laboratory scale, it is necessary to trial it at an industrial scale. The first step is to design an experiment for obtaining the energy consumption of recycled plastics using industrial equipments, and to perform an economic assessment on the real scale industrial manufacturing procedure. Then, recycled materials can be used for making new automobile parts in a real production environment, and detailed tests can be performed on the parts to carry out comprehensive assessments.

References

- Aasetre, S., Augestad, M. and Toeraa, D. (1998). Talc containing polypropylene compositions. European Patent, WO1998EP0721619981109.
[http://worldwide.espacenet.com/publicationDetails/biblio?CC = WO&NR = 9924501A1&KC = A1&FT = D.](http://worldwide.espacenet.com/publicationDetails/biblio?CC=WO&NR=9924501A1&KC=A1&FT=D)
- Abbas, K.B., Knutsson, A.B. and Berglund, S.H. (1977). Reprocessing of thermoplastics: Models predicting the effect of physical properties. *Proceedings of the American Chemical Society Meeting*, 383-388.
- Abbas, K.B., Knutsson, A.B. and Berglund, S.H. (1978). New thermoplastics from old. *Chemtech*, 8:502-508.
- Abbas, K.B. (1980). Reprocessing of thermoplastics. II. Polycarbonate. *Polymer Engineering and Science*, 20:376-382.
- Abbas, K.B. (1981). Degradational effects on bisphenol A polycarbonate extruded at high shear stresses. *Polymer*, 22:836-841.
- Abdi, H. and Williams, L.J. (2010). Principal component analysis. *Wiley Interdisciplinary Reviews: Computational Statistics*, 2:433-459.
- Abdul-Wahab, S.A., Bakheit, C.S. and Al-Alawi, S.M. (2005). Principal component and multiple regression analysis in modeling of ground-level ozone and factors affecting its concentrations. *Environmental Modeling & Software*, 20:1263-1271.
- Adhikary, K.B., Pang, S. and Staiger, M.P. (2008). Dimensional stability and mechanical behaviour of wood-plastic composites based on recycled and virgin high-density polyethylene (HDPE). *Composites Part B: Engineering*, 39:807-815.
- Ahmed, N., Khan, J.H., Hussain, I. and Hamid, S.H. (1999). Thermal, chemical and mechanical property evaluation of recycled–reprocessed high density polyethylene. *Journal of Polymer Materials*, 16:341-345.
- Ahrens, M. (2005). U.S. Vehicle Fire Trends and Patterns. National Fire Protection Association, Quincy, MA, US.
- Ahrens, M. (2006). U.S. Fires in Selected Occupancies. National Fire Protection Association, Quincy, MA, US.
- Al Maadeed, M.A., Kahraman, R., Khanam, P.N., and Madi, N. (2012). Date palm wood flour/glass fibre reinforced hybrid composites of recycled polypropylene: Mechanical and thermal properties. *Materials & Design*, 42:289-294.
- Alexandre, M. and Dubois, P. (2000). Polymer-layered silicate

- nanocomposites: preparation, properties and uses of a new class of materials. *Materials Science and Engineering: R: Reports*, 28: 1-63.
- Allen, N.S and McKellar, J.F. (1980). Photostabilisation of recycled pigmented polypropylene crate material. *European Polymer Journal*, 16:549-551.
- Amin, M.U., Scott, G. and Tillekeratne, L.M.K. (1975). Mechanism of the photo-initiation process in polyethylene. *European Polymer Journal*, 11:85-89.
- Andričić, B., Kovačić, T., and Klarić, I. (2008). Properties of recycled material containing poly (vinyl chloride), polypropylene, and calcium carbonate nanofiller. *Polymer Engineering and Science*, 48:572-577.
- Ardestani, M.M., Chen, Z., Wang, L., Lian, Q., Liu, Y., He, J., Li, D., and Jin, Z. (2014). Feed forward artificial neural network to predict contact force at medial knee joint: Application to gait modification. *Neurocomputing*, 139:114-129.
- Ashori, A. (2008). Municipal solid waste as a source of lignocellulosic fiber and plastics for composite industries. *Polymer-Plastics Technology and Engineering Journal*, 47:741-744.
- Ashori, A. and Nourbakhsh, A. (2009). Characteristics of wood-fiber plastic composites made of recycled materials. *Waste Management*, 29(4): 1291-1295.
- Aslan, N. and Unal, I. (2009). Optimisation of some parameters on agglomeration performance of Zonguldak bituminous coal by oil agglomeration. *Fuel*, 88:490-496.
- Aslan, N. (2012). Multi-Objective Optimisation of Some Process Parameters of Lead Flotation Using Grey Relational Analysis. *Separation Science and Technology*. 47:599-605.
- Awaja, F., Daver, F. and Kosior, E. (2004). Recycled poly(ethylene terephthalate) chain extension by a reactive extrusion process. *Polymer Engineering and Science*, 44:1579-1587.
- Awaja, F. and Pavel, D. (2005a). Injection stretch blow moulding process of reactive extruded recycled PET and virgin PET blends. *European Polymer Journal*, 41:2614-2634.
- Awaja, F. and Pavel, D. (2005b). Statistical models for optimisation of properties of bottles produced using blends of reactive extruded recycled PET and virgin PET. *European Polymer Journal*, 41:2097-2106.
- Aziz, S.H., Ansell, M.P., Clarke, S.J., and Panteny, S.R. (2005). Modified polyester resins for natural fibre composites.

- Composites Science and Technology*, 65:525-535.
- Baeurle, S.A., Hotta, A. and Gusev, A.A. (2006). On the glassy state of multiphase and pure polymer materials. *Polymer*, 47:6243-6253.
- Bair, H.E., Boyle, D.J. and Kelleher, P.G. (1980). The effects of light and heat on the rubber content and impact strength of acrylonitrile-butadiene-styrene. *Polymer Engineering and Science*, 20:995-1001.
- Bahlouli, N., Pessey, D., Ahzi, S. and Rémond, Y. (2006). Mechanical behavior of composite based polypropylene: Recycling and strain rate effects. *Journal de Physique IV France*, 134:1319-1323.
- Balatinecz, J.J. and Sain, M.M. (1998). The influence of recycling on the properties of wood fibre–plastic composites. *Macromolecular Symposia*, 135:167-173.
- Bajracharya, R.M., Manalo, A.C., Karunasena, and W., Lau, K.T. (2014). An overview of mechanical properties and durability of glass-fibre reinforced recycled mixed plastic waste composites. *Materials & Design*, 62:98-112.
- Barkhudaryan, V.G. (2000). Alteration of molecular characteristics of polyethylene under the influence of UV radiation. *Polymer*, 41:5787-5791.
- Bedworth, D.D., Henderson, M.R. and Wolfe, P.M. (1991). *Computer-integrated Design and Manufacturing (International Edition)*. New York: McGraw-Hill.
- Bellanti, F., Tomassetti, A., Visco, G. and Campanella, L. (2008). A chemometric approach to the historical and geographical characterisation of different terracotta finds. *Microchemical Journal*, 88:113-120.
- Bernardo, C.A., Cunha, A., and Oliveira, M.J. (1996). The recycling of thermoplastics. Prediction of the properties of mixtures of virgin and reprocessed polyolefins. *Polymer Engineering and Science*. 36:511-519.
- Bikbov, R. and Chernov, M. (2011). Yield curve and volatility: Lessons from Eurodollar futures and options. *Journal of Financial Econometrics*, 9:66-105.
- Bikiaris, D.N. and Karayannidis, G.P. (1995). Chain extension of polyesters PET and PBT with N,N'-bis(glycidyl ester) pyromellitimides. I. *Journal of Polymer Science Part A: Polymer Chemistry*, 33:1705-1714
- Bikiaris, D.N. and Karayannidis, G.P. (1996). Chain extension of polyesters PET and PBT with two new diimidodiepoxides. II. *Journal of Polymer Science Part A: Polymer Chemistry*, 34:1337-1342.

- Billiania, J. and Fleischmanna, E. (1990). Influence of injection rate and melt temperature on polypropylene during injection moulding without packing. *Polymer Degradation and Stability*, 28:67-75.
- Billingham, N.C. and Calvert, P.D. (1983). In: N.S. Allen, Editor, Degradation and stabilisation of polyolefins, Applied Science Publishers.
- Bizarria, M., Giraldi, A.L.F.M., de Carvalho, C.M., Velasco, J.I., d'Ávila, M.A. and Mei, L.H.I., 2007. Morphology and thermomechanical properties of recycled PET–organoclay nanocomposites. *Journal of Applied Polymer Science*, 104:1839-1844.
- Boldizar, A., Gevert, T. and Markinger, M. (1995). Quality assessment of polymeric recyclates part 1-repeated processing and thermo-oxidative ageing of LDPE. *Polymer Recycling*, 1:249-255.
- Boldizar, A. and Möller, K. (2003). Degradation of ABS during repeated processing and accelerated ageing. *Polymer Degradation and Stability*, 81:359-366.
- Boronat, T., Segui, V.J., Peydro, M.A., and Reig, M.J. (2009). Influence of temperature and shear rate on the rheology and processability of reprocessed ABS in injection moulding process. *Journal of Materials Processing Technology*, 209:2735-2745.
- BPF. (2013). A History of Plastics, by The British Plastics Federation (BPF).
http://www.bpf.co.uk/plastipedia/plastics_history/default.aspx, retrieved on July, 2013.
- Brachet, P., Høydal, L.T., Hinrichsen, E.L., and Melum, F. (2008). Modification of mechanical properties of recycled polypropylene from post-consumer containers. *Waste Management*, 28:2456-2464.
- Brady, M. and Brady, P. (2007a). Automotive composites - the search for efficiency, value and performance. *Reinforced Plastics*, 51:26-29.
- Brady, P. and Brady, M. (2007b). Automotive composites: which way are we going? *Reinforced Plastics*, 51:32-35.
- Brooks, D.W. (2013). Classification of Plastics.
<http://dwb.unl.edu/Teacher/NSF/C06/C06Links/qmlink.queensu.ca/~6jrt/chem210/Page3.html>. Retrieved on 2013-10-1.
- Brossas, J. (1989). Fire retardance in polymers: An introductory lecture. *Polymer Degradation and Stability*, 23:313-325.

- Brown, R.P., Kockott, D., Trubiroha, P., Ketola, W., and Shorthouse, J., (1995). A Review of Accelerated Durability Tests. Versailles Project on Advanced Materials and Standards, VAMAS Report No.18.
- Burat, F.I., Güney, A., Olgaç Kangal, M., 2009. Selective separation of virgin and postconsumer polymers (PET and PVC) by flotation method. *Waste Management*, 29:1807-1813.
- Burroughes, J.H., Bradley, D.D.C., Brown, A.R., Marks, R.N., MacKay, K., Friend, R.H., Burns, P.L. and Holmes, A.B. (1990). Light-emitting diodes based on conjugated polymers. *Nature*, 347:539-541.
- Caceres, C.A. and Canevarolo, S.V. (2008). Chain scission in the thermo mechanical degradation of polystyrene under multiple extrusions. *Polimeros-Ciencia E Tecnologia*, 18:348-352.
- Canevarolo, S.V. (2000). Chain scission distribution function for polypropylene degradation during multiple extrusions. *Polymer Degradation and Stability*, 1:71-76.
- Capone, C., Di Landro, L., Inzoli, F., Penco, M. and Sartore, L. (2007). Thermal and mechanical degradation during polymer extrusion processing. *Polymer Engineering and Science*, 47:1813-1819.
- Cardi, N., Po, R., Giannotta, G., Occhiello, E., Garbassi, F. and Messina, G. (1993). Chain extension of recycled poly(ethylene terephthalate) with 2,2'-Bis(2-oxazoline). *Journal of Applied Polymer Science*, 50:1501-1509.
- Carlson, D., Yamazaki, H., Fukuda, S., K., Leboeuf, C. and Kasserra, H.P. (2003). Application of nylon composite recycle in technology to automotive parts. *SAE Transactions*, 112(5): 353-358.
- Çaydaş, U. and Haşçalık, A. (2008). Use of the grey relational analysis to determine optimum laser cutting parameters with multi-performance characteristics. *Optics & Laser Technology*, 40:987-994.
- CBI China. (2013). Compound Batch Import, a compound batch merchandise trading corporation in China, <http://cbijill.cn.globalimporter.net/>, in Chinese [retrieved on 29/10/2013]
- Cebeci, Y., and Sönmez, I. (2006). Application of the Box-Wilson experimental design method for the spherical oil agglomeration of coal. *Fuel*, 85:289-297.
- Cecere, F., Carraro, A., Ferro, D. and Visco, G. (2008). Individuation of characteristic parameters of "glass paste"

- of Meridional Etruria by the use of scientific methodologies. *Microchemical Journal*, 88: 130-135.
- Chand, N., Tiwary, R.K. and Rohtagi, P.K. (1988). Structure-properties of natural cellulosic fibres - an annotated bibliography. *Journal of Materials Science*, 23(2): 381–387.
- Chang, M.K., Hwang, S.S., and Liu, S.P. (2014). Flame retardancy and thermal stability of ethylene-vinyl acetate copolymer nanocomposites with alumina trihydrate and montmorillonite. *Journal of Industrial and Engineering Chemistry*, 20: 1596-1601.
- Chen, C.I., Chen, H.L. and Chen, S.P. (2008). Forecasting of foreign exchange rates of Taiwan's major trading partners by novel nonlinear grey Bernoulli model NGBM(1, 1). *Communications in Nonlinear Science and Numerical Simulation*, 13: 1194-1204.
- Chen, C.I., Hsin, P.H. and Wu, C.S. (2010). Forecasting Taiwan's major stock indices by the Nash nonlinear grey Bernoulli model. *Expert Systems with Applications*, 37: 7557-7562.
- Chen, H.C., Chen, T.Y. and Hsu, C.H. (2006). Effects of Wood Particle Size and Mixing Ratios of HDPE on the Properties of the Composites. *Holz als Rohstoff und Werkstoff*, 64: 172-177.
- Chen, T.Y. (2014). Interval-valued fuzzy multiple criteria decision-making methods based on dual optimistic/pessimistic estimations in averaging operations. *Applied Soft Computing*, 24: 923-947.
- Cheng, X., 2007. The Feasibility Analysis of Setting Up A New Plastics Recycling Factory (in Chinese). *Agriculture of Shanxi*, 6: 50-51.
- Cheong, C.W. (2011). Parametric and non-parametric approaches in evaluating martingale hypothesis of energy spot markets. *Mathematical and Computer Modelling*, 54: 1499-1509.
- Chernov, M. and Bikbov, B. (2010). No-arbitrage macroeconomic determinants of the yield curve. *Journal of Econometrics*, 159: 166-182.
- Chin, J., Forster, A., Clerici, C., Sung, L., Oudina, M., and Rice, K. (2007). Temperature and humidity aging of poly(p-phenylene-2,6-benzobisoxazole) fibers: Chemical and physical Characterisation. *Polymer Degradation and Stability*, 92: 1234-1246.
- CCS. (2011). China Customs Statistics, <http://www.haiguan.info/newdata/Index.aspx>, ,

- in Chinese [retrieved on 30/04/2011]
- Chtourou, H., Riedl, B. and Ait-Kadi, A. (1992). Reinforcement of recycled polyolefins with wood fibers. *Journal of Reinforced Plastics and Composites*, 11(4):372-394.
- Chrysostomou, A. and Hashemi, S. (1996). Influence of reprocessing on properties of polycarbonate. *Journal of Materials Science*, 31:5573-5582.
- Chrysostomou, A. and Hashemi, S. (2000). Effect of reprocessing on mechanical properties of short glass fiber reinforced styrene maleic anhydride. *Plastic Rubber Composites*, 29:235-242.
- Commereuc, S., Vaillant, D., Philippart, J.L., Lacoste, J., Lemaire, J. and Carlsson, D.J. (1997). Photo and thermal decomposition of iPP hydroperoxides. *Polymer Degradation and Stability*, 57:175-182.
- Corbière-Nicollier, T., Gfeller-Laban, B., Lundquist, L., Leterrier, Y., Månson, J.A.E., and Jolliet, O. (2001). Life cycle assessment of biofibres replacing glass fibres as reinforcement in plastics. *Resources, Conservation and Recycling*, 33:267-287.
- CPS. (2011). Application and Development Trend of Plastics in China's Auto industry, www.chinaplasonline.com/CPS11/Files/Show/pdf/Ind_Automotive_en.pdf, Shanghai Automotive Trade Association.
- Cudeck, R. and MacCallum R.C. (2007). Factor Analysis at 100: Historical Developments and Future Directions. Lawrence Erlbaum, Mahwah, New Jersey.
- Cullis, C.F. and Hirschler, M. (1981). The Combustion of Organic Polymers. Oxford: Clarendon Press.
- Dalmijn, W.L. and De Jong, T.P.R. (2007). The development of vehicle recycling in Europe: sorting, shredding, and separation. *JOM-US*, 59:52-56.
- Dang, Y.G., Liu, S.F. and Liu, B. (2005). The GM models that $x(1)(n)$ be taken as initial value. *Chinese Journal of Management Science*, 13:132-135.
- Daver, F., Gupta, R. and Kosiorec, E. (2008). Rheological characterisation of recycled poly(ethylene terephthalate) modified by reactive extrusion. *Journal of Materials Processing Technology*, 204:397-402.
- Davis, J.C. (1986). Statistics and Data Analysis in Geology. New York: Wiley.
- Denac, M., Musil, V., Šmit, I., and Ranogajec, F. (2003). Effects of talc and gamma irradiation on mechanical properties and morphology of isotactic

- polypropylene/PP/talc composites. *Polymer Degradation and Stability*. 82:263-270.
- Deng, J.L. (1982). Control problems of grey system. Beijing: Systems and Control Letters. 1:288-294.
- Deng, J.L. (1985). Grey system (society and economics). Beijing: National Defense Industry Press.
- Deng, J.L. (1989). Introduction to grey system theory. *The Journal of grey System*, 1:1-24.
- Deng, J.L. (1992). The Essential methods of grey systems. Wuhan: Huazhong University of Science and Technology Press.
- Díez-Gutiérrez, S., Rodríguez-Pérez, M.A., De Saja, J.A., and Velasco, J.I. (1999). Dynamic mechanical analysis of injection-moulded discs of polypropylene and untreated and silane-treated talc-filled polypropylene composites. *Polymer*. 40:5345-5353.
- Dintcheva, N.T., Jilov, N. and La Mantia, F.P. (1997). Recycling of plastics from packaging. *Polymer Degradation and Stability*, 57:191-203.
- Dintcheva, N.T. and La Mantia, F.P. (2004). Photo-re-stabilisation of recycled post-consumer films from greenhouses. *Polymer Degradation and Stability*, 85:1041-1044.
- dos Santos, L.M., Simões, M.L., de Melo, W.J., Martin-Neto, L. and Pereira-Filho, E.R. (2010). Application of chemometric methods in the evaluation of chemical and spectroscopic data on organic matter from Oxisols in sewage sludge applications. *Geoderma*, 155:121-127.
- Doukas, H., Papadopoulou, A., Savvakis, N., Tsoutsos, T. and Psarras, J. (2012). Assessing energy sustainability of rural communities using Principal Component Analysis. *Renewable and Sustainable Energy Reviews*, 16:1949-1957.
- Drake, W.O., Pauquet, J.R., Todesco, R.V. and Zweifel, H. (1990). Processing stabilisation of polyolefins. *Die Angewandte Makromolekulare Chemie*, 176(1):215-230.
- EC, European Commission. (2013). End-of-waste criteria for waste plastic for conversion - the technical proposals, final draft report, march, 2013. <http://susproc.jrc.ec.europa.eu/activities/waste/documents/EoWPlasticsfinalDrepMar2013WEB.pdf> [visited on April 2014].
- Eder, B.K. (1989). A principal component analysis of SO₂⁻⁴ precipitation concentrations over the eastern United States.

- Atmospheric Environment*, 23:2739-2750.
- Eguiazabal, J.I. and Nazabal, J. (1989). Effect of reprocessing on the properties of bisphenol-A polycarbonate. *European Polymer Journal*, 25:891-893.
- Eguiazabal, J.I. and Nazabal, J. (1990). Reprocessing polycarbonate/acrylonitrile-butadiene-styrene blends: influence on physical properties. *Polymer Engineering and Science*, 30:527-531.
- Ehrig, R.J. (1992). *Plastics Recycling: Products and Process*. New York: Carl Hanser Verlag.
- EIA. (2010). International Energy Outlook 2010, [http://www.eia.doe.gov/oiaf/ieo/pdf/0484\(2010\).pdf](http://www.eia.doe.gov/oiaf/ieo/pdf/0484(2010).pdf).
- EIA. (2012). World Crude Oil Prices, http://www.eia.doe.gov/dnav/pet/pet_pri_wco_k_w.htm.
- Elloumi, A., Pimbert, S., Bourmaud, A., and Bradai, C. (2010). Thermomechanical properties of virgin and recycled polypropylene impact copolymer/CaCO₃ nanocomposites. *Polymer Engineering and Science*, 50:1904-1913.
- Enviros. (2002). Potential markets for recovered plastics, <http://www.londonremade.com/Uploads/medialibrary/potentialmarketsforrecoveredplastics.pdf>.
- EPA. (2013). Plastics Recycling - Resin Identification Code. <http://www.epa.gov/osw/conserva/materials/plastics.htm#recycle>.
- EUPC. (2011). The European market for plastics automotive components, <http://www.plasticsconverters.eu/markets/automotive>
- Fadigas, J.C., dos Santos, A.M.P., de Jesus, R.M., Lima, D.C., Fragoso, W.D., David, J.M. and Ferreira, S.L.C. (2010). Use of multivariate analysis techniques for the characterisation of analytical results for the determination of the mineral composition of kale. *Microchemical Journal*, 96:352-356.
- Farhadinia, B. (2014). Distance and similarity measures for higher order hesitant fuzzy sets. *Knowledge-Based Systems*, 5543–5548.
- FEMA. (2003). *Motor Vehicle Fires: What You Need to Know*. Federal Emergency Management Agency, U.S. Fire Administration, FA-243.
- Feller, J.F., and Bourmaud, A. (2003). Rheological and calorimetric properties of recycled bisphenol A poly(carbonate). *Polymer Degradation and Stability*, 82:99-104.
- Fernandez, A., Muniesa, M., and Javierre, C. (2014). In-line rheological testing of thermoplastics and a monitored

- device for an injection moulding machine: Application to raw and recycled polypropylene. *Polymer Testing*, 33:107-115.
- Fiebig, J., Gahleitner, M., Paulik, C., and Wolfschwenger, J. (1999). Ageing of polypropylene: processes and consequences. *Polymer Testing*, 18:257-266.
- Fischer, H. (2003). Polymer nanocomposites: from fundamental research to specific applications. *Materials Science and Engineering: C*, 23:763-772.
- Fortelný, I., Kruliš, Z. and Michálková, D. (2002). Use of additive compatibilisation for recycling of municipal plastics waste. *Polimery/Polymers*, 47(7-8):534-537.
- Fouk, J.A., Chao, W.Y., Akin, D.E., Dodd, R.B. and Layton, P.A. (2004). Enzyme retted flax fiber and recycled polyethylene composites. *Journal of Polymers and the Environment*, 12:165-171.
- Freinkel, S. (2011). A Brief History of Plastic's Conquest of the World. [http://www.scientificamerican.com/article.cfm?id = a-brief-history-of-plastic-world-conquest](http://www.scientificamerican.com/article.cfm?id=a-brief-history-of-plastic-world-conquest), 2011, retrieved on July, 2013.
- Froelich, D., Maris, E., Haoues, N., Chemineau, L., Renard, H., Abraham, F. and Lassartesses, R. (2007). State of the art of plastic sorting and recycling: feedback to vehicle design. *Minerals Engineering*, 20: 902-912.
- Fu, S.Y., Lauke, B., Mäder, E., Yue, C.Y., Hu, X. (2000). Tensile properties of short-glass-fiber- and short-carbon-fiber-reinforced polypropylene composites. *Composites Part A: Applied Science and Manufacturing*. 31:1117–1125.
- Fung, H.C. and Kang, P.C. (2005). Multi-response optimisation in friction properties of PBT composites using Taguchi method and principal component analysis. *Journal of Materials Processing and Technology*, 170:602-610.
- Gahleitner, M., Wolfschwenger, J., Bachner, C., Bernreitner, K., and Neißl, W. (1996). Crystallinity and mechanical properties of PP-homopolymers as influenced by molecular structure and nucleation. *Journal of Applied Polymer Science*, 61:649-657.
- Gann, R.G., Dipert, R.A., and Drews, M.J. (1987). *Encyclopedia of Polymer Science and Engineering*, 2nd ed. New York: John Wiley & Sons.
- Gao, J.L., Liu, Y.H., and Li, D.M. (2011). Preparation and properties of recycled polypropylene/carbon nanotube composites. *Advanced Materials Research*, 279:106-110.

- Gao, Z.M., Amasaki, I. and Nakada, M. (2003). A thermogravimetric study on thermal degradation of polyethylene. *Journal of Analytical and Applied Pyrolysis*, 67:1-9.
- Garg, S. and Jana, A.K. (2007). Studies on the properties and characteristics of starch–LDPE blend films using cross-linked, glycerol modified, cross-linked and glycerol modified starch. *European Polymer Journal*, 43:3976-3987.
- Georgel, O. (2004). Le recyclage des déchets au Japon. Report, ambassade de France au Japon, service pour la science et la technologie. <http://www.ambafrance-jp.org>.
- Gerrard, J. and Kandlikar, M. (2007). Is European end-of-life vehicle legislation living up to expectations? Assessing the impact of the ELV Directive on 'green' innovation and vehicle recovery. *Journal of Cleaner Production*, 15:17-27.
- Gibert, J.P., Cuesta, J.M.L., Bergeret, A., and Crespy, A. (2000). Study of the degradation of fire-retarded PP/PE copolymers using DTA/TGA coupled with FTIR. *Polymer Degradation and Stability*, 67:437-447.
- Giesse, R. and De Paoli, M.A. (1988). Surface and bulk oxidation of low-density polyethylene under UV-irradiation. *Polymer Degradation and Stability*, 21:181-187.
- Gilman, J.W., Jackson, C.L., Morgan, A.B., Harris, R., Manias, E., Giannelis E.P., Wuthenow, M., Hilton, D., and Phillips, S.H. (2000). Flammability properties of polymer-layered-silicate nanocomposites - Polypropylene and polystyrene nanocomposites. *Chemistry of Materials*, 12:1866-1873.
- Giraldi, A.L.F.de M., Bartoli, J.R., Velasco, J.I., and Mei, L.H.I. (2005). Glass fibre recycled poly(ethylene terephthalate) composites: mechanical and thermal properties. *Polymer Testing*, 24:507-512.
- Glockner, G. (1968). Polycarbonate degradation under processing conditions. *Plaste Kaut*, 15:632-635.
- Goitisoló, I., Eguiazabal, J.I., and Nazabal, J. (2008). Effects of reprocessing on the structure and properties of polyamide 6 nanocomposites. *Polymer Degradation and Stability*, 93:1747-1752.
- Golebiewski, J., and Galeski, A. (2007). Thermal stability of nanoclay polypropylene composites by simultaneous DSC and TGA. *Composites Science and Technology*, 67:3442-3447.
- González-González, V.A., Neira-Velázquez, G. and Angulo-Sánchez, J.L. (1998). Polypropylene chain scissions and molecular weight changes in multiple extrusion.

- Polymer Degradation and Stability*, 60: 33-42.
- Gorrasi, G., Di Maio, L., Vittoria, V. and Acierno, D. (2002). Recycling polyethylene from automotive fuel tanks. *Journal of Applied Polymer Science*, 86: 347-351.
- Gorrasi, G., Tortora, M., Vittoria, V., Galli, G., and Chiellini, E. (2002). Transport and mechanical properties of blends of poly(ϵ -caprolactone) and a modified montmorillonite–poly(ϵ -caprolactone) nanocomposite. *Journal of Polymer Science Part B: Polymer Physics*, 40: 1118-1124.
- Gosukonda, R., Mahapatra, A.K., Liu, X., and Kannan, G. (2015). Application of artificial neural network to predict *Escherichia coli* O157:H7 inactivation on beef surfaces. *Food Control*, 47: 606-614.
- Goto, M., Sasaki, M., and Hirose, T. (2006). Reactions of polymers in supercritical fluids for chemical recycling of waste plastics. *Journal of Materials Science*, 41: 1509-1515.
- Garcia-Lopez, D., Picazo, O., Merino, J.C., and Pastor, J.M. (2002). Polypropylene – clay nanocomposites: effect of compatibilizing agents on clay dispersion. *European Polymer Journal*, 39: 945-950.
- Graham, P., Yernaux, J., Dupont, S., and DeCannière, J. (2000). Post-Consumer Plastic Fuel Tank Recycling. *SAE Technical Paper*.
- Gramsch, E., Cereceda-Balic, F., Oyola, P. and Baer, D. (2006). Examination of pollution trends in Santiago de Chile with cluster analysis of PM10 and ozone data. *Atmospheric Environment*, 40: 5464-5475.
- Grassie, N. (1956). Chemistry of high polymer degradation processes, London, Butterworths Scientific Publications.
- Grassie, N. and McNeill, I.C. (1958). Thermal degradation of polymethacrylonitrile. IV. Formation and decomposition of ketene-imine structures. *Journal of Polymer Science*, 33: 171-182.
- Grassie, N. and McNeill, I.C. (1959). Thermal degradation of polymethacrylonitrile. Part V. The mechanism of the initiation step in coloration reactions. *Journal of Polymer Science*, 39(135): 211-222.
- Greenwood, J.H. (1997). Life prediction in polymers. ERA Technology Report No.97-0782R.
- Groom, L.H., Shaler, S.M. and Mott, M. (1995). The mechanical properties of individual lignocellulosic fibres. In: Virgin and recycled wood fiber and polymers for composites. *Proceedings of the Third Woodfiber-Plastic Composites*

- Conference*, Madison, USA, 1-2: 33–40.
- Groning, M. and Hakkarainen, M. (2002). Headspace solid-phase microextraction with gas chromatography/mass spectrometry reveals a correlation between the degradation product pattern and changes in the mechanical properties during the thermooxidation of in-plant recycled polyamide 66. *Journal of Applied Polymer Science*, 86:3396-3407.
- Grosso, C., Ferreres, F., Gil-Izquierdo, A., Valentão, P., Sampaio, M., Lima, J., and Andrade, P.B. (2014). Box–Behnken factorial design to obtain a phenolic-rich extract from the aerial parts of *Chelidonium majus* L. *Talanta*, 130:128-136.
- Guan, C., Jiang, Z.B., He, S.Y., Zhang, J., Jiang, H. (2009). Industry Status and Prospect of Plastics Recycling in China (in Chinese). *Plastics*, 38: 36-38.
- Guerrica-Echevarría, G., Eguiazábal, J.I. and Nazábal, J. (1996). Effects of reprocessing conditions on the properties of unfilled and talc-filled polypropylene. *Polymer Degradation and Stability*, 53: 1-8.
- Gug, J., Cacciola, D., and Sobkowicz, M.J. (2015). Processing and properties of a solid energy fuel from municipal solid waste (MSW) and recycled plastics. *Waste Management*, 35:283-292.
- Gugumus, F. (1994). Mechanisms of thermooxidative stabilisation with HAS. *Polymer Degradation and Stability*, 44:299-322.
- Guo, B.H. and Chan, C.M. (1999). Chain extension of poly(butylene terephthalate) by reactive extrusion. *Journal of Applied Polymer Science*, 71:1827-1834.
- Haghighi-Yazdi, M., Tang, J.K.Y., and Lee-Sullivan, P. (2011). Moisture uptake of a polycarbonate blend exposed to hygrothermal aging. *Polymer Degradation and Stability*, 96:1858-1865.
- Haghdadi, N., Zarei-Hanzaki, A., Khalesian, A.R., and Abedi, H.R. (2013). Artificial neural network modeling to predict the hot deformation behavior of an A356 aluminum alloy. *Materials & Design*, 49: 386-391.
- Hamskog, M., Klügel, M., Forsström, D., Terselius, B., and Gisman, P. (2004). The effect of base stabilisation on the recyclability of polypropylene as studied by multi-cell imaging chemiluminescence and microcalorimetry. *Polymer Degradation and Stability*, 86:557-566.
- Hamzehlou, S. and Katbab, A. (2007). Bottle-to-bottle

- recycling of PET via nanostructure formation by melt intercalation in twin screw compounder: Improved thermal, barrier, and microbiological properties. *Journal of Applied Polymer Science*, 106: 1375-1382.
- Hao, Y.H., Wang, Y.J. and Zhao, J.J. (2011). Grey system model with time lag and application to simulation of karst spring discharge. *Grey Systems: Theory and Application*, 1: 47-56.
- Haralabakopoulos, A.A., Tsiourvas, D. and Paleos, C.M. (1999). Chain extension of poly(ethylene terephthalate) by reactive blending using diepoxides. *Journal of Applied Polymer Science*, 71: 2121-2127.
- Harder, M.K., Forton, O.T. (2007). A critical review of developments in the pyrolysis of automotive shredder residue. *Journal of analytical and applied pyrolysis*, 79(1-2): 387-394.
- Hechang, 2011. PA707K material data sheet from supplier: Yuyao Hechang Plastic Trade co.ltd, available: <http://detail.china.alibaba.com/offer/1138794821.html>.
- Heeger, A.J., Kivelson, S., Schrieffer, J.R. and Su, W.-P. (1988). Solitons in conducting polymers. *Reviews of Modern Physics*, 6: 781-850.
- Hermanová, S., Tocháček, J., Jančář, J., and Kalfus, J. (2009). Effect of multiple extrusion on molecular structure of polypropylene impact copolymer. *Polymer Degradation and Stability*, 94: 1722-1727.
- Hinsken, H., Moss, S., Pauquet, J. and Zweifel, Z. (1991). Degradation of polyolefins during melt processing. *Polymer Degradation and Stability*, 34: 279-293.
- Holmström, A. and Sörvik, E.M. (1977). Thereto-oxidative degradation of polyethylene. IV. Blends containing poly(vinyl chloride) and chlorinated polyethylene as models for polyethylene recycle qualities. *Polymer Engineering and Science*, 17: 700-705.
- Homkhiew, C., Ratanawilai, T., and Thongruang, W. (2014). The optimal formulation of recycled polypropylene/rubberwood flour composites from experiments with mixture design. *Composites Part B: Engineering*, 56: 350-357.
- Hong, C.K., Kim, M.J., Oh, S.H., Lee, Y.S., and Nah, C. (2008). Effects of polypropylene-g-(maleic anhydride/styrene) compatibiliser on mechanical and rheological properties of polypropylene/clay nanocomposites. *Journal of Industrial and Engineering Chemistry*, 14: 236-242.

- Hotelling, H. (1933). Analysis of a complex of statistical variables into principal components. *Journal of Educational Psychology*, 24: 417-441.
- Hsu, L.C. and Wang, C.H. (2009). Forecasting integrated circuit output using multivariate grey model and grey relational analysis. *Expert Systems with Applications*, 36: 1403-1409.
- Huang, J.T. and Lin, J.L. (2008). Optimisation of machining parameters setting of die-sinking EDM process based on the Grey relational analysis with L18 orthogonal array. *Journal of Technology*, 17: 659-664.
- Huang, K.Y. and Jane, C.J. (2009). A hybrid model for stock market forecasting and portfolio selection based on ARX, grey system and RS theories. *Expert Systems with Applications*, 36: 5387-5392.
- Huang, Y.P., Huang, C.C. and Hung, C.H. (1994). Determination of the preferred fuzzy variables and applications to the prediction control by the grey modeling. *The Second National Conference on Fuzzy Theory and Application*, Taiwan, 406-409.
- Hunter, S., Brooks, W., Duranceau, C.M., Gallmeyer, W.W., Williams, R.L. and Winslow, G.R. (2003). Stake digester process for HDPE fuel tank recycling. *SAE Paper*, 2003-01-1371.
- ICIS. (2011). Global plastics market to grow 5% a year until 2015 - BASF, <http://www.icis.com/Articles/2010/06/22/9370269/global-plastics-market-to-grow-5-a-year-until-2015-basf.html>.
- Inata, H. and Matsumura, S. (1987). Chain extenders for polyesters. IV. Properties of the polyesters chain-extended by 2,2'-bis(2-oxazoline). *Journal of Applied Polymer Science*, 33: 3069-3079.
- Incarnato, L., Scarfato, P., Di Maio, L. and Acierno, D. (2000). Structure and rheology of recycled PET modified by reactive extrusion. *Polymer*, 41: 6825-6831.
- International Organization for Standardisation. (2002). ISO 22628, Road vehicles recyclability and recoverability calculation method, first ed., 02-15.
- ISO 178: 2010. Plastics - Determination of flexural properties, published by the International Organization for Standardisation (ISO), 2010.
- ISO 179-2: 2010. Plastics - Determination of Charpy impact properties - Part 2: Instrumented impact test, published by the International Organization for Standardisation (ISO),

- 2010.
- ISO 1133-1:2011. Plastics - Determination of the melt mass-flow rate (MFR) and the melt volume-flow rate (MVR) of thermoplastics, published by the International Organization for Standardisation (ISO), 2011.
- ISO 1183-3:1999. Plastics - Methods for determining the density of non-cellular plastics - Part 3: Gas pyknometer method, published by the International Organization for Standardisation (ISO), 1999.
- ISO 1873-2:2007. Plastics - Polypropylene (PP) moulding and extrusion materials - Part 2: Preparation of test specimens and determination of properties, published by the International Organization for Standardisation (ISO), 2007.
- ISO 2602:1980. Statistical interpretation of test results - Estimation of the mean -- Confidence interval, published by the International Organization for Standardisation (ISO), 1980.
- ISO 3451-1:2008. Plastics - Determination of ash Part 1: General methods, published by the International Organization for Standardisation (ISO), 2008.
- ISO 291:2008. Plastics - Standard atmospheres for conditioning and testing, published by the International Organization for Standardisation (ISO), 2008.
- ISO 527-1:2012. Plastics - Determination of tensile properties Part 1: General principles, published by the International Organization for Standardisation (ISO), 2012.
- ISO 527-2:2012. Plastics - Determination of tensile properties - Part 2: Test conditions for moulding and extrusion plastics, published by the International Organization for Standardisation (ISO), 2012.
- ISO 75-2:2004. Plastics - Determination of temperature of deflection under load - Part 2: Plastics and ebonite published by the International Organization for Standardisation (ISO), 2004.
- Jafari, S., Kalati-vahid, A., Khonakdar, H., Asadinezhad, A., Wagenknecht, U., and Jehnichen, D. (2012). Crystallization and melting behaviour of nanoclay containing polypropylene/poly (trimethylene terephthalate) blends. *Polymer Letters*, 6: 148-158.
- Jain, A.K., Murty, M.N. and Flynn, P.J. (1999). Data clustering: a review. *ACM Computing Surveys*, 31: 264-323.
- Jane, J.L., Schwabacher, A.W.N., Ramrattan, S.N. and Moore, J.A. (1992). US Patent 5,115,000 (In Vaidya, U.R., Bhattacharya, M., 1994. Properties of blends of starch and

- synthetic polymers containing anhydride groups. *Journal of Applied Polymer Science*, 52:617-628.
- Jang, B.C., Huh, S.Y., Jang, J.G. and Bae, Y.C. (2001). Mechanical properties and morphology of the modified HDPE/starch reactive blend. *Journal of Applied Polymer Science*, 82:3313-3320.
- Jayaraman, K. and Bhattacharya, D. (2004). Mechanical performance of wood fibre-waste plastic composite materials. *Resources Conservation and Recycling*, 41:307-319.
- Jenseit, W., Stahl, H. and Wollny, W. (2003). Recovery Options for Plastic Parts from End-of-Life Vehicles an Eco-Efficiency Assessment. APME Report Ref. No. 8041/GB/08/03, <http://www.oeko-institut.org>.
- Jiang, X., Kolstein, H., and Bijlaard, F.S.K. (2012). Moisture diffusion and hygrothermal aging in pultruded fibre reinforced polymer composites of bridge decks. *Materials & Design*, 37:304-312.
- Jody, J.B. and Daniels, J.E. (1991). Automobile Shredder Residue: Treatment Options. *Hazardous Waste and Hazardous Materials*, 8:219-230.
- Joliffe, I.T. (2002). Principal component analysis (second ed.). New York: Springer.
- Joyson, 2011. Personal communication with general manager of Ningbo Preh Joyson Automotive Electronics Co. Ltd. on 23/03/2011 and 12/09/2011.
- Ju, X., Cheng, M., Xia, Y., Quo, F., and Tian, Y. (2014). Support Vector Regression and Time Series Analysis for the Forecasting of Bayannur's Total Water Requirement. *Procedia Computer Science*, 31:523-531.
- Kalfoglou, N.K. and Chaffey, C.E. (1979). Effects of extrusion on the structure and properties of high-impact polystyrene. *Polymer Engineering and Science*, 19:552-557.
- Kamdem, D.P.J.H., Cui, W., Freed, J. and Matuana, L.M. (2004). Properties of wood plastic composites made of recycled HDPE and wood flour from CCA-treated wood removed from service. *Composites Part A: Applied Science and Manufacturing*, 35:347-355.
- Kanari, M., Pineau, J.L. and Shallari, S. (2003). End-of-life vehicle recycling in the European union. *Journal of the Minerals, Metals and Materials Society*, 55:15-19.
- Kang, B.S., Kim, S.G. and Kim, J.S. (2008). Thermal degradation of poly(methyl methacrylate) polymers: kinetics and recovery of monomers using a fluidized bed

- reactor. *Journal of Analytical and Applied Pyrolysis*, 81(1): 7-13.
- Kang, J.J. and Zhao, H.J. (2012). Application of improved grey model in long-term load forecasting of power engineering. *Systems Engineering Procedia*. 3:85-91.
- Karayannidis, G.P., Kokkalas, D.E. and Bikiaris, D.N. (1995). Solid-state polycondensation of poly(ethylene terephthalate) recycled from postconsumer soft-drink bottles. II. *Journal of Applied Polymer Science*, 56: 405-410.
- Karayannidis, G.P. and Psalida, E.A. (2000). Chain extension of recycled poly(ethylene terephthalate) with 2,2'-(1,4-phenylene)bis(2-oxazoline). *Journal of Applied Polymer Science*, 77:2206-2211.
- Karian, H. (2003). *Handbook of Polypropylene and Polypropylene Composites, Revised and Expanded*. New York: Marcel Dekker.
- Karimi-Varzaneh, H.A., Carbone, P. and Mueller-Plathe, F. (2008). Hydrogen Bonding and Dynamic Crossover in Polyamide-66: A Molecular Dynamics Simulation Study. *Macromolecules*, 41:7211-7218.
- Kayacan, E., Ulutas, B. and Kaynak, O. (2010). Grey system theory-based models in time series prediction. *Expert Systems with Applications*, 37:1784-1789.
- Kemsley, E.K. (1996). Discriminant analysis of high-dimensional data: a comparison of principal components analysis and partial least squares data reduction methods. *Chemometrics and Intelligent Laboratory Systems*, 33:47-61.
- Kerboua, N., Cinausero, N., Sadoun, T., and Lopez-Cuesta, J. (2010). Effect of organoclay in an immiscible poly (ethylene terephthalate) waste/poly (methyl methacrylate) blend. *Journal of Applied Polymer Science*, 117:129-137.
- Khattab, A.A. and El-Zoghby, A.A. (1998). Effect of recycling on the mechanical properties of low density polyethylene. *Journal of Engineering and Applied Science*, 45:533-547.
- Kiliaris, P., and Papaspyrides, C.D. (2010). Polymer/layered silicate (clay) nanocomposites: An overview of flame retardancy. *Progress in Polymer Science*, 35:902-958.
- Kim, H.S., Lee, B.H., Choi, S.W., Kim, S., and Kim, H.J. (2007). The effect of types of maleic anhydride-grafted polypropylene (MAPP) on the interfacial adhesion properties of bio-flour-filled polypropylene composites. *Composites Part A: Applied Science and Manufacturing*, 38: 1473-1482.
- Kirilova, E.I. and Shulgina, E.S. (1988). Aging and

- stabilisation of thermoplasts. Leningrad: Chemistry.
- Klemchuk, P.P. and Thompson, T. (1992). Stabilisation of Recycled Plastics. *Emerging Technologies in Plastics Recycling*, ACS Symposium Series, 513:74-87.
- Komitov, P., Kostov, G. and Stanchev, S. (1989). Ageing of LDPE: Structural changes. *Polymer Degradation and Stability*, 24:303-312.
- Kostadinova, M., Proietto, M., Jilov, N. and La Mantia, F.P. (1997). Recycling of high density polyethylene containers. *Polymer Degradation Stability*, 57:77-81.
- Kovács, F., Legány, C. and Babos, A. (2006). Cluster validity measurement techniques. *Proceedings of the fifth WSEAS International Conference on Artificial Intelligence, Knowledge Engineering and Data Bases*, Madrid, Spain, 388-393.
- Kumar, U., and Jain, V.K. (2010). Time series models (Grey-Markov, Grey Model with rolling mechanism and singular spectrum analysis) to forecast energy consumption in India. *Energy*, 35:1709-1716.
- La Mantia, F.P. and Capizzi, L. (2001). Recycling of compatibilised and uncompatibilised nylon/polypropylene blends. *Polymer Degradation and Stability*, 71:285-291.
- La Mantia, F.P., Curto, D. and Scaffaro, R. (2002). Recycling of dry and wet polyamide 6. *Journal of Applied Polymer Science*, 86:1899-1903.
- Labidi, S., Azema, N., Perrin, D., and Lopez-Cuesta, J.M. (2010). Organo-modified montmorillonite/poly(ϵ -caprolactone) nanocomposites prepared by melt intercalation in a twin-screw extruder. *Polymer Degradation and Stability*, 95:382-388.
- Landrock, A.H. (1983). *Handbook of Plastics Flammability and Combustion Toxicology*. New Jersey: Noyes publication.
- Lazzeri, A., Zabarjad, S.M., Pracella, M., Cavalier, K., and Rosa, R. (2005). Filler toughening of plastics. Part 1 - The effect of surface interactions on physico-mechanical properties and rheological behaviour of ultrafine CaCO₃/HDPE nanocomposites. *Polymer*, 46:827-844.
- Lederer, K., Tranninger, M., Otte, M. and Kastner, E. (2010). Polypropylene/talc composition with improved impact behavior. European Patent EP2010017045720100722. <http://worldwide.espacenet.com/publicationDetails/biblio?CC=EP&NR=2410007A1&KC=A1&FT=D>.
- Lee, N.J. and Jang, J. (1999). The effect of fibre content on the mechanical properties of glass fibre mat/polypropylene

- composites. *Composites Part A: Applied Science and Manufacturing*, 30:815-822.
- Lee, Y.S. and Tong, L.I. (2011). Forecasting energy consumption using a grey model improved by incorporating genetic programming. *Energy Conversion and Management*, 52:147-152.
- Lei, Y., Wu, Q., and Clemons, C.M. (2007). Preparation and properties of recycled HDPE/clay hybrids. *Journal of Applied Polymer Science*, 103:3056-3063.
- Leidner, J. (1981). *Plastics Waste*, Marcel Dekker Inc, New York.
- Lertwimolnun, W., and Vergnes, B. (2006). Effect of processing conditions on the formation of polypropylene/organoclay nanocomposites in a twin screw extruder. *Polymer Engineering and Science*, 46:314-323.
- Li, Y.G., Li, Q.F. and Zhao, G.F. (1992). An improvement on grey forecasting model. *Systems Engineering*, 10:27-31.
- Liao, S.J., Chang, D.Y., Chen, H.J., Tsou, S.J., Ho, J.R., Yau, H.T., Hsieh, W.H., Wang, H.T. and Su, Y.C. (2004). Optimal process conditions of shrinkage and warpage of thin-wall parts. *Polymer Engineering and Science*, 44:917-928.
- Liao, Z.P. (2007). The Review of Chinese Plastics Industry of the Year 2006 and the Trend of Integration of Plastics (in Chinese),
<http://plastic.nstl.gov.cn/commChannel/content.asp?contentid = 160326>
- Liao, Z.P. (2009). The Status of Chinese Plastics Manufacture Industry and Application of Plastics in Automobile (in Chinese),
<http://www.cppia.com.cn/cppia1/zdbd/20094395929.htm>
- Lindahla, P., Robèrta, K.H., Nya, H. and Bromana, G. (2014). Strategic sustainability considerations in materials management. *Journal of Cleaner Production*. 64:98-103.
- Liu, B., Zhao, L., Zhai, Z.J., Dang, Y.G. and Zhang, R. (2003). Optimum model of GM(1, 1) and its suitable range. *Journal of Nanjing University of Aeronautics and Astronautics*, 35:451-454.
- Liu, S.P. and Liang, C.W. (2011). Preparation and mechanical properties of polypropylene/montmorillonite nanocomposites - After grafted with hard/soft grafting agent. *International Communications in Heat and Mass Transfer*, 38:434-441.
- Liu, S.P. and Xu, J.F. (2011). Characterisation and mechanical properties of high density polyethylene/silane

- montmorillonite nanocomposites. *International Communications in Heat and Mass Transfer*, 38:734-741.
- Liu, Y.F. and Li, Q. (2006). Super fine talc powder reinforced PP R pipe material. China Patent, CN200614575420060126. <http://worldwide.espacenet.com/publicationDetails/biblio?CC=CN&NR=100365049C&KC=C&FT=D>
- Liu, Z.Q., Cunha, A.M., Yi, X.S. and Bernardo, A.C. (2000). Key properties to understand the performance of polycarbonate reprocessed by injection molding. *Journal of Applied Polymer Science*, 77:1393-1400.
- Long, T.S. and Sokol, R.J. (1974). Molding polycarbonate: Moisture degradation effect on physical and chemical properties. *Polymer Engineering and Science*, 14:817-822.
- Long, Y., Tiganis, B.E. and Shanks, R.A. (1995). Evaluation of recycled PP/rubber/talc hybrids. *Journal of Applied Polymer Science*. 58:527-535.
- Loontjens, T., Pauwels, K., Derks, F., Neilen, M., Sham, C.K. and Serné, M. (1997). The action of chain extenders in nylon-6, PET, and model compounds. *Journal of Applied Polymer Science*, 65:1813-1819.
- Lozano-Gonzalez, M.A.J., Rodriguez-Hernandez, M.A.T., Gonzalez-De los Santos, E.A. and Villalpando-Olmos, J. (2000). Physical–mechanical properties and morphological study in nylon-6 recycling by injection molding. *Journal of Applied Polymer Science*, 76:851-858.
- Lu, J.Z., Wu, Q. and Negulescu, I.I. (2005). Wood–fiber/High-Density-Polyethylene Composites: coupling agent performance. *Journal of Applied Polymer Science*, 96:93–102.
- Lu, L., Yu, H.Y., Wang, S.F. and Zhang, Y. (2009). Thermal degradation behavior of styrene-butadiene-styrene tri-block copolymer/multiwalled carbon nanotubes composites. *Journal of Applied Polymer Science*, 112:524-531.
- Lu, S.Y., and Hamerton, I. (2002). Recent developments in the chemistry of halogen-free flame retardant polymers. *Progress in Polymer Science*, 27:1661-1712.
- Luda, M.P., Ragosta, G., Musto, P., Acierno, D., Di Maio, L., Camino, G. and Nepote, V. (2003). Regenerative recycling of automotive polymer components: poly(propylene) based car bumpers. *Macromolecular Materials and Engineering*, 288:613-620.
- Lv, X., Wang, R., Liu, W., and Jiang, L. (2011). Surface and interface properties of carbon fiber composites under

- cyclical aging. *Applied Surface Science*, 257:10459-10464.
- Ma, Z.F. and Zhang, B. (2009). China Plastics Recycling Industry in 2008 (in Chinese). *China Plastics*, 23:1-5.
- Malinowski, E.R. (1991). Factor Analysis in Chemistry. New York: John Wiley & Sons.
- Makuta, M., Moriguchi, Y., Yasuda, Y. and Sueno, S. (2000). Evaluation of the effect of automotive bumper recycling by life-cycle inventory analysis. *Journal of Material Cycles and Waste Management*, 2: 125-137.
- Manders, P.W. and Bader, M.G. (1981). The strength of hybrid glass/carbon fibre composites. *Journal of Materials Science*. 16:2233-2245.
- Manly, B.F.J. (1994). Multivariate Statistical Methods-A Primer(second ed). London: Chapman & Hall.
- Mao, M.Z. and Chirwa, E.C. (2006). Application of grey model GM(1, 1) to vehicle fatality risk estimation. *Technological Forecasting and Social Change*, 73:588-605.
- Marsh, G. (2006). "50 years of reinforced plastic boats". <http://www.reinforcedplastics.com/view/1461/50-years-of-reinforced-plastic-boats/>
- Martins, A.F., Pereira, R.A. and Mano, E.B. (2000). Recycled car bumpers' impact resistance investigated by wide-angle X-ray diffraction. *Journal of Applied Polymer Science*, 75: 999-1004.
- Martin, L., Kortaberria, G., Vazquez, A., Fermeglia, M., Martinelli, L., Sinesi, S., Jimeno, A., de la Caba, K., and Mondragon, I. (2008). A comparator study of nanocomposites based on a recycled poly (methyl methacrylate) matrix containing several nanoclays. *Polymer Composites*, 29:782-790.
- Maspoch, M.L., Ferrando, H.E. and Velasco, J.I. (2003). Characterisation of filled and recycled PA6. *Macromolecular Symposia*, 194:295-303.
- McKenna, J.E. (2003). An enhanced cluster analysis program with bootstrap significance testing for ecological community analysis. *Environmental Modeling & Software*. 18:205-220.
- McMeekin, T.A., Olley, D.A., Ratkowsky, D.A., and Ross, T. (2002). Predictive microbiology: towards the interface and beyond. *International Journal of Food Microbiology*, 73:395-407.
- Meglen, R.R. (1992). Examining large databases: a chemometric approach using principal component analysis. *Marine Chemistry*, 39:217-237.
- Mehat, N.M. and Kamaruddin, S. (2011). Optimisation of

- mechanical properties of recycled plastic products via optimal processing parameters using the Taguchi method. *Journal of Materials Processing Technology*, 211:1989-1994.
- Meikle, J.L. (1995). *American Plastic: A Cultural History*. New Brunswick: Rutgers University Press.
- Mendes, A.A., Cunha, A.M. and Bernardo, C.A. (2011). Study of the degradation mechanisms of polyethylene during reprocessing. *Polymer Degradation and Stability*, 96(6):1125-1133.
- Mendiguchía, C., Moreno, C., Galindo-Riaño, M.D. and García-Vargas, M. (2004). Using chemometric tools to assess anthropogenic effects in river water: a case study: Guadalquivir River. *Analytica Chimica Acta*, 515:143-149.
- Miller, N.A., Jones, M.S., and Stirling, C.D. (1998). Waste plastics/cellulose fibre composites. *Polymers & Polymer Composites*, 6:97-102.
- Minth. (2012). Personal communication with workshop manager of Ningbo Tokai Minth Automotive Parts Co., Ltd. on 21/05/2012.
- Mitsuyoshi, F., and Tetsuo, W. (1991). As Distribution of higher-order structures in injection-molded polypropylenes. *Journal of Applied Polymer Science*, 43:57-81.
- Mitterhofer, F. (1978). Stabilising Systems for the Recycling of Plastics. *Plastverarbeiter*, 29(12):670-672.
- Mitterhofer, F. (1980). Processing stability of polyolefins. *Polymer Engineering and Science*, 20(10):692-695.
- Mngomezulu, M.E., John, M.J., Jacobs, V., and Luyt, A.S. (2014). Review on flammability of biofibres and biocomposites. *Carbohydrate Polymers*, 111:149-182.
- Mnif, N., Massardier, V., Kallel, T., and Elleuch, B. (2010). New (PP/EPR)/nano-CaCO₃ based formulations in the perspective of polymer recycling. Effect of nanoparticles properties and compatibilizers. *Polymers for Advanced Technology*. 21:896-903.
- MoDiP. (2013). *Plastics timeline*, by the Museum of Design in Plastics (MoDiP)
http://www.modip.ac.uk/resources/curators_guide/plastic_s_timeline, retrieved on July, 2013.
- Mok, P.Y., Huang, H.Q., Kwok, Y.L. and Au, J.S. (2012). A robust adaptive clustering analysis method for automatic identification of clusters. *Pattern Recognition*, 45:3017-3033.
- Moore, E.P. (1996). *Polypropylene Handbook - Polymerization*,

- Characterisation, Properties, Processing, Applications. New York: Hanser Publishers.
- Moss, S. and Zweifel, H. (1989). Degradation and stabilisation of high density polyethylene during multiple extrusions. *Polymer Degradation and Stability*, 25(24):217-245.
- Mukherjee, P.S. and Sathyanarayana, K.G. (1986). An empirical evaluation of structure-property relationships in natural fibres and their fracture behaviour. *Journal of Material Science*, 21(12):4162-4168.
- Norris, M., and Lecavalier, L. (2009). Evaluating the Use of Exploratory Factor Analysis in Developmental Disability Psychological Research. *Journal of Autism and Developmental Disorders*, 40:8–20.
- Nunes dos Santos, W., Agnelli, J.A.M., Mummery, P., and Wallwork, A. (2007). Effect of recycling on the thermal properties of polymers. *Polymer Testing*, 26:216-221.
- Ohori, N., Suyama, T., Yamamoto, N. and Yagi, N. (1996). A study of recycling technology for paint-coated plastic automotive bumper. *JSAE Review*, 17(4):414-416.
- OICA. (2011).
<http://www.oica.net/category/production-statistics/>
- Oktem, H., Erzurumlu, T. and Uzman, I. (2007). Application of Taguchi optimisation technique in determining plastic injection moulding process parameters for a thin-shell part. *Materials and Design*, 28:1271-1278.
- Oromiehie, A. and Mamizadeh, A. (2004). Recycling PET beverage bottles and improving properties. *Polymer international*, 53:728-732.
- Orr, W.W., 2000. USCAR U.S. Field Trial for Automotive Polymers Recycling: Interim Findings. *SAE Paper*, Number 2000-01-0735.
- Ozcelik, B. and Erzurumlu, T. (2006). Comparison of the warpage optimisation in the plastic injection moulding using ANOVA, neural network model and genetic algorithm. *Journal of Material Processing Technology*, 171:437-445.
- Ozcelik, B. and Sonat, I. (2009). Warpage and structural analysis of thin shell plastic in the plastic injection moulding. *Materials and Design*, 30:367-375.
- Panero, F.S. and da Silva, H.E.B. (2008). Application of exploratory data analysis for the characterisation of tubular wells of the North of Brazil. *Microchemical Journal*, 88:194-200.
- Pao, S.T., Fu, H.C. and Tseng, C.L. (2012). Forecasting of CO₂ emissions, energy consumption and economic growth in

- China using an improved grey model. *Energy*, 40: 400-409.
- Park, A.H. (1996). Robust design and analysis for quality engineering. London: Chapman & Hall.
- Pavlidou, S. and Papaspyridesb, C.D. (2008). A review on polymer-layered silicate nanocomposites. *Progress in Polymer Science*, 33: 1119-1198.
- Pearson, K. (1901). On lines and planes of closest fit to systems of points in space. *Philosophical Magazine*, 2: 559-572
- Pedroso, A.G. and Rosa, D.S. (2005). Mechanical, thermal and morphological characterisation of recycled LDPE/corn starch blends. *Carbohydrate Polymers*, 59: 1-9.
- Pérez, J.M., Vilas, J.L., Laza, J.M., Arnáiz, S., Mijangos, F. and Bilbao, E. (2010). Effect of reprocessing and accelerated ageing on thermal and mechanical polycarbonate properties. *Journal of Materials Processing Technology*, 210: 727-733.
- Pfaendner, R., Herbst, H. and Hoffmann, K. (1998). Innovative concept for the upgrading of recyclates by restabilisation and repair molecules. *Macromolecular Symposia*, 135: 97-111.
- Plastics Alchemy-Recycling. (2009). Chemistry world.
- Pontes, M., Marques, J.C. and Camara, J.S. (2009). Headspace solid-phase microextraction-gas chromatography-quadrupole mass spectrometric methodology for the establishment of the volatile composition of Passiflora fruit species. *Microchemical Journal*, 93: 1-11.
- Pospíšil, J. (1993). Chemical and photochemical behaviour of phenolic antioxidants in polymer stabilisation-a state of the art report, Part I. *Polymer Degradation and Stability*, 40: 217-232.
- Pospíšil, J., Sitek, F.A. and Pfaendner, R. (1995). Upgrading of recycled plastics by restabilisation-an overview. *Polymer Degradation and Stability*, 48: 351-358.
- Pospíšil, J., Neprek, S., Pfaendner, R. and Zweifel, H. (1997). Material recycling of plastics waste for demanding applications : Upgrading by restabilisation and compatibilisation. *Trends in Polymer Science*, 5: 294-300.
- Pospíšil, J., Fortelný, I., Michálková, D., Kruliš, Z. and Šlouf, M. (2005). Mechanism of reactive compatibilisation of a blend of recycled LDPE/HIPS using an EPDM/SB/aromatic diamine co-additive system. *Polymer Degradation and Stability*, 90: 244-249.

- Rabek, J.F. (1995). Polymer photodegradation: mechanisms and experimental methods, Chapman and Hall.
- Rabek, J.F. (1996). Photodegradation of Polymers: Physical Characteristics and Applications. Berlin: Springer-Verlag.
- Ragosta, G., Musto, P., Martuscelli, E., Russo, P. and Zeloni, L. (2000). Recycling of plastic car components: The case of a multilayer item based on polypropylene. *Journal of Materials Science*, 35(15):3741-3751.
- Raj, R.G. and Kokta, B.V. (1991). Reinforcing high-density polyethylene with cellulosic fibers I: The effect of additives on fiber dispersion and mechanical properties. *Polymer Engineering and Science*, 31:1358-1362.
- Ramírez-Vargas, E., Navarro-Rodríguez, D., Blanqueto-Menchaca, A.I., Huerta-Martínez, B.M. and Palacios-Mezta, M. (2004). Degradation effects on the rheological and mechanical properties of multi-extruded blends of impact-modified polypropylene and poly(ethylene-co-vinyl acetate). *Polymer Degradation and Stability*, 86:301-307.
- Ranby, B. and Rabek, J.F. (1975). Photodegradation, Photo-oxidation and Photostabilisation of Polymers: Principles and Applications. John Wiley, London, pp. 1-119.
- Ranby, B. (1989). Photodegradation and photo-oxidation of synthetic polymers. *Journal of Analytical and Applied Pyrolysis*, 15:237-247.
- Ranzi, E., Dente, M., Faravelli, T., Bozzano, G., Fabini, S., Nava, R., Cozzani, V. and Tognotti, L. (1997). Kinetic modeling of polyethylene and polypropylene thermal degradation. *Journal of Analytical and Applied Pyrolysis*, 40-41:305-319.
- Rausa, R. and Pollesel, P. (1997). Pyrolysis of automotive shredder residue (ASR) - influence of temperature on the distribution of products. *Journal of Analytical and Applied Pyrolysis*, 40-41:383-401.
- Ray, S.S. and Okamoto, M. (2003). Polymer/layered silicate nanocomposites: a review from preparation to processing. *Progress in Polymer Science*, 28:1539-1641.
- Razi, P.S., Raman, A.R. and Portier, R. (1997). Studies on mechanical properties of wood-polymer composites. *Journal of Composite Materials*, 31:2391-2401.
- Read, B.E., Dean, G.D., and Tomlins, P.E. (1988). Effects of physical ageing on creep in polypropylene. *Polymer*, 29:2159-2169.
- Rex, I., Graham, B.A. and Thompson, M.R. (2005). Studying single-pass degradation of a high-density polyethylene in

- an injection molding process. *Polymer Degradation and Stability*, 90(1): 136-146.
- Rijsdijk, H.A., Contant, M. and Peijs, A.A.J.M. (1993). Continuous-glass-fibre-reinforced polypropylene composites: I. Influence of maleic-anhydride-modified polypropylene on mechanical properties. *Composites Science and Technology*, 48:161–172.
- Rodriguez, R.M., Martinez, L., and Herrera, F. (2012). Hesitant Fuzzy Linguistic Term Sets for Decision Making. *IEEE Transactions on Fuzzy Systems*, 20(1).
- Rongzhi, L., Lin, Y. and Wing, Y. (1997). Effect of polyethylene particle geometry on mechanical properties of compression moulded wood-polyethylene composites. *Plastics Rubber and Composites Processing and Applications*, 26(8):368-371.
- Rosales, C., Perera, R., Gonzalez, J., Ichazo, M., Rojas, H. and Sánchez, A. (1999). Grafting of polyethylenes by reactive extrusion. II. Influence on rheological and thermal properties. *Journal of Applied Polymer Science*, 73:2549-2567.
- Ross, P.J. (1996). Taguchi techniques for quality engineering. New York: McGraw-Hill.
- Roy, R.K. (1990) A Primer on the Taguchi Method. New York: Van Nostrand Reinhold.
- Samperi, F., Puglisi, C., Alicata, R. and Montaudo, G. (2004). Thermal degradation of poly(butylene terephthalate) at the processing temperature. *Polymer Degradation and Stability*, 83:11-17.
- Sánchez, P., Remiro, P.M. and Nazábal, J. (1992). Influence of reprocessing on the mechanical properties of a commercial polysulfone/polycarbonate blend. *Polymer Engineering and Science*, 32(13):861-867.
- Santos, A.S.F., Agnelli, J.A.M., Trevisan, D.W. and Manrich, S. (2002). Degradation and stabilisation of polyolefins from municipal waste during multiple extrusions under different reprocessing conditions. *Polymer Degradation and Stability*, 77:441-447.
- Sariciftci, N.S., Smilowitz, L., Heeger, A.J. and Wudl, F. (1992). Photoinduced Electron Transfer from a Conducting Polymer to Buckminsterfullerene. *Science*, 258:1474-1476.
- Scaffaro, R. and La Mantia, F.P. (2002). Characterisation of monopolymer blend of virgin and recycled polyamide 6. *Polymer Engineering and Science*, 42:2412-2417.
- Scaffaro, R., La Mantia, F.P., Botta, L., Morreale, M., Dintcheva,

- N.T. and Mariani, P. (2009). Competition between chain scission and branching formation in the processing of high-density polyethylene: effect of processing parameters and of stabilisers. *Polymer Engineering and Science*, 49:1316-1325.
- Scheirs, J. (1998). *Polymer Recycling*. New York: John Wiley & Sons.
- Schott, H. and Kaghan, W.S. (1963). Viscous flow and degradation of molten polypropylene. *Polymer Engineering and Science*, 3:145-151.
- Scott, G. (1999). *Polymers and the environment* (1st ed.). Cambridge: Royal Society of Chemistry.
- Seiler, E., 1995. *Properties and Applications of Recycled Polypropylene*. Recycling and Recovery of Plastics. New York: Carl Hanser Verlag.
- Selke, S.E. and Wichman, I. (2004). Wood fibre/polyolefin composites. *Composites Part A: Applied Science and Manufacture*, 35:321-326.
- Sellers, T., Miller, G.D. and Katabian, M. (2000). Recycled thermoplastics reinforced with renewable lignocellulosic materials. *Forest Products Journal*, 50:24-28.
- Severini, F., Ipsale, R.G.S. and Ricca, G. (1993). Environmental degradation of LDPE observed by UV spectroscopy. *Polymer Degradation and Stability*, 41:103-107.
- Shabani, I., Haddadi-Asl, V., Seyedjafari, E., and Soleimani, M., 2012. Cellular infiltration on nanofibrous scaffolds using a modified electrospinning technique. *Biochemical and Biophysical Research Communications*, 423:50-54.
- Shah, C.S., and Patni, M.J. (1994). Accelerated aging and life time prediction analysis of polymer composites: a new approach for a realistic prediction using cumulative damage theory. *Polymer Testing*, 13:295-322.
- Shahabadi, S. and Garmabi, H. (2012). Response surface analysis of structural, mechanical, and permeability properties of polyethylene/Na⁺-montmorillonite composites, prepared by slurry-fed melt intercalation. *Polymer Letters*, 6:657-671.
- Sharaf, M.A., Illman, D.L. and Kowalski, B.R. (1986). *Chemometrics*. New York: John Wiley and Sons.
- Shea, J.W., Nelson, C.J. and Cammons, R.R. (1975). The effects of recycling on the properties of injection molded polycarbonate. *SPE ANTEC Tech Papers*, 33:614-617.
- Shea, J.W., Nelson, C.J. and Cammons, R.R. (1977). Effects of

- composition, processing and environmental exposure on mechanical integrity of polycarbonate connectors. *SPE ANTEC Tech Papers*, 35:326-329.
- Shen, J.H. and Zhao, X.R. (2001). Improvement of GM(2, 1) model by minimum squares. *Journal of Harbin Engineering University*, 22:64-66.
- Shen, Z., Day, M., Cooney, J.D., Lu, G., Brien, C.L. and Bergougnou, M.A. (1995). Ultrapyrolysis of automobile shredder residue. *Canadian Journal of Chemical Engineering*, 73:357-366.
- Shi, G., He, L.J., Chen, C.Z., Liu, J.F., Liu, Q.Z., and Chen, H.Y. (2011). A novel nanocomposite based on recycled poly(ethylene terephthalate)/ABS blends and nano-SiO₂. *Advanced Materials Research*, 150:857-860.
- Shimada, J. and Kabuki, K. (1968). The mechanism of oxidative degradation of ABS resin. Part I. The mechanism of thermo-oxidative degradation. *Journal of Applied Polymer Science*, 12:655-669.
- Shiou, F.J. and Chen, C.H. (2003). Freeform surface finish of plastic injection mould using ball-burnishing process. *Journal of Materials Processing Technology*, 140:248-254.
- Shrestha, S. and Kazama, F. (2007). Assessment of surface water quality using multivariate statistical techniques: a case study of the Fuji river basin, Japan. *Environmental Modeling & Software*, 22:464-475.
- Silva Spinacé, M.A. and De Paoli, M.A. (2001). Characterisation of poly(ethylene terephthalate) after multiple processing cycles. *Journal of Applied Polymer Science*, 80:20-25.
- Simha, R. and Wall, L.A. (1952). Kinetics of chain depolymerization. *Journal of Physical Chemistry*, 56(6):707-715.
- Sims, G.L.A. and Angus, M.W. (1996). Recycling of automotive foam/fabric laminates by incorporation into rebonded polyurethane foam. *Cellular Polymers*, 15:436-449.
- Singh, K.P., Malik, A. and Sinha, S. (2005). Water quality assessment and apportionment of pollution sources of Gomti river (India) using multivariate statistical techniques-a case study. *Analytica Chimica Acta*, 538:355-374.
- Sirringhaus, H. (2005). Device Physics of Solution-Processed Organic Field-Effect Transistors. *Advanced Materials*, 17:2411-2425.

- Škrbić, B. and Đurišić-Mladenović, N. (2007). Principal component analysis for soil contamination with organochlorine compounds. *Chemosphere*, 68: 2144-2152.
- Slobodetskaya, Y.M., Magomedova, T.V., Karpukhin, O.N. and Protasov, V.G. (1982). Change in the physicochemical properties of polyethylene on photo-oxidation. *Polymer Science U.S.S.R.*, 24: 257-263.
- Sousa, S.I.V., Martins, F.G., Alvim-Ferraz, M.C.M. and Pereira, M.C. (2007). Multiple linear regression and artificial neural networks based on principal components to predict ozone concentrations. *Environmental Modeling & Software*, 22: 97-103.
- Spearman, C. (1904). General intelligence, objectively determined and measured. *American Journal of Psychology*, 15: 201-292.
- Stark, N.M. and Mautana, L.M. (2004). Surface chemistry and mechanical property changes of wood-flour/high-density-polyethylene composites after accelerated weathering. *Journal of Applied Polymer Science*, 94(6): 2263-2273.
- Staudinger, J. and Keoleian, G.A. (2001). Management of End-of-life Vehicles (ELVs) in the US, Rep. of the Center for Sustainable Systems, Michigan, USA, No. CSS01-01.
- Stevens, M.P. (1999). Polymer chemistry: an introduction (3rd ed.). Oxford: Oxford University Press.
- St-Pierre, N., Favis, B.D., Ramsay, B.A., Ramsay, J.A. and Verhoogt, H. (1997). Processing and characterisation of thermoplastic starch/-polyethylene blends. *Polymer*, 38: 647-655.
- Su, K.H., Lin, J.H. and Lin, C.C. (2007). Influence of reprocessing on the mechanical properties and structure of polyamide 6. *Journal of Materials Processing Technology*, 192-193: 532-538.
- Suk, H. and Lee, K. (1999). Characterisation of a ground water hydrochemical system through multivariate analysis: clustering into ground water zones. *Ground Water*, 37: 358-366.
- Summerscales, J. and Short, D. (1978). Carbon fibre and glass fibre hybrid reinforced plastics. *Composites*, 9: 157-166.
- Szeteiová, 2010. Plastics in Automotive markets today. http://www.mtf.stuba.sk/docs/internetovy_casopis/2010/3/szeteiova.pdf (visited on 10th, Oct, 2014)
- Szustakiewicz, K., Kiersnowski, A., Gazińska, M., Bujnowicz, K.

- and Pięłowski, J. (2011). Flammability, structure and mechanical properties of PP/OMMT nanocomposites. *Polymer Degradation and Stability*, 96:291-294.
- Taguchi, G. and Konishi, S. (1987). Taguchi methods, orthogonal arrays and linear graphs, tools for quality American supplier institute. American Supplier Institute. 8-35.
- Taguchi, G. (1990). Introduction to quality engineering. New York: McGraw-Hill.
- Tall, S., Albertsson, A.C. and Karlsson, S. (2001). Enhanced rigidity of recycled polypropylene from packaging waste by compounding with talc and high-crystallinity polypropylene. *Polymers for Advanced Technologies*, 12:279-284.
- Tang, X., Guo, W., Yin, G.R., Li, B.Y. and Wu, C.F. (2007). Reactive extrusion of recycled poly(ethylene terephthalate) with polycarbonate by addition of chain extender. *Journal of Applied Polymer Science*, 104:2602-2607.
- Tang, Y., Hu, Y., Zhang, R., Gui, Z., Wang, Z.Z., Chen, Z.Y., and Fan, W.C. (2004). Investigation on polypropylene and polyamide-6 alloys/montmorillonite nanocomposites. *Polymer*, 45:5317-5326.
- Tao, K.F., and Yau, K.W. (2007). Predicting electricity energy consumption: a comparison of regression analysis, decision tree and neural networks. *Energy*, 32:1761-1768.
- Tarantili, P.A., Mitsakaki, A.N. and Petoussi, M.A. (2010). Processing and properties of engineering plastics recycled from waste electrical and electronic equipment (WEEE). *Polymer Degradation and Stability*, 95:405-410.
- Thomason, J.L. (2002). The influence of fibre length and concentration on the properties of glass fibre reinforced polypropylene: 5. Injection moulded long and short fibre PP. *Composites Part A: Applied Science and Manufacturing*, 33:1641–1652.
- Thomason, J.L. and Schoolenberg, G.E. (1994). An investigation of glass fibre/polypropylene interface strength and its effect on composite properties. *Composites*, 25:197-203.
- Thorson, J.T. and Taylor, I.G. (2014). A comparison of parametric, semi-parametric, and non-parametric approaches to selectivity in age-structured assessment models. *Fisheries Research*, 158:74-83.
- Tidjani, A. and Arnaud, R. (1993). Photo-oxidation of linear low density polyethylene: A comparison of photoproducts formation under natural and accelerated exposure. *Polymer*

- Degradation and Stability*, 39:285-292.
- Tidjani, A., Arnaud, R. and Dasilva, A. (1993). Natural and accelerated photoaging of linear low-density polyethylene: changes of the elongation at break. *Journal of Applied Polymer Science*, 47:211-216.
- Tjantelé, M. (1991). Parameter design using the Taguchi methodology. *Microelectronic Engineering*, 10:277-286.
- Tocháček, J., Jančář, J., Kalfus, J., and Hermanová, S. (2011). Processing stability of polypropylene impact-copolymer during multiple extrusion - Effect of polymerization technology. *Polymer Degradation and Stability*, 96:491-498.
- Todd, R.H., Allen, D.K., and Alting, L. (1994). Manufacturing Processes Reference Guide. Industrial Press, Inc.
- Toshino, H., Ito, S., Honjo, K. and Suehiro. (2000). Manufacture of Instrumental Panel, GRAND, Polymer: KK, Honda Motor co Ltd., JP2000007792.
- Tosun, N. (2006). Determination of optimum parameters for multiperformance characteristics in drilling using grey relational analysis. *The International Journal of Advanced Manufacturing*, 28:450-455.
<http://www.freepatentsonline.com/JP2000007792.html>.
- Tri Phuong, N., Gilbert, V. and Chuong, B. (2008). Preparation of recycled polypropylene/organophilic modified layered silicates nanocomposites part I: the recycling process of polypropylene and the mechanical properties of recycled polypropylene/organoclay nanocomposites. *Journal of Reinforced Plastics and Composites*, 27:1983-2000.
- Troitzsch, J. (1983). International Plastics Flammability Handbook. New York: Hanser.
- UK Patent office. (1857). Patents for inventions. UK Patent office, p.255.
- UL-94. Underwriter Laboratories Inc.
http://www.anixtercomponents.com/images/uploads/UL94_Flammability_Tests.pdf. [visited on 19/10/2012]
- U.S.F.A. (2002). Highway Vehicle Fires. U.S. Fire Administration, Topical Fire Research Series, vol.2, no.4.
- USCAR. (2002). USCAR (United States Council for Automotive Research). USCAR celebrates a decade of automotive progress,
http://www.uscar.org/Media/2002issue1/p1_celebrates.htm.
- USCAR. (2007). USCAR (United States Council for Automotive Research)'s VRP Contracts with ECO2 Plastics to Explore

- 'Rinse and Recycle' Applications,
http://www.uscar.org/guest/article_view.php?articles_id = 146.
- Utracki, L.A. (2002). Compatibilization of Polymer Blends. *The Canadian Journal of Chemical Engineering*, 80:1008-1016.
- Vaillant, D., Lacoste, J. and Dauphin, G. (1994). The oxidation mechanism of polypropylene: contribution of ¹³C-NMR spectroscopy. *Polymer Degradation and Stability*, 45:355-360.
- Valente, M., Sarasini, F., Marra, F., Tirillò, J., and Pulci, G. (2011). Hybrid recycled glass fiber/wood flour thermoplastic composites: Manufacturing and mechanical characterisation. *Composites Part A: Applied Science and Manufacturing*, 42:649-657.
- Valenza, A. and La Mantia, F.P. (1988). Recycling of polymer waste: Part II-Stress degraded polypropylene. *Polymer Degradation and Stability*, 20:63-73.
- Vasile, C. (1993). In: R.B. Seymour, Editor, Handbook of polyolefins: synthesis and properties. New York: Marcel Dekker.
- Vilutiene, T. and Zavadskas, E.K. (2003). The application of multi-criteria analysis to decision support for the facility management for a residential district. *Journal of Civil Engineering and Management*, 9:241-252.
- Vittoria, V. (1988). Investigation of the ageing of isotactic polypropylene via transport properties. *Polymer*, 29:1118-1123.
- Wambua, P., Ivens, J., and Verpoest, I. (2003). Natural fibres: can they replace glass in fibre reinforced plastics? *Composites Science and Technology*, 63:1259-1264.
- Wang, K., Addiego, F., Bahlouli, N., Ahzib, S., Rémond, Y., Toniazzo, V., and Muller, R. (2012). Analysis of thermomechanical reprocessing effects on polypropylene/ethylene octene copolymer blends. *Polymer Degradation and Stability*, 97:1475-1484.
- Wang, K., Bahlouli, N., Addiego, F., Ahzi, S., Rémond, Y., Ruch, D., and Muller, R. (2013). Effect of talc content on the degradation of re-extruded polypropylene/PP/talc composites. *Polymer Degradation and Stability*, 98:1275-1286.
- Wang, K., Addiego, F., Bahlouli, N., Ahzi, S., Rémond, Y., and Toniazzo, V. (2014). Impact response of recycled polypropylene-based composites under a wide range of temperature: Effect of filler content and recycling.

- Composites Science and Technology*. 95:89-99.
- Ward's. (2000). Ward's Motor Vehicle Facts & Figures 2000. Southfield, Michigan: Ward's Communications.
- Wesseh, P.K. and Zoumara, B. (2012). Causal independence between energy consumption and economic growth in Liberia: evidence from a non-parametric bootstrapped causality test. *Energy Policy*, 50:518-527.
- Westerhout, R.W.J., Waanders, J., Kuipers, J.A.M. and van Swaaij, W.P.M. (1997). Kinetics of the low-temperature pyrolysis of polyethylene, polypropene, and polystyrene modeling, experimental determination, and comparison with literature models and data. *Industrial & Engineering Chemistry Research*, 36(6):1955-1964.
- White, J.R. and Turnbull, A. (1994). Review: Weathering of polymers: mechanisms of degradation and stabilisation, testing strategies and modelling. *Journal of Materials Science*, 29:584-613.
- WRAP. (2006). UK Plastics Waste - A review of supplies for recycling, global market demand, future trends and associated risks.
www.wrap.org.uk/downloads/UK_Plastics_Waste.345a82f2.5543.pdf.
- WRAP. (2010). China Market Sentiment Survey Report 2010, www.wrap.org.uk/document.rm?id=852.
- WRAP. (2011). China MSR update 2011, http://www.wrap.org.uk/sites/files/wrap/China_MSR_2011.10601.pdf.
- Wright, D.C., 2001. Failure of Plastics and Rubber Products – Causes, Effects and Case Studies involving Degradation. Rapra Technology Report, ISBN: 1-85857-261-8.
- Wu, C.S. (2005). Improving Polylactide/Starch Biocomposites by Grafting Polylactide with Acrylic Acid - Characterisation and Biodegradability Assessment. *Macromolecular Bioscience*, 5:352-361.
- Wu, Y. and Wu, A. (2000). Taguchi methods for robust design. New York: The American Society of Mechanical Engineers.
- Wypych, G. (2003). Handbook of Materials Weathering. Toronto: ChemTec publishing.
- Xiao, X.P., Song, Z.M., and Li, F. (2005). The basis of grey technology and application (in Chinese). Beijing: Science Press.
- Xie, N., Yuan, C., and Yang, Y. (2015). Forecasting China's energy demand and self-sufficiency rate by grey forecasting model and Markov model. *International Journal of Electrical*

- Power & Energy Systems*, 66:1-8.
- Xu, J., Tan, T., Tu, M. and Qi, L. (2011). Improvement of grey models by least squares. *Expert Systems with Applications*, 38:13961-13966.
- Yam, K.L., Gogai, B.K., Lai, C.C. and Selke, S.E. (1990). Composites from compounding wood fibers with recycled high-density polyethylene. *Polymer Engineering and Science*, 30(11):693-699.
- Yang, K., Yang, Q., Li, G., Sun, Y., and Feng, D. (2006). Morphology and mechanical properties of polypropylene/calcium carbonate nanocomposites. *Materials Letters*, 60:805-809.
- Yavuz, M., Oztaysi, B., Onar, S.C., and Kahraman, C. (2014). Multi-criteria Evaluation of Alternative-Fuel Vehicles via a Hierarchical Hesitant Fuzzy Linguistic Model. *Expert Systems with Applications*, In Press, Accepted Manuscript.
- Ye, J. (2014). Correlation coefficient of dual hesitant fuzzy sets and its application to multiple attribute decision making. *Applied Mathematical Modelling*, 38:659-666.
- Yin, Y., Zhang, Y., Zhen, Z., Chu, P.K., Lv, F., Ji, J. (2013). Thermal degradation and flame retarding characteristics of polypropylene composites incorporated with boron mud. *Composites Science and Technology*, 85:131-135.
- Yoo, Y., Kim, S.S., Won, J.C., Choi, K.Y., and Lee, J.H. (2004). Enhancement of the thermal stability, mechanical properties and morphologies of recycled PVC/clay nanocomposites. *Polymer Bulletin*, 52:373-380.
- Yong, W.H. and Tarng, Y.S. (1998). Design optimisation of cutting parameters for turning operations based on Taguchi method. *Journal of Materials Processing Technology*, 84:122-129.
- Youngquist, J.A., Myers, G.E., Muehl, J.H., Krzysik, A.M., Clemens, C.M. and Padella, F. (1994). Composites from recycled wood and plastics: a project summary. US-Environment Protection Agency.
- Yu, Z.Z., Yan, C., Yang, M., and Mai, Y.W. (2004). Mechanical and dynamic mechanical properties of nylon 66/montmorillonite nanocomposites fabricated by melt compounding. *Polymer International*, 53:1093-1098.
- Yunker, M.B., Belicka, L.L., Harvey, H.R. and Macdonald, R.W., 2005. Tracing the inputs and fate of marine and terrigenous organic matter in Arctic Ocean sediments: a multivariate analysis of lipid biomarkers. *Deep-Sea Research II*, 52(24-26):3478-3508.

- Zahavich, A.T.P., Latto, B., Takacs, E. and Vlachopoulos, J. (1997). The effect of multiple extrusion passes during the recycling of high density polyethylene. *Advances in Polymer Technology*, 16:11-24.
- Zahedi, M., Pirayesh, H., Khanjanzadehc, H., and Tabara, M.M. (2013). Organo-modified montmorillonite reinforced walnut shell/polypropylene composites. *Materials & Design*, 51:803-809.
- Zameri, M. and Saman, M. (2006). End of life vehicles recovery: process descriptio, its impact and direction of research. *Journal Mekanikal*, 21:40-52.
- Zare, Y. and Garmabi, H., 2012a. Analysis of tensile modulus of PP/nanoclay/CaCO₃ ternary nanocomposite using composite theories. *Journal of Applied Polymer Science*, 123:2309-2319.
- Zare, Y. and Garmabi, H., 2012b. Nonisothermal crystallization and melting behavior of PP/nanoclay/CaCO₃ ternary nanocomposite. *Journal of Applied Polymer Science*, 124:1225-1233.
- Zavadskas, E.K., and Kaklauskas, A. (1996). Multiple criteria evaluation of buildings. Technika, Vilnius.
- Zhang, H. (2004). Fire-Safe Polymers and Polymer Composites. Federal Aviation Administration technical report; U.S. Department of Transportation: Washington, D.C.
- Zhang, H.S., Guo, W.H., Yu, Y.B., Li, B.Y. and Wu, C.F. (2007). Structure and properties of compatibilised recycled poly(ethylene terephthalate)/linear low density polyethylene blends. *European Polymer Journal*, 43:3662-3670.
- Zhang, S., and Horrocks, A.S. (2003). A review of flame retardant polypropylene fibres. *Progress in Polymer Science*, 28:1517-1538.
- Zhang, S.D., Ban, Q., Huang, H.X., and Li, Y.Z. (2009a). Modified recycled glass fibre reinforced flame retardant PBT with improved mechanical properties by nanoparticles. The 5th ISFR, Chengdu, China, 171-177.
- Zhang, Y., Guo, W.H., Zhang, H.S. and Wu, C.F. (2009b). Influence of chain extension on the compatibilisation and properties of recycled poly(ethylene terephthalate)/linear low density polyethylene blends. *Polymer Degradation and Stability*, 94:1135-1141.
- Zhang, Y.Q., Lee, J.H, Jang, H.J. and Nah, C.W. (2004). Preparing PP/clay nanocomposites using a swelling agent.

- Composites Part B: Engineering*, 35:133-138.
- Zhao, Q.L., Li, X.G., Gao, J. and Jia, Z.J. (2009a). Degradation evaluation of ethylene–propylene–diene monomer (EPDM) rubber in artificial weathering environment by principal component analysis. *Materials Letters*, 63:116-117.
- Zhao, Q.L., Li, X.G., Gao, J. and Jia, Z.J. (2009b). Evaluation of ethylene–propylene–diene monomer (EPDM) aging in UV/condensation environment by principal component analysis (PCA). *Materials Letters*, 63:1647-1649.
- Zhu, S.P., Chen, J.Y., Zuo, Y., Li, H.L., and Cao, Y. (2011). Montmorillonite/polypropylene nanocomposites: Mechanical properties, crystallization and rheological behaviors. *Applied Clay Science*, 52:171-178.
- Zoboli, R., Barbiroli, G., Leoncini, R., Mazzanti, M. and Montresor, S. (2000). In: Leone, F. (Ed.), Regulation and Innovation in the Area of End-of-life Vehicles. The European Commission JRC-IPTS and Enterprise DG. EUR 19598 EN..

Appendix

Table 1 Plastic components in automobile

Components	Sub Components	Requirements	Types of Plastics
Rigid Dashboard		Humid Resistance, Abrasion Resistance, Thermal Stability, High Rigidity, Sound Absorption	M-PP, PC, ABS, ABS/PC, M-PPO, SMA-GF15
Covered Dashboard	Surface	Humid Resistance, Abrasion Resistance, Can be Decorated	PVC, TPO, PVC/ABS, PP/EPDM
	Skeleton	High Rigidity	ABS, GFAS, M-PP, PC/ABS, TPO, M-PP
	Cushion Substance	Impact Resistance, Sound Absorption	PU
Inner Door	Surface	Humid Resistance, Abrasion Resistance, Can be Decorated	PVC, TPO, PVC/ABS, PP/EPDM

	Skeleton	High Rigidity	ABS, GFAS, M-PP, PC/ABS, TPO, M-PP
	Cushion Substance	Impact Resistance, Sound Absorption	PU
	Handle		ABS, M-PP, PC/ABS, POM
	Threshold		ABS

Seat	Surface	Humid Resistance, Abrasion Resistance, Can be Decorated	PVC, PU
	Skeleton	High Rigidity	GMT, ABS
	Cushion Substance	Impact Resistance, Sound Absorption	PU

Ceiling and Rear wall	Surface	Humid Resistance, Abrasion Resistance, Thermal Stability	TPO, PVC
	Basis	Light Weight, High Rigidity, High Stability, Easy to Form	TPUR, PP, PU

	Cushion Substance	Impact Resistance	PO
Sun Shade	Surface	Humid Resistance, Abrasion Resistance, Thermal Stability	PVC
	Skeleton	High Rigidity	TPO
	Cushion Substance	Impact Resistance	PU
	Engine Bonnet and Ground Mat	Sound Absorption, Shock Absorption, Heat insulation, Skidproof. Antifouling	PVC Foaming Compound
Frost-Proof		PC/ABS	
Glove Compartment and Ashtray		Abrasion Resistance, Impact Resistance	PC, ABS, PP, M-PP
Bumper	Beam	Humid Resistance, Abrasion Resistance, Thermal Stability, High Rigidity	PA, M-PP, TPO, PP+EPDM, PP+EPDM+T10, PP+EPDM+T20, PC+PBT, PUR-RIM, POE, PC/PBT, PC/PET, SMC
	Outer Plate		PPO/PS,

			PPO/PBT
	Cushion Substance	Impact Resistance	PU, EPP
Radiator Grille		Thermal Stability	PE, ABS, PC/ABS, ASA
Fender			M-PP, PC/ABS, PPO/PA
Side Impact Protection	Core		PP+EPDM+T30
	Cover		PVC, PUR
Back Spoiler		Light Weight, High Rigidity	SMC, mPPO, M-PP, PPO/PA
Light	Headlight Shell	Light Transmittance, Impact Resistance, Abrasion Resistance, Thermal Stability	PC, PMMA
	Headlight Reflector Shell	Light Transmittance, Impact Resistance, Abrasion Resistance, Thermal Stability	BMC, PPS, PC, PBT, PPO/PS, PC/PET, PC/PBT
	Headlight Reflector Support	High Rigidity	PC, ABS, PP+T40, PBT+G15, PP+G15, PC/ABS
	Back Indicator Light and Back	Thermal	PMMA, M-PP, ASA, ABS or

	Indicator Light Shell	Stability	PC/ABS
Outside Door Handle		Impact Resistance, Abrasion Resistance	POM
Locker		High Rigidity	POM
Wiper		Humid Resistance, Abrasion Resistance, High Rigidity	PBT, POM
Band for Wheel Hub		Humid Resistance, Abrasion Resistance, High Rigidity, Thermal Stability	PA, PA/PPO, ABS, PC/ABS
Steering Wheel		Abrasion Resistance, Thermal Stability	PA, M-PP, PVC, PU, ABS
Engine	Engine Cylinder Cover or cover	Engine Cover, Head Valve	High Thermal Stability, Vibration Tolerance, Sound Absorption, Shock Absorption, Heat insulation
			GFP A6, GFP A66, PA6, PA66

Ignition Device		Electrical Insulativity	PA, PBT+GF	POM,
Battery Slot		Electrical Insulativity	PP	
Fuel Feeding System	Induction Manifold, Carburetor, Oil Filter and Tank	Chemical Stability	PA, PBT, PBT/PC	
Transmission System	Gear, Pipeline, Crank, Bearing, Switch	Abrasion Resistance, Physical Stability	POM	
Electrical System		Thermal Stability, Physico-Chemical Stability, Flame Retardancy, Electrical Insulativity, Impact Resistance, Humid Resistance	PPO, PPO/PA, PPO/PS	
Air Conditioning System	Pipeline	Thermal Stability, Humid Resistance	PE	
	Shell and Cover	Thermal Stability, Humid Resistance	PP	
Body Structural Members		Abrasion Resistance,	PC/PBT, PC/PET	

High Rigidity,
Thermal
Stability
