LOW-TECH RECYCLING STRATEGY FOR THE PRODUCTION OF BUILDING MATERIALSFOR DEVELOPING NATIONS

Claire A. White[1*], Jessica C. Wood[1], John Milne[1] and Michael T. Heitzmann[1]
[1]School of Mechanical and Mining Engineering, The University of Queensland, Australia
[*]claire.white@uqconnect.edu.au

ABSTRACT

Increasing plastic production and lack of adequate recycling in developing nations is a critical global issue which must be addressed. This paper forms part of a larger feasibility study investigating a small scale plastic recycling plant housed in a shipping container for use in developing nations. The overall project is motivated by the desire to provide a cleaner environment, self-sustained communities and reduce the impact of plastics on our society. It is envisaged that the recycled mixed plastic product will be of use to the community by way of rudimentary building materials such as bricks and tiles. The concept has the potential to benefit communities in developing nations by providing secure and reliable accommodation whilst also utilising an untapped and abundant resource. This paper details the experimental component of the larger study and presents the manufacturing techniques utilised, the samples produced and resulting properties. The effects of filler materials on thermoplastic polymers are investigated in addition to the comparison of recycled and virgin polymers. It was determined that the status of the polymer used in the manufacture of samples (i.e. whether the polymer was virgin or recycled) had no significant effect on selected properties of material produced and that overall recycled PET produced the most consistently high performing sample materials. The PET samples produced had low water absorption, the highest average tensile strengths and medium impact resistance (compared to the other materials). They also exhibited the smallest decrease in tensile properties as a result of UV exposure and had no observed surface degradation. In addition, PET bottles are some of the most frequently occurring plastic wastes. A number of additional conclusions were made and are contained within this paper.

KEYWORDS

Sustainable design, recycling, thermoplastics, filler materials, developing nations, building materials, environment.

INTRODUCTION

Billions of people in developing nations are affected by the unresolved issue of plastics recycling. With no adequate system in place to sort these recyclables and no clear purpose for their reuse, non-biodegradable plastics continue to pile in the streets presenting economic, environmental and public health issues. This has a negative impact on the livelihood, sanitation and environment of communities in developing nations. One possible use for these plastics is the production of composites with reinforcement materials to be used as affordable alternative housing materials such as bricks.

Filler Materials

Biron (2013) defines filler materials asnon-plastic components which can beadded to polymers to provide increased directional strength to composite products and reduce costs. These materials include organic fillers such as natural fibres (e.g. wood flour, flax) and inorganic fillers such as glass fibres. This study investigates the use of two organic fillers: wood flour and newspaper. Due to the cellulose fibres, wood flour is hydrophilic

(attracts water) and hence increased cellulose will result in increased water absorption of the wood flour composites. Studies by Kord (2011), Maiti et al (1985) and Raj et al (1992) determined that increasing wood flour content increased the water absorption and decreased the impact resistance of thermoplastic/wood flour composites. Additionally, in their study, Peng et al (2014) concluded that prolonged exposure to UV promotes the generation of surface cracking in wood flour/polymer composites and resulted in increased water absorption.
Paper items often become mixed in with plastic wastes, and therefore it is of interest to determine if newspaper could be beneficial to the end product saving onwaste-sorting time. In their study, Serrano et al (2014) assessed the potential of replacing glass fibres with shredded newspapers as reinforcement in PP composite materials. The results indicated that newspaper fibres could be a suitable alternative to glass fibres due to increased tensile strength and Young's modulus (for up to 30% newspaper content). However, further increases to the newspaper content showed a gradual decline in tensile strength, indicating that the content of newspaper must be carefully controlled.

Mixing of Common Plastics

In order to increase productivity, it is desirable to minimise the amount of plastic sorting required in the recycling process. For example, in the case of HDPE bottles with PP caps, it is beneficial to recycle these components together rather than separating them. It is therefore important to understand the compatibility of plastics with each other. This compatibility can vary greatly due to the wide range of plastic applications and the seemingly endless number of chemical compositions manufacturers utilise. Stephan Tall's paper (2000)states that commingled polymers often become phase separated as a result of poor interfacial interactions during the recycling process. This can result in highly brittle products.An example of this issue is seen in the incompatibility of PE or PP with PET. Both PE and PP are non-polar hydrocarbons whereas PET is a polar hydrocarbon. As such, PET requires polar-polar interfacial interactions and therefore its compatibility with non-polar polymers such as PE and PP is low. Studies have shown that the compatibility of PE with PP is extremely varied. In some recycling cases, compatibilisers (e.g. elastomeric polymers) may be used to assist overall adhesion of polymer blends. This study will focus on the products obtained without the use of compatibilisers.

METHODLOGY

Manufacture

The polymers selected for testing were PET, HDPE, and PP as they are some of the most commonly occurring thermoplastic polymers, according to Plastics Europe (2013). Post-consumer plastics of this variety were collected, cleaned and dried. Labels were removed from all materials except for some PET bottles. In addition newspapers were also collected. The plastic items and newspapers were then cut into strips and shredded into rectangular flakes approximately 10x5mm in sizeusing a LabTech Engineering pelletiser. Batches weremixed together using scales to obtain the correct ratio of polymer and filler and placed in individual, labelled bags.

Each batch was extruded individually using a Thermo Scientific Eurolab 16 extruder, with a L/D ratio of 40:1. A circular die with a diameter of 3mm was used. Batches 1 to 6 were extruded at 175-185°C and batches 7 and 8 were extruded at 250°C. The screw speed was 50RPM. After extrusion, the pelletiser was used to cut the cables into pellets. The pellets were injection moulded with a Babyplast 610P Standard Injection Moulder to produce the final test specimens shown in Figure 1. It must be noted that due to material limitations, some batches could be manufactured into rectangular section samples only.

Testing

Water Absorption

The water absorption tests were conducted in accordance with ASTM D570-98 (2010), Procedure 7.4 Long-Term Immersion. Two samples from each batch were labelled and placed in a vacuum hopper dryer for 12 hours at 50°C. Each sample was then weighed (W_1). Two beakers were filled with 1000mL of tap water at room temperature. One sample of each batch was placed in each beaker and left for 24 hrs. Samples were removed one at a time and their surface was dried with paper towel before being weighed (W_2). The samples were then re-immersed back into their respective beakers and left for another 24 hrs. The weighing process was repeated for the samples every 24 hrs for a period of 2 weeks.

Impact Test

The impact tests were conducted in accordance with ASTM D6110-10 (2010). First, the dimensions of each rectangular section composite sample were measured with electronic callipers. Each sample was labelled and placed centrally on top of the Pendulum Impact Machine (Zwick D7900 Type 5102.100/00) with anvils which were set at 40mm apart. The dial on the pendulum impact machine gauge was zeroed and the pendulum was released. The pendulum impact machine gauge energy reading was recorded for each sample tested in each composite batch.

Tensile Test

The tensile tests were conducted in accordance with ASTM D638-14 (2014). The Instron 4505 machine was set up with hydraulic grips and a 10 kN load cell. An optical strain gauge with 25 mm gauge length and a cross head speed of 1200 N/min was used for the tests.

Ultraviolet-exposed Tensile Test

The ultraviolet (UV) exposure and tensile tests were conducted in accordance with ASTM D4329-13 (2013) and ASTM D638-14 (2014). The QUV Accelerated Weathering Tester was set on Cycle A for the duration of the test - UV for 8 hrs at 60 °C, irradiance at peak emission 340 nm was 0.89 W/(m^2.nm), condensation for 4 hrs at 50°C. Four samples from each batch were labelled and placed in the QUV machine for 620 hrs. At 310 hrs of exposure, the samples were removed, turned over and placed back in the QUV machine. At 620 hrs, the samples were removed from the QUV machine and left overnight to cool. The dimensions of each rectangular section and tensile test sample to be tested were measured with electronic callipers and inputted into the Bluehill 3 Instron computer program.

Table 1. Composite batch compositions

Batch Number	Batch Composition
1	50/50 HPDE/PP mix. Virgin materials
2	50/50 HDPE/PP mix. Recycled materials
3	2/5 HDPE, 2/5 PP, 1/5 newspaper. Virgin materials
4	2/5 HDPE, 2/5 PP, 1/5 newspaper. Recycled materials
5	1/3 HDPE, 1/3 PP, 1/3 wood flour. Virgin materials
6	1/3 HDPE, 1/3 PP, 1/3 wood flour. Recycled materials
7	PET (without labels). Recycled materials
8	PET (with labels). Recycled materials

Figure 1. Rectangular section and tensile test samples for composite batch 2

RESULTS AND DISCUSSION

In general, during the manufacturing process, it was observed that the batches produced using the recycled polymers exhibited less die swelling and lower screw torque than those manufactured with virgin polymers. Samples which contained fillers had significantly lower screw torque than samples without.

Water Absorption Test

Water absorption (%) of each sample was calculated using Eq. 1.Average water absorption (%) of each batch was determined by taking an average of the two sets of results (beaker A and B). Figure 2 shows the average water absorption (%) in 24 hours for each composite batch. Data from batches 1-8 are shown from left to right.

$$Water\ absorption\ (\%) = \frac{W_2 - W_1}{W_1} \times 100 \qquad [1]$$

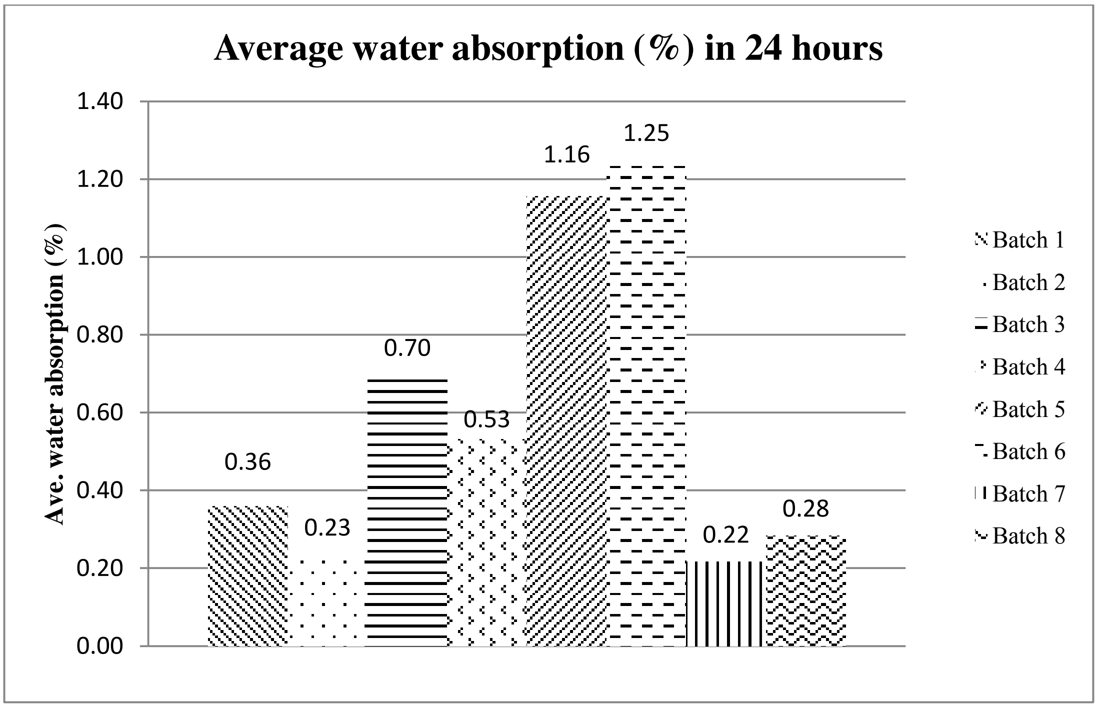

Figure 2. Average Water Absorption (%) in 24 Hours Per Batch

The samples containing wood flour (batches 5 and 6) performed the worst in terms of water absorption, as these samples showed the highest initial water absorption after 24 hours and continued to absorb the most water over the full duration of the test. Wood flour contains high amounts of hydrophilic cellulose meaning that samples from batches 5 and 6 attract water more rapidly when compared to the other samples. The next highest water absorption levels are seen in batches 3 and 4 which contain newspaper. This is also expected due to the levels of cellulose contained in the paper-based filler. The best performing materials were PET without labels which hadthe lowest average water absorption in 24 hours. The average water absorption for common construction bricks is between 0.5-10% therefore these results are acceptable.

Tensile Test

Moderate to significant discolouration and fading was evident in all UV-exposed samples. During testing, a powdery residue was present on the UV-exposed samples from batches 1 through to 6 however; the PET samples (batches 7 and 8) did not present any flaking or powdery residue as a result of UV exposure. All samples (UV-exposed and non UV-exposed) broke in a brittle manner, this was most likely due to the phase separation of mixed polymers or the added filler material. As expected, the average tensile strengths are lower for the recycled plastic samples compared to the virgin polymer samples with the lowest average tensile strength recorded at 6.8MPa (for batch 2). The samples produced comparable tensile strength results with common building materials such as brick and concrete, which range from 7-14 MPa and 2-6 MPa respectively.

Both PET composites batches produced higher average tensile strengths than the maximum brick tensile strength which is a positive result. The best performing materials regarding the effect of UV exposure on tensile properties were batches 5 and 6. UV exposure actually increased the average tensile strength of these materals by 1.85% and 2.38%, for batch 5 and 6 respectively. This is in contradition to the information contained in Peng et al. (2014) indicating that prolonged UV exposure (such as that experienced in the QUV machine) increases degradation of wood flour/polymer composites and hence the observed properties should be decreased. The result is definitely interesting and should be investigated further. The Young's modulus of the produced samples is much lower than the Young's modulus of common building materials indicating that the samples.

Table 2. Average Tensile Results, Non UV-Exposed Samples

Batch No.	Batch	Ave. Maximum Load (N)	Ave. Tensile Strength at Maximum Load (MPa)	Ave. Young's Modulus (GPa)
1	Virgin HDPE/PP mix	252.5	9	0.7443
2	Recycled HDPE/PP mix	177.3	6.8	0.7161
3	Virgin HDPE/PP/newspaper	323.0	10.0	0.914
4	Recycled HDPE/PP/newspaper	250.5	8.5	0.8839
5	Virgin HDPE/PP/wood flour	268.5	10.8	1.2819
6	Recycled HDPE/PP/wood flour	211.2	8.4	1.1802
7	Recycled PET without labels	400.5	16.3	1.3463
8	Recycled PET with labels	424.5	17.0	1.5242

Table 3. Average Tensile Results, UV-Exposed Samples

Batch No.	Batch	Ave. Maximum Load (N)	Ave. Tensile Strength at Maximum Load (MPa)	Ave. Young's Modulus (GPa)
1	Virgin HDPE/PP mix	136.4	5.2	0.8104
2	Recycled HDPE/PP mix	148.4	5.8	0.7661
3	Virgin HDPE/PP/newspaper	274.7	9.0	0.10283
4	Recycled HDPE/PP/newspaper	217.6	7.2	0.9379
5	Virgin HDPE/PP/wood flour	272.2	11	1.3879
6	Recycled HDPE/PP/wood flour	218.2	8.6	1.2986
7	Recycled PET without labels	368.6	15.0	1.7635
8	Recycled PET with labels	313.4	12.8	1.5637

Impact Test

The material which produced the highest average impact energy was the virgin HDPE/PP/newspaper mix. However it must be noted that due to material limitations, only three samples of this batch could be tested and the testing of further samples may have produced a different average impact result. The poorest performing materials regarding average impact energy were the wood flour batches (5 and 6).

This finding is supported by the work of Peng et al (2014) who determined that increasing wood flour content resulted in a decreased in impact resistance. The samples which fractured in the most brittle manner were those from batches 7 and 8, the PET composites, with some breaking into multiple pieces. According to Goodfellow (2015), the average impact energy for virgin PET is between 13 and 35 J/m. The PET samples produced here have comparable impact results with the virgin materials of 20.1 and 21.2 J/m for the unlabelled and labelled batches respectively. It is important to note that, similar to the non UV-exposed tensile specimens the labelled variety of PET produced the higher result. The average impact energy is from 20 to 210 J/m for virgin HDPE and from 20 to 100 J/m for virgin PP. All batches containing HDPE and PP exhibit average impact energies within this range, apart from the wood flour samples which produced lower results as discussed.

Table 4. Impact Test Results

	Batch Number							
	1	2	3	4	5	6	7	8
Average (Joules)	0.250	0.266	0.315	0.231	0.192	0.180	0.196	0.207
Average Impact Energy Per Unit Width (J/m)	25.694	27.364	32.374	23.778	19.761	18.536	20.144	21.262

CONCLUSIONS

From the results obtained, the following experimental product conclusions can be made:

- The status of the polymer used in the manufacture of samples (i.e. whether the polymer was virgin or recycled) had no significant effect on selected properties of material produced
- Water absorption properties of all samples were comparable with that of brick and concrete
- The addition of selected fillers promotes the absorption of water
- Tensile properties of all samples were comparable to that of bricks and concrete, with the PET samples exhibiting the highest average tensile strengths
- UV exposure had a moderate to significant effect on all samples by way of discolouration, flaking and a general reduction in average tensile strength
- Addition of wood flour in recycled polymer samples produced improvements in tensile strength for UV-exposed samples when compared to non UV-exposed samples. This is an unexpected result and further investigation is recommended
- The virgin HDPE/PP batch fared the worst, compared to the other batches, with a 42.2% reduction in average tensile strength as a result of UV exposure
- The PET samples (without labels) showed the smallest decrease in average tensile strength of 7.9% compared to the other batches
- Wood flour reduced screw torque during the extrusion and increasing tensile strength but also increases water absorption and decreases impact strength (compared to the HDPE/PP mix).It can be concluded that it would be beneficial to include this filler specifically in the HDPE/PP polymer blend, if it is available and at low-cost
- Newspaper reduced screw torque during the extrusion, increasing tensile strength and increasing impact strength but also increases water absorption (compared to the HDPE/PP mix). It can be concluded that it would be beneficial to include this filler and prior separation of HDPE/PP and newspaper waste is not necessary
- It can be concluded that filler materials improve or do not significantly reduce the properties of HDPE/PP recycled polymer blends

- PET samples with labels produced higher tensile and impact results than the unlabelled PET samples. However, the addition of labels in the PET mix resulted in increased water absorption and the second highest reduction of tensile strength as a result of UV exposure (24.7%)
- Overall, the recycled PET samples were the most consistently high performing materials. These batches had low water absorption (compared to the filled materials), the highest average tensile strengths and medium impact resistance (compared to the other materials). They also exhibited the smallest decrease in tensile properties as a result of UV exposure and had no observed surface degradation. In addition, PET bottles are some of the most frequently occurring plastic wastes

Recommendations for Further Study

- Optimisation of product – further detailed investigation is required into the quality of the recycled product which could be produced including: testing of other properties, using alternative types of plastics, use of compatibilisers and other fillers, use of single polymer types (separation of plastics), use of other plastics in combination with PET;
- Further investigation into the effects of UV-exposure on the tensile properties of wood flour/polymer.

ACKNOWLEDGEMENTS

We would like to express our gratitude to Mr. Doug Malcolm for his assistance with the mechanical testing presented in this study.

REFERENCES

ASTM (2014). "Standard Test Method for Tensile Properties of Plastics", ASTM D638-14, American Society for Testing and Materials, United States

ASTM (2013). "Standard Practice for Fluorescent Ultraviolet (UV) Lamp Apparatus Exposure of Plastics", ASTM D4329-13, American Society for Testing and Materials, United States

ASTM (2010). "Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics", ASTM D6110-10, American Society for Testing and Materials, United States

ASTM (2010). "Standard Test Method for Water Absorption of Plastics", ASTM D570-98, American Society for Testing and Materials, United States

Biron, M. (2013)."Thermoplastics and Thermoplastic Composites", William Andrew, Amsterdam; Boston

Goodfellow. (2015). "Polyethylene terephthalate (Polyester, PET, PETP) - Material Information", viewed 7 April 2015, <http://www.goodfellow.com/E/Polyethylene-terephthalate.html>

Goodfellow. (2015). "Polyethylene - High Density (HDPE) - Material Information", viewed 7 April 2015, <http://www.goodfellow.com/E/Polyethylene-High-density.html>

Goodfellow. (2015). "Polypropylene (PP) - Material Information", viewed 7 April 2015, <http://www.goodfellow.com/E/Polypropylene.html>

Kord, B. (2011). "Effect of Wood Flour Content on the Hardness and Water Uptake of Thermoplastic Polymer Composites," World Applied Sciences Journal, Vol. 12, pp. 1632-1634

Maiti, S.N., and Singh, K. (1985). "Influence of Wood Flour on the Mechanical Properties of Polyethylene," Indian Institute of Technology, New Delhi

Peng, Y., Liu, R., Cao, J., and Chen, Y. (2014). "Effects of UV weathering on surface properties of polypropylene composites reinforced with wood flour, lignin, and cellulose," Applied Surface Science, Vol. 317, pp. 385-392

Plastics Europe(2013)."Plastics – the Facts 2013", Plastics Europe: Association of Plastics Manufacturers, Brussels, viewed 4 April 2015, <http://www.plasticseurope.org/documents/document/20131014095824-final_plastics_the_facts_2013_published_october2013.pdf>

Raj, G., Kokta, B.V., and Daneault, C. (1992). "Wood flour as a low-cost reinforcing filler for polyethylene: studies on mechanical properties," Journal of Materials Science, Vol. 25, pp. 1851-1855

Serrano, A., Espinach, F.X., Tresserras, J., Pellicer, N., Alcala, M., and Mutje, P. (2014). "Study on the technical feasibility of replacing glass fibres by old newspaper recycled fibers as polypropylene reinforcement," Journal of Cleaner Production, Vol. 65, pp. 489-496

Tall, S. (2000). "Recycling of Mixed Plastic Waste - Is Separation Worthwhile?," Department of Polymer Technology Royal Institute of Technology, Stockholm