Mechanical properties and environmental assessment of recycled carbon fibre reinforced polypropylene and acrylonitrile butadiene styrene products

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Abstract. In this study, the main objective is to determine effect of recycled carbon fibre (RCF) on the mechanical properties of thermoplastics composites and associated environmental impacts. Such study is important to improve the strength of the composites as previous studies are limited on RCF composites, particularly in environmental aspects. In the compounding stage, extrusion process was carried out by using two different thermoplastics i.e. polypropylene (PP) and acrylonitrile butadiene styrene (ABS) mixing with RCF. Particle size and weight loading of RCF were chosen as parameters to be studied. Bonding strength between the RCF and thermoplastics matrix was investigated through tensile and flexural properties. Lastly, the assessment of the products was carried out to determine the environmental impacts. Generally, the incorporation of RCF into PP and ABS plastic increases the tensile and flexural properties of the samples. It can be seen that the addition of rCF significantly improves tensile modulus and flexural strength up to 10 wt% filler loading. From the environmental impact assessment, the ABS products have greater impact in all categories. The usage of rCF reduce the amount of plastic hence leads to lower environmental impacts. The product has a potential to be used in mechanical demanding application particularly those require high flexural strength and tensile modulus properties.

1. Introduction

Carbon fibre reinforced polymers (CFRPs) are advantageous materials in lightweight structural applications due to their high strength-to-weight ratio, resistance to corrosion and extremely strong materials. CFRP is common critical sectors such as in aerospace, automotive and construction [1]. For example, Airbus A350 and Boeing 787 Dreamliner have seen the expended use of CFRPs materials which is more than 50% by weight [2]. The production process of carbon fibre is complex and energy intensive, thus making CFRPs more expensive than metals. The advantage of CFRPs lies in their weight; metal materials of the same properties weight up to five times as much [3]. This makes CFRPs especially valuable in areas, where weight and cost directly correlate, but high mechanical properties are still essential.

With increasing carbon fibre demand at a rate of 15% per annum in the past few years, Tomioka et al [4] estimated CFRP waste to be approximately 140,000 tonnes in 2020. Therefore, growing of CFRP usage in established fields predicts a further rising trend because of non-stop development of new fields of application. Recycled carbon fibre (rCF) can reach low environmental impacts compared to virgin carbon fibre and other metals [5]. Low production impacts associated with recycled carbon fibre components are observed relative to lightweight competitor materials for instance, aluminium and virgin carbon fibre reinforced plastic [6]. In addition, rCF components have low in-use energy use
due to mass reductions and associated reduction in mass-induced fuel consumption. The worth for virgin energy used up to 198 - 595 MJ/kg in virgin carbon fibre production [2].

A few commercial products using recycled CFRP have been reported, although a proper system in managing CFRP wastes has not been established anyplace so far [7]. Nishikawa et al [8] evaluated that rCF pieces as conductive fillers and as electrical properties including shield effect. Meanwhile carbon fibres are used and the result of mechanical properties are also improved [8]. In general, recycling of CFRPs is thought to be difficult. It is because of its chemical stability and hardness. There are several categories of composite recycling methods, which are thermal recycling, material recycling, and chemical recycling [9].

According to Witik et al [10], using CFRP waste may be environmentally preferable. The results show that the potential reuse of rCF can powerfully influence the benefits gained. This implies that growth of potential markets for these materials have targeted towards applications. The study additionally shows that Life Cycle Assessment (LCA) is vital for increasing understanding connected to the environmental performance.

From the literature review, parametric study on rCF and the thermoplastics is not well covered particularly on mechanical properties and environmental impact. There is also limited study on which thermoplastic matrix has the best performance for rCF application. This study focuses on rCF based products using different type of commonly used thermoplastics which are polypropylene (PP) and acrylonitrile butadiene styrene (ABS). Such study is vital to improve strength and to determine which thermoplastic is the best for recycled carbon fibre.

2. Methodology

2.1. Materials
Recycled carbon fibre (rCF) acts as filler in the composite samples produced in this study. The rCF was obtained from ELG Carbon Fibre Ltd, United Kingdom. Size range of the filler is around 63 μm to 210 μm. The rCF was obtained using a pyrolysis recycling process. Polypropylene (PP) and acrylonitrile butadiene styrene (ABS) used as polymer matrices were provided by Sheng Foong Plastic Industries Sdn Bhd in Tronoh, Perak. The fillers underwent sieving process for 90 minutes with time interval 10 minutes. Intermediate size, which is 75 μm to 150 μm, was used in this study.

2.2. Composite Fabrication
Mixing of thermoplastic pellets and recycled carbon fibre was carried out in a continuous profile by using a twin - screw extruder and injection molding. This process started from feeding the materials into hopper and barrel of the extruder. Speed of the flow was set to 16 rpm for 20 minutes and the speed used was 8.5 mm/min. The temperature was set up to 200 °C and 210 °C for PP and ABS respectively. Weight loading of RCF were 0 %, 5 % and 10 %. After the extrusion process, BOY 35 E injection moulding machine was used to manufacture the samples for tensile and flexural test. The machine automatically injected the sample with temperature 200 °C and 230 °C for PP and ABS respectively. The pressure applied was 9 Pa. After 15 seconds of cooling process, the sample was ejected from the mould. Dog bone and square plate shape specimens were prepared for tensile and flexural test, respectively.

2.3. Tensile Testing
The Shimadzu Universal Testing Machine (AG-XD plus) was used for tensile test. The test was conducted according to ASTM D638 standard. The crosshead speed used was 5 mm/min. Five dog bone shape (164 mm × 19 mm × 3 mm) samples were tested for each formulation. The tensile strength, modulus of elasticity and elongation at break of samples were determined using Trapezium X Materials Testing Software.

2.4. Flexural Testing
Flexural test was conducted to determine the flexural strength and modulus. The test was conducted according to ASTM D790 with the specimen size of 12.43 mm × 122.26 mm × 3.14 mm. Flexural
properties obtained and these values were used to evaluate the sample materials ability to withstand the flexure forces. Flexural properties were determined using Trapezium X Materials Testing Software.

2.5. Morphology Characterization
Firstly, the tensile fractured surface was mounted on an aluminium stub to undergo platinum sputtering coating. The Quorum Q150R S was used to coat the samples. The samples were coated with 20 nm thin layer platinum by using an auto fine coater. Surface morphology of the fracture on the tensile tested samples was observed using Hitachi Tabletop Microscope TM3000.

2.6. Environmental Impact Assessment
The environmental impacts of the products were assessed using OpenLCA software. The life cycle assessment was conducted using data from European Life Cycle Database (ELCD) and Ecoinvent. The impact assessment method used was CML Baseline. The input considered was the material used for fabrication and electrical energy by sieving, extrusion and injection moulding processes.

3. Results & discussion
3.1. Tensile properties

Figure 1 and Figure 2 show tensile strength of PP/rCF and ABS/rCF composites with different filler loading respectively. In Figure 1, the strength for the sample with 5 wt% filler is lower (25.11 MPa) compared to the pure PP sample (23.22 MPa). The strength increases to 28.48 MPa for the sample with 10 wt% filler. In Figure 2, similar trend can be seen. The tensile strength of ABS/CF composites are 45.09 MPa, 45.07 MPa and 50.96 MPa for filler loading of 0 wt%, 5 wt% and 10 wt% respectively. The results indicate that increasing filler loading gives a tendency to increase the strength of the composite. High tensile properties depend on the effective distribution of stress from the matrix uniformly to filler [11]. Lower value for 5 wt% filler loading can be attributed to amount of filler not sufficient to provide reinforcement for the plastic.

![Figure 1. The tensile strength of PP/rCF with different filler loading](image1)

![Figure 2. The tensile strength of ABS/rCF with different filler loading](image2)

Figure 3 and Figure 4 shows Young’s Modulus of PP/rCF composites and ABS/rCF composites. The modulus increases with the addition of filler loading. This is similar to the result reported in Barkoula et al [11]. The addition of filler causes the rigidity of the composites to accelerate significantly. For both type of composites, the sample with 10 wt% filler loading has the highest modulus. From Figure 1 to Figure 4, the results show that the addition of rCF has significantly influences tensile modulus in comparison with tensile strength.
3.2. Flexural strength

From Figure 5 and Figure 6, the samples with 10 wt% filler loading have the highest value of 43.21 MPa and 92.25 MPa for PP/rCF and ABS/rCF composite respectively. Comparing Figure 1 and Figure 2, the improvement of strength for flexural seems more notably compared to tensile strength. The deformation of the matrix within the elastic zone is restricted because the adhesion convalescing, which leads to a better strength. The rCF acts as a load carrier within the composite. Thus, the stiffness of the composites increases with rCF incorporation.

3.3. Morphology analysis

Figure 9 and Figure 10 presents the morphology analysis from scanning electron microscope (SEM) for PP/rCF and ABS/rCF composites respectively. Recycled carbon fibres were distributed uniformly within the matrix and no obvious agglomerations of fibre can be observed. Some fibres pull-out and voids can be seen in the images. A good adhesion between the matrix and filler can be attributed to the strong interfacial bonding between surface of rCF and thermoplastics. Figure 7 a) and Figure 7 b) are comparable in terms of number of fibres pull out and area of voids. In Figure 8, the brittle fractured surface can be observed as a result of brittle properties of ABS.
Figure 7. SEM images for PP/rCF of (a) 5% filler (b) 10% filler

Figure 8. SEM images for ABS/rCF of (a) 5% filler (b) 10% filler

3.4. Environmental impact

Table 1 shows the environmental impact for PP/rCF and ABS/rCF composites. From Table 1, it can be seen that the ABS composites have greater environmental impact compared to PP composites, despite their high strength and modulus. The usage of rCF has successfully reduced the environmental impact for all categories.

Table 1. Percentage of changes in tensile properties in fibre reinforced products

| Environmental impact          | Unit   | Pure ABS | ABS + 5% CF | ABS + 10% CF | Pure PP | PP + 5% CF | PP + 10% CF |
|-------------------------------|--------|----------|-------------|--------------|---------|-----------|-------------|
| Acidification potential       | kg SO2 eq | 0.0123   | 0.0117      | 0.0111       | 0.0062  | 0.0059    | 0.0056      |
| Climate change - GWP 100      | kg CO2 eq | 3.8074   | 3.6172      | 3.4270       | 1.9794  | 1.8807    | 1.7819      |
| Eutrophication                | kg PO4 eq | 0.0011   | 0.0010      | 0.0010       | 0.0006  | 0.0005    | 0.0005      |

4. Conclusions

From this study, tensile properties and flexural strength of polypropylene (PP) and acrylonitrile butadiene styrene (ABS) products can be improved by reinforcing with recycled carbon fibre. The composites with 10% filler loading have the highest value of flexural strength, tensile strength and Young’s Modulus. The 5% filler loading may not be sufficient to act as reinforcement in the composites. It is predicted that higher amount of filler could improve the mechanical properties more significantly. However, this may also leads to processing difficulties, particularly for injection moulding or 3D printing methods. In terms of environmental impact, PP products are more preferable.
The usage of rCF successfully reduces the environmental impact as lower amount of thermoplastic is used. Besides, rCF also have low embodied energy and cheaper than its virgin precursor.

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