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Experimental and theoretical studies on the properties of injection moulded glass fibre reinforced mixed plastics composites

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ABSTRACT

Recycled mixed post-consumer and post-industrial plastic wastes consisting of HDPE, LDPE and PP were injection moulded with short glass fibre (10–30% by weight) to produce a new generation composite materials. Intensive experimental studies were then performed to characterise the tensile, compression and flexural properties of glass fibre reinforced mixed plastics composites. With the addition of 30 wt.% of glass fibre, the strength properties and elastic modulus increased by as much as 141% and 357%, respectively. The best improvement is seen in the flexural properties due to the better orientation of the glass fibres in the longitudinal direction at the outer layers. The randomness and length of the glass fibre were accounted to modify the existing rule of mixture and fibre model analysis to reliably predict the elastic and strength properties of glass fibre reinforced mixed plastics composites.

1. Introduction

Plastics have become a necessity in modern life with its use in packaging, automotive, industrial applications and so on. With an increasing number of applications being found, the world's annual consumption of plastics have increased from 5 million tons in 1950s to nearly 100 million tons in 2007 [1]. Majority of these plastics are used in short term applications such as packaging, hence the amount of plastics in the landfill is increasing correspondingly. Since plastics in the landfill are often a mixture of numerous blends, it is not economically viable to sort it in its generic form which is seen as a major hindrance for the recycling of mixed plastic solid waste (PSW). One huge market for recycled mixed PSW is the building and construction industry where it can be used as an alternative for timber. However, the majority of plastic found in mixed PSW are immiscible, which means when they are melted and blended, they often have inferior mechanical properties [2]. Hence, a careful separation is performed to obtain the mixed PSW as homogeneous as possible. Using floatation method, the lighter division of mixed PSW, namely high density polyethylene (HDPE), low density polyethylene (LDPE) and polypropylene (PP) commonly known as polyolefin, can be separated from the heavier plastic blends.

Many researchers have focussed their study on the mechanical behaviour of mixed polyolefin as the majority of plastic consumed, around 50–60%, is made up of HDPE, LDPE and PP [3]. For instance, Dintcheva et al. [4] had investigated the effect of filler type on the tensile properties of the mixed polyolefin. Their studies showed that the mixed polyolefin can have comparable strength but much lower modulus of elasticity than softwood timber which is seen as the main limitation of its usage in civil engineering applications. As a result, researchers [4–7] have investigated the introduction of short fibre reinforcement to enhance its strength and stiffness. While several studies have shown the potential of using glass fibres as reinforcement in recycled mixed plastics composites, limited work has been conducted to comprehensively study the effect of randomly oriented short glass fibre on the tensile, compression, and flexural behaviours [8]. Such study is essential for the use of these composites in various load bearing applications to become widespread.

Investigation of the mechanical behaviour is also important as most reinforced plastics are manufactured by the injection moulding process which produces a complex orientation of fibre in the end product. Many researchers have reported the dominance of fibre orientation in the direction of flow near the wall and transverse orientation in the core [9–11]. In addition, Barbosa and Kenny [12] had studied the relationship between fibre orientation

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and tensile properties in short fibre reinforced polypropylene as a function of the position in the plate. They found out that, for polypropylene reinforced with 40 wt.% of glass fibre, the tensile modulus of the extreme layer was almost 50 percent higher than that of the core. This indicates that the behaviour of fibre-reinforced composites strongly depends on the orientation and distribution of the fibres in the injection moulded specimen. Furthermore, this also implies that, for injection moulded composites, the effect of glass fibre content will have a different set of improvement for tensile, compression, and flexural loading. Thus, the investigation of the effect of glass fibre on the mechanical behaviour of reinforced mixed PSW will be useful in identifying its specific end product based on the improvement produced by glass fibre content on a different set of properties.

Previous work by the authors [13] dealt with the characterisation of the mechanical behaviour of mixed plastic solid waste (PSW) containing a mixture of high density polyethylene (HDPE), low density polyethylene (LDPE) and polypropylene (PP) which indicated that consistent material properties can be obtained for mixed PSW with similar compositions and produced using the same method. As the quantity of each component of mixed PSW is rarely known, it is recommended to use the coupon specimen's properties to predict the behaviour of the full-scale specimens. This paper investigates the performance of injection moulded mixed plastic solid waste composites containing 10, 20 and 30 wt.% of glass fibre under tension, compression and flexure. In addition, theoretical analyses were conducted to develop simplified equations that can reliably predict the mechanical strength of glass fibre reinforced mixed plastic solid waste composite (GMPC). The existing rule of mixture and fibre model analysis was modified to account for the randomness and length of the fibre in the predictive model. Finally, the mechanical properties of GMPC were compared with timber to determine their suitability as a new construction material.

2. Experimental program

2.1. Materials and compounding

Four types of test specimens were produced using mixed plastic solid waste (PSW) composed of HDPE, LDPE and PP supplied in the form of flakes by Repeat Plastics (Replas) Pty of Australia which was collected from post-consumer and post-industrial plastic waste; and chopped glass fibre (GF) supplied by Owen Corning under product code 147A having a length of 4.0 mm and diameter of 13.7 µm. At first, the materials were compounded using a Chubu Kagaku Kikai's single screw extruder at the temperature of 170 °C and the rotation speed of 87 revolution per minute. Then the extruded material was granulated into pellets to the length of 4–5 mm. These pellets were oven dried for 24 h at 60 °C to remove the residual water originating from the cooling step in the compounding process prior to injection moulding.

2.2. Injection-moulding

Standard test specimens were injection moulded using 75 tonnes Engel injection moulding machine with the temperature profile of 205–220 °C. The formulation of four types of specimens is shown in Table 1. The test specimens were labelled as G-#, where # denotes the weight percentage of glass fibre content.

Table 1
Designation and composition of the test specimens.

Specimen name	G-0	G-10	G-20	G-30
GF (%)	0	10	20	30
Mixed PSW (%)	100	90	80	70

2.3. Optical and scanning electron microscope observation

The cross-section of the specimens were observed under an optical and scanning electron microscope (SEM) to observe the fibre orientation and the morphology of glass fibre reinforced mixed plastic solid waste composite (GMPC). Prior to SEM observation, the fracture surface of tensile specimens were sputter-coated with gold and examined in a Phenom desktop SEM at 10 kV. The crack propagation of compression, flexure and shear test specimens were observed using an optical microscope.

2.4. Determination of fibre content and length

The fibre content and length were determined by burning out the matrix following ASTM D2584 [14]. Firstly, the GMPC specimens, 15 mm by 9.85 mm by 3.5 mm, were taken from the injection moulded specimen (shown in schematic representation of Fig. 1) and placed in a crucible. The crucible was heated in an electric muffle furnace to 600 °C for two hours to burn and remove the mixed PSW to determine the glass fibre content. Then, the glass fibres were observed under the optical microscope and image analysis software program where about 100 random length measurements were made to determine the weight average fibre length (l_w) which was computed using Eq. (1).

$$l_w = \frac{\sum n_i l_i^2}{\sum n_i l_i} \tag{1}$$

where n_i and l_i is the sample frequency and length of ith fibre, respectively.

2.5. Evaluation of mechanical properties

All the mechanical characterisation tests were carried out using a 10 kN MTS hydraulic testing machine on five specimens for each type of test. The detail of the coupon specimens is shown in Table 2. Tensile properties were measured in accordance with ISO 527-1 [15], using ISO Type 1B specimens at a crosshead rate of 5 mm/min and an extensometer gauge length of 50 mm. Compressive properties were measured in accordance with the procedure in ASTM D695 [16] with the slenderness ratio of 13 at a crosshead rate of 1.3 mm/min. Three point bending test was performed to measure the flexural properties in accordance with the procedures in ISO 178 [17] at a crosshead rate of 2 mm/min and a span length of 56 mm. As the size of the test specimens produced was relatively small, appropriate shear test methods cannot be performed and is not included in this study.

3. Experimental results and observation

3.1. Physical properties

3.1.1. Density

The density of the specimens, G-0 to G-30, was measured experimentally and found to be 0.857, 0.913, 0.981 and 1.066 g/cc, respectively. Then the density of glass fibre (ρ_f = 2.5 g/cc) and mixed PSW (ρ_m = 0.857 g/cc) was used to convert the glass fibre weight fraction (w_f) to glass fibre volume fraction (v_f) using Eq. (2). The glass fibre volume fraction for the specimens, G-10 to G-30, was calculated as 0.037, 0.079 and 0.128, respectively. Also the rule of mixture was used to predict the density of the specimens, G10 to G-30, which was found to be 0.917, 0.986 and