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Durability characteristics and property prediction of glass fibre reinforced mixed plastics composites

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This paper presents an experimental and theoretical studies of the durability of composite materials made from mixed plastic solid waste (PSW) containing high-density polyethylene, low-density polyethylene, polypropylene and short glass fibres (10–30% by weight). The effects of exposure to elevated temperatures, UV radiation and moisture ingression were the main parameters considered. The results showed that the exposure to a temperature of 60 °C or higher weakens the adhesion of the glass fibre due to the softening of the mixed PSW and resulting in reduced mechanical properties. Furthermore, exposure to UV radiation results in the shrinkage of the specimens improving the interfacing bonding whereas exposure to moisture results in the swelling of the specimens weakening the interfacial bonding. Besides, the addition of glass fibre reduces the surface degradation of composites under UV and moisture ingression resulting in higher matrix properties. For design purposes, a single equation based on modified rule of mixture was developed to predict the tensile modulus and strength of these composites by introducing environmental factors accounting the effects of different exposure conditions.

1. Introduction

Mixed recycled plastics composites have raised interest for reapplications due to the growing worldwide concern over the disposal of plastic waste as only around one-fourth of it is currently being recycled while the rest of it continues to litter roadways, clog landfills and pollute environment [1]. This paper deals with the two main components of plastic solid waste (PSW) i.e. polyethylene (PE) and polypropylene (PP) which represents 50–60% of plastics consumed in many countries [2,3]. As these two plastics have similar densities, it is practically infeasible to separate them into their generic form. Therefore, an effective way to increase the recycling rate and reduce the separation cost is converting mixture of PE and PP into products suited for building and construction industry [4]. Although the mixed plastic solid waste (PSW) reinforced with glass fibre has been used to construct vehicular bridges as in Fort Bragg in North Carolina and railroad bridge as in Fort Eustis in Virginia [5], there is a lack of published academic work on the performance of these composites under different environmental conditions which is seen as the major hindrance for their widespread use in the construction industries [6].

As in most civil engineering applications, the polymer composites are likely to be subjected to relatively high in-service temperature gradient during summer and fire exposure [6]. This is of particular interest with the polymer composites as once the temperature exceeds the glass transition temperature (T_g), the polymer will rapidly lose their strength and stiffness [7]. The other two weather factors that can contribute to degradation in plastics composites include ultra-violet (UV) exposure and moisture ingression. In general, exposure to UV radiation causes photochemical damage of composites near the exposed surface leading to discoloration and reduction in molecular weight [8,9]. Initially, it is limited to a superficial layer until cracks appear in the layer which opens new pathways for oxygen to penetrate the specimen and lead to more extensive oxidation and aggravate resin erosion. Temperature, and for some composites, moisture, are among the most severe influential variables encountered during service. The composite material tends to absorb moisture in humid environments which causes dilatational expansion and weakening of the

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Abbreviations

v_f	volume fraction of glass fibre
E_m	tensile modulus of matrix
$\sigma_m^{'}$	tensile strength of matrix at failure strain of composites
E_f	tensile modulus of glass fibre
σ_f	tensile strength of glass fibre
χ_1	reduction factor depending on orientation of glass fibre
χ_2	reduction factor depending on final length of glass fibre and bonding of fibre-matrix interface
χ_{f-m}	environmental factor for fibre-matrix interface
χ_m	environmental factor for matrix

fibre-matrix interface [10,11]. As mentioned in the recent review by Bajracharya, Manalo [1], most of the studies of degradation mechanisms of polymeric material have concentrated largely on the virgin and/or single grade polymers and their composites [12,13]. Also, it is evident that some of the engineering aspects of weathering-related failure of polymers are not as well understood as the chemical mechanisms of degradation. Thus, to be able to predict service life of recycled mixed plastic solid waste (PSW) and its composites, a more comprehensive study of the engineering aspects of failure as well as their behaviour under simulated environmental conditions is required.

As mentioned during the service periods, the composites are exposed to various environmental conditions such as elevated temperatures, ultra-violet (UV) radiation and the ingress of moisture. The performance of composite materials is governed by the response of their constituents i.e. fibre, matrix and the existing interface/interphase in that particular environment [11,14]. Although glass fibre reinforced composites are highly resistant to degradation to environmental factors, harmful effects such as debonding still play an important role in durability response under environmental exposures. The interface between fibre and matrix is most critical and decisive in maintaining sustainability, durability and also reliability of this composites, but unfortunately a comprehensive conclusion is yet to meet the label of confidence for the engineering viability [15]. The recent review by Sethi and Ray [15] have also emphasised that it is essential to accurately predict the damage phenomena, in order to explore the full potential of the mechanical properties of composites.

Thus, the aim of this paper is to thoroughly investigate the behaviour of the matrix (mixed PSW) and glass fibre reinforced mixed plastic solid waste composites (GMPC) with 10–30 wt % of glass fibre under the effect of elevated temperatures, UV radiation and moisture ingression. In the present study, the mixed PSW is a mixture of high-density polyethylene (HDPE), low-density polyethylene (LDPE) and polypropylene (PP). Firstly, the behaviour of the mixed PSW and GMPC specimens at different environmental conditions are evaluated in terms of weight difference, surface degradation, tensile stress-strain curve and interface observation. Then, the paper develops a single equation based on the modified rule of mixture considering the effect of degradation of matrix, physical and interface observation which can predict the tensile behaviour of the short glass fibre reinforced mixed PSW composites. A single equation considering environmental factors can provide an important tool for civil engineers and designers to predict the behaviour of the GMPC under different environmental conditions.

2. Experimental program

2.1. Materials

Test specimens were produced using mixed plastic solid waste (PSW) composed of HDPE, LDPE and PP (having density of 0.857 g/cc) collected by Replas from post-consumer and post-industrial waste and chopped glass fibre supplied by Owen Corning under product code 147A having length of 4.0 mm, diameter of 13.7 μm and density of 2.5 g/cc. Since the mixed PSW is a mixture of different plastics with the possibility of contamination, the differential scanning calorimetry (DSC), dynamic mechanical analysis (DMA) and X-ray photoelectron spectroscopy (XPS) analysis was performed to characterise the melting temperature, glass transition temperature (T_g) and detection of element present in the mixed PSW used in this study, respectively. The DSC curve (Fig. 1(a)) showed three different peaks one at 100 °C (melting temperature of LDPE), the other one at 130 °C (melting temperature of HDPE) and the final one at 170 °C (melting temperature of PP). This shows that the mixed PSW will start to melt at 100 °C, which means the mixed PSW and their composites will lose most of its mechanical properties after 100 °C. The loss modulus curve of DMA analysis (Fig. 1(b)) showed two distinct peaks at about −130 °C (T_g of polyethylene) and −30 °C (T_g of polypropylene) and the storage modulus (Fig. 1(c)) decreased rapidly when the temperature reaches around −30 °C. This shows the mixed PSW will start to lose its mechanical properties from −30 °C. XPS scan (Fig. 1(d)) showed oxygen and carbon as the main elements. Further to this, a high resolution spectrum of the O_{1s} region from 275 to 300 eV and of the C_{1s} region from 525 to 540 eV detected the presence of C—C and C=O bonds that are capable of absorbing the ultra violet radiation and involved in the photoreactions that can result in the UV degradation of the recycled mixed PSW.

2.2. Test specimens

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 revolutions per minute. Then the extruded material was granulated into pellets to a 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. The dumb-bell shaped tensile test specimens (Type 1B of ISO 527-2 [16] as shown in Fig. 2) were injection moulded using 75 tonnes Engel injection moulding machine with the temperature profile of 205–220 °C. The weight composition and fibre volume fraction of the test specimens is shown in Table 1. The tensile behaviour of these composites under normal environmental condition can be found in our previous work [17] which is summarised in Table 2.

2.3. Elevated temperatures, UV exposure and hygrothermal ageing

To simulate the summer weather (40 °C and 60 °C) and fire exposure without flame effect (60 °C, 80 °C and 100 °C), an Instron 3119 thermal chamber was incorporated onto the testing machine. Then the tensile test was conducted following ISO 527-1 [18] using 10 kN MTS machine at the test speed of 5 mm/min. To simulate the exposure to ultraviolet radiation, the test specimens were placed in a solar radiation simulator (ATLAS, Suntest XLS) and subjected to 2000 and 4000 h of UV radiation produced by a 2200 Watt air-cooled xenon arc lamp (cut off < 290 nm) (Item: ATL56-0777-98 supplied by ThermoFisher Scientific) in accordance with the ASTM G155 [19] standard. The weight of the specimens were measured before and after the exposure to UV radiation to calculate