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LETTER

The influence of moisture on the mechanical properties of wood polymer composites

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Introduction

Current estimates suggest that approximately 6 million tonnes of plastic materials are used in the United Kingdom every year of which roughly 2.8 million tonnes appear in the UK waste stream [1]. Recent studies have shown that only 0.5 million tonnes of polymeric waste is recycled on an annual basis leaving the remaining 2.3 million tonnes to be buried, incinerated or disposed of by other means [1]. Similarly, large amounts of waste wood are produced every year in the United Kingdom of which only relatively small amounts are reused or recycled. In order to comply with stricter European Union legislation, governments have set targets to reduce waste and to increase recycling and re-use. Currently, recycled plastics are findings increasing use in a wide range of applications including toys, compost bins, containers for non-food products and recycling bins. One interesting option receiving growing attention is the possibility of combining both polymeric and wood waste to manufacture wood fibre reinforced composites or wood-fibre plastic composites (WPCs). Current applications of WPCs include noise barriers for garden decking, all-weather furniture and window profiles [2]. WPCS are also attracting significant interest from the civil engineering sector since they offer a superior durability than wood and they require little maintenance during service [2]. The properties of WPCs depend strongly on the fibre tensile strength, the fibre weight fraction and the properties of the matrix material [3]. Yin et al. [4] studied crystallisation effects in wood fibre/polypropylene composites. They showed that for neat polypropylene, the wood fibre exhibited a poor nucleating ability, with little difference in bulk and surface crystallisation being observed. However, when a maleic anhydride modified polypropylene was added, the nucleation density at the wood fiber surface became very pronounced and a transcrystalline layer was formed around the fibre [4]. Bengtsson et al. [5] studied the effect of crosslinking on the properties of WPCs. They showed that crosslinked composites absorbed less water than non-crosslinked systems, an effect that was attributed to an enhanced level of polyethylene/wood adhesion in the crosslinked polymer. Stark and Rowlands [6] investigated the effect of wood fibre characteristics on the fracture properties of wood/polypropylene composites. They showed that aspect ratio rather than particle size had the greatest effect on the strength and stiffness of the composite. Little work has been undertaken to investigate the effect of long-term moisture absorption on the fracture properties of WPCs. Jana and Prieto [7] studied the inclusion of coupling agents on WPCs. They showed that although the compatibilising agents reduce the rate of moisture diffusion into the composite, their tensile and impact strength are adversely affected. Stark and Matuana [8] observed the formation of surface cracks and a reduction in the flexural modulus of WPCs, following accelerated weathering tests. Balatinecz and Park [9] stated that the absorption of water by the composite can cause the wood to swell, leading to a reduction of the interfacial strength and consequently a decrease in the composite strength. Indeed, Xue et al. [10] showed that the flexural strength of an aspen fibre reinforced

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polypropylene WPC were reduced by up to eighty percent when exposed to humidity at room temperature. Similar results have also been observed in WPCs based on thermoplastic materials following moisture exposure tests [11–13]. Clearly, this is an important issue since many WPC products are used in outdoor environments where moisture levels can be very high. The aim of this research project was to investigate the effect of water immersion on the fracture properties of a wood/polyethylene composite similar to that being used in the manufacture of decking structures and outdoor applications.

In this study, the influence of absorbed moisture on the mechanical properties of WPCs was investigated through a series of flexural, compression and fracture-mechanics tests on samples removed from flat plates. The plates were based on high density polyethylene (HDPE) reinforced with wood flour. The nominal weight fraction of wood flour was fifty percent in all of the samples and the nominal density of the samples was 820 kg/m^3. The average size of the wood flour particles after manufacture was assessed by sectioning a number of samples and examining them under an optical microscope. Here, the size of the flour particles was found to range from 0.1 to 1 mm with the average size being approximately 0.5 mm.

The flexural properties of the WPCs were investigated using rectangular bars with length, breadth and thickness dimensions of 240, 35 and 19 mm, respectively. The samples were supported on 10 mm diameter cylinders positioned 230 mm apart and loaded to fracture at a crosshead displacement rate of 2 mm/min. The flexural moduli, E_f, of the WPC samples were determined from the initial slope, k, of the load, P, versus displacement, δ, curve using:

$$E_f = \frac{kL^3}{4Bt^3}$$

where L is the support span, B the specimen width and t the specimen thickness.

The flexural strengths, σ_f, of the WPC samples were determined using:

$$\sigma f = \frac{3PL}{2Bt^2}$$

Here, the force P was taken as the maximum force on the load-displacement trace.

The compressive properties of the WPCs were evaluated using 22 mm square samples with a nominal thickness of 20 mm. The samples were placed between two stainless steel plattens and loaded at a crosshead displacement rate of 1 mm/min. The tests were interrupted once the force-displacement trace had passed through a maximum. The compressive strength of each individual sample was then determined by dividing the maximum force by the initial cross-sectional area of the specimen.

The single edge notch bend (SENB) sample was used to characterise the Mode I fracture toughness of the materials investigated in this study. SENB specimens with length, depth and thickness dimensions of 200 mm, 50 mm and 25 mm were removed from flat plates using a band saw. In order to guarantee maximum crack-tip constrains, fracture toughness testing requires an initial crack length of about half the depth of the specimen [14]. Therefore, notches of nominal length 25 mm were introduced at the mid-span position using the band saw. The notches were sharpened by sliding a fresh razor blade along the crack tip region. The samples were loaded at a crosshead displacement rate of 10 mm/min until the crack had propagated through the depth of the sample. In general, the load-displacement traces exhibited some non-linearity prior to maximum load and a 5% offset load was used in all calculations. Here, a straight line was drawn from the origin of the load-displacement trace with a slope equivalent to 95% of the slope of the linear portion of the trace. The value of the force at the intersection of this secant with the original curve was taken as the force P_nl, and this value was used in subsequent calculations. The Mode I fracture toughness, K_Ic, was determined using:

$$K_\mathrm{Ic} = f\left(\frac{a}{w}\right)\frac{P_\mathrm{nl}L}{bw^{3/2}}$$

where b is the thickness of the specimen, w equal to its height and $f(a/w)$ is a geometric parameter depending on the crack length. Here, the geometry factor $f(a/w)$, was given by:

$$f\left(\frac{a}{w}\right) = \frac{3\left(\frac{a}{w}\right)^{0.5}\left[1.99 - \left(\frac{a}{w}\right)\left(1-\frac{a}{w}\right)\left(2.15 - \frac{3.93a}{w} + \frac{2.7a^2}{w^2}\right)\right]}{2\left(1+\frac{2a}{w}\right)\left(1-\frac{a}{w}\right)^{1.5}}$$

where a is the crack length. The Mode I critical strain energy release rate was then determined from the values of K_Ic using:

$$G_\mathrm{Ic} = \frac{(1-v^2)K_\mathrm{Ic}^2}{E}$$

The influence of water absorption on the mechanical properties of the WPCs was investigated by immersing

25 mm cube samples in baths of cold tap water for time periods up to 35 days. The rate of water absorption was characterised by periodically removing specimens from the baths and weighing them on a high precision balance.

The fracture surfaces of many of the failed samples were examined using a Wild lower power optical microscope and a Cambridge 250 scanning electron microscope.

The absorption of water in WPCs is complex and depends on a number of parameters including the weight fraction of fibre, the type of matrix, the level of interfacial bonding, the overall temperature and the presence of a compatibilizer. Due to its hydrophobic nature and high density, HDPE does not absorb significant water in humid environments. In contrast, wood is hygroscopic and is not dimensionally stable with changes in moisture content below the saturation point. In this study, water absorption was monitored by weighing small 22 × 22 × 20 mm samples at regular intervals. Figure 1 shows the variation of water uptake with the square root of time in five nominally identical specimens. All samples exhibited an initial rapid increase in water uptake that may be associated with water permeating wood particles on the cut edges of the specimen. With prolonged exposure, the slope of the absorption curve drops and becomes more linear, as would be expected if the process obeyed Fick's law. In this region, it is possible that water is penetrating deeper into the material, reaching particles embedded some distance from the surface.

The variation of the flexural modulus of the WPCs with absorbed moisture is shown in Fig. 2. From the figure, it is clear that the modulus falls as the moisture content increases with the final value being approximately twenty-five percent below the initial, as-received value. Figure 3 shows the variation of the flexural strength of the composites with moisture content. Here, a reduction of fourteen percent is registered in samples containing three percent of moisture. The recorded reductions in flexural strength and modulus may be due to plastification of the matrix associated with disruption and fracture of the Van der Waals forces between the chains of the HDPE. Similarly, the disruption of the highly ordered hydrogen bonds in the structure of the wood weakens the resistance of the wood to applied stress resulting in a loss of strength and stiffness within the reinforcement. An examination of the fractured samples indicated that the failure mode was similar in all samples with the fracture surface exhibiting a relatively smooth appearance. A more detailed investigation of the fracture surfaces was subsequently undertaken using a scanning electron microscope. Figure 4a shows the fracture surface of a dry specimen following flexural failure. An examination of the micrograph highlights a fractured wood particle that has been pulled out of the neighbouring matrix. The HDPE matrix exhibits limited ductility and a number of cavities. The fracture surface of a specimen that had absorbed approximately 3% by

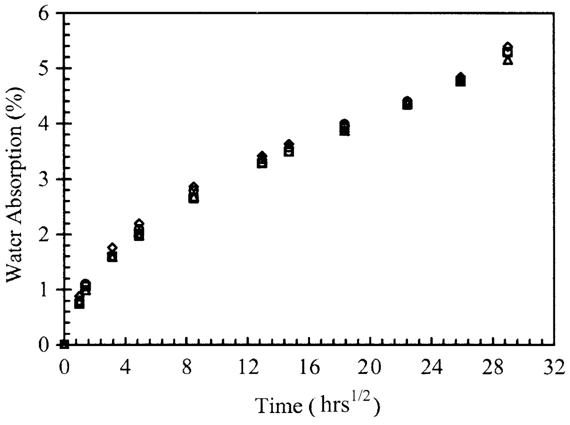

Fig. 1 The water absorption profiles of four WPC specimens

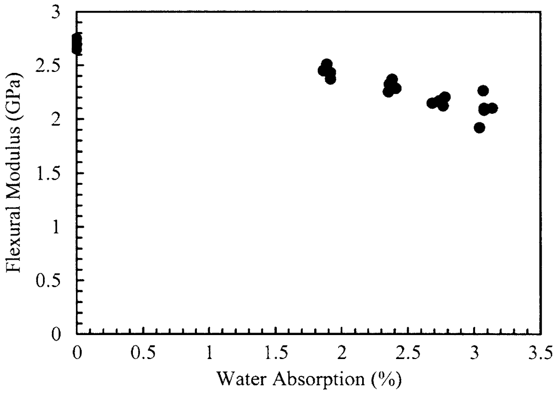

Fig. 2 The variation of the flexural modulus of the WPC samples with moisture content

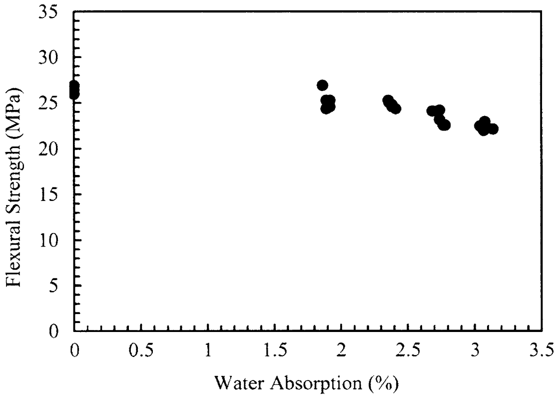

Fig. 3 The variation of the flexural strength of the WPC samples with moisture content

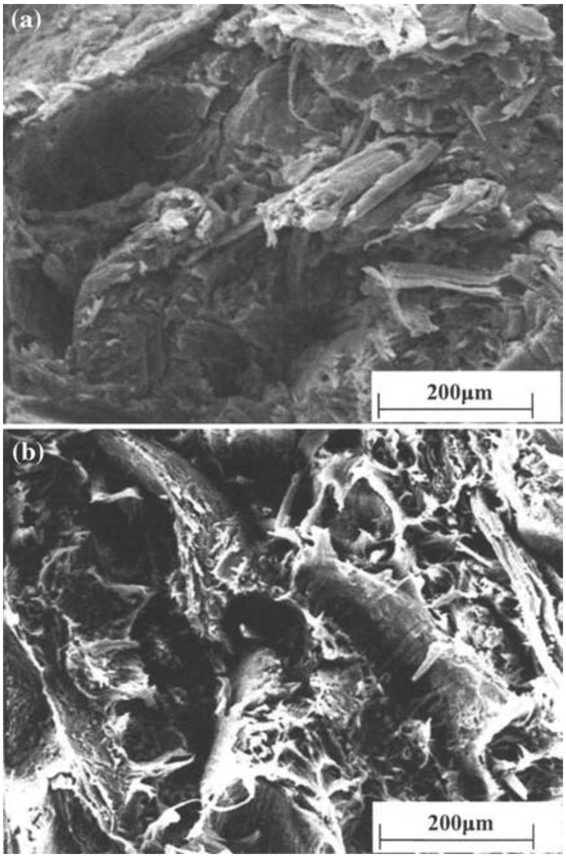

Fig. 4 Scanning electron micrographs of the fracture surfaces of as-received and moisture-conditioned flexural samples

weight of water is shown in Fig. 4b. Here, greater amounts of localised ductility are apparent within the thermoplastic matrix suggesting that the absorbed moisture has influenced the mechanical properties of the matrix material.

Figure 5 shows the effect of absorbed moisture on the compressive properties of the WPC composite. The compressive strength of the composite prior to water immersion averaged approximately 41 MPa. The figure indicates that the presence of moisture precipitated a reduction in the compressive strength of the composite. Although there is a clear lack of data up to a moisture content of three percent, the figure does suggest that the properties degrade more rapidly in samples containing more than three percent water. An examination of the associated stress-strain curves highlighted the presence of much greater levels of non-linearity prior to maximum load in samples containing greater levels of absorbed moisture. It is possible that with prolonged exposure, the wood filler began to absorb moisture resulting in a loss in stiffness and strength. Indeed, previous work has shown that humid wood filler can act as an elastomeric phase increasing deformation mechanisms in the matrix leading to an increase in the strain to failure [10].

Figure 6 shows the variation of the critical strain energy release rate, G_{Ic},, of the wood polymer composites with moisture content. The initial value of G_{Ic} for the WPC was approximately 4500 J/m^2, a value that highlights the impressive fracture properties of these systems. An examination of the figure indicates that this value decreases by forty percent over the range of water contents considered. It is unfortunate that no data are available for higher water contents. This is due to the fact that the SENB samples were significantly larger than the compression test samples and the water uptake was therefore considerably slower. Due to time limitations, it was not therefore possible to immerse these larger SENB samples for sufficient time periods to achieve the levels of water uptake observed in the small compression test samples. It is possible, therefore that the fracture toughness properties might suffer more significant reductions at higher water contents. Figure 7 shows scanning electron micrographs of the fracture surfaces of the SENB specimens. The

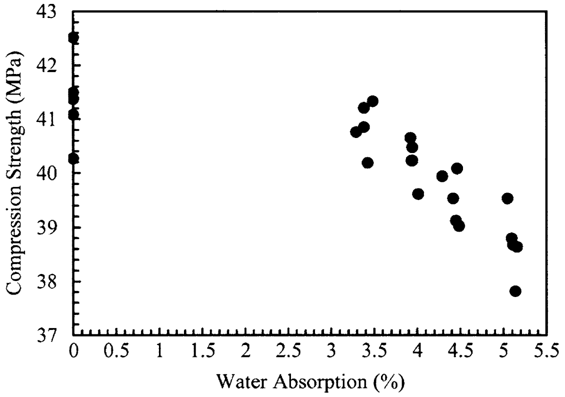

Fig. 5 The variation of the compression strength of the WPC samples with moisture content

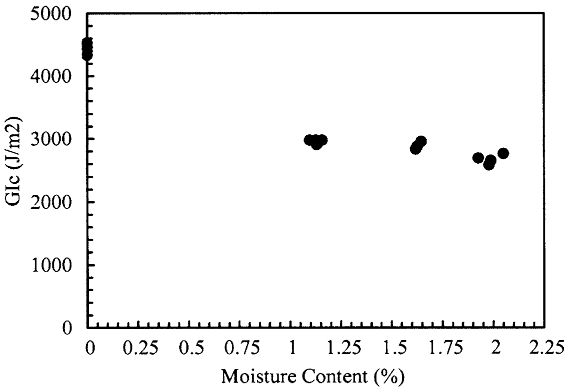

Fig. 6 The variation of the critical strain energy release rate, G_{Ic}, of the WPC samples with moisture content

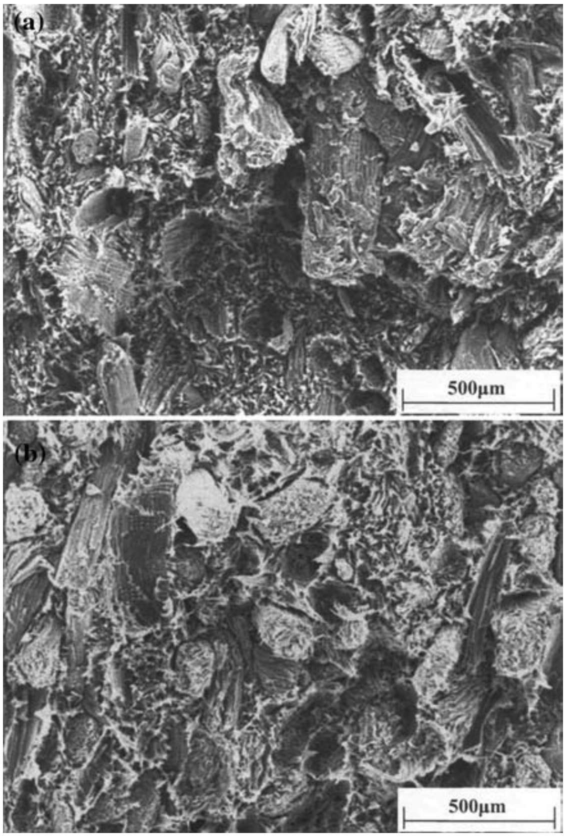

Fig. 7 Scanning electron micrographs of the fracture surfaces of as-received and moisture-conditioned SENB samples

as-received sample, Fig. 7a, exhibits a number of fractured wood particles and limited matrix ductility within the thermoplastic matrix. Similar observations can be made following an examination of the fracture surface of a sample containing two percent absorbed water, Fig. 7b.

The results of this study indicate that the fracture properties of wood polymer composites are sensitive to the presence of absorbed moisture. Data from compression tests on small WPC cubes suggests that high levels of absorbed moisture may be particularly detrimental to the load-bearing properties of these fibrous materials. Further work is required to fully assess the effects of higher moisture levels on other key fracture properties.

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