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Determination of interfacial shear strength of white rot fungi treated hemp fibre reinforced polypropylene

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ABSTRACT

Short untreated and white rot fungi treated hemp fibre, polypropylene (PP) and maleated polypropylene (MAPP) coupling agent were extruded and injection moulded into composite tensile test specimens. The tensile properties of untreated and treated fibre and their composites were measured. The fibre length distributions in the composite were obtained by dissolving the PP/MAPP matrix in boiling xylene to extract the fibre. Both the Single Fibre Pull-Out test and the Bowyer and Bader model were used to determine the interfacial shear strength (IFSS) of these composites. IFSS was found to be lower for the Single Fibre Pull-Out test, which was considered to be largely due to axial loading of fibre and the resulting Poisson's contraction occurring during this technique. This suggests that the Bowyer and Bader model provides a more relevant value of IFSS for composites. The results obtained from both methods showed that IFSS of the treated fibre composites was higher than that for untreated fibre composites. This supports that the hemp fibre interfacial bonding with PP was improved by white rot fungi treatment.

1. Introduction

Improving interfacial bonding between fibres and matrices is an important issue in using hemp fibre for reinforcement in composites. Previous research has shown that white rot fungi treatment is able to separate hemp fibre bundles, remove non-cellulosic compounds and roughen hemp fibre surfaces. In addition, improvement in composite strength with a PP matrix was obtained which was assumed to be due to improved interfacial bonding [1]. However, direct assessment of interfacial strength was not conducted.

One common parameter for the description of interfacial strength is interfacial shear strength (IFSS). There are a number of methods to assess IFSS, including micromechanical tests such as the Single Fibre Pull-Out test, the fragmentation test, the microdebond test and the microindentation test, as well as mathematical modeling based on composite properties such as the Bowyer and Bader model.

1.1. Single Fibre Pull-Out test

The Single Fibre Pull-Out test is a commonly used technique to measure interfacial shear strength (IFSS), in which the end of a fibre is embedded in block of matrix that is held as the fibre is pulled out whilst recording load versus displacement to give a "pull-out curve". The Single Fibre Pull-Out test offers a number of important practical advantages: firstly, it is a direct measurement of interfacial strength, secondly, it requires only small amounts of fibre and matrix, and thirdly, the debonding force can be plotted as a function of displacement and information about the failure process can be gained, e.g. a sudden drop in applied load indicates a brittle failure. However, the Single Fibre Pull-Out test is based on single fibre specimens and does not reflect the failure process within a composite. Overall though, the IFSS value from the pull-out test is considered to give a good indication of interfacial adhesion for natural fibre composites [2–4].

A typical force–displacement curve can be seen in Fig. 1. This can be considered in three parts ($F < F_d$, $F_d < F < F_{max}$ and $F > F_{max}$) corresponding to the different stages involved in pull-out, where F is the applied force, F_d is the critical force at which debonding is initiated, and F_{max} is the peak load. During the first part ($0 < F < F_d$), the curve is considered to represent linear elastic behavior of the fibre–matrix system and the fibre–matrix interface remains intact. For the second stage ($F_d < F < F_{max}$), after initiation, debonding occurs by means of crack propagation along the embedded fibre length. The applied force continues to increase due to the remaining adhesion of the intact part of the interface and the presence of frictional forces between the fibre and matrix. After reaching a peak load (F_{max}), crack propagation becomes unstable and the

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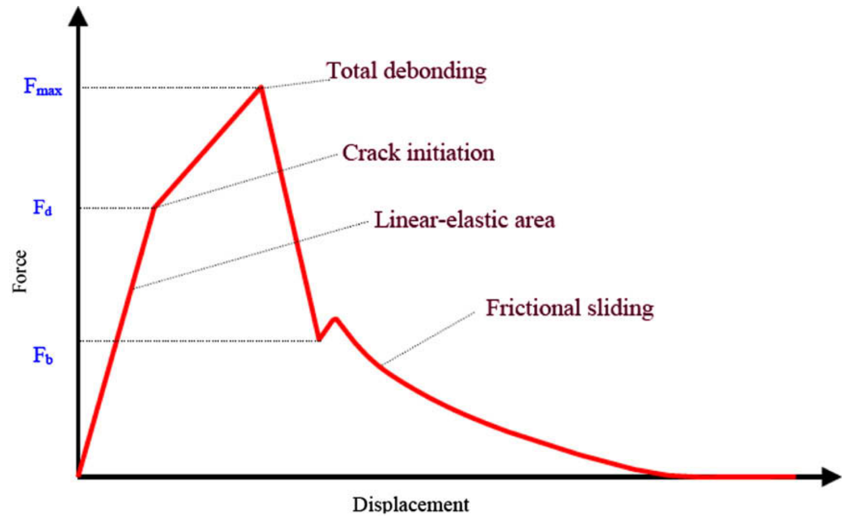

Fig. 1. Typical force–displacement curve for Single Fibre Pull-Out test.

whole embedded fibre length becomes fully debonded. The third part occurs after complete debonding has taken place, where the remaining force is due to frictional interactions between the fibre and the matrix (F_b). The apparent interfacial shear strength IFSS (τ) can be calculated using the following equation:

$$\tau = \frac{F_{\max}}{\pi D L_e} \tag{1}$$

where D is the fibre diameter and L_e is the embedded length [2].

1.2. The Bowyer and Bader model

The Bowyer and Bader model can also be used to determine the micromechanical parameters of interfacial shear strength IFSS (τ) from the macromechanical tensile stress–strain curve and fibre length distribution. This model has an enormous attraction in that it utilizes data which are readily available from standard tensile testing of composites and requires only the extra determination of fibre length distribution.

The basic premise of the Bowyer and Bader model is that at any value of composite strain, ε_c, there is a critical fibre length L_ε [5–8] such that:

$$L_\varepsilon = \frac{E_f \varepsilon_c D}{2\tau} \tag{2}$$

where E_f is the Young's modulus of fibres, D is the fibre diameter and τ is the interfacial shear strength. Fibres shorter than L_ε carry an average stress $E_f\varepsilon_c L/2L_\varepsilon$ and fibres longer than L_ε carry an average stress $E_f\varepsilon_c\ (1 - L_\varepsilon/2L)$.

The tensile stress of a discontinuous off-axis fibre composite could be determined from the sum of the sub-critical and super-critical fibre strength contributions and multiplied by fibre orientation factor and then added with the matrix contribution, as can be seen in Eq. (3).

$$\sigma_c = K_1(X + Y) + Z \tag{3}$$

where X is the contribution from the sub-critical fibres, Y is the contribution from the super-critical fibres, Z is from the matrix and K_1 is a fibre orientation factor. The individual terms can be expanded as follows:

$$X = \sum_{i}^{L_i<L_\varepsilon} \frac{\tau L_i V_i}{D} \tag{4}$$

$$Y = \sum_{j}^{L_j>L_\varepsilon} E_f \varepsilon_c V_j \left(1 - \frac{E_f \varepsilon_c D}{4\tau L_j}\right) \tag{5}$$

$$Z = E_m \varepsilon_c (1 - V_f) \tag{6}$$

where V is the volume fraction of the fibre lengths, L, subscripts i and j refer to the sub-critical and super-critical lengths, respectively. E_m is the Young's modulus of the matrix and V_f is the total fibre volume fraction.

For a practical system, E_f, E_m, and D can be readily obtained. The fibre length distribution can be determined from direct measurements on the extracted fibres. Although K_1 and τ are not generally known, values for these factors can be obtained if the composite stress (σ_1 and σ_2) at two strain values (ε_1 and ε_2) are known. Values of two strains ε_1 and ε_2 need to be selected and the corresponding stresses σ_1 and σ_2 determined from the tensile stress–strain curve. The matrix contribution (Z) can be calculated from an independent matrix Young's modulus determination and used to calculate the ratio R of the fibre load bearing contributions at the two selected strain ε_1 and ε_2 strains:

$$R = \frac{\sigma_1 - Z_1}{\sigma_2 - Z_2} \tag{7}$$

which according to Eq. (3) should be equivalent to R' as follows:

$$R' = \frac{X_1 + Y_1}{X_2 + Y_2} \tag{8}$$

An assumed value of τ is initially taken and the corresponding value of $L_{\varepsilon 1}$ and $L_{\varepsilon 2}$ are calculated. The fibre contribution terms X and Y are evaluated using the assumed values of τ and the corresponding $L_{\varepsilon 1}$ and $L_{\varepsilon 2}$ for the measured fibre length distribution. The ratio of R' is calculated by Eq. (8). The assumed value of τ is adjusted until $R' = R$. This value of τ is assumed to be correct and K_1 is determined from Eq. (3).

2. Experimental

2.1. Raw materials

Industrial hemp (*Cannabis sativa* L.) grown in Hamilton, New Zealand was used in this investigation. White rot fungi *Schizophyl-*