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The influence of fibre length and damage on the mechanical performance of polypropylene/wood pulp composites

Armin Thumm *, Alan R. Dickson

Scion, Private Bag 3020, Rotorua 3010, New Zealand

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ABSTRACT

Compression moulded wood fibre-reinforced thermoplastic composites were formed with radiata pine pulp fibres having four distinct fibre length distributions and three levels of fibre damage. The influence of these two parameters in regard to mechanical performance was investigated. Fibre length only had an influence when it dropped below a critical length. This critical length was found to be consistent with model calculations which put the critical length for radiata pine fibres at 0.8 μm. Fibre damage, defined in this study as dislocation and nodes, only had a minor influence on panel properties.

Injection moulded reference samples showed trends for the influence of fibre length and fibre damage which were consistent with compression moulded samples.

1. Introduction

Increasingly, wood pulp fibres are finding applications in fibre-reinforced thermoplastic composites. For example; NCell™ (GreenCore Composites Inc. Canada); Woodforce (Sonae Industria, Portugal); CreaMix (CreaFill Fibers Corp. USA); Kareline® (Kareline natural composites, Finland); UPM ForMi (UPM, Finland) are all products that incorporate wood pulp, rather than wood flour, for the reinforcement of plastics. There are a number of different pulp fibre types depending on wood source (relatively short but narrow hardwoods versus long but wide softwoods) or pulping method. Pulps where the fibres are liberated from each other by mechanical means at high temperature (e.g. thermo-mechanical pulps (TMPs) or medium density fibre board pulps (MDFs)) have higher yield but contain more fibre damage, such as fibre breakage and cell wall disruptions [1] than pulps produced by chemical processes that separate fibres by dissolving out wood components (e.g. kraft pulps). Additionally, pulps may be further processed (refined) by a mechanical process designed, largely, to increase fibre flexibility and generate fibrillar material. For paper products, the effect of refining is to increase the density and bonded area of the sheet, increasing the network strength. The differences in fibre dimensions, chemical composition, flexibility, amount of fines material and other pulp properties is tailored for the type and use of the paper product.

There is also growing interest in optimising wood pulp properties for composites. Fibre strength and length are critical factors for composite reinforcement performance. Investigating flax fibres between 3 and 25 mm length in polypropylene (PP) Garkhail et al. [2] found no improvement in composite strength for fibres longer than 6 mm. Laws and McLaughlin [3] conclude that the moduli of composites reinforced with short (glass) fibres behave as if they were reinforced with fibres of infinite length once the aspect ratio of the fibres is >100. The minimum length of a reinforcement fibre, i.e. the critical length, can be described as the length required to ensure sufficient adhesion between fibre and matrix so that the stress in the fibre can reach a fibre fracture stress. In its simplest form the critical length has been defined as [4]

$$\text{Critical fibre length } (l_c) = \frac{d\ \sigma_t}{2\tau} \quad (1)$$

In order to calculate the critical length, the tensile strength of the fibre (σ_t) and the interfacial shear strength (τ) need to be known. The fibre diameter is d and if the equation is divided by d it can be expressed as the "critical" aspect ratio being a ratio between fibre strength and interfacial shear strength. These factors have been measured for larger, agricultural fibres (e.g. van den Oever and Bos [5]) but are difficult to measure for small wood fibres. An alternative approach was taken by Rodriguez et al. [6] who calculated the fibre strength and interfacial shear strength through modelling of the mechanical properties of composites according to the method of Bowyer and Bader [4]. Using the deformation of the composite the critical fibre length in this case is defined as

$$l_c(\varepsilon_t^c) = \frac{E_t^f \varepsilon_t^c d}{2\tau} \quad (2)$$

* Corresponding author. Tel.: +64 7 343 5899; fax: +64 7 343 5507.
E-mail addresses: armin.thumm@scionresearch.com (A. Thumm), alan.dickson@scionresearch.com (A.R. Dickson).

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This equation requires knowledge of the modulus of the fibre in tension (E_t^f). Based on the approach described by Rodriguez, E_t^f and the interfacial shear strength (τ) can be calculated and consequently the critical fibre length determined (ε_t^c is the deformation of the composite which can be obtained from the stress/strain curve). In the case of the corn stalk fibre/PP composite used by Rodriguez critical fibre length can be calculated to be around 0.5 mm when appropriately compatibilised with maleated polypropylene (MAPP). The average diameter of the cornstalk fibres is given as 16.1 μm which would result in a "critical aspect ratio" of about 30.

Fibre strength is also important and is influenced by fibre damage and defects. The presence, terminology and effect of fibre defects in wood fibre have been reviewed a number of times in relation to wood or paper properties [7–10] and more recently in relation to composite properties [11]. For example, the number of microcompressions [8] has been shown to correlate with a reduction in fibre stiffness [12] and the presence of defects such as microcompressions and nodes [8] is known to lead to a reduction in fibre strength [13]. Such defects can be formed during pulp processing, such as mixing [14,15]. The differences in the scale and types of processing and their effects on fibres explains why laboratory produced pulps are generally stronger than those produced in mills [16].

Studies on the effects of wood pulp fibre length and damage on composite properties have been contradictory. Long fibres have been shown to be beneficial for composites made from birch chemi-thermomechanical pulp and polyethylene [17], and thermomechanical pulp (TMP) and polylactic acid [18]. On the other hand, little difference in strength performance was found for bleached kraft/PP composites [19]. However, in these studies fibre length fractions were obtained by refining [17] and screening [18,19] and it is known that under such conditions length is not independent of other factors [20]. Beg and Pickering [21] investigating kraft pulp reinforced PP, attributed reductions in composite tensile strength and stiffness to fibre damage and length reduction brought about by increased levels of pulp refining. There have been a number of studies on a range of fibre types in a range of matrices that show that processing operations such as compounding and injection moulding have a major influence on fibre length [22–27] and width [22,24,26] and consequently aspect ratio. The magnitude of the reductions in width and length are largely attributed to the magnitude of the shear forces [22] although the initial fibre dimensions can also have an influence on the dimensions after processing [24]. To our knowledge the mechanisms of fibre shortening for wood fibres in composites has not been examined in detail and will also not be examined in detail here. However, fibre breakage in flax fibres during processing [26] and in composite failure [27] has been shown to be related to the presence of prominent dislocations or nodes (generally called kink bands in non-wood fibres). Where bundles, rather than individual fibres are processed and show reductions predominantly in width but also in length, this is likely due at least in part to the separation into individual fibres. For wood fibres the effect of shear and temperature at the fibre–fibre interface is well understood and forms the basis of the different forms of mechanical pulping for the pulp and paper industries [1].

In this study we investigate, in a controlled manner, the related effects of fibre length and damage on fibre-reinforced thermoplastic composite properties independently. The influence of fibre length was investigated with a method in which an initially long fibre fraction was screened from a TMP. The fraction was then reduced in fibre length in a controlled and predictable manner by manual cutting. To investigate the influence of fibre damage a kraft pulp was submitted to extended periods of blending in a mixer (disintegrator). A wet forming technique and compression moulding were then used for composite production to minimise any further damage and length reduction that is known to occur during compounding [6,24,25,28,29]. The investigation also examined the influence of injection moulding on these materials. This was done for two reasons: firstly, to investigate whether trends observed in compression moulding would also be present in injection moulded samples and secondly, to investigate what effect injection moulding has on fibre length. The material for injection moulding was created by manually cutting compression moulded samples into pellets and feeding them directly into an injection moulder.

2. Material and methods

2.1. Materials

The TMP for fibre length investigation as well as the kraft pulp for fibre damage investigation was produced at Scion, New Zealand from *Pinus radiata* chips. Polypropylene (PP) fibres (Atofina) were provided by FiberVisions (Covington, Georgia, USA). The PP fibres were 23 μm wide and 5 mm long with a melting point (by DSC) of 165–166 °C. The fibres include an undisclosed coupling agent.

PP pellets (Seetech M1600, LG Daesan Petrochem, Korea) were injection moulded with a bleached kraft pulp (Carter Holt Harvey, NZ) to produce wood fibre tensile specimen required for modelling purposes.

2.2. Production of pulps with different fibre length

A 2-stage radiata pine slabwood TMP (120 Canadian standard freeness) was produced using 125 °C preheating and a residence time of three minutes. The pulp was pre-screened at the production site to obtain a fraction with increased fibre length. This fraction was used as a starting point for the experiments below.

To generate pulps with different fibre length independently of other fibre variables a modified version of that employed by He et al. [30] was used. The TMP was first passed through a 10 mesh screen (approximately 2 mm opening width) and the material on the screen collected to obtain a pulp with an average length weighted fibre length (LWL) of 3.0 mm.

$$\mathrm{LWL} = \left(\sum n_i l_i^2\right) * \left(\sum n_i l_i\right)^{-1} \quad (3)$$

This long fibre fraction was then reduced by making handsheets with random fibre orientation and cutting them with a guillotine. A FiberScan instrument (Andritz Sprout-Bauer) was used to measure fibre length distributions of the resulting pulps. The measurement principle of this instrument is based on fibres passing through a narrow passage between a light source and detector and the resulting light fluctuations are measured and converted to fibre length. The instrument is well suited to handle long stiff fibres such as TMP and MDF but has limited sensitivity to very small fibres such as fines. Four different fibre lengths were achieved by different cutting approaches as detailed in Table 1.

2.3. Production of pulps with different levels of fibre damage

A kraft pulp with a kappa number of 16 was prepared from *P. radiata* slabwood chips under the following conditions: 16% effective alkali charge; 30% sulphidity; 4:1 liquor:wood ratio; 90 min to 170 °C; 90 min at 170 °C. The general principles and procedures of kraft pulping can be found in [31]. The cooked chips were defibrated at 1% consistency in a Crompton Parkinson laboratory stirrer at 1400 rpm for 10 min and then screened through a 0.25 mm flatbed screen and collected on a 200 mesh screen (74 μm opening).

Damage was inflicted on the pulp by disintegration at 1.2% consistency following AS/NZS 1301.203s:2007. The disintegrator is a laboratory mixer as specified by AS/NZS 1301.214s:2007, with a