COMPARISON OF EXPERIMENTAL AND CALCULATED TENSILE PROPERTIES OF FLAX FIBRES

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ABSTRACT

The tensile properties of natural plant fibres are commonly determined by single fibre testing. The cross-sectional area used to determine the modulus and strength is usually obtained by measuring the fibre width and using this as the fibre diameter, on the assumption that the fibres are circular in section. While the assumption of circularity is reasonably true for synthetic fibres, it is not correct for natural fibres and this can lead to substantial error whendetermining the tensile properties of the fibres. The present study determined the tensile properties of 113 flax technical fibres, using an experimentally determined fibre areacorrection factor to account for the non-circularity of the fibres. The data was then compared to that obtained from back-calculation of the results obtained from longitudinal tensile testing of flax/vinyl ester unidirectional composites,which were manufactured from the same material as that used for the single fibre tests. Account was taken of the effect of fibre length on strength. The experimentally determined fibre area correction factor was found to be 2.70. Taking this into account for the single fibre tests, the back- calculated modulus of the flax fibres was within 6% of that obtained from the single fibre tests while the strength was within 7%.

KEYWORDS

Natural fibre composites, flax fibres, flax/vinyl ester, single fibre tensile testing, fibre area correction factor.

INTRODUCTION

The tensile properties of natural fibres are commonly determined from tensile testing of single technical fibres. The technical fibres themselves are composed of elementary fibres, several of which span the fibre cross-section. Conventionally, the modulus and strength of the fibres are determined assuming the fibres to be circular in nature. Accordingly, the fibre width is measured and taken as the fibre diameter in the calculations. However, as noted by Virk *et al*. (2009), and subsequently by Thomason *et al*. (2011), the fibres do not have a circular cross section and this leads to substantial error in the calculated mechanical properties.

To account for this discrepancy, Virk *et al*.(2012) introduced a fibre area correction factor *K* given by

$$K = A_D/A_T \tag{1}$$

where A_D and A_T are the measured and true fibre cross-sectional areas, respectively. The true values of the modulus and strength can then be determined by multiplying the measured values by the area correction factor. Virk *et al*. (2012) used this procedure to predict the modulus and strength of jute unidirectional composites and obtained good agreement with the measured values obtained from the composites. The present study was undertaken to compare the predicted and measured values of the modulus and strength offlax composites.

METHODOLOGY

Materials

Biotex untreated flax unidirectional fabric provided by Composites Evolution Ltd, UK, was used for the study. The fabric had an areal weight of 275 g/m^2 and was made from yarns of untwisted fibres held together by two spiral rayon wrapping threads. The spiral angle for the first thread was ~15° while that for the second was ~30°. As result of the presence of the wrapping threads, the fibres themselves became undulated with a spiral angle of

~15° (Soatthiyanon, 2013). The wrapping threads comprised 19.4% of the fabric. The yarns were held in place in the fabric by transverse threads applied every 10 mm.

Unidirectional composites with a fibre volume fraction of 25% (31% including wrapping threads) were fabricated from the flax fabric using rigid cavity vacuum resin transfer moulding. ArmorStar® IVSXH210 vinyl ester infusion resin with Arkema Luperox® DHD-9 hardener, supplied by CCP Composites, USA, was used as the matrix resin. A panel of the neat matrix resin was also fabricated in an identical manner.

Single Fibre Testing

Single fibre tensile testing was carried out on 113 technical fibres, extracted from the unidirectional flax fabric. Each fibre was glued to a 0.6-mm thick paper tab, as shown in Figure 1, using cyanoacrylate adhesive. The specimens were then conditioned in a humidity chamber at 23°C and 50% relative humidity for a minimum of 24 h.

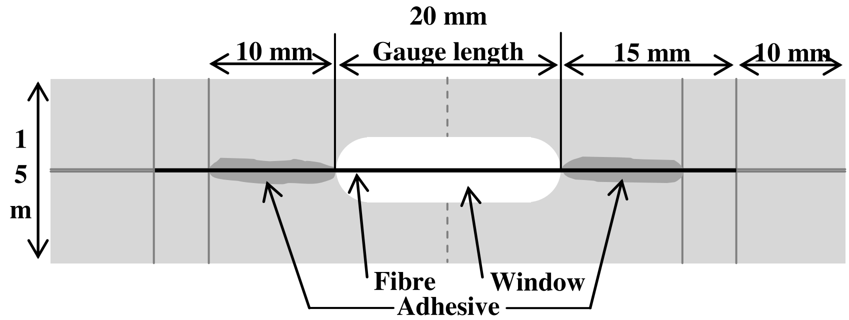

Figure 1Schematic diagram of mounting tab for single fibre testing.

The diameter of each of the technical fibres was measured in two orthogonal planes after conditioning, using a Nikon Eclipse ME600 optical microscope. The measurements were made at 18 locations, which were approximately equally spaced along the 20 mm length of the slot of the mounted specimen. The average diameter D was then calculated for each specimen and the measured fibre cross-sectional area A_D (assuming the fibre to be circular in section) was then determined as $\pi D^2/4$.

Prior to testing, the fibres were conditioned once again in a humidity chamber at 23°C and 50% relative humidity for at least 24 h. Tensile testing was then conducted under ambient conditions of temperature and humidity, using a method adapted from ASTM Standard C 1557-03. The tests were carried out using an Instron 5543 universal testing machine, with a 50 N load cell, at a crosshead speed of 0.2 mm/min, using pneumatic grips. The specimens were mounted with the grips extending right up to the end of the slot in the paper tab. The paper tab was then cut on either side of the slot and the test commenced. The measured tensile strength was determined as the maximum stress from the stress-strain curve, while the strain to failure was determined as the strain at break. The measured tensile modulus was determined over the strain range of 0.5-0.7% for fibres with a strain to failure of <1.2%, and 0.5-1.0% for fibres with a strain to failure of >1.2%.

To determine the true modulus and strength from the measured values it was necessary to determine a fibre correction factor. This was determined from 113 technical fibres extracted from the unidirectional fabric yarns and mounted in transverse cross-section in epoxy resin. The specimens were then metallographically ground and polished. The polished fibre surfaces were subsequently sputter coated with gold, then examined using a Hitachi S3400-X scanning electron microscope operated in high vacuum mode at an accelerating voltage of 15 kV. Imaging was done using backscattered electrons to enhance the contrast. The true fibre cross-sectional area $A_T$was determined from the images using Image J. The fibre area correction factor was determined fromEquation 1 using geometric means for $A_D$and A_T,as perthe procedure given by Virk et al. (2010). The true modulus and strength were then determined by multiplying the measured values by the fibre area correction factor.

Testing of Composites

Tensile testing ofthe unidirectional composites was carried out by Industrial Technology Centre (ITC), Canada, under ambient laboratory conditions (22°C and ~40% relative humidity), using a MTS Landmark load-frame with a Tovey load cell and MTS controller/acquisition software. A mechanical extensometer with a 25.4 mm gauge length was used to measure the strain. The extensometer was removed from the specimens after a strain of ~0.6% to avoid damage to the instrument and this precluded accurate measurement of the strain to failure.

Testing was carried out in accordance with ASTM D638 using dog-bone shaped specimens having Type I dimensions. The longitudinal axis of the specimens was parallel to the fibre direction and five replicate specimens were tested. The tensile modulus was determined as the chord modulus at a strain range of 0.1% - 0.3% and the ultimate tensile strength determined as the maximum stress from the stress-strain curve.

The tensile properties of the neat matrix resin were also determined in an identical manner.For subsequent analysis of the results it was necessary to determine the length of the technical fibres in the composite. This was done by measuring the length of 100 fibres randomly selected from a yarn taken from the dry unidirectional fabric.

RESULTS AND DISCUSSION

Single Fibre Testing

The results from the single fibre tensile tests are given in Table 1. The measured modulus was 19.4 GPa with a standard deviation of 7.4 GPa, the measured strength was 347 MPa with astandard deviation of 136 MPa, andthe strain to failure was 1.8% with a standard deviation of 0.5%.

The fibre area correction factor was determined to be 2.70, which compares well with the value of 2.55 obtained previously for flax fibres by Thomason *et al*. (2011). Using the fibre correction factor gave the true modulus as 52.4 GPa and the true strength as 936 MPa, Table 1.

Table 1 Measured and true tensile properties of flax technical fibres

Property	Average Value	Standard Deviation
Measured modulus (GPa)	19.4	7.4
True modulus (GPa)	52.4	20.0
Measured strength (MPa)	347	136
True strength (MPa)	936	368
Failure Strain (%)	1.8	0.5

Testing of Composites

The tensile properties for the unidirectional composite and also for the neat matrix resin are given in Table 2. The composite had a modulus of 13.2 GPa with a standard deviation of 0.4 GPa, while the strength was 122 MPa with a standard deviation of 5 MPa. The modulus of the neat resin was 3.62 GPa (standard deviation 0.02 GPa) while itsstrength was 59.8 MPa (standard deviation 4.1 MPa).

Table 2 Tensile modulus and strength for composites and neat resin

Property	Average Value	Standard Deviation
Composite		
Modulus (GPa)	13.2	0.4
Strength (MPa)	122	5
Neat Resin		
Modulus (GPa)	3.62	0.02
Strength (MPa)	59.8	4.1

The measured length of the technical fibres used to make the composite was 93 mm, with a standard deviation of 25 mm.

Calculation of Fibre Modulus and Strength from Composite Tensile Test Data

The data obtained from tensile testing of the composites was used to calculate the modulus and strength of the fibres, using the rule of mixtures, for comparison with the results obtained from the single fibre tests. As the fibres had been deformed into a spiral shape by the spiral wrapping threads, the misalignment was taken into account using the Krenchel reinforcing efficiency factor η as used by Virk *et al*. (2012) for prediction of modulus and by Shah *et al*. (2012) for prediction of strength. The Krenchel reinforcing efficiency factor is given by:

$$\eta = \cos^4 \theta \quad (2)$$

where θ is the angle between the fibre direction and the loading direction. The transverse supporting thread was not considered since it was perpendicular to the loading direction.A value for the modulus of rayon was required for the calculations. Hearle (2001) gives a range of 4.8-8.8 N/tex which equates to 7.2-13.1 GPa. The mean value of 10.2 GPa was used in the calculations.

Based on the above, and also assuming linear behaviour and isostrain conditions, the rule of mixtures equations give the modulus E and strength σ of the fibres as:

$$E_f = [E_c - (E_m V_m - E_{w1} V_{w1} \cos^4 \theta_{w1} - E_{w2} V_{w2} \cos^4 \theta_{w2})] / V_f \cos^4 \theta_f \quad (3)$$

$$\sigma_f = \left[\sigma_c - \left(E_m \varepsilon_f V_m - E_{w1} \varepsilon_f V_{w1} \cos^4 \theta_{w1} - E_{w2} \varepsilon_f V_{w2} \cos^4 \theta_{w2}\right)\right] / V_f \cos^4 \theta_f \quad (4)$$

where V is the volume fraction and the subscripts $c, f, m, w1$ *and* $w2$ refer to the composite, the fibres, the matrix and the wrapping threads, respectively.

Calculation of the modulus and strength of the fibres using these equations gave values of 47.0 GPa and of 337 MPa, respectively. The value of $E_m \varepsilon_f$ given in Equation 4 was slightly higher than the measured strength of the matrix so the latter was used when calculating fibre strength. This anomaly is considered to be due to the assumption of linear behaviour.

The predicted fibre modulus of 47.0 GPa is within 9% of the experimental true value of 52.4 GPa. The calculation was made using the 0.001-0.003 chord modulus from the composite tensile tests. However, the stress-strain curves for the composites showed a distinct knee at a strain of ~0.2%,which is in the middle of the strain range used to calculate the chord modulus, after which the slope decreased by ~40%. It is considered that the knee is the result of damage occurring in the composites, as proposed by Hughes*et al*. (2007), rather than being an intrinsic property of the fibres. On this basis, the modulus value of the composite before the knee was considered to be more appropriate for determining the fibre modulus for comparison with the single fibre data. Using the strain range of 0.0001-0.0015 for both the composite and the vinyl ester resin gave a value of 55.6 GPa, which is within 6% of the value obtained from the single fibre tests.

In contrast to the predicted modulus, the predicted fibre strength of 337 MPa is very much lower than the experimental true value of 936 MPa. However, the experimental value of fibre strength was determined using a 20 mm gauge length, whereas the average fibre length in the flax yarns used to make the composites was 93 mm. As fibre strength decreases considerably with increasing fibre length (Romhányet al.2003; Virk et al. 2011), this needs to be taken into account. Romhány*et al*. (2003) used data from testing of flax technical fibres with gauge lengths of 20, 40 and 80 mm, together with additional data for flax technical fibres reported by Stamboulis*et al*. (2000) and Bos*et al*. (2002).They found the following relationship between gauge length g (mm) and fibre strength σ (MPa):

$$\sigma = 12.2\, exp[883.7/(g + 206.4)] \quad (14)$$

This equation was used to determine the ratio of strength at a 20 mm gauge length to that at 93 mm. This ratio was then used to convert the true fibre strength of 936 MPa obtained in the present study for a 20 mm gauge length to its equivalent strength at 93 mm, giving a value of 361 MPa. The value of 337 MPa calculated from the composite tests is within 7% of this value and the agreement is again considered to be reasonably good.

CONCLUSIONS

- The fibre area correction factor for the technical flax fibres was found to be 2.70. This is in good agreement with the value obtained for flax fibres by other workers.
- The modulus and strength of the fibres for a 20 mm gauge length, determined after incorporation of the fibre area correction factor, were 52.4 GPa and 936 MPa, respectively.
- The modulus and strength values determined after incorporation of the fibre area correction factor were within 6% and 7% respectively of the values determined by back-calculation of the results obtained from longitudinal tensile testing of unidirectional composites. The good agreement is consistent with results obtained by other workers for jute fibres.

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