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Fibre cross section determination and variability in sisal and flax and its effects on fibre performance characterisation.

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Abstract

The results of a study on the measurement of fibre cross section and its variability in flax and sisal fibres are presented. Cross section values obtained from fibre "diameter" measurements were more than double the values obtained from actual observation of cross sections of the same individual fibres. The overall conclusion is that fibre "diameter" measurement is not an attractive method for accurate estimation of cross sectional area of these natural fibres. This conclusion is significant for researchers engaged in micromechanical investigation of natural fibre composites since differences in fibre cross section translate directly into differences of the same magnitude in the values obtained for the fibre modulus and strength. The error in fibre cross section introduced by the "diameter" method scales with the average fibre "diameter" which may also result in erroneous observations of fibre modulus and strength scaling inversely with natural fibre "diameter". The difference in average cross section observed from fibre to fibre was significantly greater than the variation along the length of each individual fibre. The minimum to maximum cross section variability of individual flax fibres was found to be approximately twice that observed for sisal fibres.

Keywords: A Fibres, B Mechanical Properties, B Strength D Optical Microscopy

Author Nominated - Natural Fibres

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Introduction

The use of reinforced polymer materials has increased dramatically during the last half century, becoming the standards of high performance in automotive, aeronautical and innumerable other high performance applications. There is a large and rapidly increasing market for these reinforced composites, with glass fibre reinforced plastics leading in their market share. However, prior to the tremendous success and growth of the petrochemical industry in 20th century the majority of the materials used were obtained from renewable resources. So the use of renewable materials is not a new idea and in recent years there has been a growing renewal of interest in the research of fibres derived from natural sustainable sources as potential reinforcements for high performance composite materials. This increased interest in natural fibre composites has multiple drivers, the growing environmental concern, possible cost competitiveness, the depletion and price of oil and new regulations for a cleaner and safer environment [1-3]. It has been claimed that natural fibres show significant potential as environmentally friendly alternatives to conventional reinforcements such as glass fibres [1-3] although these claims often ignore the well documented low levels of shear and transverse modulus of natural fibres [4-6]. Nevertheless, one of the basic underlying assumptions in virtually all micromechanical analysis and modelling of fibre reinforced composites is that the fibres are circular in cross section and that the fibre diameter is constant along the fibre length. Efficient determination of the simplest engineering parameters such as modulus and stress depends heavily on these assumptions. Furthermore, many researchers have identified the fibre-matrix interface in natural fibre composites as an area of potential weakness and consequently there has been a significant focus on the investigation of methods to tailor the level of natural fibre-polymer interactions [1-8]. This has naturally resulted in application of many of the fibre and interface

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characterisation tools, developed using man-made fibres, to natural fibre technology. These include many single fibre methods such as fibre pullout [7,8], fibre fragmentation [9], and determination of single fibre strength distributions [8,10-13]. These methods present researchers with significant technical and resource challenges, however up to now measurement of fibre cross section and its uniformity has not been high on the list of those challenges.

Many types of natural fibre have been identified which appear to have some appropriate mechanical properties for structural purposes, being of low density, and high specific strength and stiffness; sisal and flax are examples of such fibres, however many other suitable fibres exist. Unfortunately these cellulose based fibres suffer from the natural variability which is inherent in materials sourced directly from nature. Consequently the documentation of their structural properties usually does not quote specific values but rather present ranges which are often of the same order of magnitude as the average values themselves [1-3]. This presents engineers, used to the availability of consistent and accurate mechanical property data of manmade fibres, with a significant challenge in terms of designing reliable structures based on these natural fibre composites. Despite the inherent natural variability of these fibres it is possible that a significant contributor to the large range of specific properties found in the literature may be the cross-sectional shape of natural fibres. The measurement of the longitudinal mechanical properties of fibres depends on their cross-section being circular and uniform along their length. This allows a simple measurement of fibre diameter to be used to calculate the fibre cross-section area (CSA) required to obtain values of modulus and strength from the data taken from a load-displacement curve. Most natural fibres are neither circular in cross section nor uniform along their length. Consequently, a simple “diameter” measurement

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taken from a transversely viewed fibre image may not be sufficient to accurately assess cross-section at any point and may certainly not be representative of the fibre at any other point. In this paper we present the results of an investigation of the determination of the CSA of single fibres of flax and sisal. Furthermore we review the variability in fibre CSA along the length of these fibres and its influence on the determination of the single fibre tensile modulus and tensile strength.

Experimental

Flax fibres used in this study were sourced from Wigglesworth fibres and were originally grown in Germany. The sisal fibres were also sourced from Wigglesworth and were grown in Brazil [13]. Single technical fibres were meticulously separated from large flax and sisal yarns of intertwined fibres. The fibres were separated from one another until no fraying could be seen with the naked eye. Card frames cut from 250g/m² grade card were used to mount the fibres for testing. Fibre properties were determined at 10, 15, 20, 25, 30 mm gauge lengths. Single fibres were fixed to the card at both sides of the window using Loctite™ Gel Superglue. To investigate the diameter method of CSA measurement, fibres were photographed at three separate positions while under transverse observation using a Nikon Epiphot inverted microscope (at 50x magnification). This allowed an average fibre "diameter" to be estimated, under the assumption of uniformly circular cross section fibres. Tensile testing was carried out according to ASTM D 3822-01 (standard for tensile properties of single fibres) using a Instron 3342 tensile testing machine with a 100 N load cell at 5% strain per minute. Sample were conditioned for 24 hours prior to testing and tested at 23±1°C and 50±10% relative humidity. After testing the remaining top and bottom glued ends of each fibre sample were mounted vertically in resin for polishing and CSA analysis. These

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embedded samples were prepared for microscopy by grinding them down to a fine finish using progressively finer grinding papers (120, 1200, 2400 and 4000 grade). The fibre cross sections were then photographed under the microscope at 100x magnification. The steps of grinding, polishing and microscopy were then repeated to obtain a second measurement approximately 2 mm further along each tested fibre. Each fibre micrograph was traced using Image Pro Plus analysis software to find the CSA. The four values of area for each fibre were then averaged to give a CSA for each tested fibre. These values were used in the calculation of the Young's modulus and tensile strength of each individual fibre. To examine the variation in fibre CSA along the fibre length, a number of individual fibres were glued to card and then embedded in resin blocks. Samples were repeatedly ground, polished and photographed, in roughly 2 mm steps, following the above procedure, to give ten CSA measurement along a 20 mm length of fibre.

Results and Discussion

Figure 1 shows some typical cross section images obtained on sisal and flax fibres using electron and optical microscopy. The results presented further in this paper are based on image analysis of optical micrographs. However, SEM micrographs were also made from a selection of the samples to cross check the optical results. The non-circular cross section of these natural fibres is clearly illustrated in the micrographs in this Figure. The outline of the sisal fibre has been traced and highlighted and it is this outline which was utilised in the image analysis software to evaluate the fibre CSA. Figure 1 highlights the complex internal structural of these natural fibres. It can be seen that these 'technical' fibres are actually composite structures consisting of an assembly of many elementary fibres. In the case of flax these technical fibres are located around the stem of the plant,

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and tend to contain between 10 and 40 elementary fibres. In the case of sisal technical fibres originate from within the large leaves of the plant, and contain between 50 and 200 elementary fibres, which tend to be slightly smaller than the flax elementary fibres. The elementary fibres have a polygonal cross section, allowing them to fit closely together. Each elementary fibre then contains multiple concentric cell walls, with a void in the middle known as the lumen. It is clear from these micrographs that the structure of these fibres reveals many potential weak interfaces. Indeed, Figure 1 reveals that the flax fibre has been damaged during sample preparation and has failed at a number of internal interfaces.

Figure 2 compares the value obtained for the fibre CSA obtained by two different methods for each individual fibre. The first value is calculated, assuming a circular fibre cross section, from an average fibre "diameter" obtained from four measurements of fibre diameter taken along individual 20 mm fibre gauge lengths observed at right angles to the main fibre axis. This is a method commonly employed in many papers reporting investigations on natural fibres and their composites [7-14]. These values are plotted against the average of four CSA observations on each of the same individual fibres after testing, embedding, sectioning and polishing. As is common with natural fibres there is considerable scatter observed in the data presented in Figure 2. However, notwithstanding the degree of scatter it is striking that the CSA values obtained from fibre "diameter" measurements are on average double or more the values obtained from actual observation of the fibre cross sections. Despite the scatter observed in Figure 2, analysis of the data indicates that the averages for the two fibres fall outside the 95% confidence limits of the other fibre. Moreover, a two sample t-test of this data (for difference = 0 versus Sisal < Flax) has a p-value = 0.001 which is <<0.05.

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Consequently, we can state that flax fibres show a statistically significant greater potential error in using fibre "diameter" calculated CSA. However, the overall conclusion is that fibre "diameter" measurement is not an attractive method for accurate estimation of CSA of either of these natural fibres. This observation has important consequences for those researchers engaged in the determination of the properties of natural fibres. The above results indicate that use of a "diameter" determined fibre CSA may lead to the underestimation of properties such as modulus and strength by up to 60%. This is in good agreement with very recent results from a study of jute fibre diameter by Virk [15] who suggested the use of a "fibre area correction factor" of 1.42 in the measurement of fibre modulus and strength to account for the overestimation of the fibre CSA by the diameter method. It is relatively easy to qualitatively understand this effect when considering the transverse observation of a non-circular cross section cylinder to obtain a "diameter" measurement. Indeed it can be shown, in such a case, that the error in the estimation of the fibre CSA will increase with increasing aspect ratio of the major to minor axes of the fibre cross section, which will also result in higher values of "diameter" for fibres of equal CSA. Figure 3 shows the results for the ratio of the "diameter" calculated to measured fibre CSA plotted against the fibre "diameter". It can be seen that there is a strong correlation between these parameters. The higher slope of the flax data is indicative of a higher average aspect ratio for the flax fibre cross section. One significant result of this effect would be that fibre modulus and strength determined using a fibre "diameter" calculated CSA would give values which appear to be inversely correlated with "diameter". A number of papers have presented results indicating such an effect [11,12,14].

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Figure 4 shows the results of the measurement CSA of twelve individual sisal fibres at ten positions along a 21 mm length of each fibre. It can be observed that there is quite some variation in CSA along the length of some fibres whereas other fibres appear relatively uniform. What is also clear from the results in Figure 4 is that the difference in CSA observed from fibre to fibre is significantly greater than the variation along the length of each individual fibre. A further analysis of the data presented in Figure 4 is shown in Table 1. The first two columns give the average cross section and 95% confidence limit of that average for each individual fibre which can be compared with the overall average of all values. The average confidence limit for any fibre CSA is of the order of 5% of the mean value. However, the fibre to fibre CSA differences can be greater than a factor of two in the data shown in Table 1. The third column in Table 1 reveals that along a single fibre the largest variation from average CSA is up to 21% but typically averages about 11%. The fourth column shows that a single CSA at the centre of the gauge length of any single fibre is up to 15% different from the average, but is normally within about 7% of the average. The final column, which is relevant to the measurements of fibre modulus presented below, indicates that the average of two measurements at each end of the 20 mm fibre length gives a value up to 5% different from average, but is normally within about 2% of the average value. Similar trends in the variability of flax fibre CSA can be seen in Figure 5 and Table 2. The data show that the average CSA of the flax fibre is less than half of the sisal fibres but, with a 95% confidence limit of 7.5%, these flax fibre average CSA values have a higher level of uncertainty than the sisal fibres. This could be interpreted as flax having a greater level of CSA variability along the individual fibres. Moreover, with flax fibre, it can again be observed that the fibre to fibre differences can be greater than intra-fibre variations in CSA (along a 21 mm length). The data in Table 2 show a factor of more than four in the

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fibre to fibre variations of average flax fibre CSA. Moreover, it can be seen that along a single fibre the largest variation from average cross section is up to 23% but typically averages about 14%. A single CSA determined at centre of any single fibre is up to 15% different from the average, but is normally within about 6% of the average. Furthermore, the average of the measurements at the ends of the 20 mm flax fibres give a value up to 8% different from average, but normally within about 3% of the average. Overall these data appear to show greater levels of fibre CSA variability in flax fibres compared to sisal fibres which is an interesting correlation with the larger spread in modulus values observed in the literature on flax fibres. Furthermore, the fibre to fibre variability appears to be much greater than the variability along (relatively short) lengths of individual fibres. The minimum to maximum variability of individual flax fibres was observed to be approximately twice that observed for sisal fibres. It can also be concluded from this data that the use of an average CSA obtained over a range of individual fibres could lead to significant errors in the calculation of fibre mechanical performance from load-displacement data and that the use of (even single) measurements of the CSA of each individual fibre will probably result in a more accurate estimation of the properties of natural fibres.

Table 3 summarises the results of the tensile testing of single sisal and flax fibres. Three fibres of each type were measured at each of five different gauge lengths. The overall results indicate that the flax fibres have a higher modulus and strength but a lower tensile strain to failure than the sisal fibres in this study. It is well known that the property values obtained in single fibre tensile testing can be affected by the gauge length of the measurement and that these effects must be considered. The modulus dependence on gauge length is a phenomenon related to the use of the testing machine

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crosshead displacement to approximate the fibre strain. This does not take into account the contribution of the strain of the other components in the testing system, in particular the card tabs and the glue. The corrected fibre modulus can be obtained using the following considerations [16]. Suppose that the fibre stress-strain curve is linear up to the strain $_f$. If E^* is the experimental Young's modulus then the measured stress $_f$ is given by $_f$=E^* L_f^*/L_0 where L_f^* is the apparent system measured fibre elongation and L_0 being the initial system length. The actual fibre elongation L_f is given by $L_f = L_f^* - K$, where K is the machine and sample mounting displacement. Assuming that K is proportional to the applied stress we obtain $K=A_f.C._x$ where A_f is the fibre cross section area and C is proportional to the machine compliance. The actual fibre modulus is then given by

$$E = \frac{\sigma_f}{(\Delta L_f / L_0)} = \frac{\sigma_f L_0}{\Delta L_f^* - A_f C \sigma_f} \quad \text{and hence} \quad \frac{1}{E^*} = \frac{1}{E} + C\frac{A}{L_0} \qquad (1)$$

Using equation (1) the fibre modulus can be obtained from the intercept of a straight line plot of experimental inverse fibre modulus (1/E*) against fibre cross section divided by gauge length (A_f/L_0). Figure 6 presents the data on measured flax and sisal fibre tensile modulus plotted according to equation 1. From the intercepts of the least squares fitted lines the values for the actual fibre longitudinal Young's modulus were obtained as sisal=30.4 GPa and flax=70.8 GPa. These values are in good agreement with the accepted range of values for these fibres [1-3]. It is also worth noting that these values of modulus are significantly higher (>+40%) than the values obtained at the various gauge lengths in the experiments. This indicates the importance of compensating for the test setup compliance when measuring the modulus of these natural fibres. The values of the slopes of the lines in Figure 6 give an estimation of the testing system compliance C as discussed above. These can be used to obtain a

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compliance corrected strain to failure value for the tested fibres which are also presented in Table 3. As expected the corrected strains to failure of the flax and sisal fibres are significantly lower than the measured values. It has recently been suggested that strain to failure is a more consistent design criterion for natural fibres and their composites [14].

Given the results presented in Figure 4 and 5 on the variation of fibre CSA along the fibre length it is reasonable to ask whether this variability has a significant effect on the measured value of modulus obtained from these single fibre tests. In order to get a first estimate of the potential order of magnitude of any effects we have developed a simple model as presented below. The model uses a "fibre" length L_0 constructed of a series of N cylinders of equal length L but different cross sectional area A_i connected in series. The material of each cylinder is assumed to have identical modulus E. If this fibre construct experiences a load P then the stress in i^{th} section $_i$ is given by $_i = P/A_i$. This loading results in a change in length of the fibre L_f which is the sum of the extension of the individual elements.

$$\Delta L_f = \sum_{i=1}^{N} \frac{\sigma_i}{E}.L \tag{2}$$

With an overall fibre strain $_f$ given by

$$\varepsilon_f = \frac{\Delta L_f}{L_0} = \frac{1}{NL}\sum_{i=1}^{N}\frac{\sigma_i}{E}.L = \frac{1}{NE}\sum_{i=1}^{N}\frac{P}{A_i} \tag{3}$$

The ratio of the measured fibre modulus to the actual fibre material modulus E_f/E is

$$\frac{E_f}{E} = \frac{P}{A_f \varepsilon_f} = \frac{N}{A_f}\left[\sum_{i=1}^{N}\frac{1}{A_i}\right]^{-1} \tag{4}$$

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Figure 7 shows equation 4 plotted for different values of A/A_f using a simple model for the variation in fibre cross sectional area where A_i changes linearly from A_f- A up to A_f+ A. It can be seen that the results are sensitive to the number of sections which are used to construct the model fibre, however the results approach a constant level as the number of segments increases above 20. The Figure shows results for A/A_f = 10%, 25% and 50%, where it is noted that the largest experimental values of A observed in Tables 1 and 2 are approximately 25% of the average value. It is observed that a A value of 10% results in a negligible error in the estimation of the fibre modulus. A value of A =25%, typical of the maximum values observed experimentally, results in a value of E_f approximately 3% lower than the actual material modulus. Only when A is very large are deviations (i.e. of magnitude similar or greater than some of the other experimental issues described above) in the measured value of E_f from the actual material modulus observed. These observations are in quantitative agreement with the conclusion of a modelling study by Qui et al who studied the axial tensile modulus of a particle-reinforced composite fibre with variable radius [17]. Consequently it can be concluded that the effects of the observed level of fibre cross section variation along a single natural fibre is not the major source in any experimental variability of the measured values of fibre modulus.

Unlike many other physical parameters such as elastic modulus or density, fibre strength is a statistical parameter which cannot be fully described by a single value. The most common statistical tool used to describe the variability in strength for materials is the Weibull distribution which has been used relatively successfully in analysis of the strength of circular cross section high performance fibres such a carbon and glass which

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fail in a brittle manner. The application of Weibull analysis to tensile testing of natural fibres has produced less convincing results which often require modification of the theory and more complicated analysis regimes [8,10]. The underlying equations governing Weibull analysis are well known and will not be reproduced here [18]. The analysis relies on the assumption that the failure of fibres as a function of applied load is controlled by the random distribution of a single type of defect along the length of the fibres. If the underlying assumptions of this type of analysis are applicable to natural fibres then the average fibre strength ($_L$) at gauge length (L) and the Weibull shape parameter m are related by

$$\ln(\overline{\sigma_L}) = \frac{-1}{m}\ln(L) + \text{constant} \qquad (5)$$

Figure 8 shows the average fibre strengths of flax and sisal plotted against gauge length where the error bars indicate the 95% confidence limits on the average values. Examination of the average values alone could lead to a number of conclusions about relative strengths of the two fibre types and the trends with regard to gauge length. However, the magnitude of the error bars in Figure 8 suggests that statistical analysis is required with this data. For instance a two sample t-test of the difference in strengths of flax and sisal at any of the five individual gauge length actually showed no significant difference in the averages at the 95% confidence level. Furthermore, the differences in average strength for either fibre at the different gauge lengths were also found not to be significant at the 95% confidence level. One consequence of these results is that it is not meaningful to attempt a Weibull analysis in terms of gauge length trends. It also becomes acceptable to pool the strength values at all five gauge length and compare the overall average strength of flax and sisal. In this case we obtain a p-value = 0.015 in a two sample t-test (for difference = 0 versus Sisal < Flax). Consequently we can

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conclude that the differences in overall average strength of flax (688 MPa) and sisal (530 MPa) in Table 3 are significant at the 95% confidence level.

The above results indicate some of the challenges of characterising natural fibres, such as flax and sisal, where many of the micro-structural parameters required for dependable design of fibre reinforced composite exhibit high levels of variability. Single fibre analysis of traditional man-made reinforcements is already highly resource intensive. It appears from the results presented here that the strategy of assuming natural fibres have a constant circular cross section and using a "diameter" measurement to characterise cross sectional area can introduce high levels of error into the determination of fibre modulus and strength.

Conclusions

The ability to efficiently and accurately characterise the cross sectional area of reinforcement fibres is critical to the development of a database of engineering performance of such fibres and their interface stress transfer capability. A commonly employed shortcut in this area is the assumption that fibre cross section is uniformly circular, which reduces CSA determination to a simple measurement of fibre diameter. The results of this study on the measurement of natural fibre CSA and its variability have revealed that the CSA values obtained from fibre "diameter" measurements on flax and sisal fibres are on average double or more the values obtained from actual observation of the fibre cross sections. Such differences in CSA translate directly into differences of the same order of magnitude in the determined values of fibre modulus and strength. Consequently, the overall conclusion is that fibre "diameter" measurement is not a particularly attractive method for accurate estimation of CSA for these natural

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fibres. The level of error in the fibre CSA introduced by the "diameter" method appears to scale with the average fibre "diameter" which may go some way to explaining published observations of fibre modulus and strength scaling inversely with natural fibre "diameter". Furthermore, significant variation in fibre CSA along the length was observed with many fibres whereas other fibres appear relatively uniform. However, it was concluded that the effects of this fibre CSA variation along a single natural fibre is not the major source in any experimental variability of the measured values of fibre modulus. The difference in average CSA observed from fibre to fibre was significantly greater than the variation along the length of each individual fibre. The minimum to maximum CSA variability of individual flax fibres was observed to be approximately twice that observed for sisal fibres. It was further concluded that the use of an average CSA obtained over a range of individual fibres is likely to result in significant errors in the calculation of individual fibre mechanical performance from load-displacement data and that the use of measurements of the CSA of each individual fibre will probably result in a more accurate estimation of the properties of natural fibres. The overall results indicate that the flax fibres had a higher modulus and strength but a lower tensile strain to failure than the sisal fibres in this study. Values obtained for the fibre modulus were significantly dependent on test gauge length but the fibre tensile strengths showed no significant dependence on gauge length. Gauge length compensated fibre longitudinal Young's moduli were obtained as sisal=30.4 GPa and flax=70.8 GPa and tensile strength sisal=530 MPa and flax=688 MPa.

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Figure Captions

Figure 1 Sisal cross section a)SEM, b)Optical, Flax cross section c)SEM, d)Optical

Figure 2 Fibre cross section – diameter calculated versus directly measured

Figure 3 Diameter dependence of ratio of diameter calculated to measured fibre cross section

Figure 4 Cross section variations along sisal fibres

Figure 5 Cross section variations along flax fibres

Figure 6 Estimation of actual fibre modulus from gauge length experiments

Figure 7 Modelling the effect of fibre cross section variation of measured fibre modulus

Figure 8 Average fibre strength versus gauge length

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Fibre	Mean CSA mm^2 x1000	95% Confidence limits	Minimum to maximum range in CSA (%)	Difference of centre of gauge length CSA from mean (%)	Difference of ends of gauge length CSA from mean (%)
S1	33.09	4.1	11.9	-4.7	-2.0
S2	31.27	3.7	8.5	6.7	0.3
S3	32.66	7.5	20.6	-8.1	5.3
S4	31.43	3.3	6.9	-3.7	-0.9
S5	37.51	7.3	15.3	-9.2	0.2
S6	33.99	3.8	9.8	7.2	-5.2
S7	15.07	6.0	13.1	-11.1	0.0
S8	15.83	3.5	9.6	0.6	-1.0
S9	17.50	4.5	12.1	10.0	-3.7
S10	17.13	4.0	10.3	4.2	4.5
S11	32.33	3.5	9.6	14.6	-3.0
S12	28.66	3.3	7.5	7.9	-3.3
	27.20	**5.4**	**11.3**	**7.3**	**2.4**

Table 1 Analysis of sisal fibres cross section variations

Fibre	Mean CSA mm^2 x1000	95% Confidence limits	Minimum to maximum range in CSA (%)	Difference of centre of gauge length CSA from mean (%)	Difference of ends of gauge length CSA from mean (%)
F1	9.27	6.0	15.4	14.6	4.6
F2	8.41	7.3	17.4	-6.3	-2.2
F3	5.23	2.0	4.8	-2.7	-1.6
F4	20.80	4.0	9.9	5.2	0.5
F5	21.01	7.1	18.9	10.9	-7.6
F6	20.57	4.5	13.1	1.5	-1.3
F7	9.85	4.2	11.5	2.7	-2.5
F8	11.29	8.4	21.2	6.7	-3.5
F9	12.39	2.3	5.3	2.0	-1.7
F10	11.16	7.6	19.1	5.3	-5.3
F11	8.33	9.0	23.1	5.4	-4.7
F12	12.23	5.7	11.9	11.8	-2.6
	12.54	**7.5**	**14.3**	**6.3**	**3.2**

Table 1 Analysis of flax fibres cross section variations

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	Sisal					Flax				
Gauge (mm)	CSA (mm^2) x1000	Youngs Modulus (GPa)	Tensile Strength (MPa)	Failure Strain (%)	Corrected Failure Strain (%)	CSA (mm^2) x1000	Youngs Modulus (GPa)	Tensile Strength (MPa)	Failure Strain (%)	Corrected Failure Strain (%)
30	32.94	21.9	503	2.33	1.71	9.57	61.9	809	1.33	1.05
30	29.74	24.1	451	1.91	1.40	7.48	58.8	320	0.77	0.68
30	29.56	24.3	549	2.27	1.65	9.30	51.9	820	1.75	1.48
25	33.98	19.5	422	2.21	1.55	9.03	53.2	499	0.94	0.74
25	25.67	24.8	579	2.35	1.67	8.71	59.2	1060	1.99	1.60
25	28.20	22.4	558	2.54	1.82	7.64	57.0	365	0.81	0.69
20	33.36	16.9	342	2.03	1.38	9.98	53.6	885	1.66	1.18
20	29.22	22.4	548	2.48	1.57	10.26	49.8	940	2.13	1.61
20	29.71	24.1	765	3.44	2.15	7.96	50.9	611	1.23	0.97
15	35.47	13.5	452	3.43	2.22	8.76	47.8	890	1.94	1.38
15	29.68	20.3	678	3.38	1.85	11.56	46.9	599	1.29	0.79
15	15.97	20.0	567	2.87	2.18	10.71	43.0	682	1.66	1.13
10	33.17	14.7	287	5.31	4.23	8.77	37.6	541	1.46	0.95
10	25.87	17.1	872	4.51	1.95	10.30	40.9	692	1.73	0.97
10	18.46	16.3	382	2.52	1.72	11.44	36.8	606	1.67	0.93
Average	**28.73**	**20.2**	**530**	**2.90**	**1.94**	**9.43**	**50.0**	**688**	**1.49**	**1.08**
95% CL	2.78	1.9	79.0	0.48	0.35	0.65	3.9	108	0.21	0.16

Table 3 Tensile properties of single natural fibres

ACCEPTED MANUSCRIPT

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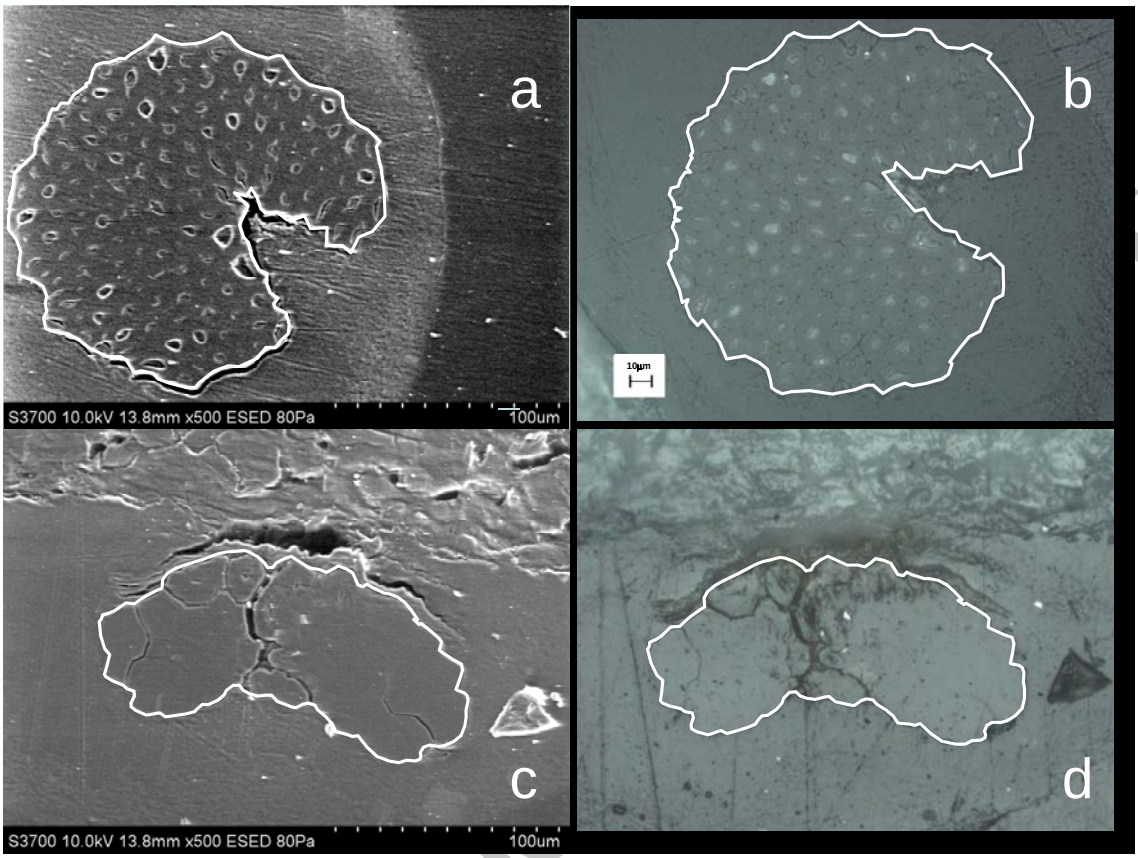

Figure 1 Sisal cross section a)SEM, b)Optical, Flax cross section c)SEM, d)Optical

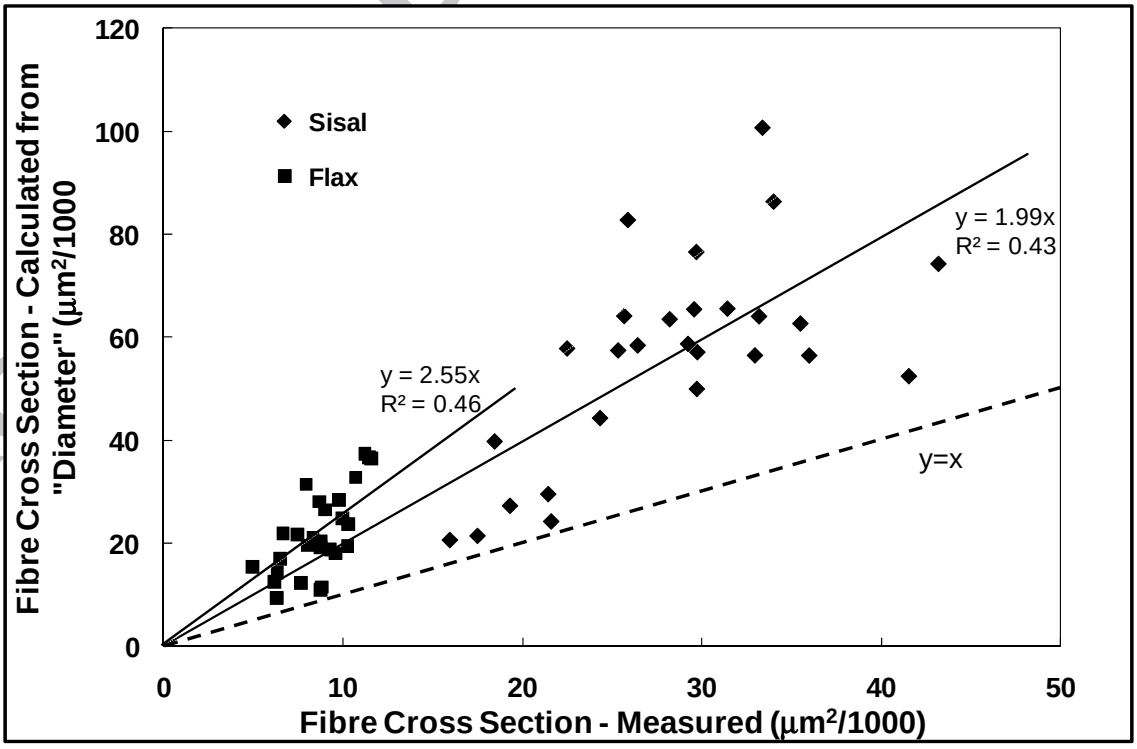

Figure 2 Fibre cross section – diameter calculated versus directly measured

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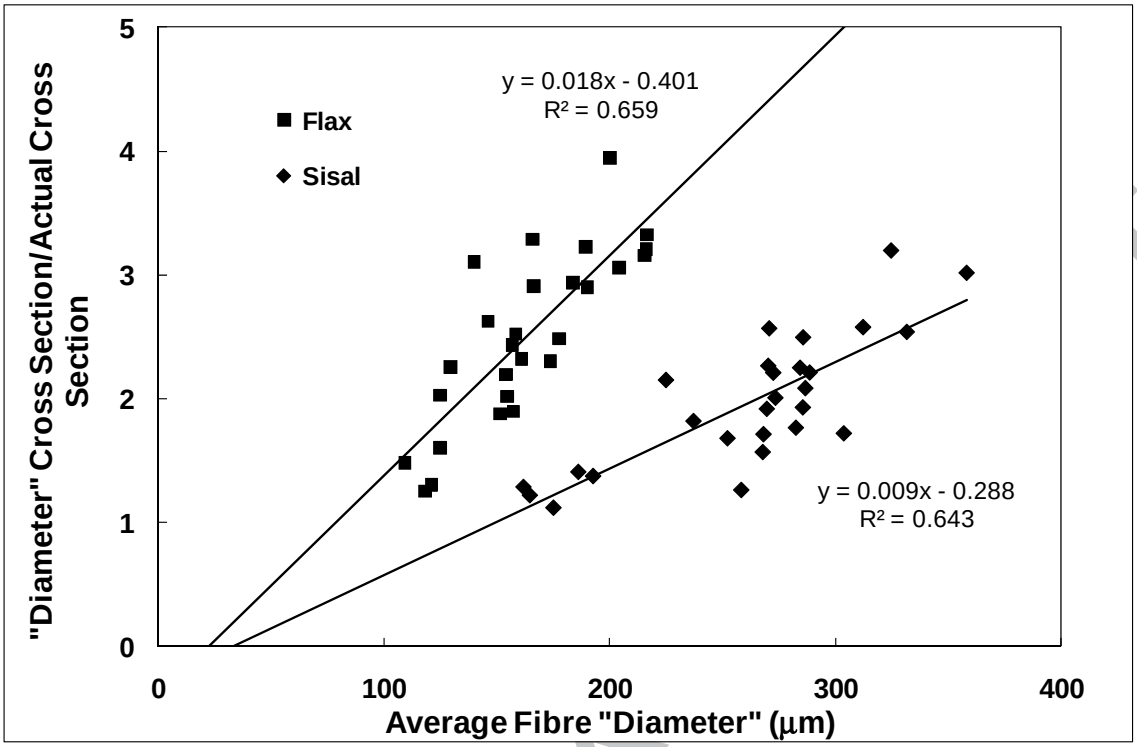

Figure 3 Diameter dependence of ratio of diameter calculated to measured fibre cross section

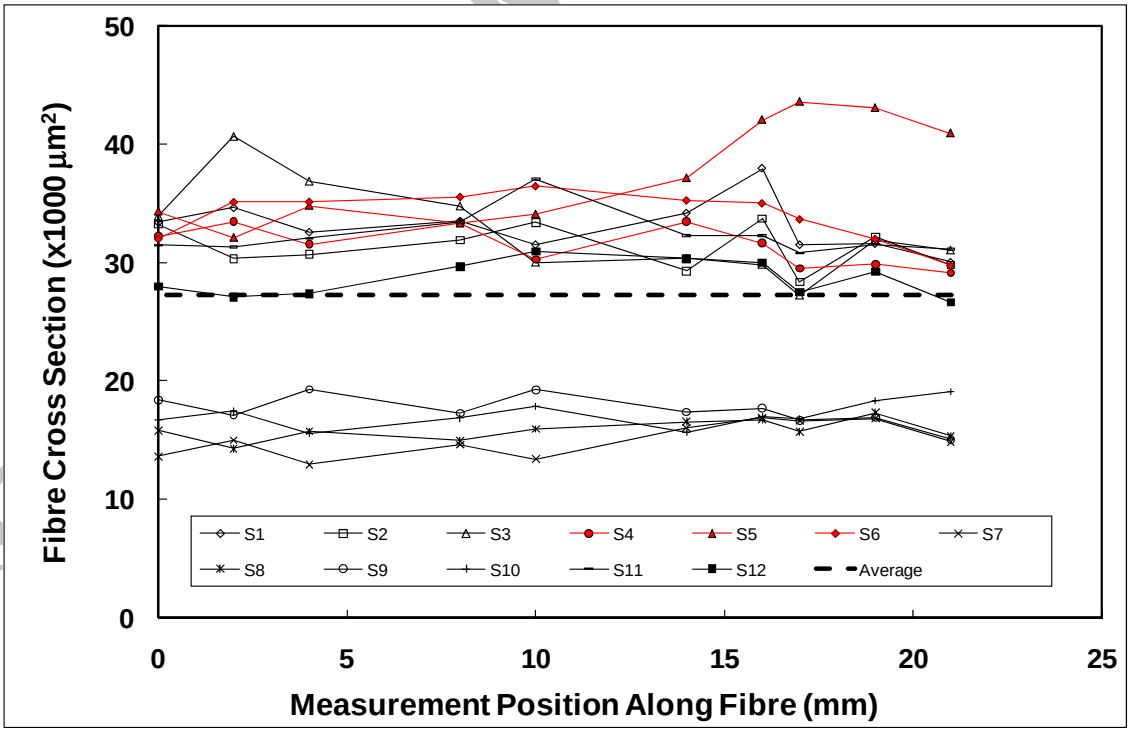

Figure 4 Cross section variations along sisal fibres

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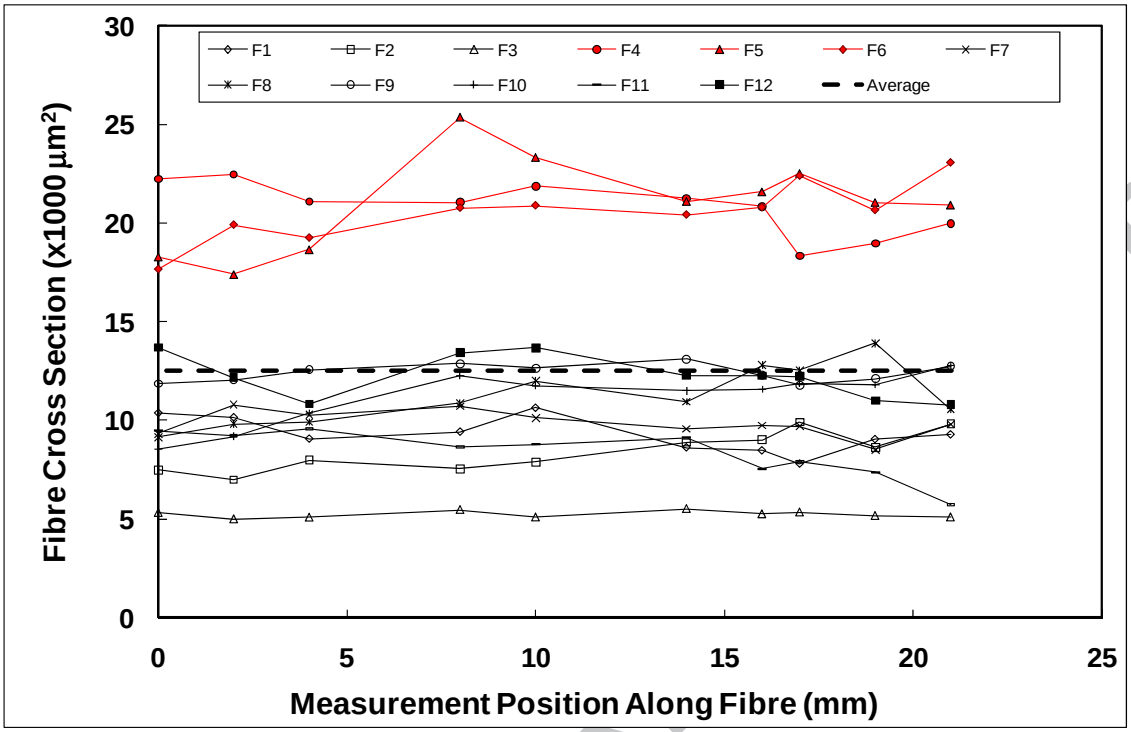

Figure 5 Cross section variations along flax fibres

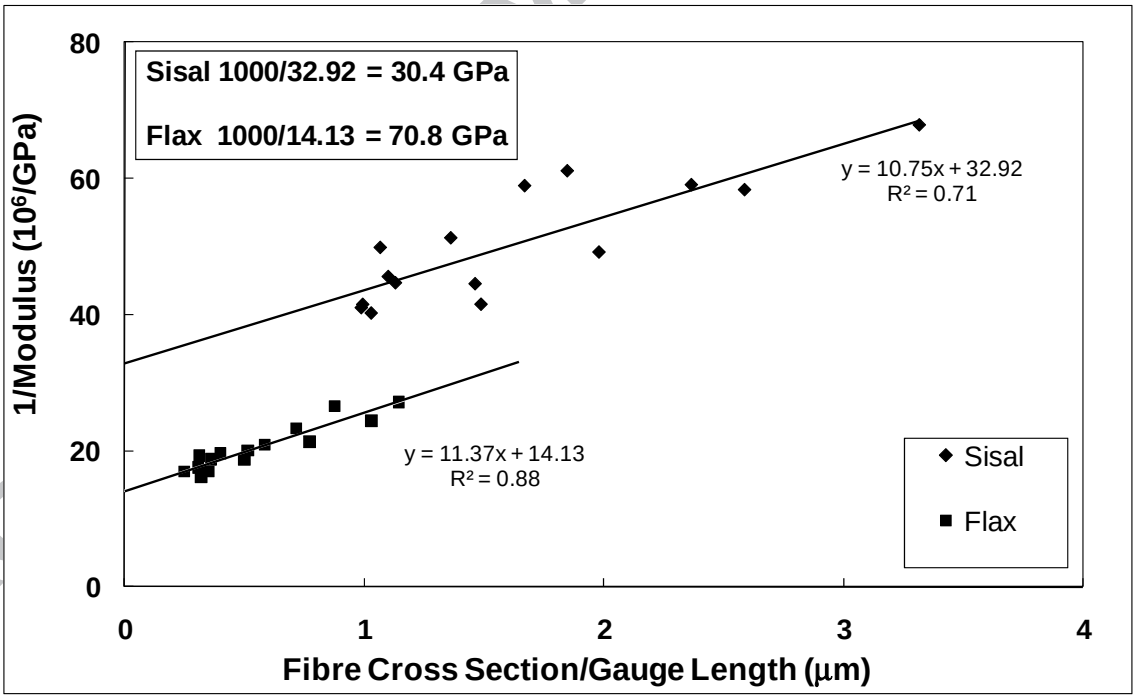

Figure 6 Estimation of actual fibre modulus from gauge length experiments

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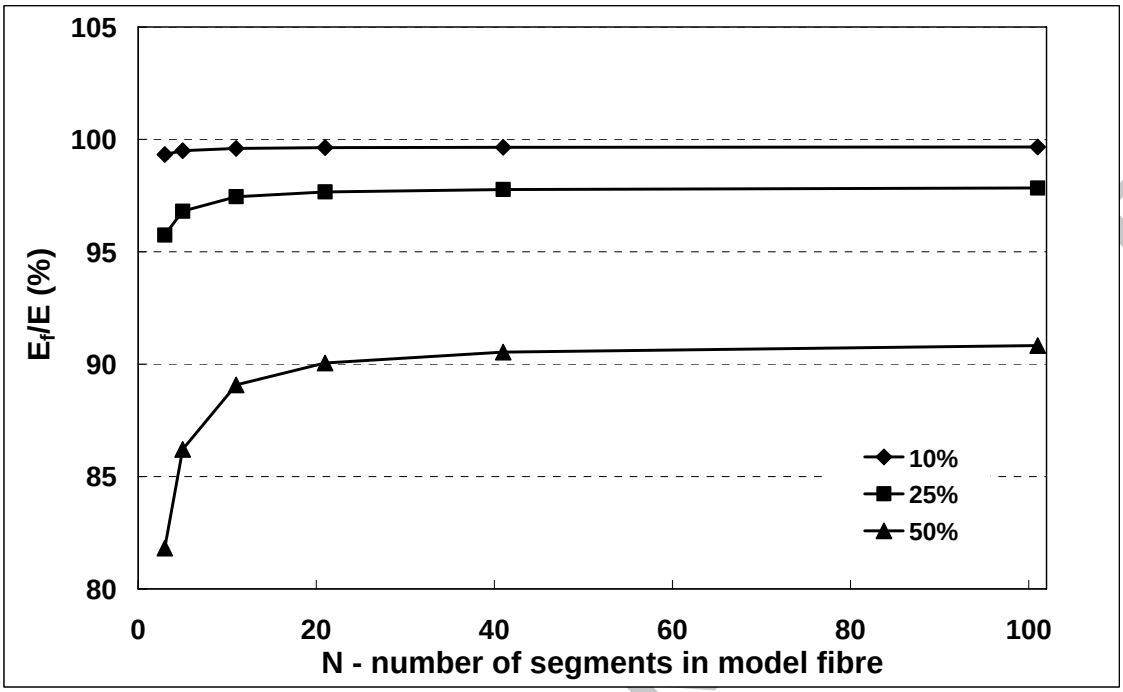

Figure 7 Modelling the effect of fibre cross section variation of measured fibre modulus

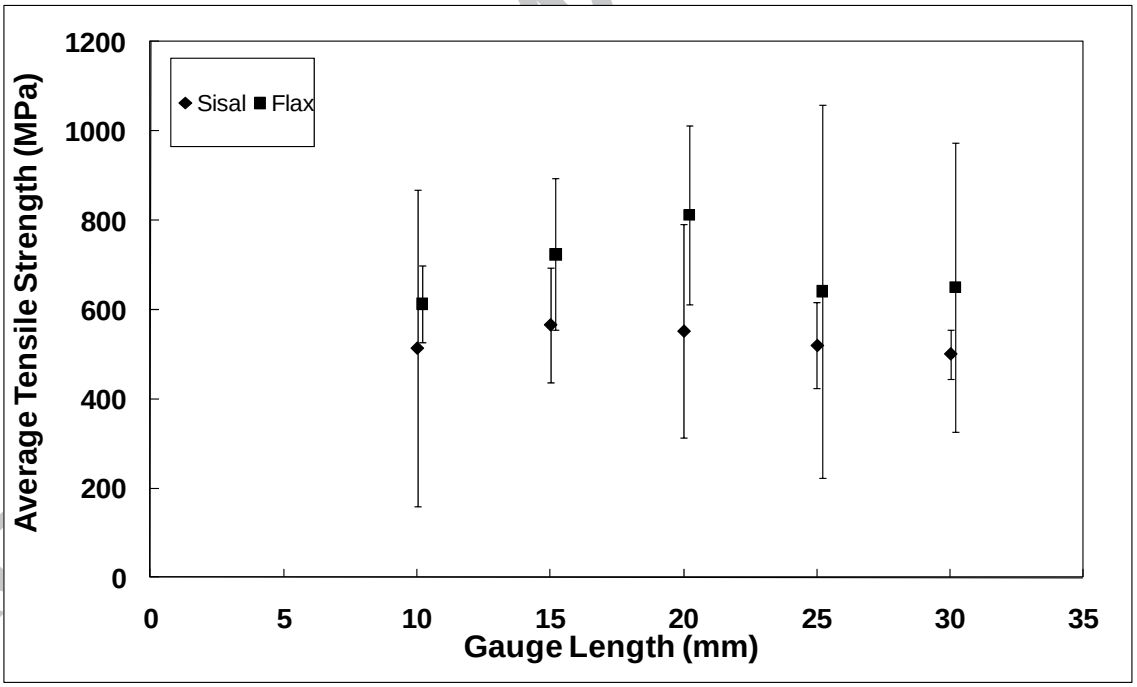

Figure 8 Average fibre strength versus gauge length