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Structure and properties of some vegetable fibres

Part 1 *Sisal fibre*

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The stress–strain curve for sisal fibres has been experimentally determined. Ultimate tensile strength (UTS), initial modulus (YM), average modulus (AM) and per cent elongation at break of fibres have been measured as function of fibre diameter, test length and test speed. UTS, YM, AM and per cent elongation lie in the range 530 to 630 MN m^{-2}, 17 to 22 GN m^{-2}, 9.8 to 16.5 GN m^{-2} and 3.64 to 5.12 respectively for fibres of diameters ranging between 100 and 300 μm. No significant variation of mechanical properties with change in diameter of the fibres was observed. However, with increase in test length of the fibres, the UTS and per cent elongation are found to decrease while YM and AM increased in the test length ranging from 15 to 65 mm. With the increase in speed of testing from 1 to 50 mm min^{-1}, YM and UTS are found to increase whereas per cent elongation and AM do not show any significant variation. At a test speed of 500 mm min^{-1} the UTS value decreases sharply. The above results are explained in terms of the internal structure of the fibre such as the cell structure, microfibrillar angle, defects, etc. Scanning electron microscope (SEM) studies of the fractured tips of the sisal fibres reveal that the failure of the fibre is due to the uncoiling of microfibrils accompanied by decohesion and finally tearing of cell walls. The tendency of uncoiling seems to decrease with increasing speed of testing.

1. Introduction

Sisal fibre is a fibre obtained from the leaves of *Agave sisalana* which was imported to India during the last decade of the fifteenth century by the Portuguese [1]. Sisal fibre is one of the four most widely used natural fibres and it accounts for half the total production of textile fibres. The reason for this is due to the ease of cultivation of sisal plants which have short renewing times and grow wild on the hedges of fields and railway tracks. It is estimated that the area of sisal under cultivation in India (about 29 000 hectares) is capable of producing fibres valued at over Rs 15 crores ($15m US), but still the fibre is imported by India from Tanzania and other countries [2, 3]. It is also reported that conversion of unutilized and wasted leaves in India adds up to about 20 000 tonnes valued at about Rs 5 crores while the total world production of this fibre is about 0.6 million tonnes [2, 4–6].

A good sisal plant yields about 205 leaves [4] with each leaf having composition of 4% fibre, 0.75% cuticle, 8% other dry matter and 87.25% moisture. Thus a normal leaf weighing about 600 g yields about 3% by weight of fibre with each leaf containing about 1000 fibres. The fibre is extracted, particularly in India, either by retting, by scrapping with the hand or by retting followed by scrapping or by mechanical means using decorticators. It is reported that retting yields a large quantity of fibre of poor quality while the mechanical process yields about 2 to 4% fibre (15 kg per 8 h) with good quality having lustrous colour [1]. After extraction, fibres are washed thoroughly in clean and plentiful water to remove chlorophyll, leaf juices and adhesive solids.

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A large quantity of this renewable resource is being under-utilized. At present, sisal fibre is mainly used for the manufacture of ropes for use in marine industry and agriculture [1, 7]. The fibre is also used in making twines, cords, in upholstery, padding and mat making, fishing nets, fancy articles such as purses, wall hangings, table mats, etc. It is reported that sisal can be used for the manufacture of flat and corrugated sheets which are strong and cheap having good fire resistance [8]. Sisal is also incorporated into plastics [9] and into cement [10]. In the latter case, flexural strength seemed to increase when sisal fibre and cement are used in suitable proportion. There is also a report about feasibility of developing polymer based composites using sisal fibres due to the low cost of production of composites and amenability of these fibres to winding, laminating and other fabrication processes [11]. However, such a versatile fibre can still be better utilized particularly for societal uses such as in low cost housing applications in view of the feasibility of developing composite materials with various matrices. This calls for a systematic study to understand the structural properties of the fibres and compatibility of the fibres with matrices. There have been some reports [12] on improving the yield and quality of fibre as well as on the chemical constituents of the fibre [2, 13]. Also, some scattered data are available on the physical properties including standardization of tests to be carried out on sisal fibres and yarns for strength and fineness [6, 14–17]. Some of the available data are listed in Table I. However, these studies do not give details regarding the variation of properties with respect to dimensions (diameter and test length) of fibre used, test speed or the strain rate at which the data are collected nor the sensitivity of the testing machines used. Furthermore, no attempt has been made in any of these studies to understand the observed physical properties in terms of structural details. Such understanding of structure–property relationship will not only help open up new avenues for fibres, but also emphasize the importance of these agricultural materials, which form one of the abundantly available renewable resources in the world.

The present investigation reports on mechanical properties of sisal fibre such as initial modulus, UTS, average modulus and per cent elongation as functions of fibre diameter, test length and speed of testing. These results and the fracture mechanism of sisal fibre are interpreted in terms of strucutral parameters which are determined using optical and scanning electron microscope (SEM) techniques.

2. Experimental procedure

Sisal fibres used in the present study were from a suburb of Trivandrum (Kerala, India) and supplied by Khadi & Village Industries Commission, Trivandrum. Fibres of different diameters ranging from 100 to 300 μm were sorted out using an optical microscope. A Metler balance was used to determine the fineness of fibres while the density of the fibres was determined using a specific gravity bottle with xylene as the fluid. For evaluating tensile properties, fibres were mounted on a piece of cardboard with a central window using sellotape and pulled in an Instron testing machine. Fibres 100 to 300 μm in diameter and 50 mm long were tested at 10 mm min^{-1} test speed; fibres 200 μm in diameter but 15 to 65 mm long were tested at a test speed of 10 mm min^{-1}, and fibres 200 μm in diameter and 50 mm long were tested at test speeds of between 1 and 50 mm min^{-1}. For each set of tests mentioned above 25 fibres were tested. A Metalloplan optical microscope was used to understand the structure of the fibre while fractured fibres were examined after suitable preparation under a JEOL scanning microscope model 35C to understand the mechanism of fibre fracture. All the tests were carried out at 65% r.h. at room temperature and after conditioning the fibres under these conditions.

3. Results

3.1. Denier and density of sisal fibre

The density of the fibre is found to be 1.45 cm^{-3}. The denier values are determined for the fibres of observed diameter (width). The variation of denier with observed diameter indicates that the fibres are not of cylindrical shape but of ribbon type. The flatness of the ribbon increases more rapidly than the thickness of the fibre, indicating anisotropy of structure in the transverse section also.

3.2. Stress–strain curve of sisal fibre

Fig. 1 shows a typical stress–strain curve of a sisal fibre of length 50 mm, diameter 200 μm and tested at a cross-head speed of 10 mm min^{-1}. The curve shows an initial linear region characterized by initial modulus. As the applied stress increases, the weak primary cell wall collapses and decohesion of

TABLE I Properties of sisal fibres

References	Diameter of fibre (μm)	Density (g cm^{-3})	Size of cells (mm)	Moisture content at 65% r.h. (%)	Major chemical constituents		Micro-fibrillar angle (deg)	UTS (MN m^{-2})	YM (GN m^{-2})	% elongation	TM (GN m^{-2})	FR (N m^{-2})
					Cellulose (%)	Lignin (%)						
[17]	–	–	2.2 mm	–	–	–	20–25	764	15.2	5	–	–
[14]	215	–	–	–	–	–	23.1	–	–	–	0.028	–
	–	1.450	–	11	–	–	–	569–640	–	2.5–4.5	–	12.5–17.5
[8]	50–200	1.450	–	–	–	–	–	568–640	9.4–15.8	3–7	–	–
[24]	50–200	–	–	–	–	–	–	–	–	–	–	–
[1]	–	–	–	–	78	8	–	–	–	–	–	–
[13]	30–150	–	0.5–4.0 long	11	66–72	10–14	–	460	–	–	–	12.5–17.5
[4]		–	0.5–0.6 wide									
[16]	160–182	–	–	–	–	–	–	412–540	–	–	–	–

TM: transverse modulus; FR: flexural rigidity.

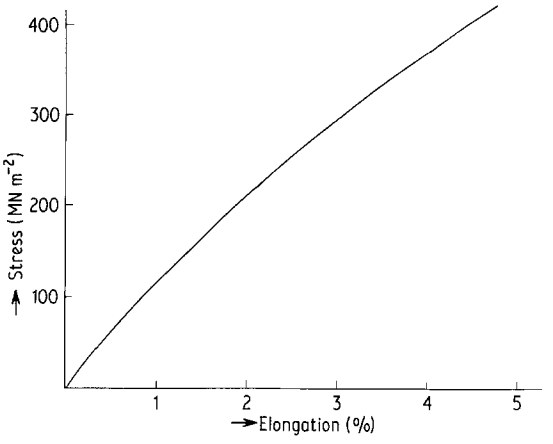

Figure 1 Typical stress–strain curve of a sisal fibre of diameter 200 μm and 50 mm long tested at 10 mm min^{-1}.

cells begins following decohesion of cellulosic and non-cellulosic molecules mainly through weak links and imperfections. This is indicated in the curvature of the stress–strain curve. The applied stress also causes the uncoiling as well as extensions of the crystalline fibrils in the secondary walls of the cells.

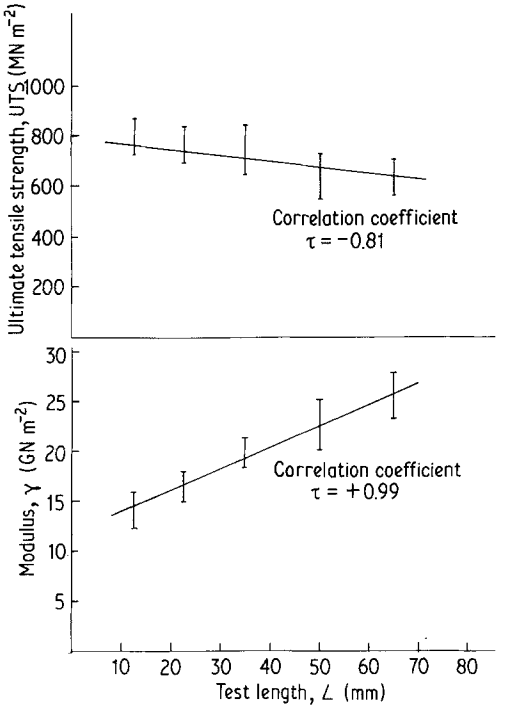

Figure 2 Variation of ultimate tensile strength (UTS) and modulus (γ) with test length (L).

3.3. Effect of diameter/denier of the fibre

Table II shows the mechanical parameters of sisal fibres of 50 mm length tested at 10 mm min^{-1}. The mechanical parameters do not show any appreciable change with increase in diameter of the fibre investigated as has been observed in the case of banana fibre [18].

3.4. Effect of test length

Sisal fibres of different test lengths having diameter 200 μm were tested at a speed of 10 mm min^{-1}. Table III lists the observed variation of mechanical parameters with test lengths. Fig. 2 shows the variation of UTS and YM with test lengths. It can be seen from Table III that both UTS and per cent elongation decrease with test length as observed in the case of banana [18] and coir [19] fibres, whereas YM and AM increase with test length. Test of significance using Student's t-test shows that the variations are significant. A regression analysis shows a linear relationship between UTS (σ in MN m^{-2}) and test length (L in m) in the range studied. The regression equation is given by

$$\sigma = 796 - 2367.9L, \qquad (1)$$

with correlation coefficient $\gamma = -0.81$ and the slope having significance level at 1%.

Since the standard deviations (SD) in mean strengths of the fibre, at particular gauge lengths, were observed to be high and variant, a further test was carried out, namely coefficient of variation (CV = standard deviation/mean) of UTS values at different gauge lengths, to verify the observed linear variation of the mean UTS values. Table IV shows the variation of CV with test lengths. The regression equation is given by

$$\mathrm{CV} \times 10^{-2} = 5.36 \times 10^{-2} + 0.17 \times 10^{-2} L,$$

TABLE II Variation of mechanical properties with fibre diameter (test length: 50 mm; speed of testing: 10 mm min^{-1})

Diameter (mm)	*Initial modulus (GN m^{-2})	*Ultimate tensile strength (MN m^{-2})	*% elongation at break	Average modulus (GN m^{-2})
0.10–0.30	17.0–22.0	530.0–630.0	3.64–5.12	9.8–16.5

*No systematic and significant variation was observed with diameter.

TABLE III Variation of mechanical properties with test length (diameter of fibre: 200 μm; speed of testing: 10 mm min^{-1})

Test length (mm)	Initial modulus (GN m^{-2})		Ultimate tensile strength (MN m^{-2})		% elongation at break		Average modulus (GN m^{-2})	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
15	14.15	1.50	793.80	59.70	8.15	1.07	9.74	1.02
25	17.26	1.62	757.10	72.25	5.70	1.44	13.28	1.55
35	19.71	1.53	728.10	85.70	4.65	1.30	15.64	2.12
50	22.52	2.53	630.10	90.00	3.98	0.62	15.83	1.93
65	25.36	2.20	620.81	98.70	3.50	0.35	17.87	1.57

having correlation coefficient $\gamma = +0.97$ at 1% significance level. Thus it shows that there exists a linear relationship between the test length and the ultimate strength of sisal fibre.

3.5. Effect of test speed

Table V lists values of UTS, YM, per cent elongation and average modulus of sisal fibres of diameter 200 μm and length 50 mm tested at different speeds. Only the YM and UTS values show significant variation and these increase with increase in test speed from 1 to 50 mm min^{-1}. However, at 500 mm min^{-1}, UTS decreases sharply. Such behaviour is also observed in banana fibres [18].

3.6. Fracture studies

Figs. 4 and 5 show SEM pictures of the fractured tips at test speeds 10 mm min^{-1} and 500 mm min^{-1} respectively. It is clear from these figures that the fracture mode in sisal fibres depends on the speed of testing as observed in the case of banana fibre [18].

4. Discussion

As reported earlier [18], the mechanical properties of plant fibres depend on (a) source, (b) age, (c) species, (d) processing parameters and (e) internal structure including chemical constituents. In the present study, the sisal fibres used were supplied from one locality and are extracted manually from the sisal leaves. Effects due to factors (a) to (d) as well as chemical constituents on the variation of observed mechanical parameters can be neglected. Hence, in the following paragraphs, we shall explain the observed properties of the fibres in terms of structural variations.

TABLE IV Coefficient of variation (SD/Mean) of UTS (from Table III) at different gauge lengths

Test length (mm)	Coefficient of variation (SD/Mean) of UTS (× 10^{-2})
15	7.5
25	9.5
35	11.7
50	14.2
65	15.8

Fig. 3 shows both transverse and longitudinal sections of sisal fibre indicating that sisal fibre is a multicellular fibre as other vegetable fibres having mainly compactly arranged sclerenchyma cells (strengthening cells). The cells have diameter (d) of 25 μm and a mean length (l) of 2.5 mm with a l/d ratio of 100 [20] for fibres of diameter 50 to 300 μm in contrast to cell diameter of 18 to 30 μm and mean length of 2.7 to 5.5 mm and l/d ratio of 150 in the case of banana fibre [18] of diameter 80 to 250 μm. The cell walls of sisal fibre appear to be thicker (8 to 25 μm) with varying lumen size of 8 to 12 μm in contrast to thinner (1.25 μm) but uniform cell walls and lumen size of 12.5 μm in banana fibre. These comparative structural differences between sisal and banana fibres indicate sisal fibre to be weaker than banana fibre.

4.1. Stress–strain curve

Sisal fibre, having both crystalline and non-crystalline components, is expected to behave like a viscoelastic material when subjected to tension. The applied stress is shared initially between crystalline and non-crystalline components in a natural fibre which is also basically a fibre-reinforced composite on a microscale. The extent to which the fibre resists the deformation in the low strain region is called the initial modulus of the fibre. The effective modulus (E_f) may then be calculated for the fibre following the equation due to McLaughlin [21]:

$$E_f = W_c E_c \cos^2\theta + W_{nc} E_{nc}, \qquad (2)$$

where E_c and E_{nc} are the modulus values of crys-

TABLE V Variation of mechanical parameters with test speed (diameter of fibre: 200 μm; test length: 50 mm)

Speed of testing (mm min^{-1})	Initial modulus (GN m^{-2})		UTS (MN m^{-2})		*% elongation	*Average modulus (GN m^{-2})
	Mean	SD	Mean	SD		
1	8.41	1.42	481.00	78.80	3.16–4.12	11.70–22.10
2	20.00	1.64	608.80	95.40		
10	22.12	2.53	630.12	90.00		
50	34.16	1.75	759.70	58.10		
500	–	–	441.60	150.70		

*No systematic significant variation was observed with speed of testing.

talline and non-crystalline regions and are assumed to be 45 GN m^{-2} and 3 GN m^{-2} respectively for the vegetable fibres [19]. W_c and W_{nc} are the weight fractions of the crystalline and non-crystalline components which have values of 0.67 and 0.12 respectively for sisal fibre [2]. The microfibrillar angle (θ) of sisal fibre is found to be 23.14° [19]. The modulus value (E_f) calculated using the above values in Equation 2 is 26 GN m^{-2}, which is of the same order as observed in the present investigation.

As the applied stress increases the viscoelastic nature of the fibre becomes clearer. Several viscoelastic models have been proposed [22] to explain the behaviour of viscoelastic materials. These models essentially consists of a dashpot (representing amorphous regions) and a spring (representing crystalline regions) in series and parallel combinations. Fig. 6 represents the calculated stress–strain behaviour of such a simple two element model of Maxwell [23] which qualitatively fits well with the observed stress–strain curve of sisal fibre shown in Fig. 1 and thus confirming the viscoelastic nature of the fibres.

The different structural and chemical parameters of sisal, banana and coir are shown in Table VI. It can easily be seen that higher cellulose content and smaller microfibrillar angle are mainly responsible for the higher strength and modulus and smaller elongation. This is in conformity with earlier studies made in the case of other plant fibres [18, 21, 24].

4.2. Effect of diameter/denier

In sisal fibres the microfibrillar angle and number of strengthening cells did not show any appreciable variation within the range of fibre diameter used in the present study. Hence, no appreciable change in values of YM, UTS and per cent elongation were observed in the diameter range of the sisal fibres studied.

4.3. Effect of test length

The observed decrease in the values of UTS and per cent elongation at break and increase in YM and AM with increasing test length of the fibre may be understood as follows: with increase in test length the number of weak links or imperfections increases, thus resulting in reduction in UTS and per cent elongation values [25] (see Appendix). On the other hand, with increase in test

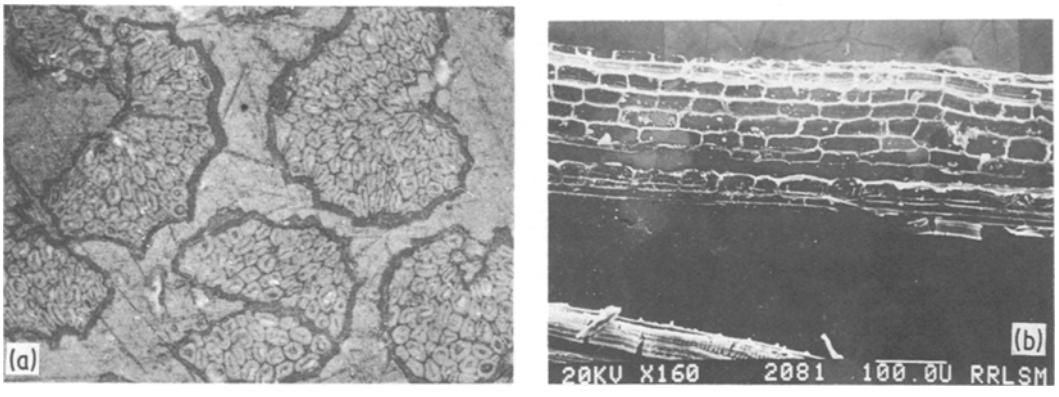

Figure 3 (a) Photomicrograph of cross-section of sisal fibre. (b) Scanning electron micrograph showing longitudinal section.

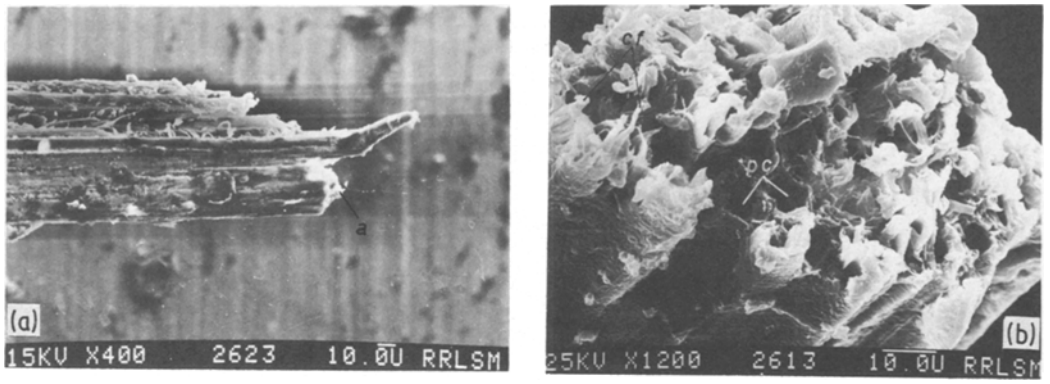

Figure 4 Fractured tips of sisal fibre tested at 10 mm min^{-1} showing (a) bonding material between the cells remaining intact; (b) uncoiling of fibrils (cf) and pull-out of the cells (pc).

length of the fibre, a higher resistance is offered by the fibre to the applied stress which results in lower elongation initially. This probably accounts for the higher modulus of the fibres at longer test lengths. The reason for such behaviour, unlike metals, is due to the multicellular structure, viscoelastic nature and non-uniform structural inhomogeneity of the natural fibres.

From the plot of UTS against test length, an estimate of density of weak links in the fibre can be made using linear equation derived relating UTS (σ) and test length (L) of the fibre (Appendix) given by:

$$\sigma_L = m_L L + \sigma_{L_0}. \quad (3)$$

The slope m_L is usually negative and expressed as MN m^{-3} when σ is expressed as MN m^{-2} and L in m. Table VII lists the values of the slopes for sisal, banana and coir, indicating the degree of flaw density along the length of the fibres. The extent of such relationships and the significance of the slope is shown in Table VI by the correlation coefficient and significance level of the slope, respectively, calculated from the experimental observation.

4.4. Effect of speed of testing

The observed variation in the strength values can be explained from the viscoelastic model of cellulose fibres (Section 4.1). A mathematical analysis of the model [22] shows that for any type of rapid mechanical test, the fibre behaves like an elastic body, i.e., the crystalline region (represented by a spring in the model) mainly shares the applied load which results in higher values of both modulus and UTS. When the speed of testing decreases, the applied load will be shared increasingly by the amorphous region (represented by the dashpot in the model). However, for a very slow mechanical test the fibre behaves like a viscous liquid and the major portion of the applied load is shared by the amorphous regions and thus results in low modulus and UTS values.

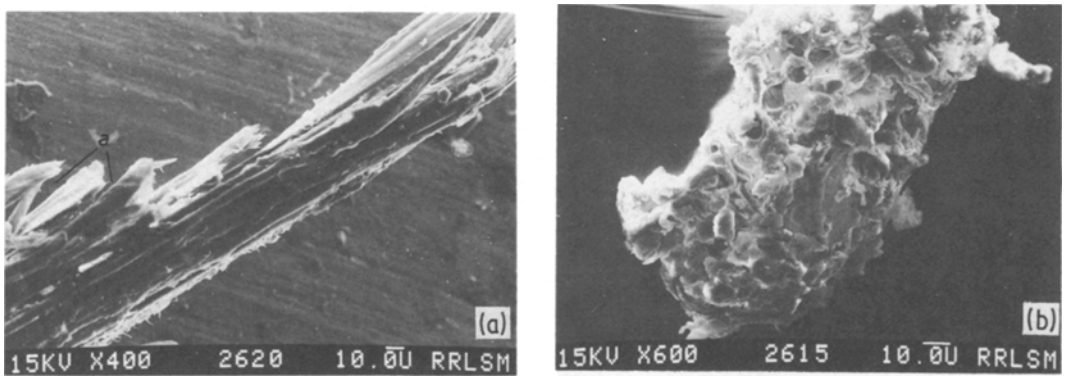

Figure 5 Fractured tips of sisal fibre tested at 500 mm min^{-1} showing (a) decohesion of the cells through the bonding material; (b) relatively little uncoiling of fibrils and pull-out of the cells.

TABLE VI Comparison of structure and properties of some natural fibres

Fibre	Diameter (μm)	Density (g cm^{-3})	Cellulose (%)/ Lignin(%) content	Cell length (l)/Cell breadth (d) ratio	Cell wall thickness (μm)	Microfibrillar angle (deg)	YM (GN m^{-2})	UTS (MN m^{-2})	% elongation
Sisal	100–300	1.450	70/12	100	12.5	20–25	17–22	530–630	3.64–5.12
Banana	50–250	1.350	83/5	150	1.25	11–12	27–33	711–789	2.4–3.6
Coir	100–450	1.150	37/42	35	8.00	30–45	3–6	106–175	17–47

However, at very high strain rate (500 mm min^{-1}), the sudden fall in UTS value may be due to the presence of imperfections in the fibre which quickly respond to the applied stress at this large strain rate and thus causing an immature failure. The large SD observed in this case may also be due to irregular response of the imperfections to the applied stress.

4.5. Fracture studies

It has been reported [26] that fracture mode in natural fibres can be of two distinct types, namely intracellular and intercellular. The intracellular fracture is generally observed in fibres having large elongation and tested at low speed. Such a fracture is accompanied by tearing of cell walls as well as pull-out of the fibrils. The intercellular fracture is commonly observed in low elongation fibres tested at high speed. Intercellular fracture occurs mainly with separation of bonding material between the cells and very little pull-out of the fibrils.

Sisal fibre is found to have a mixed mode of fracture. At low strain rate (1 mm min^{-1}) the fracture mode appears to be mostly intracellular in nature. The pull-out and uncoiling of the fibils can be clearly seen in Fig. 4b without any separation of cells near the periphery of the fibre or breaking any bonding material between the cells (Fig. 4a). However, at a much higher speed of testing, 500 mm min^{-1}, the fracture mode appears to be intercellular (Fig. 5). This can be understood since at this high speed the major contribution is from the crystalline fraction, and the fibre takes up a comparatively higher stress. The amorphous fraction, being unable to stand this stress level. develops cracks which results in failure. Thus relatively lesser amounts of uncoiling, tearing of cell walls and pull-out of the microfibrils are expected, as observed in Fig. 5b. On the other hand, a considerable amount of separation of cells by breaking through the bonding material is evident in Fig. 5a, as expected.

TABLE VII Density of weak links in plant fibres

Fibre	Density of weak links, m_L (MN m^{-3})	Correlation coefficient	Significance level (%)
Coir	2320.4	0.98	1
Sisal	2367.9	0.81	1
Banana	1376.7	0.77	1

5. Conclusions

1. The stress–strain curve for sisal fibre is characterized by an initial linear region followed by a curvature indicating the increased rate of strain produced with increase in stress. This is in accordance with the viscoelastic nature of the fibre.

2. The values of experimentally observed elastic modulus, UTS, average modulus and per cent elongation are in the range of 17 to 22 GN m^{-2}, 530 to 630 MN m^{-2}, 98 to 165 MN m^{-2} and 3.64 to 5.12% respectively for fibres in the 100 to 300 μm diameter range, indicating little variation in mechanical properties with variation in diameter of the fibre.

3. Values of UTS and per cent elongation of sisal fibre decreased from 793.8 MN m^{-2} and 8.15% for 15 mm test length of 625.6 MN m^{-2} and

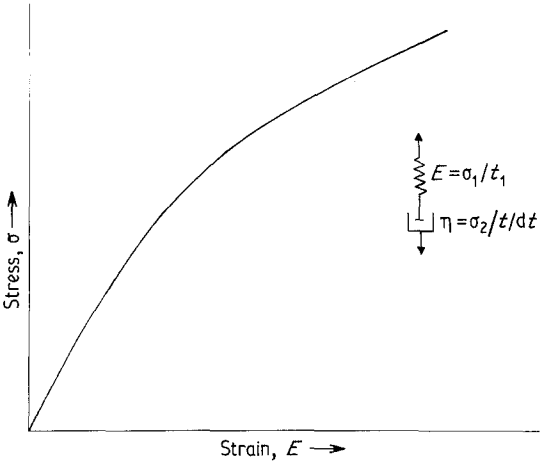

Figure 6 Stress–strain behaviour of the two element Maxwell model.

3.50% for 65 mm test length of the fibre. Also both initial modulus and average modulus increased with decrease over the test lengths mentioned above.

4. Values of initial modulus and UTS increased from 8.41 GN m^{-2} and 481.0 MN m^{-2} respectively at a test speed of 1 mm min^{-1} to 34.16 GN m^{-2} and 759 MN m^{-2} respectively at a test speed of 50 mm min^{-1}. These results confirm the viscoelastic nature of the fibre.

5. Fracture studies reveal that sisal fibre has a mixed mode of fracture. At low speed the fracture mode is mainly intracellular whereas at high speed the fracture mode is essentially intercellular.

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Appendix

In natural fibres, since the flaws or weak links are irregularly spaced in the fibre, the strength will depend upon the length of the fibre used for the tensile test [25].

If a fibre having length L and strength σ is now changed in length by dL, a corresponding change in strength $d\sigma$ will be observed. The incremental changes can be related by the equation given below:

$$d\sigma = \alpha \frac{dL}{L}, \qquad \text{(A1)}$$

where dL represents the probability of having an imperfection introduced or reduced, L represents the probability of already having an imperfection in L and α represents a measure of the frequency of occurrence of weak links in the fibre. Integrating Equation A1 we obtain:

$$\sigma_L = \sigma_0 + \alpha \ln \frac{L}{L_0}, \qquad \text{(A2)}$$

where σ_0 is the strength of the fibre of length L_0 taken as standard. Equation A2 predicts the general nature of variation of strength with test lengths in any range.

In a particular range we can write $L = L_0 + \Delta L$. Equation A2 then becomes:

$$\sigma_L = \sigma_0 + \alpha \ln \left(1 + \frac{\Delta L}{L_0}\right).$$

Assuming $\Delta L/L_0 < 1$, we obtain from first approximation

$$\sigma_L = \frac{\alpha}{L_0} \Delta L + \sigma_0,$$

or

$$\sigma_L = \frac{\alpha}{L_0} L + \sigma_0 - \alpha \quad (\text{putting } \Delta L = L - L_0)$$

or

$$\sigma_L = \alpha'_{L_0} L + \sigma'_{L_0}. \qquad \text{(A3)}$$

σ_0 and σ'_{L_0} have the same dimension, that is MN m^{-2}, while α'_{L_0} has dimension MN m^{-3}.

From Equation A3, a plot of σ_L against L gives a straight line to a first approximation. The slope of the line gives an estimate of the density of flaws along the fibre. However, absence of any variation as expected by Equation A3 should mean that the flaws are regularly distributed in the range studied and the average distance between the flaws is very small compared to the test lengths.

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