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Structure and properties of some vegetable fibres

Part 3 *Talipot and palmyrah fibres*

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The mechanical properties of palmyrah and talipot fibres have been evaluated. Like other natural fibres, these fibres were also found to be viscoelastic in nature. The variation of the initial modulus (YM), ultimate tensile strength (UTS) and elongation (%) values were determined as a function of fibre fineness, test length and speed of testing. Change in test length from 10 to 100 mm palmyrah fibres produces a decrease in UTS from 220 to 161 MN m^{-2}. Such variations were not observed in the case of talipot fibres except at low test length. The observed results have been explained in the light of the structural characteristics of these fibres namely chemical constituents espiral angle, number of defect centres, cell sizes, etc.

1. Introduction

Talipot (*Corypha umbracentifera L.*) and palmyrah (*Borassus flaballifera L.*) are the palm trees (Fig. 1) found in many areas of the comparatively dry part of India. Palmyrah is commonly grown along the coastal areas in the southern parts of India as well as in Bihar and in West Bengal, while talipot is mostly found in Western Ghats at an elevation of about 2 m. These trees are exploited at present and about 7500 tonnes of fubres valued at US $0.2 million (Rs. 1.6 million) are exported annually. Similarly, about 0.03 million talipot trees are concentrated in Kerala alone which can yield about 0.01 million tonnes of fibre annually valued at about US $1.5 million [1].

These palm trees bear crowns of 30 to 40 fan-like leaves (Fig. 1). The leaves combine stalks and yield strong and hard fibres. Fibres are extracted from these stalks by softening the ends followed by beating with a wooden mallet (Fig. 2) and are finally separated from each other by combing the strips over a steel wire brush. Fibres, thus obtained, are found to be stiff and thick. There is no systematic study of the properties of these palm fibres except for recent brief reports regarding mechanical properties [2], and details on the chemical characterization and structure [3]. Major chemical constituents of these two fibres along with those of coir are given in Table I. At present palmyrah fibres are mainly used for making hard brushes while talipot fibres are used for fancy articles like wall hangings, mattings and woven bags [2]. In view of these limited uses a lot of this abundantly available resource is going waste. However, if diversified uses for these fibres can be thought of, it would not only increase utilization of this abundant and renewable resource but also help in increasing employment opportunity in the rural sector since the fibre industry is a cottage industry. This calls for understanding of structure–property correlations of these fibres. It is in this context, that this paper deals with determination of the stress–strain curves, strength properties of talipot and palmyrah fibres as a function of fibre fineness, test length and speed of testing. Optical and scanning electron microscopic studies of these fibres are also reported which help in understanding the behaviour of the fibres under the various testing conditions mentioned above and the related fracture behaviour.

2. Experimental details

Palmyrah and talipot fibres used for the present investigations were from a suburb of Trivandrum (Kerala State, India) and supplied by Khadi and Village Industries Commission, Trivandrum. These fibres were first sorted using an optical microscope and defective brittle fibres were rejected. The fineness of the fibres was determined using a Mettler balance and grouped in different denier values. Palmyrah fibres are found to have a fineness ranging from 810 to 6000 denier whereas talipot fibres have a fineness between 180 and 1170 denier. The density of the fibres was determined using a specific gravity bottle and xylene as the liquid.

Tensile properties of these fibres were evaluated using an Instron testing machine. Variation in mechanical properties was determined for these fibres at different lengths, test speeds and denier values separately as reported earlier for coir and other fibres [4–7]. Gauge length was varied from 10 to 100 mm and test speed was varied from 0.05 to 100 mm min^{-1} for these fibres.

A Metalloplan optical microscope and a JEOL scanning electron microscope were used to study the structural characteristics as well as fracture behaviour of palmyrah and talipot fibres using appropriate sample preparation techniques. All the tests mentioned above were carried out at room temperature and at 65% r.h.

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Figure 1 Photograph of palm trees.

3. Results

3.1. Density and denier values of palmyrah and talipot fibres

The densities of palmyrah and talipot fibres were found to be 10 900 and 8900 kg m^{-3}, respectively. The diameter–denier variation in these fibres shows their ribbon-like shape as also observed in sisal and pineapple fibres [6, 7].

3.2. Microscopic studies

Figs. 3a and b show the cross-section of palmyrah and talipot fibres indicating that these two palm fibres contain cells of different types and sizes with lacuna being placed asymmetrically at the end of the section. This feature is in contrast with other natural fibres including coir where a lacuna is observed at the centre [4–8]. Figs. 4a and b show SEM photographs of the surface of palmyrah fibre. It can be seen that the surface contains a large number of dimple-like structures (pores capped with tyloses) covered by pithy and waxy material. Cracks running across the fibres are also seen on the surface (Fig. 4b). Figs. 5a and b are scanning electron micrographs of the surface of talipot fibres showing regularly spaced dimples, some of which are uncapped [8]. Figs. 6a and b show the SEM pictures of fractured surface of palmyrah and talipot fibres showing their respective modes of fracture.

3.3. Stress–strain behaviour

Figs. 7a and b show the stress–strain characteristics of palmyrah and talipot, respectively. The curves are characterized by an initial linear region, the slope of which gives the initial modulus. With increase in stress, the curves follow a uniform curvature which is found to be higher for palmyrah than talipot. Such curvature indicates a disproportionate increase in strain with stress which is due to the viscoelastic nature of the fibres as explained in the case of sisal [6]. As the stress is increased further the fibre finally fails with palmyrah having much higher elongation at break than talipot fibres.

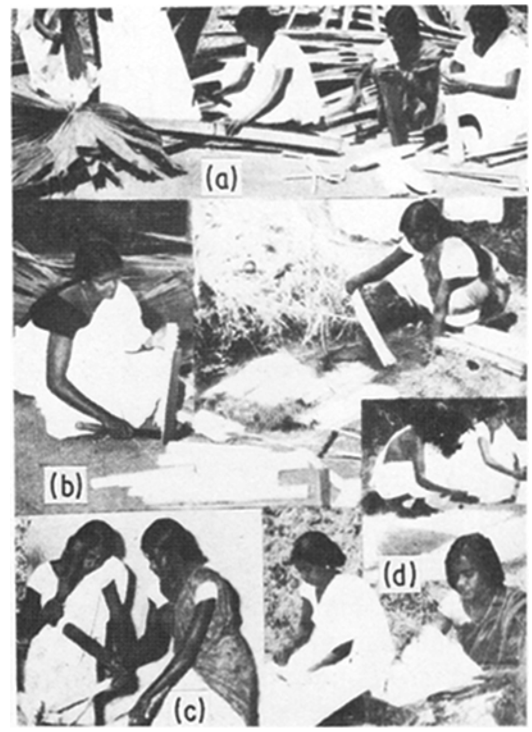

Figure 2 Photograph showing extraction of palm fibres from leaf stalk. (a) Cutting the leaf stalk, (b) sectioning the leaf stalk, (c) beating the sectioned leaf stalk and (d) extracting the fibres by combing.

3.4. Effect of test length

Tables IIA and IIB show the mechanical properties of palmyrah and talipot, respectively, evaluated at different test lengths at a crosshead speed of 20 mm min^{-1}. Palmyrah fibres tested for the purpose were within 4050 to 4200 denier range while talipot fibres were between 720 and 750 denier.

Table IIA shows that for palmyrah fibres both UTS and percentage elongation decrease with increasing test length whereas the initial modulus increases with test length. Similar results have been observed in most of the natural fibres [4–7]. A linear regression analysis between UTS (σ in MN m^{-2}) and test length (l in m) leads to the regression equation

$$\sigma = 219.6 - 669.8\,l \qquad (1)$$

with a correlation coefficient $r = -0.95$ significance at 1% level. The elongation (ε in %) at break also

TABLE I Properties of some natural fibres

Fibre	Cellulose content (%)	Lignin content (%)	Microfibrillar angle (θ)	Cell length /diameter ratio (l/d)	Initial modulus (GN m^{-2})	UTS (MN m^{-2})	Elongation (%)
Palmyrah	40–52	42–43	29–32	43	4.4–6.1	180–215	7–15
Talipot	67–68	28–29	23–26	47	9.3–13.3	143–263	2.7–5.2
Coir [4]	37–42	42–45	30–45	35	3–6	106–175	17–47
Sisal [6]	70	12	20–25	100	17–22	530–630	3.6–5.1
Pineapple [7]	85	12	12–14	450	24.3–35.7	360–740	2.0–2.8

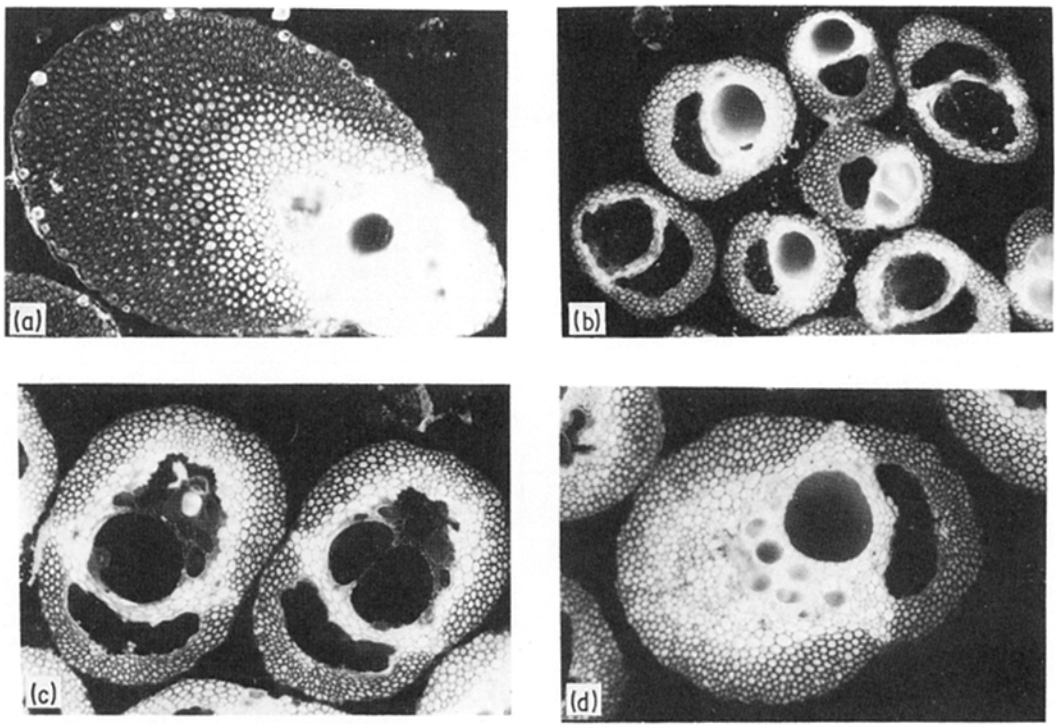

Figure 3 Micrographs of the cross-sections of palm fibres showing their multicellular nature. (a) Palmyrah fibre, and talipot fibres of (b) 180 denier, (c) 720 denier and (d) 1170 denier.

shows a highly significant decrease with test length, l, given by the linear regression equation.

$$\varepsilon = 24.3 - 215.0 l \quad (2)$$

with a correlation coefficient of $r = -0.88$ at 1% significance level.

3.5. Effect of fineness

Table IIIA and IIIB show the variation in mechanical parameters with fineness of palmyrah and talipot fibres tested at a gauge length of 50 mm and at a test speed of 20 mm min^{-1}. Palmyrah fibres do not show any significant systematic variations (Table IIA) in mechanical properties with changes in denier values from 810 to 5000. Similar results have also been observed in sisal [6] and banana fibres [5]. However, in talipot fibres (Table IIIB), elongation does not show any systematic significant variation whereas both UTS and modulus show a decreasing tendency with increase in denier values from 180 to 720 and thereafter both UTS and initial modulus show a significant increase up to 1170 denier.

4. Discussion

It is well known that the strength properties of vegetable fibres depend on various factors such as source, age, species, processing parameters, chemical constituents and internal structure. In the present investigation both talipot and palmyrah fibres were obtained from one locality near Trivandrum and extracted manually. Therefore it can be assumed that the variation in observed properties may be mainly due to the change in structural parameters of the fibres. Accordingly attempts are made in the following paragraphs to understand the observed properties in the light of the structural characteristics of these fibres.

Like other natural fibres, palmyrah and talipot fibres are multicellular and made up of crystalline (as α cellulose) and amorphous components. The crystalline content, mainly present as cellulose microfibrils, is the major factor in the high strength of these fibres. The orientation of the microfibrils about the fibre axis usually termed as microfibrillar angle (θ) is mainly responsible for the elongation of these fibres and also

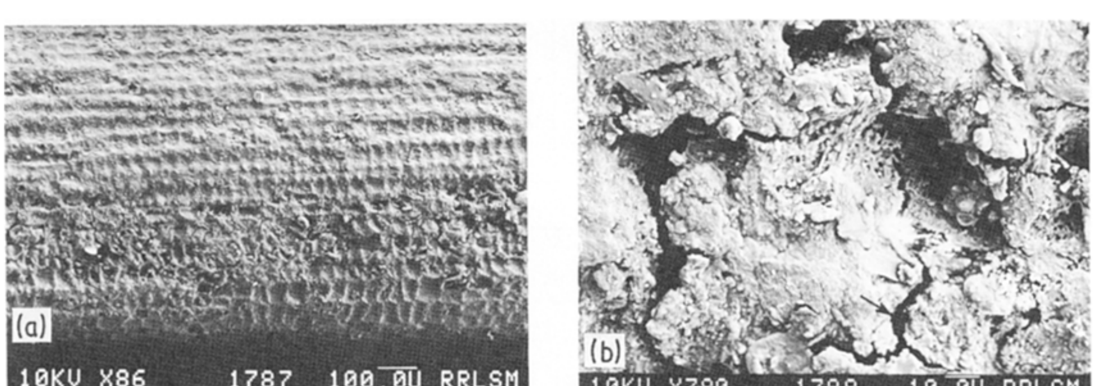

Figure 4 Scanning electrons micrographs of the surface of palmyrah fibres showing (a) pithy and waxy material and (b) the presence of cracks.

TABLE IIA Variation of mechanical properties with respect to test length for palmyrah fibres

Test length (mm)	UTS ($MN m^{-2}$)		Elongation (%)		Initial modulus (YM) ($GN m^{-2}$)	
	Mean	SD	Mean	SD	Mean	SD
10	220.00	15.60	26.70	12.50	1.98	0.01
35	192.70	26.40	12.70	2.40	3.41	0.09
50	180.50	21.70	9.50	2.60	5.20	0.50
75	161.80	21.10	7.17	2.00	6.62	0.90
100	161.20	27.09	6.10	2.20	6.84	0.70

TABLE IIB Variation of mechanical properties with respect to test length for talipot fibres

Test length (mm)	UTS ($MN m^{-2}$)		Elongation (%)		Initial modulus (YM) ($GN m^{-2}$)	
	Mean	SD	Mean	SD	Mean	SD
10	253.10	34.00	10.4	3.0	2.68	0.05
35	↑		↑		7.08	1.10
50	70* to		2.90* to		9.30	0.90
75	200		3.40		8.40	0.50
100	↓		↓		10.10	1.00

*No significant variation was observed.

contributes towards the strength [9]. The strength of these natural fibres also seems to increase with increase in cell length (l) to cell diameter (d) ratio. Table I gives a comparison of the observed structural characteristics and properties of a few natural fibres along with talipot and palmyrah fibres. It can be seen from Table I that the observed higher cellulose content in talipot (67 to 68%) compared to palmyrah (40 to 52%) is closely correlated with higher strength and modulus in talipot fibres than palmyrah fibres. Furthermore, the higher microfibrillar angle (θ) observed in palmyrah (29 to 32°) than that of talipot (23 to 26°) could account for the higher elongation and lower strength observed in these fibres. (Details of obtaining θ values are given later.) The above conclusions are in agreement with earlier results [4–7] obtained for various plant fibres.

TABLE IIIA Variation of mechanical properties with respect to fineness of palmyrah* fibres

Fineness (denier)	UTS ($MN m^{-2}$)	Elongation (%)	YM ($GN m^{-2}$)
810–5500	180–215	7.00–15.00	4.00–6.10

*No systematic significant variation was observed.

4.1. Microscopic studies

The optical micrographs of the cross-section of talipot and palmyrah (Figs. 3a and b) show that the fibres are multicellular in nature. The cell walls are much thinner (4 to 8 μm) compared to the large size of the lacuna (140 to 185 μm) [8]. The asymmetrically placed large lacuna is detrimental to the strength of both these fibres. Talipot fibres show more than one lacuna-like pore with loosely bound cells which is probably one of the major sources of defect in this fibre. Fig. 4a shows that the surface of palmyrah fibre is not smooth but contains dimple-like tyloses capped pores covered with waxy and pithy materials. The cracks observed on the surface material (Fig. 4) may sometimes cause initiation of fracture. The surface of talipot fibres (Fig. 5), however, is found to have covered regularly spaced tylose capped pores. The tyloses are sometimes found uncapped (Fig. 5b) thus exposing the pores on the surface. These open pores are highly detrimental to the strength of these fibres and may probably be the chief source of defects present in these fibres.

The SEM of the fractured surface of palmyrah fibre shows that fracture is essentially intracellular in nature (Fig. 6a) like coir [4] with considerable uncoiling seen in the cells. Talipot fibres on the other hand

TABLE IIIB Variation of mechanical properties with respect to fineness of talipot fibres

Fineness (denier)	UTS ($MN m^{-2}$)		Elongation (%)	YM ($GN m^{-2}$)	
	Mean	SD		Mean	SD
180	262.50	33.00	↑	11.48	0.70
360	192.80	44.60			
540	158.50	25.97	3.4*	10.60	1.40
			to	9.90	0.39
720	143.00	35.00	5.3	9.30	0.30
900	166.00	45.00		10.88	1.35
1170	225.00	29.00	↓	13.35	2.30

*No significant variation was observed.

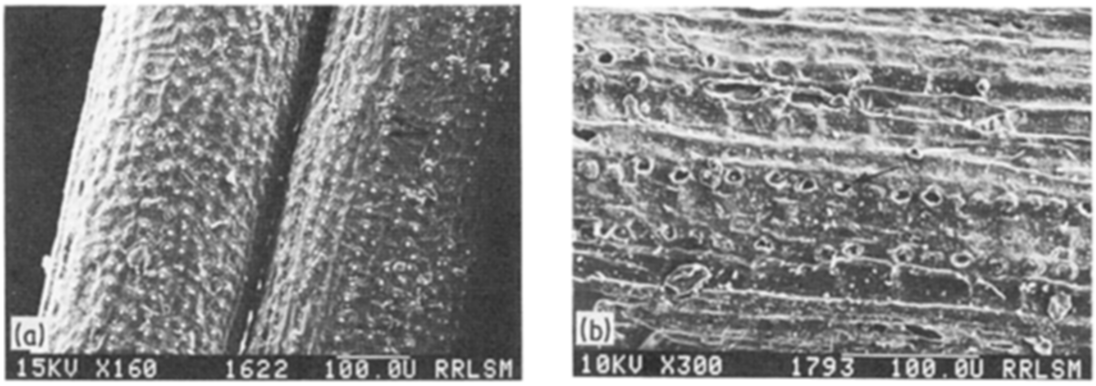

Figure 5 Scanning electron micrographs of the surface of talipot fibres showing (a) the presence of regularly spaced dimples and (b) uncapped dimples (pits).

show mostly a brittle type of fracture with much less uncoiling (Fig. 6b) indicating the major cause of fracture to be due to the defects that are present in the fibre.

4.2. Stress–Strain curve

The stress–strain curves of palmyrah and talipot (Figs. 7a and b) clearly indicate that these fibres are viscoelastic in nature [6]. The applied load is therefore shared between the crystalline and amorphous regions of these fibres. The fibres having basically spiral-like structures undergo deformation as described [10–12]. The mechanism of extension namely elongation of microfibrils by uncoiling with bending and twisting seems to be present simultaneously in these fibres. The expression for effective modulus (E_f assuming the above model is given by

$$E_f = \frac{E\cos^2\theta\,[K(1 - 2\cot^2\theta)^2]}{E\cos^2\theta + K(1 - 2\cot^2\theta)^2} \qquad (1)$$

where θ is the microfibrillar angle, K is the bulk modulus which was calculated to be $35\,\mathrm{GN\,m^{-2}}$ and E is the modulus calculated using the equation given by

$$E = E_c W_c + E_{nc}(1 - W_c) \qquad (2)$$

E_c and E_{nc} are the modulus values of crystalline and non-crystalline regions, respectively, and are assumed [9] to be 45 and $3\,\mathrm{GN\,m^{-2}}$, respectively. Using Equation 1 and the observed modulus values the microfibrillar angle for talipot and palmyrah fibre would work out to be 23 to 26° and 29 to 32°, respectively, which compares well with the observed values for other natural fibres having the same range of modulus values (Table 1).

After the region of initial extension, the matrix yields and the molecules slip past one another resulting in a higher strain rate as indicated by the curvature of the stress–strain curves (Figs. 7a and b). The fibre finally breaks and fracture in these fibres is largely caused by the innumerable defects present. Talipot shows a higher initial modulus and less curvature in the stress–strain curve because of its higher cellulose content compared with palmyrah. However, the failure of talipot fibre takes place prematurely due to the presence of surface defects (Fig. 5): asymmetrically placed large lacuna and lacuna-like pores and loosely bound outer cells (Fig. 3). Palmyrah, on the other hand having a higher lignin content is capable of arresting cracks and thus producing higher elongation.

4.3. Effect of test length

In palmyrah fibre both UTS and elongation decrease and initial modulus increases as test length increases. The same phenomenn is also observed in other natural fibres [4–7]. The decrease in UTS and elongation is due to an increase in defect centres with increasing test length. These defect centres are largely distributed irregularly in the fibre and hence the strength–length relationship as derived in the case of sisal [6] is obeyed . The initial modulus is a measure of the stiff resistance offered against any deformation of the cellulose mol-

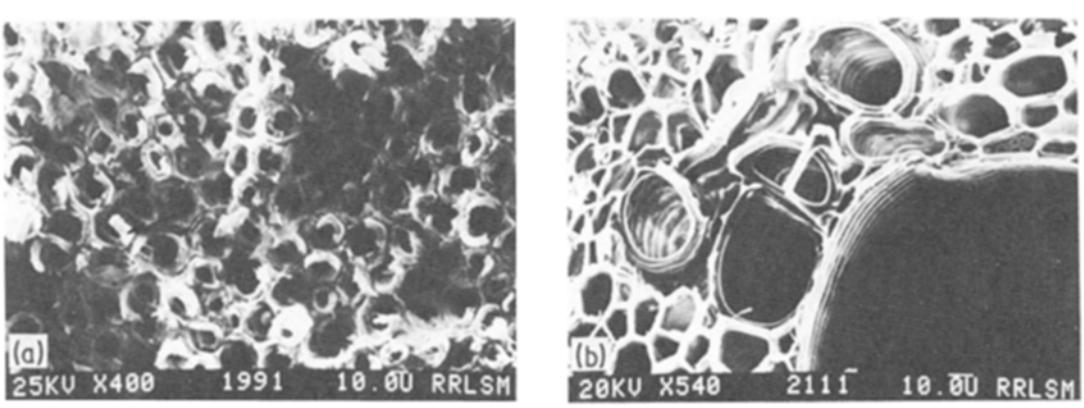

Figure 6 Scanning electron micrographs of the fracture surface of (a) palmyrah fibres showing the uncoiling of helical spirals and (b) talipot fibres showing highly brittle-type failure.

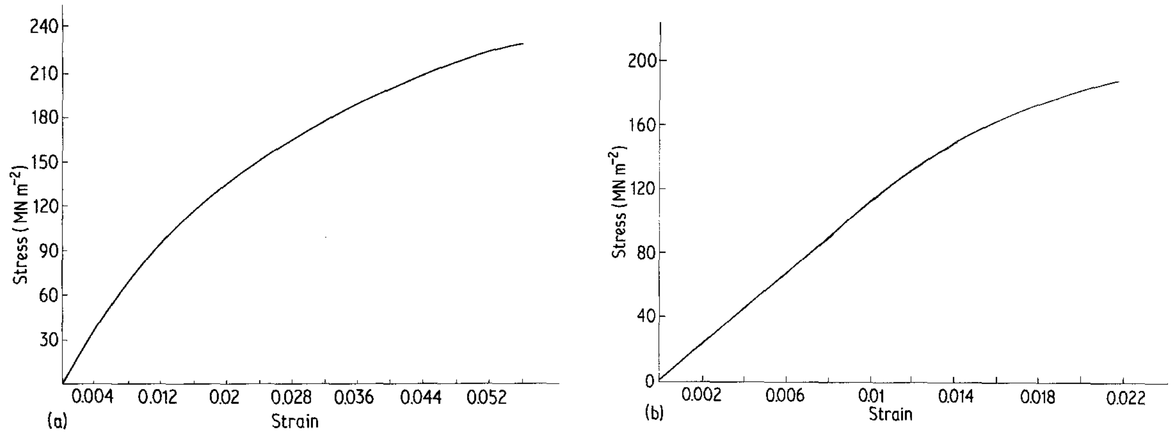

Figure 7 Stress–strain diagrams of (a) palmyrah fibres and (b) talipot fibres.

ecules which are connected by covalent and hydrogen bonding. Since initial modulus is measured at low stress levels, defects do not contribute significantly. The increase in initial modulus with increasing test lengths is due to the larger resistance put forward by the cellulose molecules resulting in lower elongation and hence higher modulus.

However, in the case of talipot the above characteristic variations are not significant in the gauge length range studied except at low gauge length (~ 10 mm). The innumerable defects present seem to control UTS and elongation values of this fibre. The strength–length relationship [13] is not valid at higher gauge lengths (> 10 mm) since the flaw distribution remains the same because of the large number of defect centres being regularly spaced in them (Fig. 5). The considerable defects (see Section 4.1) also seem to be responsible for the low UTS and elongation values in talipot fibres in spite of it having considerable cellulose content. The initial modulus however is much higher in talipot than in palmyrah and increases with test length significantly for the same reason as explained earlier in this section.

4.4. Effect of fineness

As already mentioned the mechanical parameters in a particular fibre vary due to the change in microfibrillar angle, number of strengthening cells and magnitude of defects present. With a change in denier values in palmyrah fibres the above parameters do not show any appreciable change thus resulting in no significant change in mechanical parameters. However, in the talipot fibres, the strength of the fibres showed a decrease from 180 to 720 denier and then increased up to 1170 denier. The microfibrillar angle does not show any appreciable change in these fibres (Table I). The optical micrographs of the fibres having denier values 180, 720 and 1170 are shown in Figs. 3b, c and d, respectively. It can be clearly seen that the magnitude of defects as revealed from the size and number of lacuna-like pores is maximum at 720 denier. On the other hand fibres of denier 180 and 1170 show the cells to be compact and also show a comparatively low number of lacuna-like pores. Thus these asymmetrically placed pores may be the chief cause of the lowest strength in the fibres of 720 denier.

4.5. Effect of test speed

Both talipot and palmyrah fibres are likely to be viscoelastic in nature like other lignocellulosic fibres as also revealed by their stress–strain behaviour. Though such viscoelastic fibres should be sensitive to the test speed, no significant variation is observed in the mechanical parameters of both these palm fibres at different speeds of testing (Table IV). This could be due to the considerable surface and inner structural defects (microdefects) present in these fibres (see Section 4.1). Such a structural state results in large scatter value of the mechanical parameters and thus poses a hindrance to the predicted variation with test speed for viscoelastic materials.

5. Conclusion

(a) Stress–strain characteristics of both talipot and palmyrah show the same nature as also observed in other natural fibres. Palmyrah fibres show higher elongation than talipot.

(b) Palmyrah fibres having fineness in the range 810 to 5500 denier were found to have initial modulus, UTS and elongation at break values in the ranges 4.4 to 6.1 GN m^{-2}, 180 to 215 MN m^{-2} and 7 to 15%, respectively. For talipot fibres the initial modulus, UTS and elongation values were found to be 9.3 to 13.35 GN m^{-2}, 143 to 263 MN m^{-2} and to 2.7 to 5.2%, respectively, for fibres in the denier range 180 to 1110.

(c) Both palmyrah and talipot fibres do not show any systematic variation in the mechanical properties

TABLE IV Variation of mechanical properties with respect to test speeds of palmyrah and talipot fibres*

Fibre	Crosshead speed (mm min^{-1})	UTS MN m^{-2}	Elongation (%)	YM (GN m^{-2})
Palmyrah	0.05–100.00	175–214	0.70–13.00	4.96–6.03
Talipot	0.05–100.00	123–185	2.70–4.60	5.27–9.83

*No systematic significant variation was observed.

with change in test speed from 0.05 to 100 mm min^{-1}.

(d) In palmyrah fibres the strength and elongation decreased and initial modulus increased with increase in test length of the fibre from 10 to 100 mm. However in talipot fibres variation was not found to be significant except at small test lengths (< 35 mm).

(e) The fracture tips of the fibres show that the talipot fibre has a highly brittle type of fracture whereas considerable pulling out of microfibrils was observed in the palmyrah fibres.

(f) In the talipot fibres with increase in denier values, the decrease in strength up to 720 denier and subsequent increase up to 1110 denier has been explained on the basis of lacuna-like pores which act as defect centres. The number of such centres is found to increase up to 720 denier and then decreases at 1110 denier.

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