Mechanical behaviour of coir fibres under tensile load

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Stress–strain curves of coir fibres have been determined. Mechanical properties including initial modulus, strength and percentage elongation of coir fibres have been evaluated as functions of retting treatment (during retting the coconut husks are soaked in saline water for a period of about six months to facilitate the extraction of fibres presumably due to a bacterial process), fibre diameter, gauge length and strain rate. No significant differences in mechanical properties were observed between retted and unretted fibres. The strength and percentage elongation seem to increase for both retted and unretted fibres up to a fibre diameter of 0.2×10^{-3} m whereafter they remain almost constant. On the other hand, moduli seem to decrease with increase in diameter of the fibre. The observed modulus values and percentage elongation have been related to microfibrillar angle. Observed strength values have been explained on the basis of structural changes occurring with an increase in the diameter of the fibre. Scanning electron microscope studies have indicated that the failure of the fibre is due to the fracture of the cells themselves accompanied by the uncoiling of microfibrills. There is no appreciable variation in strength and percentage elongation with strain rates for any one diameter of the fibre. On the other hand, with increase in gauge length, a decrease in both strength and percentage elongation at break has been observed. These have been attributed to an increase of probability of defects and localized deformation and gentle necking, respectively.

1. Introduction

Natural and synthetic fibres, filaments and yarns are major raw materials for textiles, building materials and composites for aerospace applications and many industries based on these fibres have been in existence for a long time. Even though the utilization of these fibres depends on their physical and mechanical properties, detailed scientific information is still lacking particularly in the case of natural fibres like coir fibre (*cocos nucifera linn*). A better understanding of the properties of these fibres will help in the development of new products.

The limited data available [1–9] for coir give no details regarding the size of the fibres or the strain rates at which the data were collected. There is also no mention of the sensitivity of the testing machine used in the work. Further, no attempt has been made to interpret the properties observed in terms of the structural details of the fibres. The deformation mechanisms leading to the observed values of mechanical properties in coir are not understood even though the mechanisms of failure in many other cellulose-based plant fibres have been studied both theoretically and experimentally in some detail [6, 10–18].

Some attempts have been made [6, 13–20] to correlate the observed values and predicted values of initial modulus and strength of some plant fibres in terms of microfibril angle. Similarly, some correlation has also been found between cellulose content and the strength or modulus of the plant fibres. However, a large variation has been observed between the experimental and the predicted values.

In this paper the mechanical properties of coir

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TABLE I Mechanical properties of the retted an unretted coir fibres with a strain rate of 2.5 × 10^{-2} m min^{-1} and a gauge length of 0.05 m.

Sample number	Diameter (× 10^{-3} m)	Mean ultimate tensile strength (MN m^{-2})		Mean percentage elongation at break		Initial modulus (GN m^{-2})	
		Retted	Unretted	Retted	Unretted	Retted	Unretted
1	0.10	106.59	111.66	17.80	18.20	4.52	–
2	0.15	138.06	126.90	26.34	25.40	4.17	4.01
3	0.20	175.82	146.18	33.74	35.12	4.41	4.62
4	0.25	169.02	149.23	36.94	36.60	5.83	5.00
5	0.30	166.49	161.41	42.88	37.20	5.20	3.51
6	0.35	175.62	157.35	43.48	43.20	4.76	3.27
7	0.40	169.53	156.34	45.64	39.00	3.71	–
8	0.45	170.55	–	47.26	–	4.10	–

*Retting is a bacterial process in which the husks are soaked in water for about 8–10 months and then beaten to produce dry fibres

fibre as functions of the retting process, the diameter and gauge length of the fibres at various strain rates are reported. Structural studies using optical and scanning electron microscopy (SEM) are also reported with a view to understanding the observed results.

2. Experimental procedure

The coir fibre material (both retted* and unretted) which is generally used by the coir industry was bought from Kovalam, near Trivandrum in India. Fibres ranging from 100 to 450 μm in diameter (width) were chosen and the fibres were mounted in a fixture made of paper board with a central window for testing breaking load, modulus and percentage elongation in an Instron machine. Some of the fibres were also tested using a strength tester, type FG100, at a strain rate of 2.5 × 10^{-2} m min^{-1}. Fibres of 0.25 × 10^{-3} m diameter were subjected to a tensile load at various strain rates ranging from 0.2 × 10^{-2} to 3 × 10^{-2} m min^{-1}.

In order to study the structural aspects of the fibre, optical and SEM work was carried out on fibres after suitable preparation. A JEOL scanning electron microscope was used in the latter case.

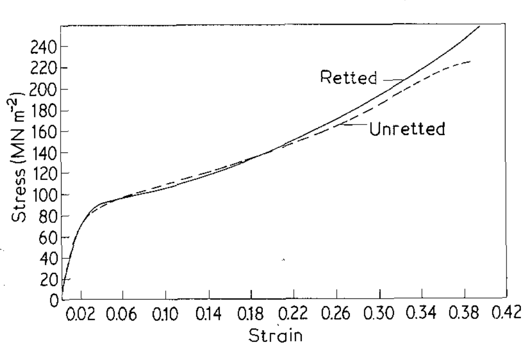


Figure 1 Stress–strain diagram of retted and unretted coir fibre.

3. Results

3.1. Stress–strain diagram of coir fibre

Fig. 1 shows a typical stress–strain diagram obtained at a strain rate of 2 × 10^{-2} m min^{-1} for retted and unretted coir fibres of 0.25 × 10^{-3} m diameter, respectively. As can be seen from the figure, the stress–strain curves of both retted and unretted fibres are similar. They are characterized by an initial portion of linear stress–strain relation (the slope of which may be taken as the initial modulus). This is followed by a non-linear region with disproportionately higher strain (the onset of this region may be taken as the yield point [15]). Then, the non-linear region is followed by a roughly linear region showing a tendency to curve upwards indicating some strain

TABLE II Properties of the retted coir fibres at different strain rates with a gauge length of 0.05 m.

Diameter of the fibre (× 10^{-3} m)	Strain rate (× 10^{-2} m min^{-1})	Tensile strength (MN m^{-2})	Percentage elongation
0.20	0.05	177.65	32.19
0.20	0.50	178.67	33.00
0.20	2.00	163.64	32.96
0.20	2.50	175.82	33.74
0.25	0.05	167.50	34.60
0.25	0.50	185.77	33.50
0.25	2.00	226.38	34.96
0.25	2.50	169.02	37.94
0.30	0.05	150.24	30.66
0.30	0.50	165.47	31.08
0.30	2.00	197.45	40.56
0.30	2.50	166.49	42.88

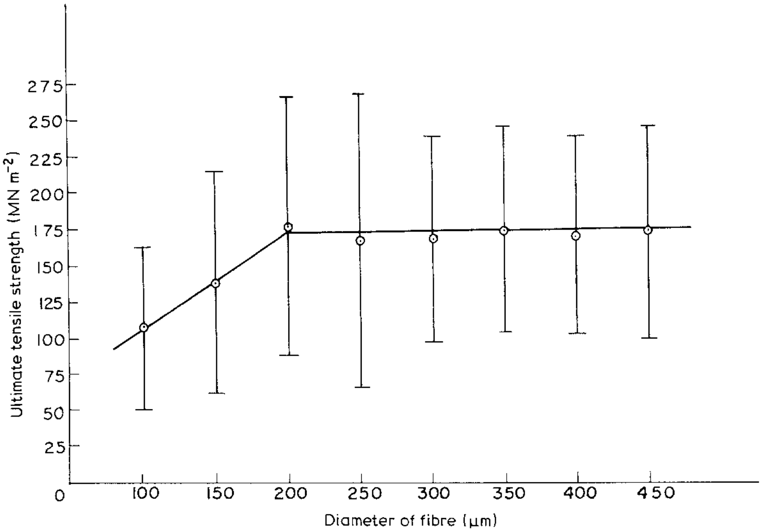


Figure 2 Plot of ultimate tensile strength against size of the coir fibre.

hardening. Such stress–strain diagrams are also observed in some polymers [15].

3.2. Effect of retting and size (diameter) of the fibre

The mechanical properties of various diameters of retted and unretted fibres are shown in Table I. These are evaluated statistically due to the variability of the test data (Fig. 2). It can be seen that no significant difference in properties is observed between retted and unretted fibres. However, the strength and percentage elongation of both types of fibres seem to increase up to a diameter of 0.2×10^{-3} m after which they remain almost constant. On the other hand, initial modulus seems to gradually decrease with an increase in the diameter of the fibres in the entire range between 0.10 and 0.45×10^{-3} m investigated (Fig. 3).

3.3. Effect of strain rate

Fig. 4 shows the initial portions of the stress–strain curve is strain-rate dependent within the meter tested at various strain rates as indicated in the figure. It can be seen that the initial stress–strain curve is strain rate dependent within the strain rates used in the present study. At a given stress value, progressively higher strains are observed as the strain rate is decreased indicating the viscoelastic nature of the coir fibre.

Table II lists the strength and percentage elongation of fibres of different diameters. It can be seen that there is no appreciable change

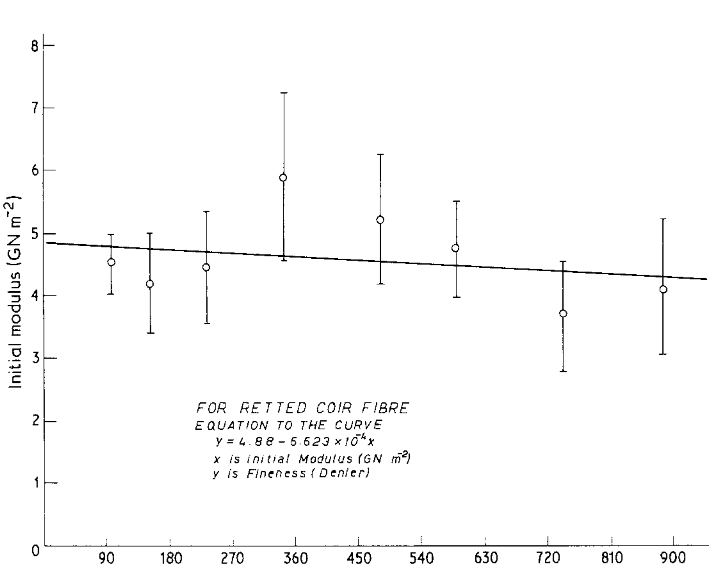


Figure 3 Relation between the initial modulus and size (fineness) of the fibre.

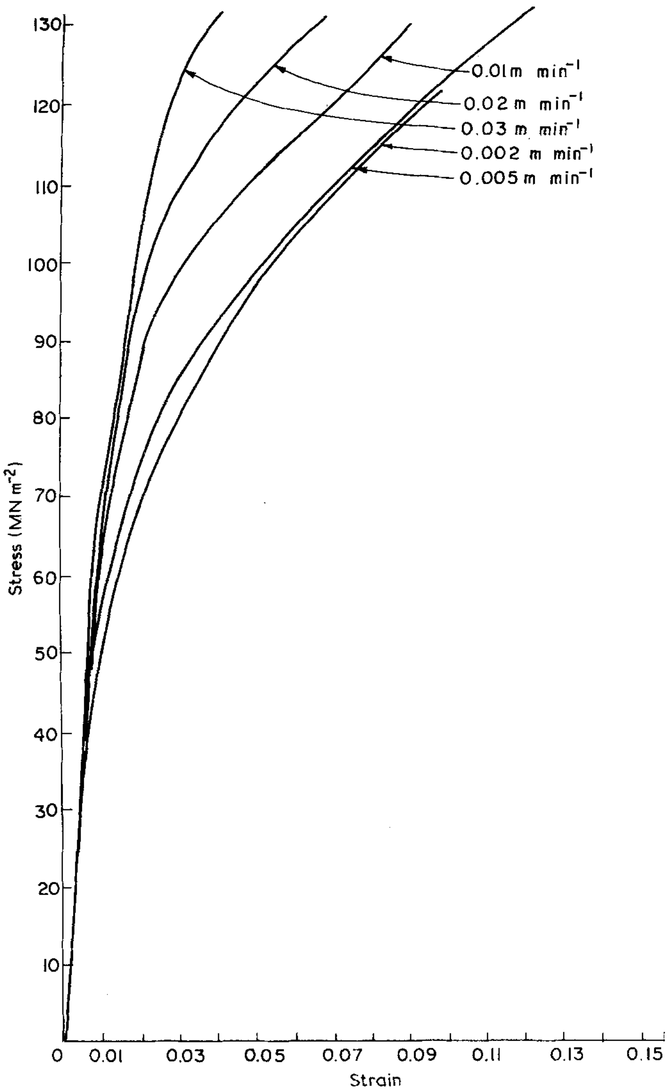


Figure 4 Stress–strain curves of 0.25×10^{-3} m diameter coir fibre tested at various strain rates.

in these two properties within the variation in strain rate (0.2×10^{-2} to 2×10^{-2} m min^{-1}) used in the present investigation.

3.4. Effect of gauge length

Various gauge lengths of coir fibres of 0.25×10^{-3} m diameter were tested to find the optimum standard test lengths of the fibre. Table III lists the values of strength, elongation and percentage strain as functions of gauge lengths of the retted fibres tested at a strain rate of 2.5×10^{-2} m min^{-1}. It can be seen that absolute elongation at fracture increases with an increase in gauge length of the fibre, however, the strength and percentage strain at fracture decrease with an increase in the gauge length. Fig. 5 shows a linear relationship between strength (σ) and length (l) of the fibre given by

$$\sigma = 302.38 - 2320.69\, l \qquad (1)$$

with a correlation coefficient of 0.983.

4. Discussion

It is well known that the properties of natural (plant) fibres depend on (a) the source (b) age and (c) internal structure of the fibres. Since the fibres in the present investigation were collected from the same place (Kovalam, India) from matured nuts usually plucked after 45 days (irrespective of the size of nuts) which are generally used in the coir industry, it can be assumed that the first two factors do not vary significantly. The results obtained in the present study are, therefore, mainly interpreted in terms of the structure of coir fibre.

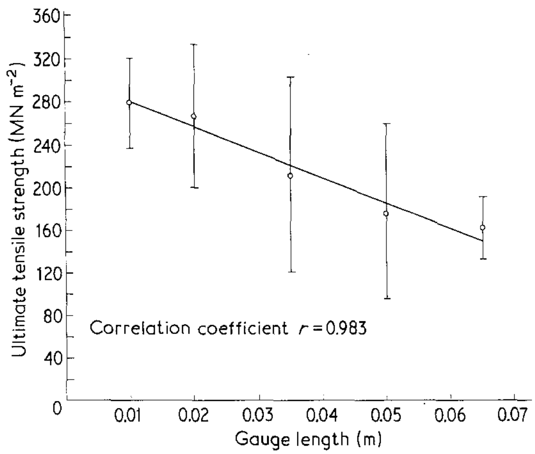


Figure 5 Variation of ultimate tensile strength with the gauge length of the fibre.

Since coir fibre is a multi-cellular plant fibre, it is appropriate to try to understand the properties observed through the cumulative effect of an array of individual cells in plant fibre being under a tensile load. The plant fibres are supposed to contain long-chain molecules forming a region with a high degree of order (crystalline-cellulose) as well as regions of less perfect order (non-crystalline-lignin complex) giving a fringed fibril structure as shown in Fig. 6 [11]. Long crystals in the form of helical spirals are supposed to be embedded in non-crystalline regions as shown in Fig. 7. However, direct support for the existence of cellulose crystals oriented at an angle between 30 and 45° with the fibre axis, comes only from X-ray studies of coir fibres [6, 12, 18–24].

4.1. Stress–strain curves

The deformation expected when a material with the structure described above is pulled in tension has been theoretically determined [12]. It is supposed that in the case of spiral-like structures (as in coir) either (a) the microfibrils along with the non-

TABLE III Variation of mechanical properties of retted coir fibre with gauge length of the specimen with a fibre diameter of 0.25×10^{-3} m and a strain rate of 25×10^{-3} m min^{-1}).

Sample number	Gauge length (m)	Tensile strength (MN m^{-2})	Elongation at fracture	Percentage elongation at fracture
1	0.010	279.17	11	110
2	0.020	265.98	12	60
3	0.035	211.15	16	45
4	0.050	175.62	18	36
5	0.065	168.42	22	33

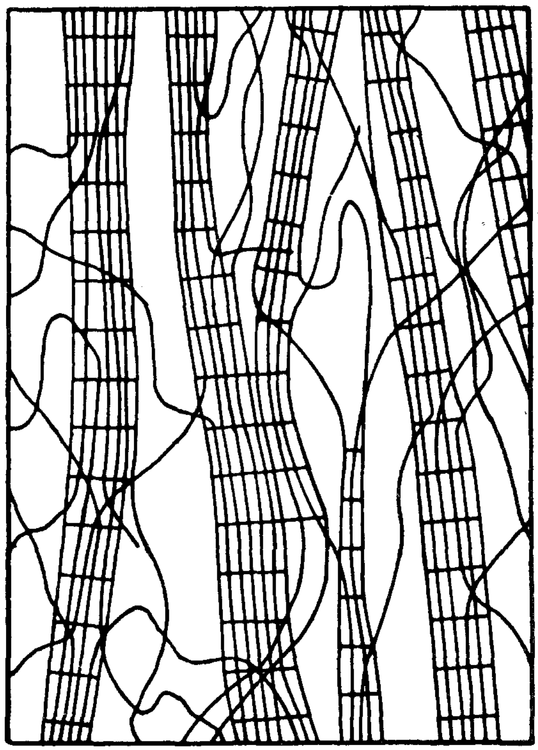


Figure 6 Typical view of fringed fibril structure (by permission of Wiley Interscience).

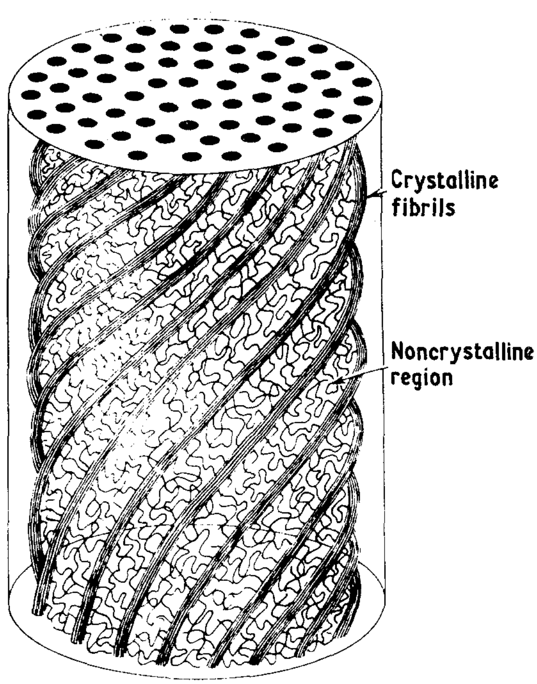


Figure 7 Typical view of helical arrangement in a natural cellulose fibre (by permission of Wiley Interscience).

crystalline regions may elongate or (b) the microfibrils may simply uncoil like springs with bending and twisting. The modulus values have been computed as a function of microfibrillar angle for situations where these two mechanisms operate alone or together. The value of the modulus and percentage strain at fracture have been calculated as functions of microfibrillar angle in plant fibres. However, in the case of coir fibre it appears that both mechanisms operate, but it is not known which of these two mechanism is predominant. The modulus values of coir measured in the present study seemed to be of the same order (about 5 GN m^{-2}) as expected from either mechanism (a) or (b) and are comparable with the value of 5.6 GN m^{-2} measured by Kaswell [5]. However the modulus values of cellulose calculated from this value of fibre modulus are very much lower (7 GN m^{-2}) than either the deduced value of 46 GN m^{-2} or the theoretical value of 56 GN m^{-2} for plant fibres [18]. This could be due to the presence of defects in cellulose fibres. Even in the case of metals the ratio between the theoretical and experimental value is of the order of 30.

Similarly, the measured values of percentage elongation at break (26–42%) compare well with the derived values (29–40%). Percentage elongation at break (26–42%) and microfibrillar angles (θ) for fibres of different diameters were measured. The regression equation relating percentage elongation (ϵ) and θ has been derived as

$$\frac{\theta^2}{60} + 1.24 = \epsilon \qquad (2)$$

with a correlation coefficient of 0.974.

It should be noted that this equation is similar in form to the regression equations derived for all plant fibres by McLaughlin and Tait [18], however, the constants in our equation are different.

The two factors above support the view that both modulus and percentage elongation at break are related to the microfibrillar angle even in the case of coir.

The stress and strain ranges at which disproportionately large strains begin to appear are 80 to 100 MN m^{-2} and 0.015, respectively. Beyond this region, the stress–strain curve shows a slight concave tendency indicating some strain hardening. The work-hardening coefficient observed in the present study is of the order of 0.08 and is comparable to that of some polymeric materials. The progressive alignment of microfibrils along the tensile axis may be one of the major reasons for the observed work-hardening in tension.

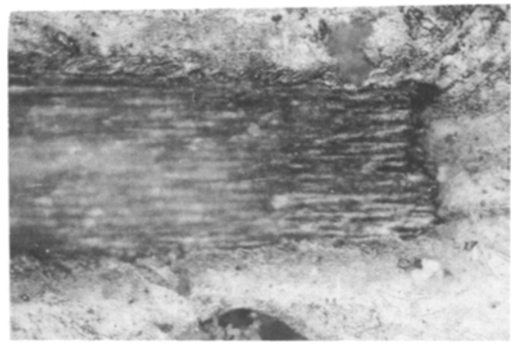


Figure 8 Longitudinal section of coir fibre after tensile testing indicating that the crack has not propagated along the cell wall and bonding between the cells is intact (× 80).

It may be worth mentioning here that in the case of coir fibre three types of bonding seem to exist, namely, the fibre surface is bonded by a gum type material called "cuticle", cells in the fibre are bonded by a resinous material (Fig. 8) and the microfibrils in the cells are embedded in a non-crystalline matrix (Fig. 7). When such a fibre breaks, it may be due to (a) either one or all three of the bondings breaking or (b) either the crystalline fibril or the non-crystalline matrix breaking. From metallographic examination no separation of the cells near the periphery of the fibre from the cuticle was observed (Fig. 9). Similarly, no breaking of the bonding material

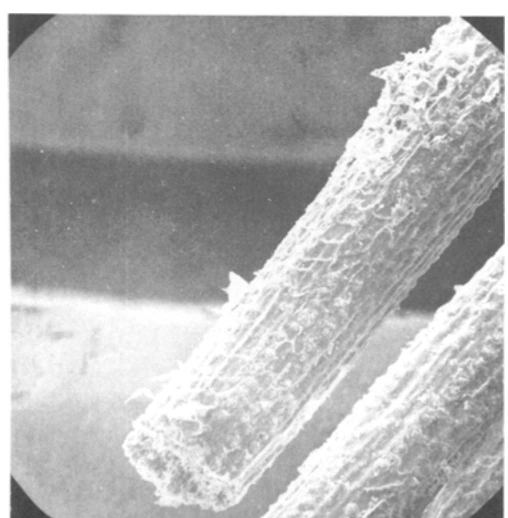


Figure 9 Fractured end of the coir fibre showing necking of the fibre (× 172).

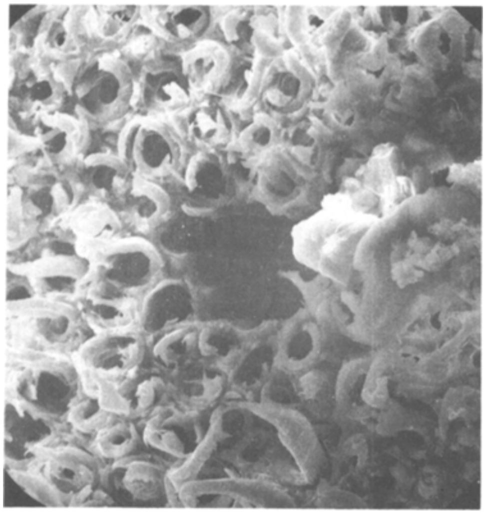


Figure 10 Fractured surface of the coir fibre showing the lacuna at the centre with uncoiling and fracture of the fibrils inside the cell walls (X 860).

Figure 11 Fractograph of the coir fibre showing pull-out of the cells and collapse of the cell walls (X 1375).

between the cells or cracks along the intercellular region were observed (Fig. 8) even at distances very close to the fracture zones. Only at the fracture surface is there some evidence of uncoiling of the microfibrils (Fig. 10). There is even evidence of decohesion of cell walls and their collapse [12] indicating that these phenomena are associated mainly with fracture. It was also found that the length of the fractured cells was nearly equal to the perimeter of the cells in Fig. 11 supporting the view that the final sudden break of the coir fibre is due to the fracture of the cells themselves, which in some cases is accompanied by the uncoiling of the fibrils.

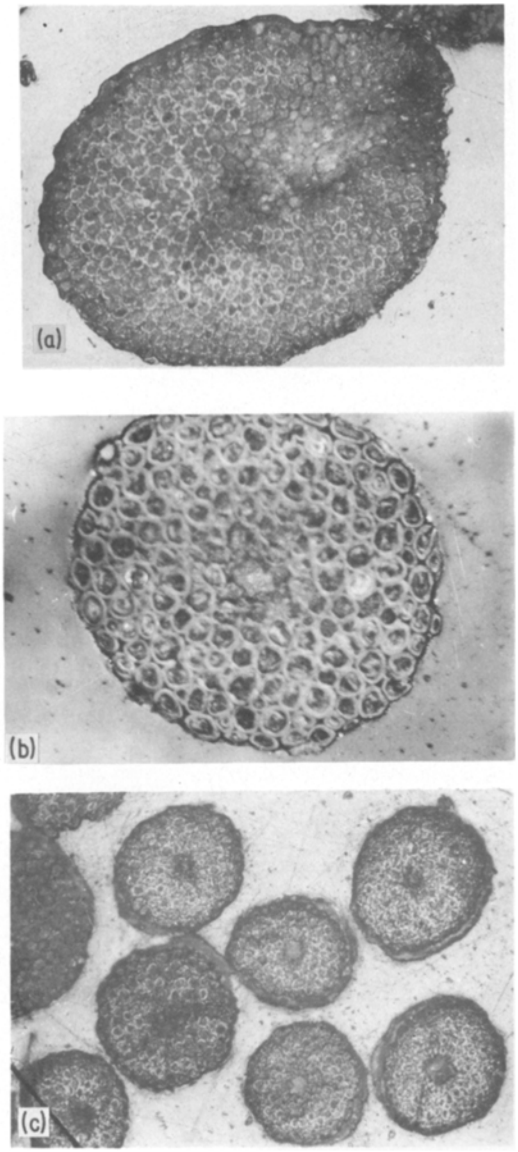
However, the value of strength observed in the present investigation compares well with those obtained by Prabhu [7] and Kaswell [5] while it is considerably lower than those reported elsewhere [18]. One of the reasons could be due to the different strain rates used or the conditions of testing (i.e. humidity and temperature at the time of testing).

4.2. Effect of size of the fibre and retting

As the diameter of the fibre increases, the total number of cells in the fibre, as well as the average cell diameter, increase, as can be seen from Figs 12 and 13. The number of cells per unit area decreased with fibre diameter. Also, defects in the fibre may increase while the crystalline component may decrease with size. It is also known that in plant fibres the coarser the fibre, the higher the microfibrillar angle will be [6, 19]. Thus, with an increase in diameter of the fibre, the initial modulus decreases as indicated by $E_p = E_c \cos^2 \theta$, where E_p is the modulus of the fibre for a microfibril of Young's modulus E_c aligned at a spiral angle of θ. Similarly, the breaking strain increases with increasing θ as expected in plant fibres [6, 18, 19]. The strength, on the other hand, showed an initial increase up to a diameter of 0.2×10^{-3} m where-

TABLE IV Relationship between diameter of the fibre and number of cells, diameter of lacuna and average diameter of the cell.

Sample number	Diameter of fibre (μm)	Average number of cells	Diameter of lacuna (μm)	Average diameter of cells (μm)	Number of cells per μm^2
1	150	264	8.080	9.20	1.49×10^{-2}
2	200	377	9.660	10.28	1.20×10^{-2}
3	250	474	10.792	11.47	0.965×10^{-2}
4	300	481	10.645	12.80	0.680×10^{-2}
5	400	584	9.027	20.00	0.464×10^{-2}



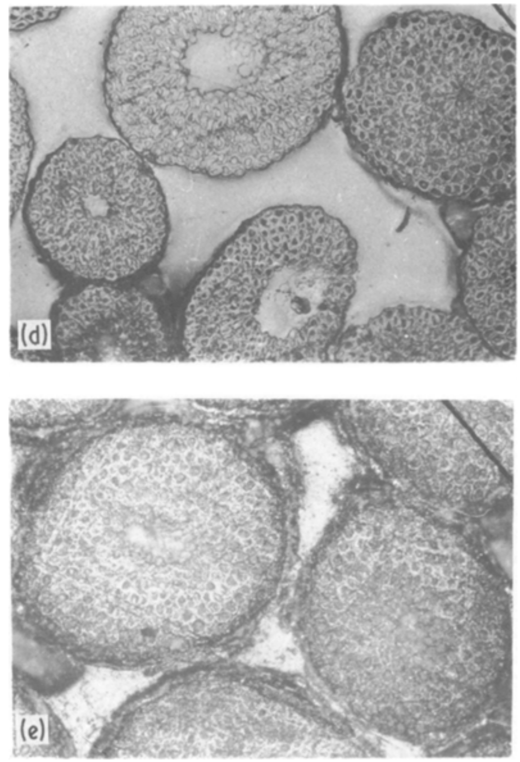


Figure 12 Transverse sections of coir fibre (a) retted coir fibre (× 320) (b) Unretted coir fibre (× 690) (c) Retted coir fibre of 0.15 × 10^{-3} m diameter (× 138) (d) Retted coir fibre of 0.25 × 10^{-3} m diameter (× 138) (e) Retted coir fibre of 0.35 × 10^{-3} m diameter (× 138).

upon it remained constant with an increase of diameter of the fibre up to 0.45×10^{-3} m. The confidence limits for increase in the mean strengths of fibres of different diameters were determined using a Student's *t*-test. The probability of increase was found to be 99.999%. It is also known that the strength of the fibre increases with the number of cells but decreases with increase in microfibrillar angle, decrease in cellulose content and increase in defects. It can be seen from Table IV that, in the present study, the number of cells increased rapidly up to a diameter of 0.2×10^{-3} m whereafter it increased slowly. Probably at this stage the effect of increase in total number of cells is more predominant than the other factors which effect the strength value of the fibre. Above a fibre diameter of 0.2×10^{-3} m, since the number of cells remains almost constant, effects due to other factors may compensate each other.

It should be noted that a large scatter was observed in the values of modulus, strength and percentage elongation in the present study. This scatter band is wider than the scatter predicted based mainly on variations in microfibrillar angle or cellulose content. This observed scatter could also be due to other factors such as sizes and number of cells, sizes of lumen and lacuna as well as the presence of defects in the fibres. If these factors are also considered, the basis for the large observed scatter may be understood.

It has been mentioned earlier [24] that since X-ray studies do not show any difference in structure between retted and unretted fibres, no appreciable change in their properties can be expected. Since retting is only a bacterial process,

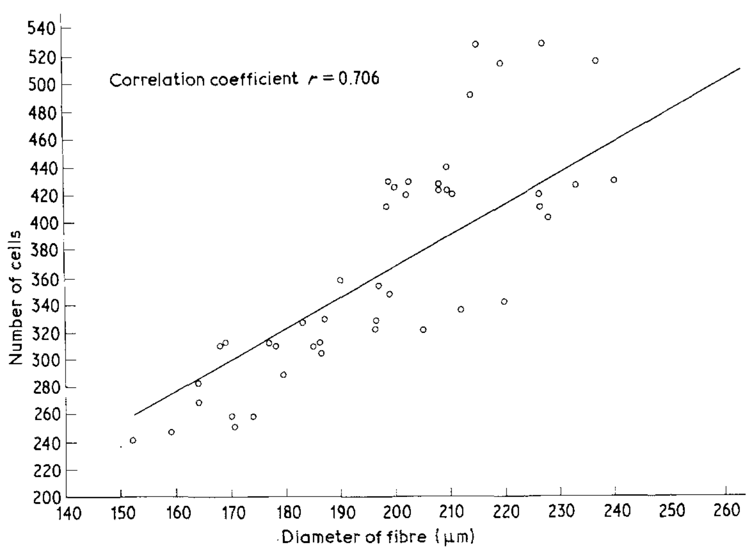


Figure 13 Relation between number of cells and diameter of the fibre.

it may not affect the internal structure very much. This may be the reason why even in the present study no significant variation in properties was observed between retted and unretted fibres.

4.3. Effect of strain rate

Although it is generally expected that strain rates do affect the final mechanical properties including the yield point of materials, it has been pointed out [15] that in certain polymeric materials strain rates up to 0.3 m min^{-1} will not significantly affect the strength properties of such materials. Apparently this is the reason why in the present study where the strain rate variation is within this range, no significant variation in ultimate tensile strength and percentage elongation is observed (Table II).

4.4. Effect of gauge length

The observed decrease in percentage elongation with test length is apparently due to localized deformation and gentle necking of fibres (Fig. 9) which is similar to ductile metals showing necking and a decrease in percentage elongation with gauge length. The decrease in strength with test length is probably due to the fact that the probability of defects and weak links increases with the length of the fibres. This kind of decrease in strength with length of test section has also been observed in polymeric materials [25]. In practice, it is always better to use the largest test length practicable which is usually about 0.05 m. For the coir fibres, the optimum test length may fall between 0.045 and 0.055 m since the value of strength and percentage strain at break seem to remain constant for the range of coir fibres lengths which are generally used in the industry (i.e. beyond 0.04 m).

5. Conclusions

(1) Stress–strain curves for coir fibres are characterized by an initial portion of linear stress–strain relation which may be taken as the initial modulus, followed by a non-linear region with disproportionately higher strain and finally a long straight region with a tendency to level-off suggesting strain hardening.

(2) The values of modulus, strength and percentage elongation at break of coir fibre of diameter 0.10 to 0.45×10^{-3} m are in the range of 3 to 6 GN m^{-2}, 106 to 175 GN m^{-2} and 17 to 47%, respectively.

(3) The modulus, strength and percentage elongation values of the coir fibres do not show any appreciable difference between retted and unretted fibres. The strength and percentage elongation of both type of fibres seem to increase up to a fibre diameter of 0.2×10^{-3} m after which they remain constant. The initial moduli seem to gradually decrease with increase in diameter of the fibres in the entire range investigated.

(4) No appreciable change in ultimate strength and percentage elongation at break was observed with the variation in strain rates used in the present study.

(5) Both strength and percentage elongation decreased with increase in gauge length. An optimum standard test length for the coir is found to be between 0.045 and 0.055 m.

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