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Structure property studies of fibres from various parts of the coconut tree

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Fibres from different structural parts of the coconut palm tree (*Cocos nucifera*, linn.) have been examined for properties such as size, density, electrical resistivity, ultimate tensile strength, initial modulus and percentage elongation. The stress–strain diagrams, fracture mode, microfibrillar angle as well as cellulose and lignin contents of these fibres have been determined. The observed properties have been related to the internal structure and chemical composition of the fibres. Some potential uses of these fibres have been listed.

1. Introduction

Renewable natural fibres could be potential substitutes for energy-intensive synthetic fibres in many applications where high strength and modulus are not required. It is therefore important to characterize and improve the strength properties of the existing fibres and to search out new sources of natural fibres. The coconut palm (*Cocos nucifera*, Linn.) (Fig. 1), a valuable tropical resource for food and energy is known to supply coir fibres from which a variety of materials including carpets and mats have been made. However, there are many other parts of the palm other than coir from which fibres can be extracted (Fig. 2) but are not currently used as resources for materials in an organized way. The availability of these various parts of coconut trees from which fibres can be extracted is estimated (Table I) but there are no data available on the mechanical and physical properties of these fibres except for coir [1–15]. In fact, all of these fibres are currently used as fuel, a use which does not take advantage of their high length to diameter ratio. Some of these fibres occur in nature already in woven form (for example, leaf sheath, Fig. 2e) which can be readily impregnated with plastics or cement. In order that these fibres may find better utilization, particularly as fillers or reinforcement in relatively low cost applications (where high strength or high modulus is not required) it is necessary to evaluate the properties of these fibres.

In this paper we report the measured strength properties and electrical resistivity of fibres from various parts of the coconut palm and compare these with those of coir. Furthermore, these properties and fracture characteristics of these fibres have been related to the structure of the fibres studied through X-ray diffraction, optical reflection, transmission and optical scanning microscopy, and to the chemical constituents of the fibres.

2. Experimental procedures

Fibres were extracted from different parts of the coconut palm (see Fig. 2) either by retting in water and/or by mechanical processing or hand picking. Since retting takes a long period to complete the extraction process as in coir, hand picking or mechanical processing was carried out. Hand picking was found to be suitable in the

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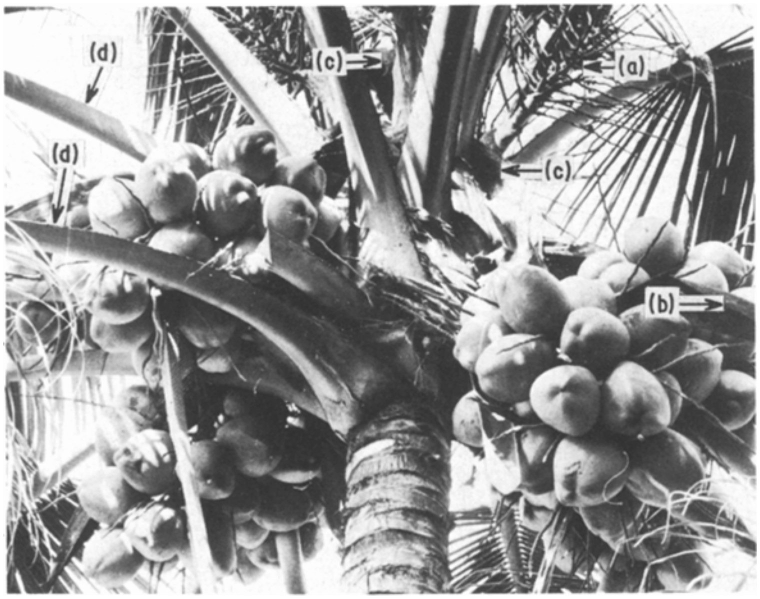


Figure 1 Photograph of coconut tree showing different parts from which the fibres have been extracted for present study: (a) Rachis and rachilla, (b) spathe, (c) leaf sheath and (d) bark of the petiole.

extraction of fibres from the bark of petiole, leaf sheath and roots. However, rachis and rachilla were beaten with a hammer, dried and then the fibres were hand picked. The fibres were then cleaned thoroughly in running water and dried.

For measuring tensile properties, a gauge length of 50 mm of each of these fibres was mounted on a cardboard sample holder and pulled in an Instron machine at a strain rate of 2.5 cm min^{-1}. A minimum of 25 samples was tested in each case. Electrical resistance was measured on a 100 mm length of each fibre using a million megohm-meter model III-IIA (British Physical Laboratory, India) at an applied voltage of between 100 V and 1000 V.

Since the cross-section of the fibres was not uniform throughout the fibre and in many cases the fibres were not circular in cross-section, the density of the fibres was used to compute strength and electrical resistivity. The densities of the fibres were determined (see Table II) using a specific gravity bottle with xylene as the solvent. All measurements were made at 65% relative humidity (r.h.) and 25° C.

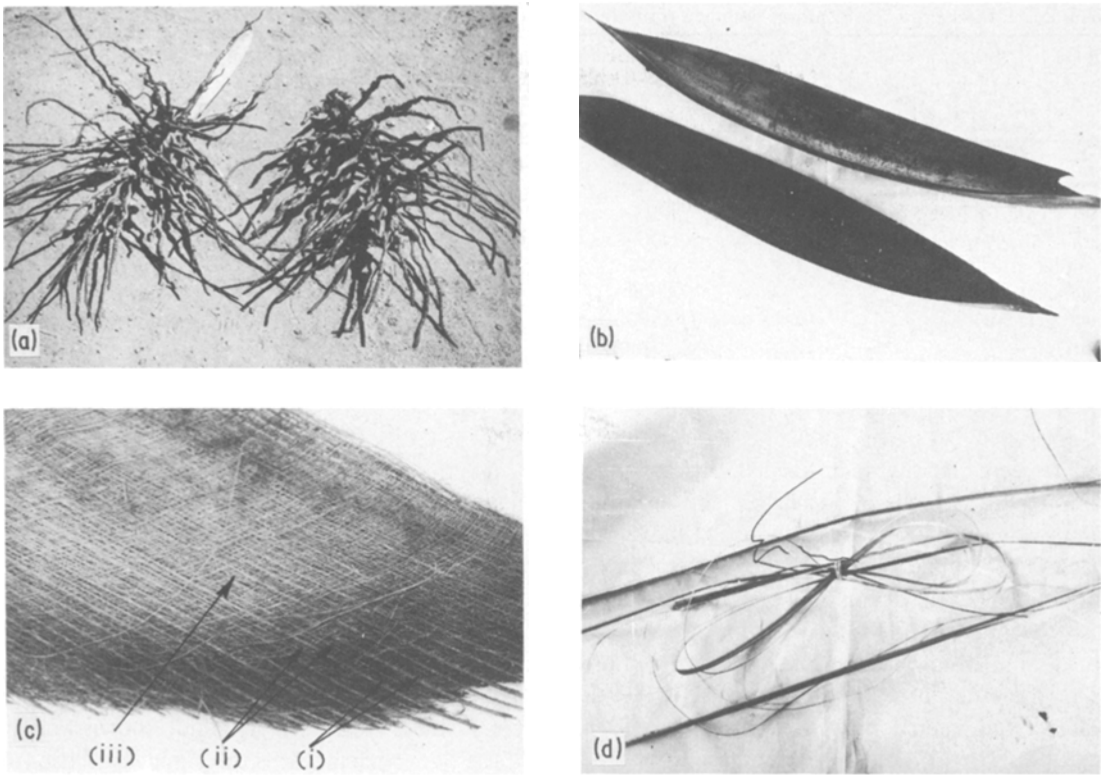
In order to study the structural aspects of the fibres, X-ray diffraction, optical microscopy, including stereo microscopy was carried out on fibres after suitable preparations. The X-ray examination of the fibres from different parts of the coconut palm was carried out using the Laue transmission method (wide angle) with CuK radiation. In all cases the incident beam was perpendicular to the length of the fibre and the sample to film distance was kept at 40 mm. For each type of the fibre, three to five samples were examined.

3. Results

Fig. 3 represents typical stress–strain diagrams for the different fibres studied in the present investigation. Included in this figure is the plot for coir for comparison. As can be seen, except for the bark of the petiole, the stress–strain diagram of the other fibres in general is characterized by an initial linear region followed by a smooth curved portion without a definite yield point. On the other hand, the stress–strain diagram of the bark of the petiole shows a steep initial linear region followed by a very short non-linear stress–strain region leading to fracture. In this case the fracture seems to run parallel to the length of the specimen due to pull out (Fig. 4a). Furthermore, the stress–strain diagrams fall into two categories:

(a) Category I. These fibres from rachis, rachilla and leaf sheath (inside top) have higher elongations (6 to 8%); the curves are comparable to that of coir and indicate that these fibres, except for spathe, are soft but tough. Fibres from spathe appear to be soft but brittle. Fractographs of these fibres (Fig. 4b to d) show gentle necking like in coir [13] with fracture more or less along a plane perpendicular to the fibre length and thus supporting the above observation.

(b) Category II. Fibres from the leaf sheath (thick and middle fibre), root and bark of the petiole give



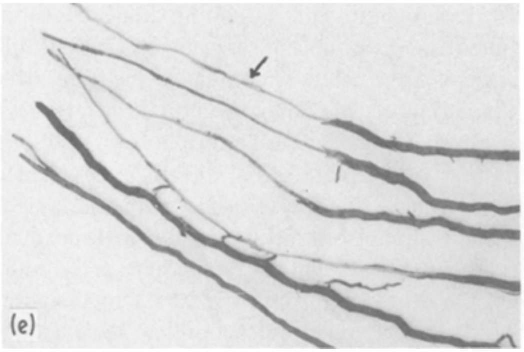


Figure 2 Photographs of different parts of coconut palm: (a) rachis and rachilla, (b) spathe, (c) leaf sheath, (i) thick fibre, (ii) middle fibre, (iii) inside top fibres, (d) bark of the petiole and (e) root.

relatively lower elongations (3 to 5%) indicating that the fibres are brittle in nature. The fractographs (Fig. 4e to g) show no necking, as can be expected in the case of uneven fractures.

Initial modulus, ultimate tensile strength, σ, and percentage elongation, ϵ, of various fibres were then evaluated using these stress–strain diagrams. These values are tabulated in Table II. Included in this table are values [14] for coir, banana, sisal and pineapple leaf fibres for purposes of comparison. As can be seen from Table II, the modulus values of fibres from rachis, rachilla, leaf sheath, spathe and root lie in the range of 2 to $6\,\mathrm{GN\,m^{-2}}$ which is comparable to that observved in coir. On the other hand, the initial modulus of the bark of the petiole is in the range of $25\,\mathrm{GN\,m^{-2}}$ which is comparable to that of sisal and pineapple leaf fibres.

Furthermore, σ and ϵ values of fibres from rachis, rachilla and leaf sheath are found to be in the range of 48 to $104\,\mathrm{MN\,m^{-2}}$ and 5.6 to 8% respectively. These values are, however, lower than those for coir. On the other hand, the fibres from bark of the petiole and root showed higher σ values ($191\,\mathrm{MN\,m^{-2}}$ and $156\,\mathrm{MN\,m^{-2}}$ respectively) which are comparable to that of coir but very low percentage elongation values (3.8 and 3% respectively).

Table II also lists the values of microfibrillar angle, density and major chemical constituents (cellulose and lignin) in these fibres. The microfibrillar angles were estimated by Preston's method [16]. The standard deviation quoted for angles indicate the accuracy of locating the intensity maxima and also reflect the variation of the angle among different samples of the same species. It

TABLE I Different types of fibres obtained from the coconut tree and their availability

Fibres	Approximate availability per year of the part of the tree from which the fibre is extracted (tonnes)		
	World	India	Kerala
Leaf sheath (inside top)	4500	900	600
Leaf sheath (thick fibres)	4500	900	600
Leaf sheath (middle fibres)	4500	900	600
Bark of the Petiole	500 000	10 000	6700
Rachilla	75 000	15 000	10 000
Pedencle (spathe)	75 000	15 000	10 000
Spadix (rachis)	4500	900	600
Root	Not Estimated		
Coir	3900 000	780 000	520 000

can be seen that the microfibrillar angle of fibres from rachis, rachilla, leaf sheath and spathe is of the same order of magnitude (30 to 38°) as that of coir, while that of bark of the petiole is rather low ($< 20°$). This however compares well with the microfibrillar angles of banana and sisal fibres. Similarly, the density values of these fibres lie in the range of 590 to $1190\,\mathrm{kg\,m^{-3}}$ while the cellulose and lignin content of these fibres lie in the range of 38 to 46% and 13 to 29% respectively.

The volume resistivity of various fibres is found to be in the same range as that of coir (Table II) and wood, all having a moisture content of 10 to 12%.

4. Discussion

The observed strength properties and electrical resistivity values can be understood in terms of structure and chemical constituents of the fibres. Like coir, the fibres studied are also multicellular and consist of four different types of cells i.e. sclerenchyma (which are very thick walled, rendering mechanical strength), xylem (which are thick on the outside and thin on the inside, for conducting water and mineral salts from roots), phloem (which are thin, for conducting down assimilated products of photosynthesis to various parts of the plant) and xylem-parenchyma (which are medium thick, for storage of food/water). The number, shape and arrangements of these various cells vary from fibre to fibre (see Fig. 5 and Table III) and appear to be one of the reasons for the observed variation in the properties of these fibres. Furthermore, these cells may be considered to consist of helical spirals (cellulose crystallites) embedded in a non-crystalline region (lignin). When such a structure is pulled in tension, the deformation expected has been theoretically calculated [17] and two situations have been identified:

(a) the microfibrils (helical springs) may elongate along with the non-crystalline regions, or.

(b) the microfibrils may simply uncoil like springs with bending and twisting.

In both these cases the microfibrillar angle is an important factor in determining the strength values, particularly the modulus. It is found that as in the case of coir [13] both mechanisms operate in these fibres, but it is not known which of these two mechanisms is predominant. Thus, from Table II it can be seen that the observed ultimate tensile strength and initial modulus of various fibres seem to depend largely on microfibrillar angle and the cellulose content of the fibres, while the influence of other structural differences is relatively small. Thus as has been observed in other natural fibres [6, 13, 17] the higher the microfibrillar angle and lower cellulose content, as is the case of fibres from rachis, rachilla, leaf sheath and spathe, the lower will be the modulus and σ values. On the other hand, fibre from bark of the petiole which has a lower microfibrillar angle ($< 20°$) shows higher modulus and ultimate tensile strength. Thus the correlation arrived at between σ and the initial modulus, Y, separately, with the combined effect of microfibrillar angle and cellulose content, using multiple regression analysis on the same lines as reported elsewhere [13] are given by

$$\sigma = -334.005 - 2.830\theta + 12.22W \quad (1)$$

and

$$Y = -105.38 - 0.5\theta + 2.97W \quad (2)$$

where θ is the microfibrillar angle in degrees and W is the cellulose content in wt%, which have significance at the 2% level and the 1% level respectively.

On the other hand, a correlation has been arrived at between the measured percentage elongation, ϵ, and the microfibrillar angle as

TABLE II Comparison of properties of fibres from various parts of the coconut palm with other natural fibres

Fibres	Width or diameter (μm)	Density ($\times 10^{-3}$ kg m^{-3})	Volume resistivity at 100 V (Ω cm)	Microfibrillar angle ($^\circ$)	% cellulose/lignin content	Tensile properties		
						Modulus* (GN m^{-2})	σ* (MN m^{-2})	% Elongation*†
Rachis	350–400	610	1.34×10^5–3.06×10^5	33 ± 5	42.75/26.40	2.306(0.79)	74.26(23.15)	13.49(4.2)
Rachilla	200–400	650	2.87×10^5–1.36×10^6	37 ± 2	42.0/16.24	2.339(0.35)	61.357(18.42)	8.09(3.48)
Spathe	150–400	590	5.15×10^5–3.05×10^6	26 ± 3	42.0/23.46	3.141	75.66	6.0
Leaf sheath (inside top)	300–600	630	5.38×10^5–4.37×10^6	30 ± 5	41.90/23.36	2.447(0.49)	88.63(22.1)	14.22(2.84)
Leaf sheath (thick fibres)	1100–1600	1190	3.75×10^7–5.77×10^7	30 ± 3	41.90/25.85	4.543(1.36)	115.236(34.94)	3.97(1.04)
Leaf sheath (middle fibres)	300–1000	750	8.37×10^6–11.5×10^7	31 ± 4	41.90/29.05	3.585(1.6)	91.965(37.03)	6.227(2.55)
Bark of the petiole	250–550	690	5.52×10^5–2.63×10^6	21 ± 1	46.03/12.09	15.094(9.06)	185.52(62.44)	2.06(0.55)
Root	100–650	1150	–	38 ± 1	39.1/29.48	6.2	157	3
Coir	100–450	1150	9×10^5–14×10^5	30–49	43/45	4–6	131–175	15–40
Banana	80–250	1350	6.5–7.0×10^5	11	65/5	7.7–20.0	529–754	1.0–3.5
Sisal	50–200	1450	0.47–0.52×10^5	10–22	67/12	9.4–15.8	568–640	3–7
Pineapple	20–80	1440	0.71–0.84×10^5	14–8	81/12	34.5–82.5	413–1627	0.8–1.6
Jute	–	1450	–	8.1	63	–	533	–

*Figures in brackets are standard deviations.

†Gauge length is 0.05 m.

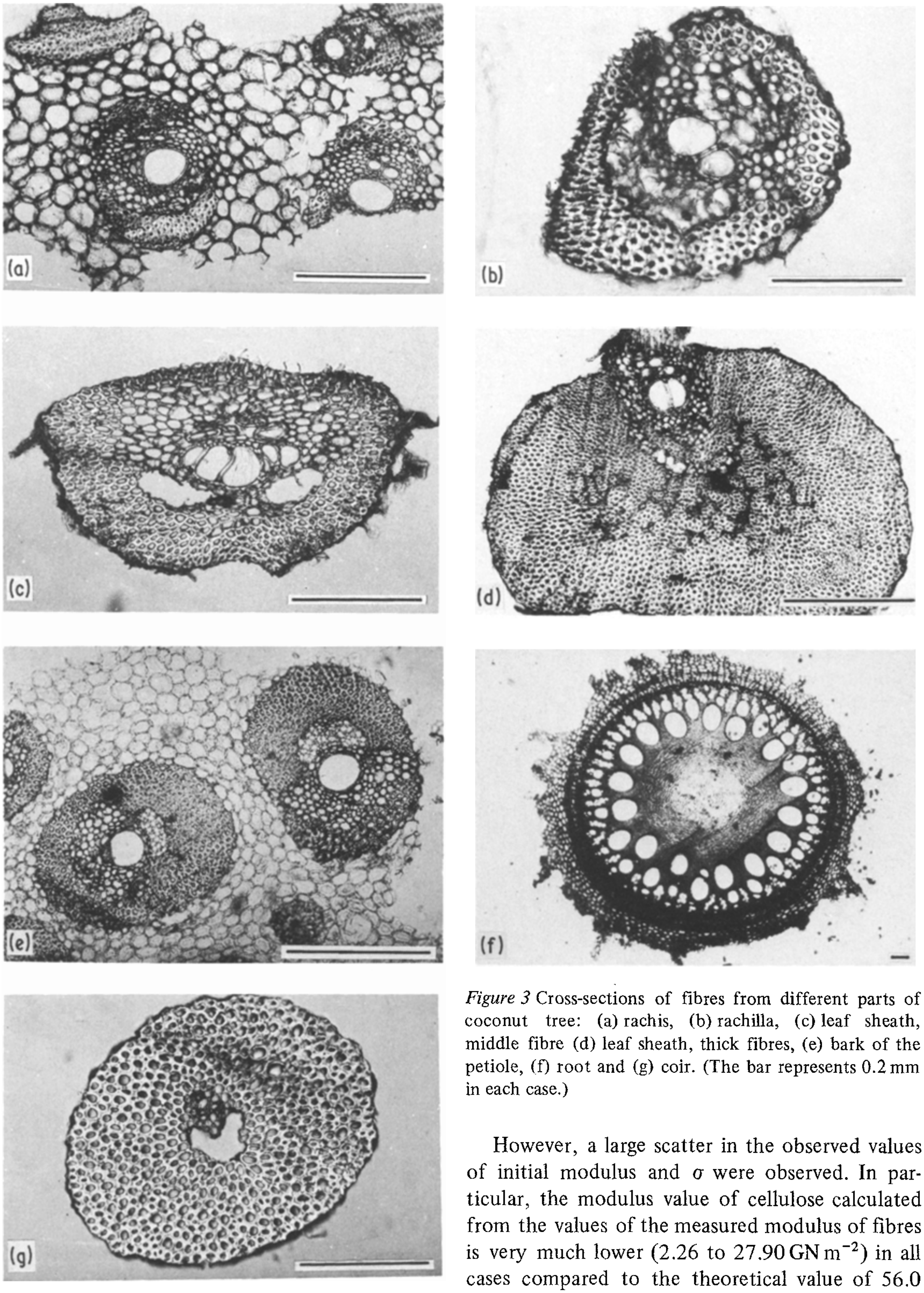


Figure 3 Cross-sections of fibres from different parts of coconut tree: (a) rachis, (b) rachilla, (c) leaf sheath, middle fibre (d) leaf sheath, thick fibres, (e) bark of the petiole, (f) root and (g) coir. (The bar represents 0.2 mm in each case.)

reported elsewhere [13, 18] which is given by

$$\epsilon = -2.78 + 7.28 \times 10^{-2}\theta + 7.7 \times 10^{-3}\theta^2 \quad (3)$$

which is significant at the 1% level.

However, a large scatter in the observed values of initial modulus and σ were observed. In particular, the modulus value of cellulose calculated from the values of the measured modulus of fibres is very much lower (2.26 to 27.90 $\mathrm{GN\,m^{-2}}$) in all cases compared to the theoretical value of 56.0 $\mathrm{GN\,m^{-2}}$ for plant fibres [18]. As suggested elsewhere [13] this could be due to the fact that the initial deformation of the fibres may not only be the result of uncoiling of cellulose chains. How-

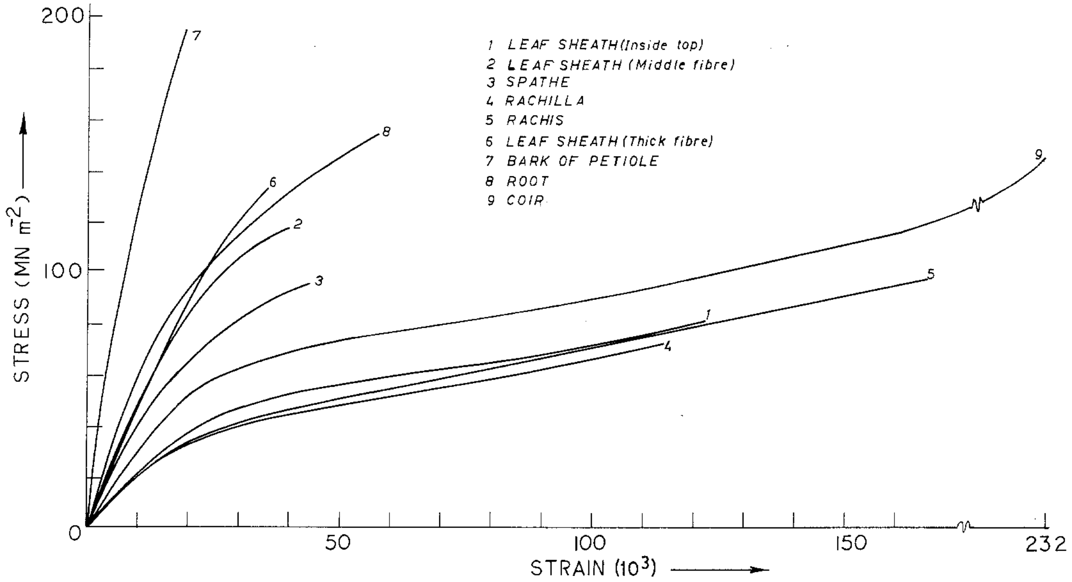


Figure 4 Stress–strain diagram of fibres from different parts of coconut treee.

ever, larger scatter between the observed and estimated values of modulus may be narrowed down if the effects of other structural aspects such as size, shape and arrangement of cells in various fibres are also considered.

Similarly, in the case of ultimate tensile strength the observed large scatter in the values may be narrowed down if the above structural aspects are taken into account. Thus, the observed σ may be understood in terms of structure of the fibres. In the case of bark of the petiole, root and coir, the number of sclerenchyma cells is greater (Table III) and they are expected to give higher strength. Further, since the number of xylem, phloem and xylem-parenchyma cells is greater in root than in fibres from either the bark of the petiole or coir, the number of defects will be more, resulting in lower strength and elongation values than that of coir or bark of the petiole. Similarly, though the number of sclerenchyma cells is greater in the fibre from the leaf sheath (thick or thin), the strength is lower due to the presence of the other three kinds of cells. Also, since the number of xylem, phloem and xylem-parenchyma cells is higher in fibres from rachis, rachilla and leaf sheath (middle fibre), the strength is expected to be lower.

In addition, there may be defects due to processing of the fibres which will certainly affect the strength and elongation. The presence of defects in these fibres is evident from the low density values though the fibre diameters are of the same or higher order than those of coir and other natural fibres [15].

Thus it becomes evident that though there are variations in the structure of these fibres, the microfibrillar angle and the cellulose content of the fibres seem to control the strength properties. The structural variations at the most may have secondary effects which may account for the scatter in the values of strength properties.

TABLE III Number of different types of cells in various fibres of the coconut palm

Fibre	Diameter of fibre (μm)	Sclerachyma	Phloem	Xylem	Xylem–Parenchyma
Rachis	350–400	278	14	6	24
Rachilla	200–400	160	37	12	–
Leaf sheath (thick)	1100–1600	1661	3	52	27
Leaf sheath (thin)	300–600	244	13	4	–
Leaf sheath (middle)	300–1000	191	28	4	–
Bark of the petiole	250–550	461	3	23	56
Spathe (pedencle)	150–400	48	–	–	–
Root	100–650	10670	66	220	400
Coir	100–450	348	36	9	–

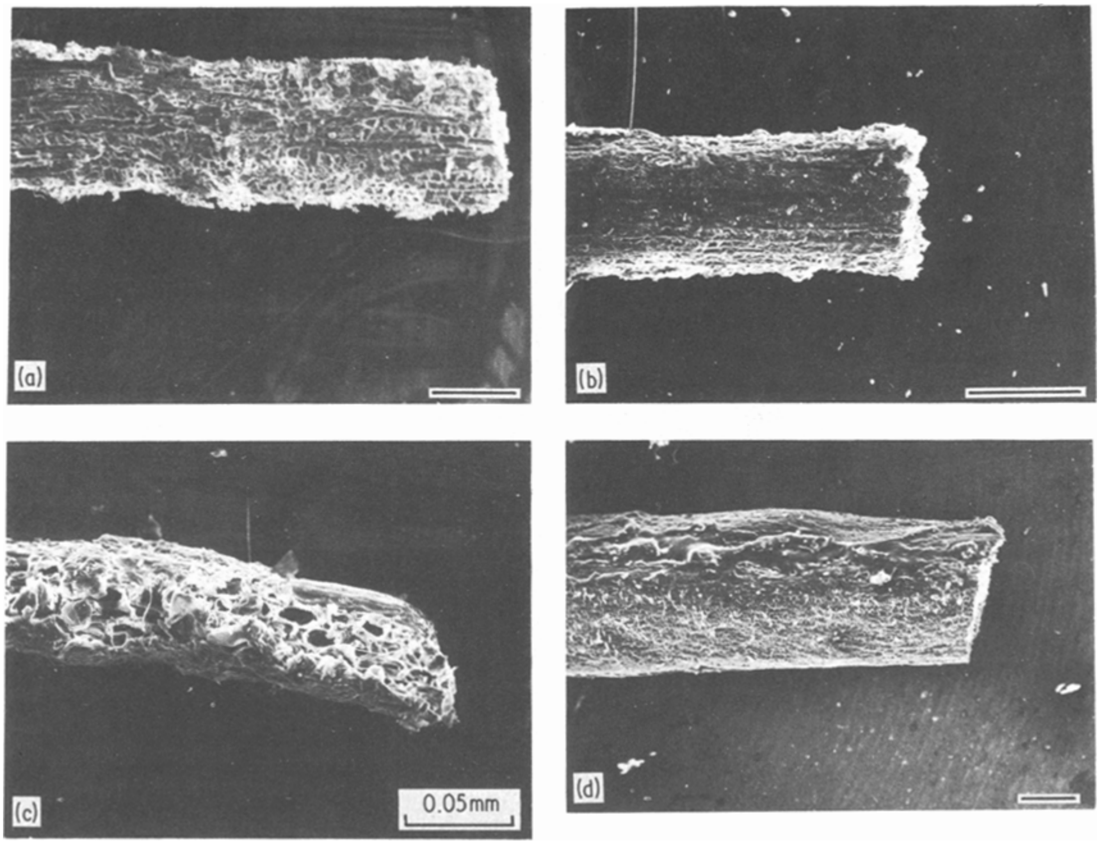


Figure 5 Fractograph of fibres from different parts of coconut tree: (a) rachilla, (b) leaf sheath, (c) spathe, (d) leaf sheath, thick fibre, (e) leaf sheath, middle fibre, (f) root, (g) rachis and (h) coir. (Bars represent 0.1 mm except where indicated.)

An interesting feature is that the electrical resistivity of the fibres when plotted as a function of % cellulose content shows behaviour remarkably similar to that of other natural fibres and seems to lie on the same line as for other natural fibres [15]. This suggests that the electrical resistivity is primarily related to the cellulose content of the fibres. It therefore becomes evident that these fibres may be used as good insulators thus becoming a satisfactory replacement for wood in insulating applications. As reported elsewhere [15] these fibres have a special advantage over wood in that (a) they can be readily pressed into complicated shapes through moulding and (b) the resources for wood are dwindling.

5. Potential uses

(i) In view of higher electrical resistivity of the fibres and easy fabrication into any complicated shapes, the fibres may be used as good insulators.

(ii) Since fibres from bark of the petiole have similar strength properties to coir, these fibres may substitute coir in certain applications including incorporation into plastics, cements and rubber.

(iii) As the lignin content is less in the fibres from bark of the petiole, this fibre may also be used in the paper industry, or for carbonization.

(vi) Fibres from leaf sheath, rachilla and rachis strength, may be used as reinforcement in concrete.

(v) The leaf sheath is available in the form of a thin woven mat and hence this could easily be incorporated into plastics to fabricate natural fibre reinforced composites.

(vi) Fibres from leaf sheath, rachilla and rachis, seemed to be tough like coir and hence may be used in applications where high energy absorption is required.

6. Conclusions

Conclusions can be drawn as follows:

(1) The density, stress–strain diagrams, chemical constituents, including structural studies of all

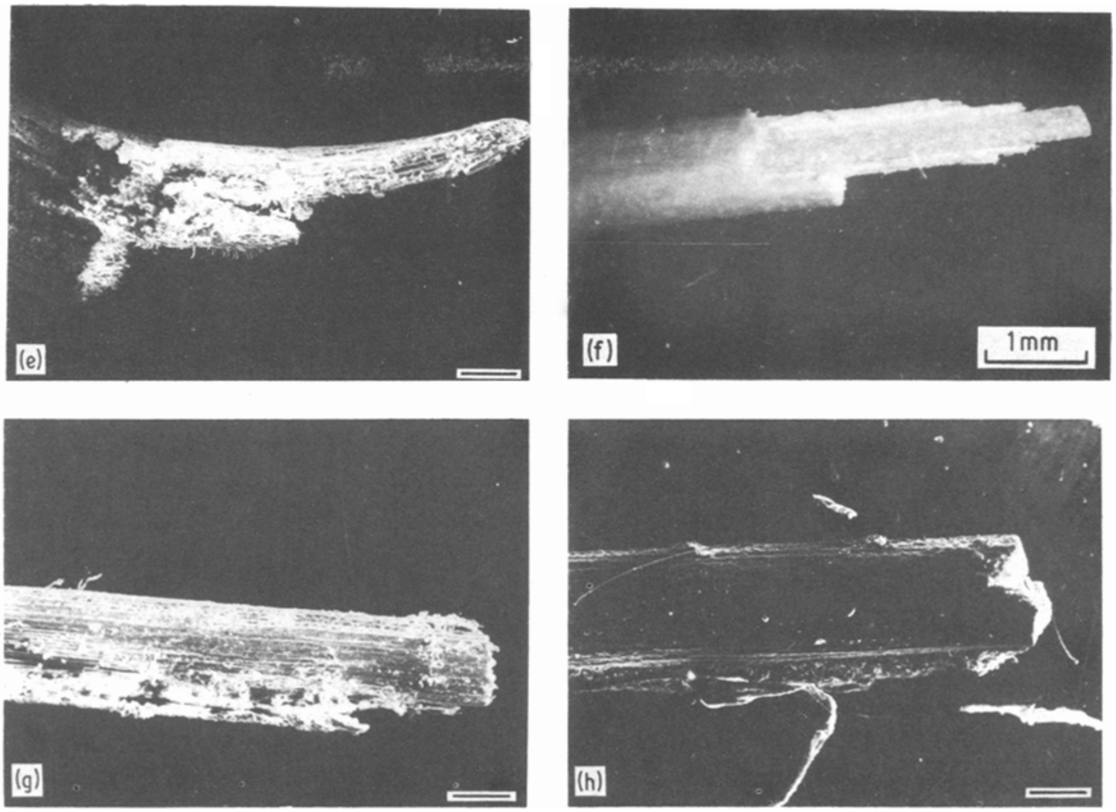


Figure 5 (Continued)

different fibres from various parts of the coconut palm, have been determined for the first time.

(2) The major chemical constituents of these fibres are found to be cellulose (39 to 46%) and lignin (13 to 25%).

(3) The microfibrillar angle of these fibres is found to be in the range of 21 to 31° using X-ray diffraction.

(4) The volume resistivity of these fibres is found to lie in the range of 1.3×10^5 to $5.77 \times 10^7\,\Omega\,\text{cm}$ and may be understood in terms of cellulose content.

(5) The modulus, strength and percentage elongation values of rachis, rachilla, leaf sheath and spathe are found to be in the range of 2 to $6\,\text{GN}\,\text{m}^{-2}$, 48 to $104\,\text{MN}\,\text{m}^{-2}$ and 5.6 to 8% respectively, while those of fibres from bark of the petiole and root are in the range of 6 to $24.7\,\text{GN}\,\text{m}^{-2}$, 157 to $191.81\,\text{MN}\,\text{m}^{-2}$ and 3 to 3.8% respectively.

(6) Initial modulus and strength of the fibres seems to be mainly controlled by the microfibrillar angle and the content of α-cellulose in the fibres. These have a correlation of $Y = -105.30 - 0.5\theta + 2.97W$ and $\sigma = -334.005 - 2.830\theta + 12.22W$ with confidence limits of 99% and 80% respectively.

(7) The percentage elongation of the fibres seems to depend on microfibrillar angle and has a correlation $\epsilon = -2.76 + 7.28 \times 10^{-2}\theta + 7.7 \times 10^{-3}\theta^2$ with a confidence limit of 99%.

(8) In view of the physical and mechanical properties exhibited by the different fibres from coconut tree they can be used for various applications, especially as composites.

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