conditions between the reagents and the plasma jet, or with more complete evaporation of aluminium a more ultra-fine γ-Al_2O_3 powder is prepared. This can be utilized as an active catalyst, sorbent, catalyst carrier, for fine surface polishing, in powder metallurgy and for application of high-temperature and corrosion-resistant coating.

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Electrical resistivity and dielectric strength of plant fibres

Insulation resistance and dielectric strength of ligno-cellulosic materials such as wood give an indication of their dielectric constant, current leakages at certain voltages, moisture content and stability under electric fields. The study of electric properties of such materials also indicates their suitability as insulating materials for special applications such as suspension insulators, bushings, studs, sleeves, gaskets, spacer panels and switch boards. However, very little work has been reported [1, 2] on the electrical properties of natural fibres. In fact, there are no standards available for measuring the electrical parameters of these fibres.

In this communication we report the volume resistivity and dielectric strength of some natural fibres (coir, banana, sisal, pineapple leaf and palmyrah fibres) which are abundantly available renewable resources, with a view to stimulate new uses for these fibres. The electrical resistivity of these fibres was measured as a function of applied voltage for all fibres at 65% relative humidity (r.h.). For coir the resistivity was also measured as a function of retting (retting is a bio-chemical process in which coconut husks are soaked for a period of 8 to 10 months in saline water to facilitate the extraction of fibres). The resistivities and dielectric strengths of the fibres were also measured after dryheat at 110° C and after damp heat at 55° C with 95% r.h.

Coir fibres (both retted and unretted) were brought from Kovalam, near Trivandrum in India, while all the other fibres used in the present study were procured from cottage industries under

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TABLE I Density, major chemical constituents and moisture content of plant fibres

Fibre	Density (kg m^{-3})	Composition (%)			Moisture content at 65% r.h. and room temperature (%)
		Cellulose	Hemicellulose	Lignin	
Coir	1150	32 – 43	0.15 – 0.25	40 – 45	10 – 12
Banana	1350	63 – 64	19	5	10 – 12
Sisal	1450	66 – 72	12	14 – 10	11
Pineapple leaf	1440	81.5	–	12.70	13.5
Palmyrah	1092	Not known	–	–	14.0

Khadi and Village Industries Commission, Trivandrum.

Fibres 0.1 m long and with diameters ranging from 0.10 to 0.50×10^{-3} m for coir, 0.08 to 0.25×10^{-3} m for banana, 0.05 to 0.20×10^{-3} m for sisal, 0.02 to 0.08×10^{-3} m for pineapple leaf and 0.70 to 1.30×10^{-3}m for palmyrah were used for the measurement of resistance and dielectric strength. A minimum of 25 samples of each were used for measurements. Electrical resistance was measured using a million meghometer model 161-IIA with the individual fibres being gripped between two terminals. The dielectric strength of individual fibres was measured using an insulation break-down tester supplied by BPL (India) Ltd.

The volume resistivity, ρ, of the fibres of area cross-section, A, length, l, and density, d, can be calculated using the measured value of resistance at different voltages from the equation

$$\rho = RA/l. \quad (1)$$

TABLE II Volume resistivity, ρ, of different materials: (a) measured in the present study in the range of 100 to 1000 V

Fibre	ρ at 65% r.h. (Ω cm)
Coir	$9 - 16 \times 10^5$
Banana	$6.5 - 7.0 \times 10^5$
Sisal	$0.47 - 0.5 \times 10^5$
Pineapple leaf	$0.70 - 0.80 \times 10^5$
Palmyrah	$0.90 - 1.1 \times 10^5$
(b) From [10]	
Material	ρ at 65% r.h. (Ω cm)
Glass fibre	$6 \times 10^{12} - 10^{16}$
Mica	$1 \times 10^9 - 1 \times 10^{10}$
Phenol formaldehyde resins (Bakelite etc)	$5 \times 10^{10} - 2 \times 10^{16}$
Rubbers	$2 \times 10^{11} - 2 \times 10^{16}$
Wood	$10^5 - 10^6$

Since the cross-sectional area is not uniform in the case of natural fibres, ρ is computed as follows:

$$\rho = \frac{R \times A \times l}{l^2} = \frac{R \times \text{vol}}{l^2}$$

$$= \left(\frac{R}{l}\right)\left(\frac{\text{wt}}{l}\right)\left(\frac{1}{d}\right). \quad (2)$$

Hence the fibres were weighted prior to the measurement of resistance. Densities were determined using specific gravity bottle and toluene solution which is described elsewhere [3]. Table I lists the densities of the fibres along with their chemical composition and moisture content [4]. Since the moisture content of pineapple leaf fibre and palmyrah were not known, these were also determined in the present study using a moisture balance.

Table II gives typical volume resistivity values (ranges) of the fibres used in the present study along with those of other insulators such as glass fibres, mica, wood fibres and some of the polymers [5]. It can be seen that the resistivity values of the plant fibres measured in the present study are of the same order of magnitude as in the case of wood at similar moisture levels (10 to 12%) [6].

Table III shows the resistivity values of various natural fibres as a function of voltage. It can be seen that the resistivity values of any one type of the fibres do not show very significant variation with applied voltages up to 1000 V, except a more frequent general increase in resistivity with voltage. As in the case of polymers [7], it is difficult to explain the high resistivity values of the plant fibres. The small currents resulting in the observed resistivity values may be due to moisture and minor impurities, e.g. silica in coir and calcium oxalate in banana fibres, and may not have any relation to the intrinsic structure of the fibres.

TABLE III Volume resistivity, ρ, of fibres at different voltages (at the same moisture content)

Fibre	ρ ($\times 10^5 \Omega$ cm)				
	100 V	250 V	400 V	500 V	1000 V
Coir (unretted)	14.22	15.380	16.06	15.140	–
Coir (retted)	9.480	10.410	10.520	10.660	–
Banana	6.650	6.680	6.720	7.000	7.000
Palmyrah	0.970	1.125	1.136	1.148	1.158
Pineapple leaf	0.710	0.808	0.797	0.804	0.843
Sisal	0.470	0.504	0.508	0.520	0.500

This may be the reason for the observed scatter in resistivity values obtained for each type of fibre. In fact, the difference in the amounts of impurities [8] may be the main reason for differences in resistivities between retted and unretted coir fibres. The effect of moisture content on resistivity of these fibres is demonstrated by Table IV and Fig. 1 showing a general decrease in resistivity with increase in moisture content. It is known that in any polymeric material the current mainly flows through the crystalline regions and the non-crystalline regions allow current to pass through mainly due to the presence of moisture [9]. Apparently, as the moisture content increases the resistance falls, because increasing currents can then flow. Fig. 1 shows that, in general, the resistance values for all the natural fibres tested in this study as a function of their moisture content, fall within the same band as wood. The resistivity of wood is known to be of the order of $10^{18} \Omega$ cm

TABLE IV Variation in resistivity values of the plant fibres with percentage moisture content

Fibre	Moisture content (%)	Resistivity (Ω cm)
	2.00	7.50×10^5
(a) Coir	11.56	1.72×10^3
	22.50	9.73×10
	3.00	1.135×10^5
(b) Banana	15.00	2.421×10^4
	33.00	2.83×10^2
	2.00	1.663×10^5
(c) Sisal	11.00	5.124×10^4
	30.00	3.256×10^2
	3.00	3.82×10^5
(d) Palmyrah	14.20	6.198×10^3
	30.000	3.21×10
	5.00	1.80×10^4
(e) Pineapple	13.50	0.78×10^4
	33.00	3.72×10^2

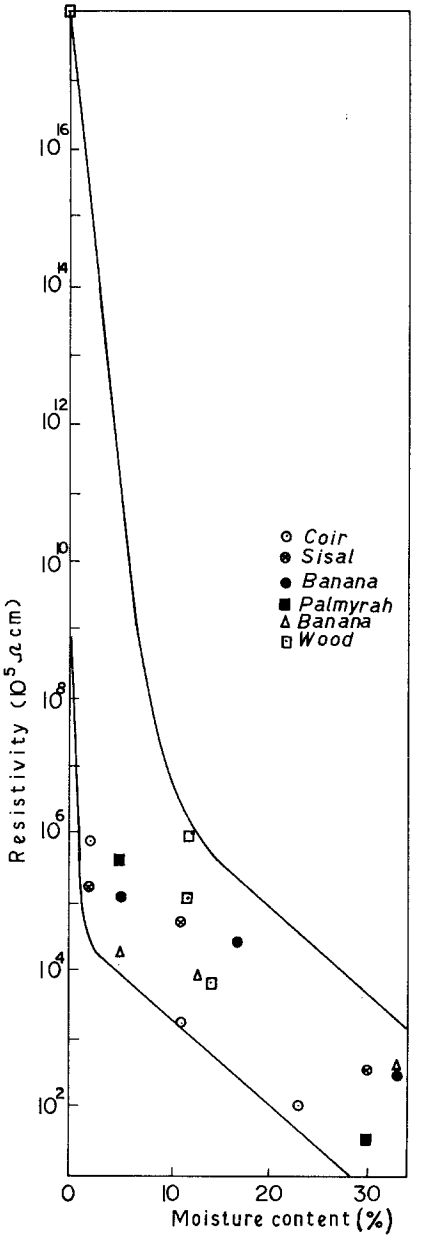

Figure 1 Relation between moisture content (%) and volume resistivity of the fibres.

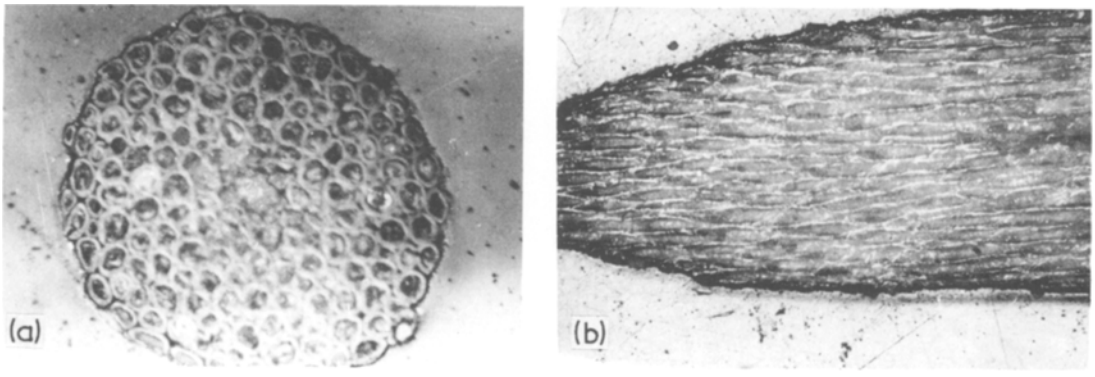

Figure 2 (a) Transverse section of coir fibre, × 340. (b) Longitudinal section of coir fibre, × 125.

and it decreases linearly with increase in moisture content up to 30% [6]. Fig. 1 also suggests that close to zero moisture content, the electrical resistivity of all the natural fibres tested in this study is likely to be of the same order as that of wood. In any case the resistivity values of the natural fibres at 0% moisture are more of an academic value since in most practical uses they will be used at ambient humidities and will have from 8 to 10% moisture content. However, when these fibres are used as insulators at high temperature the situation will be encountered where the resistivity at 0% moisture will take effect.

Tables II to IV indicate that there are significant differences in the resistivities of different fibres under the same conditions of voltage and moisture content. This variation in resistivity from one fibre to another may be related to the structures of these fibres. Figs 2 to 5 show transverse and longitudinal sections of coir, banana, sisal, pineapple and palmyrah fibres, respectively. All these fibres consist of cylinder-like cells glued together. Earlier X-ray studies have shown that the cell walls consist of crystalline cellulose with characteristic microfibril angles for different fibres in the range 18 to 48°, and the binding material is lignin and hemi-cellulose. Figs 2 to 5 show that these fibres differ from each other in size, shape and number of cells as well as in the size, shape and position of lacunae (pore). The X-ray studies have shown that the angles of the cellulose spirals in these fibres are different [4]. The chemical analysis given in Table I shows that the chemical constituents such as cellulose and lignin are also different from each other. The data collected in this study (Fig. 6) show that the resistivity of these fibres is primarily related to their cellulose content through a relation: cellulose content (%) =

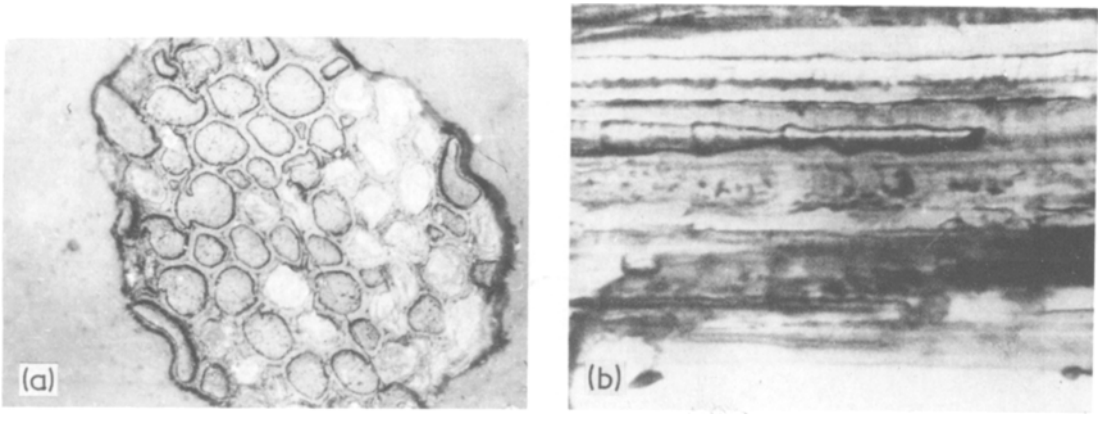

Figure 3 (a) Transverse section of banana fibre, ×345. (b) Longitudinal section of banana fibre, ×360.

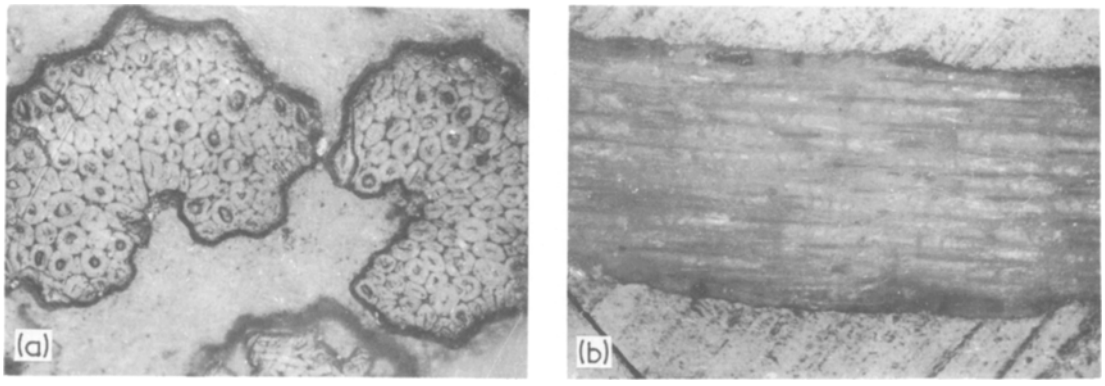

Figure 4 (a) Transverse section of the sisal fibre, ×345. (b) Longitudinal section of sisal fibre, ×140.

$73.78 - 3.09\rho$, with a correlation coefficient of 0.86. This is in agreement with earlier studies [7] which indicate that in polymeric materials current mainly flows through the crystalline regions. In addition, in composite materials the conductivity is mainly a function of the volume fraction of the conducting phase and its conductivity. Some of the observed scatter in resistivity of a given fibre, at a given voltage and a given moisture content, may be due to variations in the defects which are formed during growth or during processing of these fibres. Fig. 7a to c show typical defects in pineapple leaf fibres which could lead to an increase in resistivity.

Table V gives dielectric strengths for all the fibres measured in this study. The dielectric strengh of certain other insulating materials reported in the literature are included for comparison. It should, however, be noted while comparing the earlier data with the data in the present work, that the dielectric strength is reported in terms of voltage for a given length of a single fibre, the diameter of which is in the range 0.05 to 1.30×10^{-3} m. As expected, the dielectric strength or the voltage at which break-down or arcing potential occurs, decreases with moisture content. Table V also shows that the dielectric strength of all the natural fibres investigated in the present study is high and is comparable to ceramic material having low alumina content [10]. The high dielectric strength makes these natural fibres quite suitable for use as insulators. Variation in the dielectric constant from one fibre to another increases as the moisture content increases.

In summary, while the electrical resistance of natural fibres studied in the present investigation is a function of many variables including the cell shape, size, number, microfibril angle of cellulose, chemical composition, impurity content, moisture and voltage applied, it corelates very strongly with

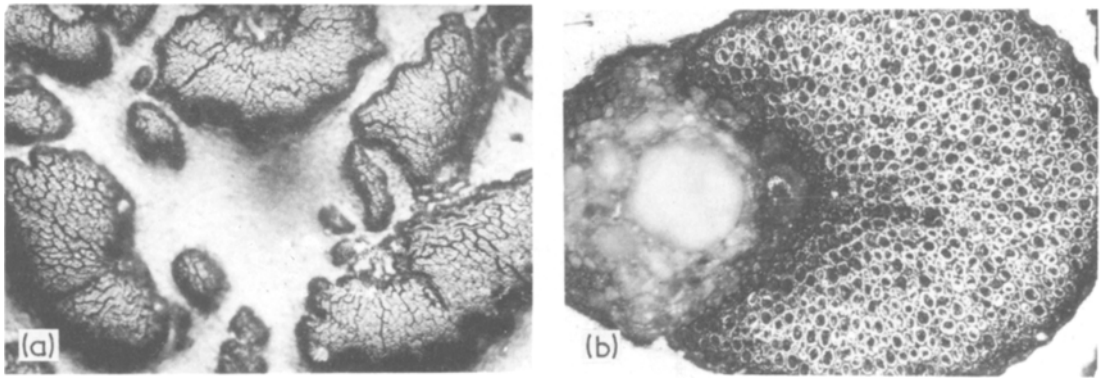

Figure 5 (a) Transverse section of pineapple leaf fibre, ×260. (b) Transverse section of palmyrah fibre, ×85.

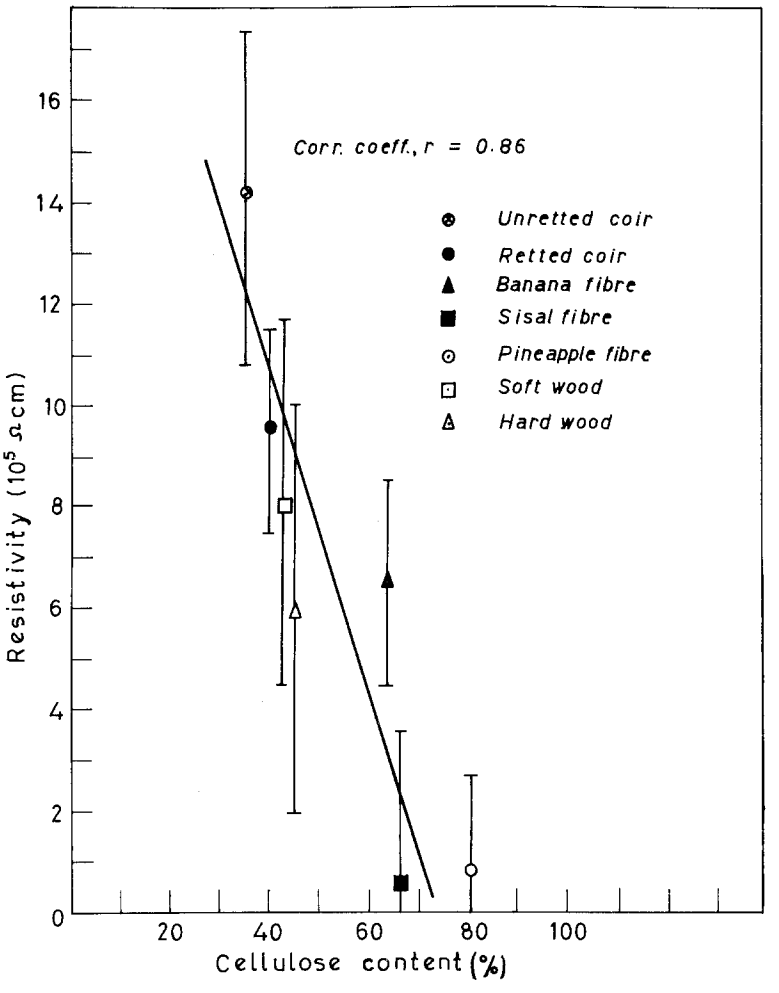

Figure 6 Relation between the percentage cellulose content and the volume resistivity of the fibres.

TABLE IV Dielectric strength of different materials

(a) Measured in the present study at various testing conditions

Fibre	Dielectric strength for 0.1 m length of the fibre		
	Just after oven drying (110 ± 5° C) (kV)	After 2 h recovery time – 30° C, 65% r.h. (kV)	After damp heat test 55° C, 95% r.h. (kV)
Coir	5.0	2.0	0.5
Banana	5.0	3.5	1.5
Sisal	5.0	4.0	1.8
Pineapple	5.0	1.5	0.8
Palmyrah	4.5	1.5	0.5

(b) From [10]

Material	Thickness (× 10^{-3} m)	Dielectric strength at room temperature (kV cm^{-1})
Glass	6 – 1	300 – 1500
Mica	1 – 0.1	300 – 2200
Ebonite	2 – 0.2	300 – 1100
Phenol formaldehyde resin	–	–
Rubber	2.5 – 3.0	120 – 400
Paper (blotting)	0.1 – 0.2	150

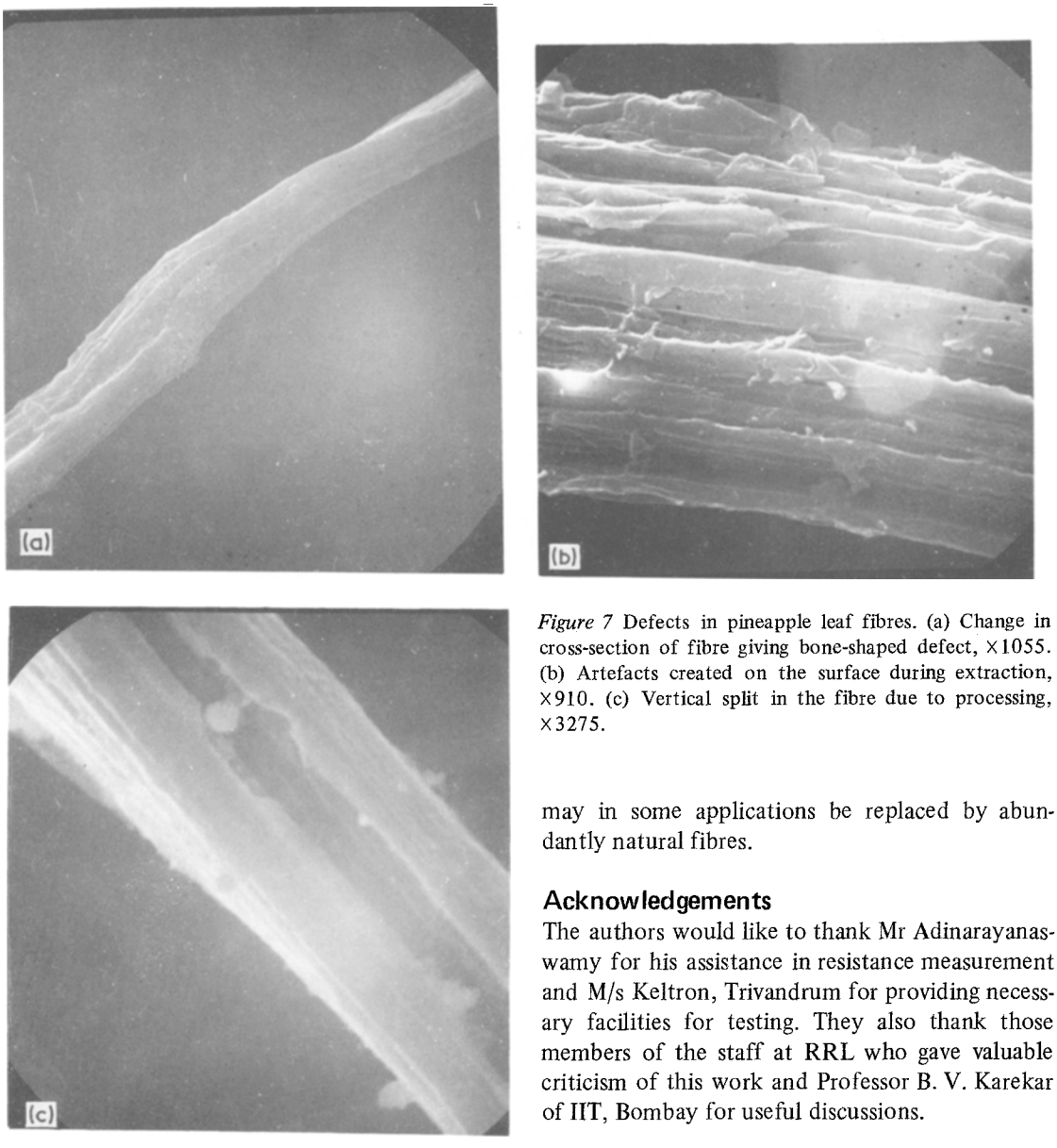

Figure 7 Defects in pineapple leaf fibres. (a) Change in cross-section of fibre giving bone-shaped defect, ×1055. (b) Artefacts created on the surface during extraction, ×910. (c) Vertical split in the fibre due to processing, ×3275.

the cellulose and moisture contents. The present measurements on the electrical resistivity and dielectric strength of coir, banana, pineapple, sisal and palmyrah fibres suggest that all these fibres have high electrical resistance and dielectric strengths and hence may be a satisfactory replacement for wood in insulating applications. The fibres will have a special advantage over wood in that they can be readily pressed in complicated shapes through moulding. This is significant in view of the dwindling resources for wood which may in some applications be replaced by abundantly natural fibres.

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Compression failures in brittle materials: relating observations to a theoretical model

Brittle materials are often used as structural materials in compression, rather than in tension, since tension gives rise to catastrophic failures. When these materials are subjected to compressive loads they show a variability in strength depending on the manner in which they are tested. The work described in this paper investigates only the effect of specimen volume. In order to do so the factors that influence the strength as a result of the chosen method of testing need to be the same for all tests. Compression testing was carried out on cement paste and mortar specimens.

An attempt was made by Hobbs [1] to explain the compressive strength of concrete cubes using the theory proposed by Daniels [2] and Jellinek [3]. In order to use this theory, Hobbs assumed the Weibull modulus, m, to be an index of the relative number of flaws in the material. In recent studies, Jayatilaka and Trustrum [4] showed that m is an index of the variability of flaw size rather than the relative number of flaws.

Observed strengths in compression and tension have different characteristics. It follows that the mechanism of fracture in compression has to be different in order to explain such behaviour. In a brittle material we have a population of cracks of different shapes, sizes and orientations (with respect to applied load). In tension, failure of a single crack leads to total failure, whereas in compression failure of one crack does not lead to total failure.

Jayatilaka and Trustrum [5–7] proposed a theoretical model based on the fact that the final failure of a brittle material, under compression, occurs only after the failure of a certain proportion of cracks, which will be a material property. The splitting of the brittle material can then be explained when several of the "failed cracks" join to form the fracture surface.

The theory is based on a statistical approach and its two main deductions are:

(1) when the volume of a material is large, its mean strength is constant;

(2) the standard deviation is inversely proportional to the square root of the volume.

Two different types of brittle materials, namely, cement paste and mortar, were used for this investigation, considering their commercial usage. In the case of cement past specimens a water: cement (w/c) ratio of 0.30 was used and for the mortar specimens cement: sand: water ratios of 1:2:0.60 and 1:4:0.47 were used.

Since the work was involved with the size influence on the compressive strength, two different specimen shapes (cubic and rectangular) were selected for the investigation. Rectangular samples were of square cross-section and their height-to-breadth ratio was 2:1. This particular dimension was used taking into account the frictional effects of the loading surfaces on the specimen surfaces [7]. For a given material, shape and size, ten samples were made. Standard methods of preparation were employed. All specimens were vibrated mechanically during the preparation stage and were cured for 28 days in water.

After 28 days the compressive strength was measured using a Versa testing machine. The cross-head speed was maintained at 0.1 mm min^{-1} for all the tests.

Generally, the specimens during testing showed a similar cracking behaviour with a large number

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