FRACTURE STUDIES OF COCONUT TREE BASED FIBRES

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ABSTRACT

This paper reports studies carried out on coir and other fibres extracted
from different parts of coconut tree for the estimation of critical strain
energy release rates in individual fibres using compliance calibration
method. The fracture mechanism of these fibres is explained on the basis of
scanning electron microscopic studies carried out on these fibres.

KEYWORDS

Natural fibres; cellulose; microfibrillar/spiral angle; compliance
calibration; strain energy release rate; uncoiling of fibrils; collapse of
cell-walls; fracture mechanism in plant fibres.

INTRODUCTION

Natural fibres like jute, coir, banana and sisal are organic in nature,
biodegradable and exhibit poor mechanical properties both in the as-received
condition and in composites when incorporated in various matrices. However,
these fibres are attracting the attention of scientists and technologists in
recent years mainly due to (i) they form renewable resource, (ii) they are
inexpensive, and (iii) have low density resulting in comparable specific
strength properties, when used in polymer/cement matrices in contrast to
expensive synthetic fibres. Also, most of the scientific data on the stru-
cture and properties of these natural fibres and some scanty information on
the properties of natural fibre incorporated composites are now available
(Bhattacharya and co-workers, 1961; Winfield and Winfield, 1974; Paramasivan
and Abdul Kalam, 1974; Naghabhushanam and co-workers, 1977; Winfield, 1977,
1979; Sathya, 1978; Composite News, 1980; Mc Laughlin, 1980; Singh and Jain,
1980; Shaw and Lakkad, 1981; Satyanarayana and co-workers, 1981, 1982,
1983a, 1983b; Sukumaran and co-workers, 1982; Sridhara and co-workers, 1982;
Kulkarni and co-workers, 1981, 1983a, 1983b; Pavithran and co-workers, 1981;
Prasad and co-workers, 1983). But there is no data available on the work of
fracture for these fibres. Such a data will help in determining the energy
of absorption in the natural fibres when used as reinforcements/fillers in

various matrices. However, there are reports available on the fracture energy of pitch pine (Gordon and Jeronimidis, 1974), bow string hemp (Mc Laughlin and Tait, 1979), certain types of wood (Jeronimidis, 1980; Gordon and Jeronimidis, 1980; Mai, 1983; Boatwright and Garrett, 1983) and rye-grass leaves (Vincent, 1982). There is also a generalised theory proposed for fracture of solids (Andrews, 1980) which can be used to explain fractures and failures in biological systems/composites, such as different types of wood, straw polyester composites without limitations as to their linearity, elastic behaviour or infinitesimal strain. Work of fracture for timber has been evaluated on the basis of fibre composite model (Gordon and Jeronimidis, 1974) indicating a very high work of fracture along with the expected mechanism of fracture in timber. It is reported that work of fracture is very high for timbers/plant fibres ($\sim 10^4$–10^5 Jm^{-2}) almost comparable with that of ductile metals on weight basis, while it is higher than any other mechanical property of timber/plant fibres. It is also found that this value is higher than that required for breaking the inter-atomic bonds (~ 2 Jm^{-2}) in timber and energy absorbed by the fibre pull cut mechanism observed in conventional synthetic fibre composites (Kelly, 1970).

In this paper, we report the values of work of fracture for pre-notched coir and other fibres from different parts of coconut tree using compliance calibration method. Fracture mechanism in these fibres and observed large fracture strains are explained on the basis of fractographs obtained using scanning electron microscope.

EXPERIMENTAL

Fibres from rachis, rachilla, bark of petiole and spathe (Fig. 1) which form different parts of coconut palm, were extracted carefully by hand picking to assure minimum damage, as explained elsewhere (Satyanarayana and co-workers, 1982). Only retted coir usually used in coir industry was used.

Notches were introduced perpendicular to the axis of the fibres using a notch cutting device fabricated in the laboratory shown in Fig.2. The device consists of a sharp razor blade used as cutting edge and fixed on to a stereo microscope. The notches were made by moving the blade while looking through the microscope so that notches of pre-determined depth could be introduced. Notch depth and diameter of the fibre in each case were measured using a Carl Zeiss biological microscope which has an accuracy of 10 μm. Fig. 3 shows a typical photograph of notched fibre with a notch depth of 50 μm.

The notched fibres of length 50 mm were then tested in an Instron Testing machine at a cross-head speed of 10×10^{-3} m/min. A JEOL 35C Scanning Electron Microscope was used to study the fracture surface of the fibres. All the tests were carried out at room temperature and at 65% RH.

RESULTS AND DISCUSSIONS

All the fibres used in the present investigation deform in a linear elastic manner as is evident from the stress-strain diagrams for both the notched and unnotched fibres (Fig. 4a & b). Although both the diagrams can be well compared for any one fibre, the ultimate value of stress and strain differ considerably indicating the occurrence of final fracture at the notches. This is also evident from SEM photographs (Fig. 5a - e) of fractured surfaces of the fibres. In otherwords, pre-cracking of the fibres was
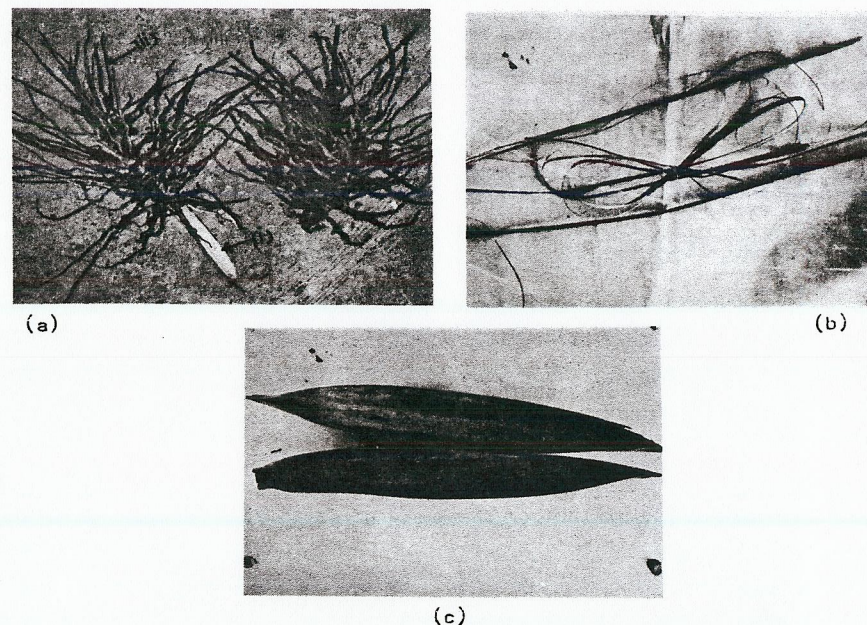

(a)

(b)

(c)

Fig. 1. Different parts of coconut tree from which fibres were taken for the present study: (a) Rachis (i) and Rachilla (ii), (b) Bark of the petiole, and (c) Spathe.
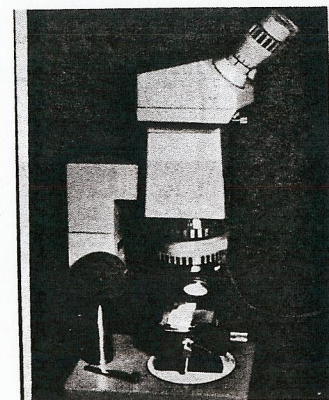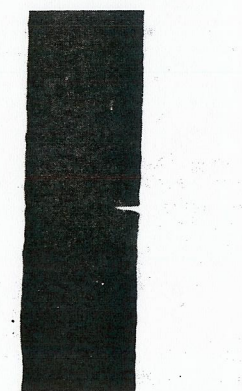

Fig. 2. Notch cutting device
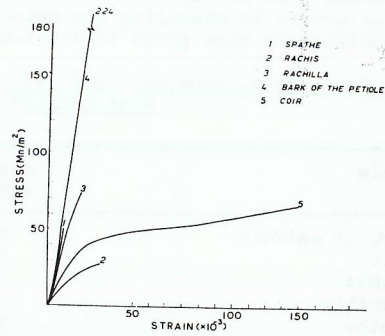
Fig. 3. Typical notched fibre with a notch depth of 50 μm

Fig. 4(a). Stress—strain diagrams of fibres from different parts of coconut palm (notched fibres)

Legend in figure:
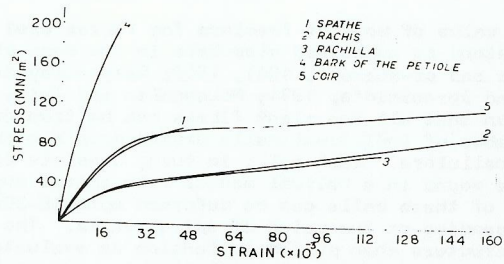1 SPATHE
2 RACHIS
3 RACHILLA
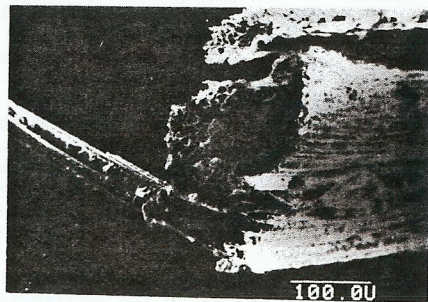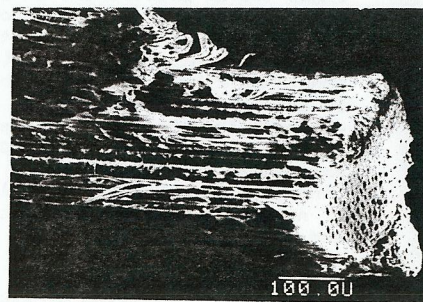4 BARK OF THE PETIOLE
5 COIR

Fig. 4(b). Stress—strain diagrams of fibres from different parts of coconut palm (unnotched fibres).
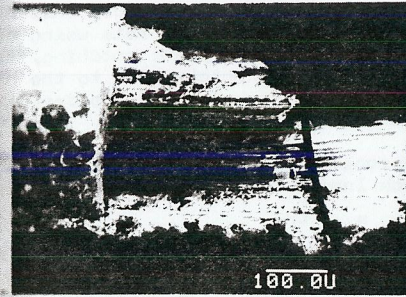
Legend in figure:
1 SPATHE
2 RACHIS
3 RACHILLA
4 BARK OF THE PETIOLE
5 COIR

5(a)

5(b)

5(c)
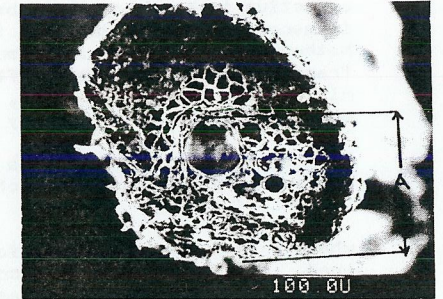
5(d)

5(e)

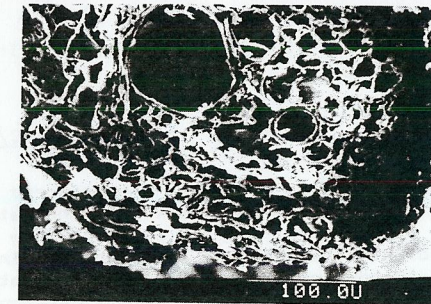Fig. 5. Scanning electron micrographs of both notched and unnotched fibres (a) Bark of the petiole (unnotched), (b) Bark of the petiole (notched), (c) Rachilla fibre (notched), (d) Fractograph of rachis fibre showing both the notched and unnotched portions, (e) 'A' at higher magnification indicating uncoiling of spirals and collapse of cell walls.
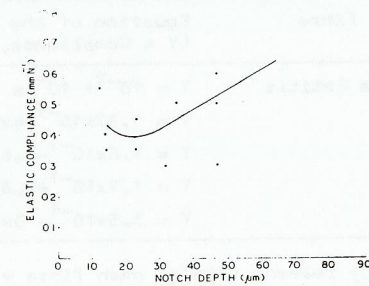

Fig. 6. Plot of compliance Vs notch depth of fibres from spathe.

effective in breaking the fibres at the notches introduced. This condition is necessary for calculating the strain energy release rate using compliance method described below. In some cases, even with prior notching, the final fracture was found to be shifted away from the notches due to the non-uniformity of the fibres. However, such values have not been considered for calculating the strain energy release rate.

Compliance of a system is the reciprocal of the slope of the load deflection curve at a particular value of crack length (Knott, 1973). In general,

$$U = CP \qquad (1)$$

where C represents the compliance, U the deflection and P the corresponding load. For an infinite body containing a crack length a, the strain energy release rate G, for an increase in crack length is given by

$$G B \delta a = \tfrac{1}{2} P \delta U \qquad (2)$$

where B represents the width of the body. Combining equations (1) and (2) for constant loading

$$G B \delta a = \tfrac{1}{2} P^2 \delta C \qquad (3)$$

$$\text{or} \qquad G = \frac{\tfrac{1}{2} P^2 (\delta C / \delta a)}{B} \qquad (4)$$

The elastic compliance in each case was measured from the load deflection curve of each fibre and this was taken as the ratio of deflection to the load. Fig. 6 shows a typical plot of compliance vs the initial crack length for spathe fibres. The observed large scatter in the compliance value may be attributed to the non-uniformity of the diameter of fibres along the length as well as the experimental errors particularly in introducing or measuring accurately the notches. The compliance calibration curves were obtained by fitting second degree polynomial. Super-imposed upon the datum points is the compliance calibration curve.

Table 1 gives the second degree equations of compliance calibration curves obtained for different types of fibres used in the present study. A multiple regression analysis followed by 'F' test showed that they are significant at a level of more than 95%.

TABLE 1   Second Degree Polynomial Equations of Compliance Calibration Curves of Various Fibres

Fibre	Equation of the best fit (Y = Compliance, a = notch depth)
Bark of the Petiole	$Y = 10^{-2} + 10^{-2}a - 12 \times 10^{-2} a^2$
Coir	$Y = 1.87 \times 10^{-1} + 4 \times 10^{-1}a - 3.2 \times 10^{-2} a^2$
Rachis	$Y = 1.6 \times 10^{-1} - 2.6 \times 10^{-2}a + 4.4 \times 10^{-2} a^2$
Rachilla	$Y = 1.7 \times 10^{-1} + 2.8 \times 10^{-1}a - 2.02 a^2$
Spathe	$Y = 3.5 \times 10^{-1} - 3 \times 10^{-1}a + 86.4 a^2$

The strain energy release rate of each fibre was then calculated using equation (4). The value of $\delta C / \delta a$ was evaluated from the equation of compliance calibration curves using the particular value of notch depth. Table 2 lists the average value of G and standard deviation (SD) obtained for each type of fibres used. Higher value of SD in the case of fibres from spathe and rachilla may be due to their internal structure including cell arrange-

ment, cell dimension and chemical constituents in addition to fibre geometry and experimental errors in measuring the notch depth. The G values for some commonly used metals are also given in the table for comparison.

TABLE 2   Average Value of G and S.D of Various Fibres and G of metals*

Materials	Average G $\times 10^3$ Jm^{-2}	S.D.
Fibre: Bark of petiole	33.4	6.2
Coir	15.6	9.4
Rachis	0.436	0.6
Rachilla	5.49	7.6
Spathe	74.78	71.0
Metals: Steel AMS 6434	159.12	–
Al-alloy No.7075 T73	52.19	–

*Fracture, edited by Liebowitz (1969)

The values of G (i.e. two times the work of fracture) obtained in the present study are comparable with those reported for timber ($\sim 10^4$ Jm^{-2}) and other plant fibres ($\sim 10^5$ Jm^{-2}) (Gordon and Jeronimidis, 1974; Vincent, 1982).

The high value of work of fracture for fibres used in the present study can be understood as explained elsewhere in the case of other plant fibres (Kulkarni and co-workers, 1981, 1983; Satyanarayana and co-workers, 1982; Gordon and Jeronimidis, 1974; McLaughlin and Tait, 1979). In short, it is well known that all the plant fibres can be treated as a composite containing a number of individual cells embedded in a matrix of lignin, cellulose and hemicellulose. Each cell, in turn, consists of cellulose molecules which are wound in a helical manner with spiral angle ranging between 6-47° and each of these cells can be deformed upto 15-20% (Page and co-workers, 1971) depending on the value of spiral angle. The deformation mechanism of such a structure when pulled in tension as evaluated theoretically (Hearle, 1964) is that either the microfibrils in each cell along with the crystalline region may elongate or the microfibrills may simply uncoil like springs with bending and twisting. Experimental observations in the case of coir and banana fibres (Kulkarni and co-workers, 1981, 1983; Satyanarayana and co-workers, 1982; McLaughlin and Tait, 1981) have revealed that presence of both the mechanisms mentioned above are present, but it is not known which of these two is predominant in each fibre. In the present study also, fracture surfaces of fibres reveal uncoiling of microfibrils, buckling of cell walls and their collapse into unnotched surface of the fibre, while cells are intact in the notched surface (Fig. 5b-c). In contrast, in the case of unnotched fibres the uncoiling/pull outs/collapse of cell walls was observed in the whole of the fracture surface of the fibres (Fig. 5d). This also explains the observed difference in values of ultimate stress and strain between notched and unnotched fibres. Fractographs also indicate lateral separation of cells ahead of notch such that they are able to deform in the unconstrained manner thus allowing large strains to be achieved in the region of notch tip as explained elsewhere (Gordon and Jeronimidis, 1974; McLaughlin and Tait, 1979). The degree of lateral separation of individual cells observed in different fibres used in the present study is found to be different from fibre to fibre and hence the difference in the average value of G. The lateral separation of individual cells followed by the propagation of crack along the length of the fibres is shown in Fig. 7a & b.

The deformation after buckling of cell wall is non-elastic in nature and therefore it contributes significantly to the total energy absorbed before failure. During this process of energy absorption, separation of helically wound microfibrils may take place leading to ultimate failure.
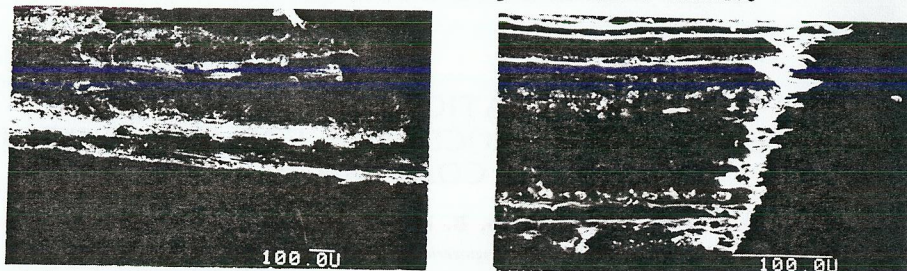
(a)   Fig. 7(a)&(b).   Fractograph (longitudinal) of spathe fibre showing lateral separation of individual cells and propagation of crack along the length of the fibre   (b)

The present study, therefore, confirms that the fracture mechanism in coir and other fibres from different parts of coconut palm is similar to that observed in other plant fibres irrespective of their origin except for the fact that internal structure including arrangement of cells play an important role in giving larger extensions to fibres at break. This study also indicates that composites, when prepared using these fibres as reinforcements/fillers in other matrices, may lead to a high work of fracture which may be due to fibres acting as crack arresters. In fact, this may eventually result in overcoming possible catastrophic failure of composites.

ACKNOWLEDGEMENT

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