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Mechanical properties of banana fibres *(Musa sepientum)*

A. G. KULKARNI, K. G. SATYANARAYANA, P. K. ROHATGI*
Regional Research Laboratory (CSIR), Trivandrum-695 019, Kerala, India

KALYANI VIJAYAN
National Aeronautical Laboratory (CSIR), Bangalore-560 017, India

The stress–strain curve for banana fibre is determined. Properties such as the initial modulus (YM), ultimate tensile strength (UTS) and percentage elongation are evaluated as a function of fibre diameter, test length and speed of testing. It is found that YM, UTS and % elongation show little variation in their values for fibres of diameter ranging from 50 to 250 μm. The UTS and breaking strain are found to decrease with an increase in the test length while both breaking strength and breaking strain remain constant with the increase of speed of testing from 0.5 to 100×10^{-3} m and thereafter they both decrease. These observed properties are explained on the basis of the internal structure of the fibre, namely, the number of cells, spiral angle and the number of defects. Scanning electron microscopic (SEM) studies of the fractured surfaces of these fibres indiacte that the failure is due to pull-out of microfibrils accompanied by tearing of cell walls; the tendency for fibre pull-out seems to decrease with increasing speed of testing.

1. Introduction

Although natural fibres like coir and banana fibres have relatively poor mechanical properties, they are renewable resources and have a low density. In India about 1.5M acres of land is cultivated with banana plantations which yield about 3×10^5 tons of fibre [1]. In Kerala, banana fibres are usually extracted manually from pseudo-stems by scraping the pithy material with a wooden scraper. Fibres are then washed in water and hung in the shade to dry. Since only a small quantity of fibres is available (1 to 2% wet weight per plant), it poses a problem in the commercial production of this fibre and a large quantity of this renewable fibre resource is being under-utilized. Presently, banana fibres are used for the preparation of hand bags, ropes, table mats and fancy goods. One of the reasons for the under-utilization of these fibres is the lack of scientific data on these fibres, except for the information available on the chemical constituents of these fibres [2, 3]. Although some scattered data is available on the physical properties, including the spiral angle of banana fibres [4–9] there is no information on the variation in properties of banana fibres with test speed and with size and length of fibres. Systematic evaluation of such data may add to the understanding of the relation between the structure and properties of the fibre and also open up new avenues for their better utilization.

In this paper the mechanical properties of banana fibre, such as initial modulus, UTS and breaking strain, are reported as functions of the fibre diameter, test length and speed of testing. Structural studies using optical and scanning electron microscopy (SEM) of the fibres before and after testing are also reported and related to the observed properties.

2. Experimental details

The banana fibres used in the present investigation were received from Veeranakkalu (southern part of Kerala) near Trivandrum, India. Fibres of various diameters (ranging from 50 to 250 μm)

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*Presently, Director, Regional Research Laboratory, Bhopal, MP.

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were sorted out using a light microscope. The fibres were conditioned before testing for about 4 h at r.h. (relative humidity) 65 ± 5% at room temperature. They were then weighed in a Mettler balance to determine the average fineness in terms of denier. The fibres were then mounted on cardboard with a central window and tested in an Instron Testing Machine for their tensile properties. Tests were carried out on fibres of 200 μm diameter, subjected to various test speeds ranging from 0.5 to 500×10^{-3} m min^{-1} and sample test lengths ranging from 10 to 300×10^{-3} m. The optical microscope was used to understand the structure of the fibre, while fractured fibre samples were examined under a JEOL scanning electron microscope after suitable preparation to study the fracture mode.

X-ray diffraction patterns of fibres were recorded on flat films by the Laue transmission technique, using Cu*Kα* radiation. The fibre axis was always kept perpendicular to the incident X-ray beam. The sample to film distance was varied from 40 to 55×10^{-3}m. In order to determine the microfibrillar angle, intensity distributions along the diffraction arcs were measured using a Carl-Zeiss microdensitometer with a circular specimen stage. The angles were determined by the method given by Preston [10].

3. Results

3.1. Optical microscopy

Fig. 1 shows that the banana fibre is a multicellular fibre like coir and other vegetable fibres. The structural details of a vegetable fibre are explained elsewhere [11, 12]. In short, the banana fibre is found to consist of four kinds of cells, namely, xylem, phloem, schlerenchyma and parenchyma arranged in a particular fashion. The shape of the cells vary from circular to polygonal with rounded corners or circular to elliptic. Table I lists various cells observed in fibres of different diameter. It can be seen that the fraction of strength rendering cells to the total number of cells almost remain constant for the fibres of a diameter in the range of 100 to 200 μm. The cells have a diameter of 18 to 30 μm, and a mean length of 2.7 to 5.5 mm with a *l/d* ratio of 150 in contrast to a cell diameter of 13 to 14 μm and *l/d* ratio of 35 in the case of coir [11]. The cell wall of the banana fibre appears to be thinner (1.25 μm) and much more uniform in comparison to coir fibre [12] where cell walls are thin to fairly thick (about 8 μm).

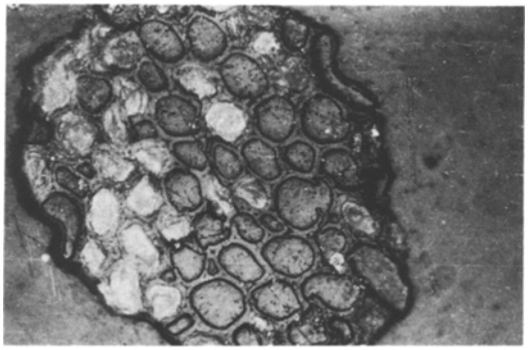

Figure 1 Cross-section of banana fibre showing that the fibre is multicellular with thin walled cells and larger lumen (X 320).

3.2. X-ray study

As in the case of other vegetable fibres, the crystalline cellulose in banana fibre is arranged in the form of a helix at an angle of 11 to 12° for fibres of diameter 100 to 200 μm in contrast to coir fibre where the spiral angle was found to vary from 40 to 47° for a fibre diameter 100 to 500 μm [11].

3.3. Stress–strain curve of banana fibres

Fig. 2 shows a typical stress–strain curve of a banana fibre of diameter 200 μm tested in tension at a test speed of 500 μm min^{-1}. This is characterized by a straight line portion (the slope of which may be taken as the initial modulus), followed by

TABLE I Number of various cells and helix angle of banana fibres for various diameters

Diameter of fibre (μm)	Average number of xylem cells	Average number of phloem cells	Average number of sclerenchyma cells	Total number of cells	Fraction of sclerenchyma cells to the total number of cells (strength donating)	Helix or microfibrillar angle (θ)
100	3	6.25	53	62.25	0.850	12 ± 1°
150	3	8.00	70	81.00	0.875	11 ± 2°
200	4	7.75	92	103.25	0.886	11 ± 1°

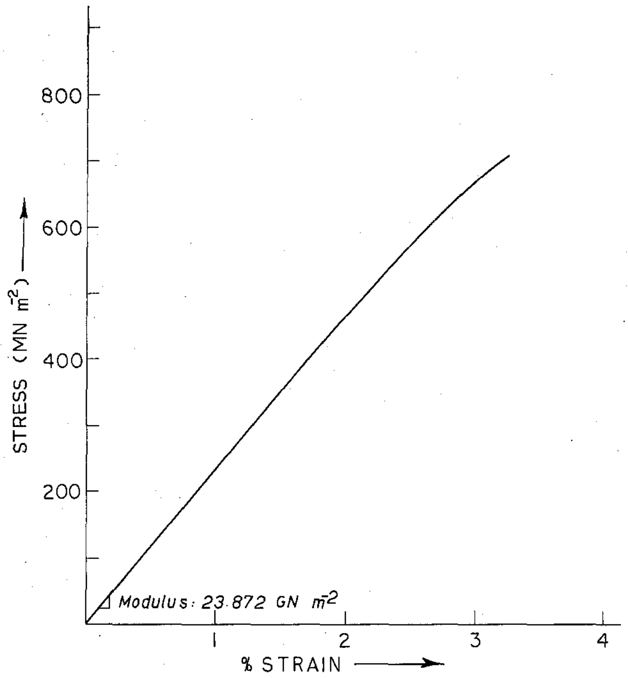

Figure 2 Typical stress-strain curve for a banana fibre of diameter 0.2×10^{-3} m tested at a speed of 0.5×10^{-3} m min^{-1}.

a small curvature indicating a disproportionate increase in strain with stress until the fibre breaks.

3.4. Effect of diameter of the fibre

Table II shows the mechanical properties of banana fibre of various diameters used in this investigation. It can be seen that there is no appreciable change in the mechanical properties of the fibres with an increase in the diameter of the fibre in the range investigated (50 to 250 μm). This behaviour of banana fibre is in contrast to that of coir fibres which showed [11] a gradual decrease in the initial modulus with an increase in the diameter of the fibres in the range 100 to 450 μm, while UTS and breaking strain increased up to a diameter of 200 μm, after which they remained constant.

3.5. Effect of test length

In order to determine the effect of the test length on the properties, banana fibres of 100 μm diameter were tested at a test speed of 25×10^{-3} m min^{-1} with test lengths ranging from 10×10^{-3} to 300×10^{-3} m. Table III lists values of mechanical properties for banana fibres for various test lengths. It can be seen that the breaking strength and percentage breaking strain increase with a decrease in test length, as observed in the case of coir fibre [11]. Fig. 3 shows a linear relationship between breaking strength (σ) of the fibre and test length (l) given by

$$\sigma = 956.698 - 1376.665\, l \qquad (1)$$

with a significance of 99%.

TABLE II Mechanical properties of banana fibres of different diameters. Gauge length = 50×10^{-3} m and CHS = 20×10^{-3} m min^{-1}

Sample number	Diameter of fibre (μm)	Initial Young's modulus (GN m^{-2})	SD* initial Young's modulus (GN m^{-2})	Breaking strength (MN m^{-2})	SD breaking strength (MN m^{-2})	% strain	SD % strain
1	50	32.703	8.190	779.078	209.300	2.750	0.957
2	100	30.463	4.689	711.661	239.614	2.469	0.798
3	150	29.748	8.561	773.002	297.104	3.583	1.114
4	200	27.698	7.083	789.289	128.588	3.340	0.688
5	250	29.904	4.059	766.605	165.515	3.244	1.284

*SD – Standard Deviation

TABLE III Mechanical properties of banana fibres of different test lengths. Diameter = 100 μm and speed of testing = 25 × 10^{-3} m min^{-1}

Sample number	Length (10^{-3} m)	Ultimate breaking strength (MN m^{-2})	SD ultimate breaking strength (MN m^{-2})	% breaking strain	SD % breaking strain
1	10.00	1055.516	260.612	13.770	3.439
2	20.00	930.734	270.430	6.735	1.393
3	35.00	891.706	196.775	6.387	1.809
4	50.00	711.661	239.614	2.469	0.738
5	100.00	731.185	224.275	2.714	0.636
6	150.00	929.551	270.009	2.475	2.003
7	200.00	744.827	271.972	1.830	0.491
8	300.00	468.965	234.076	1.958	0.659

3.6. Effect of test speed

Table IV shows the ultimate breaking strength and breaking strains of banana fibres of diameter 200 μm and test length of 50 × 10^{-3} m. It can be seen that the strength of the fibre increases as the speed of testing increases from 0.5 × 10^{-3} to 100 × 10^{-3} m min^{-1}. However, when the test speed was increased from 100 × 10^{-3} to 500 × 10^{-3} m min^{-1} the strength showed a decrease. This behaviour of the banana fibre is again different from the behaviour of coir fibres which showed little variation in breaking strength when tested at test speeds between 0.2 × 10^{-2} to 2 × 10^{-2} m min^{-1}.

4. Discussion

As pointed out elsewhere [11], the mechanical properties of plant fibres mainly depend on factors like (a) the source, (b) age, (c) the species, (d) processing parameters and (e) the internal structure. Since the banana fibres obtained for the present investigations are from a given location in the southern part of Kerala, and were manually processed from the pseudo-stem of a mature plant (the plant is felled after harvesting the fruit), the variation in the mechanical properties can be assumed to be primarily due to structural variations in the fibre. The results of the present study, therefore, are interpreted in terms of the variation in structure of the fibre. The plant fibres have both crystalline and noncrystalline components.

4.1. Stress–strain curve

When a structure like banana fibre is pulled in tension both crystalline and noncrystalline parts of the fibre undergo deformation as explained elsewhere [13]. In short, in the case of spiral-like structures (as in banana and coir fibres) either (a) microfibrils along with the noncrystalline regions may elongate, or (b) the microfibrils may simply uncoil like a spring with bending and twisting. Thus, these two mechanisms operate in the initial

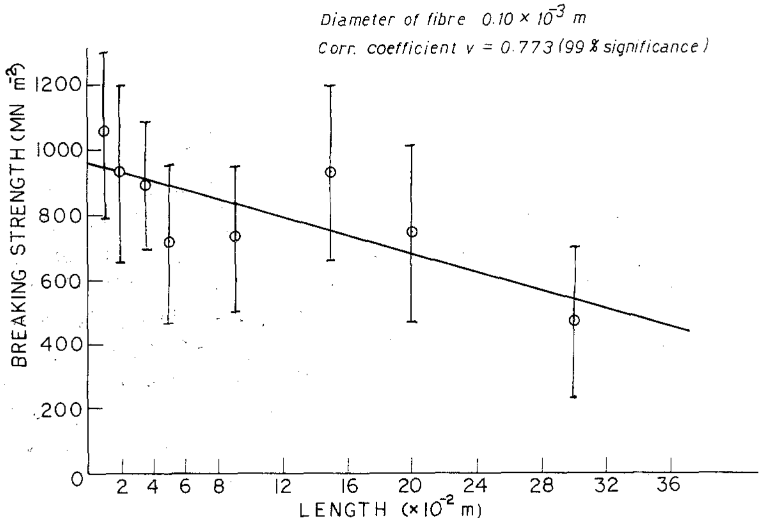

Figure 3 Variation of breaking strength with test length.

TABLE IV Effect of speed of testing on mechanical properties of banana fibres. Diameter of fibre = 200 μm

Sample number	Speed of testing (10^{-3} m min^{-1})	Breaking strength (MN m^{-2})	SD breaking strength (MN m^{-2})	% breaking strain	SD % breaking strain
1	0.50	726.723	103.340	3.70	0.618
2	20.00	789.289	128.588	3.34	0.688
3	100.00	906.644	191.081	3.54	0.777
4	200.00	737.543	125.759	2.70	0.478
5	500.00	806.719	243.669	3.55	0.880

stage, then contribute to the modulus of the fibre, i.e. at low strains, often referred to as the "initial modulus region", the fibre exhibits high resistance to stretch due to the interference between the movements of neighbouring molecular chains as well as intermolecular secondary bonding between chains. The chain or chain segments cannot react independently of their neighbours, to the developed stress. In this region of the stress–strain curve, no major displacement of one chain with respect to its neighbours occurs. The extent to which the fibre resists the deformation in this low strain region is given in Table I as the initial modulus. Since both the crystalline region and noncrystalline region will deform, the applied load is shared between these two components as in the case of composites. Therefore, the effective modulus of a fibre (E_f) may be given in terms of the amounts of components present in the fibre. This is evident from the following equation [14]

$$E_f = W_c E_c \cos^2\theta + W_{nc} E_{nc} \qquad (2)$$

where E_c, E_{nc} are the modulus values of crystalline and noncrystalline regions and are assumed [14] to be 45 and 3 GN m^{-2}, respectively, for the plant fibres. W_c, W_{nc} represent the weight fractions of the crystalline and noncrystalline materials, and in the case of banana fibre the values of these are 0.65 and 0.35, respectively [2, 3]. It is found that the modulus values calculated using the above formula compare well with the modulus values measured in this study. This indicates that the initial extensions primarily involve uncoiling of the crystalline coils.

Immediately after the decohesion of the fibrils occurs, the process of slip and translation of the chain segments with respect to one another, occurs for a short while under the additional stress, until the fibre breaks. There is disproportionately greater strain while the process of decohesion and slip is taking place, giving rise to the observed shape of the stress–strain curve.

In fact, in the case of coir fibre, where the cell wall is thick (8 μm) and the lumen is small, the fracture mode is by the uncoiling of microfibrils without any separation of cells near the periphery of the fibre from the cuticle or breaking of the bonding material between the cells. There is decohesion of cell walls and their collapse is associated mainly with the fracture. On the other hand, in the case of banana fibre, which has a thinner cell wall (1.25 μm) and a smaller amount of bonding material, once the decohesion of the fibrils takes place, fibrils separate from each other and fracture occurs shortly thereafter. However, in the regions slightly away from the fractured end, the measured microfibrillar angle shows a value of 10 ± 1°, a value close to that observed in the fresh banana fibre. Therefore, it appears that the necking of fibrils and change in microfibrillar angle is localized over a region very close to the fractured end and does not propagate along the length of the fibre.

Observed higher values of YM, UTS and the lower of percentage breaking strength for banana fibre in contrast to those of coir fibre may be due to a low value of the spiral angle (11 to 12°), the smaller number of xylem and phloem cells, the larger diameter of cells (18 to 30 μm) and the higher amount of cellulose content (65%) in the banana fibre.

4.2. Effect of diameter

The breaking strength and the breaking strain are primarily dependent on the gauge length and the number of flaws in the fibre. Also, the strength of fibres increases with the increasing number of strength rendering cells, while it decreases as the microfibrillar angle increases and the decrease in cellulose content. But it can be seen from Table IV that there is no large variation in the helical angle as well as the fraction of the sclerenchyma cells (which are supposed to render strength to the fibres) in the total number of cells up to a fibre diameter of 200 μm. The structure of banana fibres is unlike that of coir fibres which show an

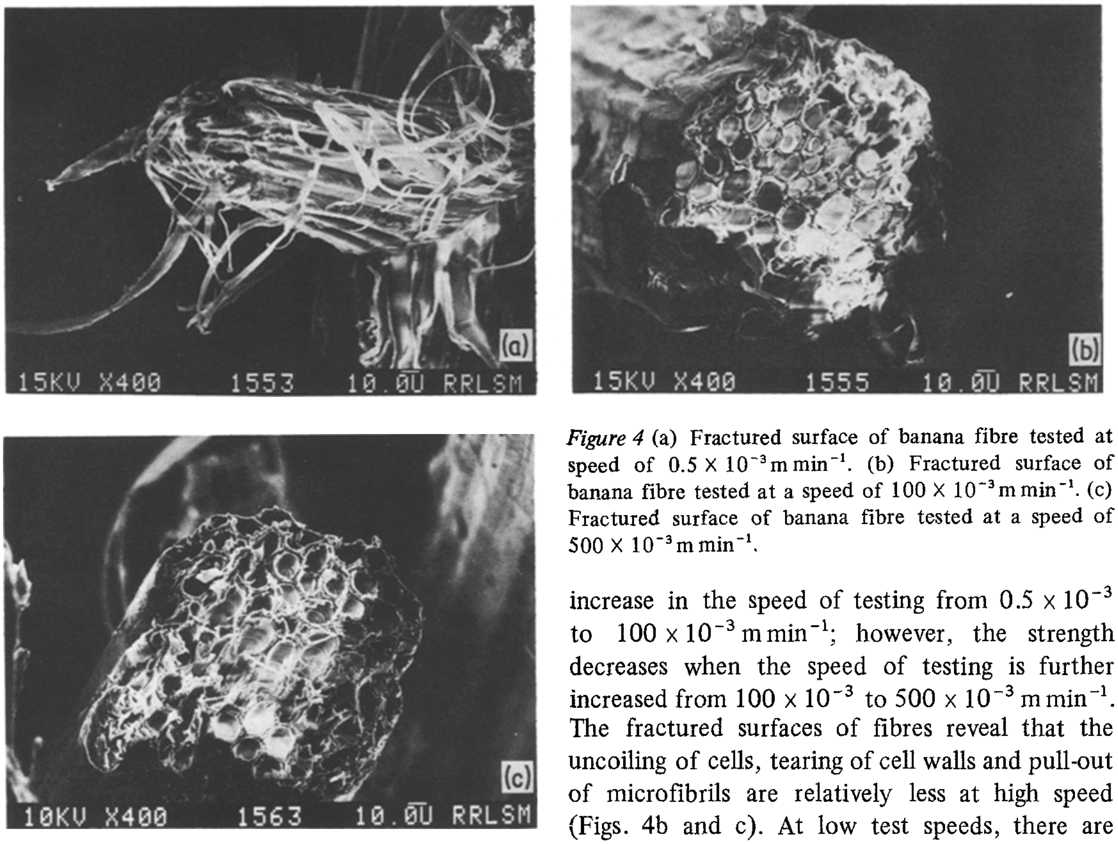

Figure 4 (a) Fractured surface of banana fibre tested at speed of $0.5 \times 10^{-3}\,\mathrm{m\,min^{-1}}$. (b) Fractured surface of banana fibre tested at a speed of $100 \times 10^{-3}\,\mathrm{m\,min^{-1}}$. (c) Fractured surface of banana fibre tested at a speed of $500 \times 10^{-3}\,\mathrm{m\,min^{-1}}$.

increase in the number of cells in fibres up to a diameter of $100\,\mu\mathrm{m}$ and thereafter the cell number remains constant. Accordingly, the strength also varies. Thus a lack of significant variation in the microfibrillar angle, as well as in the fraction of strength rendering cells in the banana fibres may be the reason that there are no significant changes in the mechanical properties with fibre diameter.

4.3. Effect of test length

The observed decrease in the breaking strain with an increase in the test length (Table III) is apparently due to localized deformation, especially at the lower speed of testing (Fig. 4); this behaviour of banana fibre is similar to what is observed in the case of coir [11]. The decrease in strength with test length may be due to the fact that the probability of defects and weak links increases with the length of fibres. Similar behaviour is observed in coir [11] and many other polymeric materials [15].

4.4. Effect of speed of testing

The strength of banana fibres shows an increase in strength (at the expense of elongation) with an increase in the speed of testing from 0.5×10^{-3} to $100 \times 10^{-3}\,\mathrm{m\,min^{-1}}$; however, the strength decreases when the speed of testing is further increased from 100×10^{-3} to $500 \times 10^{-3}\,\mathrm{m\,min^{-1}}$. The fractured surfaces of fibres reveal that the uncoiling of cells, tearing of cell walls and pull-out of microfibrils are relatively less at high speed (Figs. 4b and c). At low test speeds, there are indications of necking as can be seen from Fig. 4a. The majority of the banana fibres tested at low speeds reveal a fracture surface (Fig. 4a) similar to what was observed in the case of coir [11]. However, no explanation can be given at this stage for the observed higher strengths in the fibres tested at a test speed $100 \times 10^{-3}\,\mathrm{m\,min^{-1}}$.

5. Conclusions

1. The stress–strain curve for banana fibre is characterized by an initial linear stress–strain curve, the slope of which may be taken as the initial modulus, the linear portion is followed by a curve since the strain per unit stress is greater than that during the initial deformation.

2. The value of the experimentally observed elastic modulus, UTS and percentage elongation are in the range 27 to $32\,\mathrm{GN\,m^{-2}}$, 711 to 789 $\mathrm{MN\,m^{-2}}$ and 2.5 to 3.7%, respectively, for fibres in the 50 to $250\,\mu\mathrm{m}$ diameter range.

3. Strength of banana fibre increases from 726 to $906\,\mathrm{MN\,m^{-2}}$ at $100 \times 10^{-3}\,\mathrm{m\,min^{-1}}$ with an increase in the speed of testing from $500\,\mu\mathrm{m\,min^{-1}}$ to $100 \times 10^{-3}\,\mathrm{m\,min^{-1}}$ with a further increase in the speed of testing from 100×10^{-3} to $500 \times 10^{-3}\,\mathrm{m\,min^{-1}}$ resulting in an increase in strength.

4. An increase in the strength is observed with a decrease in the test length.

5. Banana fibre appears to fail by localized deformation followed by pull-out of microfibrils accompanied by the tearing of cell walls; the mechanism is more perceptible at lower speeds of testing.

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