

Banana Fibers – Variability and Fracture Behaviour

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ABSTRACT

Banana fibers obtained from the stem of banana plant (*Musa sapientum*) have been characterised for their diameter variability and their mechanical properties, with a stress on fracture morphology. The nature of representative stress strain curves and fracture at different strain rates have been analysed through SEM.

INTRODUCTION

Natural fibers present important advantages such as low density, appropriate stiffness and mechanical properties and high disposability and renewability. Moreover, they are recyclable and biodegradable. There has been lot of research on use of natural fibers in reinforcements. Banana fiber, a ligno-cellulosic fiber, obtained from the pseudo-stem of banana plant (*Musa sepientum*), is a bast fiber with relatively good mechanical properties.

The “pseudo-stem” is a clustered, cylindrical aggregation of leaf stalk bases. Banana fiber at present is a waste product of banana cultivation and either not properly utilized or partially done so. The extraction of fiber from the pseudostem is not a common practice and much of the stem is not used for production of fibers. This is reflected from the relatively expensive price of banana fibres (*Table I*) when compared to other natural fibres¹. The buyers for banana fibers are erratic and there is no systematic way to extract the fibres regularly. Useful applications of such fibres would regularize the demand which would be reflected in a fall of the prices.

TABLE I. Price of different natural fibres

Natural Fibre	Price(\$/kg)
Flax	0.15-0.21
Hemp	0.15-0.60
Kenaf	0.15-0.30
Banana	0.43-0.81*

*The price at which the author sourced the fibers from two different places in India.

Bast fibers, like banana, are complex in structure. They are generally lignocellulosic, consisting of helically wound cellulose microfibrils in amorphous matrix of lignin and hemicellulose. The cellulose content serves as a deciding factor for mechanical properties along with microfibril angle. A high cellulose content and low microfibril angle impart desirable mechanical properties for bast fibers. Lignins are composed of nine carbon units derived from substituted cinnamyl alcohol; that is, coumaryl, coniferyl, and syringyl alcohols. Lignins are associated with the hemicelluloses and play an important role in the natural decay resistance of the lignocellulosic material. The composition of banana pseudostem obtained by elemental analysis, as determined by Bilba et.al² is as given in *Table II*.

TABLE II. Botanical composition of studied pseudostem fibers

Sl.No	Constituents	Percentage
1.	Cellulose	31.27 ± 3.61
2.	Hemicellulose	14.98 ± 2.03
3.	Lignin	15.07 ± 0.66
4.	Extractives	4.46 ± 0.11
5.	Moisture	9.74 ± 1.42
6.	Ashes	8.65 ± 0.10

X ray analysis of banana fibres reveals that cellulose crystallites are arranged in helices with helix angles of 11-12°³. Marias et.al⁴ reported a spiral angle of 11° for banana fibers. There have been studies on use of banana fibers as reinforcement, specially in thermoset resins. Banana fiber was found to be a good reinforcement in polyester resin.^{5 6} Joseph. et.al⁷ found that the mechanical properties of banana/phenol formaldehyde (PF) composites are comparable to those of glass fiber/PF composites. The effects of chemical modification on the physical properties of banana fibers were analyzed by Joseph. et.al.⁸ Mukhopadhyay et.al⁹ investigated the behaviour of fresh and aged fibers and their reaction to alkali at different concentration. Rao et.al¹⁰ investigated their use in thermosetting polymers and

Zhu et.al¹¹ used them as reinforcement in cement. However there has been no systematic investigation on the mechanical properties of banana fibers and its fracture behaviour.

It is crucial to know the fracture morphology to prevent possible failures and more importantly to know the nature of failure. Fracture was investigated by different researchers from different viewpoints who have come out with different theories. Fracture, which implies creation of new surfaces within the body according to Andrews¹², is a continuous deformation.¹³ The process may be viewed in three levels: the initiation of a crack, stable propagation under rising or constant load and unstable propagation leading to failure. The first and second level is dependent on structure of the material, whereas the final level is always a form of unstable propagation.¹⁴ Tensile fractures can be segregated into brittle and ductile fractures.¹⁵ The principal difference between brittle and ductile fracture is the plastic deformation that takes place in ductile materials before fracture occurs whereas brittle materials show no or little plastic deformation.^{16 17} Brittle fracture can be defined as a rapid run of cracks leading to a sharp break. In ductile behaviour, cracks propagate slowly followed by plastic deformation.¹⁰ This article investigates the variability, tensile properties and fracture behaviour of banana fibers.

MATERIAL AND METHODS

Banana fibers were obtained from Krishi Vidyan Kendra, Pal, Jalgaon, Maharashtra Pin- 425504, India. Banana fibres were extracted from the stems of banana plant. Longitudinal slices were prepared from stems and fed to fiber extracting machine (Figure 1). The fiber extracting machine, also known as a mechanical decorticator, consists of a pair of feed rollers and a beater. The slices were fed to the beater between the squeezing roller and the scrapper roller, (Figure 1) following which the pulp gets separated and fibers are extracted and air dried in shade.

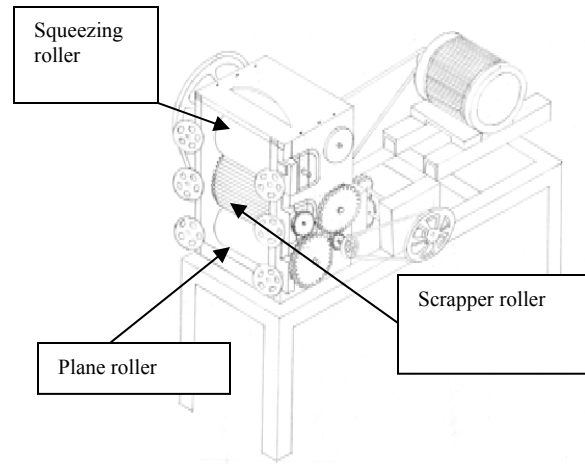


FIGURE 1. Banana fiber extracting machine

Testing

A. Conditioning

Specimens were conditioned, at 65% RH and 21⁰C for a day to ensure environmental equilibrium, prior to testing.

B. Fiber linear density

Fibre diameter was evaluated from optical observations under microscope as the average of five diameter measurements taken at different locations along the fiber with a range of standard deviation from 0.05 to 0.1. Based on the diameters of the fiber, the whole fiber samples were divided into four broad categories. The diameter of the fiber was then measured at 100 different places along the length of four fibers. 100 fibers were also taken at random from the sample and their diameter measured at 10 different places.

The tex of the fiber was calculated assuming the density of banana fibers to be 1.4g/cc, determined using a density gradient column prepared from xylene (0.865 g/cm³) and carbon tetrachloride (1.595 g/cm³) by Kumar et.al.¹⁸ Figure 2, which is the cross section of a fractured banana fiber, shows the circular nature of the fiber, along with the presence of some protruding fibrils. Thus for a circular cross section of the fiber, the tex of the fiber, defined as the weight in grams of 1000m of the fiber, would be related to the volume as

$$\text{Tex} = \text{Volume (cc)} \times 1.4 \times 1000 \dots(1)$$

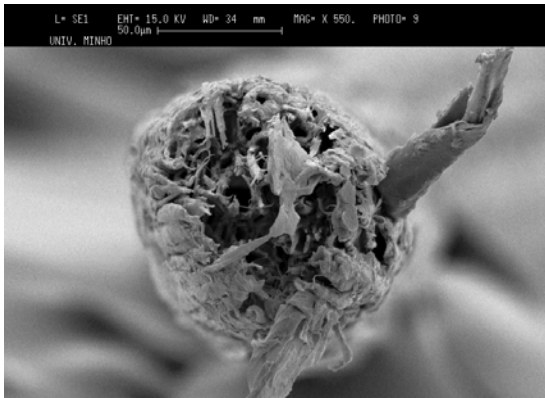


FIGURE 2. SEM of banana fiber showing the circular cross-section

C. Single fiber tensile test

Fibres were carefully manually separated from the bundles. Fibre ends were glued onto a paper frame according to the preparation procedure described in ASTM D3822-07 Standard. A Hounsfield tester was used to test the fibers. A load cell of 100 Newton was used for fiber testing. Due to variability of natural fibers, 20 samples were tested and the average value reported along with the variability of the data. The strain rate was varied to study its effect on properties.

Pneumatic grips were used to clamp the fiber with a pressure of 0.4MPa. When mounting specimens onto the tester, special care was taken to prevent fiber misalignment. The distance between the grips were fixed to 100mm and the upper end of the fiber was clamped first and the fiber was allowed to self-align, under the weight of lower paper tab, followed by clamping of the lower end.

The tenacity values are calculated based on the maximum load and the tex of the fibers, the calculation of which has already been discussed. Modulus values are not reported as the tester had no strain gauge attachment.

D. SEM

A scanning electron microscope (SEM), Model Leica Cambridge S-360 was used to study the fracture surface of the tensile and impact specimens. The specimens were coated with a thin gold-palladium layer using Sputter Coater to avoid electrical charge accumulation during examination.

RESULTS AND DISCUSSION

Hundred fibers were chosen at random from the collection of banana fibers. There was a wide range of variation of diameter starting from 0.08mm to 0.32 mm. Based on a class interval of 0.029 mm, which

was decided based on the presence of at least 10 fibers in a class, the fibers were divided into 8 classes (Figure 3). Diameter distribution of fibers measured along 100 different points along the length for four different fibers also follow a normal distribution (Figure 5) except for Fiber 1, which had a bimodal distribution. However majority of the fibers follow a normal distribution, 25% of the fibers fall in the 0.17 to 0.19 mm group and 66% of the fibers cluster around the diameter of 0.14 to 0.23 mm. This distribution is inherent in natural fibers of various origins.

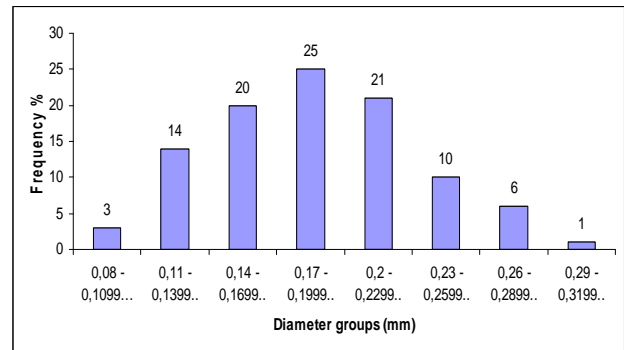


FIGURE 3. Frequency distribution of banana fibers based on diameter (Based on 100 fibers measured at 10 places along their length)

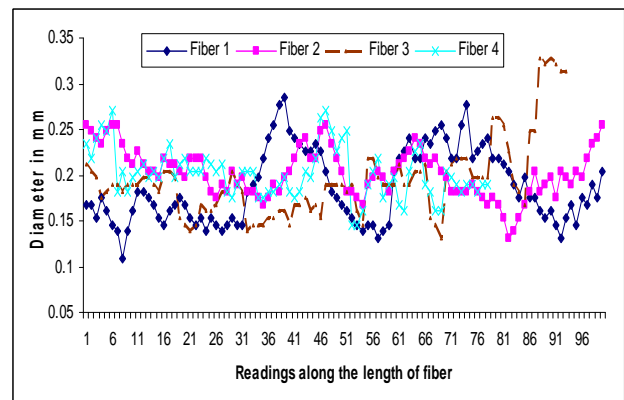


FIGURE 4. Variation of fiber diameter along fiber length (Based on 100 readings on each fiber along the length)

Figure 4 shows the diameter variation along the fiber length. It is important that the variation do not show any trend whatsoever for the different fibers tested. It is equally interesting to note the diameter distribution of fibers measured along 100 different points along the length for four different fibers also follow a normal distribution (Figure 5).

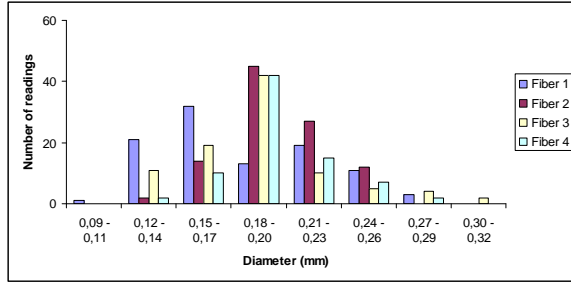


FIGURE 5. Frequency distribution of diameter along the length of four individual fibers (Based on 100 readings on each fiber along the length)

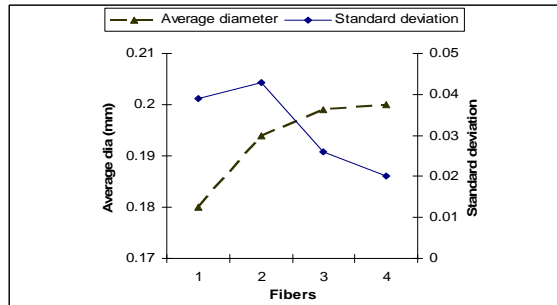


FIGURE 6. Average diameter vs. Standard deviation of fibers (Based on 100 readings on each fiber along the length)

Figure 6 establishes that the standard deviation has decreased with an increase of diameter of the fibers meaning that courser fibers were more regular in nature. The majority of the fibers, as evident from Figure 3 come in the diameter range of 0.17 to 0.19 mm. Hence such fibers were chosen for tensile testing. Results of tensile testing revealed that strain rates played an important role in the nature of the stress strain curves, the strength of the fibers and the nature of failure. The tenacity, as observed from Table III increased when the strain rate is increased to 0.5 min⁻¹ but ultimately decreased with an increment in speed.

TABLE III. Effect of variation of strain rate

Sl No	Strain rate (min ⁻¹)	Tenacity (MPa)	Extension (%)
1.	0.1	167.2 (26.8)	3.0 (17.2)
2.	0.5	203.4 (18.6)	2.7 (17.8)
3.	1	168.6 (30.1)	2.3 (27.8)
4.	10	146.2 (26.2)	1.2 (28.2)

(The results are average values from 20 tests each on fibers of 7 tex and the figures in brackets indicate the CV of testing.)

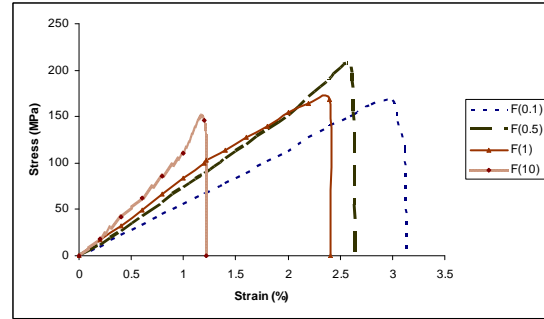


FIGURE 7. Representative stress strain curves of banana fibers (Average of 20 readings)

Figure 7 comprises the representative stress strain curves for banana fibers. There was some initial compliance of the system. The averaged curves show the tendency of a dominantly brittle fracture for the fibers except at the lowest strain rate of 0.1 min⁻¹. Some of the fibers showed evidence for strain-hardening. This phenomenon can be interpreted as a progressive reorientation of microfibrils which occur for some of the fibers. Similar observations have been made by Hornsby et.al.¹⁹ in their research with wheat and straw fibers. The modulus values were not calculated because of non availability of a strain gauge. It is apparent from the stress strain curves that higher strain rates resulted in higher apparent modulus values.

These results can be explained in terms of the internal structure of the fiber, such as cell structure, microfibrillar angle, defects, etc. At low strain rate, the applied load is borne increasingly by the amorphous region, which is evident from the stress strain diagram (curve F(0.1) in Figure 7). The fracture is not so abrupt as some fibrils extend and share some of the load before ultimate fracture. The observation in the stress strain curves has been strengthened from the fracture morphology in SEM (Figure 8), which evinces that lower strain rates have resulted in the fiber behaving in a partially ductile fashion. The side view in SEM (Figure 8(a)) clearly shows the extension of fibrils and the fibers have failed with an average extension of 3%.

With increased strain rate the fiber behaves more like a stiffer elastic body (curve F(0.5) in Figure 7), i.e. the crystalline region shares the major applied load resulting in high values mechanical properties. At 0.5min⁻¹, the fracture surface (Figure 9) demonstrates a more brittle-ductile nature of fracture. However the fibrils are conspicuous by their absence. The average elongation has fallen to 2.7% (Table I).

At higher strain rates of 1 min^{-1} a fall of tensile strength is observed (curve F(1) in *Figure 7*) which may be a result of the presence of imperfections in the fiber causing immediate failure. It has to be noted that at higher speeds, the imperfections play a major role in tenacity or breaking strength, being dependent on imperfections, deteriorates. SEM micrographs (*Figure 10*) show a majorly brittle fracture, with some element of ductility still present in the fractured surface.

With still higher strain rates 10 min^{-1} a further fall of tensile strength is observed (curve F(10) in *Figure 7*). SEM micrographs (*Figure 11*) show a substantial brittle fracture. The lower elongation of 1.2% is a result of the brittle failure of the specimen. Similar findings have been reported by Mukherjee et.al²⁰ for sisal fiber, who have reported a rise and subsequent fall in tenacity with increasing strain rate.

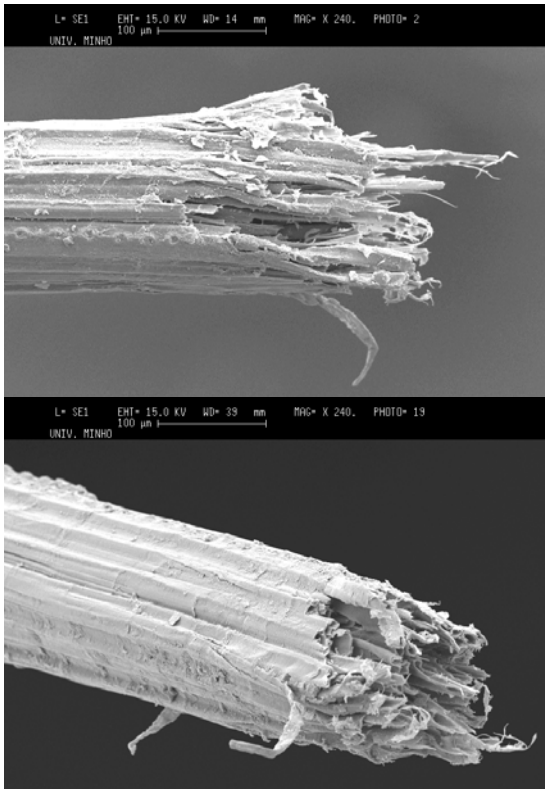


FIGURE 8. Fracture (strain rate of 0.1 min^{-1})
(a) side view (b) angular view

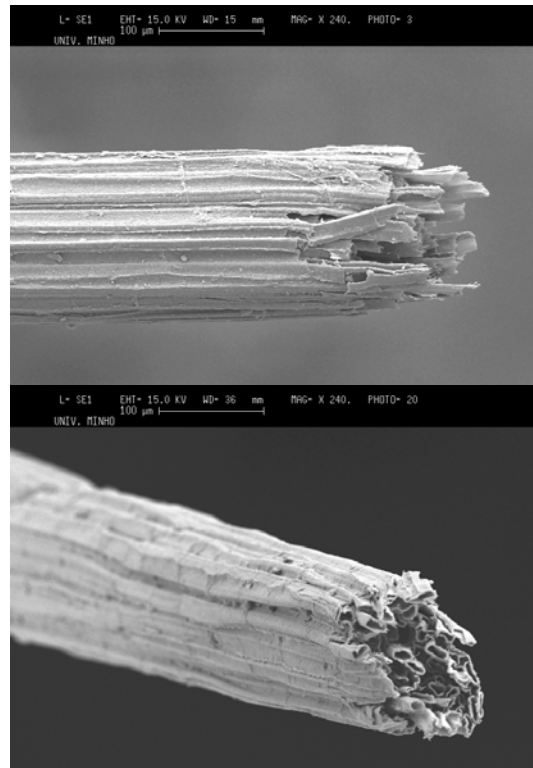


FIGURE 9. Fracture (strain rate of 0.5 min^{-1})
(a) side view (b) angular view

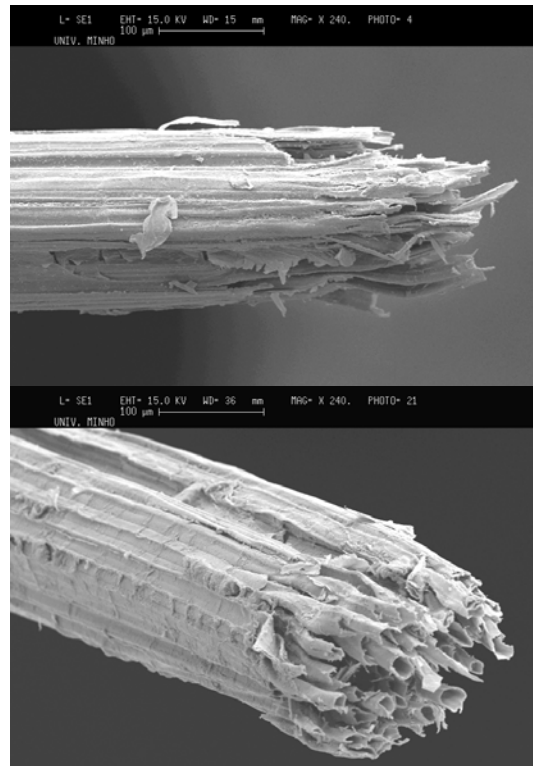


FIGURE 10. Untreated fracture (strain rate of 1 min^{-1})
(a) side view (b) angular view

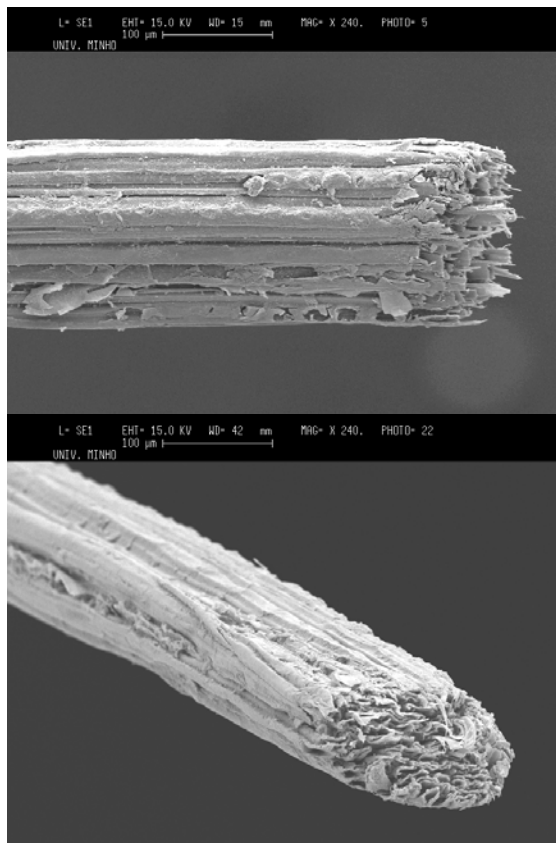


FIGURE 11. Untreated fracture (strain rate of 10 min^{-1})
(a) side view (b) angular view

CONCLUSIONS

Banana fibers have shown high variability along the length and between fibers, which is a characteristic of natural fibers. The standard deviation has been found to decrease with increasing diameter of fibers. The diameter variability had a normal distribution. The tenacity of banana fibers was a function of the testing speed. At lower strain rate, an increase in strain facilitates the amorphous to crystalline sharing of load. At higher speeds however, the faults dominate with catastrophic failure at the highest strain rates. Some of the stress strain curves showed signs of strain hardening. Banana fiber at present is a waste product of banana cultivation and either not properly utilized or partially done so. The extraction of fiber from the pseudostem is not a common practice and much of the stem is not used for production of fibers. The behaviour of the fibers also gives important hint regarding their subsequent behaviour as reinforcement in composites. There is scope for further research to completely characterise the banana fibers and facilitate proper applications in natural fiber reinforced composites.

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