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Bamboo—A functionally graded composite-correlation between microstructure and mechanical strength

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Bamboo is supposed to be one of the best functionally gradient composite materials available. In a piece of bamboo, not only the number of fibres ('vascular bundles') but also the fibre quality varies from outer to inner-most periphery. It has been observed that near the outer periphery, within 1 mm^2 area, the number of fibres is approximately 8 whereas the same at the inner-most periphery is approximately 2. Again the cross-sectional shape of fibre at outer periphery is almost circular (diameter 0.14 mm) and compacted but at the inner-most periphery, a fibre (diameter of major axis 0.93 × diameter of minor axis 0.78 mm) has been sprayed, and contain matrix in it. This structural behaviour causes the variation of tensile strength, e.g., the strength of a fibre at the outer periphery is about 160 kg/mm^2 and the same at the inner-most periphery is only 45 kg/mm^2. It has also been observed that the matrix of bamboo can preferentially be removed from the fibre by alkali treatment. 10% NaOH can remove adhered matrix with little effect on fibres while 20% or stronger alkali reduces the strength of fibre.

1. Introduction

Natural fibres could be a potential substitute for the synthetic fibres in many applications, where low density, low cost, high strength and high modulus are required. Among the known natural fibres e.g. jute, coir, straw, banana etc. used as reinforcement in plastics, bamboo has low density and high mechanical strengths [1–5]. The added incentive for partially or completely replacing glass fibres arises from the low specific gravity of bamboo (approximately 0.9 g/cm^3) compared with that of glass fibres (approximately 2.5 g/cm^3). However, the specific tensile strength of bamboo fibre (about 600 MPa) [6] is considerably less than that of glass fibres (about 1.3 GNm^{-2}). Nevertheless, cost considerations make bamboo an attractive fibre for reinforcement. Bamboo fibre is almost 10 times cheaper than glass fibre. Bamboo is one of the fastest growing grass plants, environment friendly and it is abundantly available in many countries [1].

Bamboo, a natural biomaterial, is attracting more and more attention from researchers owing to its unique biological structure and mechanical performance. Bamboo is natural ligno-cellulosic composite [7] and are composed of fibres (bast fibres in vascular bundles) and matrix (thin walled cells around vascular bundles, vessels and sieve tubes in vascular bundles). Natural bamboo can be taken as unidirectional fibre reinforced composite. The distribution of bast fibres of bamboo along the direction shows a gradient [6]. The fibre distribution is dense in the outer region and sparse in the inner region. This undoubtedly influences its mechanical properties. To be precise bamboo is an ideal example of functionally gradient material. It is also a smart material, which can withstand extreme wind flow from any direction. Since biomaterials have been naturally selected and have evolved for millions of years, a great variety of their rational composite structure could be taken as a reference in the biomimetic design of composite materials [8]. Zeng *et al.* [9] have also pointed out that both plant and animal materials confirm to the 'principle of functional adaptability'.

In the present work the bamboo fibres were separated out from different zone of virgin as well as alkali treated bamboo. A relation between the mechanical strength of virgin and alkali treated bamboo fibres and the microstructure are discussed in this work.

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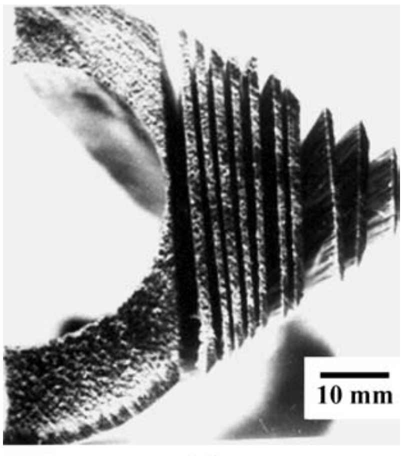
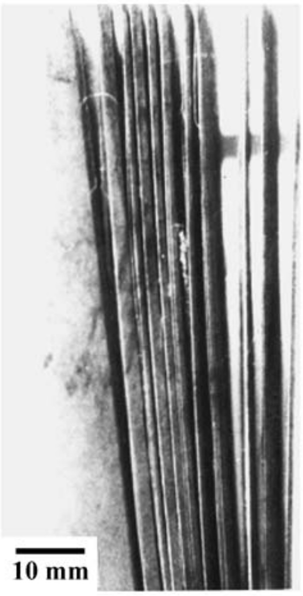


(a)



(b)

Figure 1 Virgin bamboo cut into slices, (a) cross-sectional and (b) longitudinal views.

2. Experimental procedure

The bamboo specimen used in this study was collected from the southern part of West Bengal, India. The particular species is locally known as 'Valki' and it is generally grown in plenty in the plains of this region. The particular specimen under this investigation was in the middle aged group and relatively softer. The specimen was kept for about three months for seasoning. The approximate wall thickness of the samples was 10 mm. For the measurement of tensile strength of fibres at different zone, the bamboo was sliced vertically into 10–11 pieces, each having ~1 mm thickness (Fig. 1a and b). The samples were treated with 10, 20 and 30% NaOH solution for 24 h to dissolve preferentially the matrix portion. From the central position of each slice at least 4 numbers of fibres were taken out very carefully, so that least amount of matrix remains along with the fibres.

2.1. Preparation of tensile test samples (fibre)

Two rectangular pieces of polished steel sheets of $1 \times 7 \times 20$ mm were glued on a piece of hard paper at a distance 50 mm apart from each other. Then two pieces of 7×20 mm hard papers were pasted over the steel sheets so that the fibre would not touch the metal pieces directly. Fibre was then placed over the hard paper covered steel sheets and finally two more pieces of 7×20 mm hard papers were pasted over the fibres. After loading the specimen in the fixture, the longer hard paper which was place below the fiber, was cut at the middle with a pair of scissors. This tensile test specimen was prepared as per the specification No. IS 235:1998 (Fig. 2).

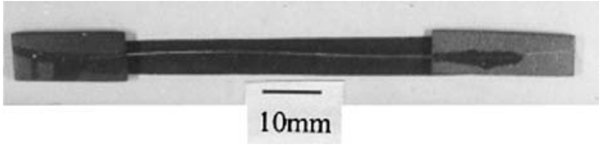


Figure 2 A bamboo fiber for the tensile strength measurement.

2.2. Measurements of tensile test

The tensile test of fibre sample was performed on Hounsefield Tensometer. The sample was gripped in between two flat plates. The standard procedure was followed for measuring the load and strength.

2.3. Microscopic study

Micrographs were obtained in a JEOL 840 Scanning Electron Microscope (SEM). Other than the fractured samples, the specimens were cut and diamond polishing was carried out for obtaining detailed microstructural features. All the specimens were gold coated for SEM studies.

3. Results and discussions

The photograph (Fig. 3) and a SEM micrograph (Fig. 4) of virgin bamboo have been examined for the measurement of cross-sectional dimension of fibres at different distances. The number of fibres has also been counted at different positions. It has been observed that the number of fibre decreases towards the centre of the bamboo. At the extreme outer periphery, there is very little matrix and the number is more than double (8.5:4) that faced

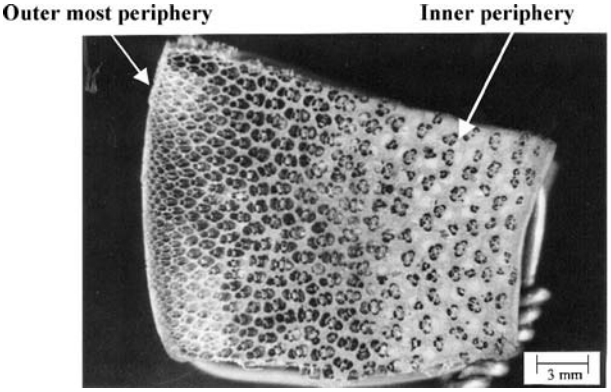


Figure 3 Photograph of transverse section of a piece of bamboo showing the population of fibers.

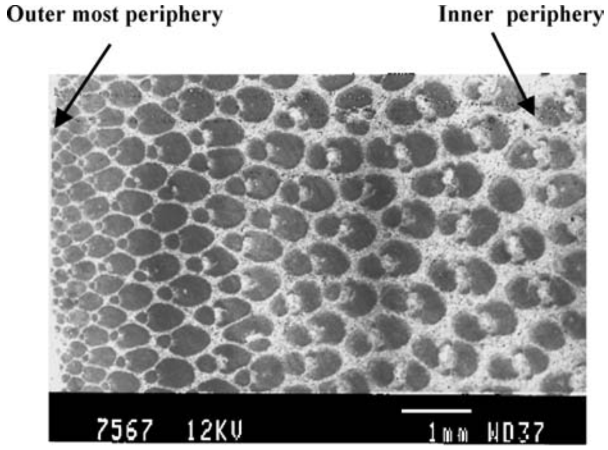


Figure 4 SEM photo micrograph of bamboo showing the population of fibers.

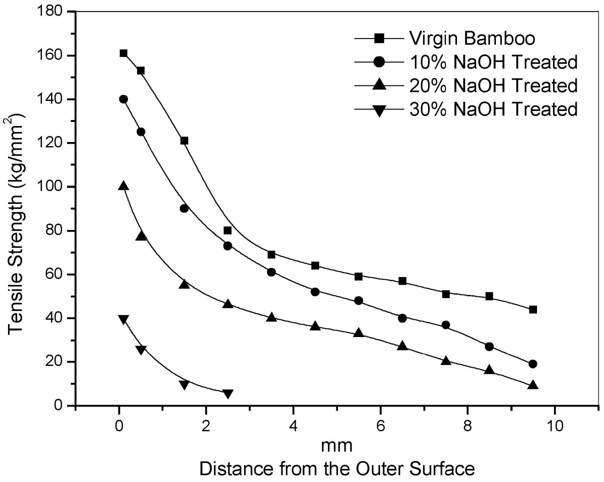


Figure 5 Tensile strength of bamboo fibers, drawn at different places from a piece of bamboo.

immediately after one or two millimetre from the periphery (Table I). Further towards the inside, not only the number of fibres are sparses but also their shape changes drastically. At the outer most regions the cross-section of the fibres is almost circular. Towards the inside it changes to elliptical. Further inside, the shape is elliptical with a circular head which faces towards the periphery. Latter, the circular head separated from the elliptical portion. After the central position fibre divides into four parts. Finally at the extreme inside the four parts of a fibre are separated from each other (Fig. 3). This observation clearly shows that at the outer periphery the fibres are more solid in nature or very little matrix present inside the fibre, whereas towards inside, the fibres contain matrix, which increases with distance towards inner zone. The fibre strength has been reported to be 600 MPa which is almost twelve times more than the matrix; and the Young's modulus of fibre is much higher (46 GPa) than that of the matrix (2 GPa), whereas the density of fibre is 1.16 and the matrix density is 0.67 gm/cm^3 [6]. The average density is 0.8–0.9 gm/cm^3 [10]. We have also observed that tensile strength of fibres varies from $\sim$160 kg/mm^2 at the outer periphery to $\sim$45 kg/mm^2 at extreme inside. It has been observed that drawing fibre from the bamboo matrix is highly critical, e.g. average diameter of bamboo fibre at the outer periphery is 0.14 mm, whereas the same at the inner most region is 0.85 mm (Table I). Therefore, one has to take special care to pull out fibre considering its diameter at different regions. These results also indicate that fibre at the inside contains substantial amount of matrix. It has also been observed that although both fibre and matrix are cellulosic material the fibres are less affected by alkali. This is due to the crystalline nature of cellulose present in fibre. 10% NaOH solution treatment shows little affect on the tensile strength, where as 30% alkali solution reduces the strength drastically (Fig. 5, Table II). That means 10% alkali has little affect on the cellulose in the fibre but 30% has good affect on both types of cellulose. Therefore, for making polymeric composite with bamboo fibre, bamboo should be treated with alkali solution of approximately 10% strength to remove low strength bamboo matrix.

Fibres at the outer region have minimum amount of matrix and are more in number than at the inner region. As a result fibres at the outer region can withstand more tensile or compressive strength than the inner region. This phenomenon helps bamboo to withstand extreme weather.

The fracture of a fibre shows that each fibre, irrespective of its position, contains many fibrils (Fig. 6). The cross-section of fibrils are observed to be almost pentagonal and they are arranged in honeycomb nature, separated by thin walls of matrix (Fig. 7). The wall thickness ranges between 1 to 5 μm and the width of fibrils varies from 10 to 20 μm. Again a fibril contains many continuously elongated cellulose staggered in twisted nature, just like a metal rope formed by many twisted wires

TABLE I Number and cross sectional feature of fibres on the different regions of the virgin bamboo

Sample position (mm from outer periphery)	Area (1mm^2)	Average no. of fibres	Size of elliptical fibres, major and minor axis (mm)	Comments
0.5	1	8.5	0.14 × 0.14	The fibre is nearly circular in cross section.
1.5	1	4.0	0.9 × 0.5	Elliptical with a head
2.5	1	3.1	1.0 × 0.52	Elliptical with a head
3.5	1	2.3	1.14 × 0.57	Elliptical with a bigger head
4.5	1	2.2	1.10 × 0.57	Elliptical with a bigger head
5.5	1	2.2	1.00 × 0.67	Elliptical with separated head
6.5	1	1.66	1.10 × 0.67	Four pieces joined together
7.5	1	1.95	1.14 × 0.81	Four pieces joined together
8.5	1	2.2	0.93 × 0.78	Four pieces separated.

TABLE II Tensile test results of fibres pulled out from different regions of bamboo samples: (a) virgin bamboo, (b) 10%, (c) 20% and (d) 30% NaOH treated bamboo

Sample position (mm from outer periphery)	Average tensile strength (kg/mm^2)			
	Virgin bamboo fibre	10% NaOH treated fibre	20% NaOH treated fibre	30% NaOH treated fibre
0.1	161.0	140.0	100.0	40.0
0.5	152.7	125.4	76.9	25.8
1.5	121.4	90.0	54.5	10.2
2.5	79.7	72.7	46.2	6.1
3.5	68.9	61.1	40.0	–
4.5	63.8	52.2	35.7	–
5.5	58.5	48.4	33.3	–
6.5	56.8	40.0	28.6	–
7.5	50.5	37.1	20.4	–
8.5	49.6	26.5	15.8	–
9.5	44.2	19.1	8.5	–

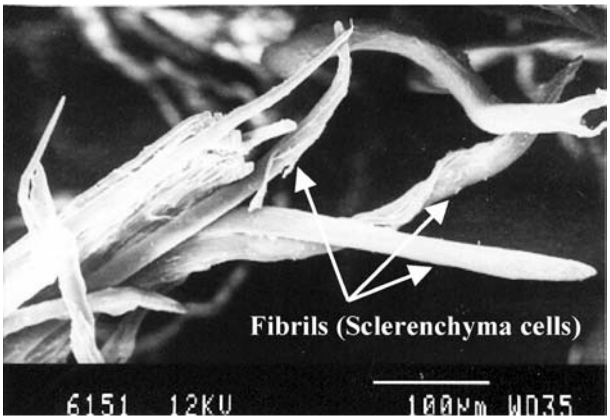


Figure 6 Fractured of a bamboo fiber shows the fibrils (sclerenchyama cells).

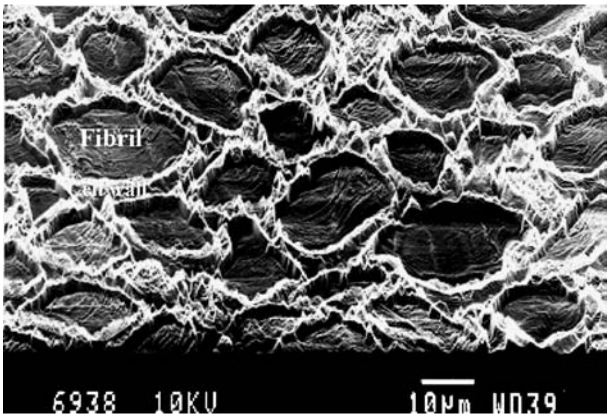


Figure 7 Topographical SEM micrograph shows the fibrils (sclerenchyma cells) and the wall thickness between the fibrils.

(Fig. 8) [11]. Thus a bamboo fibre contains several fibrils which are composed of many twisted and elongated cellulose. These structural phenomena are responsible for a small fibre of ∼1 cm length for bending 180° or more.

This matrix of bamboo is highly porous and the pores are also observed to be more- or- less hexagonal (Fig. 9). Between two fibres the width of matrix varies from 100 to 500 μm and the fibre width range is in between 0.1 to 1.14 mm (Fig.7).

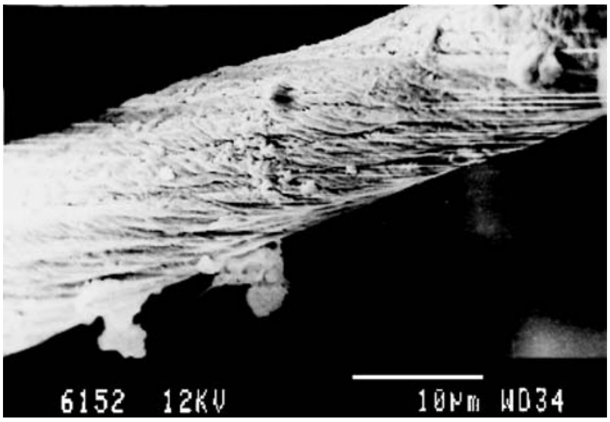


Figure 8 Microstructure of single fibril (sclerenchyma cell).

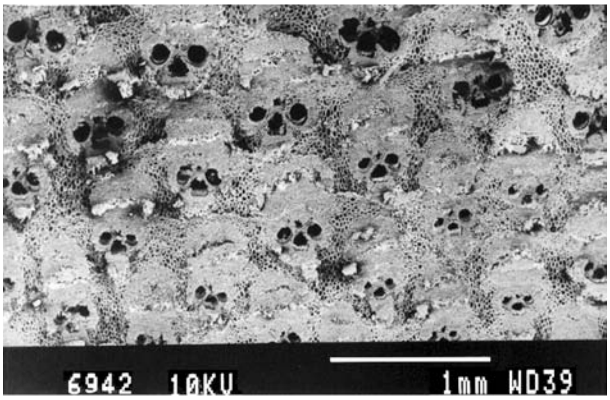


Figure 9 The micrograph shows the nature of fibers at inner and outer periphery of bamboo.

Therefore, a piece of bamboo contains thousands of fibres. It has also been observed that there are pores in the matrix, in between fibrils as well as in between fibres. These porosity of different sizes and shapes, perhaps help a bamboo to absorb the stresses during adverse natural conditions. Hence, the geometry of bamboo's longitudinal profile has a macroscopically functionally graded structure, which can withstand severe environmental wind loads [6, 12].

4. Conclusions

The microstructure and the tensile strength of bamboo fibers have correlated to evaluate the unique characteristic of bamboo to withstand the sever weather conditions. The experimental results can be summarized as follows:

1. The number of fibers are more and dense at outer than the inner periphery.
2. The fibers near the outer periphery are almost circular, whereas the same at the inner portion are elliptical type. At the inner most zone the fibers are separated into four parts and much bigger in size.
3. Each fiber is composed of several fibrils (sclerenchyama). The fibrils are arranged like a twisted rope.
4. As the fibers at the outer periphery are dense or have little/no matrix, are almost four times stronger than the fibers at the inner most zone.

5. Weaker matrix can be removed by alkali treatment. 10% NaOH solution can preferentially remove with little effect on the fibers. 20 or 30% NaOH solution dissolves matrix as well as substantial parts of the fibers.

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