Extraction of Bamboo Fibers and Their Use as Reinforcement in Polymeric Composites

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ABSTRACT: Few investigations have been carried out with bamboo fibers despite its high strength, biodegradability, and low cost. The overall objective of this work was to investigate fiber extraction from bamboo and the use of these bamboo fibers as reinforcement in polymeric composites. A combination of chemical and mechanical methods was used for the extraction of bamboo fibers. Conventional methods of compression molding technique (CMT) and roller mill technique (RMT) were explored for the mechanical separation. Fiber population from both the techniques were characterized. Mechanical properties of the fibers also were evaluated. Bamboo fibers obtained from CMT and RMT were used to make unidirectional composites of polyester. High values of tensile strength were observed in all the composites. The predominant mode of failure for the composite was shown to be the cracking of the fiber–matrix interface. Quantitative results from this study will be useful for further and more accurate design of bamboo reinforced composite materials. © 2000 John Wiley & Sons, Inc. J Appl Polym Sci 76: 83–92, 2000

Key words: natural composites; bamboo; fiber extraction

INTRODUCTION

Natural fibers from plants such as jute, bamboo, coir, sisal, and pineapple are known to have very high strengths and hence can be effectively utilized for many load-bearing applications. These natural fibers have a special advantage in comparison to the synthetic fibers, as they are available in abundance. In addition, they are biodegradable and renewable resources. A significant body of literature is available on reinforcement of polymers with natural fibers.[1–8] Development of such composite materials involves investigations in four broad areas: (a) delignification, separation, and isolation of fibers; (b) characterization of these fibers; (c) studies on the interaction of the fibers with polymers; and (d) evaluation of the composite properties. A major part of research work has concentrated on the two areas of interaction with polymer matrix and on the properties of composites.[3,6] Most of the studies have concentrated on natural fibers, such as jute and sisal, because of their wide availability.

Few investigations have been carried out with bamboo despite its high strength, biodegradability, and low cost. Several forms of bamboo can be used for reinforcement, such as the whole bamboo, sections, strips, and fibers.[1–4] These various forms of bamboo have been used in applications such as low rise construction to resist earthquake and wind loads, bamboo mat composite in combination with wood for beams, and shear wall in low-rise construction. In addition, bamboo fibers

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can be used as reinforcement with various thermoplastic and thermoset polymers.

Bamboo culm has a unique structure, which resembles that of a unidirectional fiber-reinforced composite with many nodes along its length.[9,10] It consists of cellulose fibers, oriented along the bamboo culm, embedded in a ligneous matrix. The current availability of bamboo fibers is limited because very few efforts have been devoted to the extraction of the fibers from bamboo. Because of the nonavailability, only a handful studies are available on the properties of these fibers and their use as reinforcement for polymers.[1,2] However, the available data on bamboo suggest that there is a very good potential for bamboo fibers to be used as reinforcements in polymeric composites. Such composites will have a good potential for use as consumer durable goods and for less-intensive load-bearing applications.

Structure and mechanical properties such as modulus and strength have been investigated for bamboo. These studies include testing of the whole bamboo as well as sections, strips, and fibers of bamboo. Amada et al.[10] examined the structure variation in bamboo with cross section and height. The fraction of cellulosic fibers varied from 15–20% to 60–65%. Tensile strength and modulus varied from 100 to 600 MPa and from 3 to 15 GPa, respectively. The variation in mechanical properties was shown to be a function of the relative fraction of fibers in the specimen. Nogota and Takahashi,[9] exploring bamboo for biological applications, evaluated tensile strength to be in the range of 350–900 MPa. In both the above studies, sections of bamboo were obtained from different positions with respect to height and cross section. Bangarshetti and Rao[11] studied the mechanical properties of bamboo by testing fiber bundles of 1–2 mm diameter. The results of this study confirm the variation of mechanical properties of bamboo along the length and across the cross section. Additionally, the variation of mechanical properties of fibers with different displacement rates was evaluated and shown to be small.

Jain et al.[1] studied the mechanical properties of bamboo fiber–reinforced epoxy composites with different orientation of fibers. Shin et al.[4] fabricated and tested laminated composites of bamboo strips and epoxy resins, reporting a strength that is superior to that of glass fiber–reinforced epoxy composites. It was claimed that the epoxy resin can penetrate the bamboo structure, leading to improvement in properties. At the same time, durability of bamboo in composite was shown to be superior to that of bamboo. Composites of bamboo strips and poly(methyl methacrylate) were studied by Bashar et al.[3] Tensile strength was improved, especially in the presence of additives. The potential of bamboo as reinforcement has been established from all the studies mentioned above. However, the use of bamboo fibers or fiber bundles in composites has been very limited when compared to other natural fibers.

The overall objective of this work was to investigate the fiber extraction from bamboo strips and the use of these bamboo fibers as reinforcement for polymers. A combination of chemical and mechanical methods was used for the extraction of bamboo fibers. Conventional methods of compression molding technique (CMT) and roller mill technique (RMT) were explored for the mechanical treatment. The bamboo fibers were characterized and tested for structure and mechanical properties. Subsequently, bamboo–reinforced polyester composites were processed. The composite specimen were characterized to evaluate the reinforcing role of bamboo fibers.

EXPERIMENTAL

The description in this section is divided into four parts. First, delignification of bamboo is considered, followed by a summary of mechanical treatment given to the bamboo strips. After the separation of fibers, the procedure for making the composite specimen is discussed. Finally, the characterization of fibers and composites is described.

Delignification

The chemical constituents of natural fibers can be classified into cellulose and lignin.[12] Lignin plays the role of binding the fibers of cellulose. Alkaline treatment is one of the standard procedures in the pulp and paper industries for lignin removal. Lignin can be dissolved in sodium hydroxide (NaOH) solution and then the cellulosic fibers can be extracted with relative ease.[13] NaOH causes dissolution of lignin by breaking it into smaller segments whose sodium salts are soluble in the medium.

In the present work, fibers were obtained from commercially available strips of bamboo. The width of strips were from 1.5 to 1.75 cm and the thickness was in the range of 0.65–0.75 mm. At present, very few guidelines are available regarding the alkaline treatment of bamboo and its effect on obtaining the bamboo fibers. The normality of NaOH solution and the time for soaking have to be chosen on the basis of a series of experiments to maximize the ease of fiber separation. A very strong NaOH solution and a long soaking time will lead to greater lignin dissolution. In the present work, alkaline treatment was used only as a tool for facilitation of fiber extraction. Therefore, the parameters were chosen to optimize separation of bamboo fibers, rather than for maximum lignin removal. The total lignin content of bamboo was found to be 37%, using the analytical method of acidic treatment.[12]

The bamboo strips were soaked in 0.1 N NaOH solution for different periods. After a series of experiments, 72 h was finalized as the duration of chemical treatment, based on ease of fiber separation. Weight loss for bamboo strips was 18% after 72 h of alkaline treatment, which is due to the loss of ligneous material. After removal from the NaOH solution, the strips were washed with water. Subsequently, the strips were dried at room temperature for 1 h and then were subjected to mechanical processes for completion of fiber separation.

Mechanical Techniques for Fiber Separation

A combination of chemical and mechanical processes is used in pulp and paper industries for pulping. After the chemical treatment, discs and rollers are used as means of supplying mechanical energy to facilitate fiber separation.[13] In this work, two methods were explored for mechanical separation of bamboo fibers from the alkaline-treated strips; CMT and RMT, both of which are widely used to process polymers and composites for a variety of applications. Mechanical separation processes have to be operated so that sufficient stresses are generated to complete the process of separation of the fibers. However, a very high level of stresses will cause abrasion and fracture of the fibers. In this work, both the methods were optimized to have ease of fiber separation with negligible deterioration in fiber properties.

In the CMT, a bed of strips was placed between two flat platens and subjected to a constant load of 10 tons. Compression time and the starting bed thickness are important parameters that have to be optimized to obtain good quality fibers. After a series of trials, a compression time of 10 s was chosen for the bamboo fiber separation. The starting thickness of the bed of alkaline-treated strips in the CMT was kept at 1.25–2 cm. In the RMT, the bamboo strips were forced between two rollers, of which one was fixed and the other was rotated. The diameter of rollers was 7 cm, and the separation between the rollers was 0.1 mm for a strip thickness of 0.75 mm. The speed of the rotating cylinder was 60 rpm. Both these methods yield flattened strips of bamboo. These alkaline- and mechanical-treated strips can be easily separated into individual fibers.

With both the above methods, strips of varying lengths can be processed. In this work, three different lengths of strips were processed in order to study the relative effectiveness of the techniques with strip size. It was found that the RMT was inappropriate for smaller strip size (<8.5 cm). This limitation was due to the diameter of the rollers. Similarly, compression mold size was the limiting factor in deciding the maximum strip length that could be processed in CMT. The length of bamboo fibers obtained in this work was in the range 8–20 cm. This range was appropriate for getting the bamboo fibers for applications as reinforcement for chopped-strand mat composites.

Mechanical properties of the fibers were evaluated to compare the effect of two techniques on the quality of bamboo fibers extracted. The details of mechanical testing are described in the section Fiber and Composite Testing. Scanning electron microscopy (SEM) was used to observe the surface of fibers. The regularity of fibrils and surface damage was examined for fibers obtained from both the techniques. One of the objectives of this work was to show that the above two mechanical techniques (CMT and RMT) are reliable in producing bamboo fibers. These bamboo fibers should exhibit consistent properties by themselves and when used as reinforcement.

Composite Preparation

To assess the reinforcing quality of bamboo fibers, unidirectional composites were made using polyester as the matrix. The polyester used was a room temperature curing system with Cobalt Narthanyte as hardener (polyester : hardener, by weight, 2.5 : 1). CMT was used to process the composite specimens. A bed was prepared as preform by laying unidirectional bamboo fibers. Subsequently, an appropriate amount of polyester resin was impregnated into the bed. The impregnation and polymerization sequence has to be op-

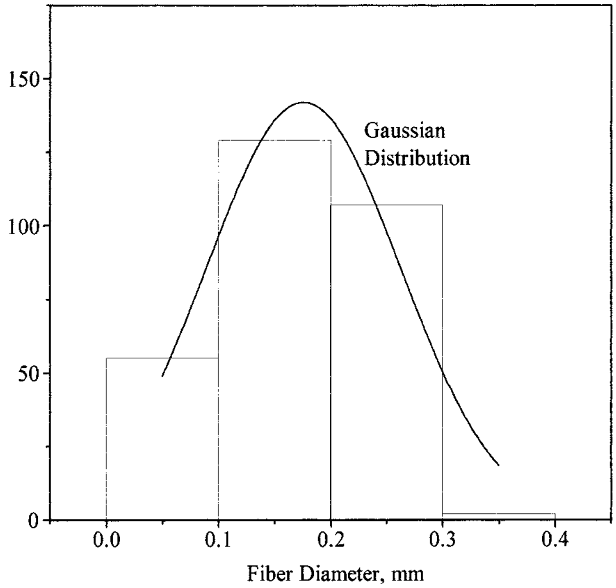

Figure 1 Diameter distribution for fibers obtained from CMT. See Table I for statistics.

timized to obtain void-free composites. However, fiber deformation and movement should be minimal to yield good quality, unidirectional fiber composites. Therefore, the time of impregnation, time of curing, and compression pressure are the important parameters to be considered to obtain composite specimens for further testing. The setting time for resin was 20 min. However, the composite specimens were cured for 24 h, and the pressure was maintained during the impregnation step. Using the same program, unreinforced polyester samples also were prepared.

Fiber configuration and volume fraction are two of the most important factors that affect the properties of the composite. In this work, configuration was limited to unidirectional, continuous bamboo fibers, and composite samples were prepared with different volume fractions of bamboo fibers. In addition, fiber populations with different diameters and fibers obtained from both the CMT and RMT were used to process the composite.

Fiber and Composite Testing

It is important to know the properties of fibers, which control the limiting values of the mechanical properties of the composite. The fiber properties are also a good indication of the consistency of the fiber population obtained from different processes. The tensile strength of bamboo fibers was measured to compare different sets of fibers. The objective of mechanical testing of fibers was to calculate ultimate strength of the fibers and not to evaluate of the stress–strain curves. Therefore, a simple assembly of fibers was used to evaluate the strength of the bamboo fibers. A set of five fibers of equal length were mounted on a grip and tested at a constant displacement rate of 0.05 mm/min. The ultimate load carried by the set of fibers and the ultimate extension before failure were measured. The tensile strength was calculated from the ultimate load and the cross-sectional area of fibers.

The unidirectional composite specimen were made as per the ASTM Standard D790M-86. The length, width, and thickness of specimen were 72, 12, and 2 mm, respectively. The volume fraction of fibers in the various test specimens varied from 15% to 30%. A three-point bend test with a span length of 50 mm was used to determine the flexural strength and flexural modulus. Failure load and slope at failure were obtained from the load-deflection curves[14] and the strength and modulus were calculated as follows:

$$\text{Flexural strength} = \frac{1.5wL}{bd^2}$$

$$\text{Flexural modulus} = \frac{\text{slope} \times L^3}{4bd^3}$$

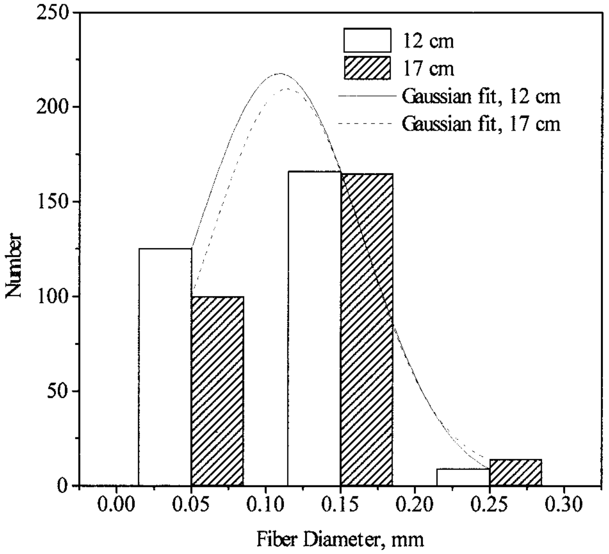

Figure 2 Distribution of fiber diameters for fibers obtained by RMT (for two different initial bamboo strip length). See Table I for statistics.

Table I Distribution of Fiber Diameters and Their Statistics

	Statistics of Fiber Diameters (mm)	
	Mean	Standard Deviation
Fiber source		
CMT	0.14915	0.07052
RMT (length, 12 cm)	0.08987	0.04149
RMT (length, 17 cm)	0.09685	0.04385
	Parameters from the Gaussian Distribution Fit	
	Center	Width
Fiber source		
CMT	0.17577	0.17227
RMT (length, 12 cm)	0.10887	0.11183
RMT (length, 17 cm)	0.11393	0.10199

where w is the ultimate load, L is the length of the specimen, and d is the thickness of the specimen.

All the tests for fiber and composite characterization were conducted on an Instron Universal Testing Machine (Model 4301; Canton, MA). The fractured surface of composite specimen was observed using an SEM.

RESULTS AND DISCUSSION

Initially, the consistency of fibers was examined for geometrical variations. The variations of diameter for fibers obtained from CMT and RMT were examined. The distributions of diameter for a representative set of fibers are shown in Figures 1 and 2 for CMT and RMT, respectively. The statistics for the diameter distributions are given in Table I. In all the cases, the means and standard deviations agree well with the centers and widths as calculated with a Gaussian distribution fit.

When CMT was used for extraction, the diameters of fibers varied from 0.05 to 0.4 mm. The highest concentration of fiber diameter was between 0.15 and 0.25 mm. Fibers with diameters of 0.05–0.15 and 0.25–0.40 mm were present in very low concentrations. For the fibers obtained from the RMT, the highest concentration of fibers was in the range of 0.05–0.10 mm. The fibers of diameter less than 0.05 mm were in low concentration. Finer fibers were obtained from this technique when compared to the fibers obtained from the CMT. Figure 2 shows diameter distribution (fibers extracted by RMT) for two initial strip lengths. There is no significant effect of initial strip length on the diameter variations of the fibers obtained after mechanical separation. Since the load application in both the techniques is only in the direction perpendicular to length, fibers with the same length as initial strip length were obtained.

The fibers obtained by CMT were larger in average diameter than those obtained from RMT. This result can be explained by the difference in the mechanisms of separation between the two techniques. In the CMT, the compressive stresses will alone exist. However, in the RMT a combination of compressive and shear stresses will come into play. Therefore, for simple configurations that were used in this work, principal stresses are likely to be higher for the RMT. A spread ratio can be defined as the ratio of the widths of strip after and before the mechanical treatment. The spread ratios of bamboo strips passed through RMT were always higher than those passed through CMT. Therefore, the pressure on bamboo strips passing through rollers is considerably higher than the pressure on the bamboo strips in CMT.

The standard deviation of the fiber diameters as obtained by CMT was larger than that obtained from RMT. Also, diameter variation for a single fiber along its length was higher for fibers obtained by CMT. The higher diameter variation in CMT can be explained by considering the details of pressure application in the two techniques. In RMT the length of the strip passes through uniform pressure conditions. On the other hand, the whole length of strips were pressurized at once in CMT. The spatial variation in local pressure in CMT would lead to variation in stresses and hence gives a higher standard deviation.

The mechanical strength of the fibers was evaluated using the experimental procedure described in previous section. As an example, mechanical strength distributions for the fibers obtained by CMT and RMT are given in Figure 3. The statistical comparison of fiber strengths for the fibers obtained by CMT and RMT is given in Table II. The tensile strength of specimens from different parts of a bamboo cross section was

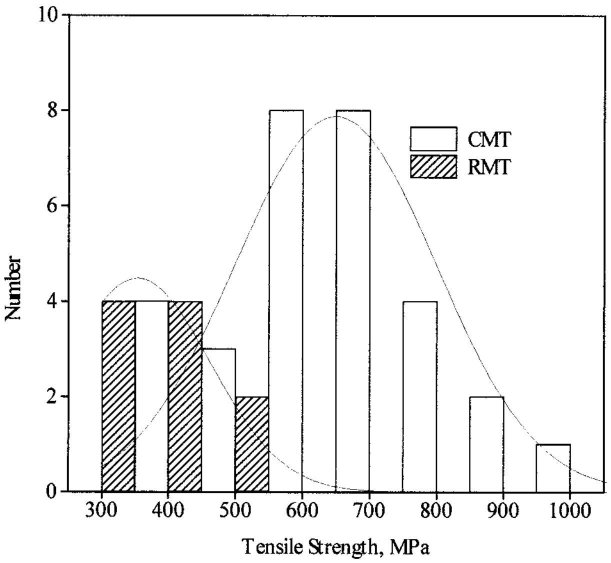

Figure 3 Tensile strength distribution for fibers obtained from different techniques. See Table II for statistics.

shown to vary between 100 and 800 MPa by Nogata et al.[9] They calculated theoretical strength of cellulosic fibrils as 810 MPa based on the rule of mixtures. From Figure 3, the maximum and average strengths for bamboo fibers from CMT was found to be 1000 and 645 MPa, respectively. However, the tensile strength of fibers obtained from RMT was considerably lower with maximum and average tensile strengths of 480 and 370 MPa, respectively. The fibers from RMT have lower tensile strength as well as lower variation in tensile strength when compared to the fibers obtained from CMT. It should be noted that fibers from RMT also had lower average diameter as well as lower variation in diameter.

We observed that the fibers with higher diameters (obtained from CMT) had higher strength compared to the fibers with lower diameters (obtained from RMT). We note that this behavior is different from what is generally observed in fibers made up of brittle materials, such as glass or metals.[15] The higher strength in smaller fibers in brittle materials is attributed to the lower density of flaws in an otherwise homogeneous material. The opposite effect that we observe in the natural fibers may be attributed to the difference in the structure of natural or polymeric fibers in comparison to the brittle fibers described above. The structure of natural fibers is characterized by a high slenderness ratio, i.e., high surface-to-volume ratio. This permits the building of structures with high local curvature (allowing for a greater twist), which allows axial strength to develop because of high interfiber friction. The probability of interaction between fibrils is higher in fibers of larger diameters than with fibers of lower diameters. Higher strength is expected from a fiber with a larger diameter. Thus, the fibers isolated from CMT, which had higher diameters, had higher average strengths in comparison with the fibers isolated from RMT, which had lower diameters. Figure 4 shows average tensile strength as a function of average diameter. The larger the average diameter was, the higher was the average tensile strength.

The surface characteristics of the fibers obtained from the two techniques were examined using SEM. The micrographs of fibers obtained from CMT and RMT at two different magnifications are shown in Figure 5. It can be seen from the figure that the extracted fiber is made up of fibrils of cellulose bonded by ligneous material. The size of each fibril is 5–15 μm. The fibers of RMT have organized fibrils along the length of a fiber. On the other hand, fibers from CMT exhibit periodic positions of attachment of resin material and void spaces. These pictures show that fibers from RMT have a more regular geometry of fibril arrangement than the fibers from CMT. However, as was shown earlier, the mechanical properties of fibers from RMT are inferior to those obtained from CMT.

Table II Statistics of Tensile Strength Distribution for Fibers Obtained with Different Techniques

	Statistics of Tensile Strength (MPa)	
	Mean	Standard Deviation
Fiber source		
CMT	644.8	145.5
RMT	370.1	71.8

	Parameters for the Fit with Gaussian Distribution	
	Center	Width
Fiber source		
CMT	649.0	299.6
RMT	362.5	145.8

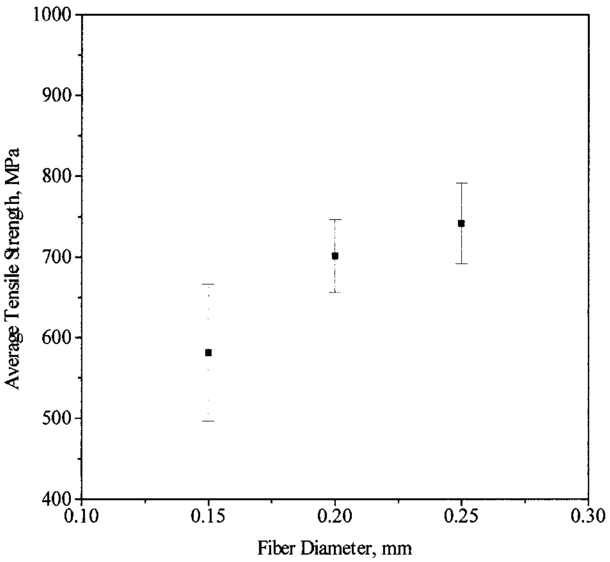

Figure 4 Average tensile strength as a function of fiber diameter.

One of the factors that could lead to inferior mechanical properties can be internal damage (microcracking in fibrils or ligneous binding material) in fibers from RMT despite having arranged topology. Another set of results, which support this factor, is the effect of fiber diameter on the tensile strength of fibers, regardless of mechanical treatment used for fiber separation. Since the finer fibers are obtained due to higher magnitude of local stresses, these fibers might have a larger density of internal defects. Hence, the fibers obtained from RMT are finer in diameter and more regular in terms of the arrangement of fibrils but exhibit inferior mechanical properties.

Figure 6 shows elongation at break for the fibers obtained from CMT and RMT techniques. The overall distribution of elongation is similar for the fibers, irrespective of the technique of mechanical treatment. This observation also supports the hypothesis of internal damage in the case of RMT fibrils. It is hypothesized that slippage occurs between fibrils due to the internal damage. Due to the slippage, the load carrying capacity of the fibers is reduced, leading to a lower tensile strength. However, the fiber elongation before macroscopic failure for fibers with internal damage is the same as in case of stronger fibers with less internal damage.

Bamboo fibers obtained from both CMT and RMT were used to process composite specimen, as described in the previous section. Composite samples were obtained with volume fraction as high as 25%. As the results from fiber separation show, variation in diameter size or tensile strength is an important factor in the extraction of bamboo fibers. To study the effect of geometrical variations of fibers on composite properties, fiber populations with different diameters were separated and used for processing composites. Hence, the three variables in our study of composite properties were fiber separation technique, fiber volume fraction, and diameter of fibers. The details of specimen analyzed in this work are given in Table III.

The flexural strengths and moduli of various composite specimen are given in Figure 7. The strengths of composites (75–175 MPa) are significantly higher than that of polyester (20 MPa) in all the cases. The flexural strength of polyester can be improved by a factor of 3 to 8 by using bamboo reinforcement. The flexural moduli of composite with CMT fibers increased monotonically with increase in the volume fraction of fibers. However, flexural moduli of composites with RMT fibers were almost the same as that of the polyester.

Shin et al.[4] studied the bending modulus and flexural strength of composites made of flattened bamboo strip–epoxy resins. The mean tensile strength was evaluated to be 203 MPa. Similarly, Jindal[2] evaluated bamboo fiber–epoxy composites (fiber diameter: 0.5–0.8 mm) with different stacking patterns in a laminate. Depending on the orientation sequence in the laminate, the strength varied from 260 to 390 MPa. Since these studies did not focus on the effect of volume fraction and fiber diameter on the mechanical properties of bamboo fibers, the results from this work can not be compared. However, if the tensile

Table III Details of Composite Specimen

Sample	Mechanical Treatment	Volume Fraction of Bamboo Fibers (%)	Average Diameter of Bamboo Fibers (mm)
cmt0845	CMT	8	0.45
cmt1045	CMT	10	0.45
cmt1515	CMT	15	0.15
cmt1525	CMT	15	0.25
cmt2040	CMT	20	0.4
rmt1515	RMT	15	0.15
rmt1525	RMT	15	0.25
Polyester	NA	0	NA

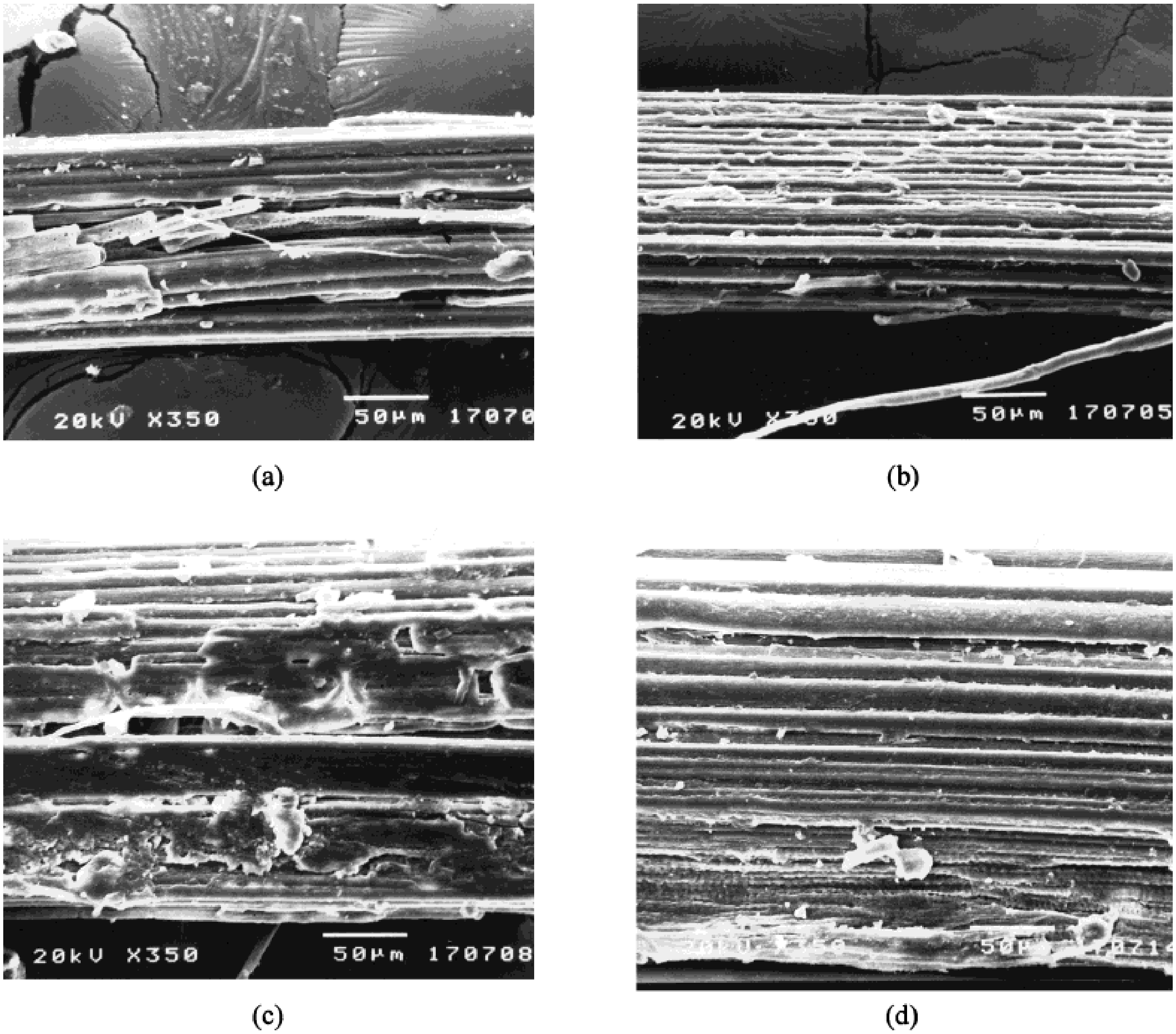

Figure 5 SEM micrographs of bamboo fibers. (a) CMT fiber with 0.1-mm diameter; (b) RMT fiber with 0.1-mm diameter; (c) CMT fiber with 0.15-mm diameter; (d) RMT fiber with 0.15-mm diameter.

strength of epoxy is assumed to be 60–90 MPa,[16] the reinforcement obtained in bamboo–polyester composites is at least as good as that obtained with bamboo–epoxy composites. Roe and Ansell[5] examined the mechanical properties of a jute–polyester composite. The tensile strength and Young's modulus for the polyester were 20 MPa and 4 GPa, respectively. Jute fiber–reinforced composite, with 15–30% fiber, exhibited tensile strength of 70–130 MPa and Young's modulus of 10–20 GPa. These results compare favorably to the reinforcement achieved with bamboo fibers in this work.

The fibers obtained by CMT and RMT lead to the same level of reinforcement as far as the flexural strength of the composite is concerned. However, the flexural modulus of composite specimens made with RMT fibers is considerably less than that of those made with CMT fibers. At present, reliable measurements for moduli of RMT and CMT fibers have not been done. The qualitative trend from the mechanical properties of fibers suggested lower modulus for the fibers obtained from RMT. Additionally, composite specimens with lower volume fraction of CMT fibers also exhibited lower flexural modulus. The composite moduli can be approximately described using rules of mixtures.[16] Depending on the moduli of fiber and matrix and the volume fractions of fibers, the composite modulus can be estimated.

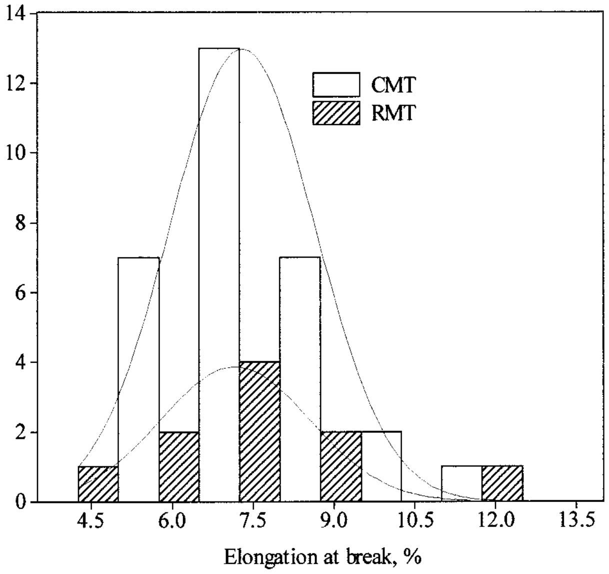

Figure 6 Distribution for elongation at break for fibers obtained from different techniques.

The modulus of a composite sample will be lower if either of the fiber modulus or fiber volume fraction is lower. The variation in moduli of composites observed in this work can be explained. For example, the modulus data of composites made with CMT fibers was extrapolated based on the following linear rule of mixture:

$$E_c = v_f E_f + v_m E_m$$

where E_c, E_f, E_m are moduli of composite, fiber, and matrix, respectively, and v_f and v_m are the volume fractions of fibers and matrix, respectively. Using linear regression, the modulus for fibers was estimated to be 27 GPa. Nogota et al.[9] estimated the modulus of 100% bamboo cellulose fibers to be 55 GPa based on relative amounts of cellulose fibers and lignin matrix. Therefore, the results of this study can be qualitatively justified.

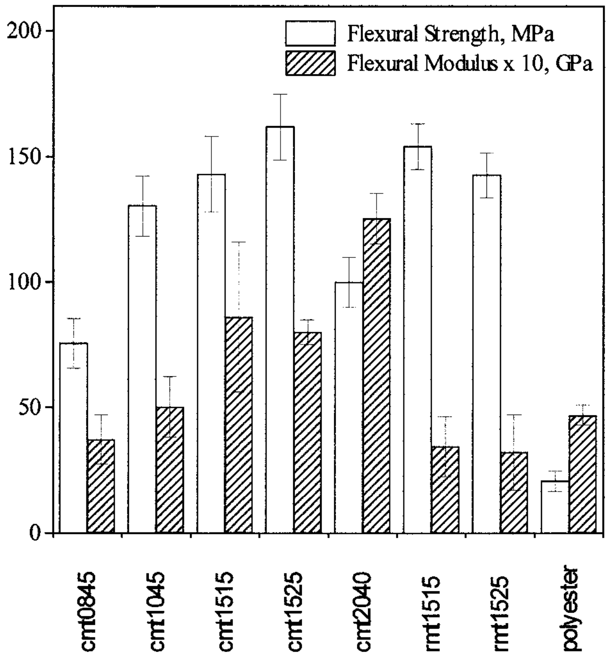

Figure 7 Tensile strength of different composite specimen. See Table III for description of the specimen.

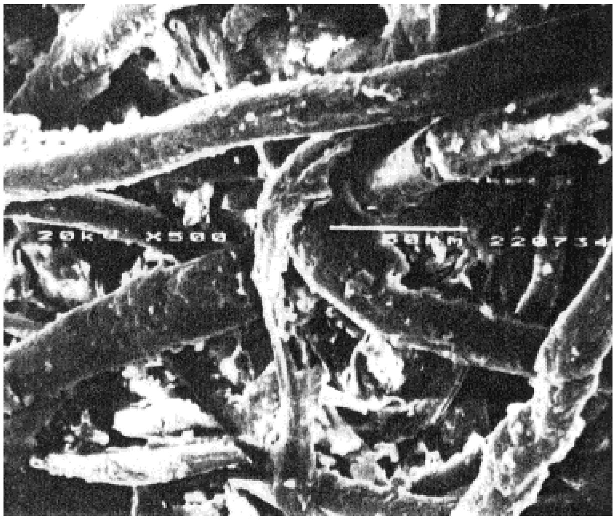

Figure 8 SEM micrograph of fractured polyester–bamboo composite specimen.

The composite specimen processed with both CMT and RMT fibers were examined by the SEM after failure. An sample micrograph is shown in Figure 8. In all the fractured specimens, large amounts of fiber pullout were observed. The predominant mode of failure was the failure of the fiber–matrix interface. Hence, the flexural strengths of composite with similar volume fraction was independent of fiber mechanical properties, and therefore, of the mechanical treatment method used to obtain fibers.

CONCLUSIONS

Despite having shown a good potential, bamboo fibers have not been studied as reinforcements in polymeric composites because of nonavailability. This work focused on the extraction of bamboo fibers from strips using two prevalent mechanical techniques in combination with the alkaline treatment. Fiber population from both the techniques, RMT and CMT, were characterized. CMT yielded fibers with larger average diameters and larger deviations when compared to fibers from RMT. The diameter variation could be justified based on the expected level of stresses in CMT and RMT. Subsequently, tensile strengths of fibers were evaluated. Average tensile strength and the deviation were larger with the fibers obtained from CMT. Also, the diameter of the fiber was larger, the higher the tensile strength. Such results will be of great relevance when choosing mechanical treatments for making a chopped-strand mat of bamboo fibers for an eventual application.

Bamboo fibers obtained from CMT and RMT were used to make unidirectional composites of polyester. The improvement in tensile strength was the same with fibers extracted using both the mechanical techniques. Hence, the difference in mechanical properties of fibers from the two techniques did not affect the strength of the composites. The predominant mode of failure for the composite was the fiber–matrix interface cracking. These results demonstrate that bamboo fibers can be extracted consistently and used successfully for reinforcements in polymeric composite. Through this study, quantitative results are available for further and more accurate design of bamboo-reinforced composite materials.

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REFERENCES

1. Jain, S.; Kumar, R.; Jindal, U. C. J Mater Sci 1992, 27, 4598.
2. Jindal, U. C. Proc of International Bamboo Workshop, 1988, 231–234.
3. Bashar, K. S.; Khan, M. A.; Idriss Ali, K. M. Polym Plastic Technol Eng 1996, 35(4), 581.
4. Shin, F. G.; Zheng, W. P.; Yipp, M. W. J Mater Sci 1989, 24, 1481.
5. Roe, J.; Ansell, M. P. J Mater Sci 1985, 20, 4015.
6. Ghosh, P.; Ganguly, P. K. Plastics, Rubbers and Composites Processing and Applications, 1993, 20(3), 171.
7. Zhu, W. H.; Tobias, B. C.; Coutts, R. S. P. J Mater Sci Lett 1995, 14(7), 508.
8. Kuruvilla, J.; Sabu, T.; Ravithran, C.; Brhmakumaar, M. J Appl Polym Sci 1993, 47(10), 1731.
9. Nogota, F.; Takahashi, H. Comp Eng 1995, 5(7), 743.
10. Amada, S.; Ichikawa, Y.; Munekata, T.; Nagase, Y.; Shimizu, H. Composites Part B 1997, 28B, 13.
11. Bangarshetti, P. S.; Lakshmana Rao, C. National Symposium on Structural Mechanics, Bangalore, 1994.
12. Welcher, F. J., Ed. Standard Methods of Chemical Analysis; Van Nostrand: Princeton, NJ, 1963.
13. Elvers, B.; Hawkins, S.; Shulz, G., Eds. Ullmann's Encyclopedia of Industrial Chemistry, A18, VCH: Weinheim, 1991.
14. ASTM D790M-86, Standard test methods for Flexural properties of unreinforced and reinforced plastics.
15. McClintock, F. A.; Argon, A. S. Mechanical Behavior of Materials, Addison Wesley, 1966.
16. Jones, F. R., Ed. Handbook of Polymer–Fiber Composites; Longman Scientific & Technical, London, 1994.