Journal of Applied Polymer Science

High Performance of Bamboo-Based Fiber Composites from Long Bamboo Fiber Bundles and Phenolic Resins

Yang-Lun Yu,[1] Xian-Ai Huang,[2] Wen-Ji Yu[1]
[1]Key Laboratory of Wood Science and Technology of State Forestry Administration, Research Institute of Wood Industry, Chinese Academy of Forestry, Xiang Shan Road, Haidian District, Beijing, China
[2]Université du Québec à Chicoutimi, Canada 555, boul. de l'Université, Chicoutimi, Québec, Canada G7H 2B1
Correspondence to: Y.-L. Yu (E-mail: yuyanglun@caf.ac.cn) and W.-J. Yu (E-mail: yuwenji@caf.ac.cn)

ABSTRACT: Lignocellulosic materials can be used for the development of bio-based composites. This study explores the potential of long bamboo fiber bundles extracted directly from bamboo stems using the novel mechanical method and bamboo-based fiber composites (BFC) fabricated using long bamboo fiber bundles and phenolic resins via cold pressing and thermal cure process. The microstructure, mechanical properties, and durability of BFC were evaluated, results being compared with raw bamboo and other commercialized bamboo fiber composites. The mechanical properties of BFC reinforced with 87% (w/w) long bamboo fiber bundles increased more than 50% than those of raw bamboo and were significantly higher than those of other bamboo-based composites. Lower water absorption and thickness swelling were obtained in the case where bamboo fiber bundles with the small fineness. Higher tensile strength was obtained in the case where bamboo fiber bundles with large sizes of bamboo fiber bundles. © 2014 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2014**, *131*, 40371.

KEYWORDS: fibers; composites; mechanical properties; manufacturing; microscopy

Received 29 June 2013; accepted 30 December 2013
DOI: 10.1002/app.40371

INTRODUCTION

Polymer–matrix composites such as carbon or glass fiber reinforced composites have been widely used in industry, building, and civil engineering because they have a high strength and modulus, as well as superior dimensional properties and other properties that gained popularity and slowly replaced natural fibers used in different applications.[1–3] However, some of the disadvantages are the cost of the raw materials, a large amount of energy required for the production of synthetic composites, and the environmental pollution during the production and recycling of these synthetic materials.[2,3] This has drawn attention toward the use of lignocellulosic materials due to their distinct advantages. Long plant fibers have the potential to rival glass fiber in the manufacturing of composite materials using matrix materials such as phenolic resins, polypropylene, and epoxy.[1,4–6]

Bamboo fiber (BF) is one of the most commonly used natural fibers due to its fast growth, abundant availability, and good mechanical properties, with longitudinally aligned fiber structures of 610 MPa strength called "natural glass fiber."[7,8] However, the BF is often brittle compared with other natural fibers because the fibers are covered with lignin, pectin, and other natural polymers, which makes it difficult to extract BF, with its superior mechanical properties.[5] Therefore, devised processes such as mechanical, chemical, or mechanical–chemical methods have been adopted to extract the short BFs for reinforcement of thermosetting and thermoplastic matrix composites.[1,5,9] However, most short BF reinforced materials suffer from a lack of mechanical properties and durability, and only a few applications have been realized. Fortunately, previous research indicates that the parenchyma cells (PCs) do not need to be separated to provide good reinforcing capability. In some instances, the remained fragments of PCs can act as effective reinforcing elements for composite manufacturing.[10] We hope to realize the use of producing bamboo composites using long fiber bundles that are directly extracted from the bamboo stems. In the previous studies, an industrial apparatus has been developed to extract long fiber bundles from bamboo stem at the Research Institute of Wood Industry, Chinese Academy of Forestry.[11]

The hydrophilic and polar nature of the lignocellulosic fibers and the nonpolar characteristic of many thermoplastic and thermoplastic matrices could alter composite properties, owing to the lack of adhesion and nonuniform dispersion of the fiber in the resin.[6,12,13] When phenolic resins (PF) are used as materials and natural fibers are used as reinforcement materials, the lack of adhesion can be considerably minimized by favorable

Table I. Composition and Mechanical Properties of Several Bamboos

	Volume fraction of bamboo tissues (%)			Chemical constituents (%)		Strength (MPa)	
Bamboo species	Fiber	Metaxylem vessel	Parenchyma cells	Holocellulose	Lignin	Tensile	Compression
Ci bamboo	45.0	5.5	49.5	73.55	24.35	227.55	70.49
Moso bamboo	32.0	8.9	59.1	68.25	23.65	188.77	69.92
Lv bamboo	30.0	8.7	54.3	68.74	23.46	199.10	54.36
Dan bamboo	40.5	8.8	52.7	62.40	23.35	185.89	62.45
Ma bamboo	32.5	6.4	62.1	69.61	22.77	182.20	59.59

interactions between polar hydroxyl groups of the phenolic resin and the hydrophilic fibers. This represents an important advantage of this resin compared to the hydrophobic matrix[14–16] because the intensity of the intermolecular interactions through the interface controls various properties of the composites.[17] Another advantage of using phenolic resins is their water solubility and low processing temperature, which is below the thermal decomposition temperature of the lignocellulosic fibers.[18]

This article describes the benefit of the use of long fiber bundles extracted from bamboo stems and water-soluble phenolic resins in the fabrication of bamboo-based fiber composites (BFC) for commercial and industrial purposes. First, the long BF bundles are extracted directly from bamboo stems using the novel mechanical method. Second, composites using two types of fineness BF bundles are fabricated with a novel cold pressing and thermal cure process. Finally, their mechanical properties and durability after the fabrication are evaluated.

EXPERIMENTAL

Materials

The characteristic, composition, and performance of bamboo vary greatly according to the species.[8] Table I lists the volume fraction of bamboo tissues, chemical constituents, and tensile strength of five commercial specials: Ci bamboo (*Neosinocalamus affinins (Rendle) Keng f.*), Moso bamboo (*Phyllostachys pubescens*), Lv bamboo (*Dendrocalamopsis oldhami (Munro) Keng f.*), Dan bamboo (*Phyllostachys glauca McClure*), and Ma bamboo (*Dendrocalamus latiflorus Munro*), abundantly grown in the southern China.[19,20] It can be seen that Ci bamboo has a considerably high volume fraction of fiber, holocellulose, and shows relatively higher mechanical properties compared to other bamboo species. Therefore, Ci bamboo obtained from Hongya Forest Reserve, Sichuan Province, Southwest China was selected as reinforcing material in this study.

The matrix material used in this study was based on a commercially available low-molecular-weight phenol formaldehyde resin (trade name: PF16L510) supplied by Beijing Dynea Chemical Industry Co., whose parameters are as follows: 5.59% of solid content, 36 mPa•s of viscosity, and 10.45 of pH.

Processing

The bamboo was sawn into a bamboo tube with a length of 2000 mm, which was then longitudinally split into two semicircular bamboo tubes. After the inner nodes were removed, the semicircular bamboo tubes were pushed into the fluffer[11] along the grain direction. The bamboo tube was fluffed along the longitudinal fiber direction to form a series of dotted and/or linear-shaped cracks along the fiber direction for five and seven times, as shown in Figure 1(a). Two types of fineness fiber bundles were formed, as shown in Figure 1(c,d), respectively, and then dried in an air-circulated stove at 85°C until the moisture content was approximately 10%.

To obtain a uniform glue spread, the solid content of phenolic formaldehyde resin was adjusted to 15% (in weight percent). Next, the BF bundles were immersed in the resin at a room temperature (RT) for 6 min. Then, the BF bundles were taken out and placed vertically for several minutes until the mass fraction of resin was approximately 13%. The glued BF bundles were dried in an air-circulated oven at 55°C until the moisture content was around 12%.

The glued BF bundles were weighed according to the designated density and uniformly laid in the mould. They were then pressed at 82 MPa in the mould using a cold press machine (Qingdao Guosen Machinery Co.). Once pressed to the position of the pinhole, the mould was locked by the pin, as shown in Figure 1(b). The moulds with slabs were placed in the air-circulated baking chamber at a temperature of 132°C and cured for 10 h. Then, the moulds were taken out from the baking chamber, and the slabs were demoulded. Finally, the BFC with dimension of $2000 \times 145 \times 150$ mm^3 were obtained, which reinforced with type 1 fiber bundles fluffed five times and type 2 fiber bundles fluffed seven times as shown in Figure 1(e,f), respectively.

Diameter of Bamboo Fiber Bundles Testing

The diameter of fiber bundles was measured by image analysis. A cross-section of BF bundles was imaged by a CCD video camera, and the image data were transformed into a binary-processed image. To avoid the error according to the irregularity of bamboo bundles on cross-section, the width measurement of each fiber bundle was repeated at different position. The mean of the four values was taken as the diameter. One hundred observations were recorded.

Mechanical Testing

Tensile Testing. Dumbbell-shaped specimens of BFC samples with dimensions of $408 \times 25 \times 20$ mm^3 were cut from the composite plates and then tested according to ASTM D3500-

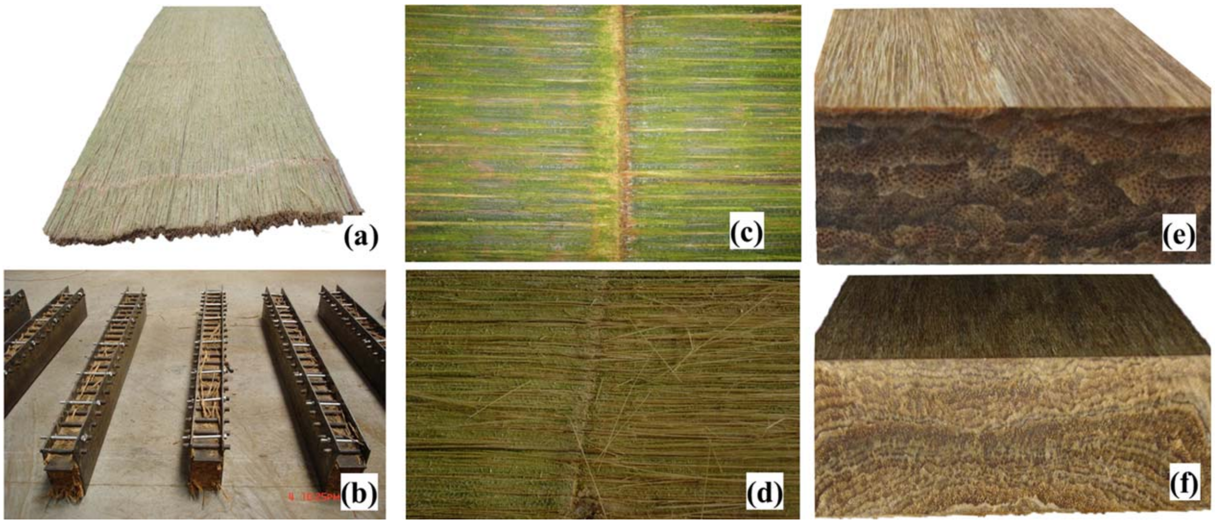

Figure 1. Bamboo fiber bundles and bamboo-based fiber composites. (a) Long bamboo fiber bundles; (b) slabs with moulds; (c) longitudinal surface of bamboo fiber bundles fluffed for five times (type 1 fiber bundles); (d) longitudinal surface of bamboo fiber bundles fluffed for seven times (type 2 fiber bundles); (e) cross-section of bamboo-based fiber composites reinforced with type 1 fiber bundles fluffed for five times; (f) cross-section of bamboo-based fiber composites reinforced with type 2 fiber bundles fluffed for seven times. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

1990 (Reapproved 2003). Specimens were tested to failure under tension at crosshead speed of 2 mm s^{-1} using a standard material testing system (MWD-W10, Jinan Shiguang test Instrument Co.). An extensometer was attached to the gauges section of the specimen for strain measurement. Twenty-five specimens from five separately manufactured composites reinforced with two types of fiber bundles were tested. The tensile Young's modulus and strength were recorded.

Compressive Testing. Cuboid-shaped specimens of BFC samples with dimensions of 81.6 × 25.0 × 20.0 mm^3 were produced from the composite plates and then tested according to ASTM D3501-2005 using a crosshead speed of 1 mm min^{-1}. An extensometer was attached to the gauges section of the specimen for strain measurement. Twenty-five specimens from five separately manufactured composites reinforced with two types of fiber bundles were tested. The compressive Young's modulus and strength were recorded.

Environmental Aging

Cuboid-shaped specimens of BFC samples with dimensions of 50 × 50 × 20 mm^3 were immersed in distilled water at RT (23°C) and boiling temperature (BT) (100°C) for up to 240 h. Mass and thickness change of the sample were recorded using an electronic balance and micrometer at regular time intervals. Twenty-five specimens from five separately manufactured composites reinforced with two types of fiber bundles were tested. The water absorption and thickness swelling were calculated according to ASTM D1037.

Scanning Electron Microscopy

To study the microscopic structural variations during the manufacturing process, the surfaces of raw bamboo, BF bundles, and BFC specimens were examined using a scanning electron microscope (JEOL JSM-5500 LV). The raw bamboo and BFC samples were sawn with cuboid-shaped specimens with dimensions of 10 × 5 × 5 mm^3 (length × width × thickness). Their surfaces were smoothed with a sliding microtome. The BF bundles were sawn into a bamboo splinter with lengths of 10 mm. The cross-sections of bundles were cut smoothly with a sliding microtome but not for the longitudinal sections. Then surfaces of all specimens were sputter-coated with gold prior to morphological examination. The scanning electron microscope (SEM) micrographs were obtained under conversation secondary electron imaging conditions with an acceleration voltage of 10 kV.

RESULTS AND DISCUSSION

Microstructures of Raw Bamboo

Figure 2(a) shows a cross-section of raw bamboo. It can also be observed that the ci bamboo column mainly consists of vascular bundles and parenchymatous ground tissues, where the inhomogeneous distribution of vascular bundles that are embedded in the PCs [Figure 2(b)], densely dispersed in the outer part and sparsely in the inner part of the culm wall; therefore, the higher amount of vascular bundles in the outer culm wall is a perfect structural adaptation toward a high bending stiffness and strength of the bamboo culm. The vascular bundles mainly consisting of hollow metaxylem vessel (MV) and sclerenchymatous fiber caps or sheaths are the fundamental structural components of a bamboo culm, and the caps or sheath of fibers consists of many longitudinal single BF, whose diameter is approximately 7–23 μm each for an average of 13.63 μm, [Figure 2(c)]. The fibers, playing a decisive role in the physiological growth and biomechanical function of bamboo, are the main components that determine the mechanical properties of bamboo owing to their unidirectional arrangement in the tissue as well as their unique cell wall structure.[21]

Bamboo Fiber Bundle Characteristics

Figure 1(a) shows the long BF bundles, wherein a series of dotted and/or linear-shaped cracks are formed on the cylinder wall

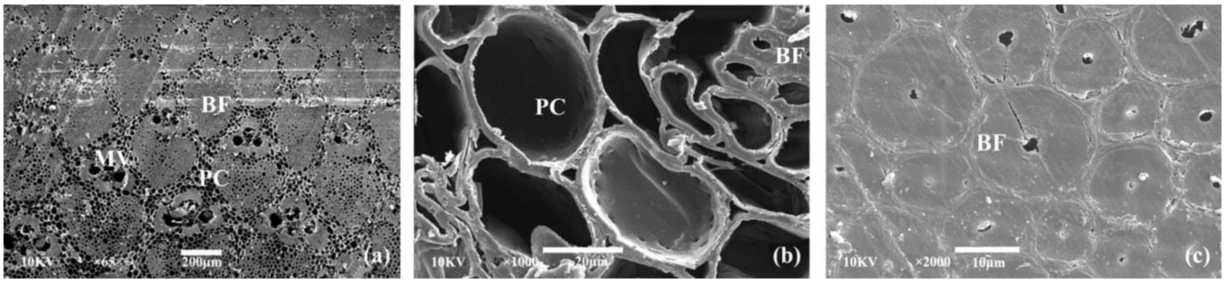

Figure 2. SEM image of Ci bamboo (a) cross-section of raw bamboo; (b) parenchyma cells; (c) bamboo fiber.

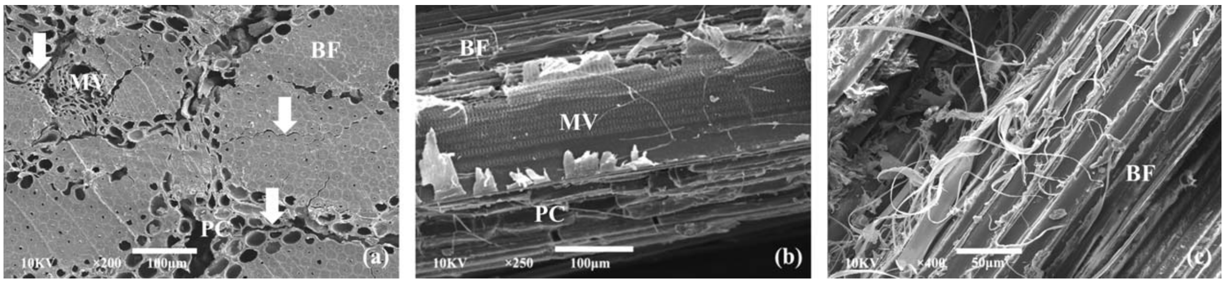

Figure 3. SEM image of bamboo fiber bundles (a) cross-section of bamboo fiber bundles; (b) parenchyma cells and metaxylem vessel on longitudinal direction; (c) bamboo fiber on longitudinal direction.

Table II. Morphology of Bamboo Fiber Bundles

Fiber type	Fluffed times	Length (mm)	Diameter (μm) Range	Average
Type 1	5	2000	113–262	183 (35)
Type 2	7	2000	88–145	107 (25)

of a semicircular bamboo tube. The epidermis on the outer layer of bamboo and the pith tissue on the inner layer of bamboo have been removed. Figure 3 shows the SEM images of BF bundles in different directions. During fluffing processing, a series of cracks are formed along the PCs and MVs between fibers [see arrows in Figure 3(a)]. However, the fibers are not destroyed. It can be observed that the bundles are not separated into single fiber, and a large amount of PCs remain on the surface of the bundles, which can be seen in the SEM images of bundles in a longitudinal direction [Figure 3(b,c)]. The fibers with good performance are exposed to the surface with high rates of fibrillation and fragmentation [Figure 3(b)]. Fine voids are present in the wall of the PC and MV, which are around the surfaces of fibers [Figure 3(c)]. Therefore, the resin impregnation path and the effective bonding area of bamboo are increased due to fluffing processing.

Figure 1(c,d) shows the BF bundles fluffed for five and seven times. It can be observed that, with increasing the times of the fluffed treatment, the more dotted and/or linear-shaped cracks are formed in the culm wall. As shown in Table II, the diameter of BF bundles decreases with the increase in fluffing times. This increases the specific surface area of BF bundles, which makes it more efficient to distribute PF resin on the surface of fiber bundles during the impregnation process and may potentially improve bonding performance. However, the increase of fluffing process might lead to the further broking of fiber, and then the tensile strength of BF bundles may decrease.

Microstructures of BFC

Figure 4 shows the SEM micrograph of BFC reinforced with BF bundles. It can also be observed from the micrographs that the honeycomb structures of the MVs and PCs of BFC [Figure 4(a)] become denser comparing to those of raw bamboo [see Figure 1(a)] according to the high pressure and heating

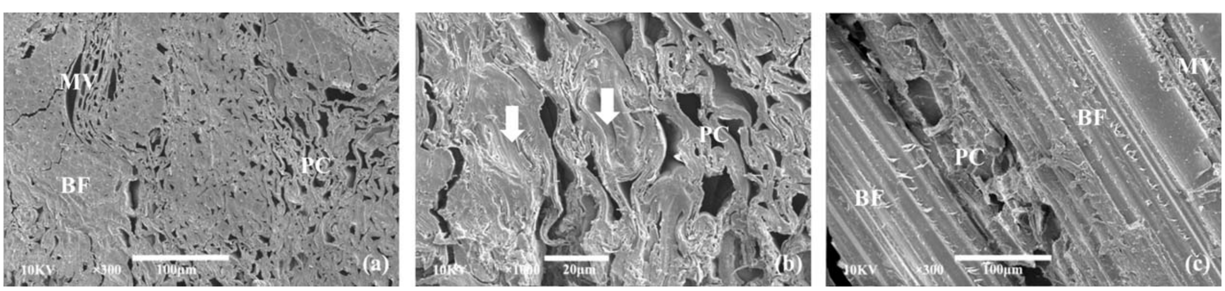

Figure 4. SEM image of bamboo-based fiber composites. (a) Cross-section of BFC; (b) cross-section of dense parenchyma cells of BFC; (c) longitudinal direction of BFC.

Table III. Mechanical Properties of Bamboo Composites

Types of composite		Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	Compression strength (MPa)	Young's Modulus (GPa)
Ci bamboo fiber bundles	Type 1/PF	1.15	354.78 (16.43)	31.65 (1.68)	129.08 (5.21)	31.97 (1.90)
	Type 2/PF	1.16	328.17 (20.30)	34.65 (1.48)	143.73 (4.05)	34.66 (2.84)
Bamboo short fiber/PF [1]		1.19	29.9	2.92	24.5	1.6
Bamboo short fiber/EP [1]		1.11	36.1	3.26	41.3	2.15
Bamboo long fiber/EP [1]		1.18	203	51	129	24.9
Bamboo laminated lumber/PF [2]		0.66	114.4	—	52.6	—
Bamboo scrimber/PF [2]		1.08	115.7	—	77.9	—

Numbers in parentheses are deviation of the 25 specimens.
PF and EP are phenolic resin and epoxy resin, respectively.

temperature during the moulding and curing process. This is also reflected in the increase of BFC specific gravity (1.16 and 1.15 g/cm^3 shown in Table III) compared with that of raw bamboo (0.72 g/cm^3).[19] In addition, it is possible to observe the presence of the adhesive inside or between the collapsed MVs and PCs [see arrows in Figure 4(b)]), where the dilute phenolic resins can penetrate through the subtle cracks of thin-walled structure during the immersing process. The collapsed and thin-walled tissue could lead to more intimate contacts and therefore the better inter-fiber bonding and compacting due to high pressure (82 MPa). It can be observed from the longitudinal surface that significant amounts of dense PCs are mingled with aligned BF. These PCs and MV are recovered with, and then adhered to the phenolic resin [Figure 4(c)]. This confirms that the dilute phenolic resin penetrates through the subtle crack formed by the fluffed treatment of bamboo tube when it was immersed in the phenolic resin liquid during the impregnation process.

Figure 1(e,f) shows the BFC reinforced with type 1 fiber bundles fluffed five times and type 2 fiber bundles fluffed seven times. It can also be observed that, with increasing the times of the fluffed treatment, the bonding interface of BFC between BF bundles become mistiness. Consequently, the material is more uniform.

Mechanical Property

The results of tensile and compressive properties tests, with respect to the BFC of the phenolic resins without any additives or curing agents and reinforced with 87% (w/w) BF bundles, are presented in Table III. The results of BFC are compared with those of other bamboo composites prepared by different bamboo bundles, and different additives published are also referenced to investigate the influence of long BF bundles and phenolic resin on mechanical properties.[22] Other bamboo engineered products, such as bamboo laminated lumber and bamboo scrimber, were used as controls for comparison.[23]

In comparison with the raw bamboo (see Table I), it can be seen that the tensile and compression strength of both BFC reinforced with BF bundles are increased by 44%–56% and 83%–104%, respectively. Figures 3 and 4 display that the BFs, playing a decisive role in the mechanical property of composites, maintain the orientation of framework structure without severe rupture after fluttering treatment and loading process. Therefore, the BFs maintain their high mechanical performance. However, the honeycomb ground tissues such as the MV and PCs are broken by fluttering treatment and condensed by high pressure. It can be obtained by image analysis that the volume fraction of fiber in BFC is approximately 57%, which significantly increased compared with that of raw bamboo (45%). The strength (610 GPa) and Young's modulus (46 GPa) of BF are 12 and 23 times more than those of the PCs (50 MPa and 2 GPa), respectively.[7] Increasing the volume fraction of fiber would lead to enhanced mechanical properties.[24]

The tensile strength and compression strength of BFC reinforced with Ci long BF bundles are overwhelmingly higher than those of other bamboo-based composites. The excellent mechanical properties of BFC are due to the superior mechanical characteristics of Ci long BFs and good bonding performance.

The tensile strength and Young's Modulus of BFC reinforced with long BF bundles in this study are more than 10 times higher than those of composites reinforced with bamboo short fibers/PF or EP, and its compression strength is more than 5 times higher than that of composites reinforced with bamboo short fibers/PF. The separation of short BFs destroys the original strength of bamboo. The orientation of the natural BF is disrupted for short bamboo composites, which results in the damage of the basic performances of bamboo and consequently the loss of mechanical strengths. For long BF composites, the tensile strength of BFC/PF composites is more than 1.6 times higher than that of long BF/EP composites, while its compression strength is slightly higher than that of long BF/EP composites. This indicates the important advantage of phenolic resins compared to the hydrophobic thermoplastic matrix. Their characteristic of water solubility brings about the good penetrability of matrix in to reinforcement and then enhances the intensity of the intermolecular interactions. Another advantage of using phenolic resins is their low processing temperature, which is below the thermal decomposition temperature of the lignocellulosic fibers.[18] The higher processing temperature (180°C) of long BF/EP results in the decomposition of BF, which decreases the

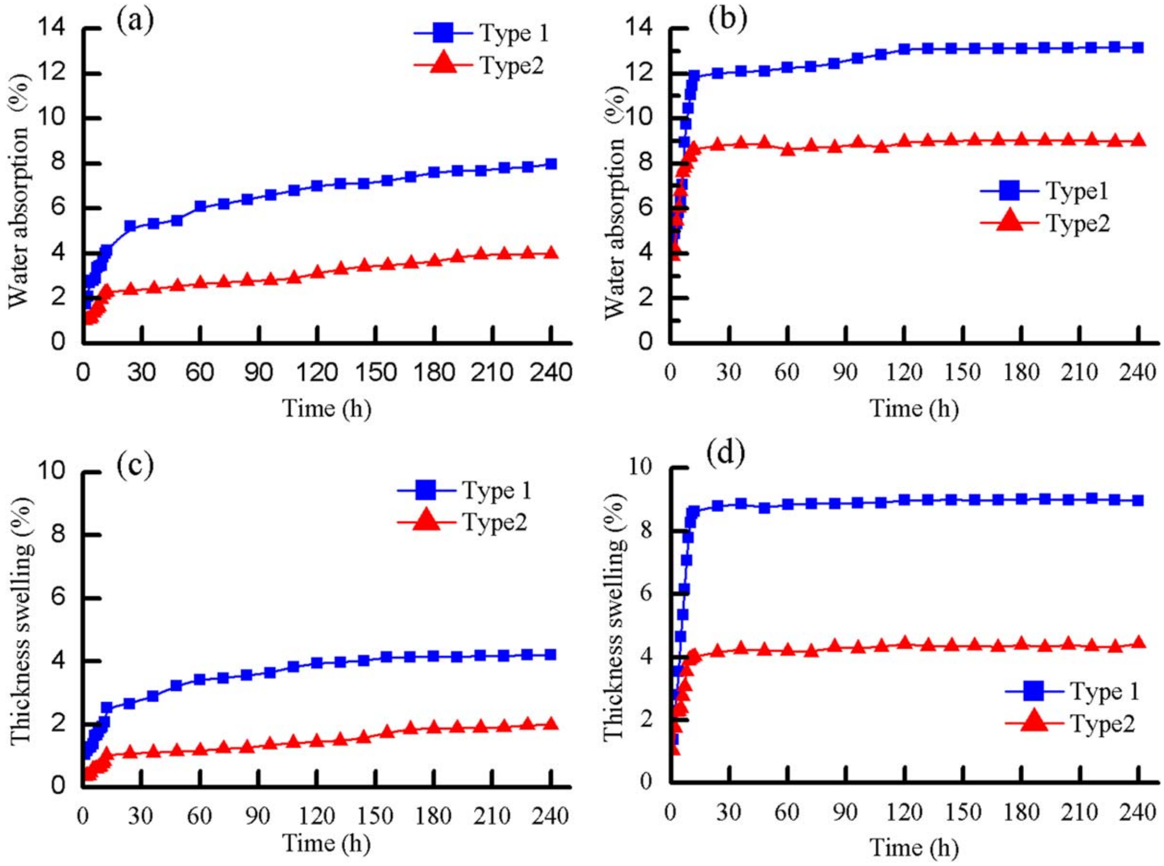

Figure 5. Durability of bamboo-based fiber composites. (a) Water absorption treated at RT; (b) water absorption treated at BT; (c) thickness swelling rate treated at RT; (d) thickness swelling rate treated at BT. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

mechanical properties. In addition, investigation of the mechanical properties of BFC comparing with those of commercial bamboo scrimber and laminated bamboo lumber was carried out. For tensile strength, BFC reinforced with both type fiber bundles shows more than 2.8 times higher than those of bamboo laminated lumber and bamboo scrimber. The compression strength of BFC is more than 2.5 times higher compared to that of bamboo laminated lumber and more than 1.6 times higher compared to that of bamboo scrimber. Bamboo laminated lumber and bamboo scrimber are mainly commercialized bamboo-based composites. Bamboo laminated lumber, similar to the laminated veneer lumber, is made from parallel bamboo strip. Bamboo scrimber, similar to the scrimber developed in Australia, is a novel, engineered composite made from parallel bamboo bundles. Compared with other bamboo composites, bamboo scrimber has comparatively higher raw material utilization rate because it has relatively more raw material sources, which include small-sized bamboo culm.[23] The BF is the reinforcement, and the phenolic resin represents the matrix during the system of bamboo-based composites. The interaction between BFs and resins are strongly dependent on the contact surface. In other words, the phenolic resin distributes more uniformly with the increasing fineness of BF bundles. The cracks in thin-walled tissue could lead to increase of fineness of BF bundles and better contacts between bamboo cells and PF resin, and hence the excellent inter-fiber compacting and bonding [see arrows in Figure 4(b)]. The excellent bonding is able to efficiently distribute the stress along the fiber bundles during loading of pressing process. Thus, the mechanical properties of BFC composite are improved. However, the resin is generally distributed in the surface of the units of bamboo strip, or bamboo bundle for bamboo laminated lumber and bamboo scrimber, which makes it difficult to improve the properties of honeycomb foams.

The results also show that the compression strength and Young's modulus of the BFC reinforced with type -1 fiber bundles fluffed five times are lower than that of BFC reinforced with type 2 fiber bundles fluffed seven times. As for polymer–matrix composites, the compression strength depends on the interaction between the reinforcement and the matrix more than the reinforcement alone.[25] With decreasing fineness of fiber bundles, the phenolic resin distribution is more uniform. Consequently, the bonding performance between BF bundles and resin is improved, which leads to higher compression strength. However, it can be observed that the tensile strengths show the opposite results. The tensile strength of BFC reinforced with type 1 fiber bundles is higher than that of BFC reinforced with type 2 fiber bundles. The tensile strength mainly depends on the strength of the reinforcement for polymer–matrix composites.[26] As for BFC composites system, long BF bundles represent the reinforcement. Increase of fluffing treatment time leads to form more short bamboo bundles and reduce the length and amount of long BF bundles. Therefore, the tensile strength declines with the fluffing treatment times increasing.

Environmental Aging

Water Absorption. Figure 5(a,b) shows water absorption as a function of time for BFC immersed in distilled water at RT and at BT.

It is clear that BFC reinforced with 87% (w/w) BF bundles have excellent water resistance compared with those of raw bamboo,[8] SFC reinforced with bamboo short fibers/PF[22] and bamboo scrimber.[27] The low molecular weight phenol resin, penetrated into the intercellular space of bamboo and lumens of thin-walled cells through cracks during the immersed process, and adhesive inside the collapsed, thin-walled tissues, formed an excellent three-dimensional network of thin protecting water-resistant film on the surface of BF bundles. The phenol resin film can effectively prevent the hydroxyl groups of BFs from interacting with water molecules. The mutually penetrated and interlocked structures of dense, thin-walled cells and phenol resin decrease the impregnation path of water. The effect of fiber size and temperature on water absorption can be clearly seen. The weight gain percentage at the moisture saturation point for BFC with type 1 and type 2 fiber bundles is 7.98% and 3.98% at RT and 13.14% and 9.01% at BT, respectively. Both initial rate of water absorption and moisture saturation point decrease as the diameter of BF bundles decreases. Compared with large fiber bundles, the resin is well distributed to form a continuous firm film, and the voids are obviously reduced in small fiber bundles.

If the temperature of immersion increases, the moisture saturation time shortens greatly. And the rate of approach to equilibrium is clearly more rapid. The water uptake process is linear in the beginning and then decreases and approaches saturation after a prolonged time. The higher and faster weight gain upon exposure to boiling water may be attributed to the different diffusivity of water into the materials, leading to moisture-induced interfacial cracks at an accelerated rate as a result of degradation in the fiber resin interface region, as well as the state of water molecules existing in the BFC. Other studies have also reported a similar trend for aging of polymer composites at elevated temperature.[26,28]

Thickness Swelling. The evaluation of the dimensional stability of the materials is especially important for the application of bio-based composites. Hence, the thickness swelling of BFC composites was carried out. Figure 5(c,d) present the thickness swelling curves of phenolic BFC reinforced with 87% (w/w) BF bundles (type 1 and type 2) immersed in water at RT and at BT. It is shown that BFC reinforced with 87% (w/w) BF bundles have excellent dimensional stability compared with those of SFC reinforced with bamboo short fibers/PF[22] and bamboo scrimber.[27] Thickness swelling is lower for composites reinforced with type 2 fiber bundles, demonstrating that this composite is dimensionally more stable than the one reinforced with type 1 fiber bundles. This indicates that the fiber bundles are better covered by the phenolic resin in the composites reinforced with type 2 fiber bundles, owing to a better fiber–resin adhesion. The extreme thickness swelling time is greatly shortened, and the rate of approach to equilibrium is clearly more rapid when the temperature of immersion increases. Thickness swelling has positive correlation and hysteresis with water absorption.

CONCLUSIONS

BF embedded in ground tissue is difficult to extract from bamboo club. Hence, processes have been adopted to extract short BFs for reinforcement of thermosetting and thermoplastic matrix composites; however, most short BF composites suffer from a lack of mechanical and dimensional properties, and only a few applications have been realized. In addition, the polar and nonpolar characteristics of BFs and many polymeric resins could result in composites without appropriate properties, mainly owing to lack of adhesion at the interface.

If long BF bundles are used as reinforcement and phenolic type resins are used as matrix, as in this study, these problems can be considerably minimized due to the interaction between polar groups present in their chemical structure and the phenolic resin. This is able to efficiently distribute the stress along the fiber bundles and protect BF erosion by water molecules.

In addition, for the first time, the long BF bundles were extracted by mechanical methods without any chemical alteration or special alteration of the epidermis and pith tissue of the bamboo. The remained fragments of PCs can act as effective reinforcing elements for composite manufacturing, and the PCs do not need to be separated to provide good reinforcing capability. The phenol thermoset resin was reinforced by BF (87% w/w) using a novel cold pressing and thermal cure process, owing to their excellent mechanical and dimensional properties. The mechanical properties of BFC increased more than 50% than those of raw bamboo and were significantly higher than those of other bamboo-based composites. Two different sizes of BF bundles are used: type 1, the diameter of the fibers bundles ranges from 113–262 μm; type 2, the diameter of the fibers bundles ranges from 88 to 145 μm. Type 2 displays the better adhesion between the resin and the BFs, along with excellent compression strength, Young's modulus, water absorption, and thickness swelling, whereas type 2 displays the lower tensile strength due to the fiber broken down further by the process. These results are promising and demonstrate that BFC can be prepared using high proportions of materials obtained from BF bundles.

ACKNOWLEDGMENTS

This study is partially supported by a grant from national forestry public welfare industry research project (201304503).

REFERENCES

1. Kalia, S.; Kaith, B. S.; Kaur, I. *Polym. Eng. Sci.* **2009**, *49*, 1253.
2. Joshia, S. V.; Drzalb, L. T.; Mohanty, A. K. *Compos. Part A* **2004**, *35*, 371.
3. Thostenson, E. T.; Ren, Z. F.; Chou, T. W. *Compos. Sci. Technol.* **2001**, *61*, 1899.
4. Mohanty, A. K.; Drazl, L. T.; Misra, M. *J. Adhes. Sci. Technol.* **2002**, *16*, 999.

5. Okubo, K.; Fujii, T.; Yamamoto, Y. *Compos. Part A* **2004**, *35*, 377.
6. Elaine, C. R.; Jackson, D. M. J.; Christian, G. *Biores. Technol.* **2010**, *101*, 1998.
7. Shigeyasu, A.; Yoshinobu, I.; Tamotsu, M.; Yukito, N.; Hiroyuki, S. *Compos. Part B* **1997**, *28*, 13.
8. Jiang, Z. H. Bamboo and Rattan in the World; China forestry publishing house: Beijing, **2007**.
9. Kim, B. J.; Yao, F.; Han, G. P. *Polym. Compos.* **2012**, *33*, 68.
10. Hepworth, D. G.; Hobson, R. N.; Bruce, D. M.; Farrent, J. W. *Compos. Part A* **2000**, *31*, 1279.
11. Yu, W. J.; Yu, Y. L.; Su, Z. Y. US Patent 20110293885A1, **2011**.
12. Paul, S. A.; Pasta, D.; Spange, S. *Biomacromol.* **2008**, *9*, 1802.
13. Jackson, D.; Cristina, G. S.; Derval, S. R. *Polym. Degr. Stab.* **2008**, *93*, 1109.
14. Jackson, D. M. J.; Franciéli, B. O.; Derval, S. R. *Macromol. Bio. Sci.* **2007**, *7*, 1121.
15. Trindade, W. G.; Hoareau, W.; Megiatto, J. D. *Biomacromolecules* **2005**, *6*, 2485.
16. Trindade, W. G.; Hoareau, W.; Razera, I. A. T. *Macromol. Mater. Eng.* **2004**, *289*, 728.
17. Jocob, P. N.; Berg, J. C. *Langmuir* **1994**, *10*, 3086.
18. Oliveira, F. B.; Gardrat, C.; Enjalbal, C.; Frollini, E. *J. Appl. Sci.* **2008**, *109*, 2291.
19. Xie, J. L.; Qi, J. Q.; Zhou, Y. W.; Xiao, H. *J. Bamboo Res.* **2011**, *30*, 30.
20. Yao, X. S.; Liang, J. S.; Ma, N. X.; Ma, Z. L.; Xu, H. The Microstructure of Main Chinese Bamboos; Dalian Publishing House: Dalian, **1992**.
21. Wang, X. Q.; Ren, H. Q.; Zhang, B.; Fei, B. H.; Burgert, I. J. R. *Soc. Interface* **2012**, *9*, 988.
22. Lu, B.; Zhang, W. L.; Zeng, J. C. Natural Fiber Reinforced Composites. Chemical Industry Press: Beijing, **2006**.
23. Meng, F. D.; Yu, W. J.; Chen, G. S. *Wood Process. Machinery* **2011**, *22*, 32.
24. Tony, B. Wind Energy Technology. Science Press: Beijing, **2007**.
25. Wang, R. M.; Zhen, S. R.; Deng, Y. P. Polymer-Based Composite. Science Press: Beijing, **2011**.
26. Thwe, M. M.; Liao, K. *Compos. Part A* **2002**, *33*, 43.
27. Hou, R. G.; Liu, Y.; Li, X. J.; Sun, R. H.; Qiao, J. Z. *J. Cent. S. Univ. Forest. Tech.* **2013**, *33*, 101.
28. Dhakal, H. N.; Zhang, Z. Y.; Richardson, M. O. W. *Compos. Sci. Technol.* **2007**, *66*, 1674.