Effect of fabricated density and bamboo species on physical–mechanical properties of bamboo fiber bundle reinforced composites

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ABSTRACT

Bamboo stems were subjected to a mechanical treatment process for the extraction of bamboo fiber bundles. The fiber bundles were used as reinforcement for the fabrication of high-performance composites with phenolic resins as matrix. The influence of fabricated density and bamboo species on physical–mechanical properties of bamboo fiber bundle reinforced composites (BFCs) was evaluated. The results revealed that BFCs with density of 1200 kg/m^3 exhibited lower water absorption, better dimensional stability, and higher mechanical properties with comparison to those with lower density. The changes in microstructures of BFCs with respect to density gave evidence that the high performance of BFCs with high density was due to the almost complete collapse of bamboo lumens, which resulted in the formation of solid bamboo and thin resin films with water resistance ability. BFCs fabricated from five bamboo species all showed better properties compared to commercialized bamboo-based composites. However, significant differences in physical–mechanical properties of BFCs among bamboo species were also found. This may be attributed to the variations in anatomical structure and physical–mechanical properties among original bamboo species. From a practical production view, the effect of bamboo species on properties of BFCs should be properly taken into consideration.

Introduction

Renewable raw materials have attracted more and more attentions on the development of bio-based green materials because of the rising concerns regarding the depletion of fossil oil and environmental issues [1]. Natural fibers derived from plants have been used as reinforcement elements in the fabrication of fiber/polymer composites for versatile applications with benefits including biodegradability

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and environmental protection. Among various natural fiber plants, bamboo has been considered as the most promising material owing to its high growth rate, abundant availability, renewable nature, short maturity cycle, and unique biological structure and high mechanical performance. Meanwhile, the mechanical properties such as tensile strength and modulus of single bamboo fibers are nearly two times of that of single Chinese Fir and Masson Pine fibers, and significantly higher than that of most other softwood fibers, the average tensile strength and modulus for bamboo fibers are 1.55 and 36.7 GPa, respectively [2, 3].

Because of the excellent performance of bamboo, it has been widely used in the manufacturing of artificial craftworks since ancient times. Over the past decades, a number of bamboo-based products such as bamboo panel [4], orientation strand board [5, 6], keyboard [7], laminated composites [8, 9], bamboo mat/wood veneer plywood [10], and bamboo cement composites [11] have been developed. For the production of bamboo panels or laminated composites, outer and inner layers were usually removed to increase the bonding performance, which resulted in the low efficiency of use of bamboo and waste of resources. As reported, the utilization ratio of bamboo in bamboo-based plywood, panel, and flooring was 35–48, 50, and 20–25 %, respectively [12].

Recently, polymer matrix composites reinforced with bamboo fibers have been extensively explored due to the favorable properties of bamboo fibers [13, 14]. As for the fiber-reinforced composites, fiber extraction methods, fiber characteristics, and preparation techniques were main parameters affecting the mechanical properties of the composites [15]. However, the usually employed bamboo fibers for the preparation of fiber-reinforced composites were extracted using chemical treatment process, from which the original orientation of natural bamboo fibers was disrupted and the performances of fibers were damaged. Moreover, the chemical processes consumed large amount of chemical reagents and energy resulting in environment pollutions and high cost.

In order to address the aforementioned problems for the industrial production of bamboo-based composites for construction of engineering materials, Yu developed a novel mechanical treatment process for the preparation of bamboo fiber bundle mat [16]. Basically, bamboo fiber bundle mats are formed by differential cleavages, where partial linear- and dotted-shaped cracks are caused to occur in the rolling process using fluffer. The fluffer includes driving rollers connected to the motor and fluffing rollers with several fluffing teeth distributed in the circumferential surface. The driving and fluffing rollers are rotary and fixed horizontally on a support frame. By inputting bamboo logs into a fluffer, impact forces are delivered to the surfaces of bamboo skins, causing ruptures to occur explosively along natural cleavage planes forming a reticulated sheet [17]. The produced bamboo fiber bundle mat via this novel technique has been applied in the fabrication of bamboo fiber bundle reinforced composites [18], bamboo scrimber which is a novel engineered composite made from parallel bamboo bundles [19], reconstituted bamboo lumber [20], and bamboo-bundle laminated veneer lumber [21, 22]. The composites with this new fiber bundle mat as matrix all showed excellent physical–mechanical properties. Even though a reduction in mechanical properties of bamboo fiber reinforced composite was observed after 2 years' outdoor exposure tests, the samples still exhibited high mechanical strength and good dimensional stability [23].

In all these studies, only one bamboo species was used as raw resource for the fabrication of bamboo-based composites. However, there are 75 genera with 1250 bamboo species worldwide [24], and bamboo properties including anatomical structure and physical–mechanical properties are reported to be significantly different with species [25–27]. The differences in bamboo properties could also significantly affect its mechanical or chemical processing procedures and the performance of end products [28–30]. Therefore, research on fabrication of bamboo fiber bundle reinforced composites from more bamboo species still needs to be conducted. And the evaluation of their performance is also essential to ensure that the fabricated composite could meet with the requirements of construction design. In this study, structures and physical–mechanical properties of bamboo fiber bundle reinforced composites (BFCs) with different fabricated density were first investigated. Then, BFCs with density of 1100 kg/m^3 were fabricated from five bamboo species because density of 1100 kg/m^3 is close to that of the industrial products. The objective of this study was to provide primary understanding of the formation mechanism of BFCs and the influence of bamboo species on properties of BFCs. The results in this study may

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provide fundamental information for quality control system in a practical production.

Experimental

Materials and chemicals

Bamboo culms (4-year old) of five bamboo species (*Neosinocalamus affinis* (NA), *Dendrocalamus farinosus* (DF), *Phyllostachys heterocycla* (PE), *Dendrocalamus latiflorus* (DL), *and Bambusa pervariabilis McClure* × *Dendrocalamopsis daii* (BD)) were harvested in Sichuan province, China. Ten bamboo logs with length of 4 meters were cut at about 10 mm above the ground. A commercial phenol–formaldehyde (PF) resin obtained from the Taier Corporation (Beijing, China) was used as matrix for the composite fabrication. The parameters of the PF resin were as follows: 44.6 % of solids content, viscosity of 41 mPa.s, pH of 11.2, and its ability to dissolve in water 7–8 times.

Preparation of bamboo fiber bundles

Bamboo logs with length of 1000 mm were first split longitudinally into two semicircular bamboo sections. After bamboo inner nodes were removed, the semicircular bamboo tubes were pushed into a fluffer. With brooming and rolling, the bamboo sections were processed into a loosely laminated sheet. The laminated sheet was cross-linked in the width direction with a series of dotted- and/or linear-shaped cracks along the longitudinal/fiber direction. The netlike bamboo sheet with uniform thickness and maintaining the original bamboo fiber arrangement was finally cut into pieces with length of 500 mm using an electrical saw.

Preparation of bamboo fiber bundle reinforced composites (BFCs)

The PF resin solution was diluted with water to a solids content of 15 %. The bamboo fiber bundles were immersed into the PF resin for 3 min and placed for 5 min to avoid PF resin flowing out; the amount of glue was controlled to about 12 % of the oven-dry weight of the bamboo fiber bundles, and then air-dried to a moisture content of 9 %. The bamboo fiber bundles were weighted out according to the desired density (800, 1000, and 1200 kg/m^3) and were assembled in a designed mold. For evaluating the effect of bamboo species on the properties of BFCs, the density was set as 1100 kg/m^3. A hot press was used to press the BFCs at a platen temperature of 150 °C. The pressure was kept 2.5 MPa for a holding time of 1.5 min/mm. The dimension of BFCs was 450 mm (length) × 160 mm (width) × 15 mm (thickness).

Characteristics of original bamboo

Anatomical properties

Bamboo samples were boiled in distilled water for 6 h until soft. The softened blocks were sliced into 30-μm sections on a sliding microtome. The cross-sections were stained with 0.1 % safranin-o and dehydrated through an alcohol series, and then mounted on a slide with a cover slip. The air-dried slides were examined on a digital photomicroscope (Olympus DP20), and the anatomical properties were analyzed by Image-Pro Plus (Media Cybernetics, version 6.0). The vascular bundle density was determined by counting the numbers of the vascular bundle on the cross-section images per mm^2. Six replicates were carried out for each sample.

For the analysis of fiber morphology, the Jeffrey's solution (10 % chromic acid:10 % nitric acid mixtures = 1:1) method was used. Bamboo splits were macerated in the Jeffrey's solution, and then were washed carefully with distilled water. Macerated splints were stained with 0.1 % safranin-o for a few seconds to contrast the fiber's images. Little part of the stained splints was dispersed in a drop of 50 % glycerol solution on a slide. Slides of cross-section were projected using microscope with digital camera at 20× for the determination of fiber length and at 400× magnification for lumen diameter and cell wall thickness, respectively. A total of fifty complete and reasonable fibers were selected randomly and measured for each bamboo species.

Physical–mechanical properties

Physical–mechanical properties of original bamboo were determined according to a referenced method [31]. A 25-mm section was used for specific gravity test, which was obtained from the middle portion of an internode from each bamboo. For each species, six samples were prepared for specific gravity test. Volumetric shrinkage was estimated on green and oven-

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dry volume dimensions. Samples for volumetric shrinkage determination were oven-dried at 105 ± 2 °C until constant weight was obtained. The green volume of samples was determined using the water displacement method.

Shear strength (SS) and compressive strength (CS) parallel to grain were determined using a universal testing machine (Reger, RGM-4100, China). Sample size for the measurement of shear strength and compressive strength was 35 × 20 mm × culm wall thickness and 20 × 20 mm × culm wall thickness, respectively. Compressive and shear strength were measured by loading the specimen at a constant rate of 0.5 mm/min until the maximum load was reached or when failure occurred. The force was loaded from top to bottom along the longitudinal direction of the samples for both SS and CS test. The samples for CS were organized with two steel plants of testing machine, one attaching upper surface and the other one supporting lower surface of test pieces. Shear and compressive strength were calculated by formula (1) and (2), respectively. Thirty replicates were carried out for each sample.

$$\text{Shear strength} = \frac{P_{\max}}{hL} \quad (1)$$

$$\text{Compressive strength} = \frac{P_{\max}}{bh}, \quad (2)$$

where $P_{\max}$ is the maximum load at which the sample fails (N), L represents the length of shear surface, b represents the width (mm), and h represents the depth (culms wall thickness, mm).

Properties of BFCs

Microstructure analysis

The structure and the surface morphology of the BFCs were observed using a scanning electron microscope (SEM, JCM-5000). Test samples were coated with gold using a vacuum sputter coater before subjected to the SEM analysis.

Physical properties of BFCs

The water absorption (WAR), width swelling (WS), and thickness swelling (TS) of BFCs were measured according to a standard procedure in ASTM D-1037. Samples with size of 50 × 50 × 15 mm were subjected to a water boil proof treatment in accordance with Chinese National Standard for Testing and Materials (GB/T 30364-2013). The samples were immersed in boiling water for 4 h, and then dried in oven for 20 h. Thereafter, the samples were immersed in boiling water for another 4 h.

Mechanical properties of BFCs

Bending strength (MOE) and modulus of elasticity (MOR) of BFCs were tested in accordance with Chinese National Standard for Testing and Materials (GB/T 17657-1999). Sample size for bending strength test was 360 × 50 × 15 mm. Compressive strength (CS) and shear strength (SS) were tested in accordance with ASTM D3501-2005 and ASTM D 2344-2013, respectively. Samples for compressive and shear strength were 80 × 15 × 15 and 90 × 40 × 15 mm, respectively. All samples for mechanical test were conditioned at 20 °C and 65 % relative humidity for at least 4 weeks prior to testing. Six specimens of BFCs were tested for each bamboo species.

Data analysis

Statistical analysis was carried out using SAS (version 9.1, SAS Institute, Cary, NC). Analysis of variance (ANOVA) was performed to determine significant differences ($\alpha = 0.05$) in the properties of both original bamboo and BFCs. Correlation analysis was also performed to investigate the relationship between properties of original bamboo and those of BFCs.

Results and discussion

Effect of density on physical–mechanical properties of BFCs

Bamboo fiber reinforced composites (BFCs) with density of 800, 1000, and 1200 kg/m^3 were fabricated using DF bamboo fiber bundles with phenol–formaldehyde resin. Table 1 represents the water absorption and dimensional stability of the composites with respect to the fabricated density. The water absorption (wet state) decreased from 43.03 to 5.01 % as the density increased from 800 to 1200 kg/m^3, indicating that the increase in fabricated density could significantly reduce the water absorption ability of the composites. Both the width and thickness swelling showed a decrease with increasing the

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Table 1 Water absorption and dimensional stability of BFCs from *Dendrocalamus farinosus* with respect to fabricated density

Density (kg/m^3)	Wet state			Dry state		
	WS (%)	TS (%)	WAR (%)	WS (%)	TS (%)	WAR (%)
800	3.78 ± 0.24[a]	8.56 ± 0.43	43.0 ± 3.00	3.54 ± 0.24	9.91 ± 1.03	51.1 ± 4.09
1000	1.57 ± 0.22	6.18 ± 0.52	13.5 ± 1.34	1.36 ± 0.28	7.22 ± 0.71	20.2 ± 7.96
1200	0.70 ± 0.10	5.50 ± 0.54	5.01 ± 0.92	0.46 ± 0.22	6.19 ± 0.47	6.66 ± 1.22

[a] Mean ± standard deviation of six replicates

fabricated density. The width swelling, thickness swelling, and water absorption of BFCs with density of 1200 kg/m^3 were 0.7, 5.5, and 5.01 %, respectively. This result revealed that BFCs with density of 1200 kg/m^3 showed good water resistance ability. This could be attributed to that with high-pressure hot-pressing process lumens of bamboo such as vessels, parenchymas, and fibers were deformed resulting in the close of the lumens, which reduced the water pathways in the composites during water treatment.

Table 2 shows the mechanical properties (MOE, MOR, CS, and SS) of the composites with respect to fabricated density. The MOE, MOR, CS, and SS for BFCs with density of 800 kg/m^3 were 170.88, 21231, 105.17, and 10.01 MPa, respectively. For comparison, the composites fabricated in this research showed comparable strength to that of the bamboo-based composite as reported in other studies [18, 30]. Compared to BFCs with density of 800 kg/m^3, the MOE, MOR, CS, and SS for BFCs with density of 1200 kg/m^3 increased by 41, 43, 52, and 85 %, respectively.

Bamboo culm wall was characterized by vascular bundle embedded in parenchymas, and the vascular bundle density was closely associated with the properties of bamboo culm wood. As for bamboo wood, evidence that vascular bundle density has positive relationship with the specific gravity (density) and mechanical properties has been provided [32]. In order to further clarify the relationship between mechanical properties of the composites and the vascular bundle, the microstructure and the characteristics of the vascular bundle were investigated.

The cross-sections of the DF bamboo culm and BFCs were observed using SEM and the images are presented in Fig. 1. As shown in Fig. 1a, the DF bamboo culm wood was composed of vascular bundles and parenchymas. The vascular bundles consist of central vascular and fiber strands embedded in parenchymas with regular lumen. In the SEM image of BFCs with density of 800 kg/m^3, the shape of the parenchymas and the central vascular including vessels and phloem became irregular, i.e., lumens became thinner and the circular vessel became elliptic. Although the lumen for BFCs with 800 kg/m^3 were deformed and became thinner compared to that of the original bamboo, the deformed lumens could still provide pathways for water impregnation, this may provide evidence that BFCs with density of 800 kg/m^3 still exhibited high water absorption and width and thickness swelling. Increasing the density to 1000 kg/m^3, lumens of the vessels, phloem, and most parenchymas were compressed into a closing state (Fig. 1c). Further increasing the density to 1200 kg/m^3, the lumens except for that of the thick fibers were all collapsed resulting in an almost solid-state composite.

As the lumens were almost completely collapsed because of the hot-pressing and formation process in fabricating BFCs with density of 1000 or 1200 kg/m^3,

Table 2 Mechanical properties of BFCs from *Dendrocalamus farinosus* with respect to fabricated density

Density (kg/m^3)	MOR (MPa)	MOE (GPa)	CS (MPa)	SS (MPa)
800	171 ± 26.9[a]	21.2 ± 1.03	105 ± 8.07	10.0 ± 0.68
1000	193 ± 36.0	22.7 ± 1.53	138 ± 2.84	15.5 ± 1.76
1200	213 ± 12.5	30.1 ± 1.29	162 ± 11.1	18.6 ± 1.19

[a] Mean ± standard deviation of six replicates

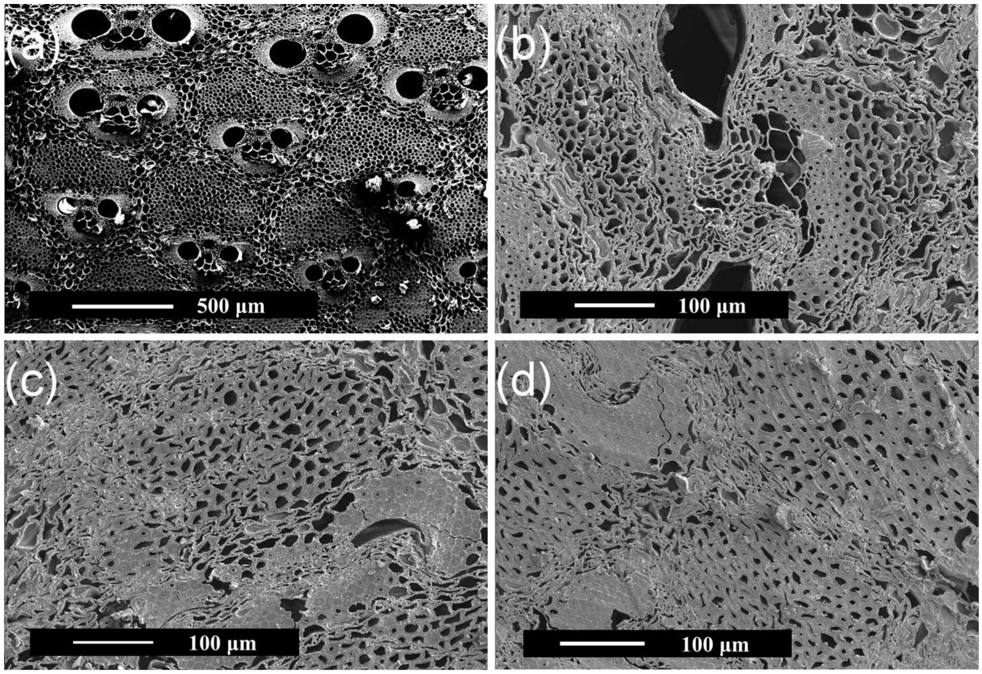

Figure 1 SEM images of cross-sections of **a** *Dendrocalamus farinosus* bamboo culm and composites with density of **b** 800 kg/m^3, **c** 1000 kg/m^3, and **d** 1200 kg/m^3.

water impregnation pathways were dramatically reduced, which somewhat contributed to the lower water absorption and width and thickness swelling as discussed above. Meanwhile, the phenol–formaldehyde resin which penetrated into the lumens during the resin immersing process was also compressed into a thin film when the bamboo tissue lumens were closed with the high-pressure hot pressing. This thin film performed excellent ability in water resistance and prevented the hydroxyl groups of the bamboo fiber bundles from interacting with water molecules [18]. Therefore, both the closing of the bamboo lumens and the formation of the phenol–formaldehyde resin film contributed to good water resistance properties of the composites with high density (1000–1200 kg/m^3).

From the analysis of the microstructure of the composites, it could be concluded that during the fabrication of BFCs, with the compression loading in the radial direction of the composites, the parenchyma portions were first compressed and deformed, then the stress was transferred into the vascular bundle which resulted in the deformation of the vessels and phloem. Thereafter, the deformed bamboo lumens changed the vascular bundle dimension and density. Figure 2 shows the variation in vascular bundle dimension and vascular bundle density among BFCs. The radial diameter of the vascular bundle decreased with increasing the fabricated density, while the vascular bundle density showed an increasing trend. The vascular bundle diameter and the vascular bundle density for the original bamboo culm wood were 458 mm and 3.26 bundle/mm^2, respectively. For comparison, the composites had smaller vascular bundle size and larger vascular bundle density because of the deformation of the lumens. For vascular bundle diameter, BFCs with density of 1200 kg/m^3 showed more than 25 % smaller than that for BFCs with density of 800 kg/m^3, while the vascular bundle density of BFCs with density of 1200 kg/m^3 was about 1.9 times of that for the composites with density of 800 kg/m^3. This result allowed the statement that high vascular bundle density resulted in high mechanical properties of the composites.

Variation in original bamboo properties among species

In order to investigate the effect of bamboo species on the physical–mechanical properties of BFCs, anatomical structure, fiber morphology, and

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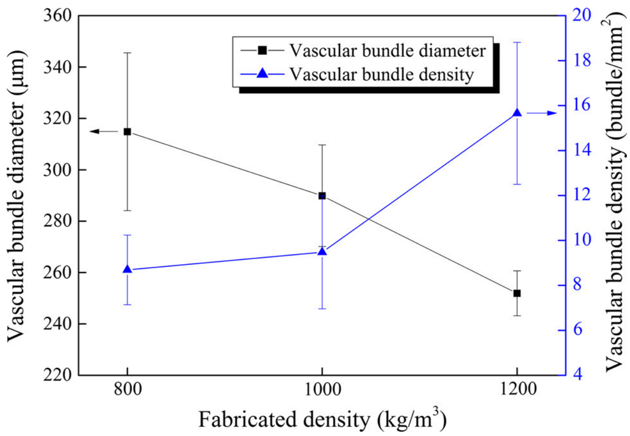

Figure 2 Vascular bundle diameter and density of BFCs with respect to fabricated density.

physical–mechanical properties of the five bamboo species were first evaluated to provide fundamental information for analysis of variation in properties of BFCs among species.

Transverse sections of the five bamboos were observed using microscope, and the microstructure images were presented in Fig. 3. Differences in vascular bundle shape and size were observed as indicated in the images. The vascular bundle type of NA, DL, DF, and BD was "open type," which consists of only one part: the central vascular bundle, with a supporting tissue of four sclerenchyma sheaths on the sides [33]. The vascular bundle type of PE was "broken-waist type," and was composed of a central vascular strand and an isolated fiber bundle located at the protoxylem side [33].

As shown in Table 3, NA had the highest vascular bundle density, while that of PE was lowest. According to the analysis of the fiber morphology, DL had long fibers with thin cell wall and large lumen diameter. Fibers of NA and PE were thicker than those of DL, DF, and BD. Fibers of DL had the largest lumen diameter (12.61 μm), while those of PE had the smallest lumen diameter (2.74 μm). Compared to DF, DL, and DB, NA and PE showed higher basic density, lower volume shrinkage, and stronger compressive strength and shear strength. The variance analysis results indicated species had significant influence on properties of bamboo culm wood ($p < 0.05$).

Effect of bamboo species on properties of BFCs

BFCs with density of 1100 kg/m^3 were fabricated from the five bamboo species. The water absorption and dimensional stability (width and thickness swelling) of BFCs are listed in Table 4. The width swelling both at wet and dry state of BFCs fabricated

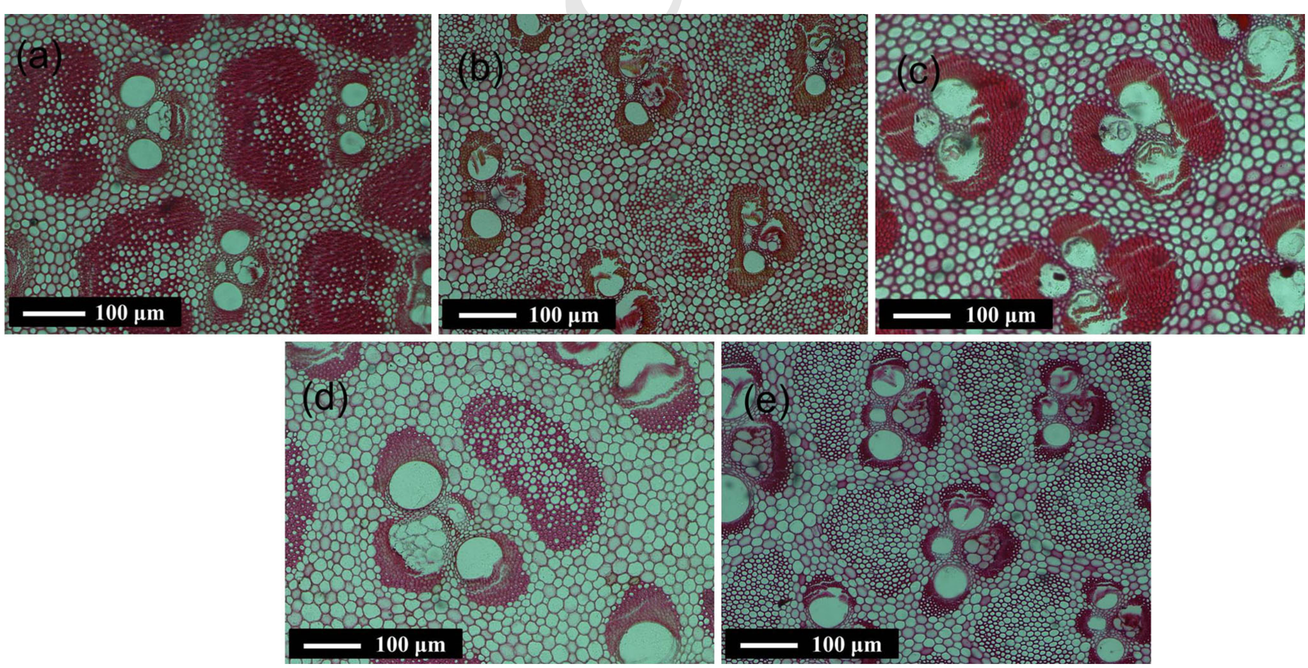

Figure 3 Microstructure images of transverse sections of **a** NA, **b** DF, **c** PE, **d** DL, and **e** DB.

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Table 3 Anatomical, physical, and mechanical properties of the five original bamboo culms

Bamboo species	Vascular bundle density (n/mm^2)	Fiber length (mm)	Fiber wall thickness (μm)	Fiber lumen (μm)	Aspect ratio (%)	Density (kg/m^3)	Volume shrinkage (%)	Compressive strength (MPa)	Shear strength (MPa)
NA	4.11 ± 0.14[a]	2.48 ± 0.12	9.91 ± 1.23	6.71 ± 0.77	165 ± 12.4	690 ± 30	9.08 ± 0.23	66.5 ± 3.89	12.9 ± 0.94
DF	3.26 ± 0.22	2.58 ± 0.20	6.19 ± 0.89	8.70 ± 0.89	146 ± 6.71	580 ± 70	10.5 ± 1.30	54.9 ± 7.68	12.0 ± 2.15
PE	2.71 ± 0.19	2.21 ± 0.11	8.96 ± 0.54	2.74 ± 0.22	189 ± 14.8	640 ± 40	9.01 ± 0.54	70.3 ± 5.52	13.1 ± 0.56
DL	0.83 ± 0.04	3.72 ± 0.28	6.18 ± 0.33	12.6 ± 2.07	198 ± 13.9	460 ± 70	15.5 ± 1.60	40.1 ± 5.61	8.49 ± 2.15
BD	1.96 ± 0.08	2.14 ± 0.09	6.04 ± 0.27	9.84 ± 1.25	135 ± 4.98	550 ± 60	11.9 ± 1.44	58.9 ± 4.20	12.2 ± 0.84

[a] Mean ± standard deviation of six replicates

from the five bamboo species was less than 2 %, and the thickness swelling was less than 8 %. Compared to strand board made from Moso bamboo, BFCs exhibited lower thickness swelling, i.e., thickness swelling for strand board was 39.4 % [5]. The water absorption of BFCs except for that fabricated from NA was less than 10 %. As reported, the water absorption values for bamboo mat plywood [10], oriented strand board made from Betung bamboo [6], and bamboo short cellulosic fiber reinforced composites [34] were about 28, 46–48, and 17–33 %, respectively. This result showed that all BFCs had high dimensional stability and good water resistance property.

BFCs fabricated from NA, DF, DL, and BD exhibited higher water absorption, width and thickness swelling than those from PE. This may be due to that PE had the smallest fiber lumen diameter as aforementioned. According to correlation analysis, positive correlation between fiber lumen diameter and water absorption and dimensional stability was found, indicating that bamboo with larger fiber lumen contributed to higher water absorption, width and thickness swelling of BFCs. Another explanation for the highest width swelling of BFCs from NA may be attributed to its thick fiber cell wall. As the fiber lumen was compressed and became thinner due to compression deformation because of hot pressing, the lumen became wider and the stress was stored in the cell wall along the thickness direction. Thicker cell wall resulted in more stress stored, and the tendency to spring back was stronger. Therefore, larger width swelling generated when exposed to water treatment procedure. The variance analysis result showed that significant differences ($p < 0.05$) in water absorption and dimensional stability among BFCs from five bamboo species were found. This result indicated bamboo species had significant influence on the water absorption and dimensional stability of BFCs.

Figure 4 shows the mechanical properties of BFCs. As presented, the CS of BFCs from all five bamboo species was more than 130 MPa. The CS for bamboo-laminated composites was 55–88 MPa [9]. The comparative result revealed that BFCs fabricated in this study possessed higher CS. Significant difference in CS was observed between BFCs from DF and PE. SS of BFCs from NA, PE, and DL was higher than that for BFCs from DF and BD, and BFCs from NA showed the highest SS. The MOE and MOR of BFCs

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Table 4 Water absorption and dimensional stability of BFCs fabricated from five species

Species	Wet state			Dry state		
	WS (%)	TS (%)	WAR (%)	WS (%)	TS (%)	WAR (%)
NA	1.23 ± 0.49a[a]	4.80 ± 0.47b	10.0 ± 1.78a	1.69 ± 0.58a	5.80 ± 0.75bc	10.5 ± 2.42a
DF	0.77 ± 0.26b	6.52 ± 0.72a	9.38 ± 1.00ab	1.03 ± 0.28ab	7.65 ± 0.69a	9.76 ± 1.06ab
PE	0.68 ± 0.09b	3.55 ± 0.37c	6.21 ± 0.40c	1.00 ± 0.16b	4.25 ± 0.54d	6.61 ± 0.54c
DL	0.87 ± 0.10ab	3.71 ± 0.59bc	7.05 ± 1.25bc	1.15 ± 0.12ab	4.58 ± 1.01cd	7.14 ± 1.43bc
BD	1.12 ± 0.25ab	6.31 ± 0.74a	7.33 ± 1.08abc	1.49 ± 0.40ab	5.82 ± 0.19b	8.12 ± 1.44abc

[a] Mean ± standard deviation of six replicates; Values followed by the same letter in the same row are not significantly different at 0.05 probability

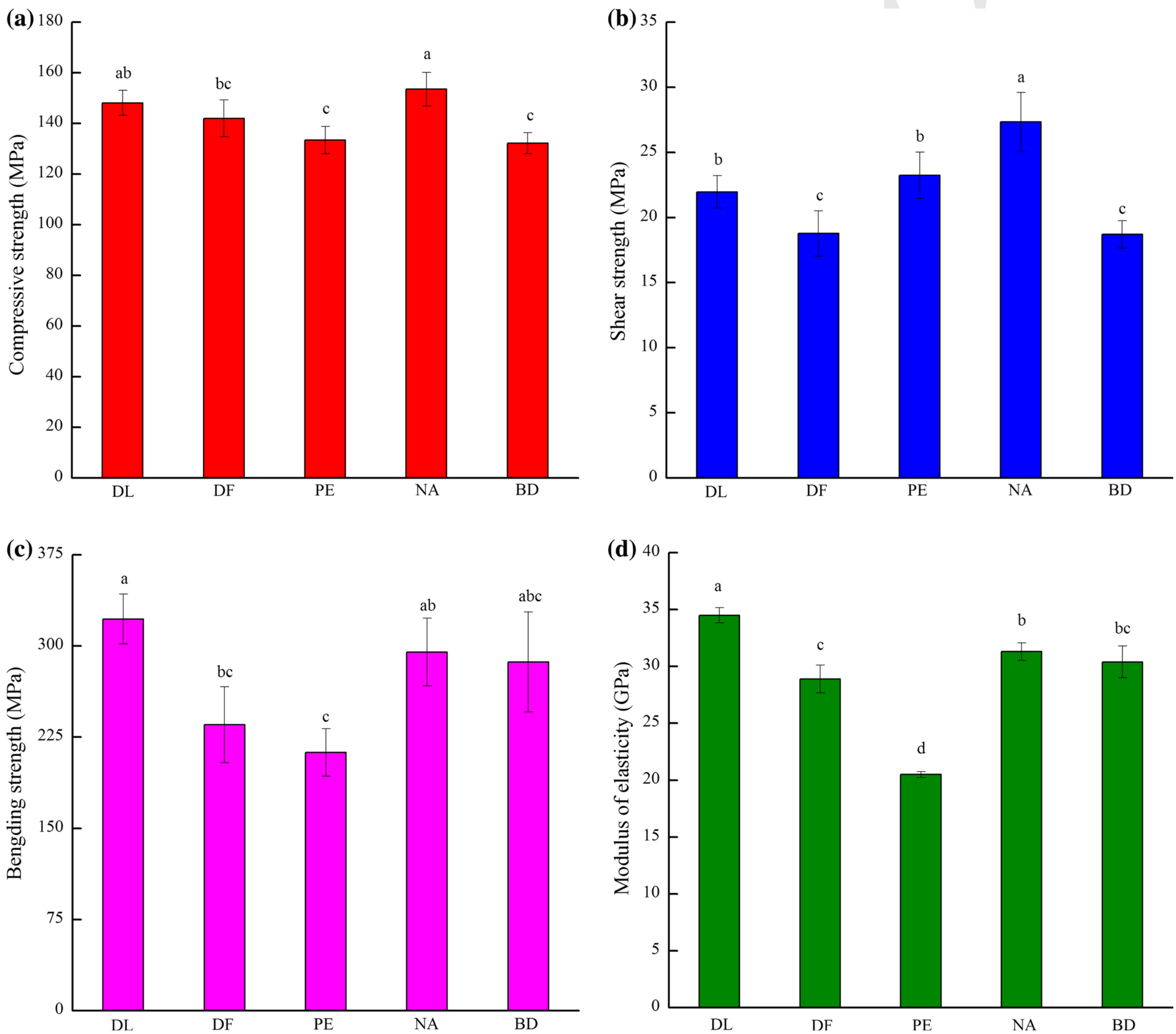

Figure 4 Effect of bamboo species on **a** compressive strength, **b** shear strength, **c** bending strength, and **d** modulus of elasticity of bamboo fiber reinforced composites. Some *letters* above the columns indicate no significant different at 0.05 probability.

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were more than 200 MPa and 20 GPa, respectively. As compared to other bamboo fiber reinforced materials such as bamboo fiber-polyester composites, MOE for bamboo fiber-polyester composite was 16.4–42.3 MPa [14]; MOE of BFCs was much higher. BFCs from PE showed the lowest MOE and MOR compared to BFCs from the other species. The higher mechanical properties of BFCs compared to commercialized bamboo composites were mainly due to the fact that bamboo fiber bundles maintained their original fiber arrangement and orientation of framework structure. A significant positive correlation between bamboo fiber wall thickness and SS of BFCs was observed ($R = 0.90$, $p < 0.05$), whereas a negative correlation was found between fiber wall thickness and MOE and MOR. There was also a significant positive correlation between fiber lumen diameter and MOR ($R = 0.88$, $p < 0.05$).

Although all BFCs fabricated from different bamboo species exhibited better dimensional stability, lower water absorption, and stronger mechanical properties with comparison to other bamboo-based materials, differences in physical and mechanical properties among BFCs from various bamboo species were also observed. Therefore, for using BFCs as a structural material, the effect of bamboo species on properties of BFCs should be under consideration because uniformity of raw materials for structural design is highly required [21].

Conclusions

Bamboo fiber bundle reinforced composites (BFCs) with density of 800, 1000, and 1200 kg/m^3 were fabricated. The microstructure images of BFCs showed that the bamboo lumens were deformed due to hot-pressing process. The vascular bundle density of BFCs increased with increasing the fabricated density, while the radial diameter of the vascular bundle showed a decreasing trend. The increase in fabricated density of BFCs resulted in the improvement in dimensional stability and mechanical strength. This may be due to the closing of bamboo lumens and formation of phenolic resin films. Differences in anatomical structure and physical–mechanical properties were observed among five original bamboo wood. Bamboo species had significant influence on the physical–mechanical properties of BFCs with density of 1100 kg/m^3. The smaller fiber lumen diameter of PE contributed to its lower water absorption of BFCs. BFCs from NA showed the highest shear strength and those from PE showed the lowest bending strength and modulus of elasticity. Although differences in physical–mechanical properties of BFCs among bamboo species were observed, BFCs still showed significantly higher performance compared to commercialized products.

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