Comparison of the Properties of Fiberboard Composites with Bamboo Green, Wood, or their Combination as the Fibrous Raw Material

Wei Song,[a,b,c] Minghao Zhu,[a] and Shuangbao Zhang [a,b,c,*]

The potential of bamboo green (B), an abundant lignocellulosic residue from the bamboo processing industry, was evaluated to serve as an alternative fibrous raw material in the production of fiberboard. Urea-formaldehyde resin-bonded fiberboards were prepared from B, wood fiber (W), and a mixture of the two (BW). The board type depended on the mass fraction of B in fibrous raw materials (including B and W), which were 0%, 20%, 40%, 60%, 80%, and 100%. The analytical methods used to characterize fibers and fiberboards included X-ray diffraction, thermogravimetric analysis, dynamic mechanical analysis, contact angle analysis, physical-mechanical analysis, and scanning electron microscopy. Compared with W, B showed a higher crystallinity index and thermogravimetric stability, but lower surface hydrophilicity and weaker interactions with urea-formaldehyde resin. Compared with W fiberboards, B fiberboards possessed a lower interfacial adhesion but fibrous raw materials in B fiberboards were better dispersed; moreover, B fiberboard displayed a higher dynamic viscosity, thermogravimetric stability, surface wettability, water absorption, and flexural modulus, but lower thickness swelling and flexural strength. The fiberboards produced with BW had better performances than the fiberboards produced with B and W. The 40% B mass fraction resulted in BW fiberboards with the best physical-mechanical properties.

Keywords: Fiberboard; Bamboo green; Urea-formaldehyde resin; Interfacial adhesion; Physical-mechanical property

Contact information: a: Beijing Key Laboratory of Wood Science and Engineering, Beijing Forestry University, Beijing 100083, China; b: MOE Key Laboratory of Wooden Material Science and Application, Beijing Forestry University, Beijing 100083, China; c: MOE Engineering Research Center of Forestry Biomass Materials and Bioenergy, Beijing Forestry University, Beijing 100083, China;
** Corresponding author: shuangbaozhangj5@163.com*

INTRODUCTION

Because of merits such as good processability, a smooth surface, and high dimensional stability, fiberboards have become one of the most commonly applied natural fiber composites, and it is used extensively in construction, building, furniture, and interior decorating (Wang *et al*. 2016a; Guan *et al*. 2017). For example, in North America, particleboard and medium density fiberboard (MDF) are the most extensively applied engineered wood products used in the manufacturing of furniture components (Dettmer and Smith 2015). Typically, fiberboard consists of wood fiber and a binder, and it is fabricated by pressing at a high pressure and temperature (Hong *et al*. 2017). In recent years, the increase in population has raised the demand for these wood products substantially (Kusumah *et al*. 2017). A high rate of wood consumption has aggravated deforestation and environmental pollution around the world (De Almeida *et al*. 2017).

Because limited wood resources cannot meet this growing need, there is an increasing interest in exploring alternative biomass materials that could be used to sustain fiberboard production (Klímek *et al*. 2018).

Every year, the agricultural and forestry production industries generate abundant lignocellulosic residues (Huang *et al*. 2016; Cao *et al*. 2017). Until now, most of these residues have been burned or buried, which results in environmental pollution and wasted resources (Fan *et al*. 2015; Theng *et al*. 2017a). Recently, utilizing these residues in the fabrication of fiberboard has been considered a promising strategy, from both environmental and economic perspectives (Jin *et al*. 2017; Zhang *et al*. 2017). For example, Basta *et al*. (2017) manufactured bagasse boards bonded with activated carbon-modified urea-formaldehyde resin. Cao *et al*. (2017) prepared isocyanate-glued boards from sodium hydroxide-treated and ammonia-treated wheat straw. Dukarska *et al*. (2017) fabricated rapeseed straw boards bonded with mixed isocyanate/phenol-formaldehyde resin. Araújo Jr. *et al*. (2017) investigated boards produced from unripe coconut husk. Klímek *et al*. (2018) evaluated boards produced from *Miscanthus* stalk. Kusumah *et al*. (2017) studied the effects of the hot-pressing process on boards produced from sweet sorghum bagasse. Lenormand *et al*. (2017) surveyed the thermal and acoustic behaviors of sunflower pith boards. Qu *et al*. (2017) observed the influence of composting on the properties of rice straw and straw boards. Sahin *et al*. (2017) measured the physical-mechanical properties of boards made from peachnut shell and glass flour. Sam-Brew and Smith (2017) prepared boards from flax shive and hemp hurd residues. Theng *et al*. (2017a) assessed boards fabricated from the rice straw that was modified by a digestion plus defibration process. Uitterhaegen *et al*. (2017) manufactured boards from the coriander straw that was treated with a twin-screw extrusion method.

As a perennial woody grass, bamboo is cultivated worldwide (Li *et al*. 2013; Deng *et al*. 2017). Because bamboo is highly productive and fast-growing, it has been applied in a wide range of industries, such as in board production and the pulp and paper industries (Fan *et al*. 2015; Ramage *et al*. 2017). For bamboo, the stem consists of skin, timber, and pith, and the timber is further divided into the green, meat, and yellow according to the density of the vascular bundle (Xin *et al*. 2015; Wang *et al*. 2016b). In the bamboo processing industry, bamboo green and yellow are usually removed from the timber and become waste (Li *et al*. 2014; Pan *et al*. 2017). The reason for removing them has been explained by some researchers. Zhang *et al*. (2013) pointed out that bamboo green and yellow have abundant hydrophobic substances, such as silica and wax, which adversely affect the surface wettability and gluability of bamboo during board production. Xu *et al*. (2016) noted that the abundant silica in these fibrous raw materials negatively influences the pulping and papermaking processes, particularly the operations that occur in the evaporator, recovery furnace, and lime kiln. Currently, the utilization rate of crude bamboo is still lower than 40% by weight, and removing bamboo green produces abundant lignocellulosic residues (Fan *et al*. 2015). For example, China is recognized as the "bamboo kingdom" because of its abundant bamboo resources; it possesses the largest plantation area and highest annual yield in the world (Song *et al*. 2015). In China, the bamboo processing industry generates approximately 50 million tons of lignocellulosic residues each year, which are mainly composed of bamboo green and yellow (Huang *et al*. 2016).

With the development of the bamboo industry, the utilization of bamboo green has received increasing attention. During the past few years, some studies have been conducted on converting bamboo green into various biochemicals and biofuels. Huang *et al*. (2015) characterized hemicellulose extracted from bamboo green. Huang *et al*. (2016) isolated

ferulic acid from the cell walls of bamboo green. Li *et al*. (2014) studied the sulfite treatment of bamboo green for enzymatic saccharification. Li *et al*. (2015) assessed the impact of different reagents on the enzymatic hydrolysis of bamboo green. Xin *et al*. (2015) compared the influence of dilute acid and aqueous ammonia treatments on the physicochemical properties and enzymatic hydrolysis of bamboo green. Yang *et al*. (2016) employed visible-near infrared spectra to establish a fast method for analyzing the chemical composition and enzymatic digestibility of bamboo green. In addition to the above-mentioned reports, some researchers have investigated the surface properties of bamboo green and their effects on bamboo board production. Zhang *et al*. (2013) measured the impact of alkali treatment of bamboo green on the adhesion between the bamboo green strip and isocyanate. Deng *et al*. (2015) investigated the influence of the degree of bamboo green removal on the performance of laminated bamboo-bundle veneer lumber. Zhang *et al*. (2015) observed the surface chemistry and wettability of bamboo green that was modified by physical and chemical treatments. Although some fruitful research on bamboo green has been done, there are still many untouched issues that remain that need to be explored. For example, the literature does not currently contain any publications that report the effects of bamboo green on the properties of fiberboard. Therefore, it is still unknown whether bamboo green can serve as a desirable alternative material to sustain fiberboard production.

To address these unknowns, urea-formaldehyde resin-bonded fiberboards were prepared using bamboo green, wood, and a mixture of the two as the fibrous raw material in this research. The board type was determined by the mass fraction of the bamboo green in fibrous raw materials, which ranged from 0% to 100%. The analytical methods used to characterize the fibers and boards included X-ray diffraction, thermogravimetric analysis, dynamic mechanical analysis, contact angle analysis, physical-mechanical analysis, and scanning electron microscopy. Using these methods, the following analyses were conducted: (1) comparison of the properties of the bamboo green and wood; (2) comparison of the properties of the bamboo green fiberboard and wood fiberboard; and (3) analysis of the influence of the bamboo green mass fraction on the properties of the fiberboards made with a mixture of bamboo green and wood. The conclusions in this study can provide some new insights for the development of natural fiber composites from lignocellulosic residues.

EXPERIMENTAL

Materials

The bamboo green (species: *Neosinocalamus affinis*; main particle size: 20 mesh to 40 mesh) was purchased from Chitianhua Group (Guiyang, China). The wood fiber (species: *Populus tomentosa*; main particle size: 20 mesh to 40 mesh) and urea-formaldehyde resin (molar ratio of formaldehyde to urea: 1.1; solid mass fraction: 52%; pH: 8.5; viscosity: 40 cP; ammonium chloride curing agent mass fraction: 1% compared with solid resin) were purchased from Krono Wood-based Panels Co., Ltd. (Beijing, China).

Board Preparation

The bamboo green and wood were oven-dried to a moisture content of 3%. Using a laboratory blender, these fibrous raw materials were mixed with the resin. In fibrous raw materials (including bamboo green and wood), the mass fraction of the bamboo green

ranged from 0% to 100%. In total materials (including fibrous raw materials and resin), the mass fraction of the resin was 17%. Next, the resinated fibers were manually formed into mats, which had a moisture content of 12%. The target density and thickness of the boards were 0.75 g/cm^3 and 10 mm, respectively. Finally, the pre-pressed mats were hot-pressed at 180 °C for 2 min at a pressure of 2 MPa. Similar parameters for preparing boards have been used by other researchers (Kargarfard and Jahan-Latibari 2014; Lü *et al*. 2015; Hong *et al*. 2017; Kusumah *et al.* 2017; Theng *et al*. 2017b).

In this study, when the bamboo green mass fractions in fibrous raw materials were 0%, 20%, 40%, 60%, 80%, and 100%, the corresponding boards were labeled B0W1, B2W8, B4W6, B6W4, B8W2, and B1W0, respectively. It should be noted that when the bamboo green mass fraction was 0%, the fibrous raw material in the board was only wood and the corresponding board (B0W1) was a wood fiberboard; when this mass fraction was 100%, the fibrous raw material in the board was only bamboo green and the corresponding board (B1W0) was a bamboo green fiberboard. Three duplicate boards were produced for each level of bamboo green mass fraction in fibrous raw materials.

Analytical Methods

X-ray diffraction

The X-ray diffraction patterns of the fibers were collected with an X'Pert Pro X-ray diffractometer (PANalytical, Almelo, Netherlands) from the 2θ angles of 8° to 40° at a scanning rate of 2°/s. The diffractometer used Ni-filtered CuKα radiation (wavelength: 1.5406 Å) and was operated at 40 mA and 40 kV. The crystallinity index (*Crl*, %) of the cellulose was calculated with the following equation (Segal *et al*. 1959),

$$Crl = (I_{002} - I_{am})/I_{002} \times 100 \quad (1)$$

where I_{002} (a.u.) and I_{am} (a.u.) represent the peak intensities corresponding to the crystalline and amorphous fractions of the cellulose, respectively.

Thermogravimetric analysis

The thermogravimetric curves of the fibers and boards were recorded using a TGA Q500 thermogravimetric analyzer (TA Instruments, New Castle, DE, USA) from 100 °C to 500 °C at a heating rate of 10 °C/min and with a 60-mL/min nitrogen flow rate.

Dynamic mechanical analysis

The storage modulus and loss factor of the boards (dimensions: 55 mm × 12 mm × 3 mm) were measured using a DMA Q800 dynamic mechanical analyzer (TA Instruments) from 50 °C to 210 °C at a heating rate of 5 °C/min, under a dual-cantilever mode, and with a frequency of 1 Hz and amplitude of 30 μm.

Contact angle

The water contact angle with respect to the boards was recorded with an OCA20 contact angle meter (DataPhysics Instruments GmbH, Filderstadt, Germany). The measurement was repeated eight times.

Physical-mechanical properties

The water absorption of the boards was measured according to the Chinese national standard GB/T 17657 (2013). The thickness swelling, flexural strength, and flexural modulus of the boards were measured according to the Chinese national standard GB/T

11718 (2009). The water absorption and thickness swelling were measured after the boards were soaked in 20 °C water for 24 h. The flexural properties were measured with the three-point flexural test. The water absorption measurement was repeated three times, and the flexural measurement was repeated six times. The mechanical measurement was performed using an MWW-50 universal mechanical testing machine (Tayasaf Corporation, Beijing, China). The statistical analysis was done using the software SPSS 20 (IBM, Armonk, NY, USA).

Scanning electron microscopy

The flexural fracture surface of the boards was observed using an SU8010 scanning electron microscope (Hitachi, Tokyo, Japan) under an acceleration voltage of 5 kV. Before observation, the samples were sputter-coated with gold.

RESULTS AND DISCUSSION

Comparison of the Bamboo Green and Wood Properties

X-ray diffraction analysis

Figure 1a shows the X-ray diffraction patterns of the bamboo green and wood. Both fibers showed peaks at the 2θ angles of 16°, 22°, and 35°, which indicated that they possessed a crystalline structure of native cellulose I (Song *et al*. 2015).

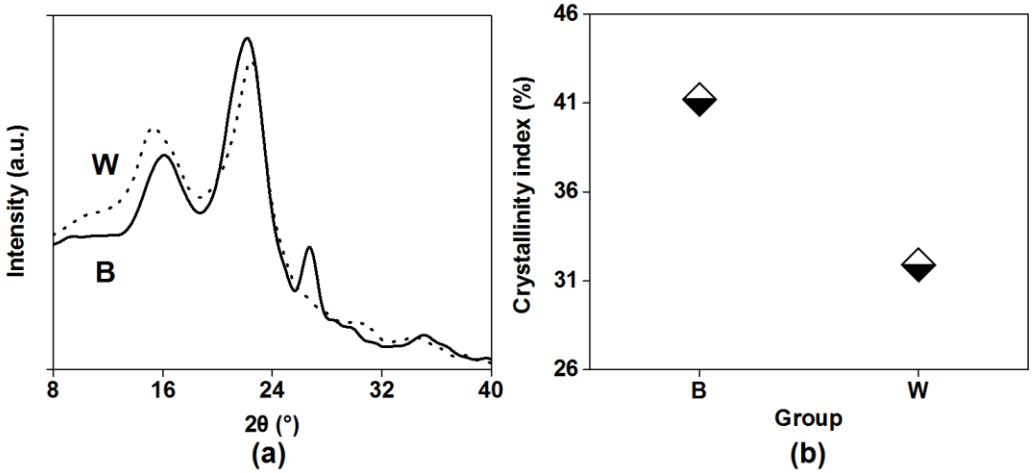

Fig. 1. X-ray diffraction pattern (a) and crystallinity index (b) of bamboo green (B) and wood (W)

Moreover, at the 2θ angle of 26°, there was a peak in the diffraction pattern of the bamboo green, but not in that of the wood. This peak was related to silica (Lee *et al*. 2017). Therefore, Fig. 1a demonstrates that, compared with the wood, the bamboo green contained more silica, which is a hydrophobic substance that will adversely influence the surface wettability and gluability (Zhang *et al*. 2013). Similar results can be found in previous reports. Deng *et al*. (2015) observed the contact angle of bamboo with different removal degrees of bamboo green, and found that increasing the removal degree decreased the contact angle of phenol-formaldehyde resin on the bamboo. Zhang *et al*. (2013) evaluated the bonding performance of sodium hydroxide-treated bamboo green, and found that the treatment enhanced the adhesion between the bamboo green strip and isocyanate. These authors explained that the surface of the bamboo green is usually covered with abundant

silica and wax. Removing the bamboo green reduced the amount of these hydrophobic substances, and thus promoted the surface wettability of the bamboo. Moreover, alkali conditions dissolved these hydrophobic substances, which boosted the gluability of the bamboo green.

Figure 1b shows that the crystallinity index of the bamboo green was higher than that of the wood. This difference may have been related to their chemical composition. For example, the presence of some amorphous compounds, such as hemicellulose, lignin, and amorphous cellulose, can decrease the crystallinity index of lignocellulosic fiber (Song *et al*. 2017a). Therefore, Fig. 1b indicates that the bamboo green may have had a lower content of these amorphous compounds compared with the wood. In the future, the differences in the chemical composition between the bamboo green and wood should be further studied.

Thermogravimetric analysis

Figure 2 shows the thermogravimetric curves for the bamboo green and wood. When the temperature increased from 100 °C to 200 °C, the weight loss of the fiber was mainly caused by dehydration (Feng *et al*. 2012). Over this temperature range, the bamboo green lost less weight than the wood, which indicated that the bamboo green had a lower hygroscopicity and moisture content. This may have been because the surface of the bamboo green was covered with an abundant amount of hydrophobic substances, such as silica and wax (see Fig. 1 analysis). Moreover, this may also have been related to the higher crystallinity index of the bamboo green (see Fig. 1 analysis), which could have decreased the accessibility of hydrophilic hydroxyl groups in the bamboo green to water molecules (Song *et al*. 2017a).

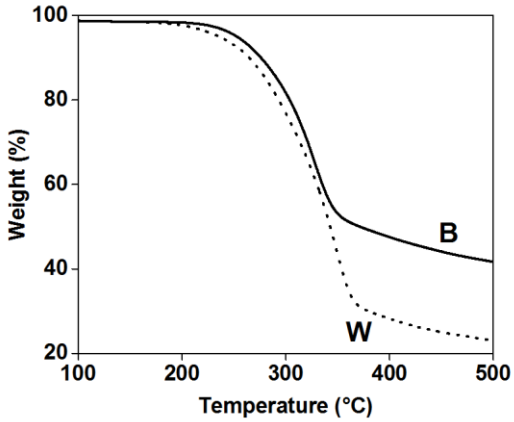

Fig. 2. Thermogravimetric curves of the bamboo green (B) and wood (W)

When the temperature was increased from 200 °C to 500 °C, the weight loss of the fiber was mainly attributable to the degradation of cell wall compounds, such as hemicellulose, cellulose, and lignin (Song *et al*. 2017b). Over this temperature range, the bamboo green lost less weight than the wood, which indicated that the bamboo green possessed a higher resistance to pyrolysis. This may have been because the bamboo green contained abundant silica (see Fig. 1 analysis), which hindered the heat transmission and enhanced the thermal stability (Liu *et al*. 2016). Similar results can be found in previous reports. Wang *et al*. (2011) observed the thermogravimetric curves of a starch-based wood adhesive and found that the silica-modified adhesive lost less weight from 200 °C to 500

°C. They explained that the silica enhanced the molecular structure of the adhesive, which improved its thermal stability.

Comparison of the Properties of the Bamboo Green Fiberboard and Wood Fiberboard

Dynamic mechanical analysis

Figure 3 shows the dynamic mechanical properties of B1W0 and B0W1. When the temperature increased from 50 °C to 210 °C, the storage modulus retention ratio of the boards (*i.e*., the ratio of the storage modulus at a given temperature to the storage modulus at 50 °C) decreased, but the loss factor increased. This was because increasing the temperature weakened the intermolecular forces in the composites, which decreased the stiffness and elasticity of the boards and increased their toughness and viscosity (Ren *et al*. 2014; Song *et al*. 2017b).

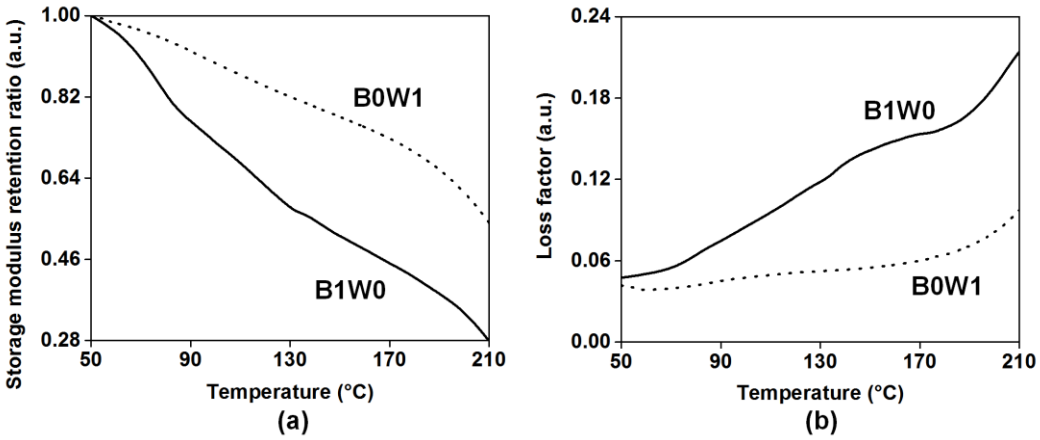

Fig. 3. Dynamic mechanical properties of B1W0 and B0W1: (a) storage modulus retention ratio and (b) loss factor

Using the dynamic mechanical data, the interfacial bonding of the natural fiber composites can be evaluated by analyzing the adhesion factor (*A*, a.u.), which can be calculated with Eq. 2,

$$A = 1/(1\text{-}V_f) \times \tan\delta_b/\tan\delta_r - 1 \quad (2)$$

where V_f represents the fiber volume fraction in the boards, and $\tan\delta_b$ and $\tan\delta_r$ represent the loss factor of the board and resin, respectively (Wang *et al*. 2017).

Because B1W0 and B0W1 possessed the same V_f and $\tan\delta_r$ values, their *A* value was affected only by the $\tan\delta_b$ value. Figure 3b shows the $\tan\delta_b$ value of B1W0 was higher than that of B0W1 from 50 °C to 210 °C; thus, the *A* value of B1W0 was higher than that of B0W1. Typically, a lower *A* value reflects a stronger interaction between the fiber and resin, which leads to a higher interfacial bonding in the composites (Luo *et al*. 2017). Therefore, the *A* values indicated that the bamboo green had a weaker interaction with the resin and that B1W0 had a lower interfacial bonding. This may have been because the bamboo green contained abundant silica and wax (see Fig. 1 analysis), and these hydrophobic substances adversely affected its wettability and gluability.

Figure 3a shows B1W0 exhibited a lower storage modulus retention ratio than B0W1 from 50 °C to 210 °C, which indicated that the stiffness properties of B1W0 were more thermally unstable than those of B0W1 (Ren *et al*. 2014). This could be explained by

the lower interfacial bonding in B1W0, which made the stress transfer not very efficient; hence, it was more likely for the stiffness properties of B1W0 to be negatively affected by the increase in temperature (Lu *et al*. 2014).

Figure 3b shows B1W0 gave a higher loss factor than B0W1 from 50 °C to 210 °C, which indicated that the viscosity and elasticity of B1W0 was higher and lower than that of B0W1, respectively (Song *et al*. 2017b). This result was also supported by the lower interfacial bonding in B1W0 (Ren *et al*. 2014). Typically, a higher loss factor means that a material possesses a greater damping capacity (Li and Wang 2017). Under loading, this material is more likely to convert energy into heat, which is dissipated within the material itself, rather than released into the air as noise (Ren *et al*. 2014). Therefore, Fig. 3b reveals that bamboo green could make the boards more efficient at absorbing sound or other undesirable vibrations (Zhu *et al*. 2017).

Thermogravimetric analysis

Figure 4 shows the thermogravimetric curves of B1W0 and B0W1. When the temperature increased from 100 °C to 200 °C, the weight loss of the fiberboard was primarily attributed to water evaporation (Song *et al*. 2017b). Over this temperature range, B1W0 lost less weight than B0W1, which indicated that B1W0 had a lower hygroscopicity and moisture content. This may have been because the bamboo green had a lower hygroscopicity and moisture content than the wood (see Fig. 2 analysis). Moreover, when the temperature increased from 100 °C to 200 °C, B1W0 lost less weight than the bamboo green and B0W1 lost less weight than the wood. These results indicated that the hygroscopicity and moisture content of the boards were lower than those of the corresponding fibrous raw materials. This may have been because these boards were prepared through a hot-pressing process, and the heat treatment reduced the hygroscopicity and moisture content of the materials (Song *et al*. 2017a).

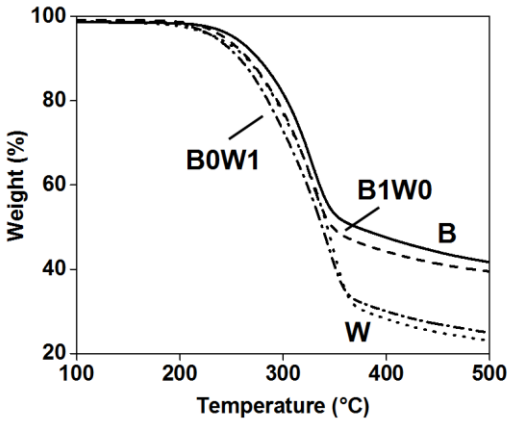

Fig. 4. Thermogravimetric curves of the bamboo green (B), wood (W), B1W0, and B0W1

When the temperature increased from 200 °C to 500 °C, the weight loss of the fiberboard was primarily attributed to the degradation of plant cell wall components (Song *et al*. 2017b). Over this temperature range, B1W0 lost less weight than B0W1, which indicated that B1W0 had a higher pyrolysis resistance. This may have been because the bamboo green possessed a higher pyrolysis resistance than the wood (Fig. 2). When the temperature increased from 200 °C to 360 °C, B1W0 lost more weight than the bamboo green and B0W1 also lost more weight than the wood, which indicated that the pyrolysis

resistances of the boards were lower than those of the corresponding fibrous raw materials. This may have been because the urea-formaldehyde resin in the boards began to degrade after 200 °C and accelerated the degradation of the boards over this temperature range (Feng *et al*. 2012). When the temperature increased from 360 °C to 500 °C, B1W0 lost more weight than the bamboo green but B0W1 lost less weight than the wood, which indicated that the pyrolysis resistance of B1W0 was still lower than that of the bamboo green, but the pyrolysis resistance of B0W1 was higher than that of the wood. This may have been because the interaction between the resin and bamboo green was different from that between the resin and wood. It has been reported that urea-formaldehyde resin can enhance cross-linking between the main components of lignocellulosic fiber and inhibit the degradation of fiberboard over this temperature range (Feng *et al*. 2012). Therefore, the urea-formaldehyde resin noticeably inhibited the degradation of B0W1. However, the bamboo green had a weaker interaction with the resin (Fig. 3), and thus the urea-formaldehyde resin did not remarkably inhibit the degradation of B1W0.

Contact angle analysis

Figure 5 shows the initial water contact angle on B1W0 and B0W1. The contact angle of B1W0 was lower than 90° and that of B0W1 was higher than 90°, which indicated that the surface of B1W0 was hydrophilic and that of B0W1 was hydrophobic (Song *et al*. 2018). Because the fibrous raw materials in B1W0 and B0W1 were encapsulated within the urea-formaldehyde resin, the contact angle results indicated that the resin in B1W0 was more hydrophilic than that in B0W1. This could have been because when using urea-formaldehyde resin to prepare natural fiber composites, the hydrophilic active functional groups in the resin react with the fibrous raw materials, during which some of these groups are consumed (Chen *et al*. 2017; Zhou *et al*. 2017). When analyzing the results exhibited in Fig. 3, it was demonstrated that, compared with the wood, the bamboo green experienced a weaker interaction with the resin. Therefore, when preparing B1W0, many hydrophilic active functional groups in the resin could not be consumed, which made the resin in B1W0 more hydrophilic. Typically, to improve the physical-mechanical properties of fiberboards and to reduce their formaldehyde emissions, boards will be coated with some decorative surface materials, and a good board wettability is required when performing this treatment (Buyuksari *et al*. 2010). Therefore, as the results displayed in Fig. 5 indicated, the bamboo green was able to improve the wettability of the boards, and thus made them easier to be coated.

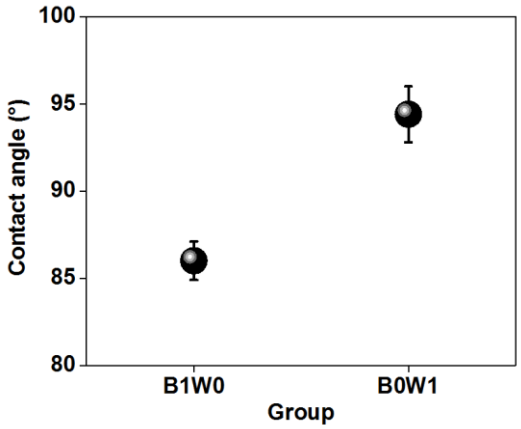

Fig. 5. Initial water contact angle on B1W0 and B0W1

Physical-mechanical analysis

Figure 6 shows the physical-mechanical properties of B1W0 and B0W1. The water absorption of B1W0 was 6.3% higher than that of B0W1, which indicated that B1W0 absorbed more water during 24 h of water immersion. The thickness swelling of B1W0 was 9.8% lower than that of B0W1, which indicated that B1W0 exhibited a better dimensional stability after absorbing water. The flexural strength of B1W0 was 16.8% lower than that of B0W1, which indicated that B1W0 had a lower resistance to flexural fracture. The flexural modulus of B1W0 was 31.7% higher than that of B0W1, which indicated that B1W0 displayed a higher resistance to flexural deformation.

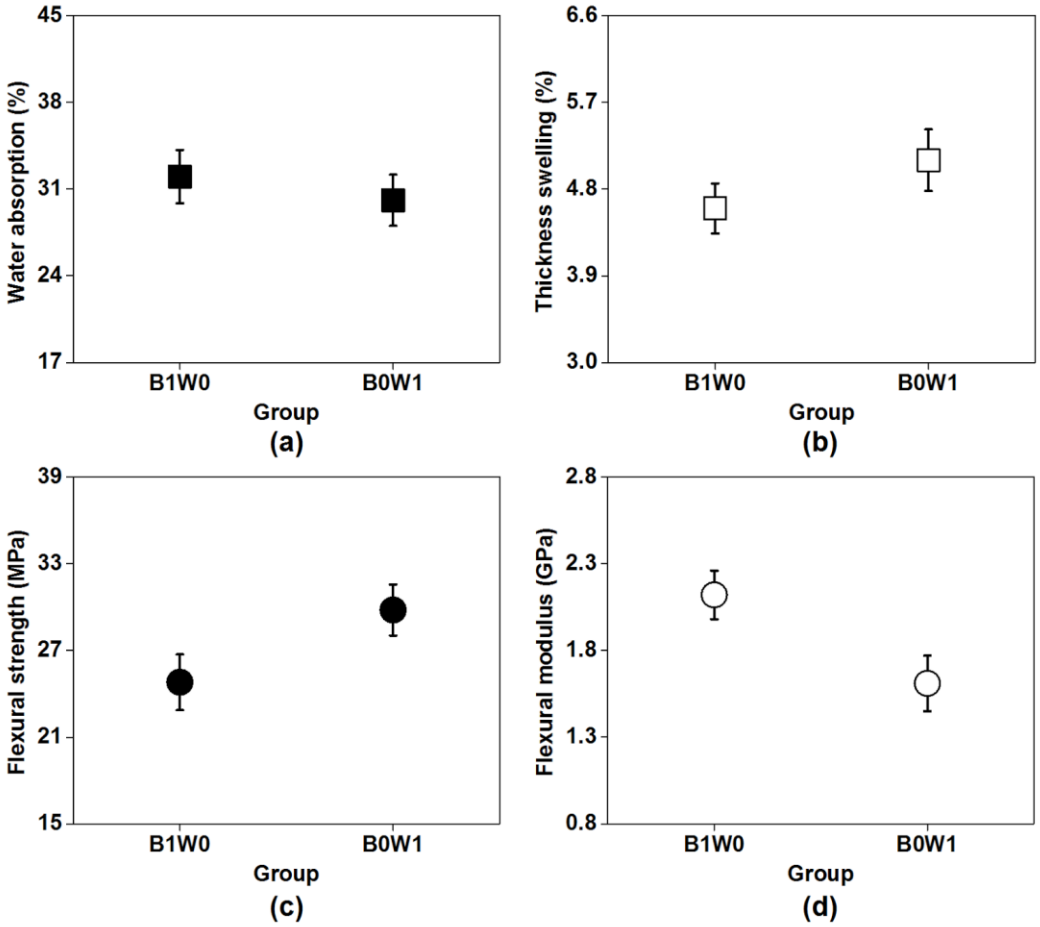

Fig. 6. Physical-mechanical properties of B1W0 and B0W1: (a) water absorption, (b) thickness swelling, (c) flexural strength, and (d) flexural modulus

When analyzing the results displayed in Fig. 3, it was confirmed that B1W0 had a lower interfacial adhesion than B0W1. Therefore, the interface of B1W0 will have more gaps, which allowed more water to enter the boards during water immersion and negatively affected the stress transfer in the boards, causing B1W0 to show a higher water absorption and lower flexural strength (Song *et al*. 2017b; Xu and Fu 2017). Similar results can be found in previous reports. For example, Tang *et al*. (2017) observed that increasing the resin content improved the interfacial adhesion of poplar wood fiberboards, and thus reduced the water absorption of the boards. Kurokochi and Sato (2015) reported that rice straw contains abundant silica and wax; after removing these hydrophobic substances, the

interfacial adhesion of the straw boards was enhanced, which increased the flexural strength of the boards.

When analyzing the results shown in Fig. 2, it was noted that the bamboo green possessed a lower hygroscopicity than the wood. During water immersion of the boards, the lower hygroscopicity prevented the bamboo green from absorbing water and expanding, which caused B1W0 to exhibit a lower thickness swelling (Chang *et al*. 2018). When analyzing Fig. 1, it was determined that the bamboo green displayed a higher crystallinity index than the wood. The higher value gave the bamboo green a higher stiffness and caused B1W0 to obtain a higher flexural modulus (Cao *et al*. 2017). Similar results can be found in previous reports. For example, Kurokochi and Sato (2015) determined that when the content of silica and wax in rice straw increased, the hygroscopicity of the straw decreased, which led to a lower thickness swelling for straw boards. Cao *et al*. (2017) found that a sodium hydroxide treatment for wheat straw increased its crystallinity index, and resulted in straw boards with a higher flexural modulus.

Scanning electron microscope analysis

Figure 7 shows the flexural fracture surface of B1W0 and B0W1. Compared with B0W1, B1W0 exhibited a surface with a more homogenous texture, which indicated that there was a better dispersion of the fibrous raw materials in B1W0 (Liu *et al*. 2014). This was because the surface of the bamboo green was coated with abundant silica and wax (Fig. 1), and these hydrophobic substances made the fibrous raw materials unlikely to agglomerate, which led to a higher fiber dispersion in the boards (Ahamad Nordin *et al*. 2017). Figure 7a shows that there were many small gaps on the surface of B1W0, which reflected a lower interfacial adhesion (Song *et al*. 2017b). Similar to the dispersion result, this result was also related to the abundant silica and wax in the bamboo green, as these hydrophobic substances negatively affected its wettability and gluability (Deng *et al*. 2015). In contrast, Fig. 7b displays fiber splitting and tearing on the surface of B0W1, which meant that stress was transferred from the resin to the fibers (Liu *et al*. 2014). This revealed a higher interfacial adhesion between the wood and resin (Ahamad Nordin *et al*. 2017).

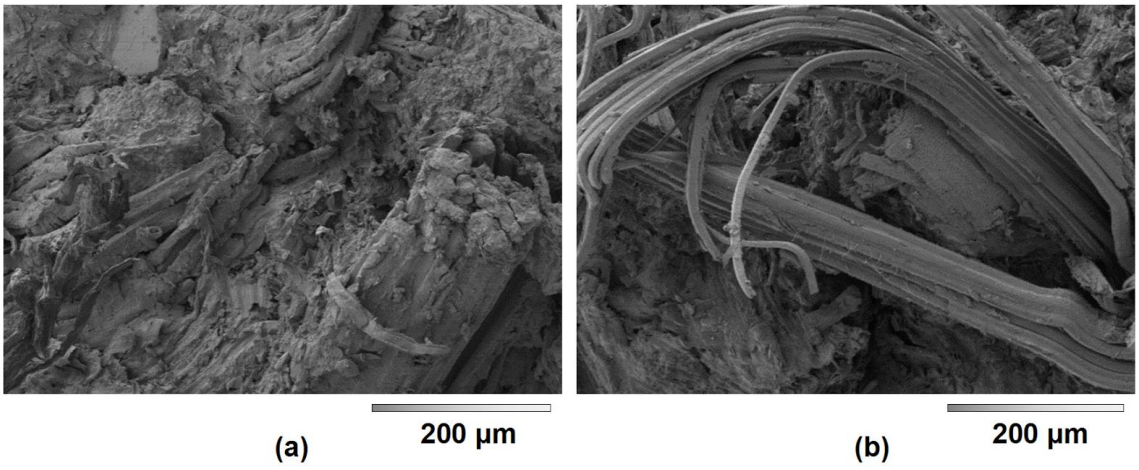

Fig. 7. Flexural fracture surface of (a) B1W0 and (b) B0W1

Influence of the Bamboo Green Mass Fraction on the Properties of the Fiberboards Made with a Mixture of Bamboo Green and Wood

Physical-mechanical analysis

Figure 8 shows the physical-mechanical properties of the boards with different bamboo green mass fractions in fibrous raw materials.

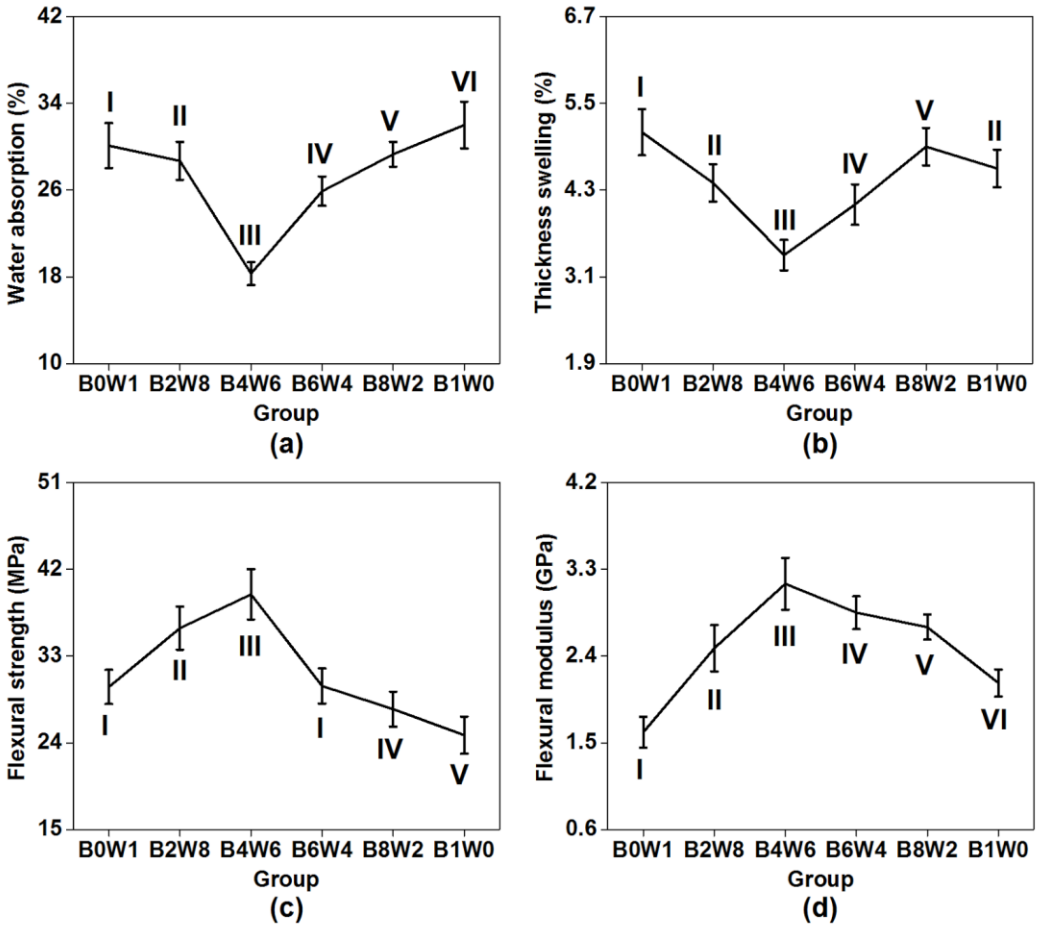

Fig. 8. Physical-mechanical properties of B0W1, B2W8, B4W6, B6W4, B8W2, and B1W0: (a) water absorption, (b) thickness swelling, (c) flexural strength, and (d) flexural modulus; different Roman numerals (I to VI) indicate differences at a 0.05-significance level between groups

The B0W1, B2W8, B4W6, B6W4, B8W2, and B1W0 boards corresponded to the bamboo green mass fractions of 0%, 20%, 40%, 60%, 80%, and 100%, respectively. Compared with the data recorded for B0W1, the water absorption of B2W8, B4W6, B6W4, B8W2, and B1W0 varied by -4.7%, -39.2%, -14.0%, -2.7%, and 6.3%, respectively; their thickness swelling values varied by -13.7%, -33.3%, -19.6%, -3.9%, and -9.8%, respectively; their flexural strength values varied by 20.5%, 32.2%, 0.3%, -7.7%, and -16.8%, respectively; and their flexural modulus values varied by 54.0%, 95.7%, 77.0%, 67.7%, and 31.7%, respectively. The analysis of variance indicated that the different bamboo green mass fractions in fibrous raw materials produced a significant effect at the 0.05-significance level for all four properties. The optimum water absorption, thickness swelling, flexural strength, and flexural modulus values were all measured with B4W6.

The results shown in Fig. 8 indicated that increasing the bamboo green mass fraction in fibrous raw materials could positively or negatively affect the physical-mechanical properties of the boards. For example, increasing the bamboo green mass fraction from 0% to 40% decreased the water absorption and thickness swelling of the boards and increased the flexural strength and flexural modulus. However, increasing the bamboo green mass fraction from 40% to 100% increased the water absorption and thickness swelling of the boards and decreased the flexural strength and flexural modulus. At the different bamboo green mass fractions, the changes of physical-mechanical properties of the boards were attributed to the interactions between the bamboo green and wood (Lü *et al*. 2015; De Almeida *et al*. 2017). When analyzing the results shown in Figs. 6 and 7, the positive effect and negative effect of bamboo green and wood on the four physical-mechanical properties and microscopic morphology of fiberboard were already explained. Overall, the results displayed in Fig. 8 revealed that the interaction between the bamboo green and wood had the greatest positive effect on the physical-mechanical properties of the boards when the bamboo green mass fraction was 40%.

When preparing boards made with a mixture of wood and other fibrous raw materials, the physical-mechanical properties of the boards could be positively or negatively affected by the mixture ratio. Similar results can be found in previous reports. For example, Lü *et al*. (2015) studied boards produced from a mixture of corn stalk skin and poplar wood particles. They found that varying the ratio of the mixture from 3:7 to 5:5 decreased the thickness swelling and flexural strength of the boards, and varying the ratio from 5:5 to 7:3 increased the thickness swelling and decreased the flexural strength. Moreover, De Almeida *et al*. (2017) studied boards produced from a mixture of *Dendrocalamus asper* and eucalyptus wood particles. They found that varying the ratio of the mixture from 0:10 to 2.5:7.5 increased the flexural strength and flexural modulus of the boards. The above authors explained their results based on the physicochemical properties of the different fibrous raw materials.

Scanning electron microscope analysis

Figure 9 shows the flexural fracture surface of B2W8, B4W6, B6W4, and B8W2. Compared with B2W8, B6W4, and B8W2, B4W6 had a surface with a more homogenous texture, which indicated that the fibrous raw materials in B4W6 were better dispersed (Liu *et al*. 2014). Compared with the surface of B2W8, B6W4, and B8W2, the surface of B4W6 also displayed fewer gaps, which reflected a higher interfacial bonding (Song *et al*. 2017b). Moreover, the surface of B4W6 exhibited splitting and tearing of its fibers, as its good interfacial bonding allowed the efficient transfer of stress from the resin to the fibers (Liu *et al*. 2014). When comparing the flexural fracture surface of B1W0 and B0W1 (see Fig. 7 analysis), it was noted that the fibrous raw materials in B1W0 were better dispersed, but B0W1 had a higher interfacial bonding. Therefore, for the results exhibited in Fig. 9, the better morphological properties of B4W6 indicated that, when using a mixture of bamboo green and wood to prepare the boards, the bamboo green improved the dispersion of the fibrous raw materials and the wood enhanced the interfacial bonding in the boards. Overall, the results displayed in Fig. 9 demonstrated that when the mass fraction of bamboo green was 40%, the interaction between the bamboo green and wood resulted in the biggest positive influence on the morphological properties of the boards.

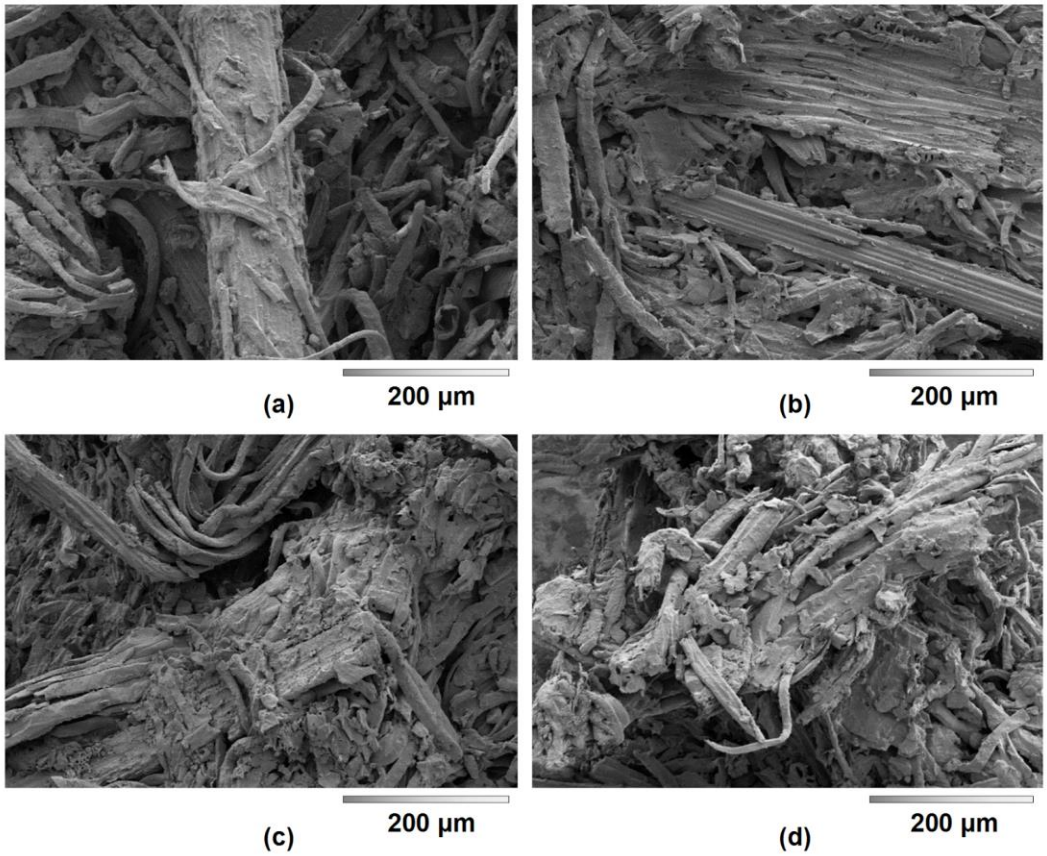

Fig. 9. Flexural fracture surface of (a) B2W8, (b) B4W6, (c) B6W4, and (d) B8W2

Performance evaluation

In this study, the thickness swelling, flexural strength, and flexural modulus of the boards were measured according to the Chinese national standard GB/T 11718 (2009) for MDF; thus, the results were evaluated based on the requirements of this standard. According to GB/T 11718 (2009), when the thickness of the boards is 9 mm to 13 mm, the highest requirement for the thickness swelling is 7.0% for MDF-FN EXT (furniture-grade boards for use in exterior conditions) and the highest requirements for the flexural strength and flexural modulus are 32.0 MPa and 2.80 GPa, respectively, for MDF-LB HMR (load-bearing boards for use in high-humid conditions). Figure 8 shows that B4W6 had better physical-mechanical properties than the other boards. Compared with the above requirements, B4W6 possessed a lower thickness swelling and higher flexural strength and flexural modulus.

Compared with B4W6, B0W1 showed a higher water absorption and thickness swelling and lower flexural strength and flexural modulus. Although the thickness swelling of B0W1 met the requirement for MDF-FN EXT, its flexural strength and flexural modulus did not meet the requirements for MDF-LB HMR. The fiber type in B0W1 was wood, but B4W6 contained a mixture of bamboo green and wood. Therefore, the better performance of B4W6 indicated that adding a certain amount of bamboo green noticeably improved the physical-mechanical properties of the fiberboard.

This research demonstrated the potential of bamboo green to act as an alternative material in the development of fiberboards. Fiberboards made from a mixture of bamboo green and wood should be further studied. This would allow, for example, an optimum

bamboo green mass fraction in fibrous raw materials to be determined. Moreover, the effects of elements of the hot-pressing process, such as the temperature and duration, on the physical-mechanical properties of the boards could also be investigated.

CONCLUSIONS

1. It was determined that bamboo green has the potential to serve as an alternative fibrous raw material in the production of fiberboards.
2. The properties of the bamboo green were found to be different from those of the wood. Compared with the wood, the bamboo green exhibited a higher crystallinity index and thermogravimetric stability, but lower surface hydrophilicity and weaker interaction with the urea-formaldehyde resin.
3. The properties of bamboo green fiberboard B1W0 were different from those of wood fiberboard B0W1. Compared with B0W1, B1W0 displayed a lower interfacial adhesion, but the fibrous raw materials in B1W0 were better dispersed. Moreover, B1W0 had a higher dynamic viscosity, thermogravimetric stability, surface wettability, water absorption, and flexural modulus, but lower thickness swelling and flexural strength.
4. Fiberboards produced with a mixture of bamboo green and wood can give a better physical-mechanical properties than B0W1, but their properties were distinctly affected by the mass fraction of bamboo green in fibrous raw materials. Compared with the bamboo green mass fractions of 0%, 20%, 60%, 80%, and 100%, the mass fraction of 40% (corresponding to board B4W6) resulted in a lower water absorption and thickness swelling and higher flexural strength and flexural modulus.

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REFERENCES CITED

Ahamad Nordin, N. I. A., Ariffin, H., Hassan, M. A., Shirai, Y., Ando, Y., Ibrahim, N. A., and Wan Yunus, W. M. Z. (2017). "Superheated steam treatment of oil palm mesocarp fiber improved the properties of fiber-polypropylene biocomposite," *BioResources* 12(1), 68-81. DOI: 10.15376/biores.12.1.68-81

Araújo Jr., C. P., Coaquira, C. A. C., Mattos, A. L. A., de Souza Filho, M. d. S. M., de Andrade Feitosa, J. P., de Morais, J. P. S., and de Freitas Rosa, M. (2017).

"Binderless fiberboards made from unripe coconut husks," *Waste Biomass Valori.*, 1-10. DOI: 10.1007/s12649-017-9979-9

Basta, A. H., El-Saied, H., Baraka, A. M., and Lotfy, V. F. (2017). "Performance of carbon xerogels in the production of environmentally friendly urea formaldehyde-bagasse composites," *CLEAN-Soil Air Water* 45(6), 1600524. DOI: 10.1002/clen.201600524

Buyuksari, U., Avci, E., Ayrilmis, N., and Akkilic, H. (2010). "Effect of pine cone ratio on the wettability and surface roughness of particleboard," *BioResources* 5(3), 1824-1833. DOI: 10.15376/biores.5.3.1824-1833

Cao, Y., Song, W., Yang, Z., Chen, Z., and Zhang, S. (2017). "The properties of particleboard made from alkaline-treated wheat straw and methylene diphenyl diisocyanate binder," *BioResources* 12(2), 3265-3276. DOI: 10.15376/biores.12.2.3265-3276

Chang, L., Tang, Q., Gao, L., Fang, L., Wang, Z., and Guo, W. (2018). "Fabrication and characterization of HDPE resins as adhesives in plywood," *Eur. J. Wood Wood Prod.* 76(1), 325-335. DOI: 10.1007/s00107-016-1117-z

Chen, Y., Li, J., Liu, F., Xie, L., and Xiao, H. (2017). "Effects of temperature and solid content on the pre-curing behavior of urea-formaldehyde resin," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 41(3), 145-150. DOI: 10.3969/j.issn.1000-2006.200607036

De Almeida, A. C., De Araujo, V. A., Morales, E. A. M., Gava, M., Munis, R. A., Garcia, J. N., and Barbosa, J. C. (2017). "Wood-bamboo particleboard: Mechanical properties," *BioResources* 12(4), 7784-7792. DOI: 10.15376/biores.12.4.7784-7792

Deng, J., Li, H., Wang, G., Chen, F., and Zhang, W. (2015). "Effect of removing extent of bamboo green on physical and mechanical properties of laminated bamboo-bundle veneer lumber (BLVL)," *Eur. J. Wood Wood Prod.* 73(4), 499-506. DOI: 10.1007/s00107-015-0897-x

Deng, L., Zhan, H., He, W., Zhao, J., and Wang, S. (2017). "Developmental changes of fiber wall of *Fargesia fungosa*," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 41(4), 147-152. DOI: 10.3969/j.issn.1000-2006.201701001

Dettmer, J., and Smith, G. D. (2015). "Comparing properties of North American manufactured particleboard and medium density fiberboard – Part I: Particleboard," *BioResources* 10(3), 6014-6031. DOI: 10.15376/biores.10.3.6014-6031

Dukarska, D., Czarnecki, R., Dziurka, D., and Mirski, R. (2017). "Construction particleboards made from rapeseed straw glued with hybrid pMDI/PF resin," *Eur. J. Wood Wood Prod.* 75(2), 175-184. DOI: 10.1007/s00107-016-1143-x

Fan, L., Ruan, R., Liu, Y., Wang, Y., and Tu, C. (2015). "Effects of extraction conditions on the characteristics of ethanol organosolv lignin from bamboo (*Phyllostachys pubescens* Mazel)," *BioResources* 10(4), 7998-8013. DOI: 10.15376/biores.10.4.7998-8013

Feng, Y., Mu, J., Chen, S., Huang, Z., and Yu, Z. (2012). "The influence of urea formaldehyde resins on pyrolysis characteristics and products of wood-based panels," *BioResources* 7(4), 4600-4613. DOI: 10.15376/biores.7.4.4600-4613

GB/T 11718 (2009). "Medium density fiberboard," Standardization Administration of China, Beijing, China.

GB/T 17657 (2013). "Test methods of evaluating the properties of wood-based panels and surface decorated wood-based panels," Standardization Administration of China, Beijing, China.

Guan, C., Zhang, H., Miao, H., and Zhou, L. (2017). "Non-destructive determination of modulus of elasticity and in-plane shear modulus of full-size wood composite panels," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 41(4), 153-159. DOI: 10.3969/j.issn.1000-2006.201609020

Hong, M.-K., Lubis, M. A. R., and Park, B.-D. (2017). "Effect of panel density and resin content on properties of medium density fiberboard," *Journal of the Korean Wood Science and Technology* 45(4), 444-455. DOI: 10.5658/WOOD.2017.45.4.444

Huang, C.-X., He, J., Min, D.-Y., Li, X., Du, L.-T., and Yong, Q. (2016). "Quantitative determination of ferulic and *p*-coumaric acids in cell wall of moso bamboo green and bamboo yellow," *Chemistry and Industry of Forest Products* 36(3), 16-22. DOI: 10.3969/j.issn.0253-2417.2016.03.003

Huang, C.-X., He, J., Min, D.-Y., Li, X., and Yong, Q. (2015). "Isolation and characterization of hemicellulose from *Moso* bamboo green and bamboo yellow," *Chemistry and Industry of Forest Products* 35(5), 29-36. DOI: 10.3969/j.issn.0253-2417.2015.05.006

Jin, X., Wu, G., Sun, E., Tang, W., Huang, H., and Chen, L. (2017). "Improving processability of rice straw by fermentation using *Streptomyces rochei*," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 41(2), 122-128. DOI: 10.3969/j.issn.1000-2006.2017.02.018

Kargarfard, A., and Jahan-Latibari, A. (2014). "The effect of press temperature on properties of medium density fiberboard produced from *Eucalyptus camaldulensis* fibers," *International Journal of Lignocellulosic Products* 1(2), 142-150.

Klímek, P., Wimmer, R., Meinlschmidt, P., and Kúdela, J. (2018). "Utilizing *Miscanthus* stalks as raw material for particleboards," *Ind. Crop. Prod.* 111, 270-276. DOI: 10.1016/j.indcrop.2017.10.032

Kurokochi, Y., and Sato, M. (2015). "Effect of surface structure, wax and silica on the properties of binderless board made from rice straw," *Ind. Crop. Prod.* 77, 949-953. DOI: 10.1016/j.indcrop.2015.10.007

Kusumah, S. S., Umemura, K., Guswenrivo, I., Yoshimura, T., and Kanayama, K. (2017). "Utilization of sweet sorghum bagasse and citric acid for manufacturing of particleboard II: Influences of pressing temperature and time on particleboard properties," *J. Wood Sci.* 63(2), 161-172. DOI: 10.1007/s10086-016-1605-0

Lee, M., Jang, J., Lee, S., and Park, S. (2017). "Effect of loess treatment and carbonization on the hygric performance of medium-density fiberboard," *BioResources* 12(3), 6418-6426. DOI: 10.15376/biores.12.3.6418-6426

Lenormand, H., Glé, P., and Leblanc, N. (2017). "Investigation of the acoustical and thermal properties of sunflower particleboards," *Acta Acust. United Ac.* 103(1), 149-157. DOI: 10.3813/AAA.919040

Li, K., Wang, X., Wang, J., and Zhang, J. (2015). "Benefits from additives and xylanase during enzymatic hydrolysis of bamboo shoot and mature bamboo," *Bioresource Technol.* 192, 424-431. DOI: 10.1016/j.biortech.2015.05.100

Li, Z., Jiang, Z., Fei, B., Cai, Z., and Pan, X. (2014). "Comparison of bamboo green, timber and yellow in sulfite, sulfuric acid and sodium hydroxide pretreatments for enzymatic saccharification," *Bioresource Technol.* 151, 91-99. DOI: 10.1016/j.biortech.2013.10.060

Li, Z., Jiang, Z., Fei, B., Pan, X., Cai, Z., Liu, X., and Yu, Y. (2013). "Ethanosolv with NaOH pretreatment of moso bamboo for efficient enzymatic saccharification," *BioResources* 8(3), 4711-4721. DOI: 10.15376/biores.8.3.4711-4721

Li, Z., and Wang, W. (2017). "Preparation and properties of polypropylene based composites with high wood fibers content," *Journal of Forestry Engineering* 2(2), 9-15. DOI: 10.13360/j.issn.2096-1359.2017.02.002

Liu, R., Chen, Y., and Cao, J. (2016). "Effects of modifier type on properties of *in situ* organo-montmorillonite modified wood flour/poly(lactic acid) composites," *ACS Appl. Mater. Inter.* 8(1), 161-168. DOI: 10.1021/acsami.5b07989

Liu, R., Peng, Y., Cao, J., and Chen, Y. (2014). "Comparison on properties of lignocellulosic flour/polymer composites by using wood, cellulose, and lignin flours as fillers," *Compos. Sci. Technol.* 103, 1-7. DOI: 10.1016/j.compscitech.2014.08.005

Lü, H., Zhang, X., and Yu, B. (2015). "Optimization of corn-stalk skin flake-wood shaving composite technology," *J. Forestry Res.* 26(3), 759-763. DOI: 10.1007/s11676-015-0054-8

Lu, T., Liu, S., Jiang, M., Xu, X., Wang, Y., Wang, Z., Gou, J., Hui, D., and Zhou, Z. (2014). "Effects of modifications of bamboo cellulose fibers on the improved mechanical properties of cellulose reinforced poly(lactic acid) composites," *Compos. Part B-Eng.* 62, 191-197. DOI: 10.1016/j.compositesb.2014.02.030

Luo, S., Cao, J., and Sun, W. (2017). "Evaluation of kraft lignin as natural compatibilizer in wood flour/polypropylene composites," *Polym. Composite.* 38(11), 2387-2394. DOI: 10.1002/pc.23821

Pan, H., Tu, Q., Lin, S., and Liu, Y. (2017). "Design and simulation of a combined cutting tool for inner section and tabaxir cutting from the natural bamboo section," *Journal of Forestry Engineering* 2(2), 127-132. DOI: 10.13360/j.issn.2096-1359.2017.02.021

Qu, P., Huang, H., Zhao, Y., and Wu, G. (2017). "Physicochemical changes in rice straw after composting and its effect on rice-straw-based composites," *J. Appl. Polym. Sci.* 134(22). DOI: 10.1002/app.44878

Ramage, M. H., Sharma, B., Shah, D. U., and Reynolds, T. P. S. (2017). "Thermal relaxation of laminated bamboo for folded shells," *Mater. Design* 132, 582-589. DOI: 10.1016/j.matdes.2017.07.035

Ren, W., Zhang, D., Wang, G., and Cheng, H. (2014). "Mechanical and thermal properties of bamboo pulp fiber reinforced polyethylene composites," *BioResources* 9(3), 4117-4127. DOI: 10.15376/biores.9.3.4117-4127

Sahin, A., Tasdemir, H. M., Karabulut, A. F., and Gürü, M. (2017). "Mechanical and thermal properties of particleboard manufactured from waste peachnut shell with glass powder," *Arab. J. Sci. Eng.* 42(4),1559-1568. DOI: 10.1007/s13369-017-2427-0

Sam-Brew, S., and Smith, G. D. (2017). "Flax shive and hemp hurd residues as alternative raw material for particleboard production," *BioResources* 12(3), 5715-5735. DOI: 10.15376/biores.12.3.5715-5735

Segal, L., Creely, J. J., Martin Jr., A. E., and Conrad, C. M. (1959). "An empirical method for estimating the degree of crystallinity of native cellulose using the X-ray diffractometer," *Text. Res. J.* 29(10), 786-794. DOI: 10.1177/004051755902901003

Song, W., Wei, W., Ren, C., and Zhang, S. (2017a). "Effect of heat treatment or alkali treatment of veneers on the mechanical properties of eucalyptus veneer/polyethylene film plywood composites," *BioResources* 12(4), 8683-8703. DOI: 10.15376/biores.12.4.8683-8703

Song, W., Wei, W., Wang, D., and Zhang, S. (2017b). "Preparation and properties of new plywood composites made from surface modified veneers and polyvinyl chloride films," *BioResources* 12(4), 8320-8339. DOI: 10.15376/biores.12.4.8320-8339

Song, W., Xu, Z., and Zhang, S. (2018). "Using surface modified E-glass fiber cloths to enhance poplar laminated veneer lumber composites: Effects of modification conditions, gluing processes, hot-pressing parameters, and assembly patterns on physical-mechanical and interfacial properties," *BioResources* 13(1), 597-631. DOI: 10.15376/biores.13.1.597-631

Song, W., Zhao, F., Yu, X., Wang, C., Wei, W., and Zhang, S. (2015). "Interfacial characterization and optimal preparation of novel bamboo plastic composite engineering materials," *BioResources* 10(3), 5049-5070. DOI: 10.15376/biores.10.3.5049-5070

Tang, Q., Fang, L., and Guo, W. (2017). "Investigation into mechanical, thermal, flame-retardant properties of wood fiber reinforced ultra-high-density fiberboards," *BioResources* 12(3), 6749-6762. DOI: 10.15376/biores.12.3.6749-6762

Theng, D., Arbat, G., Delgado-Aguilar, M., Ngo, B., Labonne, L., Evon, P., and Mutjé, P. (2017a). "Comparison between two different pretreatment technologies of rice straw fibers prior to fiberboard manufacturing: Twin-screw extrusion and digestion plus defibration," *Ind. Crop. Prod.* 107, 184-197. DOI: 10.1016/j.indcrop.2017.05.049

Theng, D., El Mansouri, N. E., Arbat, G., Ngo, B., Delgado-Aguilar, M., Pèlach, M. À., Fullana-i-Palmer, P., and Mutjé, P. (2017b). "Fiberboards made from corn stalk thermomechanical pulp and kraft lignin as a green adhesive," *BioResources* 12(2), 2379-2393. DOI: 10.15376/biores.12.2.2379-2393

Uitterhaegen, E., Labonne, L., Merah, O., Talou, T., Ballas, S., Véronèse, T., and Evon, P. (2017). "Impact of thermomechanical fiber pre-treatment using twin-screw extrusion on the production and properties of renewable binderless coriander fiberboards," *Int. J. Mol. Sci.* 18(7), 1539. DOI: 10.3390/ijms18071539

Wang, C., Cheng, H., Xian, Y., Wang, G., and Zhang, S. (2017). "Improving dynamic mechanical property of bamboo pulp fiber reinforced epoxy resin composite treated by nano calcium carbonate," *Transactions of the Chinese Society of Agricultural Engineering* 33(6), 281-287. DOI: 10.11975/j.issn.1002-6819.2017.06.036

Wang, J., Wang, F., Gao, Z., Zheng, M., and Sun, J. (2016a). "Flame retardant medium-density fiberboard with expanded vermiculite," *BioResources* 11(3), 6940-6947. DOI: 10.15376/biores.11.3.6940-6947

Wang, C., Song, W., Cheng, H., Yu, X., Li, W., and Zhang, S. (2016b). "Dipping modification with nano-$CaCO_3$ to improve tensile properties of individual bamboo fiber for developing bamboo-plastic composite," *J. Nat. Fibers* 13(6), 737-748. DOI: 10.1080/15440478.2015.1137526

Wang, Z., Gu, Z., Hong, Y., Cheng, L., and Li, Z. (2011). "Bonding strength and water resistance of starch-based wood adhesive improved by silica nanoparticles," *Carbohyd. Polym.* 86(1), 72-76. DOI: 10.1016/j.carbpol.2011.04.003

Xin, D., Yang, Z., Liu, F., Xu, X., and Zhang, J. (2015). "Comparison of aqueous ammonia and dilute acid pretreatment of bamboo fractions: Structure properties and enzymatic hydrolysis," *Bioresource Technol.* 175, 529-536. DOI: 10.1016/j.biortech.2014.10.160

Xu, M., and Fu, X. (2017). "Study on application of modified wood powder/alkali lignin in wood/rubber composite," *Journal of Forestry Engineering* 2(4), 84-89. DOI: 10.13360/j.issn.2096-1359.2017.04.014

Xu, Y., Zhang, W., Yue, X., and Zhang, D. (2016). "Determination of aluminum in bamboo pulp black liquor by ICP-AES," *BioResources* 11(2), 3964-3971. DOI: 10.15376/biores.11.2.3964-3971

Yang, Z., Li, K., Zhang, M., Xin, D., and Zhang, J. (2016). "Rapid determination of chemical composition and classification of bamboo fractions using visible-near infrared spectroscopy coupled with multivariate data analysis," *Biotechnol. Biofuels* 9(1), 35. DOI: 10.1186/s13068-016-0443-z

Zhang, F., Sun, H., Zhang, X. C., Qian, J., Yang, X., and Yu, C. (2015). "Replacement of the wood substitute packaging materials with modified bamboo timber," *Packaging Engineering* 36(15), 55-61.

Zhang, X., Cheng, X., Lin, L., Tang, Y., and Wu, H. (2013). "Effect on bonding performance of bamboo skin and bamboo pith through chemical processing," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 37(4), 171-174. DOI: 10.3969/j.issn.1000-2006.2013.04.033

Zhang, Z., Guan, M., and Liu, Y. (2017). "Degradability of bamboo shoot shell/UF modified starch adhesive composites," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 41(4), 160-166. DOI: 10.3969/j.issn.1000-2006.201610029

Zhou, X., Chen, M., and Du, G. (2017). "Research progress on surface modification of agriculture and forestry biomass materials by plasma treatment," *Journal of Forestry Engineering* 2(1), 1-7. DOI: 10.13360/j.issn.2096-1359.2017.01.001

Zhu, X., Wang, M., Huang, J., Li, P., Zhang, B., Wen, R., and Liu, Y. (2017). "Research progress of sound absorption properties of wood-plastic composites," *Journal of Forestry Engineering* 2(3), 10-15. DOI: 10.13360/j.issn.2096-1359.2017.03.002

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