Research on Properties of Reconstituted Bamboo Lumber Made by Thermo-Treated Bamboo Bundle Curtains

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Abstract

Untreated and 160°C, 180°C, and 200°C thermo-treated bamboo bundle curtains were reconstructed to make high-density board by impregnation with phenol–formaldehyde resin. The physical and mechanical properties of the boards were examined to evaluate the effect of temperature on their qualities. The modulus of rupture decreased with the increase in thermo-treatment temperature and was reduced by nearly 50 percent after 200°C treatment; however, the modulus of elasticity and bonding shear strength did not change much between untreated and thermo-treated specimens. Thermo-treatment improved the dimensional stability of the boards. Thickness swelling after water immersion and wet–dry cyclic testing decreased with increasing thermo-treatment temperature. Compared with the control specimens, the total color difference (ΔE^*) changed greatly as the thermo-treatment temperature increased. The chemical and Fourier transform infrared spectroscopy results showed that the major component content and functional groups in the major components changed after thermo-treatment.

Recently the rapid development of the construction industry has led to an increasing demand for lumber products, but the decline in quantity and quality of the wood resource from forests is driving the development of new alternative resource. As a fast-growing, nonwood lignocellulosic material with a short rotation age and high mechanical strength, bamboo is a very important forest resource in China, with a stock area of over 4.2 million hectares (Jiang 2002). However, only large-diameter bamboo such as moso bamboo has been widely used in furniture manufacture, housing construction, and decorative products; small-diameter bamboo is abandoned as firewood, which is a waste of resources and pollutes the environment.

Reconstituted bamboo lumber, also called bamboo zephyr board in Japan, can make full use of small-diameter bamboo. This bamboo-based lumber is made from a fibrous, net-like structure of bamboo bundle curtains that have been crushed in rollers. The preparation of reconstituted bamboo lumber is quite similar to scrimber developed in Australia (Hutchings and Leicester 1988, Jordan 1989). Given the regional limitation of bamboo, there are only a few studies on reconstituted bamboo lumber. The fundamental properties of bamboo zephyr board with emulsion methyldiisocyanate resin were evaluated and found to exhibit superior strength properties and good dimensional stability compared with commercial products (Nurgroho and Ando 2000, 2001). Studies on reconstituted bamboo lumber showed that the physical and mechanical properties rise as the resin content and composite density increase (Cheng 2009). A previous study on the properties of reconstituted bamboo lumber with different crushing technology showed that photoirradiation affected the surface color and mechanical properties after an artificial weathering test, but thermo-treated specimens were less affected (Qin and Yu 2009).

According to the preliminary statistics, there are about 60 reconstituted bamboo lumber manufacturing enterprises in China at present with an annual capability of 600,000 m^3 (Yu and Yu 2013). Because thermo-treated reconstituted bamboo lumber has a good appearance, some producers

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Forest Prod. J. 62(7/8):545–550.

would like to use it to replace high-grade flooring, even other furniture materials, but there has been no specific research on the lumber. As previous research has shown, thermo-treatment darkens light-colored wood, making it look more precious (Mitsui et al. 2001, Bekhta and Niemz 2003). Thermo-treatment also improves dimensional stability (Sandland 1998, Bekhta and Niemz 2003, Wang and Cooper 2005, Welzbacher et al. 2008) but decreases mechanical properties (Kubojima et al. 2000, Bekhta and Niemz 2003, Unsal and Ayrilmis 2005, Fruhwald 2007), which will discourage its use. Since bamboo has similar major components to wood, the properties change after thermo-treatment and may have similar characteristics.

The objective of our study was to investigate the effect that the application of thermo-treatment temperature to Omei Mountain bamboo (*Neosinocalamus affinis* (Rendle) Keng f.) bundles had on property changes of reconstituted bamboo lumber, including color and mechanical and physical properties. Fourier transform infrared (FT-IR) spectroscopy was used to characterize chemical and structural changes occurring in bamboo components.

Experimental

Materials

Three- to four-year-old Omei Mountain bamboo was acquired from Sichuan province in southwest China. The average thickness of the culm wall was about 0.5 cm and the moisture content was in the range of 30 to 40 percent. The bamboo was cut along the longitudinal section into two parts and then crushed into bundle curtains with fracturing equipment (ZL 200910077384.6) as shown in Figure 1. The bamboo bundle curtains were kept in the air for 2 weeks, the moisture content was about 10 percent.

Thermo-treatment and composite preparation

The bamboo bundle curtains were thermo-treated with saturated steam in a Lignomat Wood Drying Machine (made in Germany) at 160°C, 180°C, and 200°C for 2 hours. In the thermo-treatment phase, the oxygen content was controlled at 2.5 percent. After the thermo-treatment, the bamboo bundle curtains were reconditioned to reach equilibrium.

The bamboo bundle curtains were immersed in phenol–formaldehyde adhesive for 5 minutes, and the target resin content of bamboo bundle curtains was controlled at 15 percent (ratio of resin dry weight to bamboo bundle's dry weight). The bundles were then dried to achieve a moisture content of 8 percent. The dried bamboo bundle curtains were reconstituted in a hot pressing mould (450 by 160 by 15 mm) at 160°C for 20 minutes. The thickness of the composite was controlled to be 15 mm and the target density was 1.1 g/cm^3.

Color difference

The surface color changes of specimens were determined by a portable chromatic aberration meter (CR400, Minolt). The measurements were made using D65 light, and the sensor head was 8 mm. The CIE L^* a^* b^* were obtained directly from the color meter. L^* axis represents the lightness, varying from 100 (for white) to 0 (for black); a^* and b^* describe the chromatic coordinates on the green–red ($+a^*$ for red, $-a^*$ for green) and blue–yellow ($+b^*$ for yellow, $-b^*$ for blue) axes, respectively. With the L^*, a^*, and b^*, the total color difference (ΔE^*) of specimens was calculated with Equation 1:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad (1)$$

where ΔL^*, Δa^*, and Δb^* represent the changes in L^*, a^*, and b^* of specimens after thermo-treatment, respectively. A smaller ΔE^* value corresponds to a lower color difference.

Figure 1.—The manufacture of bamboo bundle curtains.

Physical and mechanical properties

The reconstituted bamboo lumber specimens were conditioned at a controlled temperature of 25°C and 65 percent relative humidity for 10 days. All lumber samples were trimmed and cut into test specimens. The modulus of elasticity (MOE) and modulus of rupture (MOR) were measured on 240 by 20 by 12-mm (length [L] by width [W] by thickness [T]) specimens with a three-point device. The horizontal shear strength was determined with 72 by 40 by 12-mm (L by W by T) specimens according to JAS SE-11 (Anonymous 2003); the force was applied perpendicular to the adhesive layer with a three-point device. The thickness swelling (TS) was assessed on 50 by 50-mm specimens after immersion into 20°C water for 30 days and five wet–dry cycle tests. One wet–dry cyclic test consisted of immersion in boiling water for 4 hours and then drying in an oven at 63°C for 20 hours. The measurements were carried out for five replications.

FT-IR spectra

FT-IR spectra were recorded by a direct transmittance method on a Nicolet Impact 410 spectrometer (Thermo Nicolet, USA). The KBr method with an internal standard was used. The control and thermo-treated bamboo bundle curtains were milled and sieved, and the fine powder was mixed with KBr with a weight ratio of about 1:100 and pressed to form a pellet. The spectra were collected between 4,000 and 400 cm^{-1} with a resolution of 8 cm^{-1} and 64 scans. FT-IR spectra were baseline corrected and normalized at the absorption of 1,515 cm^{-1} according to Windeisen et al. (2007). OMNIC software (Version 7.3, Nicolet Instruments Corporation, USA) was used to measure the peak height of the absorption band.

Chemical components

Holocellulose separation.—After extracting with benzene–ethanol, bamboo powder (2 g) was placed in a conical flask containing 65 mL distilled water and heated at 75°C. Acetic acid (0.5 mL) and sodium chlorite (0.6 g) were added into the solution each hour for 5 hours until the mixture turned white. The mixture was filtered and the residue washed with water and then washed with acetone three times and dried at 105°C to a constant mass.

α-Cellulose separation.—Bamboo powder (2 g) was mixed with 17.5 percent NaOH (30 mL) in a beaker. The beaker was then placed in the 20°C water bath for 45 minutes. The mixture was diluted with distilled water three times, washed with 9.5 percent NaOH three times, and washed again with distilled water. Acetic acid was then added into the residue and the residue washed with water and finally dried at 105°C to a constant mass.

Lignin separation.—After extracting with benzene–ethanol, bamboo powder (1 g) was mixed with 72 percent H_2SO_4 (15 mL) in a conical flask. The flask was put in a 18°C to 20°C water bath for 2.5 hours. The mixture was then diluted with distilled water until the volume reached 560 mL, heated for 4 hours, and filtered. The residue was washed with hot water and dried at 105°C to a constant mass.

Results and Discussion

Color changes

Figure 2 shows the effect of thermo-treatment temperatures on color. With the increase of temperature, the surface color turned rapidly from bright to dark, indicated by the decreasing value of lightness (L^*); the value decreased nearly 50 percent compared with the control specimens. The a^* value also changed as the thermo-treatment temperature increased. It reached its peak at 180°C and then decreased, which showed a tendency to turn red first and then green. The decreasing b^* value was reflected in the trend to turn blue as the temperature increased. The total color difference (ΔE^*) increased significantly as the temperature increased.

Many research results attributed wood color changes at the surface to the movement of sugars, phenols, antioxidants, and other compounds from the center of a sample to the surface layer as water evaporated (Kosikova et al. 1999, Kang 2006)

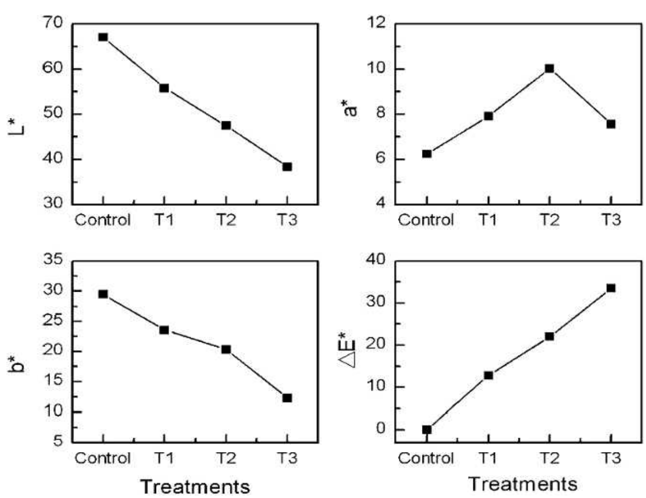

Figure 2.—Color changes of bamboo composite before and after thermo-treatment at 160°C (T1), 180°C (T2), and 200°C (T3).

with thermo-treatment. As the treatment temperature increased, the surface color of the wood darkened with a decrease in lightness and the color difference increased (Brauner and Loos 1967, Bourgois et al. 1991), which is similar to the results of our research on bamboo.

Mechanical properties

Table 1 shows the average values and analysis of variance (ANOVA) of mechanical properties of thermo-treated bamboo composite with different thermo-treatment temperatures. The ANOVA indicated significant differences of MOR and shear strength among different thermo-treatment temperatures ($P < 0.01$), and no difference of MOE among different treatment temperatures.

The changes in mechanical properties of bamboo composite with thermo-treatments are shown in Figures 3, 4, and 5. Figure 3 shows that the MOR decreased rapidly with increasing temperature. According to the Duncan test, the MOR of bamboo treated with different temperatures was varied significantly from each other ($P < 0.01$). Compared with control specimens, the MOR of 200°C-treated bamboo composite decreased nearly 50 percent. Similar results have been reported on wood (Bekhta and Niemz 2003, Fruhwald 2007). Bamboo, like wood, is composed of three structural polymers—cellulose, hemicellulose, and lignin. When exposed to high temperature, the hemicellulose degrades (hydrolysis) first because of its low molecular weight, followed by cellulose crystallization and lignin modification, which usually lead to the decrease in mechanical properties of wood.

As shown in Figure 4, the variation of MOE value was small; the highest value was only 3.6 percent higher than the lowest value. It was almost constant with increasing temperature, reflecting it is less affected than other characteristics by the thermo-treatment, which is in agreement with previous studies on birch and aspen wood (Sundqvist et al. 2006, Kocaefe et al. 2007).

The horizontal shear strength was used to evaluate the bonding properties of wood/bamboo-based panels. The force on the surface of specimens produced a shear stress on the plane, which led to the weak glue interface breaking and permitting the shear strength to be calculated (Rammer 1996, Zhu et al. 2006). At present, the short-beam shear test, the V-style notch beam shear test, and the double notch shear test were mainly used in the shear strength measurement of laminated board. Because of the convenient operation of the short-beam shear test, it is widely used in materials selection and quality control, especially with regard to bonding properties (Wang et al. 2004, Zhu et al. 2006). Therefore, the short-beam shear test was used in this research. The horizontal shear strength of bamboo composites decreased with the increase in temperature as shown in

Table 1.—Average values and analysis of variance of bamboo composite with thermo-treatment temperature.

		Treatment temp (°C)			
Property[a]	Control	160	180	200	Calculated F
Density (g/cm^3)	1.11	1.10	1.10	1.11	
MOR (MPa)	267	225	193	141	92.9[b]
MOE (MPa)	27,487	26,788	26,506	27,344	1.0
SS (MPa)	20.19	19.29	16.82	15.45	18.9[b]

[a] MOR = modulus of rupture; MOE = modulus of elasticity; SS = shear strength.
[b] Significant at $P < 0.01$.

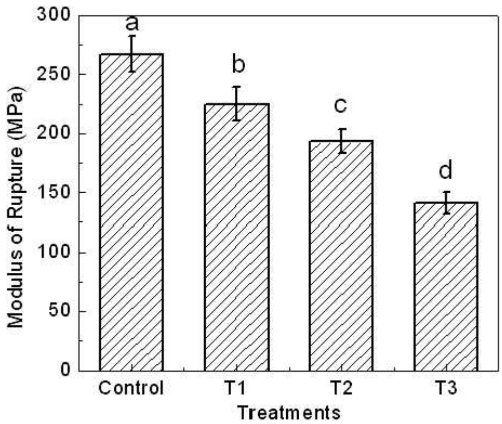

Figure 3.—Modulus of rupture (MOR) of bamboo composite before and after thermo-treatment at 160°C (T1), 180°C (T2), and 200°C (T3). Lowercase letters indicate significant difference of MOR.

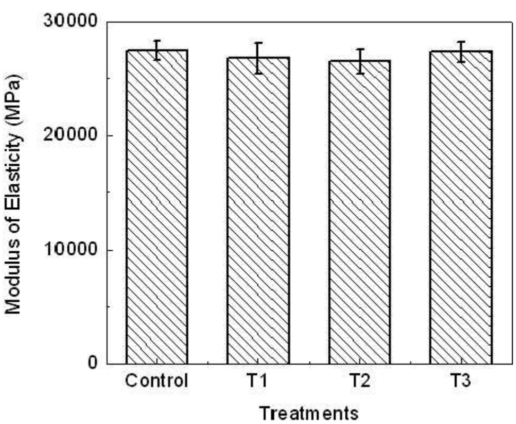

Figure 4.—Modulus of elasticity (MOE) of bamboo composite before and after thermo-treatment at 160°C (T1), 180°C (T2), and 200°C (T3).

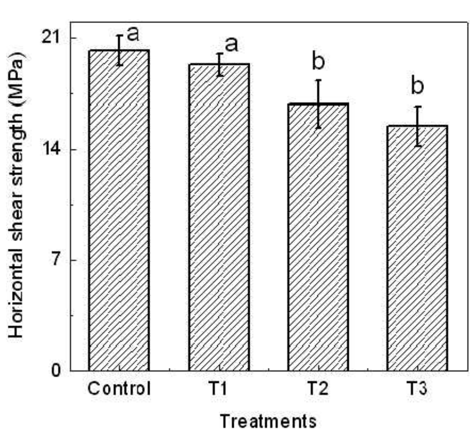

Figure 5.—Horizontal shear strength of bamboo composite before and after thermo-treatment at 160°C (T1), 180°C (T2), and 200°C (T3). Lowercase letters indicate significant difference of horizontal shear strength.

Figure 5. Compared with control specimens, the horizontal shear strength of 160°C-treated bamboo composites decreased little and were not significantly different; however, the 180°C- and 200°C-treated bamboo composites clearly decreased and were significantly different from the control and 160°C-treated specimens ($P < 0.01$) according to the Duncan test. The horizontal shear strength decreased nearly 25 percent after 200°C treatment. For the control specimens, the broken position happened at the glue line. However, for the thermo-treated specimens, the broken position took place on the bamboo bundles.

Dimensional stability

The reconstituted bamboo lumber specimens were immersed in 20°C water and underwent wet–dry cycling to imitate the outdoor environments. Figures 6 and 7 show the TS changes of reconstituted bamboo lumber after continuous immersion and the wet–dry cycle experiment.

As Figure 6 indicates, the TS and its changing rate decreased with the increasing thermo-treatment temperature; the TS of the control specimens was nearly 8 percent after 30 days of immersion, which is about 45 percent higher than the 200°C-treated specimens. After 16 days, the TS increase rate slowed, especially for the 200°C-treated specimens, and became nearly level from 16 to 30 days.

As Figure 7 shows, the TS of thermo-treated specimens decreased as the thermo-treatment temperature increased during the five wet–dry cycles, indicating that the thermo-treated specimens are more dimensionally stable than the controls. The TS of control specimens after five wet–dry cycles was 3.82 percent, about 47.5 percent higher than the 200°C-treated specimens.

Wood becomes more dimensionally stable after being exposed to high temperatures (Sandland 1998, Bekhta and Niemz 2003, Wang and Cooper 2005, Welzbacher et al. 2008). Treated wood becomes less hygroscopic because some cell walls reorganize and the number of hydrogen bonds decrease; further, the softening lignin blocks water from entering into the wood structure during heat treatment (Homan et al. 2000, Rowell et al. 2000).

Compared with other reconstituted bamboo lumber or other kinds of wood-based panels, reconstituted bamboo lumber in our research has its own advantages. In a previous study, Ye et al. (1996) investigated the dimensional stability of reconstituted bamboo lumber and found that the TS was 2.6 percent with a density of 1.12 g/cm^3 after 24-hour water immersion, which is a little higher than the control specimens in this study. Additionally, Saotome et al. (2009) studied the dimensional stability of high-density (1.1 g/cm^3) and high-resin-content boards (I-board) by impregnating the phenolic resin into the board materials. The TS of the board was 1.9 and 4.8 percent after 24 hours and 30 days of water immersion, respectively, which is very close to the results of 200°C-treated lumber. Although the I-board and reconstituted bamboo lumber have similar densities, the resin content of I-board was two or three times that of the reconstituted bamboo lumber, which may lead to the dimensional stability differences.

FT-IR spectra of bamboo samples

As a natural lignocellulosic material, bamboo has similar chemical components to wood, and the bamboo and wood spectra are quite alike. Therefore, the IR peaks can be

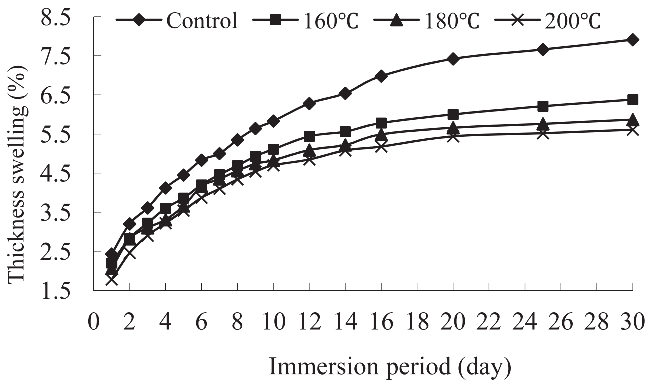

Figure 6.—Changes in thickness swelling of reconstituted bamboo lumber by continuous water immersion.

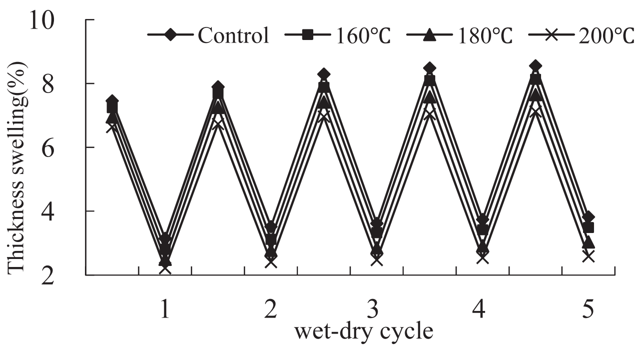

Figure 7.—Changes in thickness swelling of reconstituted bamboo lumber during wet–dry cyclic treatment.

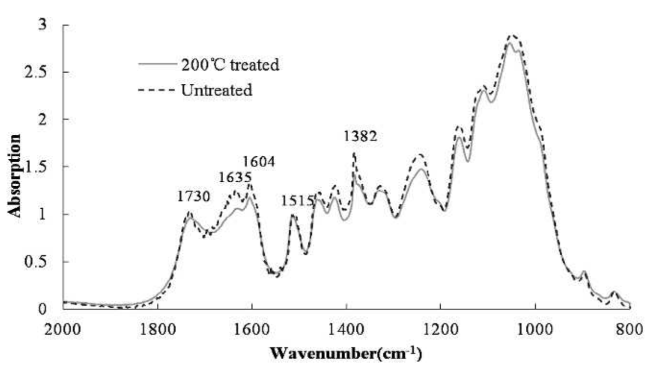

Figure 8.—Fourier transform infrared (FT-IR) spectroscopy spectra of bamboo before and after thermo-treatment.

analyzed by reference to wood (Pandey 1999, Li 2003, Pandey and Pitman 2003, Roger 2005).

The chemical changes of bamboo samples caused by temperature were characterized with FT-IR spectroscopy. The FT-IR spectra of bamboo before and after thermal treatment are shown in Figure 8. Obvious decrease in the intensities of absorption peaks occurred at 1,730, 1,635, 1,604, and 1,382 cm^{-1}. The intensity decrease at 1,730 cm^{-1} was due to the C=O groups, mainly in xylan (hemicellulose). There was a decrease at band 1,635 cm^{-1} after thermo-treatment because of the absorbed O-H and conjugated C=O groups in cellulose. The changes of carbohydrate bands at 1,604 and 1,382 cm^{-1} were caused by aromatic skeletal vibration and the C-H deformation, respectively.

Table 2.—Chemical characteristics of untreated and thermo-treated bamboo.

	Holocellulose (%)	α-Cellulose (%)	Lignin (%)
Control	71.40	49.78	22.32
Treatment temp (°C)			
160	72.39	48.42	23.83
180	69.63	45.28	24.89
200	64.11	38.97	26.06

Chemical components of bamboo samples

Chemical characteristics of thermo-treated and control bamboo samples are given in Table 2. Compared with the control specimens, holocellulose of 160°C-treated bamboo slightly increased and then decreased as the treatment temperature increased; α-cellulose decreased with the increasing treated temperature. When the treatment temperature was higher than 180°C, holocellulose and α-cellulose decreased rapidly, which was attributed to the thermo-degradation of most of the amylose in bamboo.

Lignin content changed differently from cellulose; it rose as the treatment temperature increased, which was similar to results in beech and pine (Nguila et al. 2007). The increase of lignin content may be caused by two factors: (1) the degradation of cellulose and hemicellulose at the high temperature and high humidity conditions, and (2) some of the degraded products had properties similar to lignin and were calculated in lignin content, which led to the lignin content increase.

Conclusions

High temperature has obvious effects not only on color, but also on the mechanical properties and dimensional stability of reconstituted bamboo lumber made from thermo-treated bamboo bundle curtains.

The surface color darkened and the total color difference (ΔE^*) increased with increasing thermo-treatment temperature. MOR decreased nearly 50 percent and horizontal shear strength decreased about 25 percent after 200°C treatment, while the MOE did not change much. TS results showed that reconstituted bamboo lumber made from thermo-treated bamboo bundle curtains was more resistant to water, and the water absorption rates decreased as the thermo-temperature increased. FT-IR analysis showed that the functional groups of cellulose, hemicellulose, and lignin were changed after thermo-treatment. The chemical results revealed that the major components in bamboo changed greatly when the treatment temperature was higher than 180°C.

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