Evaluation of Water Absorption and its Influence on the Physical-Mechanical Properties of Bamboo-Bundle Laminated Veneer Lumber

Haidong Li, Yu Xian, Jianchao Deng, Haitao Cheng, Fuming Chen,* and Ge Wang *

To investigate the possibility of using bamboo-bundle laminated veneer lumber (BLVL) as a cooling tower packing material, the water absorption rates, thickness swelling rates, and flexural properties of three different composite materials were studied. The BLVL was combined with either 12% or 24% phenol formaldehyde resin (PF), and the moso bamboo strips were exposed to water baths at three different temperatures (45, 65, and 85 °C) for 30 d. After the aging treatments, the 24%-BLVL samples showed lower water absorption rates and better bending properties than the other two composites. The temperature was found to have a significant effect on the modulus of rupture (MOR), modulus of elasticity (MOE), and the thickness swelling rate. As the temperature increased, the swelling rate and the rate of weight gain increased and the MOE and MOR decreased. According to the activation energies for swelling calculated from the Arrhenius-type plots, compared with the 24%-BLVL (22.95 kJ·mol^{-1}) and the moso bamboo strips (12.69 kJ·mol^{-1}), the effect of temperature on the swelling rate was greatest for the 12%-BLVL (24.15 kJ·mol^{-1}). Results showed that the BLVL material is a promising candidate for a novel cooling tower packing material.

Keywords: Bamboo-bundle laminated veneer lumber; Cooling tower packing; Temperature; Flexural properties; Water absorption

Contact information: International Centre for Bamboo and Rattan, Beijing, P.R. China, 100102;
** Corresponding authors: chenfuming1985@126.com; sunic_bamboo@126.com*

INTRODUCTION

Bamboo is considered to be a renewable resource that is recognized as one of the most important non-timber forest resources in the world. Therefore, it has recently been attracting a lot of attention (Peng *et al*. 2013). Because of its rapid growth rate (bamboo can be harvested in less than four years), high strength and toughness, abundant availability, and biodegradability, bamboo is regarded as a potential replacement for traditional construction materials (Jiang 2007; Yu *et al*. 2011; Zheng *et al*. 2014; Yu *et al*. 2015). In China, bamboo has been used to fabricate special products such as cooling tower packing materials and winding composite pipes. Packing (filling) is an important part of a cooling tower, where it helps with the heat exchange or the closely related cooling effect. At present, the main packing material is made from polyvinyl chloride. The uses of bamboo packing are few, but some organizations have begun to use bamboo as packing materials because of high strength, high heat-transfer coefficient, large specific surface, and other advantages. When used as a cooling tower packing material, the bamboo or bamboo composites not only need to possess excellent mechanical properties, good thermodynamic behavior, and a low pressure drop per theoretical stage, but also should exhibit excellent dimensional stability and durability (Goshayshi and Missenden 2000; Gharagheizi *et al*.

2007). The cooling tower packing materials are usually exposed to a spray-water environment with a temperature range from 40 to 50 °C. Therefore, the durability of bamboo or bamboo composite materials used for the fabrication of cooling tower packing materials must be evaluated to assess their application potential in a spray water environment.

Recently, a newly engineered composite, denoted bamboo-bundle laminated veneer lumber (BLVL), has been developed as a novel construction material. The BLVL manufacturing process is inspired by the manufacturing process of scrimber (bamboo scrimber) and laminated veneer lumber, which is manufactured using the following steps, in brief (Chen *et al*. 2014; Deng *et al*. 2014; Li *et al*. 2014). First, the bamboo is processed into bamboo bundles. Second, the bamboo bundles are arranged and tied together in such a way that the separated and loose bundles are linked to a uniform veneer piece. Finally, the bamboo bundle veneers are treated with a phenol formaldehyde (PF) resin and then pressed to the desired density and thickness at an elevated temperature. Based on the above methods, the fabricated BLVL not only exhibits good mechanical properties, but also superior stability and uniformity for structural design (Chen *et al*. 2014).

Because BLVL is reinforced with long natural fiber bundles, it exhibits greater sensitivity to moisture and high temperatures, compared to other man-made, fiber-reinforced composite materials. Bamboo fibers contain a large number of polar hydroxyl groups, resulting in a high moisture sorption levels; the absorbed water negatively affects the mechanical properties of the reinforced composites (Thwe and Liao 2003a,b; Vasoya *et al*. 2007; Chen *et al*. 2009). Hence, the durability of the BLVL becomes a critical issue for long service times, especially under hygrothermal loading conditions, *e.g.*, when used as a cooling tower packing material. Various methods have been adopted for characterizing the aging resistance of bamboo/wood composites (Heller 2009; Kojima and Suzuki 2011; Yu *et al*. 2013; Huang *et al*. 2014; Yu *et al*. 2015), and several accelerated aging tests have been conducted according to the relevant standards. However, to improve the application potential of BLVL, it is important to understand the effects of long-term hygrothermal loading on the physical and mechanical properties of BLVL.

In this work, the behavior of bamboo strips and BLVL was studied under hygrothermal aging conditions. The objectives of this study were as follows: (1) to study the water absorption behavior at different temperatures and (2) to clarify the effects of long-term hygrothermal loading on the bending properties of bamboo strips and BLVL.

EXPERIMENTAL

Materials

Cizhu bamboo (*Neosinocalamus affinis*), aged three to four years, was acquired from Changning, Yibin, Sichuan Province, China. The bamboo was sawn into 2000-mm bamboo tubing and then split longitudinally into four pieces of approximately the same size. Then, the bamboo strips were pushed into an untwisting machine along the longitudinal direction. The bamboo note and part of bamboo green were removed; meanwhile, the bamboo strips were rolled and broomed into loosely reticulate bamboo bundle sheets with a certain thickness uniformity. Thereafter, a sewing machine was used to connect the bamboo bundles along the width , linking separate bamboo bundles into a uniform one-piece veneer. The untwisting machine and sewing machine are of our own design. The bamboo bundle veneers were lastly cut into pieces of 300 mm in length and air-dried to a moisture content (MC) between 8% and 12%.

Moso bamboo (*Phyllostachys pubescens*), aged four years, was obtained from a bamboo plantation located in Anhui Province, China. The bamboo was sawn into 200-mm bamboo tubing, split longitudinally into two pieces of approximately the same size, and air-dried to a MC between 8% and 12%.

Phenol formaldehyde (PF) resin, the matrix material, was supplied by Beijing Dynea Chemical Industry Co., Ltd, of China; this is a commercially available, low-molecular weight, and water-soluble PF. The parameters of the PF are as follows: a solids content of 45.53%, pH value 10 to 11, and viscosity 38 CPs.

Methods

Preparation of BLVL

To obtain different resin loadings, the solids content of the PF polymer was modified to various concentrations using water. The resin loading of the bamboo bundle was calculated as follows,

$$W = \frac{(M-m)n}{m(1-a)} \times 100\% \tag{1}$$

where W is the amount of resin loading (%), M is the weight of bamboo bundle after the resin bath (kg), m is the weight of bamboo bundle before the resin bath (kg), n is the solids content of the resin (%), and a is the MC of the bamboo bundle before the resin bath (%).

In this study, two types of resin loadings were designed: 12% and 24%. For convenience purposes, the resin loadings were abbreviated 12%-BLVL and 24%-BLVL. To achieve a uniform adhesive spread, the bamboo bundle veneers were immersed into the PF resin for 7 min and then were dried to a MC between 8% and 12% (Li *et al*. 2014). Thereafter, layers of bamboo-bundle sheets were assembled along the grain direction, and BLVL was shaped at a hot-pressing temperature of 150 °C, 3.5 MPa pressure, and 10 min hot-press time. The dimensions of the BLVL were 300 mm (length) × 140 mm (width) × 7.0 mm (thickness) with a target density of 1.0 g cm^{-3}.

Water absorption performance tests

The BLVL and moso bamboo strips water absorption tests were conducted in accordance with Chinese national standard GB/T 17657 (2013), ASTM D-1037 (2012), and GB/T 15780 (1995). The dimensions of the BLVL and the moso bamboo specimens were 50 mm × 50 mm ×7.0 mm and 10 mm × 10 mm × t mm, respectively, where t is the thickness of the bamboo culm wall. The approximate thickness of the bamboo chosen for this experiment was 7 to 8 mm. The specimens were subsequently subjected to three different temperatures (45, 65, and 85 °C) in a water bath for 30 d. The water content and thickness of the samples were measured at different times during the study using a balance and micrometer calipers, respectively. Six replicates were used for each experiment type.

According to previous studies (Shi and Gardner 2006; Deng *et al*. 2014), a thickness swelling rate parameter, K_{SR}, can be used to quantify the swelling rate of wood and bamboo-based composites, as expressed in the following equation,

$$TS(t) = \left(\frac{H_\infty}{H_0 + (H_\infty - H_0)e^{-K_{SR}t}} - 1 \right) \times 100 \tag{2}$$

where $TS(t)$ is the thickness swelling rate at time t (%), K_{SR} is a constant referred to as the intrinsic relative swelling rate (h^{-1}), t is the time (h), H_0 is the initial thickness of the board (mm), and H_∞ is the equilibrium thickness of the board (mm).

Bending tests

The bending tests were performed in accordance with the procedures recommended in the GB/T 15780 (1995) testing standard. Specimens were tested for modulus of rupture (MOR) and modulus of elasticity (MOE) under loading parallel to the glue line or parallel chord wise to the bamboo strips. The specimens were measured for MOE first. After the MOE was measured, the samples were immersed at different temperatures (45, 65, and 85 °C) in water baths. At certain time intervals the samples were removed from the water and had their surfaces dried with filter paper. After the samples were dried, they were immediately had their MOE and MOR measured in wet condition. All the tests were performed at 21 °C, and an INSTRON 5582 mechanical testing machine (Instron Co., Massachusetts, USA) was used for all the testing.

Statistics

Nonlinear fitting and graphs were drawn by origin 8.0 software (Originlab Corp.; Northampton, MA).

RESULTS AND DISCUSSION

Water Absorption Behavior

After 30 d of water immersion, the water absorption and thickness swelling rate observed for the moso bamboo strips and the BLVL samples are shown in Fig. 1. The water absorption and thickness swelling behavior obviously depend on the composition of the composite and the temperature.

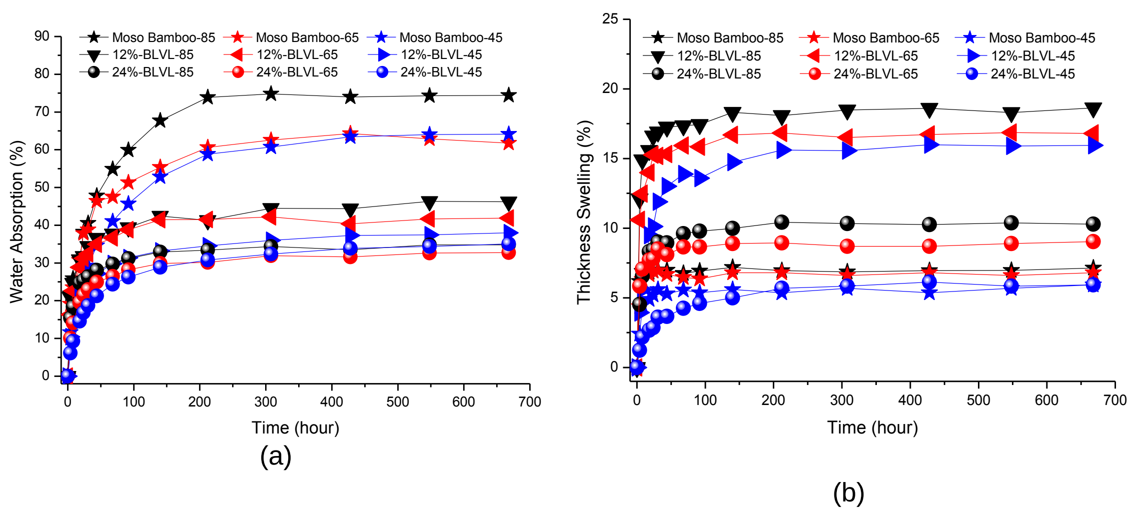

Fig. 1. Durability of moso bamboo strips and BLVLs: (a) the effect of temperature on the water absorption process for moso bamboo strips and BLVLs and (b) the effect of temperature on the thickness swelling rate for moso bamboo strips and BLVLs

Overall, the samples showed a high water absorption and thickness swelling rate during the initial stage; however, the rates leveled off as time passed. Furthermore, the water absorption and thickness swelling rates increased with increasing temperature; this is because water molecules move more quickly at higher temperatures.

Figure 1(a) shows that the bamboo strips absorbed more water than the 12%-BLVL and 24%-BLVL samples, and that the 24%-BLVL samples showed an excellent water resistance at the different temperatures. These results are attributed to the structural composition of the composites. The bamboo strips are a naturally porous fiber composite material that consist of many vascular bundles and parenchyma tissue (Khalil *et al*. 2012; Zakikhani *et al*. 2014), increasing their water absorption rate. In comparison to the bamboo strips, the structure of the BLVL is denser because of the high pressure and temperature employed during the manufacturing process. Meanwhile, the bamboo cell interstices and lumina, cracks, and other spaces were penetrated with the PF resin, preventing the hydroxyl groups of the bamboo bundles from interacting with the water molecules (Yu *et al*. 2014). In fact, as the PF resin content increased, the water uptake of the BLVL decreased.

Figure 1(b) shows that the bamboo strips exhibited a lower thickness swelling rate than the other samples and that the 12%-BLVL exhibited the highest thickness swelling rate. Because BLVL is a natural composite, the thickness swelling rate obtained for the bamboo strips was within the expected range. However, for the 12%-BLVL, which contained half the amount of PF resin compared with the 24%-BLVL, this meant that more hydrophilic groups were exposed, increasing the water absorption and swelling abilities.

Table 1. Thickness Swelling Rate Parameters and Equations Fitting for MOE *vs.* Aging Time for Moso Bamboo Strips and BLVLs

Composite type	Air-dry Density (g/cm^3)	Aging temperature (°C)	Thickness swelling rate parameter K_{SR} (h^{-1})	Fitting model	R^2
Moso Bamboo	0.746	85	0.112	Y =5.49+4.20*exp(-x/4.60)	0.929
		65	0.101	Y =5.99+4.34*exp(-x/9.86)	0.951
		45	0.066	Y =6.37+3.63*exp(-x/9.90)	0.971
12%-BLVL	0.961	85	0.107	Y = 9.96+8.02*exp(-x/3.13)	0.973
		65	0.073	Y =9.74+7.00*exp(-x/10.53)	0.969
		45	0.039	Y =11.08+6.87*exp(-x/17.33)	0.981
24%-BLVL	0.968	85	0.081	Y =12.41+5.55*exp(-x/9.78)	0.933
		65	0.051	Y =12.83+5.43*exp(-x/12.42)	0.924
		45	0.031	Y =14.00+4.32*exp(-x/24.85)	0.946

The K_{SR} value can be used to quantify the intrinsic relative swelling rate of wood or bamboo-based composites. The values obtained for the thickness swelling rate, K_{SR}, for the bamboo strips and the BLVL samples are compared in Table 1. The results showed that the K_{SR} value increased with increasing temperature.

The relationship between ln K_{SR} and 1/T is illustrated in Fig. 2. The corresponding activation energy, E, for the thickness swelling was calculated using the Arrhenius-type equation,

$$K_{SR} = Ae^{-E/RT} \quad (3)$$

where A is a constant, R is the universal gas constant (8.314 J·mol^{-1}·K^{-1}), and T is the temperature (K).

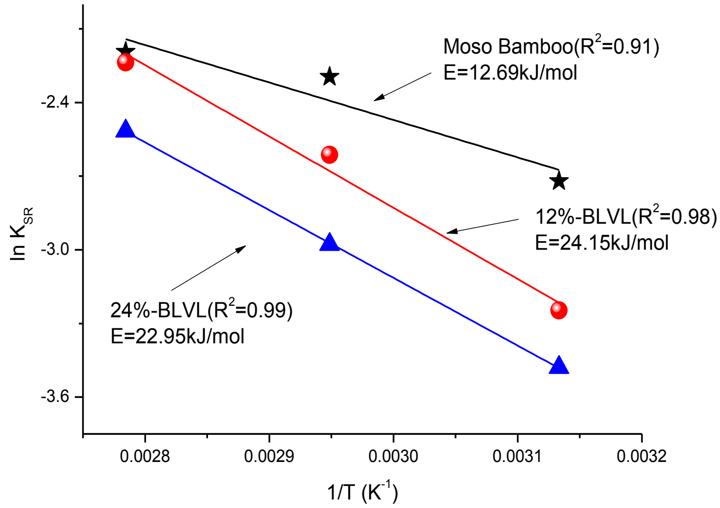

Fig. 2. The relationship between ln K_{SR} and 1/T

From Fig. 2, the activation energy was 12.69, 24.15, and 22.95 kJ·mol^{-1} for the bamboo strips, the 12%-BLVL, and the 24%-BLVL, respectively. This indicates that the effect of the temperature on the swelling rate was greater for the BLVL sample than the moso bamboo strips, and the effect of temperature on the swelling rate was greater for the 12%-BLVL than the 24%-BLVL.

Bending Behavior

The effect of time and temperature on the mechanical properties of the moso bamboo strips and the BLVL samples is illustrated in Figs. 3 and 4.

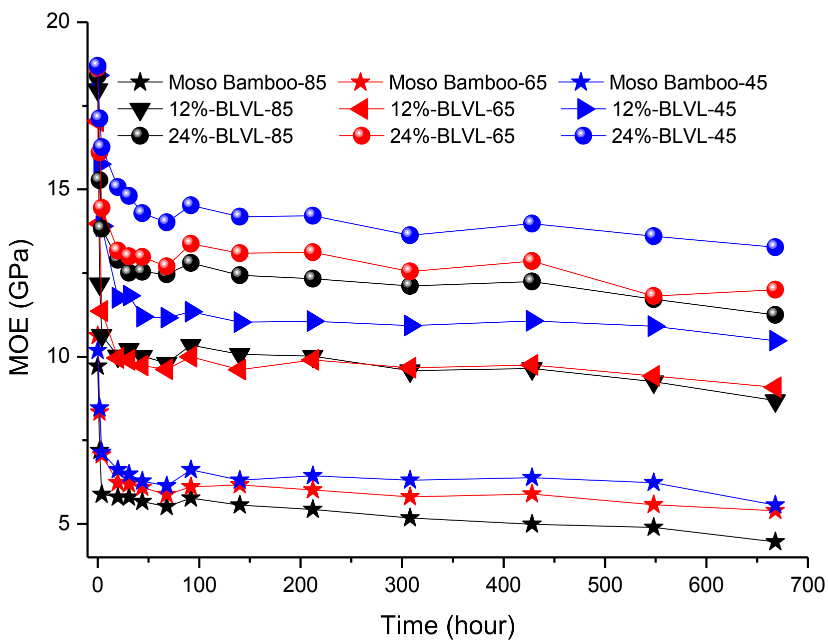

Fig. 3. The effect of temperature on the MOE for moso bamboo strips and BLVL samples

According to Fig. 3, there was a notable relationship between the temperature and the modulus of elasticity (MOE); as the temperature increased, the rate of degradation for the MOE also increased. This was attributed to the fact that the moisture absorption had a softening effect on the bamboo strip and the composites (Chen *et al*. 2009). The degradation curves were fitted using the following exponential decay function: $y = a+b*\exp(-x/c)$. The fitting parameters obtained for the moso bamboo strips and the BLVL samples are compared in Table 1. The results of the regression analyses indicated that the model is in agreement with the experimental results, and the correlation coefficients were all greater than 0.92.

Figures 3 and 4(c) reveal the decrease in MOE and modulus of rupture (MOR) after 30 days of immersion in water at 45 °C. After 30 d of immersion, the MOE decreased by 45.35%, 43.10%, and 29.00%, and the MOR decreased by 36.71%, 53.96%, and 37.47% for the moso bamboo strips, the 12%-BLVL, and the 24%-BLVL samples, respectively. Similarly, as shown in Fig. 3 and Fig. 4(b), the MOE decreased by 49.22%, 46.67%, and 36.21%, and the MOR decreased by 41.35 %, 57.09%, and 42.97% for the moso bamboo strip, the 12%-BLVL, and the 24%-BLVL samples, respectively, at 65 °C. At 85 °C (Fig. 3 and Fig. 4a) both the MOE and the MOR of the composites exhibited the largest decrease. After 30 d of exposure to the water bath, the MOE decreased by 54.06%, 51.68%, and 38.87% for the moso bamboo strip, the 12%-BLVL, and the 24%-BLVL, respectively, compared to the untreated composites. At the same time, the MOR decreased by 53.43%, 61.14%, and 50.99% after 30 d.

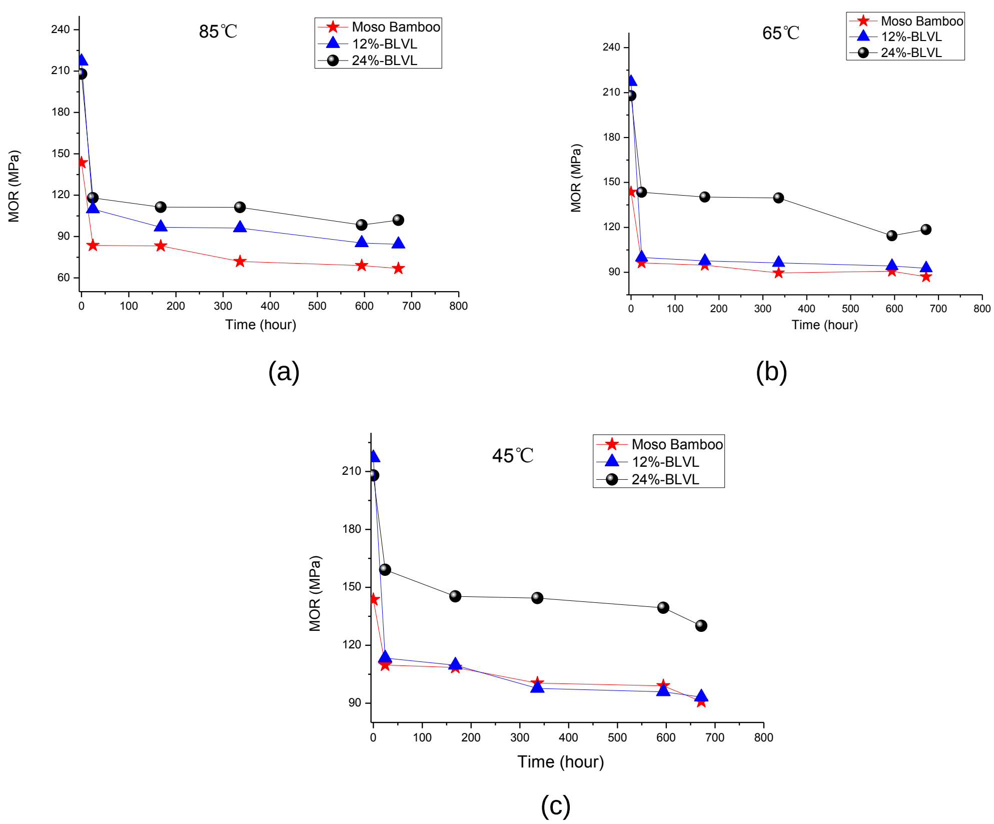

Fig. 4. The effect of temperature on the MOR for moso bamboo strips and BLVL samples

The results indicated that the decrease of bamboo strip specimens in MOE was larger than that of BLVL samples at all temperatures, and the probable reason for this might be that bamboo strips absorbed more water than BLVL samples, which makes it softer. Meanwhile, the greatest decrease rate for MOR was the 12%-BLVL at all temperatures. This might be due to the fact that the 12%-BLVL exhibited the highest thickness swelling rate thereby resulting in localized yielding of PF resin and loss of adhesion between bamboo fiber and PF resin (Tamrakar and Lopez-Anido 2011).

The 24%-BLVL composites exhibited better mechanical properties than the 12%-BLVL composites after exposure to the water baths with different temperatures. This was attributed to the poor adhesion between the fibers and the PF in the 12%-BLVL samples, which promotes the formation of microcracks at the interface. Because the 12%-BLVL samples contained less PF resin, void formation is promoted during the processing, again leading to the formation of a larger number of microcracks under loading.

CONCLUSIONS

1. This study indicates that the BLVL material could be used as a cooling tower packing material, but further studies are required to determine its applicability in practice.
2. The 24%-BLVL samples exhibited a greater improvement in mechanical properties than the 12%-BLVL samples and the moso bamboo strips after exposure to the water baths at different temperatures. After the different aging treatments, the largest decrease in MOE was observed in the bamboo strips at all temperatures compared with the BLVL samples; however, the greatest change in the rate of MOR was observed for the 12%-BLVL.
3. The MOE and MOR significantly decreased with increasing water bath temperature for all of the composites. As the temperature increased, the water absorption and the swelling rate increased. According to the activation energies for swelling calculated from the Arrhenius plots, compared with the 24%-BLVL and moso bamboo strips, the effect of temperature on the swelling rate was greatest for the 12%-BLVL.

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