Research Article

The Influence of Media Treatments on Color Changes, Dimensional Stability, and Cracking Behavior of Bamboo Scrimber

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The purpose of this study is to evaluate the influence of media treatments on color changes, dimensional stability, and cracking behavior of bamboo scrimber, which has many applications in construction. The bamboo scrimber specimens comprised bamboo bundles with a low molecular weight phenol formaldehyde resin which were manufactured via a cold-in and cold-out hot-pressing process. Small clear specimens were sampled and treated under ten different conditions: water immersion at 25°C, 63°C, and 100°C; oil immersion at 100°C and 150°C; air drying at 63°C, 100°C, and 150°C; and infrared drying at 100°C and 150°C. Then, tests were conducted to determine the color changes, dimensional stability, and cracking behavior of the bamboo scrimbers. The results showed that the bamboo scrimber specimens became darker after all treatment conditions, especially the oil treatments and infrared drying. The color of the oil-treated bamboo scrimbers was found to be more homogenous than the others. The dimensional stability of the bamboo scrimbers was more or less influenced by the water treatments, air drying, and infrared drying, and the oil-treated bamboo scrimbers were relatively stable. Moreover, during the 4-hour treatments, cracks were found in the bamboo scrimbers after air drying at 150°C or infrared drying at 100°C or 150°C.

1. Introduction

Bamboo scrimbers are increasingly explored as a material with significant potential for construction applications [1]. Bamboo scrimbers could be the ideal materials to fulfil the demand of wood in the construction sector because bamboo grows rapidly and matures to structural strength within 3–5 years [2]. Bamboo is a sustainable resource, abundantly available, and biodegradable, and it is widely used in producing bamboo-based composites such as bamboo scrimber, laminated bamboo lumber, bamboo plywood, and bamboo particle board [3, 4]. Compared with other bamboo-based composites, bamboo scrimbers have received an increasing amount of attention due to their higher utilization ratio and excellent physical and mechanical properties, which have

extensive applications in flooring, furniture, buildings, and the civil engineering field.

Recently, a significant amount of research has been devoted to study the physical and mechanical properties of bamboo scrimbers. Sharma et al. [5] studied the mechanical properties of two types of commercially available products—bamboo scrimber and laminated bamboo sheets—and compared these to that of timber and engineered timber products. They found that both bamboo products exhibited comparable mechanical properties to other structural materials such as timber and raw bamboo. Sharma et al. [6] also evaluated the effect of processing methods on the mechanical properties of engineered bamboo. Kumar et al. [7] investigated the influence of bamboo scrimber densities on the mechanical and water absorption properties. They

FIGURE 1: General manufacturing process of bamboo scrimbers in the laboratory.

concluded that the density had a significant influence on the mechanical and water absorption properties of bamboo scrimber. Yu et al. [8] investigated the use of bamboo as a promising raw material for fabricating bamboo scrimbers. Their study aimed to determine the water absorption, dimensional stability, and mechanical properties of bamboo scrimbers with different weight percentages of phenol formaldehyde resin and different heat treatments of bamboo bundles. They also investigated the mechanical properties of bamboo fiber-reinforced composite and compared these to that of commercial bamboo scrimber and laminated bamboo lumber. They presented the tensile, compressive, and shear strengths of a bamboo scrimber with a density of 1100 kg/m^3 [9]. Zhu et al. [10] evaluated the physical and mechanical properties of bamboo scrimbers subjected to outdoor exposure. They studied the surface color, modulus of rupture, modulus of elasticity, and swelling properties of bamboo scrimbers after 2 years of exposure. Xie et al. [11] evaluated the influence of fabricated density and bamboo species on the physical-mechanical properties of bamboo fiber bundle-reinforced composites (BFCs). They found that BFCs with a density of 1200 kg/m^3 exhibited lower water absorption, better dimensional stability, and higher mechanical properties compared to those with a lower density. Shuangguan et al. [12] studied the physical characteristic, mechanical properties, and chemical composition of heat-treated bamboo scrimber. Du et al. [13] investigated the influence of different application methods of a fire retardant, that is, $(\text{NH}_4)_2\text{HPO}_4$, on the physical and mechanical properties of bamboo scrimber.

However, there is little research regarding the effect of media treatments on the changes of bamboo scrimber itself, either domestic or overseas, especially the dimensional stability and color changes. The present study investigates the influences of media treatments, such as water immersion, oil immersion, air drying, and infrared drying, on color changes, dimensional stability, and cracking behavior of bamboo scrimbers.

2. Materials and Methods

2.1. Materials. Moso bamboo bundles (*Phyllostachys pubescens*) with an age of 3–4 years were purchased from Anji, Zhejiang province. The maximum diameter of bundles was between 3.11 mm and 4.82 mm with moisture content of approximately 10%. The matrix material used in this study was based on a commercially available low molecular weight phenol formaldehyde resin, with the following parameters:

TABLE 1: Media treatments of bamboo scrimbers.

Name	Treatment conditions
A	Water immersion at 63°C
B	Water immersion at 100°C
C	Hot oil immersion at 100°C
D	Hot oil immersion at 150°C
E	Air drying at 63°C
F	Air drying at 100°C
G	Air drying at 150°C
H	Infrared drying at 100°C
J	Infrared drying at 150°C
K	Water immersion at 25°C

solid content of 45%, viscosity of 38 cP·s, and pH value of 12. It was supplied by Nanjing Dynea Chemical Industry Co., Ltd.

2.2. Preparation of Bamboo Scrimbers. The bamboo scrimbers comprised bamboo bundles with a low molecular weight phenol formaldehyde resin which were manufactured via a cold-in and cold-out hot-pressing process [8]. The process of manufacturing bamboo scrimber is shown in Figure 1. The resin-impregnated bamboo bundles were assembled along the grain direction in the hot-pressing mold. When the temperature of the hot plate heated up to 55°C , the bamboo mat was put into the press. The pressure was kept at 5.5 MPa according to relative density at $140 \pm 2^\circ\text{C}$ for 30 min to cure the mat. Afterwards, cold water was introduced into the hot plate and cooled down to 55°C . The pressure was released and the cured mat was removed from the press. The nominal dimension of bamboo scrimber was $300 \times 180 \times 13 \text{ mm}^3$. The resulting products were tested as a final product with no additional modifications. The average density of the bamboo scrimber specimens was $1080 \text{ kg}\cdot\text{m}^{-3}$. All specimens were conditioned in a room under a controlled environment at $20 \pm 2^\circ\text{C}$ and $65 \pm 3\%$ relative humidity (RH) for 2 weeks prior to testing.

2.3. Media Treatments of Bamboo Scrimbers. Media treatments were carried out under ten different conditions as shown in Table 1. The duration of all treatments were 4 hours. During the tests, the specimens, with dimensions of $40 \times 20 \times 13 \text{ mm}^3$ (length $\times$ width $\times$ thickness), were measured every 30 minutes. Fifteen replicate tests were conducted at each treatment condition.

TABLE 2: Effect of media treatments on the color change of bamboo scrimbers.

Treatment	Color in CIE $L^*a^*b^*$ system			Color difference				Change (%)		
	L^*	a^*	b^*	ΔL^*	Δa^*	Δb^*	ΔE^*	ΔL^*	Δa^*	Δb^*
Untreated	56.9	10.5	22.5	--	--	--	--	--	--	--
A	56.2	10.4	21.9	-0.7	-0.1	-0.6	0.9	-1.23	-0.95	-2.67
B	54.6	10.7	23.8	-2.3	0.2	1.3	2.6	-4.04	1.90	5.78
C	44.4	12.2	19.9	-12.5	1.7	-2.6	12.9	-22.24	16.35	-11.87
D	39.9	10.9	16.6	-17.0	0.4	-5.9	18.0	-31.14	3.74	-24.79
E	56.0	10.9	22.3	-0.9	0.4	-0.2	1.0	-2.03	3.28	-1.01
F	56.8	11.2	23.1	-0.1	0.7	0.6	0.9	-0.25	6.42	3.61
G	49.4	10.8	19.5	-7.5	0.3	-3.0	8.1	-13.39	2.75	-13.45
H	49.5	11.1	18.6	-7.4	0.6	-3.9	8.4	-13.03	5.36	-16.88
J	29.9	6.3	7.2	-27.0	-4.2	-15.3	31.3	-54.66	-38.89	-78.46
K	53.3	11.4	23.5	-3.6	0.9	1.0	3.8	-7.27	8.11	5.38

2.4. Color Measurements. The surface color of the bamboo scrimber specimens was measured with a color measurement instrument according to the CIELAB color system (instrument: Konica Minolta Color Reader (Minolta CR-10, Osaka, Japan); diameter of measured circle: 10 mm; light source: Standard Illuminant D65, which represents normal daylight including the UV region; and 108 standard observers), where L^* is the measure of lightness, a^* is the chroma from green to red, and b^* is the chroma from blue to yellow. The color difference is defined by the following equation:

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

where ΔE^* is the color difference, ΔL^* is the lightness difference, and Δa^* and Δb^* are the chroma differences. Δ means the differences between the initial and final parameters of the samples after the treatments. L^* , a^* , and b^* are the average values of six locations on each sample.

2.5. Evaluation of Physical Properties. The weight percentage change of the samples was based on the weight of the specimens before and after the 4 h treatments (measured every 30 minutes). For the water immersions and oil treatments, the weights of the treated samples were measured immediately after the removal of the surface media with a dry cotton fabric. The same specimens were used for the determination of dimensional stability. The properties were evaluated based on thickness change and width change after the treatments. One hundred and twenty specimens were prepared, and the changes in the width and thickness of all samples were measured before and after the treatments. The weight change and dimensional stability (width change and thickness change) of the specimens were calculated from the following equations.

$$\text{Weight percentage change (\%)} = \frac{M_1 - M_0}{M_0} \times 100, \quad (2)$$

where M_0 is the weight (g) before treatment and M_1 is the weight (g) after treatment.

$$\text{Width percentage change (\%)} = \frac{W_1 - W_0}{W_0} \times 100, \quad (3)$$

where W_0 is the width (mm) before treatment and W_1 is the width (mm) after treatment.

$$\text{Thickness percentage change (\%)} = \frac{T_1 - T_0}{T_0} \times 100, \quad (4)$$

where T_0 is the thickness (mm) before treatment and T_1 is the thickness (mm) after treatment.

2.6. Evaluation of Cracking Behavior of Bamboo Scrimbers. The cracking behaviors of the bamboo scrimbers were analyzed by a stereomicroscope (Olympus SZ61, Tokyo, Japan) attached to a computer with an appropriate magnification to observe the cross-section of the bamboo scrimbers after the 4-hour media treatments.

3. Results and Discussion

3.1. The Effect of Media Treatments on the Color Changes of Bamboo Scrimbers. The results of changes in color (ΔE^*) and lightness (ΔL^*) of bamboo scrimbers after the 4-hour media treatments are presented in Table 2. The L^* values of the bamboo scrimbers are shown in Table 2. The decrease in L^* for all treatments indicates that the specimens became darker after the 4-hour treatments, especially the treatments of C, D, G, H, and J. The values were -12.5 for C, -17.0 for D, -7.5 for G, -7.4 for H, and -27.0 for J. Darkening as a result of the media treatments was also clearly visible in Figure 2, and we found that it increased with treatment time. Similar results were observed by other researchers [14–16]. The change in the color of the bamboo scrimbers during the treatments may be due to the degradation of hemicellulose and other noncellulosic polysaccharides [14, 17–19]. As shown in Table 2, the lightness of the bamboo scrimbers decreased 1.23% (A), 4.04% (B), 22.24% (C), 31.14% (D), 2.03% (E),

FIGURE 2: Digital photograph of bamboo scrubbers after media treatments.

0.25% (F), 13.39% (G), 13.03% (H), 54.66% (J), and 7.27% (K). The maximum reduction was obtained for the treatment of infrared drying at 150°C for 4 h. As Figure 2(J) shows, the surface color of the bamboo scrubber turned dark after 4 hours of infrared drying. The green-red (a^*) and yellow-blue (b^*) color coordinates also changed significantly under the treatment conditions. The positive values of Δa^* indicate a tendency of the sample surface to become reddish. The media-treated bamboo scrubbers showed a more reddish color except for the treatments of A and J, which showed a more greenish color. It is interesting note that the Δa^* value of treatment C was higher than that of treatment D. The color of bamboo scrubber may be affected by oil uptake [20]. The b^* values of samples are also presented in Table 2. The positive values of Δb^* indicate a tendency of the specimen surface to become yellow, while the negative values mean a tendency to become blue. For B, F, and K, after the 4-hour treatments, these specimens became yellower, while the others became bluer. The maximum reduction of Δb^* was obtained for the treatment of infrared drying at 150°C for 4 h. The greater value in the changes of Δb^* compared to Δa^* indicates that yellowing of the treated bamboo scrubbers is more dominant than the reddish changes. The total color changes (ΔE^*) of the treated bamboo scrubbers are given in Table 2. Our results showed that ΔE^* remarkably increased after the oil and infrared drying treatments. These results are in accordance with the results of Figure 2.

3.2. The Effect of Media Treatments on the Weight Percentage Changes of Bamboo Scrubbers. Figure 3 shows the effect of media treatments on the mean weight percentage change of the treated specimens. As shown in Figure 3, the weights of bamboo scrubbers increased after treatments of A, B, C, and K. The gain in the specimen weight increased with the increase of treatment time. As Figure 3 (A, B, and K) shows, the water absorption of bamboo scrubbers increased with the treatment temperature. For the 4 h treatments, the weight percentage change values of bamboo scrubbers after treatments of A, B, and K were approximately 13.57%, 35.51%,

FIGURE 3: Weight percentage change of bamboo scrubbers in different media at different treatment temperatures. A, B, and K: water immersion at 63°C, 100°C, and 25°C; C and D: oil immersion at 100°C and 150°C; E, F, and G: air drying at 63°C, 100°C, and 150°C; H and J: infrared drying at 100°C and 150°C.

and 8.19%, respectively. Compared with the water treatment, the oil treatment did not lead to an obvious change in the weight of bamboo scrubbers. The weight percentage change value was only 1.37%. When the oil temperature increased to 150°C, during the 4-hour treatments, the weights of bamboo scrubbers decreased with the treatment time (Figure 3(D)). The weight percentage change value was -0.45% . Compared to treatment D, the weights of bamboo scrubbers remarkably decreased during the treatment time. In particular, for the treatment of J, the weights of bamboo scrubbers obviously decreased after 2 h of treatment. The weight percentage change values of bamboo scrubbers after treatments of E, F, G, H, and J were approximately -2.99% , -5.78% , -8.80% , -8.69% , and -12.97% , respectively. For both air drying and infrared drying, the weight percentage change values of bamboo scrubbers increased with the treatment temperature. As the treatment temperature increases, most of the thermally weak polymeric components, that is, hemicelluloses, begin to degrade, resulting in the production of methanol, acetic acid, and various volatile heterocyclic compounds [14, 16]. Undeniably, the water loss in bamboo scrubbers was the primary cause for the decrease in the weight of the specimens.

3.3. The Effect of Media Treatments on Dimensional Stability of Bamboo Scrubbers. Figures 4 and 5 present the results of width percentage change and thickness percentage change of the differently treated bamboo scrubbers, respectively. As the figures show, the water immersions can sensitively change the dimension of bamboo scrubbers, especially the treatment of B. The width percentage change and thickness percentage

FIGURE 4: Width percentage change of bamboo scrimbers during 4-hour treatments. A, B, and K: water immersion at 63°C, 100°C, and 25°C; C and D: oil immersion at 100°C and 150°C; E, F, and G: air drying at 63°C, 100°C, and 150°C; H and J: infrared drying at 100°C and 150°C.

change of the treated bamboo scrimbers after 4-hour treatments of A, B, and K increased with the temperature. The width percentage change values after 4-hour treatments of A, B, and K were 1.81%, 7.49%, and 0.66%, and the thickness percentage change values were 12.13%, 58.71%, and 2.14%, respectively. Compared with the water treatment, the oil treatment did not obviously change the dimension of the bamboo scrimbers. After 4-hour treatments of C and D, the width percentage change values of the bamboo scrimbers were only 0.129% and -0.018%, respectively. In the thickness change study, after 4-hour treatments, the 100°C oil-treated bamboo scrimbers showed less swelling than the 150°C oil-treated samples. The thickness percentage change value was only 0.541% for treatment C, but 4.095% for treatment D. For all of the air drying and infrared drying treatments, as shown in Figure 4 (E, F, G, H, and J), the width percentage change values of the bamboo scrimbers decreased with the treatment time. For the 4 h treatments, the width percentage change values after treatments of E, F, G, H, and J were approximately -0.25%, -0.74%, -1.34%, -1.32%, and -1.53%, respectively. The bamboo scrimbers after 4 hours of infrared drying at 150°C showed the greatest width shrinkage of 1.53%. However, the thickness of the bamboo scrimbers increased 2.20% after 4 hours of infrared drying at 150°C as shown in Figure 5 inset. This could be explained by the gradual decrease of water in the bamboo scrimbers during the 4-hour infrared drying. The rate of water loss in and out of the bamboo scrimbers was not uniform. This can quickly lead to the cracking of the bamboo scrimbers after 0.5 hours of infrared drying, which caused an increase in the thickness. The results were supported by the following cracking research.

FIGURE 5: Thickness percentage change of bamboo scrimbers during 4-hour treatments. A, B, and K: water immersion at 63°C, 100°C, and 25°C; C and D: oil immersion at 100°C and 150°C; E, F, and G: air drying at 63°C, 100°C, and 150°C; H and J: infrared drying at 100°C and 150°C.

3.4. The Effect of Media Treatments on Cracking Behavior of Bamboo Scrimbers. The cracking behavior is one of the most important properties of bamboo scrimbers and is used to evaluate the quality of bamboo products. The effects of media treatments on the cracking behavior of bamboo scrimbers during the 4-hour treatments are presented in Figures 6 and 7. As Figure 6 shows, after 4-hour immersion in water at 25°C (K) and 63°C (A), no surface cracks were observed in the cross-section of treated bamboo scrimbers. However, when the water temperature was raised to 100°C (Figure 6(B)), some cracks appeared in the bamboo scrimber after only 0.5 hours of treatment. The size and number of cracks increased with the treatment time. Water absorption affected the physical properties of bamboo scrimbers, as well as the matrix structure and fiber-matrix interface, resulting in the change of dimensional and physical properties of the bulk materials, especially under high temperature [8]. Nevertheless, we did not observe cracks in oil-treated bamboo scrimbers after 4-hour immersion at 100°C (Figure 6(C)) and 150°C (Figure 6(D)). This result showed that water, compared with oil, was a suitable medium to test the dimensional and physical properties of bamboo scrimbers within a short time. As shown in Figure 7, no surface cracks were observed in treated bamboo scrimbers after 4 hours of air drying at 63°C (Figure 7(E)) and 100°C (Figure 7(F)). Cracks appeared in bamboo scrimbers after the treatment temperature was raised to 150°C (Figure 7(G)) for 0.5 h. However, the cracks disappeared with the drying time. The same results could be observed in Figure 7(H). After the 4-hour infrared drying treatment, the size and numbers of cracks decreased and even some cracks disappeared. This could be explained by the

FIGURE 6: Representative optical images of the cross-section of bamboo scrimbers during the 4-hour treatments of K, A, B, C, and D.

FIGURE 7: Representative optical images of the cross-section of bamboo scrimbers during the 4-hour treatments of E, F, G, H, and J.

gradual decrease of moisture in bamboo scrimbers during the 4-hour drying. The rate of moisture loss in and out of bamboo scrimbers was not uniform. The surface layers of the bamboo scrimbers first lost moisture, and then the internal layers of bamboo timber lost moisture [21]. This can quickly lead to the cracking of bamboo scrimbers after 0.5 hours of air drying at 150°C or infrared drying at 100°C. With the increase of treatment time, the moisture in bamboo scrimbers gradually decreased and finally maintained equilibrium. Therefore, the cracks in bamboo scrimbers gradually disappeared. However, the size and number of cracks in bamboo scrimbers increased with the treatment time with infrared drying at 150°C (Figure 7(J)). From Figure 2(J), we can conclude that the bamboo scrimber was excessively charred after 4 hours of infrared drying at 150°C, which gave it a darker shade. Darkening occurring from the treatment was due to colored compounds being developed during the chemical changes of lignin, hemicelluloses, and the extractives [15]. Finally, the size and number of cracks in bamboo scrimbers increased with the infrared drying time.

Based on the above experimental results, we found that the water medium sensitively changed the dimension and physical properties of bamboo scrimbers compared to the others. We can use the water medium to quickly test the cracking behavior and qualified rate of bamboo products. From the results shown in Figure 7, the high temperature of the air drying or infrared drying treatment can cause cracks and color change in the bamboo scrimbers. We need to choose an appropriate drying temperature to treat the products according to one's demand. The color of the oil-treated bamboo scrimbers was found to be homogenous without any resin patches. Oil as a treating medium provides an oxygen-free environment and uniform heat can be transferred from the oil to bamboo scrimbers compared to air drying or infrared drying; thus, the color was more uniform [22]. In addition, the physical property and cracking behavior of bamboo scrimbers were relatively stable during the oil treatment process. More interestingly, we found that the bamboo scrimbers became more water repellent after the oil treatment. Further work is currently in progress in our laboratory to optimize the process parameters of oil treatments.

4. Conclusion

The present work focused on the influence of media treatments such as water, oil, air drying, and infrared drying on color changes, dimensional stability, and cracking behavior of bamboo scrimbers. The experimental results showed that the bamboo scrimber specimens became darker after all treatment conditions, especially the oil treatments and infrared drying. However, the color of the oil-treated bamboo scrimbers was found to be more homogenous than the others. The dimensional stability of bamboo scrimbers was more or less influenced by water immersion, air drying, and infrared drying, and the oil-treated specimens were relatively stable. Moreover, during the 4-hour treatments, cracks were found in the bamboo scrimbers after air drying at 150°C or infrared drying at 100°C or 150°C.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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