Effects of Compressive Deformation on Wettability and Water Uptake Behavior of Poplar

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Abstract

Wood compression is a method of increasing the density and stiffness of wood. Using heat (thermal compression) or impregnating wood with various resins can also increase its dimensional stability. Compressed wood can be used as a structural component in buildings, but it generally must be painted to improve its durability. The objective of this research was to investigate the surface wettability and water uptake behavior of compressed poplar wood with and without melamine-formaldehyde resin impregnation in order to be able to predict the behavior of resins or paints on surfaces of compressed wood. Samples of poplar wood were pressed both in the presence of resin and without resin at 180°C for 30 minutes under different pressures (0 to 8 MPa). Compression ratios were 10, 20, and 50 percent, depending on the pressure. Results indicate that the surface contact angle of the compressed wood, without resin, increased as the compression ratio increased. The water absorption of compressed wood, without resin, was much higher than that of the compressed wood with resin treatment. Also, the amount of absorbed water in the direction of the grain was greater than that in the perpendicular-to-grain direction for both compressed wood samples.

There have been many studies on how to make wood denser in order to improve its hardness and other mechanical properties (Sekino et al. 1997, Blomberg and Persson 2004, Shams et al. 2004, Shams and Yano 2004, Yoshihara and Tsunematsu 2007a). Compressing wood increases the stiffness and quality of timber from low-density and low-quality wood species so that they can be used as structural materials (Yoshihara and Tsunematsu 2007b), and wood compression can be combined with heating and chemical impregnation in order to maximize both the wood's hardness and its dimensional stability. In particular, thermally compressed wood, with or without resin impregnation, has emerged as a new type of wood-based material whose physical and mechanical properties can be increased because its density can be increased (Kutnar et al. 2009). By a process called deformation fixation, wood first is impregnated with a low-molecular-weight and water-soluble melamine-formaldehyde (MF) or phenol-formaldehyde (PF) resin and then compressed while heating (Inoue et al. 1993, Shams et al. 2006a), yielding highly compressed wood at low pressing pressure (Shams et al. 2006b). The final product is improved in mechanical properties and is also biologically resistant (Ryu et al. 1993). In recent years, techniques for fabricating compressed wood have rapidly developed, and several common products, such as flooring and handrails, are made using compressed wood. In addition, thermally compressed wood can be used not only for structural solid wood products, which generally require painting, but also as panel products. For example, plywood manufactured from compressed veneer sheets has various construction applications and has better properties and lower production costs compared with traditionally produced plywood (Bekhta et al. 2009). As these products have been developed, so too has scientific study of the properties of compressed wood (Yoshihara and

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Tsunematsu 2007a). Study of the surface wettability of thermally compressed wood is particularly important because the surface wettability plays an important role in the ability of adhesives and paints to wet, flow, penetrate, and cure on the surface of wood.

Poplar, which is one of the dominant species used for forest plantation in China, cannot be used directly as a solid wood product because of its low density, low stiffness, and low strength. Thermal compression treatment is one way to improve the quality of this wood. To date, there has been limited research on the surface wettability of compressed wood. Information about the water absorption of compressed wood over a certain time cycle can help predict the performance of compressed wood products in different conditions. The objective of this research was to investigate the effect of thermal compression, both without and with MF resin impregnation, on the surface wettability of wood using contact angle and liquid sorption capacity measurements. The water uptake behavior was also investigated in response to wetting and wicking phenomena, providing a guide to appropriate applications for compressed wood.

Materials and Methods

Sample preparation

Poplar (*Populus euramericana*) was obtained from Jiangsu Province, China. Its initial ovendried density was 0.41 g/cm^3.

The MF resin was provided by Jiangsu Lodgi Woods Industry Co., Ltd. (China). The resin's solid content was 52.3 percent, its viscosity was 45 mPa·S, and its pH value was 9.0. It was low-molecular-weight MF with an average molecular weight of about 400. Two kinds of samples were prepared. One was compressed without resin, and the other was compressed with MF resin; the resin was introduced into pores of poplar wood as impregnation with about 20 percent resin (based on dry weight of wood) under vacuum conditions (0.1 MPa). The compression conditions were the same for both kinds of samples: the temperature was 180°C, the pressure was from 0 to 8.0 MPa, and the pressing time was 30 minutes. The thermal compression was performed along the radial direction with the restriction of transverse deformation by a laboratory hot press equipped with various gauges to control the compression ratio, *C,* at 0, 10, 20, and 50 percent. The *C* can be represented as follows:

$$C = \frac{T_0 - T_c}{T_0} \times 100\%$$

where T_0 and T_c are the thickness in the radial direction before and after the compression, respectively.

The specimens for the surface wettability study were cut from the originally prepared samples to a length of about 15 mm and a width of 5 mm. The specimens for testing the water uptake behavior were cut to a size of approximately 10 mm (length) by 10 mm (width) from the original samples. There were 10 samples for every test condition. The thickness of all samples was 1.5 to 2.0 mm. In order to control the influence of moisture content of the samples on the testing result, all prepared specimens were placed into desiccators over a saturated water solution of potassium acetate that maintained a relative humidity of 23 percent at a room temperature of 21°C to 23°C. The final moisture content of the samples was about 5 percent.

Contact angle measurement

The Wilhelmy plate method was used to evaluate the surface wettability of the compressed wood (without resin and with resin treatment). The test was carried out using a Cahn DCA-322 Dynamic Contact Analyzer (DCA 322, Thermo Cahn Instruments). Each prepared sample was suspended perpendicular to the liquid's surface, and the balance was zeroed. Then the sample was lowered until it contacted the liquid's surface and the rising of the liquid caused a positive force. As the sample was partially immersed in the liquid, the buoyancy increased, causing a decrease in force on the balance. The forces were recorded for the calculation of advancing contact angle. After having reached the desired depth, the sample was pulled out of the liquid. During the withdrawal process, the forces were recorded for the calculation of the receding contact angle.

Water uptake measurement

The evaluation of water uptake behaviors of the samples was carried out by a wicking test performed on a DCA-322 instrument following our previous method (Zhang et al. 2007); the effect of the compression deformation on the water uptake behavior of wood, both in the presence of resin and without resin treatment, was determined as the amount of water uptake at different times during the sorption process. In this test, each sample was immersed and held just below the liquid surface, and the weight change (the amount of water absorbed by the sample) was recorded as a function of time. In this study, the sample was immersed in distilled water at a depth of 1.0 mm and held in fixed position by the electro-balance attached to the instrument. The sample was immersed in the grain direction or perpendicular to the grain direction with the expectation that when the grain was parallel to the immersion direction, it would absorb water more quickly. The weight change was recorded as a function of time. The total running time for each specimen was 8 hours (28,800 s), and data were collected at various time intervals. The test was performed at room temperature (21°C to 23°C).

Results and Discussion

The change of the surface contact angle for compressed poplar wood

The contact angle, which is a function of a liquid's surface tension and the solid's surface energy, is used to describe a solid's wetting by a liquid and to measure the surface wetting characteristics of wood (Garcia et al. 2006). The contact angle is important in the study of the behavior of adhesives and coatings on wood and wood-based composite surfaces (Tze and Gardner 2001, Pétrissans et al. 2003). Figure 1 presents the change of the surface contact angle for the compressed samples without resin and with resin. From Figure 1, it is clear that the surface contact angle of the compressed poplar without resin increased as the compression ratio of the wood was increased. This indicates that the wettability of compressed poplar decreases as the compression ratio increases. There are several factors that may have influenced the change in the surface contact angle for the wood, such as the condition of thermal compression, chemical changes on the wood surface, etc. (Kutnar et al. 2008). Pétrissans et al. (2003) reported a decrease in the wettability of wood and an increase in its hydrophobicity

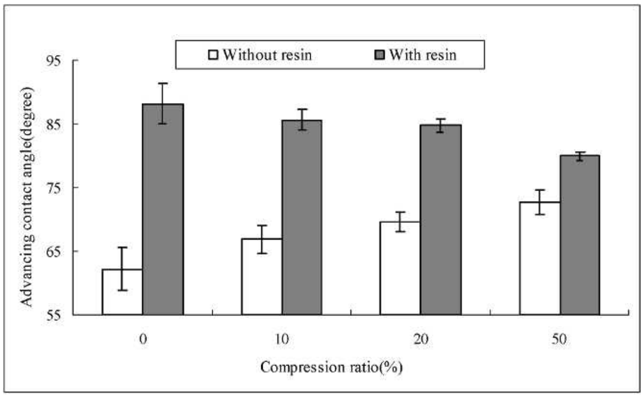
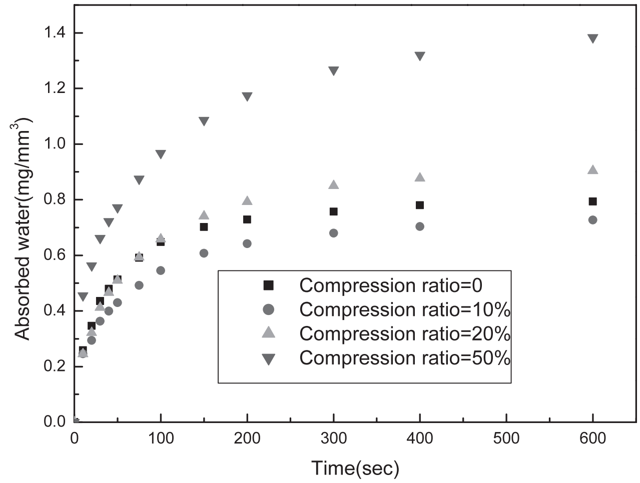


Figure 1.—The relationship between compression ratio and surface contact angle of samples without resin and with resin.

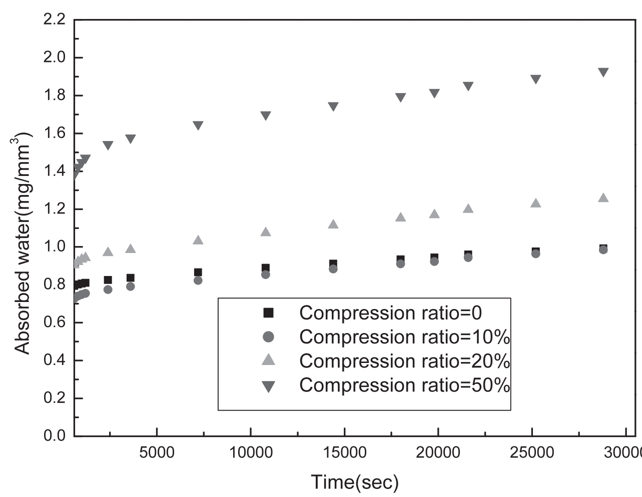
after heat treatment. The main effect of heat treatment on wood structure is degradation of the hemicellulose, which is the most unstable and hydrophobic component of wood (Tjeerdsma and Militz 2005). On the one hand, the higher compression ratio at high temperature can reduce the surface free hydroxyl groups of wood and decrease its hydrophilic character while increasing the surface contact angle of the wood with polar liquids. On the other hand, water will permeate into wood when its surface contact angle is tested. A high compression ratio could reduce some of the surface pores on the wood so that less water permeates into the wood than with a low compression ratio. Therefore, a high compression ratio can be responsible for increasing the contact angle of compressed poplar without resin. Moreover, Figure 1 shows that the change of surface contact angle of the compressed poplar with MF resin had a different tendency compared with the samples without MF resin. The main reason was that the cured MF resin could form waterproof points to prevent water entering into the wood and become less important under high compression ratio.

Influence of the compression ratio on the water uptake behavior of compressed poplar wood

Figures 2a and 2b show the change in absorption of water for compressed poplar (without resin) in a two-stage process. There is a rapid absorption followed by a slow and relatively linear absorption. From these two figures it can be seen that the tendency of water sorption for compressed poplar rose gradually as the compression ratio increased during the second stage. These results are in contrast with data related to the contact angle of compressed samples, which show an increase in the hydrophilic character of wood after compression (in samples without resin). This phenomenon can be explained as follows: although temperature can decrease the hydrophilic character of wood, it is probably not the main reason in our study, and some other factor, perhaps higher pressure, only temporarily increased the contact angle. This is logical because the duration of pressing and contact with heat in this study was relatively short compared with other research (Pétrissans et al. 2003, Tjeerdsma and Militz 2005). In the water uptake process, the sample with the highest compression ratio showed clearly different water uptake behavior, and the water uptake of other samples was similar. Pressure may have only limited the penetration and wetting of the surface



(a)



(b)

Figure 2.—The relationship between compression ratio and water absorption per cubic millimeter of wood of samples without resin: (a) the first stage (first 10 min) of the wicking test; (b) the second stage (from 10 min to the end) of the wicking test.

because of densification of the wood for a short time, but during the wicking test and in longer-lasting contact with water, water penetration and swelling of the cell walls creates more paths for penetration and consequent absorption of the water by the cell walls (Fig. 3). Figure 3 shows that the thickness of the sample without resin returned almost to its original size after 8 hours of water absorption when the compression ratios were 0 to 25 percent as the thickness swelling was almost equal to the compression ratio. However, its thickness increased greatly, to even more than its original thickness when the compression ratios were 25 to 50 percent, which gives water more space to enter the wood. When the sample was treated with MF resin, the amount of space for absorption of water was much smaller. It is clear that the thickness of the specimen changed only a little after 8 hours of water absorption (Fig. 3). According to test results, the weight gain value increased 20 percent based on an ovendried sample after MF resin impregnation. The density of cured MF resin is 1.3 g/cm^3, and its volume gain

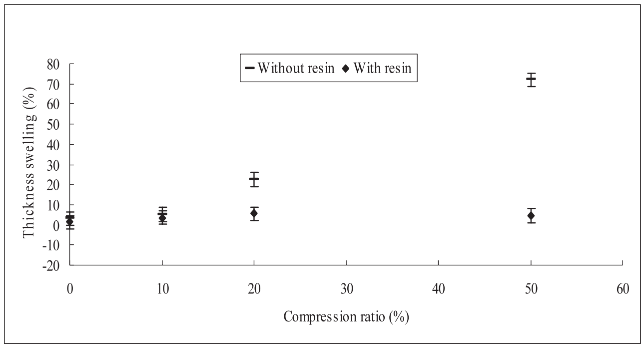


Figure 3.—The relationship between compression ratio and thickness swelling of samples without resin and with resin.

is smaller. However, the cured MF resin can prevent parts of water entering into the cell wall of a sample to restrict its spring back. Therefore, the thickness swelling for the sample with resin decreased a little at the higher compression (50%). If the sample has no resin, its spring back will be increased significantly and include spring back of compressed cell and wood swelling itself. So the thickness swelling for the sample without resin is very high at the higher compression (50%).

Figures 4a and 4b show that the change in water absorption for compressed samples (with MF resin) took place in a two-stage process, which also indicates a rapid absorption followed by a long, slow, and relatively linear absorption. Compared with samples without resin, there was a significant difference between the two groups. It is clear that the presence of resin in the wood compressed with MF resin leads to a lower amount of water being absorbed and a slower water uptake rate than those of samples without resin. Samples with a compression ratio of 10 to 20 percent have the lowest water absorption. It seems that low pressure can help distribution of resin on the surface of wood and can prevent water absorption, but that using high pressure can cause the penetration of resin into the inner cells and can

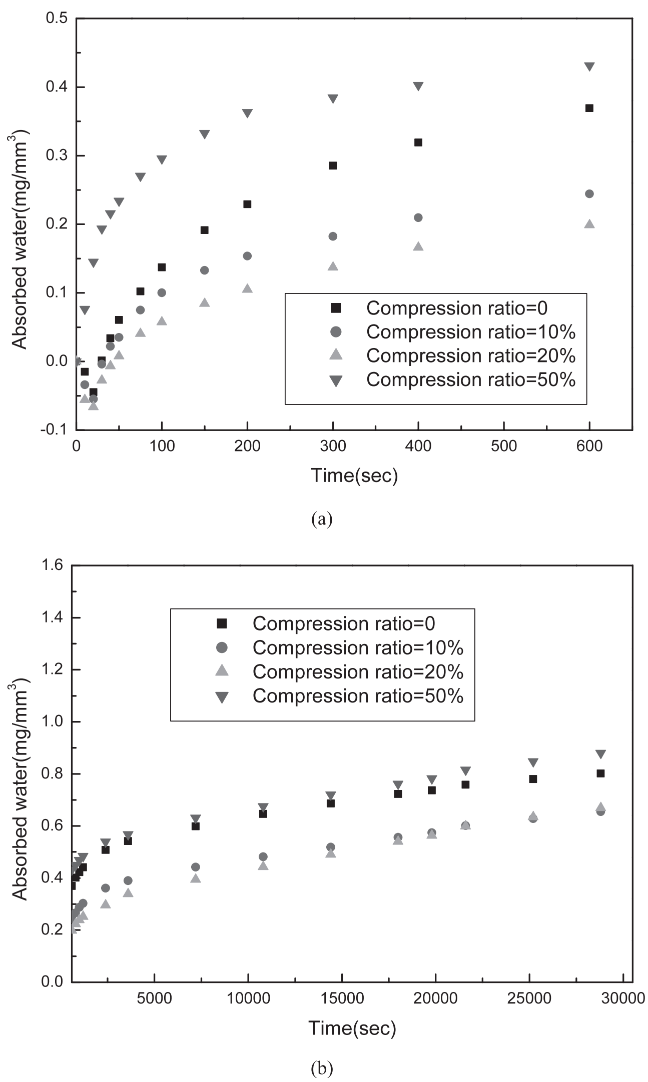


Figure 4.—The relationship between compression ratio and water absorption per cubic millimeter of wood of samples with melamine-formaldehyde resin: (a) the first stage (first 10 min) of the wicking test; (b) the second stage (from 10 min to the end) of the wicking test.

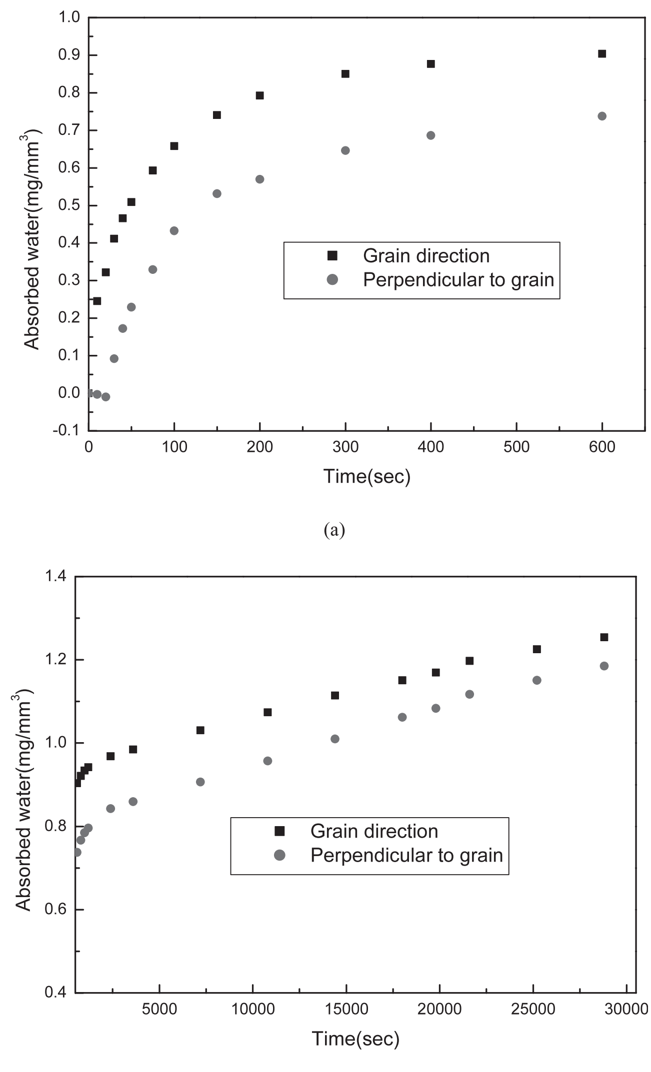
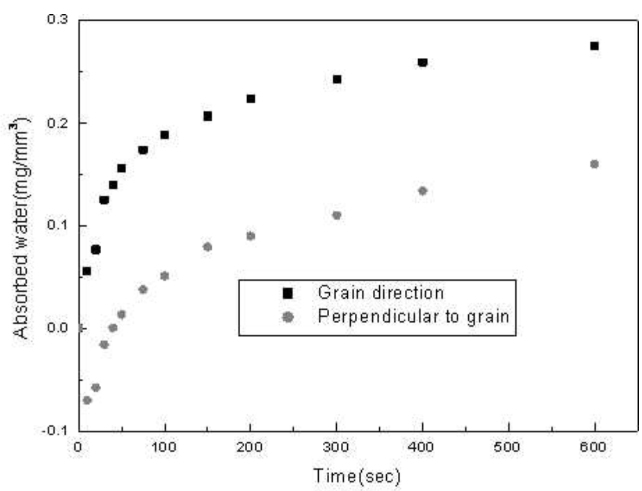


Figure 5.—The effect of grain direction on water uptake behavior of compressed wood without resin: (a) the first stage (first 10 min) of the wicking test; (b) the second stage (from 10 min to the end) of the wicking test.

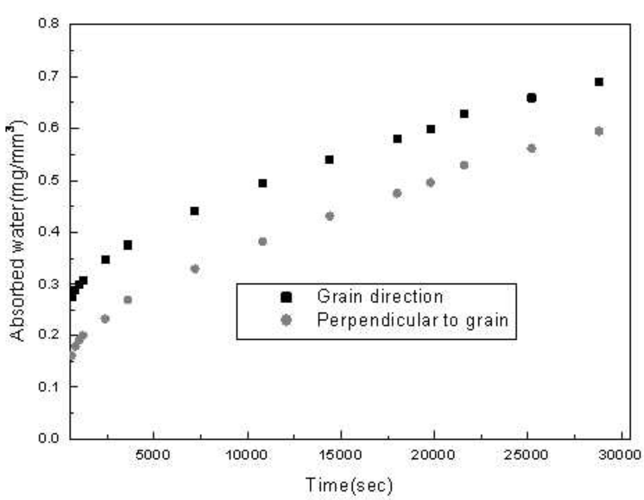
decrease the waterproofing effect of resin on the surface of the wood, as is also seen in the contact angle results.

Comparing the water uptake behaviors in two directions

Figures 5a and 5b show the water uptake behavior of a compressed sample (without resin) at a compression ratio of 20 percent is different in two directions. The amount of absorbed water in the grain direction of wood samples was greater than the amount of water absorbed in the perpendicular-to-grain direction. However, this difference between the two directions became gradually smaller with the duration of the test time. The explanation is that in the grain direction (longitudinal direction), the adsorption of water in natural wood is faster than in its radial or tangential direction, mainly because of the capillary effect of the lumens. Similarly, compressed wood keeps this natural characteristic and has higher water absorption in the grain direction. A similar situation can be seen in Figures 6a and 6b for water absorption of samples with MF resin in different directions (at a compression ratio of 20%). However, among the samples, the highest amount of water absorption in the grain direction for the compressed poplar wood with MF resin treatment was about 0.69 mg/mm^3, which was much lower than the about 1.25 mg/mm^3 observed for the compressed wood without resin (also in the grain direction). The highest amount of water absorption perpendicular to the grain direction for the compressed wood with MF resin treatment was about 0.59 mg/mm^3, which was only half that of the compressed poplar wood without resin in the same direction (1.18 mg/mm^3). We conclude that water uptake was lower because MF resin covered the surface of wood samples and entered into the cell pores on the surface of the wood, which is also the case for the other water uptake results of these samples. Furthermore, the hindering effect of resin in the perpendicular-to-grain direction was greater than that in the grain direction.



(a)



(b)

Figure 6.—The effect of grain direction on water uptake behavior of compressed wood with melamine-formaldehyde resin: (a) the first stage (first 10 min) of the wicking test; (b) the second stage (from 10 min to the end) of the wicking test.

Conclusions

Although the contact angle for compressed samples without MF resin increased with increasing compression ratio, it seems unlikely to be because of the character of wood changing from hydrophilic to more hydrophobic, since the water uptake of samples did not support the contact angle data. The presence of resin resulted in a decrease in water absorption compared with that of samples without resin. The increasing compression ratio in the samples with resin resulted in penetration of the resin into inner cells and had the reverse effect on contact angle and water uptake. Waterborne adhesives and paints can be used for compressed wood and they can be used for noncompressed wood because no significant change and even higher hygroscopocity (at a compression ratio of 50%) were observed after compression of the wood samples.

Acknowledgments

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