Effect of Core Temperature on Some Important Properties of Poplar Scrimber Boards during the Heat Curing Process

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Abstract

In this study, poplar wood and a phenol-formaldehyde (PF) resin were used to produce a large-scale scrimber product by a combined cold pressing and heat curing method. The water resistance, mechanical properties, and formaldehyde emission of the scrimber boards prepared at different core temperatures (100°C, 110°C, 115°C, and 120°C) were investigated. The results showed that the peak core temperature had a significant effect on the scrimber performance. The thickness swelling rate and width swelling rate of the scrimber boards prepared at a core temperature of 100 °C were significantly higher than other samples. The formaldehyde emission from the surface layer of the scrimber boards prepared at a high core temperature (115°C and 120°C) was much lower than that at a core temperature of 100°C and 110°C. These results can be explained by the correlation between curing degree and temperature of the PF resin in the scrimber. With increasing core temperature, the modulus of rupture, compression strength, and horizontal shear strength of the scrimber boards first increased and then decreased, suggesting that core temperature during the heat curing process also played an important role in determining mechanical properties. The scrimber boards with the best mechanical properties were prepared at a core temperature of 115°C. The results of the study demonstrated that the optimal core temperature necessary to produce a low-cost and high-performance scrimber was 115°C.

Poplar scrimber is a high-performance wood-based composite material made from poplar fluffed veneers and a low-molecular-weight phenol-formaldehyde (PF) resin, which has the characteristics of not disrupting the orientation of the fibers and maintaining the basic properties of the wood (Zhang et al. 2018a). The selected PF resin is a type of thermosetting adhesive widely used in bamboo and wood-based panels. A complete and uniform curing of the resin in large-scale materials is essential for ensuring the quality of the products, particularly their dimensional stability (Gabrielli and Kamke 2010). After high-pressure forming and heat curing, the low-molecular-weight PF resin filled the intercellular space and cell wall cavity of the fluffed veneers (Bao 2017, Meng 2017), binding the components together and thereby reinforcing the material to result in high mechanical properties (Bao et al. 2016, Yu et al. 2018). When compared with traditional scrimber made from frequently used species, poplar scrimber often has better mechanical properties and dimensional stability (Zhang et al. 2018b, 2018c). This novel strategy for manufacturing a high-performance scrimber overcomes the inherent defects of low density and poor mechanical properties that are associated with fast-growing wood and allows engineering the performance, structure, and dimensions of the novel scrimber. This scrimber process also significantly promotes the serialization and diversification of the end use of its products (Zhang et al. 2016). This method can completely utilize the rich advantages of the plantation resources of China and simultaneously compensate for the shortage in high-quality timber resources.

Currently, the forming method for wood scrimber is similar to that of bamboo scrimber, in which first hot and then cold pressing are performed and then a heat curing process is adopted. During hot pressing, a slab of 244 by 122

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by (1.5 to 4) cm (longitudinal by radial by tangential) is prepared by flat pressing, and the pressurization is accompanied by the transfer of water and heat, producing cuboid materials of size 193 by 10.5 by 15 cm or 200 by 14.5 by 15.0 cm (Yu 2012). Previous research has found that both methods can produce poplar scrimbers with excellent physical and mechanical properties, which can be applied to the fields of flooring and decoration (Zhang et al. 2016). In a recent work, cuboid materials of size 2,000 by 200 by 150 cm (Zhang et al. 2018b) were produced. The production efficiency of large-scale scrimber made by a combined cold pressing and heat curing process (hereafter referred as cold pressing/heat curing process) is nearly three times higher than that of the hot pressing method. However, the large dimensions of the cuboid materials and the independence of the pressurization and heating process in the former will affect the degree of resin diffusion and curing in the scrimber. This results in differences in the physicomechanical properties and environmental performance in different parts of the produced scrimber products. During the industrial production of scrimber by the cold pressing/heat curing method, the temperature and heating time are not precisely controlled. The lack of precise process control results in an unacceptable variation in the core temperature over time, eventually leading to a nonuniform quality of the produced scrimber. To improve the production efficiency, to save energy consumption, and to ensure product quality, it is necessary to investigate the effect of the core temperature on the mechanical and physical properties of scrimber.

The purpose of this article was to provide technical support for the optimization and industrialization of the cold pressing/heat curing method for producing a high-performance poplar scrimber on a large scale. In the present study, poplar scrimbers with dimensions of 2,560 by 300 by 200 mm were prepared industrially by heating to 140°C for different times during the heat curing process. During the heat curing, the temperature behavior of the scrimber and its influence on the water resistance, mechanical properties, and formaldehyde emission of the scrimber were investigated.

Materials and Methods

Materials

Poplar wood (*Populus* ssp.), aged 4 to 5 years, was obtained from Hebei province in China (65% moisture content [MC], 30- to 35-cm diameter, and 0.38 to 0.42 g cm^{-3} density). Round wood with a length of 2,000 mm was first rotary cut into 6-mm-thick veneers, and then a pilot-scale fluffing machine was used to fabricate fluffed veneers with a series of uniform linear-shaped cracks along the grain. The fluffed veneers were then oven-dried to an MC of approximately 10 percent. Subsequently, the fluffed veneers were soaked in a 20 weight percent PF solution for approximately 5 minutes to attain a resin content of 19 to 20 weight percent and then dried again to 12 percent MC. The PF resin was purchased from Guangdong Dynea Chemical Industry Co. Ltd (Guangdong, China), and further information provided by the supplier is presented in Table 1.

Table 1.—Basic information of the phenol-formaldehyde (PF) resin used in this study.

Properties of adhesive	PF resin
Solid content, wt%	52.08
Viscosity at 30°C, MPa/s	65
pH at 25°C	9.68
Water solubility multiple	11
Alkalinity, %	2.95
Gelation time at 130°C, s	303
Free phenol content, wt%	1.189
Free formaldehyde content, wt%	0.29

Preparation of scrimber boards

The poplar scrimbers were prepared according to the standard procedure of Zhang et al. 2018a. The cold pressing/heat curing process was employed for scrimber manufacturing from the poplar (Zhang et al. 2018c). Fluffed veneers with glue were weighed according to the target density of 1.05 g cm^{-3} and then assembled along the grain direction in a 2,560 by 300 by 200-mm (longitudinal by radial by tangential) mold. Simultaneously, temperature sensors were sandwiched in the top and middle layers of the veneers. Under the action of pressure and pins, these materials were fixed in the mold at room temperature (Zhang et al. 2018a). Next, they were transferred together to an air-circulated baking chamber for PF resin curing at 140°C (Zhang et al. 2016). To eliminate the influence of the internal stress in the scrimber, the resultant square stocks were conditioned in a chamber at 65 ± 5 percent relative humidity at 20°C ± 2°C for 2 weeks before testing. Each resultant scrimber square stock was sawed along the tangential (height) direction into nine scrimber boards (denoted as SBs) with a thickness of 20 mm (material loss of 20-mm thickness caused by sawing), and three samples of plates of 800 by 600 by 20 mm (longitudinal by radial by tangential) to be tested were cut from the surface layer board (denoted as S-SB) and the core layer board (denoted as C-SB) randomly (see Fig. 1). Some important properties of the S-SB and C-SB were tested to characterize the overall properties of the resultant scrimber.

Characterization of PF resin and scrimber boards

A differential scanning calorimetry (DSC) thermogram was obtained on a DSC Q20 V24.10 Build 122 from 10°C to 280°C at a heating rate of 10°C/min under a nitrogen atmosphere. The initial sample weight was 6.600 mg. The measurement was made in accordance with the International Standard 11409:1993 (International Standard Organization 1993).

The real-time temperature changes in the SBs were monitored using sensors inserted at the geometric center of the S-SB and C-SB before the heat curing process (Fig. 1).

The thickness swelling rate (TSR) and width swelling rate (WSR) of the SBs were tested according to the procedure described in GB/T 30364-2013 (Standardization Administration of the People's Republic of China [SAC] 2013a). The 48-hour treatment cycle consisted of 24 hours of immersion in boiling water, 20 hours of oven-drying at 60°C ± 3°C, and another 4 hours of immersion in boiling water. The density, modulus of rupture (MOR), modulus of elasticity (MOE), and compression strength (CS) were measured using the standard GB/T 17657-2013 (SAC 2013b) system in the three-point bending mode. The horizontal shear strength (HSS) was determined using the GB/T 20241-2006 (SAC 2006) standard. All samples were taken from the one core layer

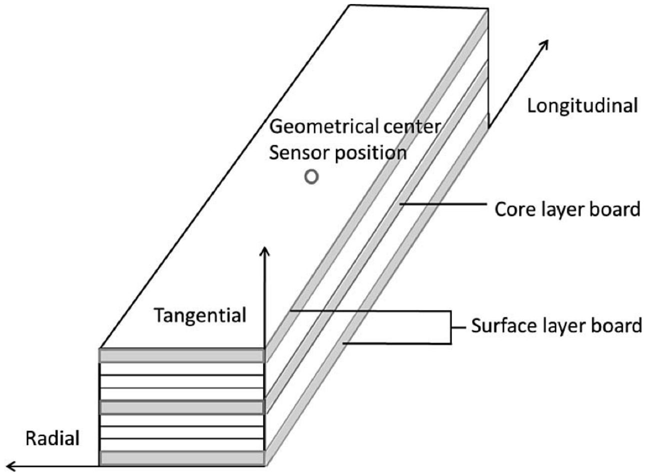

Figure 1.—Selection of the surface layer board and core layer board samples.

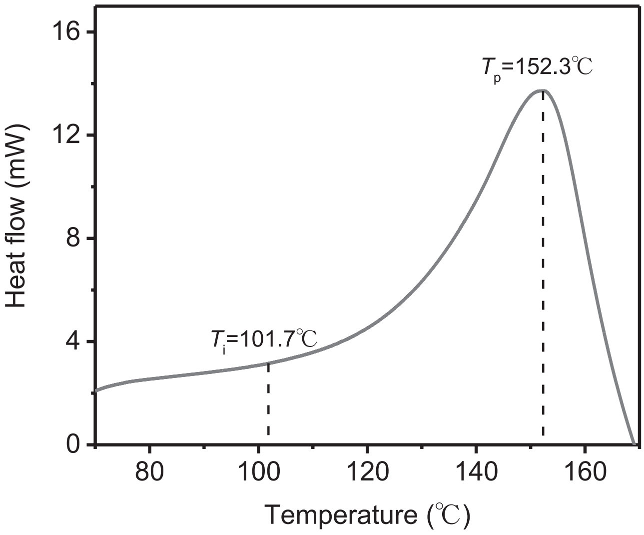

Figure 2.—Differential scanning calorimetry thermogram of the phenol-formaldehyde resin.

or surface layer board of the same scrimber. Six replicate measurements were performed on each test, and the average data were recorded. The formaldehyde emission of the S-SB specimen was obtained with the GB/T 18580-2001 (SAC 2001) standard using the desiccator method.

Statistical analysis

Analysis of variance was performed using the SPSS software package (version 21.0; IBM, New York, New York, USA), and the corresponding curves were drawn using OriginLab OriginPro 2016 (version 2016 SR0 b9.3.226; OriginLab Corporation, Northampton, Massachusetts, USA).

Results and Discussion

DSC analysis of PF resin

The DSC thermogram of the PF resin is shown in Figure 2, in which an exothermic process is evident as a broad peak. The peak temperature (T_p), which was further related to the curing properties (Chow 1972), is 152.3°C. In addition, the initial curing temperature (T_i) of the resin is 101.7°C, after which the molecular weight of the first-order resin increased further and the degree of curing increased continuously with time (Wang et al. 1994). When the temperature continues to rise to T_p or higher, the additional reactions are almost complete, and the condensations are the dominant reactions (He et al. 2003). Moreover, additional reactions could occur simultaneously to form high-molecular-weight species by condensation (Astarloa-Alerbe et al. 1998). The resin used in this study was a second-order resin, a mixture of free phenols, phenol, and various aldehyde-methyl congeners with insoluble and melted polymers. At high temperatures (170°C to 200°C), the resin was further polymerized into an inert resin, namely, a third-order resin. Therefore, when a PF resin is used as the adhesive in the manufacture of scrimber by the cold pressing method, attention should be paid closely to the heat transfer and temperature distribution in the material during the curing process.

Temperature behavior of different positions in scrimber

The temperature behavior at the center of the S-SB and C-SB is characterized as the curves shown in Figure 3. The heat accumulates on the surface layer as the heating time lengthens and then passes to the core layer, eventually increasing the interior temperature from Scrimber A (S_A) to Scrimber D (S_D). The maximum interior temperature of the scrimber square stock during the heat curing process is listed in Table 2. For a scrimber square stock with a large size and obvious thickness gradient, the material temperature distribution is not uniform due to the nonlinear heat source in the heat conduction process (Shujian et al. 2015). With increased time, the core layer temperature in all the scrimbers' treatments reaches 100°C within 11 to 14 hours, mainly because they are of the same size, leading to similar heating rates in the baking chamber. As discussed in the previous section, it is known from the thermal analysis that when the retention time is such that the interior temperature reaches T_i, then the cross-linking of the adhesive due to curing is favorable. The overall quality of the scrimber square stock can be guaranteed only when the PF resin is cured completely in the core layer. Therefore, the core layer temperature is regarded as the main parameter for measuring the effect of the curing temperature on the properties of scrimber.

Water resistance of scrimber boards

As a new type of engineering and flooring material for outdoor use, the water resistance of scrimber determines and affects the outdoor service life of a material. Table 3 presents the effect of the core temperature on the water resistance of the scrimber samples. The results show that there is a positive correlation between the core temperature during the heat curing and water resistance. When the temperature of the core layer increases from 100°C to 120°C, the TSR of the C-SB increases by 87.59 percent. The TSR and WSR of the S_CB and S_DB are not only lower than those of the SB prepared by the hot pressing process (Zhang et al. 2016) but are also able to reach the requirement of the GB/T 30364-2013 standard for outdoor bamboo scrimber floors (SAC 2013a).

The PF resin penetrates the wood cells under increased pressure (Gabrielli and Kamke 2010, Hass et al. 2012), and the fluffing process allows a veneer with cracks to provide

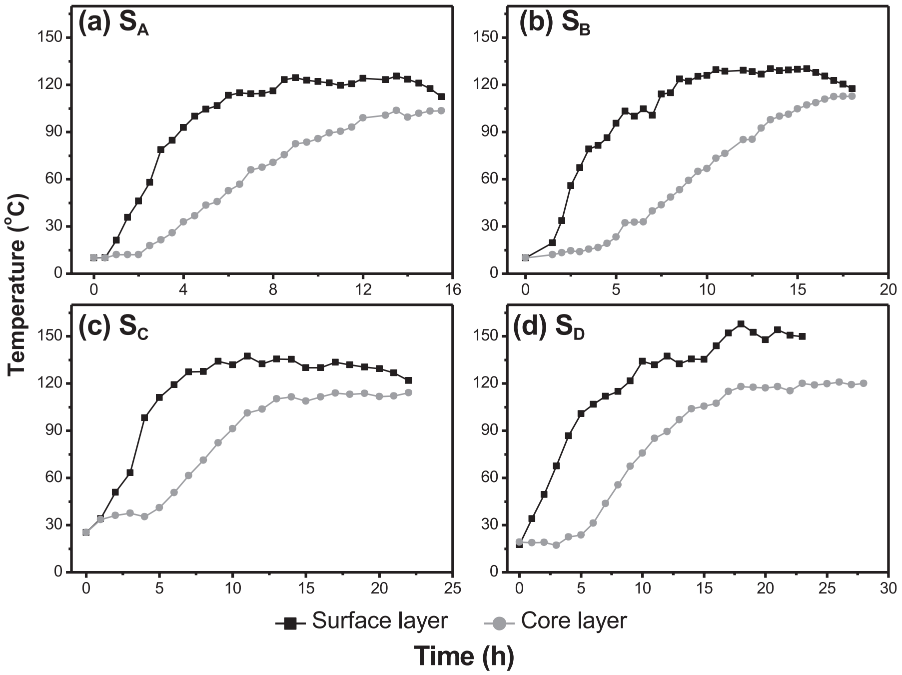

Figure 3.—Surface layer and core layer temperature of a scrimber square stock as a function of the curing time during the heat curing process.

more channels for resin penetration (Zhang et al. 2018c). Temperature is the main factor affecting the curing of a thermosetting PF resin. After completely curing the PF resin at a high core temperature, the hydrophobic film so formed can effectively prevent the hydroxyl groups of the veneers from interacting with water molecules (Bao et al. 2016). In addition, mutually penetrated and interlocked structures of the dense thin-walled cells and phenol resin are formed, decreasing the impregnation path of water (Yu et al. 2014a, 2014b). All these factors can reduce the moisture absorption. The plasticizing effect of a PF resin on the wood cell wall (Shams et al. 2004) effectively inhibits the spring back of the compressed deformable cells due to the internal stress release when the specimen is exposed to moisture (Rao et al. 2017).

In terms of the TSR and WSR of the S_AB and S_BB, there were significant differences between the S-SB and C-SB, whereas an insignificant difference was found between the S_CB and S_DB. When the core temperature was raised from 100°C to 115°C, the rate of change in the TSR of the S-SB and C-SB was decreased from 33.4 to 1.38 percent. A small

Table 2.—Maximum interior temperature of a scrimber square stock during the heat curing process.

Scrimber square stock	Scrimber board	Interior temperature (°C)
Scrimber A, S_A	S-S_AB	124.5
	C-S_AB	103.4
Scrimber B, S_B	S-S_BB	130.2
	C-S_BB	112.6
Scrimber C, S_C	S-S_CB	135
	C-S_CB	115
Scrimber D, S_D	S-S_DB	150
	C-S_DB	120

Table 3.—Density, thickness swelling rate (TSR), and width swelling rate (WSR) of the scrimber boards (SBs).[a]

Materials	Density (g cm^{-3})	TSR (%)	WSR (%)
S_A			
S-S_AB	1.02 (0.01)	29.47 (3.85) A	4.23 (0.35) A
C-S_AB	1.00 (0.02)	44.25 (4.12) a	6.75 (0.93) a
S_B			
S-S_BB	1.03 (0.05)	9.56 (1.39) B	1.84 (0.46) BC
C-S_BB	1.01 (0.02)	13.72 (2.37) b	2.94 (0.29) b
S_C			
S-S_CB	1.01 (0.01)	7.14 (0.58) B	2.17 (1.41) B
C-S_CB	1.05 (0.004)	7.24 (0.87) c	1.93 (0.14) c
S_D			
S-S_DB	0.99 (0.004)	6.05 (1.17) B	1.41 (0.30) C
C-S_DB	1.03 (0.01)	5.49 (0.26) c	2.58 (0.14) bc
SB prepared by hot pressing process (Zhang et al. 2016)	1.05	5.52	2.35
GB/T 30364-2013 (SAC 2013a)			
Indoor use	≥0.8	≤12.0	≤4.0
Outdoor use	Salable product, ≥0.8	≤10.0	≤4.0
	High-class product, ≥0.8	≤5.0	≤3.0

[a] Standard deviations are in parentheses. Different uppercase and lowercase letters indicate significant differences between the S-SBs and C-SBs as determined by the Duncan multiple range test ($P < 0.05$, $N = 6$).

difference in the rate corresponded to adequate solidification. The reason was that there was a gradient in the heat transfer in the scrimber during the heat curing process, causing the surface layer temperature to be higher than the core temperature. The high core temperature ensured the complete curing of the resin in the C-SB, thus improving the bonding performance of the SBs and exhibiting excellent water resistance. Concurrently, the difference in the water resistance of the S-SB and C-SB was further reduced, indicating that the quality of the resultant scrimber could be guaranteed.

Mechanical properties of scrimber boards

The test results of the mechanical properties of the scrimber samples at different core temperatures are presented in Table 4. When the core temperature is raised from 100°C to 115°C, the MOR, CS, and HSS of the C-SB increase significantly, and the increased ranges are 33.16, 48.83, and 128.86 percent, respectively. At the core temperature of 120°C during the heat curing process, the related mechanical properties of the SBs decrease. The main reason is that the heating time needs to be prolonged with the increase in the core temperature, which leads to a certain degree of carbonization of the wood. However, the carbonization not only deepened the color of the SB (see Fig. 4) but also led to a decrease in the mechanical properties of the wood matrix material. The mechanical properties of SBs depend mainly on the matrix material, resin, and bonding interface formed between them. Therefore, under the same conditions of density, resin content, and complete curing of the resin, the mechanical properties of the SBs decrease due to the carbonization of the matrix material. In this experiment, the bending property of all the SBs prepared at the core temperature of 115°C (S$_C$B) achieves a strength index of the highest level of 180 E, making them superior products for engineering laminated veneer lumbers, as specified in GB/T 20241-2006 (SAC 2006) for ''laminated veneer lumber.'' Moreover, the horizontal shear strength reaches the requirement for high-class outdoor-use bamboo scrimber flooring products stated in GB/T 30364-2013 (SAC 2013a) for ''bamboo scrimber flooring'' ($\geq$12 MPa). The MOR and HSS of the S$_C$B are much less than those of the SB prepared by the hot pressing process. This was because pressure is no longer applied during the cold pressing as it is during hot pressing, resulting in slightly less fluidity of the resin (Zhang et al. 2016). Similarity in density leads to minor differences in the MOE. However, the MOR and MOE of the S$_C$B (1.05 g cm^{-3}) significantly surpass those of other wood products. The CS of the S$_C$B is practically twice as large as that of glubam and glulam Guadua.

Because of the temperature difference between the surface and core during the heat transfer, the mechanical properties of the S-SB are slightly higher than those of the C-SB. Consequently, once the core temperature is sufficient to cure the resin completely, we can enhance the bonding interface of the C-SB and further realize a high mechanical performance of the complete resultant scrimber.

Formaldehyde emission of scrimber boards

Because the scrimber employs a PF resin as the adhesive, the environmental safety performance is crucial for its use in indoor decoration and furniture applications. Any incomplete curing can result in formaldehyde emissions, which are dangerous for human safety. Additionally, the ether bond in the first-order PF resin may be converted into a methylene bond when the scrimber is heated, releasing formaldehyde. If the heating temperature is raised further, half of the released formaldehyde is immediately condensed with the unreacted active hydrogen on the phenol nucleus in the resin

Table 4.—Density and mechanical properties of the scrimber boards (SBs) and compared engineered wood products.[a]

Materials	Density (g cm^{-3})	MOR (MPa)	MOE (MPa)	CS (MPa)	HSS (MPa)
S$_A$					
S-S$_A$B	1.04 (0.02)	117.08 (5.28) B	19,512.50 (217.04) B	95.33 (14.77) B	7.46 (0.85) C
C-S$_A$B	1.00 (0.01)	108.92 (17.63) c	18,324.00 (946.05) a	77.60 (8.25) c	6.41 (0.16) d
S$_B$					
S-S$_B$B	1.02 (0.02)	123.53 (3.93) B	18,273.00 (15.56) BC	99.20 (0.47) B	10.97 (0.62) B
C-S$_B$B	1.01 (0.02)	122.56 (9.32) b	17,504.50 (506.97) bc	94.18 (8.27) b	7.40 (0.30) c
S$_C$					
S-S$_C$B	1.03 (0.01)	149.17 (11.03) A	21,206.50 (1045.01) A	120.76 (3.22) A	15.09 (0.30) A
C-S$_C$B	1.07 (0.02)	145.04 (7.81) a	16,026.80 (380.61) c	115.49 (2.93) a	14.67 (0.29) a
S$_D$					
S-S$_D$B	1.01 (0.02)	131.55 (20.74) AB	17,640.00 (900.88) C	118.90 (5.02) A	11.27 (0.23) B
C-S$_D$B	1.01 (0.03)	131.68 (8.80) b	17,105.33 (502.28) b	103.74 (6.56) ab	11.45 (0.91) b
SB prepared by hot pressing process (Zhang et al. 2016)	1.05	221	19,076		17.59
LVL (Wang and Chui 2012)	0.51	85.4	14,264		6.8
Glubam (Xiao et al. 2013)	0.80–0.98	99.0	10,440	51.0	
Glulam Guadua (Correal et al. 2014)	0.74	122.4	13,260	62.0	9.5
GB/T 20241-2006 (SAC 2006)	180E	67.5			
	80E		8,000		
	65V-55H				5.5

[a] MOE = modulus of elasticity; MOR = modulus of rupture; CS = compression strength; HSS = horizontal shear strength. Standard deviations are in parentheses. Different uppercase and lowercase letters indicate significant differences between the S-SBs and C-SBs as determined by the Duncan multiple range test ($P < 0.05$, $N = 6$).

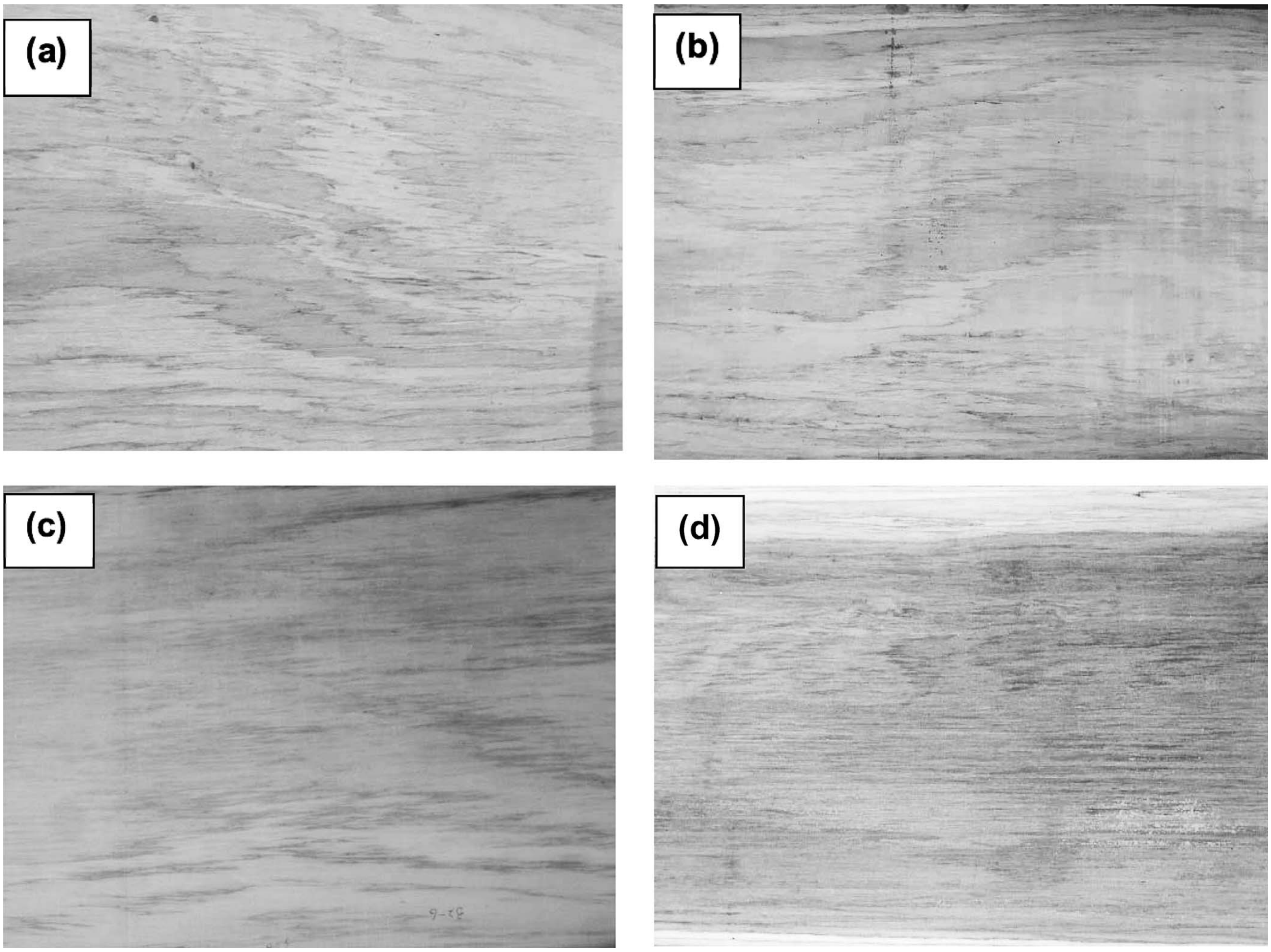

Figure 4.—Core layer board samples prepared at (a) 100°C, (b)110°C, (c) 115°C, and (d) 120°C core temperature during the heat curing process.

molecule. The data of the formaldehyde emission for the S-SB were collected by the desiccator method and are presented in Table 5. It can be observed that the core temperature has an obvious effect on the formaldehyde emission from the scrimber. The formaldehyde emissions from the S-S_CB and S-S_DB are 0.3 and 0.1 mg L^{-1}, respectively, much lower than that of the S-S_AB (15.0 mg L^{-1}) and S-S_BB (10.0 mg L^{-1}). They are also lower than the limit value of E_1, which is a level specified in the GB/T 20241-2006 (SAC 2006) standard of ''interior decorating and refurbishing material—limit of formaldehyde emission of wood-based panels and finishing products.'' According to this standard, the scrimber prepared at the core temperature of 115°C and 120°C exhibits a good environmental safety performance and can be directly used in an indoor environment. This can be explained by the fact that when the first-order phenolic resin is converted to the second-order resin, a low core temperature makes it difficult for the partially released formaldehyde to continue to react with the resin molecules. Although the core temperature difference between the S-S_BB and S-S_CB is only 5°C, the formaldehyde emission is quite different. This is because the curing rate of the resin is significantly affected by the temperature required for the curing onset. When the temperature difference is 10°C, the curing rate at room temperature and approximately 130°C is four times and two times different, respectively. On the premise of meeting the standard of formaldehyde emission, the curing temperature of 115°C is more suitable for the production of scrimber with a low processing cost.

Table 5.—Formaldehyde emissions of the surface layer of board samples.

Core temperature (°C)	Formaldehyde emission (mg L^{-1})
C-S_AB	15.0
C-S_BB	10.0
C-S_CB	0.3
C-S_DB	0.1
GB/T 20241-2006 E_1 level (SAC 2006)	≤1.5

Conclusions

In this study, large-scale production of poplar scrimber was conducted by a cold pressing/heat curing method at different core temperatures (100°C, 110°C, 115°C, and

120°C) during the heat curing process, and some important properties of the SBs were investigated. With an increase in the core temperature, the water resistance and mechanical properties of the SBs were significantly enhanced. Concurrently, the differences between the S-SB and C-SB in terms of the TSR and WSR were reduced, indicating that the resultant scrimber exhibited a high stability. All the SBs prepared in this experiment had excellent mechanical properties to meet the requirements for engineering materials, particularly when the core temperature was 115°C. The S-SB prepared at a high core temperature (115°C and 120°C) exhibited good environmental safety performance and could be directly used indoors. Thus, based on the results of this study, a core temperature of 115°C is the most appropriate for producing novel poplar scrimber for general applications.

Acknowledgments

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