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Effects of preheating temperature, preheating time and their interaction on the sandwich structure formation and density profile of sandwich compressed wood

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Abstract

Effects of preheating times (4, 8, and 12 min), preheating temperatures (75–210 °C, with 15 °C interval), and their interactions on structures and density profiles of sandwich compressed poplar wood (*Populus* × *euramericana* cv. 'Neva') were studied to achieve better control of the position(s) of compressed layer(s), with the aim of better utilization of the low-density wood resources. Our findings revealed that, as a result of preheating temperature elevation or preheating time extension, compressed layers move gradually from wood surfaces to wood interior center, forming three types of sandwich compressed wood, namely, surface compressed wood, internal compressed wood, and central compressed wood. The characteristics of wood cell deformation in the sandwich compressed wood match well with the density distribution, and no obvious cell-wall cracks were observed. Effects of preheating temperature, preheating time, and preheating temperature–time interaction on the density of the compressed layer(s) are statistically insignificant. But their effects on the position and thickness of the compressed layer(s) in the sandwich compressed wood were statistically highly significant ($p < 0.001$), and the preheating temperature and compressed layer(s) positions were significantly related to the functions and fitted the polynomial of the fourth order.

Keywords: Sandwich compression, Preheating temperature–time interaction, Position of the compressed layer, Structural formation, Density profile

Introduction

Wood densification improves the physical and mechanical properties of solid wood by increasing the wood density via reducing the void volume of the lumens [1–3]. Most studies on wood densification refer to wood surface densification, which is generally achieved by surface pressing at high temperatures (higher than 140 °C) after long terms of conditioning for uniform moisture distribution or after water spraying on surfaces [4–9]. However, the position and thickness of the compressed layer(s) are not controllable. Recently, a novel wood sandwich compression technology has been developed by Huang et al. [2, 10]. For wood sandwich compression, solid wood is generally wetted on the surfaces, conditioned for around 20 h, then preheated and compressed to the target sandwich compressed wood. Compared with the traditional wood compression, the signature advantage of sandwich compressed wood is that the compressed layer(s) can be controlled to any positions in wood interior. Wood sandwich compression can minimize the volume loss of wood during compression, and also the physical and mechanical properties can be adjusted and thus controlled. Unlike wood surface densification where compression only occurs on the softened surfaces [11], wood sandwich

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compression technology can soften wood at different positions via adjusting preheating time and preheating temperatures [2, 12]. During the preheating process, temperature and moisture gradients are formed in the wood thickness direction, forming yield stress gradients inside wood. The layer with smaller yield stress is much easier to get compressed during pressing, forming the compressed layer, while other parts with higher yield stress are intact.

Wood softening is highly related to moisture and temperature [13], and complete softening of wood avoids fissure and fracture of wood cells in the compressed wood [14], and thus exerts no negative effects on the physical and mechanical properties of the compressed wood [15]. Moisture content in compressed wood depends on the pressing variables, but highly dependent of temperature and time [16]. It has been reported that pressing/preheating temperature is the key parameter affecting moisture diffusion and transferring rate in wood [17], while pressing/preheating time mainly affects the heat-transfer scope and vapor pressure. Extending the heating time can increase both the temperature and moisture content in the core layers [18], thus forming temperature gradient and moisture gradient in wood. In addition, higher pressing/preheating temperatures accelerate moisture immigration and can thus reduce the required time for compression and drying [19, 20]. Thus, temperature, time, and their interaction are also the key factors affecting the position, thickness, and density, and the density peaks of the compressed wood.

Low heating temperature and short platens' closing time contribute to a position of the compressed layer(s) close to wood surfaces, while higher heating temperature or longer closing time induce the compressed layers' position toward the wood center. Compared with the results from compression for 0.5 min, 5 min of compression time was found to yield a smaller, larger density peak, but more uniform density distribution, larger density thickness, as well as more central position of the density peak [6]. When the pressing time is 17 min, density is uniformly distributed along the wood thickness [21]. In our previous research [12], when wood was preheated at 60–210 °C for 12 min, distance between the compressed layer(s) and the wood surfaces increased from 0 to 7.70 mm when the temperature elevated, and the thickness of the compressed layer(s) ranged from 4.98 to 8.10 mm and the average density of the compressed layer(s) is larger than 0.60 g/m^3. Compressed wood samples with compressed layers either on the wood surfaces or the inside of wood were obtained after 10, 40, 240, and 420 s of preheating and being compressed at 180 °C [2].

Based on our previous study [2, 12], this study systematically examines the effects of the preheating temperature, preheating time, and their interactions on the density distribution in the sandwich compressed wood and the deformation characteristics of the wood cells in the compressed wood. Besides, the functional relationship between the positions of the compressed layer(s) and the compression process parameters was established by applying the multiple nonlinear regression analysis method, which helps to provide an effective pathway for precisely tailoring the position of the compressed layer(s) in the sandwich compressed wood.

Materials and methods

Materials

Poplar (*Poplar* × *euramericana* cv. 'Neva') flat-sawn lumbers sourced from Guan County, Shandong Province, China, with a dimension of 500 mm (*L*) × 150 mm (*T*) × 30 mm (*R*) were kiln dried to a moisture content (MC) of 8.0%. Every lumber was cut into two sapwood lumbers with a dimension of 210 mm (*L*) × 110 mm (*T*) × 25 mm (*R*). 180 sapwood lumbers with the dimension of 210 mm (*L*) × 110 mm (*T*) × 25 mm (*R*) were prepared, and these 180 specimens were separated into three groups for three preheating times of 4, 8, and 12 min. Each group contained 60 specimens. Sapwood lumbers were preheated at 75, 90, 105, 120, 135, 150, 165, 180, 195, or 210 °C, with six replicates for each condition. As shown in Fig. 1, control A with the size of 50 mm (*L*) × 50 mm (*T*) × 25 mm (*R*) was cut out from the sapwood lumber specimen as the control before preheating. The rest part with a dimension of 156 mm (*L*) × 110 mm (*T*) × 25 mm (*R*) was used for the preparation of the sandwich compressed wood.

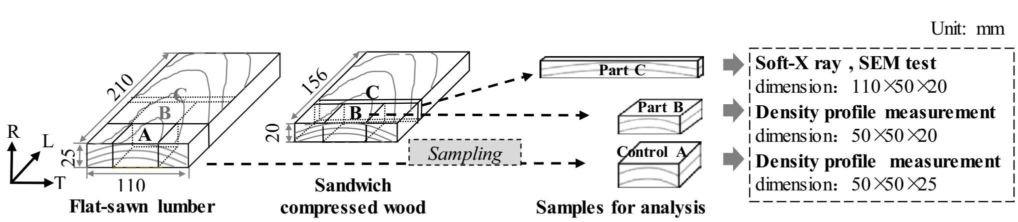

Fig. 1 Scheme of the preparation of samples for soft X-ray scanning, SEM, and density profile measurements

Methods

Preheating treatment and compression process

Before preheating and compression, the wood specimens were first coated with wax on the transverse sections and then soaked in water. After 2 h soaking in water, the specimens were stored in sealed plastic bags for 18 h (MC ≈ 20%). After 18 h storage in plastic bags, six specimens were weighed and then placed immediately on the lower preheated press platen. The distance between upper platen and bottom platen was adjusted to exactly 25 mm for preheating the specimens. After the preheating, each specimen was weighed and returned to the heating platen for intermittent compression. In all cases, the elapsed time from weighing the specimens to the start of intermittent compression was set as less than 1 min. Intermittent compression was applied on the preheated wood under 6.0 MPa at a rate of 1 mm/s. Each intermittent compression cycle consisted of 1 s of compression and 10 s of unloading. The specimens were compressed to 20 mm thickness from the original thickness of 25 mm after five compression cycles. The final compressed wood thickness of 20 mm was maintained for 30 min at the preheating temperature. The heating platens were then cooled down to 60 °C, and the sandwich compressed wood was removed from the hot press for further characterizations. Conditions for the whole process are illustrated in Fig. 2.

Characterizations of sandwich compressed wood

Density measurement To minimize the error, part B with a dimension of 50 mm (*L*) × 50 mm (*T*) × 20 mm (*R*) was cut out from the sandwich compressed wood, as illustrated in Fig. 1. Control A and part B were then conditioned to constant weight at 20 °C in 65% relative humidity. Control A and part B were then scanned using an X-ray densitometer (DENSE-LAB mark 3, E.W.S. GmbH, Germany) at intervals of 20 µm from the top surface to the bottom surface, to measure the density in the sandwich compressed wood. An average value of the six specimens was applied for the evaluation.

Determination of compressed layer(s) The average density of poplar wood was 0.44 g/cm^3. Since compression ratio of sandwich compressed wood was 20%, the compressed layer(s) is identified as the parts with a density that is 20% higher than the average density of the control specimen. The region with density less than the average density of the control is considered as the uncompressed layer. The number of the compressed layers is defined as the number of compressed layers in the thickness direction of the compressed wood. The position of compressed layer(s) is defined as the distance from the edge of the compressed layer(s) to the corresponding surface(s) of the compressed wood. The compressed layers' thickness is the sum of all the compressed layers' thicknesses. The compressed layer(s) density and the peak density are the mean

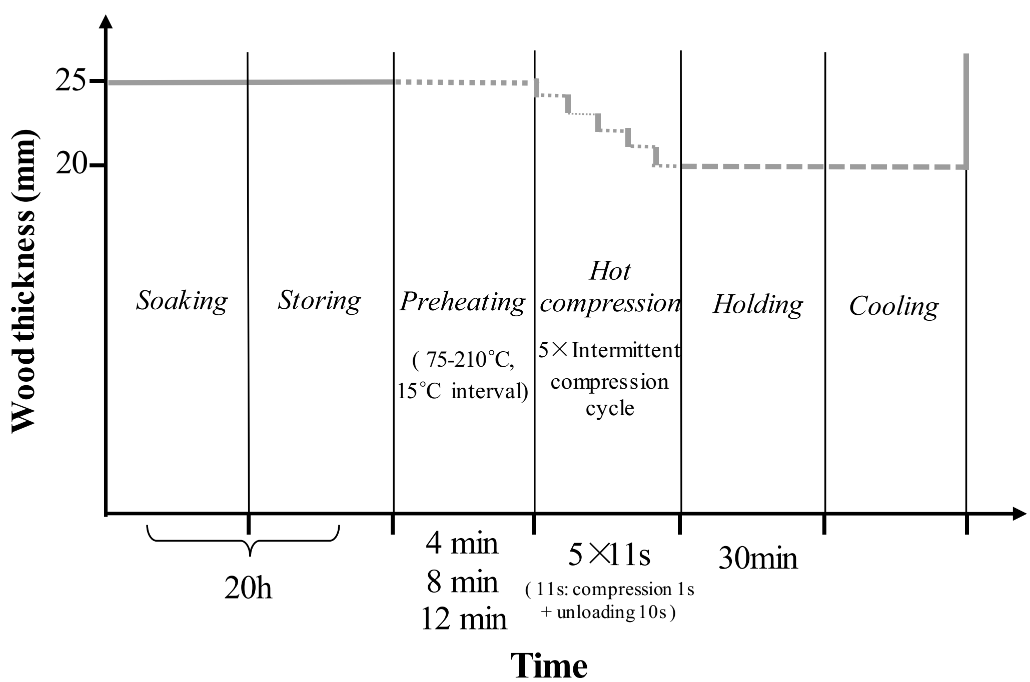

Fig. 2 Scheme of process for forming sandwich compressed wood

density and maximal density of the compressed layer(s), respectively.

Morphological structure As shown in Fig. 1, specimen with a dimension of 5 mm (L) × 5 mm (T) × 5 mm (R) that consisted of compressed layer and uncompressed layer was cut from part C of each compressed lumber (as shown in Fig. 1). The cutting surfaces were sputter-coated with gold, and the transverse surfaces of each specimen was scanned using scanning electric microscope (SEM) at magnifications of 30×, 200× and 400×, to investigate the morphological structure of the compressed wood.

Data statistical analysis

The analysis of variance (ANOVA) and fitting function calculation were applied for the data analysis using SPSS software (SPSS V18, USA).

Results and discussion

Structural formation of sandwich compressed wood

Density profiles analysis

Figure 3a shows the density profiles of the sandwich compressed wood preheated at 75 °C for 4, 8, and 12 min. The density profile of the sandwich compressed wood preheated at 75 °C for 4 min has two compressed layers with a density peak of 0.75 g/cm^3. The compressed layers are formed at around 4 mm below the upper surface and 4 mm above lower surface, respectively. While the density profile in the area that is 10 mm away from the center along the thickness of the compressed wood is almost the same as that of the control specimen, suggesting that the central layer is uncompressed. This sandwich compressed wood is defined as surface compressed wood. By adjusting the original moisture content of wood [12], a moisture gradient can be formed, namely high moisture content on the wood surfaces but low moisture content in the wood center. When moisture content is 20%, T_g of lignin is only 80 °C [13]. Preheating temperature elevation to the T_g is required for the wood surface softening and compression. When the preheating time is extended to 8 or 12 min, the position of density peak in compressed layer(s) moves forward to the wood center, but the moving distance is comparatively small and the thickness of the compressed layer(s) increases a little. This is attributed to the fact that at low preheating temperature, moisture moves slowly and thus limits the wood softening area.

Due to the preheating temperature elevation and preheating time extension before compression, density peak of the compressed layer(s) moved forward into the wood center (Fig. 3b). When wood is preheated at 150 °C for 4 min, two compressed layers with a density peak of 0.7 g/cm^3 in both the compressed layers are observed. The density peaks are 3 mm above and below of the associated surfaces of the sandwich compressed wood. Extension of preheating time to 8 min leads to the integration of two compressed layers into single layer in the wood center, forming the central compressed wood. The conditions of 150 °C and 8 min are considered as the integration point for compressed layers, even though at this point, the compressed layers are not completely overlapped and two density peaks exist. When the preheated time is further extended to 12 min, the compressed layer becomes the one with only one density peak, but the density peak is lower than that of compressed layer(s) obtained from preheating for 4 or 8 min. During the preheating, water/moisture move from higher moisture content areas to lower moisture content areas through cell cavities and

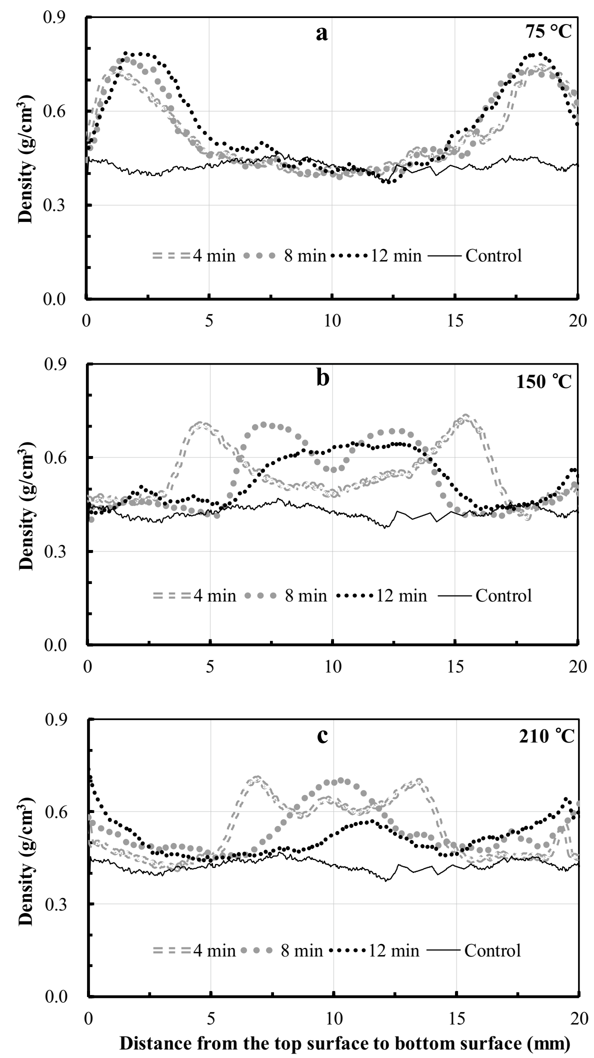

Fig. 3 Effect of preheating time, temperature, and their interaction on the density distribution of sandwich compressed wood

pit openings, water/moisture, and heat transfer from the wood surfaces to the wood interior, and new temperature and moisture gradients were formed in the compression direction of wood [22]. Once pressure is loaded on the wood, a new yield stress gradient is formed, yielding various positions of compressed layers, and the distance between the wood surface and the associated edge of compressed layer (the compressed layer position) gradually increases, and the compressed layers eventually integrate to form a single layee in the wood center. In this process, the function of temperature gradient transfer from the thickness direction into horizontal direction is to transfer heat; the moisture vapor diffuses into the transverse section of wood, resulting in reduced moisture content and thereby decreasing the moisture gradient, forming a more uniform density distribution in wood. This observation is consistent with Wang's report [21]. However, this finding varies with our previous report wherein higher preheating temperature resulted in higher density of the compressed layer [12], which could be resulting from the smaller specimen size and faster water loss during the preheating.

Figure 3c shows that when the preheating temperature is elevated to 210 °C and the preheating time is extended to 8 or 12 min, the surface density increases, and two compressed layers are formed on the surfaces of the resulting compressed wood, and one central compressed layer also appears in the wood center. This is due to the fact that the wood interior with lower yield stress can be compressed much more easily, while those with higher yield stress require higher pressures to get compressed. When the preheating temperature and preheating time are 210 °C and 4 min, respectively, a single overlapped compressed layer cannot be formed in the wood center, leading to the inference that even at high temperature, 4 min preheating time is not long enough for effective heat transfer from the surface to the center.

Microscopic analysis

Microscopic imaging on the transverse sections of the compressed wood was performed to examine the characteristics of the wood cell's deformation. Figure 4 presents soft X-ray and SEM images of specimens from the surface compressed wood, the internal compressed wood, and the central region of the central compressed wood. The density profiles are also presented for the transverse sections of the sandwich compressed wood specimens. The compressed layer is the dark area in the photographs, whereas in the soft X-ray images, the compressed layer is the high luminance layer.

Wood sections as shown in the small box of the photographs and X-ray images in Fig. 4 are used for SEM scanning. As illustrated by the SEM images, the compressed wood obtained via preheating at 75 °C for 4 min has different degrees of flexion in the shape of the first layer from the surface layer to the depth of 3.5–4.0 mm below the surface (Fig. 4I). When the preheating temperature is 120 °C, the cell deformation occurs at the position of 1.5–2 mm below the surface, and the thickness of the compressed layer is approximately 4 mm (Fig. 4II). When the preheating temperature elevates to 180 °C and the preheating time extends to 12 min, all the cell walls locate in the area around 5 mm from the center of the thickness direction deform (Fig. 4III).

The microscopic observations also reveal that the vessels and the wood fiber cells are intact in the uncompressed layer. However, the lumen of some vessels and the wood fibers in the compressed layer(s) disappear, and some greatly deformed vessel lumens are also observed at low magnification (30×). Even though a large number of the deformed wood fiber cell lumens are observed at high magnification (200×), no obvious cell–wall fissure appears in SEM image of internal compressed wood with 400× magnification as shown in Fig. 4II. Small cracks in the surface compressed wood and central compressed wood are observed in Fig. 4I and III. However, similar cracks are also found in untreated samples. Reason for this cracking might be resulting from kiln drying of wood [23]. Most of the vessels in the compressed layer of central compressed wood are greatly deformed, but only some of the vessel lumens completely disappear. Meanwhile, most of the wood fibers slightly deform, and the cell lumens are still clearly visible, i.e., the compressed layer contains more cell lumens compared to that in the surface and interior compressed woods.

Scanning electric microscope observations are consistent with the density profiles. The regions with lower density correspond to areas with more voids, i.e., open vessels, whereas the vessels are completely closed in the high-density regions. The sandwich compression characteristics observed here and the degree of the wood cells deformation in the compressed layer are consistent with the density profile characteristics of the sandwich compressed wood, further confirming the feasibility of controlling the density distribution by adjusting the preheating time and temperature. In addition, the wood cells only deform in the compressed layer(s). Finally, it is observed that the cell deformation is caused by the buckling deformation of the wood cell wall in the compression direction and that the deformed cell wall is not broken.

Density profile of sandwich compressed wood

Thickness, density, and density peak of the compressed layer(s)

Number, thickness, mean density, maximal density of the compressed layer(s), and the wood density are

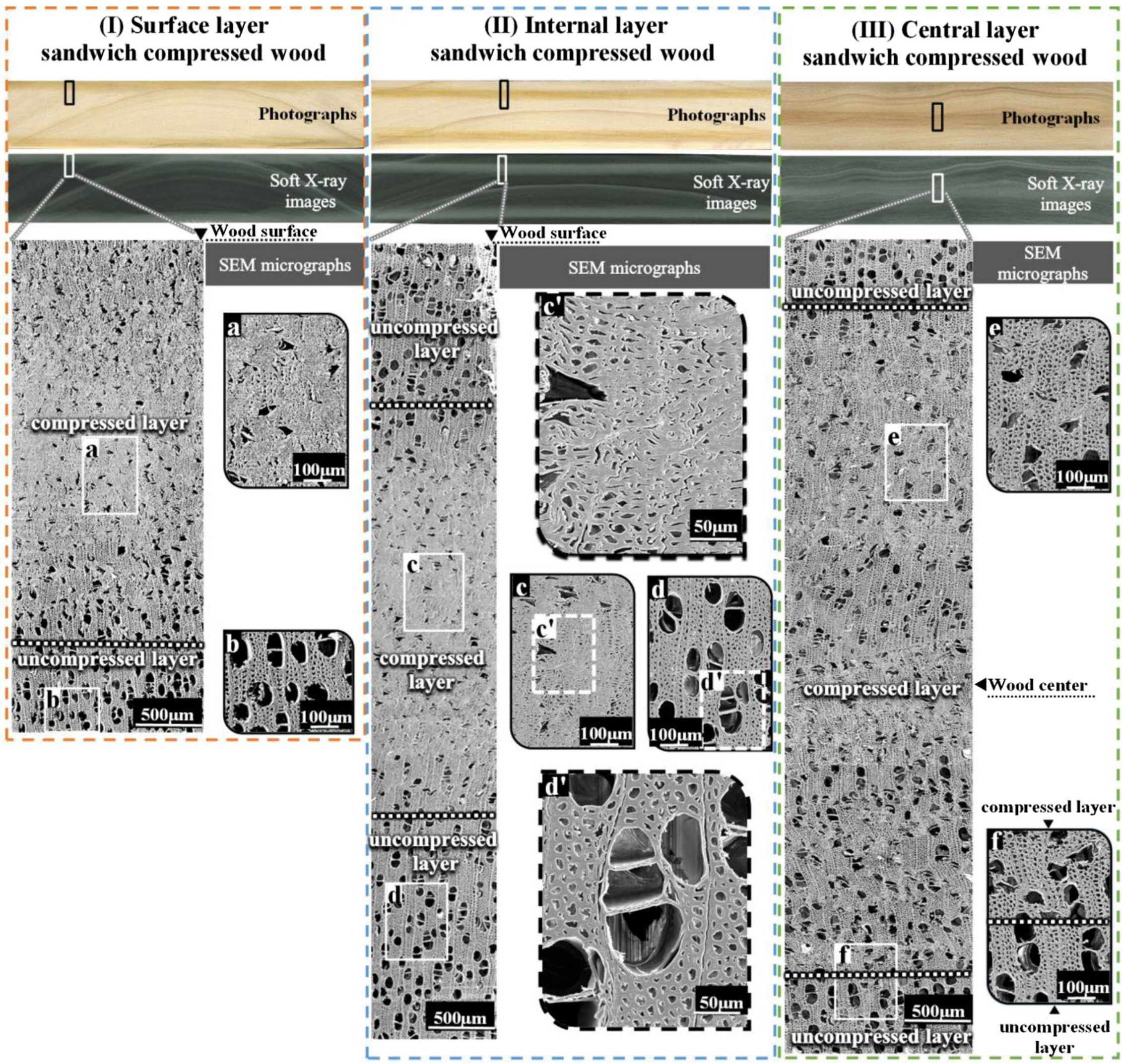

Fig. 4 Soft X-ray images and SEM micrographs of transverse section of sandwich compressed wood. Three sandwich structure formation types: (I) surface layer sandwich compressed wood, (II) internal layer, and (III) central layer; a, c, e magnifications of compressed layer; b, d uncompressed layer; f both compressed and uncompressed layers

summarized in Table 1. Preheating at 135 °C for 12 min, 150 °C for 8 min, and 165 °C for 4 min are conditions for the convergence of the compressed layers.

The thicknesses of compressed layer(s) range from 3.12 to 10.75 mm. When the preheating time is 4 min, the thickness first decreases, then increases as a result of temperature elevation, and the top and bottom compressed layers integrate into one, reaching to the largest thickness of 10.30 mm when wood is preheated at 165 °C for 4 min. In contrast, when the preheating time is longer than 8 min, the thickness of the compressed layer first increases then reduces due to the preheating temperature elevation, and the largest compressed layer(s) thickness of 10.75 mm appears when the preheating temperature and time are 120 °C and 12 min, respectively.

The average density of all the compressed layers is greater than 0.64 g/cm^3, and the mean density and maximum density of the compressed layers tend to increase first, and then decrease as a result of the temperature elevation. For compressed wood preheated at 120 °C for 4 min, the highest average density and density peak are 0.685 and 0.802 g/cm^3, respectively, which are 55.68 and 82.27% higher than that of the control. When the preheating time is extended to 8 or 12 min, the highest average density of the compressed layers can be obtained at 105 °C.

Analysis of variance (Table 2) suggests that the preheating temperature and preheating time–temperature

Table 1 Density profile characteristics of sandwich compressed wood formed under different preheating conditions

Preheating parameters		Mean density of wood (g/cm³)	Mean density of sandwich compressed wood (g/cm³)	The characteristic parameters of compressed layer			
Time (min)	Temperature (°C)			Number	Thickness (mm)	Mean density (g/cm³)	Maximum density (g/cm³)
4	75	0.439 (0.028)	0.537 (0.030)	2	7.52 (0.48)	0.666 (0.026)	0.771 (0.232)
	90	0.432 (0.026)	0.550 (0.038)	2	8.56 (0.97)	0.674 (0.032)	0.773 (0.056)
	105	0.423 (0.022)	0.531 (0.032)	2	8.68 (1.18)	0.658 (0.037)	0.768 (0.061)
	120	0.434 (0.021)	0.564 (0.043)	2	7.86 (0.66)	0.685 (0.038)	0.802 (0.053)
	135	0.452 (0.020)	0.549 (0.026)	2	7.78 (0.66)	0.664 (0.027)	0.747 (0.036)
	150	0.442 (0.024)	0.539 (0.029)	2	7.45 (0.44)	0.653 (0.017)	0.751 (0.025)
	165	*0.457 (0.027)*	*0.539 (0.016)*	*1*	*10.30 (0.09)*	*0.609 (0.036)*	*0.688 (0.030)*
	180	0.423 (0.027)	0.516 (0.035)	1	10.21 (0.46)	0.613 (0.038)	0.702 (0.056)
	195	0.439 (0.030)	0.536 (0.043)	1	9.70 (0.72)	0.627 (0.043)	0.713 (0.031)
	210	0.417 (0.021)	0.511 (0.025)	1	9.36 (0.58)	0.575 (0.043)	0.689 (0.017)
8	75	0.422 (0.023)	0.554 (0.034)	2	8.99 (0.83)	0.665 (0.028)	0.760 (0.033)
	90	0.435 (0.009)	0.556 (0.025)	2	9.23 (0.78)	0.660 (0.023)	0.761 (0.033)
	105	0.441 (0.008)	0.567 (0.033)	2	8.61 (1.10)	0.684 (0.025)	0.782 (0.043)
	120	0.426 (0.024)	0.537 (0.035)	2	9.23 (0.83)	0.642 (0.020)	0.741 (0.032)
	135	0.431 (0.026)	0.538 (0.032)	2	8.22 (0.36)	0.619 (0.030)	0.695 (0.035)
	150	*0.426 (0.017)*	*0.519 (0.024)*	*1*	*8.06 (1.20)*	*0.618 (0.017)*	*0.688 (0.040)*
	165	0.442 (0.035)	0.531 (0.026)	1	8.11 (1.16)	0.64 (0.027)	0.689 (0.034)
	180	0.427 (0.011)	0.517 (0.026)	1	7.51 (0.96)	0.652 (0.016)	0.718 (0.023)
	195	0.436 (0.022)	0.515 (0.024)	1	5.25 (1.04)	0.632 (0.029)	0.718 (0.043)
	210	0.454 (0.041)	0.542 (0.038)	3	4.67 (0.79)	0.627 (0.044)	0.703 (0.035)
12	75	0.423 (0.026)	0.537 (0.049)	2	9.28 (0.82)	0.640 (0.026)	0.725 (0.051)
	90	0.427 (0.016)	0.557 (0.018)	2	10.21 (0.43)	0.654 (0.020)	0.758 (0.026)
	105	0.443 (0.029)	0.554 (0.033)	2	9.17 (0.64)	0.661 (0.030)	0.760 (0.045)
	120	0.432 (0.015)	0.547 (0.034)	2	10.75 (1.44)	0.626 (0.017)	0.695 (0.038)
	135	*0.439 (0.025)*	*0.530 (0.025)*	*1*	*8.83 (0.41)*	*0.610 (0.034)*	*0.697 (0.034)*
	150	0.451 (0.039)	0.543 (0.043)	1	7.97 (0.72)	0.647 (0.047)	0.687 (0.047)
	165	0.438 (0.025)	0.516 (0.023)	1	5.56 (0.94)	0.628 (0.028)	0.707 (0.033)
	180	0.433 (0.021)	0.518 (0.028)	1	5.18 (0.72)	0.600 (0.071)	0.666 (0.071)
	195	0.448 (0.026)	0.534 (0.040)	3	3.76 (1.27)	0.599 (0.021)	0.669 (0.024)
	210	0.447 (0.047)	0.511 (0.051)	3	3.12 (0.15)	0.565 (0.043)	0.588 (0.035)

Each value in parenthesis is standard deviation of six specimens; italic emphasizes preheating at 135 °C for 12 min, 150 °C for 8 min, and 165 °C for 4 min are conditions for the convergence of the compressed layers; when there are three compressed layers, the thickness, mean density, and maximum density of the compressed layer are the results of the central compressed layer

interaction both exert statistically highly significant effects on the position and thickness of the compressed layer ($p < 0.001$). The effect of preheating time on the position of the compressed layer is also statistically highly significant, while its effect on the thickness is just statistically significant. However, the density of the compressed layer is not significantly affected by the preheating time, preheating temperature, or preheating time–temperature interaction in the investigated ranges.

Position of compressed layer(s)

A multiple nonlinear regression equation is used to build up the relationship between the preheating temperature and position of compressed layer(s). Position of compressed layer(s) is defined as the distance between the edge of the compressed layer(s) and the corresponding surface(s) of the compressed wood. As shown in Fig. 5, preheating temperature and compressed layer(s) position are significantly related to the fitted function relationships, and the determination coefficients (R^2) are 0.9967 and 0.9908, respectively. All the curves have three turning temperature ranges with the elevated temperature: range (75–105 °C) for slow moving rate; range for the fast moving rate, 105 °C is the starting temperature point for the convergence of the compressed layers; and the third range is the platform area after the convergence of the compressed layers.

Table 2 Effects of preheating time, temperature, and their interaction on the characteristic parameters of compressed layer

Characteristic parameters of compressed layer	Impact factor	SS	Df	MS	F	Sig.
Position	TIM	71.510	2	35.755	101.55	***
	TEM	699.434	6	116.572	331.07	***
	TIM × TEM	35.503	12	2.959	8.40	***
Thickness	TIM	7.409	2	3.704	3.54	*
	TEM	56.802	6	9.467	9.04	***
	TIM × TEM	167.737	12	13.978	13.34	***
Density	TIM	0.386	2	0.193	0.75	ns
	TEM	1.855	6	0.309	1.20	ns
	TIM × TEM	3.062	12	0.255	0.99	ns

TIM—preheating time; TEM—preheating temperature; TIM × TEM —interactions between preheating time and preheating temperature; *, **, and *** indicate significances at the $p<0.05$, $p<0.01$, and $p<0.001$ levels, respectively; ns indicates no significant difference

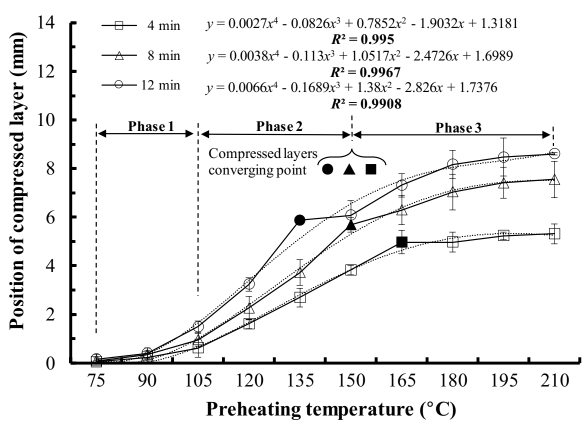

Fig. 5 Relationship between preheating temperature and position of compressed layer(s). Phase 1 means range for slow moving rate; Phase 2 means range for fast moving rate; Phase 3 means platform area after the convergence of compressed layers. Each point represents the average of measurements on six specimens, and the error bar is the standard deviation value

Range for slow moving rate (Phase 1): When the preheating temperature elevates from 75 to 105 °C, the distance between the compressed layer and the compressed wood surface increase. And the rate of distance increasing increases with the increase in the extended preheating time, ranging from 0.18 to 1.09 mm/°C (Fig. 6a). In contrast, the rate of distance increasing due to the preheating time extension reduces (Fig. 6b). For the sandwich compressed wood preheated for 4, 8, or 12 min, distance from the edge of the compressed layer(s) to the corresponding surface(s) of the compressed wood increases sharply when the preheating temperature elevates from 90 to 105 °C, which is 2, 2.5, or 4.5 times of that attributed to the temperature elevation ranging from 75 to 90 °C, respectively. At 90 °C, water in wood moves slowly; when the temperature is above 100 °C, water in the wood exists as vapor and the vapor moving rate accelerates, but water conversion into vapor requires more energy [12], and water vaporization retards the heating transfer [16]. Thus, the moving rate of the compressed wood in this temperature range is comparatively slow.

Range for fast moving rate (Phase 2): namely, from 105 °C to the converging point of the compressing layers. Compared with the range for slow moving rate, the rate of increasing distance between the compressed layer and the compressed wood surface attributed to each 15 °C elevation is large and the compressed layers converge into one, and the distance changes become the highest, which are 1.15, 1.97, and 2.66 mm, respectively. Temperature elevation and time extension accelerate the rates of temperature transfer and water immigration, making the position of compressed layers move faster toward the wood center. As shown in Fig. 6b, the distance changes (between the compressed layer and the compressed wood surface) increase because the preheating time extensions from 0 to 4 min, 4 to 8 min, 8 to 12 min are higher when the preheating temperature is larger, and the highest distance changes are 4.97, 1.86, and 2.17 mm, respectively. It is obvious that the distance changes increase due to the preheating time extension from 0 to 4 min is much higher than that resulting from the preheating time extension ranges from 4 to 8 min, and from 8 to 12 min. This is due to the fact that at high temperatures, high moisture content contributes to a larger heat-transfer rate [6]. Meanwhile, higher temperatures lead to higher temperature gradient [12], while longer preheating time makes the temperature gradient smaller, which slows down the moisture immigration and thus reduces the position of compressing layer's moving rates.

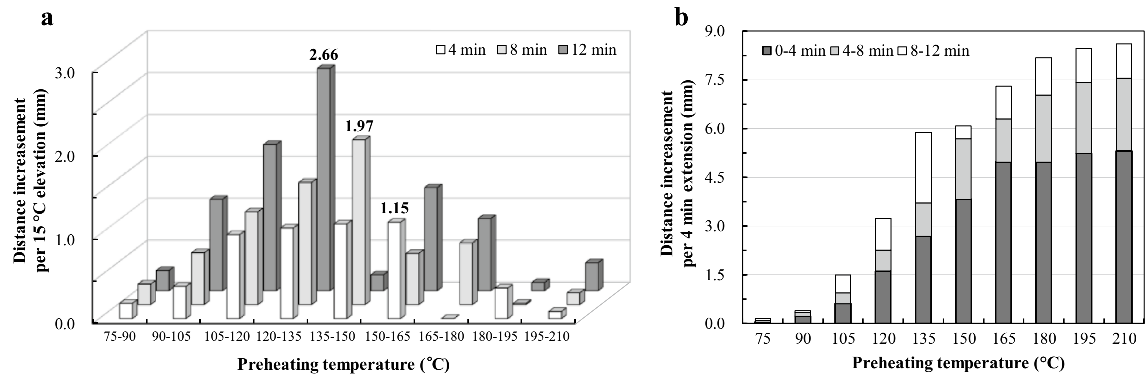

Fig. 6 Effects of preheating time and preheating temperature on the position of compressed layer(s). **a** Distance increment with each 15 °C elevation interval during 4, 8, and 12 min preheating time; **b** distance increment with each 4 min extension interval under different preheating temperatures. Distance means from the position of compressed layer to top or bottom surface of wood

Platform area after the convergence of the compressed layers (Phase 3): from the converging temperature to 210 °C, every 15 °C elevation (Fig. 6a) or every 4 min of preheating time extension (Fig. 6b) results in slow movement of the compressing layers. When the preheating temperature is higher than the converging point of the compressing layers, moisture content in the wood center increases and for heating up this part, more energy is required. Also, the lower the surface moisture content is, the higher the moisture content appears in wood. Changes of temperature gradient and moisture gradient decelerate moisture immigration. Meanwhile, the temperature elevation and the preheating time extension at high temperature (higher than 165 °C) reduce the moisture content of wood and thus decrease the vapor pressure as well as the heat transfer. Extension of preheating time from 8 to 12 min results in the rate of distance increasing to 0.25 mm/min, which is just one half of that resulting from the preheating time extension from 4 to 8 min (Fig. 6b). When preheating time extends from 0 to 4 min, the moisture content of wood is still comparatively high, and the rate of distance increasing is around 1.25 mm/min.

Conclusion

In this study, three structure modes of sandwich compressed wood were achieved by controlling the preheating temperature and the preheating time. The density characteristics of the sandwich compressed wood depended on the extent of the wood cell-wall deformation, which was affected by the preheating temperature and time. No obvious cracks were observed in the cell wall of the compressed layer(s), regardless of the preheating temperature or preheating time in the investigated ranges. Our findings revealed that effects of the preheating temperature, preheating temperature/time interaction on the position, and thickness of the compressed layer(s) in the compressed wood were statistically highly significant. Effect of preheating time on the position of the compressed layer(s) was also statistically highly significant, while the effect of preheating time on the thickness of the compressed layer(s) was just statistically significant. In addition, the preheating temperature and compressed layer(s) position were significantly related to the functions that fitted the polynomial of the fourth order. However, effects of preheating temperature, preheating time, or preheating temperature–time interaction on the density of the compressed layer(s) were insignificant.

Abbreviations

MC: moisture content; SEM: scanning electric microscope.

Authors' contributions

RH and YW designed the experiments and were major contributors in writing the manuscript; YW and ZG performed the experiments; All authors contributed to interpretation and discussed results. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials
Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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