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Comparative study on overall, surface and centre compressed solid wood

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For more efficient utilisation of low-density solid wood, this study used white poplar (Populus tomentosa) solid wood as the material. Surface, centre, and overall compressed solid wood were subsequently obtained, and a comparative analysis was conducted on their structure, density, modulus of elasticity (MOE), modulus of rupture (MOR), and hardness. The results indicated that different thermos-hydro-mechanical (THM) treatment processes could effectively and accurately control the wood structure. In addition, when the compression rate was the same, an uneven structure was more conducive to improving wood density and bending resistance. Moreover, the higher the surface layer density, the greater the bending properties and hardness. Consequently, surface-compressed wood exhibited the highest compressed layer density, peak density, MOE, MOR, and hardness among the three types of compressed wood. Specifically, when the overall compression rate was 20.0%, its layer density, peak density, MOE, MOR, and hardness were 0.73 g/cm^3, 0.85 g/cm^3, 15.97 GPa, 105.19 MPa and 35.60 N/mm^2, respectively. In summary, in wood applications, positioning the densified layer in the most critical areas could improve the physical and mechanical properties of wood and promote more efficient utilisation.

Keywords Overall compressed solid wood, Surface compressed solid wood, Centre compressed solid wood, Physical and mechanical properties

The solid wood is highly favored by people due to its natural properties, and with the development of society, the demand for solid wood in China has always been high[1]. But with the reduction of natural wood resources and the ban on logging, the contradiction between wood supply and demand becomes increasingly prominent[2]. China is rich in poplar resources, but it has several drawbacks, including a loose structure, low density, low strength, and poor dimensional stability, which severely limit its applications[3]. Therefore, how to modify the functionality of poplar wood through technological research and development to compensate for the inherent defects of poplar, and transform low-quality poplar wood into high-quality wood, will become an important driving force to alleviate the contradiction between wood supply and demand.

Currently, there are two main methods used to improve the physical and mechanical properties of poplar wood: chemical and physical methods[3,4]. The chemical method involves increasing wood density and enhancing performance by immersing the wood's pore structure with chemical polymers such as resins[4]. The physical method reduces wood porosity by moisture, heat and applying a load, thereby increasing its substantial density per unit volume and achieving the goal of enhancing performance[3].

Both methods can significantly improve the physical and mechanical properties of poplar wood; however, physical methods are more environmentally friendly. At present, physical methods mainly include overall compression, surface compression and centre compression[5–7].

Overall compression is a traditional physical modification method for poplar wood[8]. Following preliminary softening treatment, the physical and mechanical properties of low-quality wood can be effectively improved through uniform compression[6]. However, to obtain wood with better physical and mechanical properties, it is necessary to continuously optimise the compression rate.

Surface and centre compression are emerging methods for the physical modification of poplar wood[5,9,10]. These techniques utilise the hygrothermal softening characteristics of wood, where an increase in moisture content significantly reduces the softening temperature of hemicellulose and lignin[11–13]. Initially, the wood is soaked and placed before being preheated using a hot plate at a specific temperature. High temperatures increase the moisture diffusion coefficient[14,15]while the resulting water vapour generates steam pressure, promoting moisture diffusion[16]. In addition, moisture affects temperature conduction within the wood, leading to varying

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moisture and temperature distributions inside the wood after preheating. Under the combined effects of moisture and temperature, differences in yield stress occur across the wood layers in the thickness direction due to varying degrees of softening[17–20]. When a load is applied, the layers with low yield stress compress and deform first, forming compressed wood with distinct sandwich structures[5,9,10]. Research has shown that sandwich compression significantly improves the physical and mechanical properties of poplar wood[5,9,10].

Three types of compressed solid woods that are overall, surface and center compressed solid wood can be obtained by above three compression methods, and the physical and mechanical properties of three types of compressed solid wood are improved effectively. But, on the end application of poplar, how to select the appropriate compressed solid wood, there are no research reports on it. Selecting the appropriate compressed solid wood is more conducive to efficiently utilizing and saving wood resources. So, the comparative study on overall, surface and center compressed solid wood to identify differences among each other is necessary.

This article is based on research into overall compression, as well as surface and centre compression. Under identical hot-pressing temperature and compression rate conditions, surface and centre compressed wood were obtained through processes such as immersion, placement, and preheating, while overall compressed wood was obtained through direct preheating and compression. A comparative analysis was conducted on structure, density, MOE, MOR, and hardness, aiming to provide a reference for the more efficient utilisation and saving of wood resources.

Experimental
Materials
Twenty-five-year-old white poplar (*Populus tomentosa*) trees with a diameter of 25 cm to 35 cm at breast height were harvested from a plantation forest in Guan County, Shandong Province, China. Lumber with dimensions of 500 mm (longitudinal) ×150 mm (tangential) ×50 mm (radial) was cut from these poplar logs. After kiln-drying, the lumber samples were further machined into sapwood specimens (MC = 10.6%) with dimensions of 400 mm (longitudinal) ×110 mm (tangential) ×25 mm (radial).

Methods
Compression process of overall compressed solid wood
The kiln-dried specimens were preheated directly on a 180 °C hot plate for 22 min. After this, intermittent radial compression was performed. The compression rate was 20.0%, with a hot-pressing temperature of 180 °C, and a pressure of 6 MPa. Each compression cycle consisted of a 3-s compression time followed by a 30-s interval. After 10 compression cycles, the pressure and pressing temperature were maintained for 30 min. The heated platens were then cooled using a water-cooling system until the temperature dropped below 100 °C before the load was released. Five replicates were performed.

Compression process of surface compressed solid wood
The kiln-dried specimens, coated with paraffin on the transverse surfaces, were soaked in water for 2 h. They were then placed on a hot plate for preheating. The hot-preheating temperature and time were 180 °C and 10 s, respectively. After that, intermittent radial compression was performed. The compression rate was 20.0%, the hot-pressing temperature was 180 °C, and the pressure was 6 MPa. Each compression cycle consisted of a 3-s compression period followed by a 30-s interval. After 5 compression cycles, the pressure and pressing temperature were maintained for 30 min. The heated platens were then cooled using a water-cooling system until the temperature dropped below 100 °C before releasing the load. Five replicates were performed.

Compression process of centre compressed solid wood
The kiln-dried specimens, coated with paraffin on the transverse surfaces, were soaked in water for 2 h and then stored in sealed plastic bags for 18 h (MC = 18.3%). They were subsequently placed on a hot plate for preheating at 180 °C for 12 min. After this, intermittent radial compression was performed. The compression rate was 20.0%, with a hot-pressing temperature of 180 °C and a pressure of 6 MPa. Each compression cycle consisted of a 3-s compression time followed by a 30-s interval. After 5 compression cycles, the pressure and pressing temperature were maintained for 30 min. The heated platens were then cooled using a water-cooling system until the temperature dropped below 100 °C before the load was released. Five replicates were performed.

Density profile
Samples with dimensions of 50 mm (longitudinal) × 50 mm (tangential) × 20 mm (radial) were cut from the centre of the specimens. They were conditioned at 65% relative humidity and 20 °C until they reached a constant weight. Their density profile was measured using an X-ray density profiler (DENSE-LAB X, Electronic Wood Systems Gmbh, Hameln, Germany) with a step size of 20 µm.

Determination of compressed layer
The mean density and maximum density of the poplar wood control specimen are 0.44 and 0.49 g/cm^3, respectively. The compressed layer was defined as the area with a density 20.0% higher than the maximum density (0.59 g/cm^3).

Morphological structure
Samples were cut from the transverse section and analysed using a scanning electron microscope (SEM) (S-3400 N, Hitachi, Tokyo, Japan) to examine cell wall deformation.

Mechanical properties

The determination methods for MOR and MOE followed GB/T 1936.12009 and GB/T 1936.2–2009, respectively. The hardness determination method followed GB/T 1941–2009. After the measurement was completed, the load per unit area of the indentation was calculated using Eq. 1:

$$H = F/(\pi Dh) \tag{1}$$

where H is the load per unit area of the indentation (N/mm^2), F is the pressure (N), D is the steel ball diameter of the indenter (mm) and $h$is the indentation depth (mm).

Results and discussion

Formation of the compressed solid wood

Figure 1 shows the formation of the compressed solid wood. The transverse section colours of the compressed wood are significantly darker than that of the control. Among the three types of compressed wood, the colour of the overall compressed wood is the darkest, while the centre compressed wood is darker than the surface compressed wood; this is due to the high temperature of 180 °C, and as the preheating time increases, the colour gradually deepens.

This study employs an open hot press at a temperature of 180 °C. When wood is exposed to high temperatures, it comes into direct contact with air. Previous research has shown that hemicellulose begins to degrade at 180 °C, and if oxygen is present under these conditions, cellulose and lignin can also undergo degradation[21]. Lignin contains chromogenic groups such as carbonyls, carbon-carbon double bonds, and benzene rings, which can cause changes in wood colour when subjected to high temperatures[22]. Although cellulose and hemicellulose do not contain chromogenic groups in the molecular chains, thermal degradation produces furfural and other substances containing chromogenic groups, which also lead to changes in wood colour[23].

In addition, there are some dark layers in the transverse sections of the sandwich compressed wood, while the colour of the overall compressed wood is relatively uniform. X-ray images confirm this observation. A brighter image indicates higher material density, indicating that the dark layers in the transverse sections are compressed layers.

It can also be seen from the density profile (Fig. 2) that two density peaks appear at the surface in the surface compressed wood, while a single density peak appears at the centre in the centre compressed wood. Meanwhile, the density of the overall compressed wood increases uniformly compared with the control. Density profiles of compressed solid woods confirm the observation of Fig. 1.

The microscopic examination is presented in Fig. 3. It is observed that the cell walls collapse into different shapes, and some fibre cells are almost closed. Even though cell wall buckling occurs, no significant cell wall failures are observed in the wood. The above results indicate that the structure of the compressed wood can be effectively controlled by adjusting the hydrothermal process.

Softening treatment is a necessary condition for wood compression[24]. Moisture and temperature are the most important factors affecting wood softening, with the hygrothermal softening characteristics of hemicellulose and

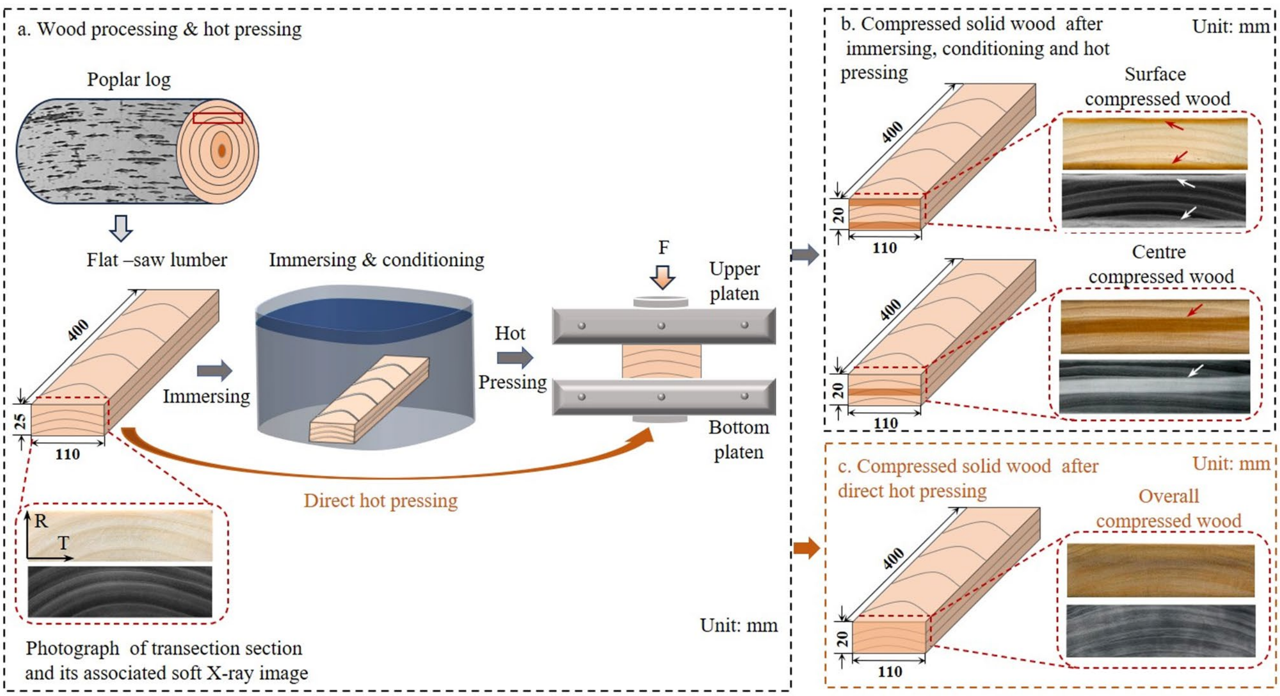

Fig. 1. Schematic diagram of the compressed solid wood.

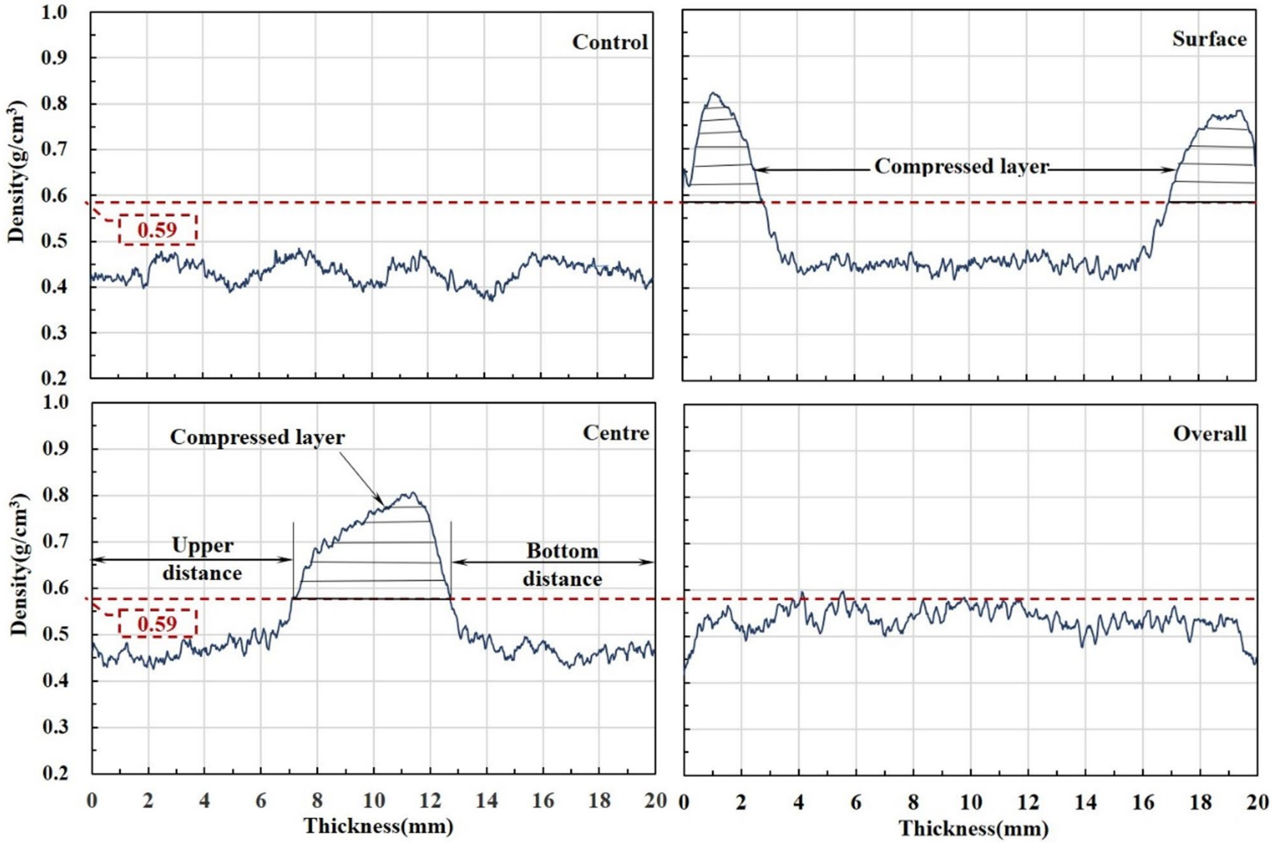

Fig. 2. The density profile of the compressed solid wood.

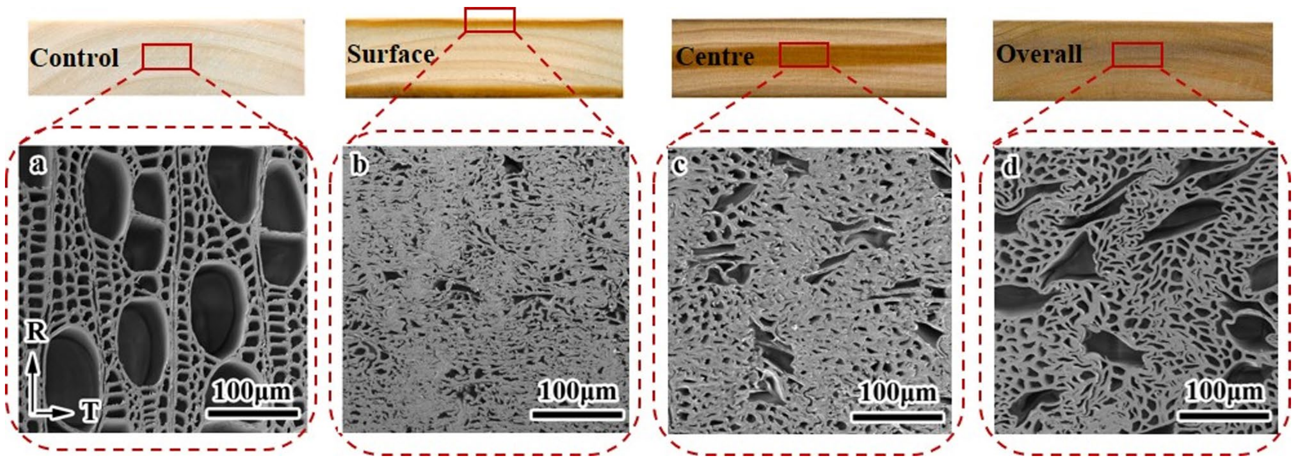

Fig. 3. SEM micrographs of the compressed solid wood.

lignin being the main contributors[11,12]. The softening temperatures of oven-dried hemicellulose and lignin are approximately 200 °C and 150 °C, respectively. However, when the moisture content is 20.0%, their softening temperatures decreases to 100 °C and 80 °C, respectively[13]; this suggests that the combined effect of moisture and temperature plays a significant role in enhancing wood plasticity.

In this study, the wood was soaked in water for 2 h and preheated for 10 s at a temperature of 180 °C. This caused the surface layer of the wood to have the highest moisture content and temperature, reaching the glass transition point first compared with the other layers in the thickness direction[7]. When the load was applied, the surface layer deformed first, forming the surface compressed wood. As the preheating time increased, the wood surfaces dried, while the moisture content and temperature inside the wood increased[25,26]. When preheated at 180 °C for 12 min, the temperature of centre layer exceeded 120 °C and its moisture was higher than that of other

Compressed solid Wood	Entire Thickness(g/cm^3)	LSD multiple comparison	2.82 mm Surface Layer (g/cm^3)			
			Upper	LSD multiple comparison	Bottom	LSD multiple comparison
Control	0.44(0.01)	b	0.43(0.01)	d	0.44(0.01)	d
Surface	0.54(0.01)	a	0.72(0.03)	a	0.74(0.01)	a
Centre	0.54(0.01)	a	0.45(0.01)	c	0.46(0.01)	c
Overall	0.54(0.01)	a	0.52(0.02)	b	0.51(0.02)	b

Table 1. Density values of the compressed solid wood. The values in () are the standard deviations of 5 runs. Same letters indicate the absence of a significant difference between the two groups (α = 0.05).

Compressed solid Wood	Compressed Layer(g/cm^3)		Peak Density(g/cm^3)		Compressed layer distance(mm)	
	Upper	Bottom	Upper	Bottom	Upper	Bottom
Control	–	–	0.51(0.02)		–	–
Surface	0.73(0.02)	0.73(0.02)	0.85(0.02)	0.80(0.04)	0	0
Centre	0.72(0.01)		0.82(0.01)		7.18(0.37)	7.21(0.13)
Overall	–	–	0.64(0.01)		–	–

Table 2. Density values of the compressed layer. The values in () are the standard deviations of 5 runs. Same letters indicate the absence of a significant difference between the two groups (α = 0.05).

parts of wood. Under the above condition, the glass transition temperatures of hemicellulose and lignin were both below 120°C[7]. This indicated that centre layer of wood has been softened. In addition, the yield stress calculation showed that the yield stress of centre layer was the lowest[7,27]. Therefore, preheating led to the formation of the densified core and the centre compressed wood was formed[5]. Moreover, the moisture content of air-dried wood was approximately 10%. When preheated using the hot plate, the softening of the wood mainly depended on the temperature[13]. After adequate preheating at 180 °C, the entire wood could be fully softened[8]. Therefore, overall compressed wood was formed after being preheated at 180 °C for 22 min and then compressed.

Density profile characteristics

The density values of the compressed wood are displayed in Table 1.

Across the entire thickness, the average density differences among the compressed woods were not significant (F test, $P > 0.05$), indicating that different compression processes do not cause severe degradation or a decrease in wood density. However, for the 2.82 mm surface layer thickness, the density differences among the compressed woods were significant (F test, $P < 0.001$). The surface compressed wood exhibited the highest density, measuring 0.74 g/cm^{3,} with an increase rate of 68.2% compared with the control when the compression rate of the entire piece of wood was 20.0%. In addition, the density of the 2.82 mm surface layer in the centre compressed wood was lower than that of the overall compressed wood. This is because that the compressed area is located in the centre layer of the centre compressed wood while all areas of the overall compressed wood are compressed.

The density values of the compressed layer are displayed in Table 2.

The compressed layer density of surface compressed wood is the highest, at 0.73 g/cm^{3,} which is almost the same as the density of the 2.82 mm surface layer (0.0.74 g/cm^3). This is because compressed layers are formed on the surface of the wood. Additionally, the peak density of the surface compressed wood is also the highest, at 0.85 g/cm^3, which is 1.7 times the control's peak density. For the centre compressed wood, the differences in the distances of the compressed layer from the upper and bottom surfaces are not significant, meaning that its compressed layer is formed at the centre of the wood; this indicates that, during the migration of moisture and temperature from the upper and bottom surfaces to the wood's interior, although there are differences in migration paths, they do not affect the formation of the compressed layer at the centre of the wood.

From the above, it can be seen that the density of compressed wood can be effectively and accurately controlled through THM treatment processes. Additionally, the formation of compressed layers on the wood surface is the most conducive to an increase in wood density.

Mechanical properties

The MOE, MOR, and hardness of compressed woods are shown in Table 3.

It is evident that the bending properties of surface and centre compressed wood are superior to those of overall compressed wood (F test, $P < 0.01$); this implies that an uneven structure is more conducive to improving the bending resistance of wood when the compression ratio is constant. Moreover, surface compressed wood has the highest MOE and MOR, at 15.97 GPa and 105.19 MPa, respectively. Their increase rates compared with the control are 43.68% and 45.25%, respectively (Fig. 5); this is because the surface of wood experiences the highest stress during bending, and the surface layer density of surface compressed wood is the highest. Therefore, the bending properties of surface compressed wood are the best.

Compressed solid wood	MOE (GPa)	LSD multiple comparison	MOR (MPa)	LSD multiple comparison	Hardness (*N*/mm²)	LSD multiple comparison
ontrol	11.11(0.44)	c	74.42(0.70)	d	18.35(0.12)	d
Surface	15.97(0.55)	a	105.19(1.16)	a	35.60(1.01)	a
Centre	13.82(0.63)	b	98.27(3.68)	b	21.40(0.77)	c
Overall	13.39(0.63)	b	86.73(4.15)	c	24.78(0.60)	b

Table 3. MOE, MOR and hardness of the compressed solid wood. The values in () are the standard deviations of 5 runs. Same letters indicate the absence of a significant difference between the two groups (α = 0.05).

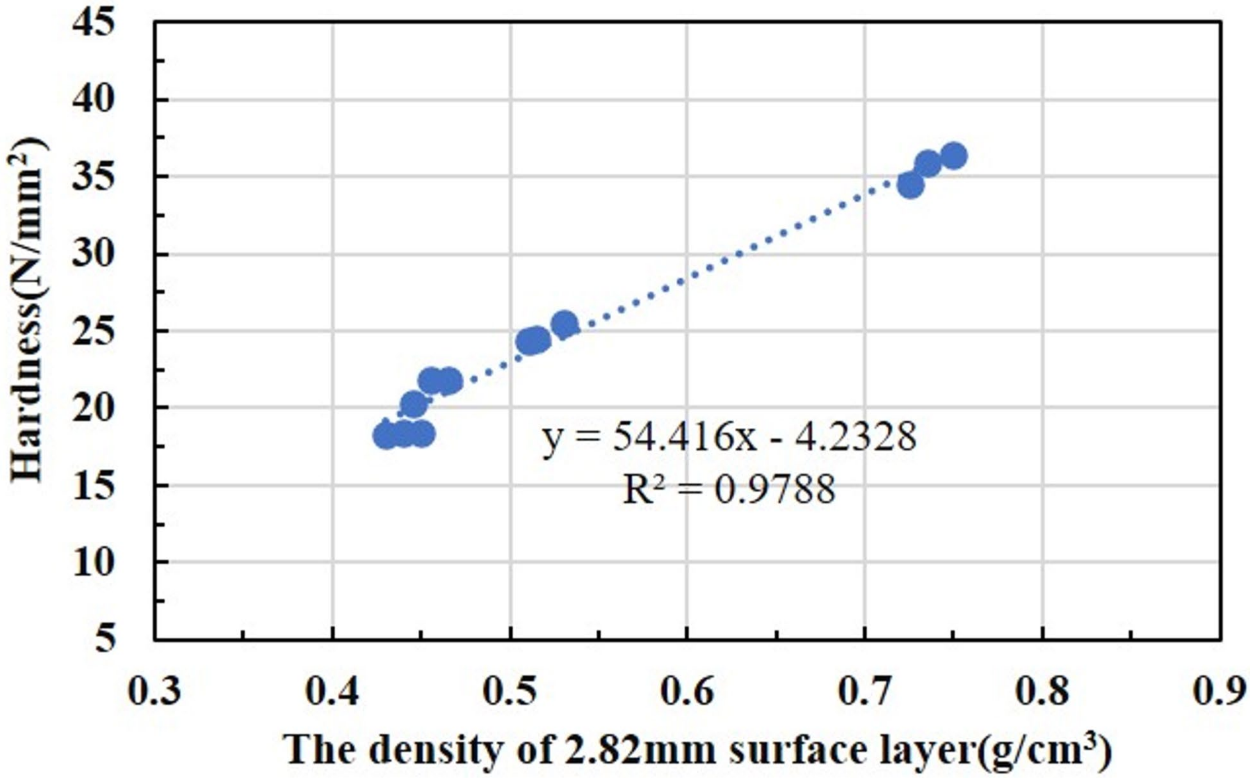

Fig. 4. Relationships between the 2.82 mm surface layer density and hardness.

It is observed that the variation trend of wood hardness is similar to that of the 2.82 mm surface layer densities; the higher the surface layer density, the greater the wood hardness (Table 1; Fig. 4). This finding is consistent with previous research results[9,20,28]. Therefore, the hardness of surface compressed wood is also the highest, at 35.60 N/mm², with an increase rate of 93.95% compared with the control (Fig. 5).

In summary, during the application process of wood, the moisture and temperature distribution can be adjusted through THM treatment processes according to specific requirements, allowing control over the softening position of the wood; this enables the densified layer to be positioned where it is most needed, thereby improving the mechanical properties of the wood and achieving more efficient utilisation.

when the compression rate is 20.0%.

Conclusions

The formation of compressed woods with three completely different structures proves that moisture and heat have a significant impact on the softening and deformation of wood.

By utilizing the significant influence of moisture and heat on the softening and deformation of wood, the structure of compressed wood can be effectively controlled through the synergistic effect of pressure, heat and moisture.

The MOE, MOR, and hardness of surface compressed wood are the highest among three types compressed woods. Additionally, when the compression ratio is 20.0%, the MOE, MOR, and hardness of surface compressed wood are more than 20.0% higher than those of overall compressed wood. This indicates that solid wood

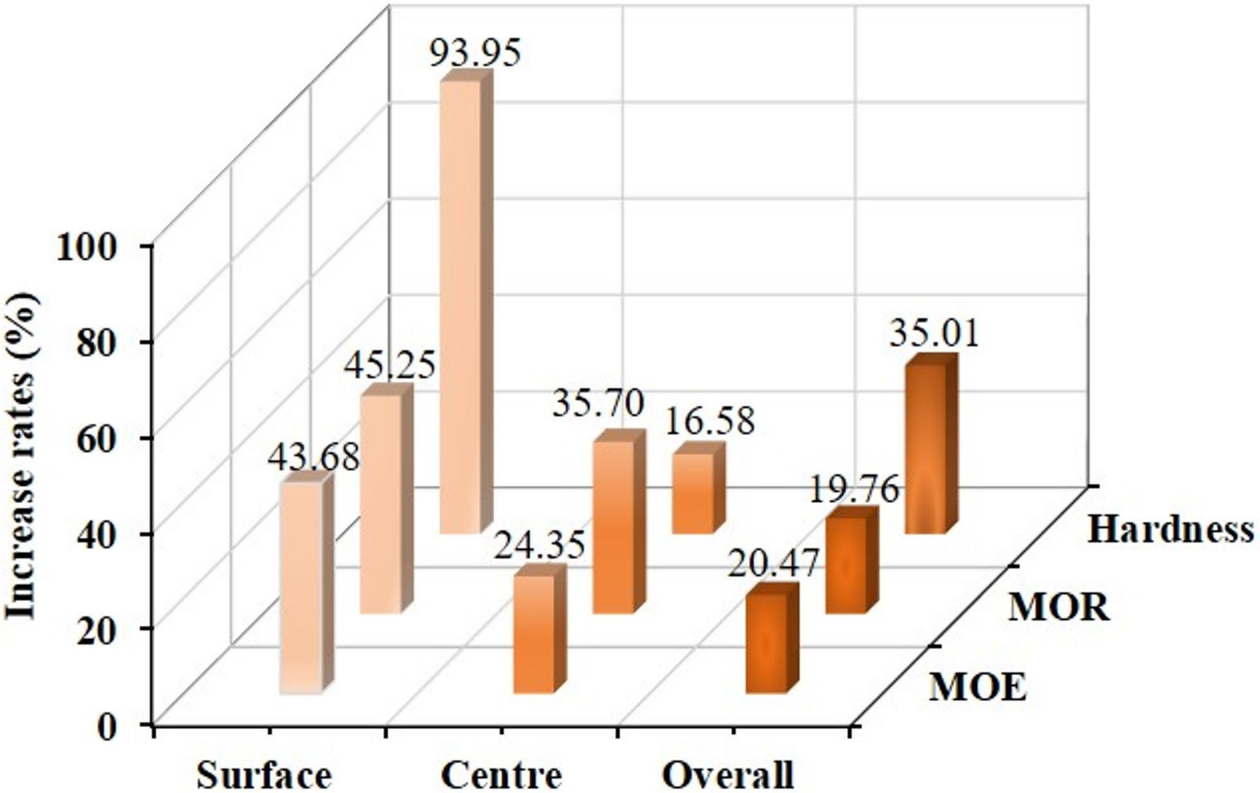

Fig. 5. Increase rates of the mechanical properties compared with those of the control.

compressed by surface compression can achieve the same MOE, MOR, and hardness at lower compression ratio compared with overall compression, which can save wood resources effectively.

The structure of the compressed solid wood affects its physical and mechanical properties. The densified area is located in the most critical position, which is more conducive to improving physical and mechanical properties, efficiently utilizing and saving wood resources.

Data availability

Data is provided within the manuscript.

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Author contributions

Ren Li wrote the main manuscript text, prepared figures and reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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