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THE EFFECT OF SURFACE-DENSIFICATION AND SUPERHEATED STEAM MODIFICATION ON IMPACT RESISTANCE AND SURFACE PROPERTIES OF RUBBERWOOD

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ABSTRACT

Employing rapid surface loading (160°C, 10 s) during hot pressing can elevate the peak density of the wood's surface, thus augmenting its rigidity and impact resistance capabilities. Subsequently treatment with superheated steam (190°C, 1.5 h). The findings of the study indicate that the impact resistance of the modified rubberwood increased by 29.2% compared to the untreated control samples. Remarkably, it even surpassed that of *Fraxinus mandshurica,* a premium quality hard wood species. Moreover, the wood's colour has transformed into a purple brown hue, endowing it with a more aesthetically pleasing and refined appearance. Additionally, the paint film on the wood's surface exhibits strong adhesion, meeting the requirements of Grade 1 as stipulated by the national standard. This combined modification method effectively enhances the overall performance of rubberwood.

KEYWORD: Surface-densification, superheated steam modification, impact resistance, contact angle, adhesion of paint film.

INTRODUCTION

Rubberwood is a very important woody raw material in Southeast Asia and China. Thailand updates and harvests 300,000 ha annually, with over 90% exported to China (Cheng et al. 2017). China can also regenerate and produce more than 2 million m^3 of rubber tree logs annually, making it a sustainable raw material for plantation timber. Rubberwood has an attractive grain and excellent processing properties, making it one of the most important materials for furniture and interior decoration.

However, rubberwood is rich in 8% starch and free sugars, making it prone to decay and insect infestation (Jie et al. 2018, Li et al. 2012). Heat treatment is an effective method to improve the biological durability of wood, as it does not use chemical agents and can enhance

the application value of low-grade wood (Ke et al. 2022). However, heat treatment degrades hemicellulose and part of the amorphous cellulose, weakening the wood's strength (Zhao et al. 2019, Cai et al. 2019, Korkut et al. 2015). Surface-densification of wood is an effective method to improve the physical and mechanical properties of wood (especially surface hardness, bending strength, and impact resistance) (Gong et al. 2010, Laskowska et al. 2017, Candan et al. 2013). Previous studies on wood surface-densification have mainly focused on fast-growing timber from low-density plantations, such as spruce, pine, and poplar (Welzbacher et al. 2008, Zaman et al. 2000, Chen et al. 2020), as low density affects strength and impact resistance. Rubberwood, with its medium density, can be used for stress and wear resistance in important applications like load-bearing wooden components, solid wood flooring, and wall panels after surface-densified and heat treatment. The relationship between wood density and most of its physical and mechanical properties is approximately linear. Surface-compressed wood resembles a three-layer composite structure (Hao et al. 2018, Anshari et al. 2012), with high-density surfaces on both sides providing most of the mechanical strength for the overall composite (Anshari et al. 2012), and an uncompressed core layer in the middle. The effects of surface-densified and heat treatment on the physical-mechanical properties and decay resistance of rubberwood have been discussed in previous studies (Gu et al. 2025). However, for structural applications such as flooring, wall panels, and countertops, impact resistance is equally critical as strength. Moreover, high-temperature heat treatment can improve the wood's surface characteristics (colour, contact angle, adhesion of paint film), thereby further improving the practical value of rubberwood (Zhu et al. 2021,2024).

MATERIAL AND METHODS

Materials

The test materials were sourced from defect-free kiln-dried flat-sawn boards of rubberwood (*Hevea brasiliensis*) from Danzhou, Hainan Province (1000 × 100 × 26 mm³, L×T×R). The wood had a moisture content of 8% and an average oven-dry density of 592 kg/m³. The boards were processed into the dimensions of 330 × 100 × 26 mm (L×T×R). Seven groups of boards (four groups for surface densification, two for surface densification first followed by heat-treated, and one group for control) were prepared, and each group included 8 replicated boards.

Surface densification

The rubberwood boards were surface-densified in the radial direction at the Laboratory of Nanjing Forestry University using a conventional laboratory hot-press with an electric heating system and press platen of 500×500 mm (Fig. 1). Metal stickers of 20 mm thickness were used to control the target thickness with a nominal compression ratio of 23.1%. The thermo-mechanical densification process consisted of three phases: preheating (for softening of the wood), compression, and pressure holding. To determine the effect of compression temperature and pressing duration on the vertical density profiles (VDP) of the surface-densified wood, four compression processes were selected, including two temperatures (160°C and 180°C) and two durations (10 s and 60 s), as shown in Tab. 1. The 10 min pressure holding

phase in the compression process serves to release residual compressive stress, thereby reducing deformation recovery and moisture-induced rebound. After this phase, the platen pressure is gradually reduced to 0.5 MPa, followed by gentle slight loosening the platen to release steam between the plate and wood, thereby lowering surface steam pressure and preventing blistering and splitting.

In this study, the conventional water cooling followed by reheating step, commonly used in previous research (Welzbacher et al. 2008, Chen et al. 2020) was omitted, significantly reducing energy consumption and time. This approach was proved particularly suitable for large-scale industrial application.

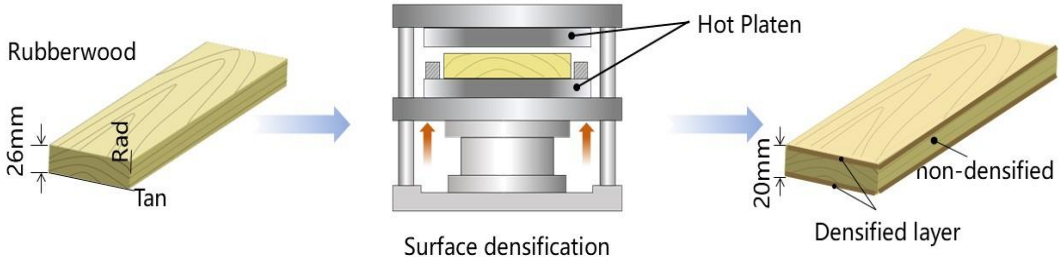

Fig. 1: Scheme of rubberwood surface-densification in the radial direction.

Tab. 1: Parameters for densification process of rubberwood.

Process	Preheating phase	Compression phase		Pressure holding phase		Platen temperature
	Time (s)	Time (s)	Pressure (MPa)	Time (min)	Pressure (MPa)	(°C)
I	30	10	10	10	1.5	160
II	30	60	10	10	1.5	160
III	30	10	10	10	1.5	180
IV	30	60	10	10	1.5	180

Vertical density profiles (VDP) measurements

The VDP of the wood specimens were measured using an X-ray densitometer (DENSE-LAB Mark3, Germany). Wood density was measured at intervals of 0.05 mm through the thickness of the specimens. Specimens with dimensions of 50×50×20 mm and 50×50×26 mm (L×T×R) were cut from each group of the surface-densified and non-densified board.

Post heat treatment

Thermal modifications were conducted in a superheated steam chamber with an electric heating and steaming system at laboratory scale. Two groups of board 330 × 100 × 26 mm (L×T×R) were surface-densified using the parameters of densification process I, then they were piled up in the chamber for superheated steam treatment and conditioning. Two groups of boards were subjected to different heat treatment process: one group was heated to 170°C and held for 1.5 h (T_1), while the other group was heated to 190°C and held for 1.5 h (T_2). After heat treatment, the temperature was reduced to 110°C, followed by conditioning for 2 h.

Post heat treatment material mass loss rate

Before heat treatment, 12 specimens of 50 × 50 × 5 mm (L×T×R) were cut from the surface-

densified wood of both groups. The specimens were dried at 103±2°C to a constant mass, weighed and labelled as W_1. They were then subjected to heat treatment alongside the board stack. After the treatment, the small specimens were removed and dried again to a constant mass, weighed and labelled as W_2. The mass loss rate ρ (%) was calculated using Eq. 1:

$$\rho = (W_1 - W_2) / W_1 \times 100\% \quad (1)$$

Properties determination

The dimensions and number of repetitions for the test specimens used to measure the impact resistance, colour, contact angle, and adhesion determination of wood are shown in Tab. 2. All specimens were adjusted to moisture equilibrium in a conditioning chamber at 20°C and 65% relative humidity.

Tab. 2: The dimensions of specimens and measurement replicates for different tests.

Test method	Dimension (mm)			Replicate of measurement	Groups
	Long.	Tang.	Rad.		
Impact resistance	140	100	20	12	4
Colour	140	100	20	24	4
Contact angle	50	20	20	24	4
Adhesion determination	140	100	20	12	4

Impact resistance test

The impact resistance properties of wood specimens were evaluated base on GB/T 17657-2022, with a drop ball impact method. The diameter and mass of the steel ball were 42.8 mm and 324 g respectively. The ball was dropped at a height of 1 m and impacted on the surface of specimens. The indentation diameters of the specimen surface were measured and evaluated as the impact resistance properties of wood specimens.

Chromatic aberration measurement

The colour measurements of wood samples for four groups were conducted according to GB/T 3979-2008, with a CHROMA METER CR-400. The parameters of L^*, a^* and b^* were used to describe the colour of samples. The L^* is the brightness ranging from black (0) to white (100). The a^* is the colour coordinate from red (positive) to green (negative) and the b^* is the colour coordinate from yellow (positive) to blue (negative). The values of L^*, a^* and b^* of six samples were determined at four different locations on each. Twenty-four replicates were used for each group and the average value was calculated. In chromatic aberration system the ΔE was used to indicate the difference between the treated samples and the control sample. If the colour difference is larger, the ΔE value is larger. The ΔE was calculated with Eq. 2:

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

Contact angle determination

The water contact angle of the wood surface indicates the wettability of wood surface with water. It was measured according GB/T 30693 (2014) with a contact angle meter (FCA200A).

The water drop size was 8 µl. The data after the water droplet contacts the wood surface for 16 s were recorded. Six specimens were determined for each group, and the contact angles were measured at four different points of each specimen. The average value was calculated.

Adhesion determination

The adhesion was determined according to GB/T 4893.4-2023 Cross-cut test method. Each test group consisted of 4 specimens, with measurements taken at 3 different positions on each specimen. The specimens were first sanded with 360-mesh sandpaper, followed by manual application of water-based polyurethane transparent resin paint in 3 coats with coating weight of 39 g/m^3 each coat. The coated specimens were then air-dried for 24 h at 25°C and 60% relative humidity. A single-edged cutting tool was used to make 6 horizontal and 6 vertical cuts at 2 mm intervals at 3 different positions on the paint film surface. The peeling condition of the paint film in the cross-cut areas was carefully observed with a magnifying glass to evaluate the adhesion grade between the paint film and the wood surface.

RESULTS AND DISCUSSION

Vertical density profiles analysing (VDP)

The VDP curves of four compressed by different process and control samples were displayed in Fig. 2. Each curve represents a specific compression technique. The curve I exhibits high left and right peak densities near the compressed surface. This occurs because preheating raises the surface temperature and moisture content, causing the cell walls to soften under thermal compression. In this thermal-hygroscopic environment, hemicellulose and lignin transition from glassy to rubbery states (Lenth et al. 2001). Rapid compression results in a steep VDP curve (curve I).

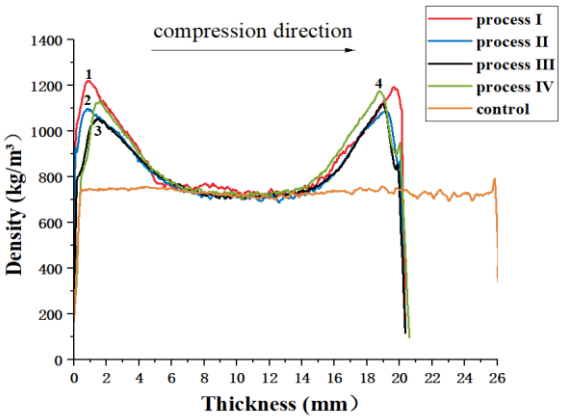

Fig. 2: VDPs of surface densified and non-densified wood specimen along thickness.

As compression time increases and temperatures rise, the amorphous hemicellulose and lignin in the sub-surface layers lose rigidity, allowing easier compression and shifting the density peaks inward (curve 4). Thus, compression time and temperature significantly influence the values and positions of left peak density (PD_l) and right peak density (PD_r) as well as the compressed layer thickness, as detailed in Tab. 3.

Tab. 3: The density (kg/m³) and thickness (mm) of VDPs of surface-densified and control wood.

Process	PD_l		PD_r		Thickness of den. layer		Thickness of non-den. layer	Average density
	Value	Pos.*	Value	Pos.	Left	Right	Core	
I	1219	0.90	1192	0.66	7.09	6.08	7.13	873
II	1096	0.80	1088	1.14	6.24	5.20	8.59	831
III	1055	1.52	1117	1.32	6.61	5.39	8.09	822
IV	1129	1.56	1175	1.85	6.75	6.15	7.61	842
Control	/	/	/	/	/	/	26	723

PD_l - left peak density; PD_r - right peak density; Pos.* - position, thickness between the surface and peak-tip.

The data in Fig. 2 and Tab. 3 demonstrate that the surface-densified wood produced by process I (preheating and hot pressing at 160°C for 10 s) exhibits higher peak density and thicker densified layer, with relatively low hot pressing temperatures, ensuring safety for both experimental and industrial applications. Therefore, process I was selected as the representative method for surface-densified and will be further investigated.

Mass loss rate of specimens after heat-treated process

The mass loss rate of the specimens after heat treatment were shown in Tab. 4. The average values were 1.10% and 2.25%, respectively, indicating that higher heat treatment temperatures lead to greater degradation of hemicellulose and amorphous cellulose in wood (Gu et al. 2025, Sandberg et al. 2013, Tu et al. 2021), resulting in higher mass loss rates. However, since the heat treatment temperature did not exceed 190°C, the treatment time was only 1.5 h. Consequently, the mass loss rates of both heat-treated wood samples were relatively low, and their effect on the wood's impact resistance was limited.

Tab. 4: Mass loss rate of specimens after heat-treated process.

Treatment temperature	Mass loss rate (ρ/%)						Average
170°C	1.00	1.14	1.10	0.93	1.13	1.13	1.1（0.08）
	1.14	1.08	1.19	1.22	1.03	1.08	
190°C	2.09	2.25	2.20	2.12	2.44	2.32	2.2（0.15）
	2.30	2.61	2.30	2.19	2.20	2.01	

Standard deviations are in brackets.

Impact resistance

The indentation diameters of control material, surface-densified (I), densified followed by post heat-treated (IT_1 and IT_2) and well-known hardwood Manchurian ash were shown in Fig. 3. The control material, due to insufficient wood rigidity, showed a larger impact indentation diameter of 12 mm. After surface densification, the wood rigidity increased significantly, reducing the surface indentation diameter to 8.7 mm, with decrease of 27.5%. Further heat treatment reduced the indentation diameter to 8.8-8.5 mm, indicating minimal change in wood rigidity. Therefore, the wood impact resistance, when first surface-densified and then heat-treated, was significantly improved compared to the control material, with an increase of 26.7%–29.2%. This impact resistance even exceeded that of the high-quality hardwood material Manchurian ash (Chen et al. 2020) by 12%-15%.

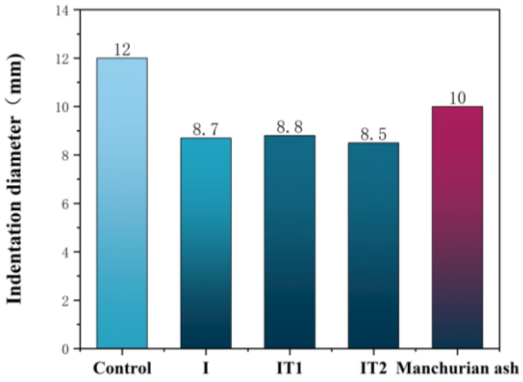

Fig. 3: The indentation diameters of four groups wood specimens and Manchurian ash.

Chromatic aberration

The wood colour comparison was shown in Fig. 4 As surface densification and heat treatment temperatures increased, the wood colour gradually darkened from the pale yellow (control wood) to the purplish-brown (heat-treated 190°C, 1.5h). This purplish-brown hue was a premium warm tone favoured by consumers, which could simulate the colour of high-grade red oak and significantly enhanced its application value.

Fig. 4: Wood colour comparison of control, surface-densified (I), densified and post heat-treated (IT_1, IT_2) rubberwood.

The colour parameters of the four wood samples were presented in Tab. 5. As the surface-densified or heat treatment temperature increased, the L^* value (luminance) significantly decreased while the a^* value (chromaticity) markedly increased, with minimal variation in the b^* value. The colour difference $\Delta \boldsymbol{E}$ was larger significantly after heat treatment. This phenomenon primarily results from the thermal cracking of hemicellulose and amorphous cellulose during heat treatment, where oxidation of hydroxyl functional groups generated carbonyl functional groups, thereby deepening the wood colour (Shukla et al. 2014, Srinivas et al. 2012). Additionally, changes in the content of wood extracts, particularly phenolic compounds, induced by heat treatment also influenced the wood colour (Esteves et al. 2008).

Tab. 5: Colour parameters and difference between control, surface-densified (I), densified and post heat-treated (IT_1, IT_2) rubberwood.

Process	**Colour CIE parameters**			**Colour difference ΔE**
	L^*	a^*	b^*	
Control	75.27	6.38	20.62	/
I	70.65	7.39	24.87	6.36
IT_1	66.05	8.12	24.64	10.21
IT_2	59.99	9.07	23.89	15.86

Contact angle

The pictures of water contact angle of surface densified, post heat-treated and control one were presented in Fig. 5. The average values of water contact angle of four groups of wood were shown in Fig. 6. It is clear that the water contact angle increased as the densified and heat treatment temperature increased. The reason for above phenomenon is the porosity in surface layer of densified wood reduced by hot pressing, which increases the contact angle value of wood surface (Diouf et al. 2011). In addition, during post heat treatment hemicellulose in wood is degraded resulting in hydroxyl groups decrease (Gu et al. 2025, Tjeerdsma et al. 2005, Boonstra et al. 2007). Although the water contact angle was increased by heat treatment, the wood surface still exhibits hydroscopic ability. It was beneficial for making a good bonding between the wood surface and coating.

Fig. 5: The pictures of water contact angle of control, surface-densified (I), densified and post heat-treated (IT_1, IT_2) rubberwood.

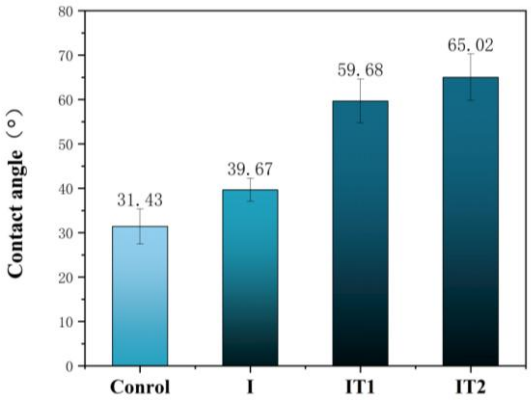

Fig. 6: The values of water contact angle of control, surface-densified, densified and post heat-treated rubberwood.

Adhesion analysing

The cross-cut images of paint film adhesion test for surface-densified (I), densified and post heat-treated (IT_1, IT_2), and control material were shown in Fig. 7. All four test specimens demonstrated high paint film adhesion, with no peeling observed at the cut line intersections, achieving the Grade 1 class of national standard requirements. This result aligned with previous studies (Zhu et al. 2024). While surface compression initially smoothed the wood surface and reduced porosity, adversely affecting adhesion, but heat treatment enhanced the extraction of abundant extractives from rubberwood, increasing surface porosity and improving adhesion. The combined effects of these processes maintain the original high level of paint film adhesion (Zhu et al. 2024).

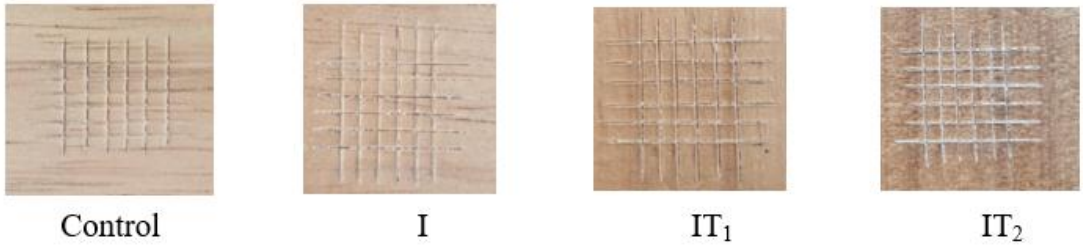

Fig. 7: Cross-cut lines of adhesion determination for control, surface-densified (I), densified and post heat-treated (IT_1, IT_2) rubberwood.

CONCLUSIONS

Rapid surface pressing (160°C, 10 s) to enhance the peak density of the test specimens was employed. Special pressure reduction and relief measures eliminated the cooling phase and subsequent reheating steps, resulting in energy and time savings, and easier industrial production. Combined with a 190°C, 1.5 h short-term heat treatment, the modified rubberwood demonstrated significantly improved impact resistance (29.2%) compared to untreated wood, surpassing the high-quality hardwood species Manchurian ash (15%). The treated wood's colour transitioned from light yellow to purplish-brown, achieving more uniform pigmentation and significantly enhanced visual appearance. Although the modified rubberwood exhibited increased water contact angle and hydrophobicity, its lacquer film adhesion still met the national standard Grade 1 level. The combined modification comprehensively improved the impact resistance and surface properties of rubberwood, enabling its application in solid wood flooring, wall panels, load-bearing wooden components, furniture and interior decoration.

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