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High-pressure densification and hydrophobic coating for enhancing the mechanical properties and dimensional stability of soft poplar wood boards

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Abstract

Effects of high-pressure (HP) treatment on densification of poplar sapwood boards and subsequent coatings were evaluated. Tung oil (TO) and epoxy resin (ER)-coated treatments were used to improve the dimensional stability of HP-densified wood. The density of the wood after HP densification increased from 450 ± 50 kg/m^3 for the control to 960 ± 20 kg/m^3 at 125 MPa. This process also resulted in the average thickness of HP-densified boards to reduce significantly from 29.7 ± 0.11 mm for the control to 18.8 ± 0.53 mm after HP densification at 25 MPa and 14.3 ± 0.10 mm after 125 MPa treatment for 30 s. The mechanical strength measured as the hardness of densified wood significantly increased from 35% at 25 MPa to 96% at 125 MPa treatment, compared to untreated wood. As expected both TO and ER-coated treatments significantly reduced set-recovery of densified wood when stored at four relative humidity environments. ER showed better anti-swelling performance than TO, and would be a better choice.

Keywords: High-pressure densification, Low-density wood densification, Hardness improvement, Tung oil and epoxy resin-coated treatments

Introduction

As a porous biomass material, low-density plantation-tree wood strength and hardness could be increased by (1) impregnating the void volume of wood with bulking chemicals (e.g., monomers, polymers, resins and waxes); (2) compressing in the transverse direction to reduce the void volume [1]. These two kinds of method could significantly improve the wood density, while the wood density correlates well with its mechanical properties. Based on these two principles, many specific methods have been proposed and improved [2–7]. The development of densification technology has opened the door for broader use of low-density plantation-tree species (for example, Scots pine wood, poplar wood, Norway spruce, European beech, Paulownia wood, etc.), whose normal mechanical properties are often inadequate for use in structural applications [5].

It is well recognized that the mechanical strength of wood can be increased by densification which also increases its density. There are many different densification methods available in the literature [8]. These include thermal compression methods [6, 9–11] and semi-isostatic densification method [12–14]. Thermal compression methods have the same two main phases—wood softening and wood compression. Furthermore, the methods usually include a post-treatment phase, which decreases irreversible thickness swelling when the densified wood is exposed to humid or wet conditions. One wood densification method developed is known as "thermo-hydro-mechanical processing" [15–18]. This method involves the use of steam and thermal compression, resulting in mechanical compression of wood with

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more plasticizing properties, which makes densified wood more dimensionally stable. Another wood densification method developed by Kamke and Sizemore [19] is known as "viscoelastic thermal compression". The process has a wood softening phase above the glass transition temperature (T_g), under saturated steam, followed by a compression phase, heat-treatment, and cooling [20]. High densities are achieved through a dynamic process which combines temperature ranging from 150 to 190 °C, saturated steam and mechanical compression perpendicular to the grain. This process needs energy and time. Gao's method [6] was developed to compress Chinese white poplar wood by adjusting the moisture and temperature distributions within the lumber which is also based on thermal compression. The wood is soaked to adjust wood moisture content instead of steam preheating. The temperatures of the upper and lower plates of the hot press are controlled at 180 °C, and a pressure of 6–10 MPa is applied. A new compression method in which no heating was needed is developed by Blomberg and Persson [14]. This method is known as *semi-isostatic densification* or the *Quintus press*. This method can yield pressures of up 140 MPa, mediated through a flexible oil-filled rubber diaphragm that is pressed against a rigid press table. This processing can give densified wood irregular shape but homogenous density. The Quintus press makes use of a high-pressure equipment and can give densified wood with only one side uniform and regular shape. It is semi-isostatic compression for wood densification, and as used against a flat surface produces smooth surface on one side.

High-pressure (HP) treatment has been proved to be a useful densification method for fast-growing wood species by quickly reducing the void volume of wood through isostatic hydrostatic pressure, in a high-pressure equipment [20, 21]. HP densification works as shown in Fig. 1. The wood product, already sealed in its final package, are introduced into a high-pressure cylindrical vessel and subjected to a high level of isostatic pressure (up to 600 MPa) transmitted by water. In this technology, applied pressure is uniformly distributed throughout the entire sample, whether in direct contact or in flexible container [22]. This method is a new alternative to the classic thermomechanical ones. With no thermal pre-treatment needed, this process allows for very short treatment times and make it very efficient with possibility of applications on an industrial scale. Plastic compressive strains occur predominately in HP-densified wood and the delayed elastic strain is very small. This advantage makes HP-densified wood attractive for long-term indoor use when the environment relative humidity (RH) is low and the climate is relatively stable. Moreover, results showed that HP densification could make the densities of Chinese fir wood/poplar/paulownia wood to increase 2–3 times within 5 min [20, 21, 23]. This treatment is shown to be universally effective for various low-density species of wood. Studies on HP treatment of wood for densification applications have just begun, and basic research are still scarce.

Poplar (*Populus euramericana*) is a fast-growing tree with short cultivation time and is mainly used for making paper, veneers, and sawn wood [24]. Poplar is a genus of

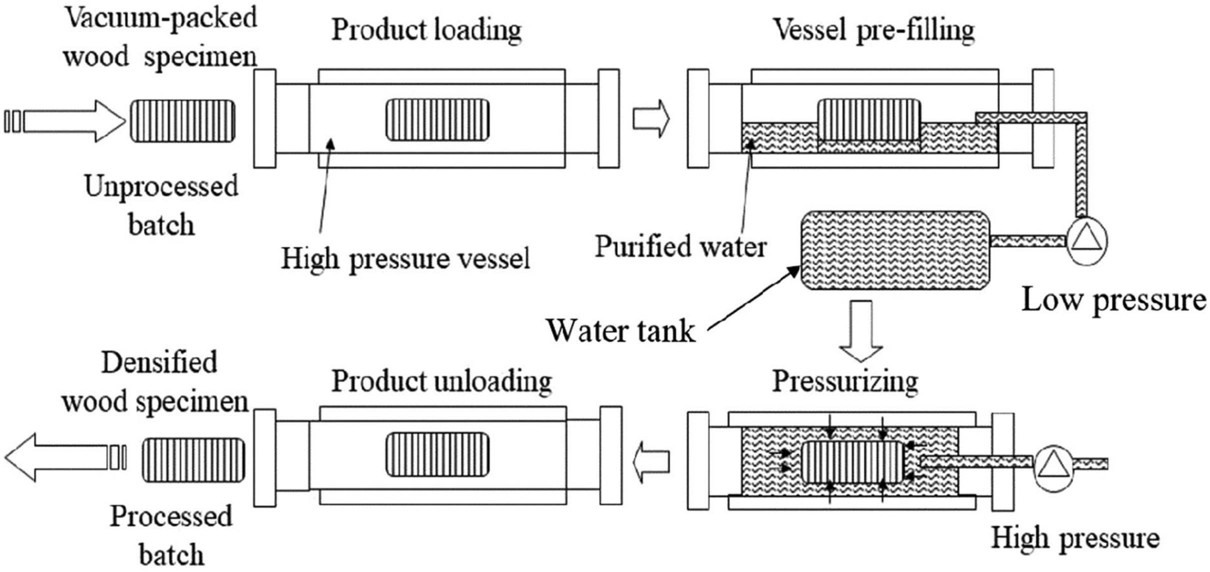

Fig. 1 Schematic illustration of the high-pressure treatment process

25–35 species of deciduous flowering plants in the family Salicaceae, native to most of the Northern Hemisphere. In addition to the use as raw materials, poplar wood can be subjected to special treatments for added values, such as enhancing mechanical strength and other structural properties and/or proving new functionalities relative to the natural wood, and thereby enabling wider applications. Poplar wood is targeted in this study because of its broad range of use in China. Yu et al. [21] demonstrated the densification effects of poplar wood treated by HP densification in which technological parameters of 50–200 MPa pressure levels for 30 s holding time were applied. Their results show that densities and mechanical properties of treated wood could be significantly improved with HP densification up to 150 MPa, and they tend to stabilize or show a decline beyond 150 MPa. This was a first study on effects of poplar wood densification by HP densification and the operational range is focused on the lower side in this study to explore the possibility for more meaningful industrial applications.

A major disadvantage of HP densification is the high recovery of the original dimensions when densified wood is exposed to high air relative humidity. A significant positive correlation between set-recovery and moisture/water absorption has been found [20]. When densified wood is subsequently exposed to a humid environment, both reversible and irreversible swellings can occur through moisture adsorption/desorption. Reversible swelling is due to the hygroscopic nature of wood, but irreversible swelling is a result of the densified wood partly or completely returning towards its original dimensions. This is commonly referred to as set-recovery [25]. This phenomenon was found in semi-isostatic densification, which is also based on HP principle [8]. A combination experiment of semi-isostatic densification and heat-treated method was conducted by Boonstra and Blomberg [1]. Their results showed no or only a limited effect on the shape-recovery when densified radiata pine was exposed to moisture. It is well known that water repellents can reduce the rate of water uptake into porous materials. The rate of water uptake can be considerably reduced either by providing a water barrier or by rendering the wood hydrophobic [26]. These hydrophobic treatments only slow down water penetration, and they do not fully prevent it. However, most wood in Class 2 (above ground covered) and Class 3 (above ground uncovered) (European Committee for Standardization, 2006) applications are exposed only for limited periods to extreme weathers, and water repellents perform well in such conditions. Tung oil (TO) is a drying oil obtained by pressing seeds from the nut of the Tung tree (*Vernicia fordii*; *V. montana*). TO dries quickly when exposed to air, forming a transparent film [27]. Its excellent water repellence has been proven in several laboratory and field trials [26, 27]. Epoxy resin (ER) has been widely used to fabricate superhydrophobic coating to reduce the abrasion and corrosion in many fields due to its high adhesion and chemical corrosion resistance [28]. Research indicates that ER can be used as a high-quality water repellent for wood members [29]. In this study, these two hydrophobic-coated treatments were used to improve the dimensional stability of HP-densified wood in high air humidity environments. Simple and effective water resistance methods are very meaningful for HP-densified wood to improve their dimensional stability.

Set-recovery is a significant issue for the usability and stability of densified wood, and therefore, it is important to explore effective methods to prevent the set-recovery. Our previous research showed set-recovery of HP-densified wood is significantly related to water/moisture absorption and therefore water repellent offered an alternative treatment. These tests therefore, even if effective, do not reflect of the normal end-use conditions [7]. In the current study, densified wood with uncoated/coated treatments were exposed to different RH conditions (five RH environments at 25 °C) and the dimensional stability was assessed by measuring the set-recovery. Effects on preventing the set-recovery of densified wood of these two water repellents could be confirmed.

The purpose of this study was to investigate the HP densification process for poplar (*Populus euramericana*) sapwood between 25 and 125 MPa pressure levels followed by surface coating of TO or ER. Treatment efficiency was monitored by evaluating compression ratio and hardness. Their dimensional integrity was evaluated under five RH storage conditions at 25 °C.

Experimental

Materials preparation

Poplar (*Populus euramericana*) sapwood board specimens machine cut to size 1000 mm (longitudinal) × 300 mm (tangential) × 30 mm (thickness) with no defects were obtained from XinZheng, Henan province, China. The material was pre-conditioned (at 65% RH, 20 °C) for at least 2 months prior to use, and the equilibrated moisture content was ~ 12% (dry basis). The average density (at 65% RH, 20 °C) of the pre-cut boards was 460 ± 50 kg/m^3. From these pre-cut boards, smaller specimens with dimensions of 150 mm (longitudinal) × 70 mm (tangential) × 30 mm (thickness) were cut for HP densification. In total, 75 specimens were treated and 15 specimens were used without treatment as control. All specimen boards were conditioned at 65% RH and 20 °C prior to use.

Methods

High pressure treatment

Schematic of the HP densification process (Fig. 1) as well as positioning of the test specimen was reported by Li et al. [20]. A test specimen board [150 mm (longitudinal) × 70 mm (tangential) × 30 mm (thickness)] was sandwiched between two stainless steel plates (the area and thickness of each plate were 70 mm × 150 mm and 5 mm, respectively, and matched the two parallel surface areas of the board) first, is shown in Fig. 2. Then this specimen board along with the two steel plates was wrapped in a flat polyethylene pouch (16 silk, Shandong Xinhua Packing Co., Ltd. Shandong, China) and vacuum-sealed with a vacuum package machine before HP densification. Width of steel plates was less than that of wood specimen, since the width of wood specimens would shrink after high pressure treatment.

The HP densification process was carried out in a single vessel (5 L) HP apparatus (UHPF-750, Kefa, Baotou, China), which also has been described in the previous study [20]. Briefly, the system consisted of the HP unit and equipped with K-type thermocouples (Omega Engineering, Stamford, CT, USA) and a data logger (34970A, Agilent Technologies GMBH, Germany) for temperature measurement and a thermostat jacket connected to a water bath (SC-25, Safe, China) for maintaining the processing temperature. Water was used as pressure transmitting medium, and the pressure vessel was maintained at 25 °C before pressurization. Since test samples were packaged in a flat polyethylene pouch, they did not directly contact the process water. The pressure come up rate was 100–150 MPa per minute, so the come up times for various treatments were less than a minute. The pressure release time was kept less than 5 s. Normally sample temperature is expected to increase by 3 °C every 100 MPa pressure rise (assuming no heat loss to pressure vessel) due to adiabatic compression. This was not a limitation because the vessel was jacketed and the maximum pressure was only 125 MPa.

Pre-packaged board specimen was placed in the pressure chamber and the system was brought to the required pressure level, held for exactly 30 s and then the pressure immediately released. So the total treatment time was less than 2 min. Each pressure treatment was given with one piece of the test board at a time, and then repeated again with new specimens to obtain 15 replicates. Five pressure levels (25 MPa, 50 MPa, 75 MPa, 100 MPa and 125 MPa) were used for treatment. Wood specimens without HP densification were used as control samples.

Determination method for compression ratio

After HP densification, densified woods were conditioned at RH 65% and 20 °C until equilibrium moisture was reached. The thickness of densified poplar boards was measured, both before and after densification, for calculating the compression ratio. The compression ratio (CR) was calculated according to Eq. 1, where T_o is the original thickness and T_c the final compressed thickness:

$$\text{Compression ratio }(\%) = \frac{T_O - T_C}{T_O} \times 100. \tag{1}$$

Measurements of hardness

Each test board was polished by sandpaper first before the following test. Then a section of 50 mm

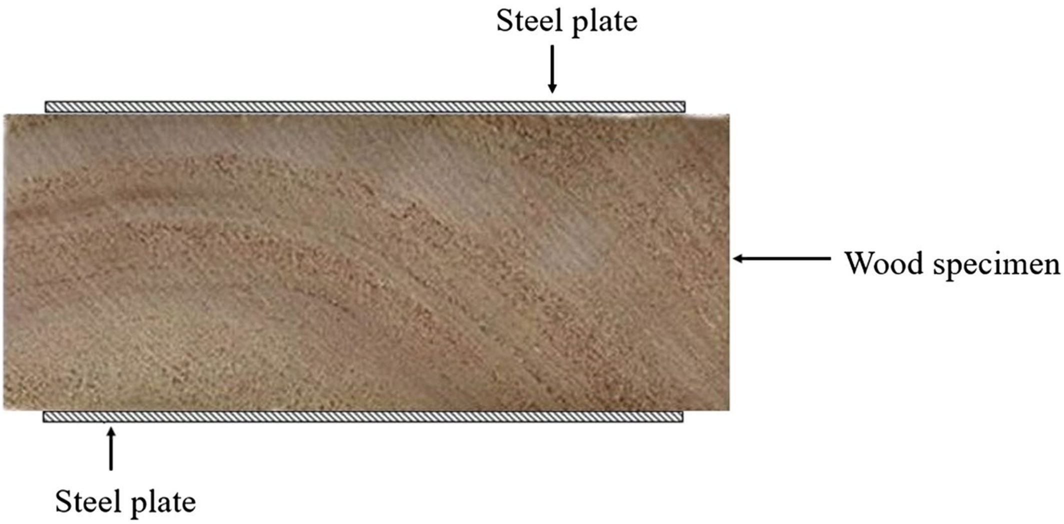

Fig. 2 Schematic diagram of fixing method of poplar board. Poplar board was fixed between two steel plates, and then wrapped in a flat polyethylene pouch and vacuum-packed

(longitudinal) × 50 mm (tangential) × thickness (radial) (different thickness after various pressure levels densification) was cut from the center of each specimen for hardness measurement (Fig. 3). Totally 15 specimens for each group was prepared and measured. Hardness was measured with a static hardness standard ISO 3350:1975 with minor modification. In this method, a semicircular steel ball of 5.64 mm radius is pressed into the wood surface with an average speed of 6 mm/min to create an indentation of 5.64 mm depth. The hardness is calculated using the following equation (Eq. 2):

$$H_{12} = KP, \tag{2}$$

where H_{12} is the hardness of the wood specimen at 12% moisture content; P is the applied force (N); and K is the coefficient of radius for the steel ball indenter at a depth of 5.64 mm, which is 1.

Tung oil and epoxy resin-coated treatments

Tung oil and epoxy resin-coated treatments were made with samples cut to size 20 mm (longitudinal) × 20 mm (tangential) × thickness (radial) (Fig. 3). Each group (pressure treatment and control) had a total of 40 treatment samples which were randomly divided into two groups (TO coated and ER coated). For TO (100% concentration, commercially available from Huangshi Gongjiang Company, Shanghai, China) coated treatment, test samples were immersed into TO for 5 h for better penetration and adherence (tested initially for 5 days to make sure change in mass was negligible) and then dried in room temperature. For ER-coated treatment, epoxy and curing agent (Yituo Company, Kunshan, China) were mixture at volume ratio of 2.3:1. Two thin layers of ER coats were applied on to each test sample. Each group contained 20 treatment samples and these samples were randomly divided into five groups for subsequent test.

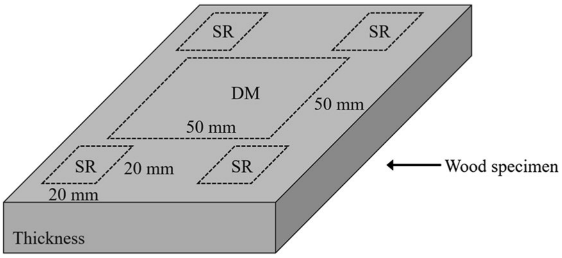

Fig. 3 Illustration of the sampling presenting one specimen: DM for hardness measurement, and SR for equilibrium moisture experiment and set-recovery experiment

Set-recovery measurement and equilibrium moisture experiment

Uncoated, TO-coated and ER-coated samples were used to measure set-recovery in five RH environments at a constant temperature of 25 °C. Five saturated inorganic solutions [$MgCl_2$, $Mg(NO_3)_2$, KI, KCl and KNO_3 solutions] were used to maintain five RH (33%, 52%, 69%, 86% and 93%) conditions [30]. These five conditions were created by placing saturated salt solutions onto the bottom of desiccators, respectively. Each pressure treatment group involved five of these desiccators. These sorption tests were carried out in temperature-controlled incubators and maintained at 25 ± 1 °C, allowing a precise RH control. The specimens were weighed periodically until the change in mass was negligible (at least < 0.01% per day). It was assumed that the equilibrium moisture content (EMC) was then reached. After establishing EMC, the thickness of specimen samples was measured with a micrometer.

For uncoated specimens, after above measurements, all test specimens were oven-dried (103 °C) to evaluate the EMC. The EMC was calculated according to Eq. 3:

$$\mathrm{EMC}_{\mathrm{uncoated}}(\%) = \frac{m_{\mathrm{c}} - m_{\mathrm{dry}}}{m_{\mathrm{dry}}} \times 100, \tag{3}$$

where m_c and m_{dry} were the weight of the specimen at each given RH environment and after oven-drying, respectively.

For coated specimens, the EMC was calculated according to Eq. 4:

$$\mathrm{EMC}_{\mathrm{coated}}\ (\%) = \frac{m_{\mathrm{c}} + m_{\mathrm{o}} - m_{\mathrm{dry}}}{m_{\mathrm{dry}}} \times 100, \tag{4}$$

where m_c was the mass change of the coated specimens before and after EMC established at each given RH environment; m_o was the weight of the test specimens before coated treatments; and m_{dry} was the calculated average dry mass of each specimen according to corresponding uncoated treatment specimens.

For set-recovery of test samples stored under five RH conditions, the thickness of each specimen used was measured. Set-recovery was calculated according to Eq. 5:

$$\text{Set-recovery}\ (\%) = \frac{T_{\mathrm{s}} - T_{\mathrm{d}}}{T_{\mathrm{o}} - T_{\mathrm{d}}} \times 100, \tag{5}$$

where T_s is the recovery thickness under various RH conditions, T_d the actual thickness after densification and T_o is the original thickness before densification.

Statistical analysis

All measured values were represented as mean ± standard deviation calculated using SPSS version 20.0 (IBM, America) and an analysis of variance with least significant difference set at $p < 0.05$ used to compare the means.

Results and discussion

Densification effects on thickness, density and mechanical strength

Effects of HP densification (30 s) at different pressures levels on poplar boards are shown in Fig. 4. HP densification significantly reduced the thickness of test specimen boards, and the reduction gradually progressed with increasing pressure level. Figure 4 also confirms that the HP densification technique with the poplar board sandwiched between two steel plates resulted in more uniform radial densification of the boards which could not be obtained in previous studies [20]. The shaping tool used in this research is very simple and works reasonably well. However, at present, this simple shaping tool could not create the degree of uniform thickness as traditional hot-plate compression methods do. Even so, HP densification offers some clear advantages for wood densification—requires no heat and completed in a short treatment time of 30 s—therefore saves time and energy. The steel plates were slightly bent (~ 4 mm) following the pressure treatments. Hence, better and more effective shaping tools and packaging methods may be needed and to be further explored.

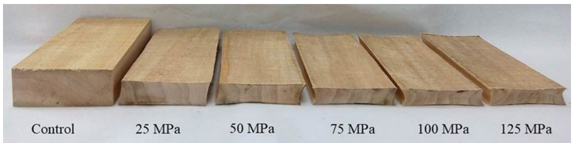

Fig. 4 Photograph image of cross-section of poplar wood after various pressure treatments for 30 s

Quantitative data on board densification effects are detailed in Table 1. After densification treatment, the thickness of poplar boards reduced by increasing pressure and thickness factor decreased by 35.4% at 25 MPa to 50.9% at 125 MPa. CR increased from the decreased thickness of poplar boards, also shown in Table 1. CR under various HP densification was between 36.8 ± 1.05% to 51.9 ± 0.92%. With HP densification at 100 MPa and above, CR increase was small.

As expected, with a decrease of board thickness and increase in CR, the density of the treated board increased significantly ($p < 0.05$) by 55.6%, 86.7%, 91.1%, 102% and 113% at 25 MPa, 50 MPa, 75 MPa, 100 MPa and 125 MPa, respectively. In our preliminary experiments, density was observed to decrease when pressure level exceeded 150 MPa [21]. These results indicate that HP densification for wood densification improves compression effects up to a certain pressure level gradually compressing the void spaces in the boards after which the degree of densification will be small. Further increase in pressure level could decrease the degree of densification and eventually may result in board rupture. This result also supports our previous research [20], which illustrated the same trend with Chinese fir, but the densification magnitudes were different. There applicable optimal pressure levels could depend on the different tree species.

In traditional hot-plate methods, CR is an important processing parameter [10, 30]. CR primarily influences density; both average density and peak density are improved when the CR gets enhanced. CR, however, also has an impact on the width of the density peak and the distance of the peak from the surface [30]. In Laine's [11] study, when CR were set to 40, 50 and 60%, and the average density of compressed Scots pine wood increased to 760 kg/m^3, 900 kg/m^3 and 920 kg/m^3. In Gao's [6] report, when CR of plantation poplar wood were 9, 20, 33, 40 and 47%, the average density of high densification layer reached 730, 790, 820, 870 and 890 kg/m^3, respectively. In the current study, HP densification yielded a much higher

Table 1 Average compress ratios and density of wood samples after various HP densification for 30 s

Pressure (MPa)	Original Thickness (mm)	Thickness after densification (mm)	Compression ratio (%)	Density (kg/m^3)	
				Before densification	After densification
25	29.7 ± 0.11^a	18.8 ± 0.53^b	36.8 ± 1.05^a	450 ± 50^a	700 ± 60^b
50	29.7 ± 0.11^a	17.6 ± 0.72^c	40.7 ± 0.89^b	450 ± 50^a	840 ± 90^c
75	29.7 ± 0.11^a	16.4 ± 0.41^d	44.8 ± 1.12^c	450 ± 50^a	860 ± 80^d
100	29.7 ± 0.11^a	15.8 ± 0.21^e	46.7 ± 1.02^d	450 ± 50^a	910 ± 60^e
125	29.7 ± 0.11^a	14.3 ± 0.10^e	51.9 ± 0.92^d	450 ± 50^a	960 ± 20^e

Measured values are represented as mean ± standard error of 15 replicates. Means followed by the different letters (a, b, c, d and e) are significantly different among original thickness and thickness after densification ($p < 0.05$). Means followed by the different letters (a, b, c and d) are significantly different among CR ($p < 0.05$). Means followed by the different letters (a, b, c, d and e) are significantly different among density ($p < 0.05$)

density with a relative lower CR. In addition, in Blomberg' s [13] report, when Scots pine was semi-isostatically compressed at 140 MPa in a Quintus press, the density reached about 1000 kg/m^3, which was similar to the present findings. This may indicate that different pressure treatments could have similar densification effects, but need further validations.

As an important processing parameter, CR of traditional densified wood should be set first. But in HP densification, the final CR of board specimens only could be adjusted by the pressure level used, which was very different from the convention. Figure 5 shows the relationship between CR and pressure level after treatment. CR increased linearly with the pressure between 25 and 125 MPa with R^2 values about 0.98. This was in accordance with our experimental results. This relationship could be used to predict the required density and thickness from pressure levels.

Hardness of treated/untreated poplar wood

As expected, the hardness value significantly increased following the densification treatment (Fig. 6). The average hardness for untreated samples was 1140 N, while those for the densified samples at 25 and 125 MPa were 1540 and 2240 N, respectively. This result suggests that hardness could significantly enhance even by the 25 MPa treatment for 30 s, and nearly doubled at 125 MPa.

As we know, the hardness of wood is generally measured by the ability of a steel ball to penetrate the wood surface. Slightly different approaches to evaluating hardness are adopted in various standard test methods [31]. So care should be taken when comparing hardness results on nonhomogeneous materials when different indentation techniques are used in the test. According to EN 1534 (2000), Brinell hardness was calculated by measuring 10-mm-diameter metal ball indentation diameter and the applied force, while in our study, hardness values were calculated by measuring 5.64 mm indentation depth and applied force (according to ISO 3350:1975). A similar procedure conducted by Boonstra and Blomberg [1], which used semi-isostatic densification of radiata pine wood at the pressure level of 140 MPa, confirmed that Brinell hardness of densified wood improved nearly three times than untreated wood. Our results were supported by these reports. Excluding differences in hardness measurement standards restrictions, hardness has been confirmed to significantly increase during wood densification in various studies [31, 32].

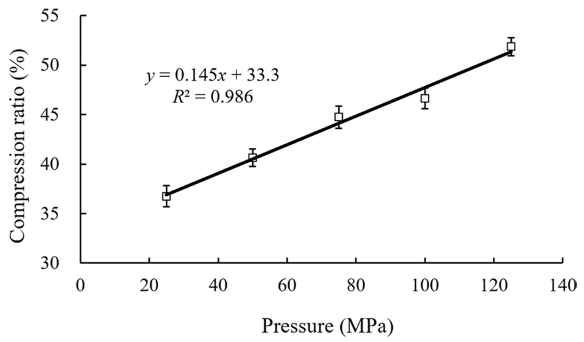

Fig. 5 Relationship between compression ratios and pressure levels after treatment

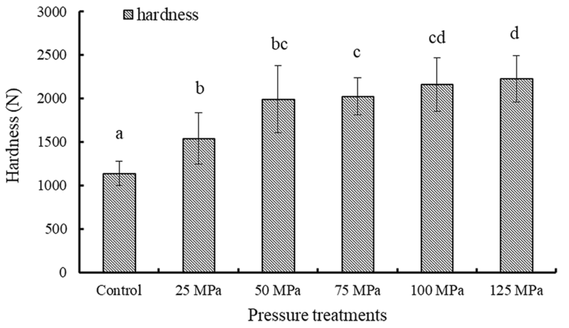

Fig. 6 Average hardness of specimens which were control (0.1 MPa), 25 MPa treatment, 50 MPa treatment, 75 MPa treatment, 100 MPa treatment and 125 MPa treatment. (Error bars present standard deviations, and letters mean significantly different levels at $p = 0.05$)

Set-recovery of densified wood with uncoated/coated treatments

Set-recovery of wood samples under various conditions is presented in Fig. 7. Set-recovery of uncoated treatments during storage at 58% RH was lower than those at other RH storage environments. When RH was maintained at 68% or above, set-recovery increased significantly with increasing RH. Moreover, the set-recovery decreased with an increasing HP densification treatment pressure level. TO and ER-coated treatments could significantly decrease set-recovery of densified wood in high air humidity, and the effect of ER was better than TO.

An unusual phenomenon was observed in that the set-recovery of densified wood was higher for storage at 33% RH than at higher at 58% RH. This is obviously due to the prevalence of lower moisture environment resulting in a moisture loss from the sample (desorption) rather than the adsorption behavior at other storage conditions. The correlation coefficient (R^2) between mass (moisture) change and set-recovery of densified wood with uncoated/coated treated was in the range 0.98 (25 MPa) and 0.92 (100 MPa) (data not shown). These results in general indicate that set-recovery of HP-densified wood were significantly correlated with moisture absorption.

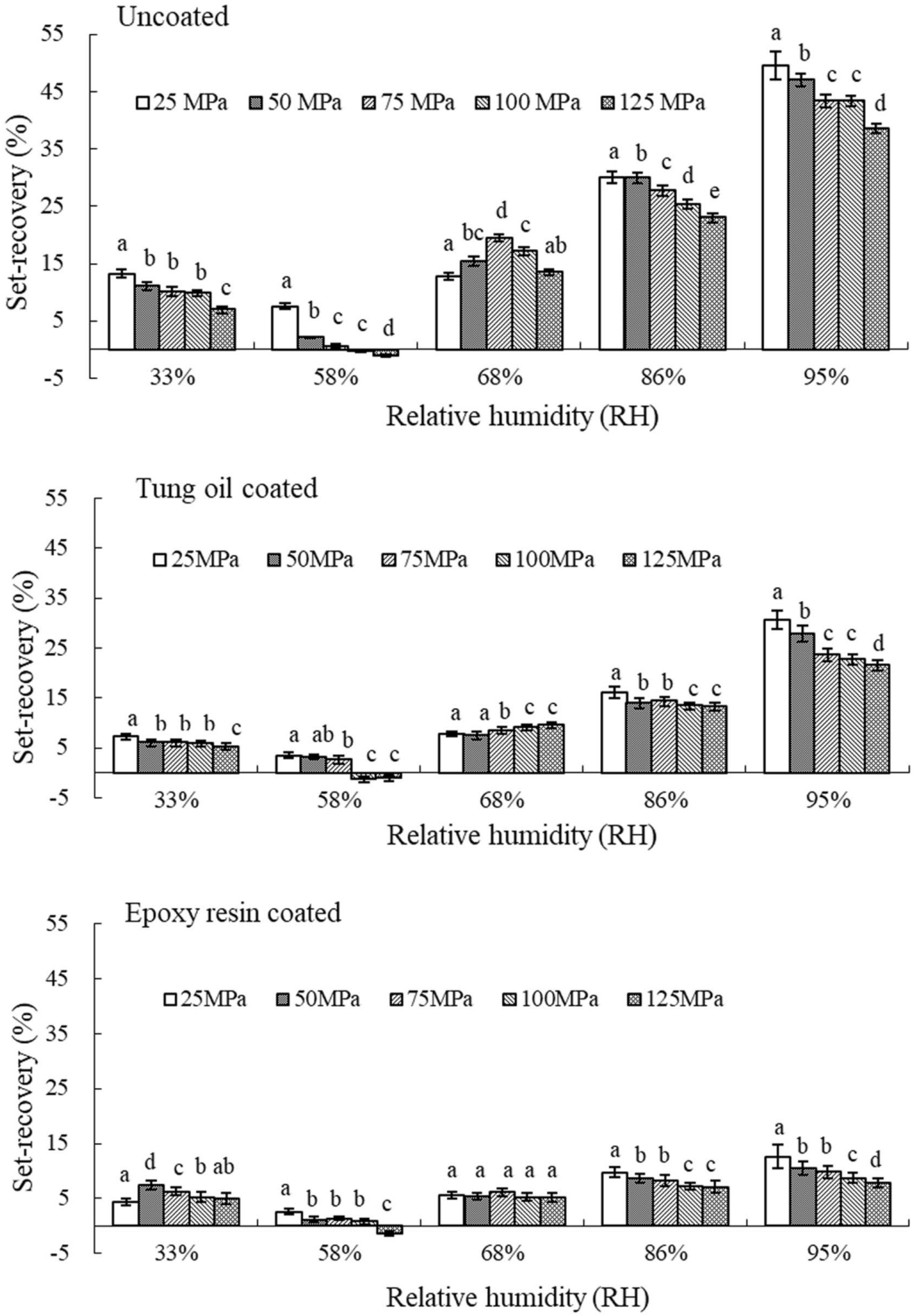

Fig. 7 Average set-recovery (%) of uncoated treated, TO-coated treated and ER-coated treated wood samples under different RH environments at 25 °C (error bars present standard deviations, and letters mean significantly different levels at $p = 0.05$)

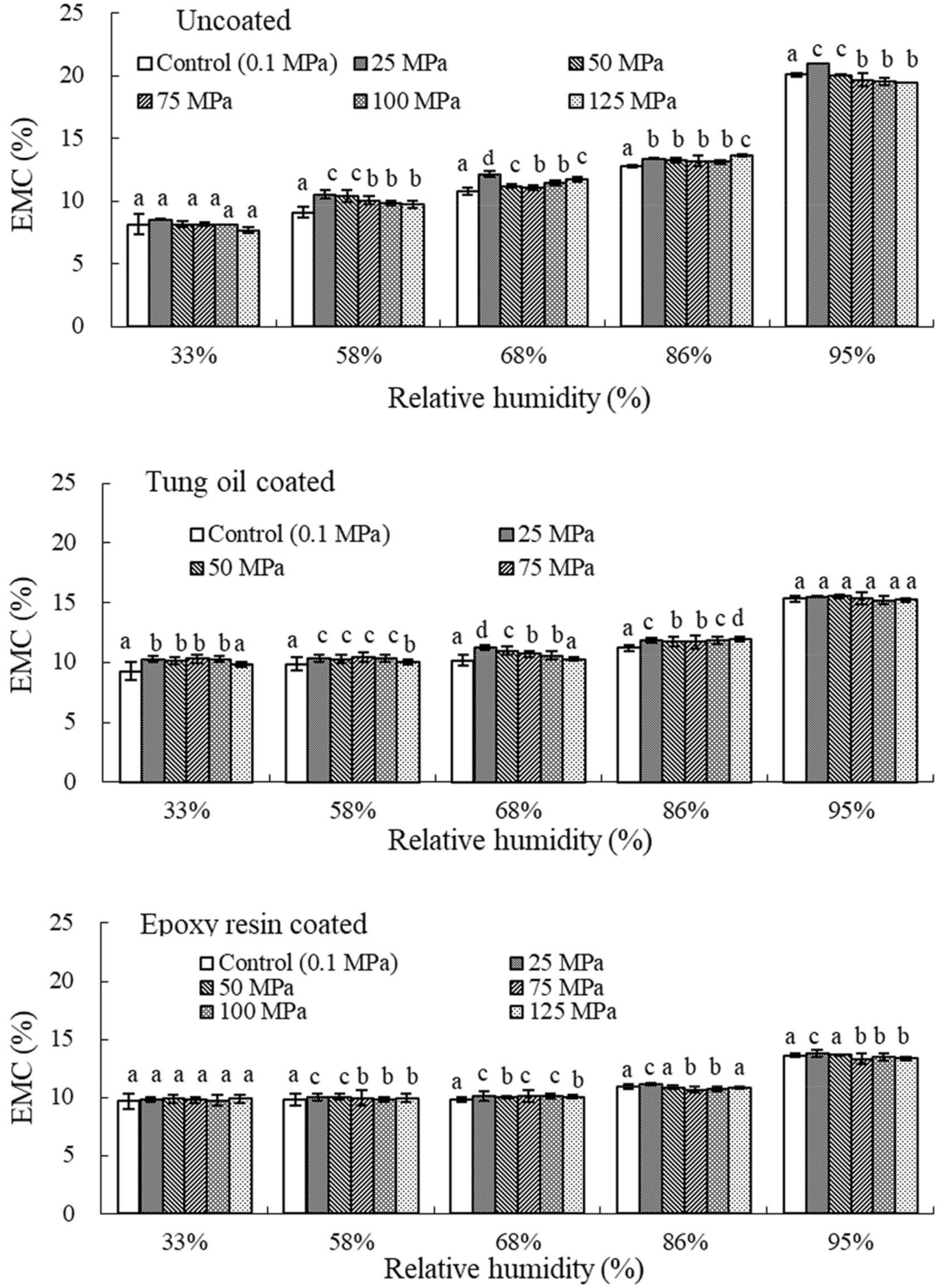

Fig. 8 EMC of uncoated treated, TO-coated treated and ER-coated treated wood samples under different RH environments at 25 °C (error bars present standard deviations, and letters mean significantly different levels at $p = 0.05$)

Preventing moisture absorption/desorption could significantly improve dimensional stability of HP-densified wood. In this study, hydrophobic coating treatments although cannot totally prevent moisture absorption, could be an alternative method, which could dramatically improve dimensional stability of HP-densified wood in high air humidity.

A few theories could explain the phenomenon of set-recovery of densified wood. For example, during traditional hot-plate compression, the crystalline regions of the microfibrils are mainly deformed affecting its elasticity (but also plastically under very high forces). The elastic strain energy is stored in the cellulose macromolecules, and the release of this energy causes high set-recovery [7], while in HP densification method, plastic compressive strain occurred predominately, and delayed elastic strain of densified wood was very small. Moisture/water adsorption plays a dominant role in thickness swelling and set-recovery of HP-densified wood. Hydrophobic coating methods were preliminarily explored in this research, and the significant effects were indicated. More hydrophobic coating methods need be further explored.

EMC of densified/control poplar wood with uncoated/coated treatments

In order to characterize the effect of HP densification with and without follow-up coating on the hygroscopicity of treated wood, EMC data under various RH environments at 25 °C were measured. As shown in Fig. 8, HP densification of wood without the follow-up coating significantly increased its EMC at 68%, 86% and 95% RH environments as compared with control (EMC, 12–18%), with treated samples showing slightly more moisture pick up than the control. There was no correlation between pressure level and EMC. This may be due to the destruction/disruption of cellular structure during the densification HP densification, making the uptake/evaporate of moisture easier. However, HP-densified wood only had a decrease in EMC when stored at 33% RH (from 12 to 8%), and the difference between treated and untreated was statistically not significant. This obviously results from the moisture loss potential when stored at 33% RH (12% moisture in the samples when equilibrated at about 65% RH at 20 °C).

TO and ER coating of HP-densified wood reduced the moisture pick up from samples when stored at different RH environments. With TO and ER coating, the related moisture had a significant decrease compared to uncoated samples at higher RH environments. In addition, there were lower differences among difference RH environments in the related moisture compared to uncoated samples. For example, with ER coating, the resulting ranges were 9.67–13.6% for control, 9.84–13.8% for 25 MPa, 9.92–13.7% for 50 MPa, 9.81–13.3% for 75 MPa, 9.76–13.5% for 100 MPa and 9.91–13.4% for 125 MPa HP-densified wood, respectively. Data therefore demonstrate lower differences in moisture change between test samples. HP-densified wood with ER-coated treatments illustrated best water resistance. Combined with set-recovery effects, an obvious advantage of coated treatments on improving dimensional stability of HP-densified wood was found.

Conclusions

In the present study, the potential of high pressure treatment as an alternative rapid densification method of poplar wood and its combination with TO or ER-coated treatment to improve dimensional stability of densified wood in high air humidity environments were demonstrated. The HP densification treatment could increase the wood density from 450 ± 50 kg/m^3 to 960 ± 20 kg/m^3 for 30 s holding time, the density increasing pressure up to 125 MPa pressure level. The density parameter was well correlated with pressure level. Hardness of the densified wood was significantly increased due to densification, which again depended on pressure with a magnitude increase of 35% at 25 MPa to 96% at 125 MPa, compared to untreated wood. For uncoated treatments, set-recovery of densified wood changed minimally at 58% RH, but increased when stored at 33%, 68%, 86% and 95% RH. TO and ER-coated treatments showed similar trend with uncoated treatments, but significantly reduced set-recovery in 33% RH, 68% RH, 85% RH and 95% RH. Coated treatments indicated good anti-swelling properties, while ER-coated treatment was better than TO. The results provided a reference for development of HP densification combining with hydrophobic coating methods to increase softwood value in wood industry.

Abbreviations

TO: Tung oil; ER: Epoxy resin; HP: High pressure; EMC: Equilibrium moisture content; CR: Compression ratio; RH: Relative humidity.

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Authors' contributions

YY, HL, and AL designed the study. HL conducted high pressure treatment on densification of poplar sapwood boards, and was a major contributor in writing the manuscript. YY and AL conducted tung oil and epoxy resin-coated treatments on densified samples and subsequent data analysis.KY performed Image drawing and analysis.SZ and HSR contributed to writing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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