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Preparation of hydro-thermal surface-densified plywood inspired by the stiffness difference in "sandwich structure" of wood

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HIGHLIGHTS

- Surface-densified plywood was manufactured inspired by "sandwich structure" of wood.
- Much surface densification was obtained at greater temperatures or moisture contents.
- Mechanical properties of surface-densified plywood were significantly enhanced.

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ABSTRACT

Inspired by stiffness difference in the "sandwich structure" of earlywood and latewood, surface-densified (SD) plywood was manufactured based on a hydro-thermal approach. A series of veneer moisture contents (MCs) and hot-pressing temperatures were selected to prepare the SD plywood. Great surface densification was observed according to density distribution through plywood thickness. The densification was attributed to the thermal softening and mechano-sorptive behavior of constituents in the wood cell wall. A greater degree of surface densification could be achieved at higher hot-pressing temperatures or higher surface veneer MCs. Final MCs of the SD plywood met the requirement of the Chinese national standard. No significant variation was observed for the bonding strength among SD and control (CK) plywood. Mechanical properties – including modulus of rupture (MOR), modulus of elasticity (MOE) and hardness – of the SD plywood were significantly higher than the CK plywood. The enhancements of MOR, MOE and hardness could be attributed to its high-density surfaces. The greatest increment of MOR, MOE and hardness was 54, 104 and 144%, respectively. Comparing to some domestic Chinese hardwood species, SD plywood possessed greater surface hardness with less average density. The results indicated that, inspired by the stiffness difference in the "sandwich structure" of wood, preparation of the SD plywood based upon hydro-thermal treatment is feasible.

1. Introduction

As a sustainable resource, plantation accounts for a large part of the worldwide wood demand. The common plantation species in China are poplar (*Populus* spp.) and Chinese fir (*Cunninghamia lanceolata*). The average air-dried densities of these plantation woods are less than 0.4 g/cm^3. Consequently, their mechanical properties are weak. According to previous studies [3], the modulus of rupture (MOR) and modulus of elasticity (MOE) of both poplar and Chinese fir are less than 60 and 8000 MPa, respectively. The mechanical properties of these plantation woods were not qualified for construction and engineering uses. For better utilization of the wood resources, increasing their density and mechanical properties has become necessary [28,11,48].

Thermal-hydro-mechanical (THM) treatment is an effective approach for enhancing mechanical properties of wood and its products [10,12,17,7,8]. Generally, mechanical properties of wood are correlated with its density (i.e., high-density wood has greater mechanical properties than low-density wood) [4,39]. Compressing wood in the transverse direction could reduce void volume of lumens and increase the wood density [42]. Prior to the densification process, the wood substance should experience a softening

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stage. The softening stage is most often carried out by increasing the ambient temperature and/or wood moisture content (MC). As temperature or MC increases, a decrease in stiffness and an increase in damping could be observed [49,47]. After being softened, wood cells can be compressed transversely by more than 50% without damage [34].

The compressing performance of wood is influenced by anatomical characteristics besides temperature and MC. As an anisotropic material, wood has different properties in three main directions: longitudinal (L), radial (R) and tangential (T). In the R and T directions, wood is relatively soft and weak. Compressive strength and modulus in transverse directions (R and T) are one order less than that in L direction.

For some softwoods and ring porous hardwoods, the compressive stress-strain curve in the radial direction could be illustrated as shown in Fig. 1a. In the radial direction, the thin-walled earlywood cells would be compressed and densified prior to the deformation of thicker-walled latewood cells (Fig. 1b). This compressive behavior implies that: when a laminated composite is being compressed, the lower-stiffness layer would be densified prior to the deformation of higher-stiffness layer.

Veneer-based composites are a series of typical lamination materials, such as plywood and laminated veneer lumber [5,6,9]. A common method for manufacturing plywood is by first assembling veneers into a mat, and then hot-pressing this mat into a plywood. The compression ratio of each veneer in the plywood is nearly identical. Based on the radial compression behavior as shown in Fig. 1, it is reasonable to assume that: if veneers have different stiffness in a mat, the compression ratio of low-stiffness veneers would be greater than that of high-stiffness veneers. When the low-stiffness veneers are placed in the surface of the mat, a great extent of surface layer compression could be achieved. Greater compression at the surface could enhance the mechanical properties of plywood: after all, the mechanical properties of laminated materials are closely related to the properties of surface layers [2,19,46].

Softening intrinsic of wood under hydrothermal conditions provides the possibility for reducing its stiffness. Theoretically, when high- and low-MC veneers are placed in the surface and core, respectively of the mat, and surface-densified (SD) plywood could be obtained after hot-pressing. In this study, the feasibility of the hydro-thermal approach for manufacturing SD plywood was verified. A series of hot-pressing temperatures and veneer MCs were selected for analyzing the softening influence on surface densification extent. In addition, the mechanical properties of SD plywood were tested.

2. Materials and methods

2.1. Materials

Poplar veneers were obtained from the north area of Henan Province, China. The dimensions were $360 \times 360 \times 1.8\ mm^3$ and the MC was ~12%. Phenol formaldehyde (PF) resin with a solid content of 45% (formaldehyde/phenol ratio = 2:1) was synthesized in the laboratory.

Prior to the preparation of plywood, the veneers were divided into 6 groups for moisture conditioning. The veneers were first dried to an oven-dried state, and then sprayed with distilled water on both sides alternately at room temperature (~25 °C). The mass of the sprayed water was calculated at 5, 10, 15, 20, 25 and 30%, respectively to the mass of oven-dried veneer in each group. After the water spraying process, the veneers in each group were stacked for 48 h, and covered with polyethylene film. The purpose of stacking was to obtain uniform distribution of water within and among veneers before any mold or decay could appear.

2.2. Moisture distribution of veneer

Before manufacturing plywood, the moisture distribution of veneer was tested. The testing veneer was cut into 9 pieces (Supplementary Fig. S1). These pieces were then oven-dried at 103 ± 2 °C. For the calculation of the MC of each piece (Eq. (1)), the mass of the pieces was weighed before (M_w) and after being oven-dried (M_0):

$$MC = \frac{M_w - M_0}{M_0} \times 100\% \quad (1)$$

Five veneers were randomly selected in each MC level. The MCs of 45 pieces in each level were obtained for evaluating the uniformity of water distribution.

2.3. Manufacturing of plywood

Seven-plies of veneers were assembled into an SD plywood with the PF resin amount of 200 g/m^2 applied on a single face. A series of pressing temperatures (140, 150 or 160 °C) and veneer MCs (5, 10, 15, 20 25 or 30%) were selected for manufacturing the plywood (see Table 1). The schematic of top- and bottom-surface veneer, and core veneers in plywood are illustrated in Fig. 2. All of the SD plywood was hot-pressed at 1.5 MPa, and the compression ratio was 38%. The final thickness was 7.8 mm, and was achieved by using a gauge bar with a same thickness. Hot-pressing time was 1 min for each millimeter.

For comparing the SD performances, a control check (CK) plywood sample was prepared as well. Seven-plies of veneers with

Table 1
Technique parameters for manufacturing the surface-densified (SD) plywood.

Hot-pressing temperature (°C)	Moisture content	
	Top- or bottom-surface veneers (%)	Core veneers (%)
140, 150, 160	10, 15, 20, 25, 30	5

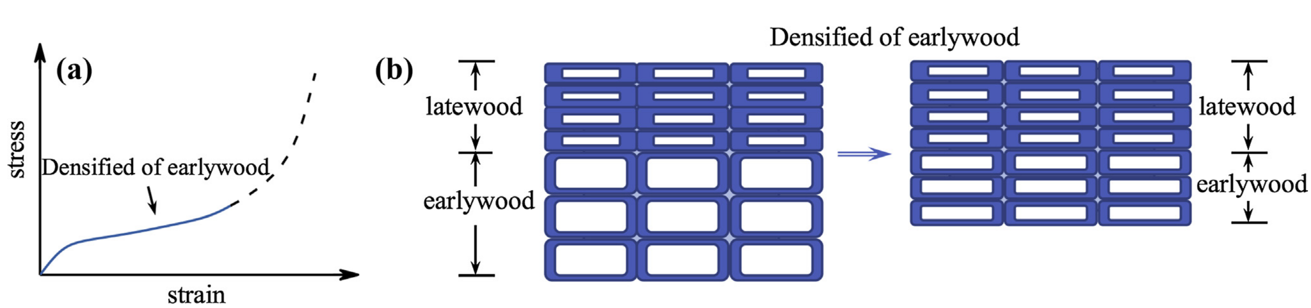

Fig. 1. A typical stress-strain curve of wood (a) and the schematic of earlywood and latewood deformation (b) during radial compression.