VERTICAL COMPRESSION RATE PROFILE AND DIMENSIONAL STABILITY OF SURFACE-DENSIFIED PLANTATION POPLAR WOOD

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Hot-pressing densification is nowadays widely applied to modify plantation wood. In this study, plantation poplar wood lumbers, 300 mm by 50 mm by 10 mm, respectively, in longitudinal, tangential, and radial directions, were surface-densified at 125 ^{o}C for 2, 3, and 5 minutes, with or without water addition on the surface of lumbers. The pressure was 1 MPa. The vertical compression rate profile (VCRP) in thickness direction of densified specimens was acquired through an X-ray densitometer combined with a mathematical model. In addition, the time-related springback rate (*S*) of densified specimens was recorded. It was shown that all specimens were compressed by 9.38 to 14.10% on average in the thickness direction, and *CR* values decreased from surface to core of specimens, resulting in U-shaped VCRP curves. The surface layers had the maximum *CRs* of 33.45 to 37.24%, while 21 to 53% of the whole thickness at core position showed no significant residual compression (*CRs* lower than 1%). After conditioning at room temperature and 65% relative humidity for 240 hours, all the specimens were shown to be dimensionally stable with *S* values under 2%. Water addition on the specimen surface helps densify the surface layers and stabilize the densified wood. The acquired data and results were thought to be helpful for the precisely control of wood loss in a densification process.

Keywords: Poplar wood; Densification; Compression rate; Springback

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INTRODUCTION

Plantation wood is increasingly utilized worldwide as an alternative for naturally grown wood species especially in forest-limited countries or regions, *e.g.*, the P.R. of China. Currently, existing plantation forests in China account for nearly 62 million hectares with growing stock about 1.96 billion cubic meters, which is equivalent to nearly 12% of the total forests in this country (CSFA 2008). However, plantation wood is generally characterized with low strength, low hardness, and serious moisture-related warping tendency. These shortages limited the direct use of plantation wood in many applications such as constructions, floorings, *etc*.

Densification has been shown to be an effective way to modify plantation wood in numerous studies, which could be dated back to a patent at the beginning of the 20th century (Kollmann *et al*. 1975). Subsequently, considerable research achievements continued to appear (Inoue *et al*. 1990, 1993; Navi and Girardet 2000; Blomberg and

Persson 2004; Kamke and Sizemore 2005; Kutnar *et al.* 2009; Gong *et al*. 2010; Candan *et al*. 2010; Anshari *et al*. 2011). In these studies, improved processes were developed to prevent springback of densified wood. One crucial point is to use steaming or simple heating method to fully plasticize the wood, and then the wood was mechanically compressed without significant fracture or destroying of cell walls. This process, termed as "themo-hydro-mechanical treatment (THM)" (Navi and Girardet 2000; Diouf *et al.* 2011) or similarly as "viscoelastic thermal compression (VTC)" (Kamke and Sizemore 2005; Kutnar *et al*. 2009), is dependent on the visco-elasticity of wood itself, and was demonstrated to be effective in control of densification recovery. As well, other methods to stabilize densified wood, such as resin impregnation (Fukuta *et al*. 2008), oil-bathing (Fang and Cloutier 2011), *etc*., were experimentarily developed.

For some cases, wood densification needs to be transmitted along a complete wood block, *i.e*., wood was compressed not only at positions close to surfaces but far into the core part, termed herein as "whole densification". In these cases, the thickness of the wood specimens to be densified was relatively limited. As an example, specimens used in Kutnar's (2009) research were 4, 5, and 6 mm in thickness compressed to 2.5 mm with compression rate (*CR*) at 63%, 98%, and 132%, respectively. More work was actually conducted to densify veneers (Wang *et al*. 2006; Fang and Cloutier 2011; Diouf *et al.* 2011). Correspondingly, the general compression rate of wood was relatively high, and the densified wood is more liable to spring back (Fukuta *et al.* 2008; Kutnar *et al*. 2009; Anshari *et al*. 2011).

In other cases, however, only the two surface layers (or merely the upward surface layer) of plantation lumbers need enhancing, *e.g*., for flooring. Consequently, the product has a stiff and strong surface bearing routine abrasion, stepping, long-term static loads (*e.g*., tables, chairs) and occasional impact loads (*e.g*., cup falling). The core part maintains low-density and porous and the product as a whole may provide stepping comfortability, heat insulation, low recovery rate, and low wood volume loss. To differentiate, this process is termed as "surface densification", which can be applied onto wood lumbers of any thickness (Inoue *et al.* 1990; Gong *et al*. 2010) .

Poplar (*Populus deltoids Bartr. cv. 'Lux'*) was first imported into China from Italy in 1972, and was successfully propagated in south China (Tang and Li 1983). In the last two decades, poplar wood became the overwhelming raw materials for manufacture of composition panels, *i.e*., plywood, particleboard, and fiberboard. Recently, however, some pilot plants started production of solid wood floorings with poplar wood without any modifications. Consequently, considerable products showed quality defects in applications, such as warping, imprints, *etc*. Hence, with the financial support from a local government project (Grant. No. BC 2009476, Jiangsu province, China), the objectives of this study were to preliminarily establish the quick surface densification process of poplar wood flooring substrate and to evaluate the springback tendency of densified wood. An X-ray densitometer was used to acquire the *in-situ* density data following Kutnar's work (2009) and the density data were then converted to *CR* values following a simple mathematical equation. When many parts of this world are facing the challege of natural wood shortage, this work may be helpful for the industrial utilization of densified plantation wood.

EXPERIMENTAL

Materials

Poplar wood lumbers, 300mm (longitudinal direction) by 50 mm (tangential direction) by 10 mm (radial direction), were randomly sampled from a pilot plant (Dewei Wood Works Co.Ltd), Siyang county, Jiangsu province. All lumbers were tangentially sawn by a band saw from logs (diameter over 35 cm at breast height) locally produced from a plantation forest (east longitude: 118^{o}20'~118^{o}45'; north latitude: 33^{o}23'~33^{o}58'). The fresh lumbers were then dried at a steam-heated industrial kiln for 6 days to final moisture content of approximately 10%. During drying, the adjacent lumbers were cross-piled to prevent warping deformations. The dried lumbers were then moved to a laboratory of Nanjing Forestry University for surface densification.

Methods

Surface densification

The poplar lumbers were densified following technical parameters shown in Table 1 with a 600 mm by 600 mm lab-scale hotpress. The hot-pressing parameters, *i.e.*, temperature, time, and pressure, were designed as 125 ^{o}C, 2 to 5 minutes, and 1 MPa, similar to the conditions reported in Gong's study (2010). The temperature of press platens was designated at 125 ^{o}C for three reasons: (1) merely the surface layers of a specimen need full heating, not the core; (2) the temperature level is high enough to vaporize the liquid water in the surface layers of a specimen; and (3) too high temperature may blacken or carbonize the surface of poplar wood (Diouf *et al*. 2011), which may lead to an unfavorable appearance. Under the pressure of 1 MPa, wood volume loss (or compression rate) can be controlled lower than 15%. Following Table 1, a short-term, low-presure and moderate-temperature densification process was established, so as to satisfy the industrial requirements of high-productivity, low energy consumption and low wood volume loss.

To improve the plasticization of specimens following the THM (Navi and Girardet 2000) or VTC (Kamke *et al.* 2005; Kutnar *et al.* 2009) procedures, ten grams of distilled water was sprayed on the surface of each lumber for conditions B, D, and F (to compare with conditions A, C and E, respectively), with a hand-sprayer. The water added was thought to be fully vaporized at 125 ^{o}C during hot pressing and help plasticize the wood issues in surface layer, which is beneficial to fix the densification. To avoid surface contamination during densification, all specimens were wrapped with thin aluminum sheets.

Table 1. Technical Parameters of Poplar Specimens Densification *

No.	Temperature(^{o}C)	Time(min)	Pressure(MPa)	Surface water addition
A	125	2	1	No
B	125	2	1	10 grams
C	125	3	1	No
D	125	3	1	10 grams
E	125	5	1	No
F	125	5	1	10 grams

* Every condition was conducted with 2 repetitions.

Average compression rate

The densified wood lumbers were released from the hotpress and naturally cooled down to room temperature. Small specimens of 50 mm by 50 mm were cut from every densified lumber. The average compression rate (*ACR*) of a specimen was calculated as follows,

$$ACR(\%) = \frac{h_0 - h_1}{h_0} \times 100 \;............(1)$$

where, h_0 and h_1 were the thickness of a densified specimen at the center point before and after densification. For every densification condition, ten specimens were measured to get the mean *ACR* value.

Vertical compression rate profile (VCRP)

The *ACR* value calculated following formula (1) stands for the general compression of a specimen in the whole thickness range, but it fails to tell the actual compression rate of every microlayers. In this study, an X-ray densitometer (Dense-lab, EWS corporation, Germany) was used to scan the densified specimens with the scanning step length of 0.05mm (*i.e.*, a 10 mm thick specimen was divided into 200 microlayers). The acquired density data of individual microlayers were induced to an EXCEL software (Edition 2003, Microsoft corporation) for conversion to compression rate values following equation (6) (see below the mathematical deduction procedures).

As shown in Fig.1, with a poplar wood specimen compressed from thickness H_0 (a) to H_1(b), the thickness of the microlayer at Z decreases accordingly from $\triangle Z_0$ to $\triangle Z_1$. Hence, the compression rate of the microlayer (*mCR*) at Z is:

$$mCR(\%) = \frac{\Delta Z_0 - \Delta Z_1}{\Delta Z_0} \times 100 = (1 - \frac{\Delta Z_1}{\Delta Z_0}) \times 100 \;............(2)$$

The density of the microlayer before and after compression are respectively:

$$\rho_0 = \frac{\Delta m_0}{L_0 * W_0 * \Delta Z_0} \;............(3) \text{ and}$$

$$\rho_1 = \frac{\Delta m_1}{L_1 * W_1 * \Delta Z_1} \;............(4)$$

where, L_0, W_0 and L_1, W_1 are the length and width, while $\triangle m_0$ and $\triangle m_1$ are the mass of the control and densified microlayer, respectively. Evidently, $\triangle m_0$ is equal to $\triangle m_1$. Combination of equations (2), (3), and (4) gives:

$$mCR(\%) = (1 - \frac{L_0 * W_0 * \rho_0}{L_1 * W_1 * \rho_1}) \times 100 \;............(5)$$

Following a short-term and low-pressure densification process, the in-plane dimension change of the microlayer was acceptablely ignorable (Anshari *et al*. 2011), *i.e.*, $L_0 \approx L_1$, $W_0 \approx W_1$, so equation (5) may be simplified as：

$$mCR(\%) \approx (1 - \frac{\rho_0}{\rho_1}) \times 100 \;............(6)$$

So, following equation (6), the change of density of a microlayer from ρ_0 to ρ_1 can be converted to compression rate *mCR*.

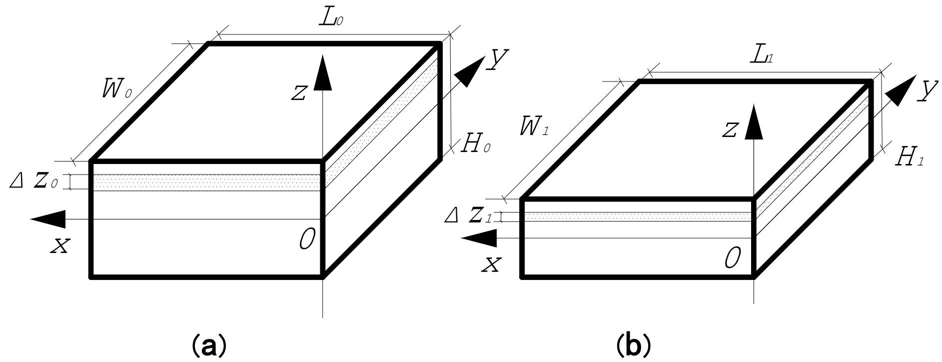

Fig.1 Schematic diagrams of wood specimens before (a) and after (b) densification

Note: Taking the core plane at 1/2 thickness as the X-Y plane, and thickness direction as the Z axis. It's assumed that the wood specimen was symmetric in thickness referred to the X-Y plane. To analyze the compression rate at Z, an exemplified micro-layer ΔZ was made.

Springback rate

The testing methods of densification springback rate were varied based on the literature (Kutnar *et al*. 2008; Gong *et al*. 2010; Anshari *et al.* 2011). Typically, wood specimens were placed in closed devices under preset conditions (relative humidity-RH, temperature) for specified durations. In this study, wood specimens were conditioned at 20℃ and 65% RH for 240 hours in a closed dessicator. The springback rate at time t (S_t) was calculated following equation (7), where h_1 and h_t were the thickness of a densified specimen at center point conditioned for time t. For each condition (A to F, see in Table 1), ten densified specimens were measured to acquire the average S_t value.

$$S_t(\%) = \frac{h_t - h_1}{h_1} \times 100 \text{............(7)}$$

RESULTS AND DISCUSSION

Average Sompression Rate of Specimens after Densification

Table 2 presents the average compression rates of all densified poplar wood specimens released from a hotpress. Under 1 MPa of pressure for 2 to 5 minutes, poplar wood specimens were compressed by 9.38% to 14.10% in thickness. In other words, wood volume decreased by about 9% to 14%, which is somewhat acceptable by solid flooring industries. Hence, following a process of short term, relatively low temperature, and low pressure, the original objective of wood "surface densification" was perfectly achieved.

The degree of wood compression in a densification process depends on many factors including wood species, densifying parameters (*i.e*., temperature, pressure, and time) and procedures (*e.g*., VTC process, Kamke and Sizemore 2005; Kutnar *et al*. 2009), wood moisture content and distribution, wood-preheating conditions, etc. Consequently, the compression rates listed in Table 2 may be significantly various for varied wood species under changed processing conditions. For a designated wood species, however, temperature and moisture content are by far the two most critical factors related to the morphological change of lignin and hemicellulose. As two main components of wood, lignin and hemicellulose may be rigid and stable, or soft, viscous, or even slightly flowable at changed ambient temperatures. In a THM or VTC process, wood specimens are originally cool, then heated up, and cooled down again. Although no significant chemical changes take place in such a short-term heating and cooling process (Rautkari *et al.* 2010; Diouf *et al.* 2011), the heated and softened lignin and hemicellulose may help plasticize and reshape wood specimens, and later reversely help fix densification when cool down and recover their rigidity. This active role played by lignin and hemiculose in densified wood production can also be theoretically justified by literatures (Gindl 2001; Furuta *et al.* 2010). Generally, higher content of moisture decreases the glass transition point (*Tg*) of lignin and hemicellulose, and further improves the above thermal-softening process (Lenth and Kamke 2001).

From Table 2, it's interesting to see that *ACR* values of specimens treated under conditions B, D, and F (with surface water addition) were overwhelmingly lower than those for conditions A, C, and E (without surface water addition). It's evident that, during such a short-term process, the added water helps densify the wood issues in surface layers while delays the densification of inner part of wood. Hence, the higher moisture content of surface layers did play an active role for "surface densification".

Table 2. Average Compression Rate of Poplar Wood under Various Processing Conditions- %

A	B	C	D	E	F
13.55(3.14*)	9.38(2.27)	14.10(2.44)	12.15(2.29)	12.95(2.72)	10.98(2.27)

* Values in parentheses are standard deviation values for 10 repetitions.

Vertical Compression Rate Profile

The THM or VTC densification changes the vertical density profile (VDP) of wood specimens (Wang and Cooper 2005). Undensified wood exhibits slightly varying density through its thickness, while compressed wood has an M-shaped density gradient. The degree of density difference and the shape of the VDP curves are closely dependent on the densification procedures (Kutnar *et al.* 2009). Similarly, the compression rate through the thickness of a poplar wood specimen is also unevenly distributed in our study (Fig.2). To simplify, Fig. 2 merely shows half the nealy symetric VCRP curves. The *mCRs* of specimen surface layers were about 33 to 37%, which is equivalent to the *ACR* values for "whole densification" process (Diouf *et al.* 2011). Accordingly, wood density in surface layers reached about 0.8 g/cm^3, which is equivalent to some naturally grown wood species. Therefore, the purpose of "surface densification" was satisfied. In contrast, no significant residual compression was detected by the X-ray densitometer in the core remaining its initial density level. Taking *mCR*=1% as a critical value to judge, specimens densified under six conditions showed about 21~53% of thickness in the core region without evident densification. Consequently, two high-*CR* surface regions plus a low-*CR* core result in a U-shaped VCRP curve.

From Fig.2, it can also be found that poplar lumbers with water addition (see in Table 1: conditions B, D, F) showed different surface-to-core compression behaviors from those treated under A, C, and E conditions. Specimens with water addition on surface during hot-pressing had a broader low-*CR* core. Hence, water addition is beneficial for the discrepant densification through specimen thickness. In many former researches, wood specimens to be densified were pre-humidified by steaming or water-bathing (Kutnar *et al.* 2009; Furuta *et al.* 2010; Diouf *et al.* 2011). These processes undoutedly prolonged the whole densification duration. To compare, a simple and quick water spraying method used in this study seems more fit for a short-term surface densification, where water vaporing and wood compressing happen in a single hotpress simultaneously.

So far, the action mechanism of water added on specimen surface in this study is still not completely clear, since it’s invisible and difficult to track within a thin layer. It’s speculated that the water must experience the following steps: heat uptake, temperature rising, vaporizing, and diffusion inwards. The surface layers of wood specimens are gradually plasticized and become denser, which prevents effective penetration of the vapor into the inner part of specimens. This process is theoretically similar to what a wood particle or fiber matrix behaves during hot-pressing (Wolcott *et al*. 1990, 1994). Consequently, only the surface layers were effectively densified resulting in a VCRP curve with one broad valley at the core (Fig.2).

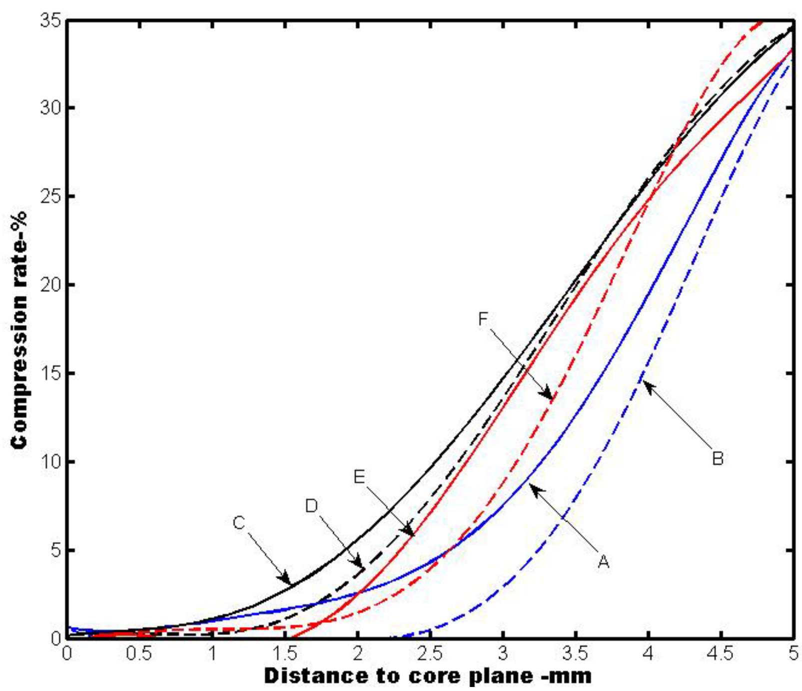

Fig. 2. Compression rate as a function of the distance to core plane in half thickness of specimens

Springback after densification

Figure 3 indicates the springback tendency of densified specimens under six conditions. The first 24 hours saw a quick recovering tendency and then the springback of compression gradually slowed down. This process is much shorter than the springback in those "whole densification" situations, since merely the surface part of wood was actually densified. After about 200 hours, specimens seem to be stable, with a steady springback rate lower than 2%. Although no universal standards are currently available to judge the degree of springback rate, since wood species and specimen dimensions, densifying procedures, and springback testing methods, etc., vary significantly (Kutnar *et al.* 2008; Gong *et al*. 2010; Anshari *et al.* 2011). However, the springback rates measured in this study were somewhat acceptable.

The springback of densified wood can be controlled by various methods (Fukuta *et al.* 2008; Fang and Cloutier 2011). Water addition was proven to be another way helping fix the compression (Fig. 3, with dashed lines). After 10 days of conditioning, the springback rates of poplar wood specimens under B, D, and F conditions were evidently lower that those for A, C, and E. This is mainly attributed to the smaller initial average compression rates (Table 2). In addition, relatively longer pressing time gave lower springback rates (Fig.3). In this study, a short-term process was used, *i.e*., pressing time was controlled among 2 to 5 minutes. Correspondingly, conditions A and B (2min) showed higher springback values than C/D (3min) and E/F(5min) conditions, while the latter two couples had similar results. It's, therefore, thought that 3 minutes of surface densification for fast-grown poplar wood was industrially suitable.

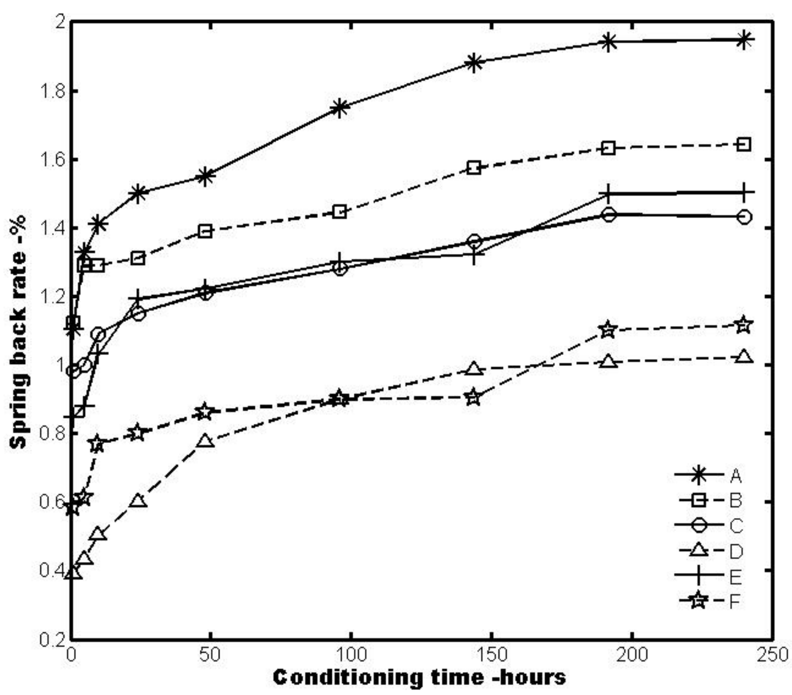

Fig. 3. Spring-back rate after conditioning at room temperature of densified poplar wood specimens

CONCLUSIONS

1. The surface densified poplar wood had gradually decreased compression rate from surface to core forming a U-shaped vertical compression rate profile. Following a short-term and low-temperature treating process, poplar wood specimens were effectively densified in surface layers, with compression rates up to 33.45 to 37.24%, and remained original density in the core accounting for 21 to 53% of the whole thickness.
2. An X-ray densitometer combined with a data converting mathematical model was shown to be an effective tool to quantitatively acquire the vertical compression rate of the surface densified wood.
3. Spraying water onto wood can help densify and fix the surface layers of lumbers, while decreases the loss of wood volume by densification.
4. The surface densified poplar wood by hot-pressing combined with water addition was demonstrated to be dimensionally stable in air environment.

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