Preparation and Characterization of Combed Sawmill Slab Residues from Chinese Fir and its Scrimber

Chungui Du,[a,b,]* Xiaoling Yao,[a] Yating Hua,[a] and Qiuli Huang [a]

To effectively utilize sawmill slab residues, self-manufactured combing equipment was used to transform residues into individual bundle sticks. The scrimber was prepared from Chinese fir by hot pressing the resulting bundle sticks. In this study, the combing process and effects of density on the mechanical and physical properties of the scrimber were investigated. The morphology of the scrimber was tested with computed tomography. The results showed that a rotary speed of 120 rpm for the coarse roller and a rotary speed of 360 rpm for the fine roller combed along the grain were the optimum combing parameters to prepare a uniform individual bundle of sticks. The moisture content of the feeding sawmill residues was above 30%. The scrimber prepared *via* bundle sticks is a new type of structural scrimber, and the density of the scrimber influenced the physical and mechanical properties. As the scrimber density increased, the modulus of rupture, modulus of elasticity, and internal bond gradually increased, while the 24-h thickness swell decreased. The studied method enhanced the density and improved the physical and mechanical properties. The striped structural characteristic of the scrimber was evident, and the density distribution varied for different faults.

Keywords: Sawmill slab residues; Chinese fir; Combing processing; Wood bundle sticks; Scrimber; Properties; Computed tomography (CT)

Contact information: a: School of Engineering, Zhejiang A&F University, Lin'an 311300, China; b: National Engineering and Technology Research Center of Wood-based Resources Comprehensive Utilization, Lin'an, Hangzhou, Zhejiang Province, 311300, China;
** Corresponding author: chunguidu@163.com*

INTRODUCTION

Chinese fir is a softwood with the largest cultivated area and softwood yield in China (Sheng 2018). A considerable number of small-diameter logs has been used in the core-board for blockboards and glulams. However, the resulting sawmill slab residues are often wasted, which has consequently decreased Chinese fir utilization, and there is not a current way to efficiently utilize these residues. Few researchers have explored the utilization of sawmill slab residues from Chinese fir (Jin *et al.* 2003; Liu *et al.* 2005; Du *et al.* 2008a,b; Zhou *et al.* 2012). A new method developed through this research used a combing process to enhance the utilization efficiency of the sawmill slab residues. Feedstocks were combed into wood bundle sticks after the residues were compressed into a net feedstock. The wood bundle sticks had a noticeable structural difference when compared with veneers in plywood, fibers in fiberboard, and flakes in particleboard (Jin and Ma 1998; Mei *et al.* 2012; Zhang *et al.* 2012; Zhou *et al.* 2012). This was considered to be a new type of unit in wood-based panels.

Scrimber, which consists of wood bundles with a network structure, provides a new approach to improve wood utilization (Jin and Ma 1998; Shang *et al.* 1998). However, technological barriers such as the need for specialized equipment, the wood bundle drying process, and orientation matting, have led to the failure of scrimber industrialization (Ma 2011; Yu and Yu 2013). Among them, the irregularities of the network structure and the large size differences of the network wood bundles appear to be the main reasons that interfered with unit operations in industrialized production, such as the drying process, gluing, and forming. Therefore, in the present work, Chinese fir sawmill slab residues were combed into the single wood bundle sticks, and prepared the scrimber by using them as the component units. These steps addressed problems associated with the network-like character of wood bundles. Recently, researchers have specifically focused on scrimber (Zhao and Zhao 2006; Wu *et al.* 2014; He *et al*. 2016; Zhang *et al.* 2016, 2018), while little work has focused on the preparation of scrimber *via* sawmill slab residues. Therefore, this study aimed to investigate the combing process and properties of the Chinese fir sawmill slab residues scrimber, and the morphology was tested by computed tomography (CT). This method has promising potential for scrimber industrialization.

EXPERIMENTAL

Materials

Sawmill slab residues were harvested from the edges of Chinese fir logs (Zhejiang Shenghua Yunfeng new material Co., Ltd, Deqing, China) with a small diameter, the dimensions were 10^3 mm × approximately 40 mm to 55 mm × approximately 10 mm to 25 mm (length × width × thickness), and an arch-shaped cross section (Fig. 1). The moisture content (MCs) of the air-dried residues and as-received residues were 15.3% and 36.1%, respectively. Water-based phenol-formaldehyde resin was purchased from Bamboo Scrimber Flooring Co. (Anji, China) and had a pH of 10.50 and a solids content of 23.7% after dilution.

Fig. 1. Appearance of the Chinese fir sawmill slabs

Methods

Combing process

Figure 2 shows the structural schematic diagram and running mechanism of the combing equipment that was manufactured in the laboratory.

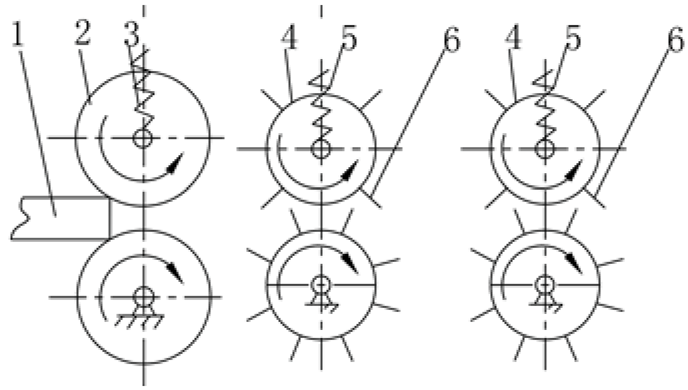


Fig. 2. Structural schematic diagram and running mechanism of the combing equipment: (1) feedstock (sawmill slabs residue), (2) compression rollers, (3) and (5) spring controllers; (4) combing rollers, and (6) combing knives

The essential structure of the combing device consisted of three pairs of rollers, including compression rollers with a shallow groove line, coarse rollers with less distributed combing knifes, and fine rollers with densely distributed knives. These three roller pairs corresponded to the preparation of the raw feedstock, preliminary combing process, and further combing process, respectively. The combing direction included combing along the grain of the Chinese fir (feeding direction was parallel to the clockwise cutting direction), combing against the grain (feeding direction was parallel to the counterclockwise cutting direction), and a combination of both combing methods. The optimum combing process was obtained by controlling the rotary speed of the coarse and fine rollers, calculating the strip yields, and observing the morphology.

Morphology of the bundles

The micro-structural morphology of the wood bundle sticks with MCs of 15.3% and 35.7% was imaged *via* scanning electron microscopy (SEM; SS-550, Shimadzu Co., Kyoto, Japan) with an accelerating voltage of 5 kV and magnification of 1000x.

Preparation and characterization of the scrimber

An optimal combing process was used to prepare bundles with the dimensions 450 mm × 6.9 mm × 3.9 mm (length × width × thickness). The bundles were dried until they reached a MC between 8% and 10%, and were then impregnated with phenol-formaldehyde resin (PF) for 7 min. The resulting bundles were dried until the MC was between 12% and 15% after removing the extra PF. They were then weighed to determine the scrimber densities, which were set to 0.7 g/cm^3, 0.8 g/cm^3, and 0.9 g/cm^3, respectively. The weighed bundles were oriented along the grain in the mold and were hot pressed to prepare the scrimber. After placing the scrimber at room temperature conditions, the thickness swelling (TS; 24 h and 63 °C), modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond (IB) of the scrimber were tested according to the standard GB/T17657-2013(General Administration of Quality Supervision, Inspection and Quarantine 2014). Each set of process conditions was repeated three times, and the properties of six samples were tested, and the average properties were taken.

Test faults structure of the scrimber

The morphology of the scrimber with a density of 0.8 g/cm^3 was tested with a 64 Slice Helical CT machine (TSX-101A, Toshiba Co., Kyoto, Japan). The horizontal (surface, core, and bottom layer) and vertical faults (front, middle, and tail section) of the scrimber were scanned at equal intervals.

RESULTS AND DISCUSSION

Combing Results

Table 1 shows the experimental design, stick yields, and visual observations of the geometric shapes.

Table 1. Combing Processing Design and Results

No.	Coarse Roller		Fine Roller		Stick Yield (%)	Morphology	Running Status
	Speed (rpm)	Cutting Direction	Speed (rpm)	Cutting Direction			
1	60	A	180	R	52	Smooth, uniform widths	Normal
2	60	A	180	R	45	Fluffing, uneven widths	Fine roller blocked
3	60	R	180	A	48	Fluffing, uneven widths	Coarse roller blocked
4	60	A	240	A	64	Smooth, uniform widths	Normal
5	60	A	300	A	75	Smooth, uniform widths	Normal
6	60	A	360	A	82	Smooth, uniform widths	Normal
7	120	A	360	A	91	Smooth, fairly uniform widths	Normal
8	120	A	360	R	86	Fluffing, uneven widths	Fine roller blocked
9	120	R	360	A	84	Fluffing, uneven widths	Coarse roller blocked
10	120	A	480	A	88	Smooth, fairly uniform widths	Normal
11	120	A	600	A	82	Smooth, fairly uniform widths	Normal
12	120	A	720	A	77	Smooth, fairly uniform widths	Normal

A: cut with the grain, R: cut against the grain

The rotary speed of the coarse and fine rollers had a noticeable influence on both the stick yield and morphology. The stick yield increased as the rotary speed increased. Under the conditions of combing along the grain and a coarse roller speed of 60 rpm, the stick yield at a 360-rpm fine roller speed was 30% higher than that at a 180-rpm fine roller speed. Under the conditions of combing with the grain and a 360-rpm fine roller speed, the stick yield increased from 82% to 91% with an increase in the coarse roller speed from 60 rpm to 120 rpm.

Additionally, the enhanced rotary speed of the coarse and fine rollers led to more uniform geometric shapes. As a result, the optimum rotary speeds were 120 rpm and 360 rpm for the coarse and fine rollers, respectively.

The specific morphology of the combed bundles after being cut with the grain and against the grain are shown in Fig. 3.

a b

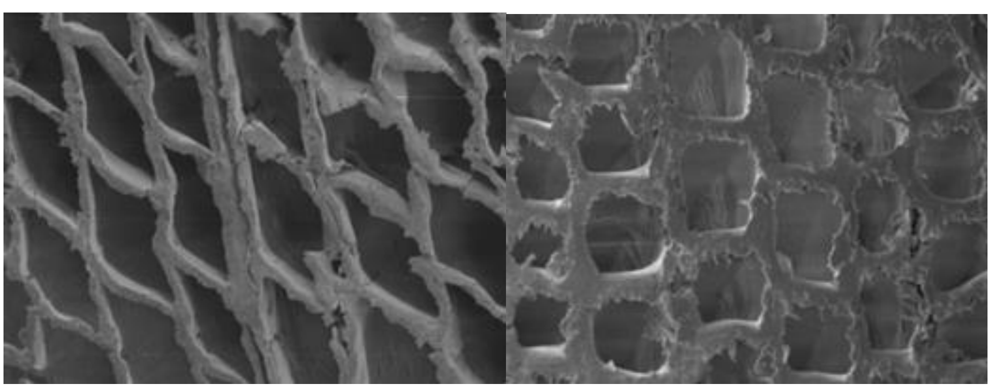
Fig. 3. Geometric shapes of the wood bundle sticks produced *via* the combing process in different directions: (a) combed with the grain and (b) combed against the grain

As is shown in Fig. 3 and Table 1, the combing direction had distinguished effects on the geometric shape of the bundle sticks and running status of the equipment. Combing along the grain resulted in uniform geometric shapes for the bundle sticks and prevented running accidents with the equipment. In contrast, the bundle sticks were prone to fluffing and unevenness in shape when combed against the grain. Therefore, combing along the grain was considered to be the better cutting method.

In addition to the thickness of the slab residues, the sharpness of the knife also affected the combing process, which should be further investigated in the future.

Morphology after Combing

Figures 4a and 4b show the micro-structural morphology of the cross section of the wood bundle sticks with MCs of 15.3% and 35.7%, respectively.



a b

Fig. 4. Cellular structures of the wood sticks at two different MCs: (a) 15.3% and (b) 35.7%

Figure 4 shows that the cells of the combed bundles presented a compressed deformation, which reduced the volume of the cell cavities at a MC of 15.3% (virtually air-dried). The cells were integrated without any damage, but they became flat, irregular elliptic, or prismatic in shape. When the MC was above 35.7% (above the fiber saturation point), only slight changes in the morphology were observed. The combed bundle sticks maintained their original rectangular and diamond shapes. Therefore, it was concluded that the combing process should be conducted above the fiber saturation point of the samples.

Physical and Mechanical Properties

Table 1 and Fig. 3 show that combing changed the sawmill slab residues to individual bundles, which was completely different from the scrimber unit (net bundles). Therefore, the resulting scrimber consisted of combed sawmill slab residues and formed a novel type of scrimber. The influence of the scrimber density on the MOR and MOE is shown in Figs. 5 and 6, respectively.

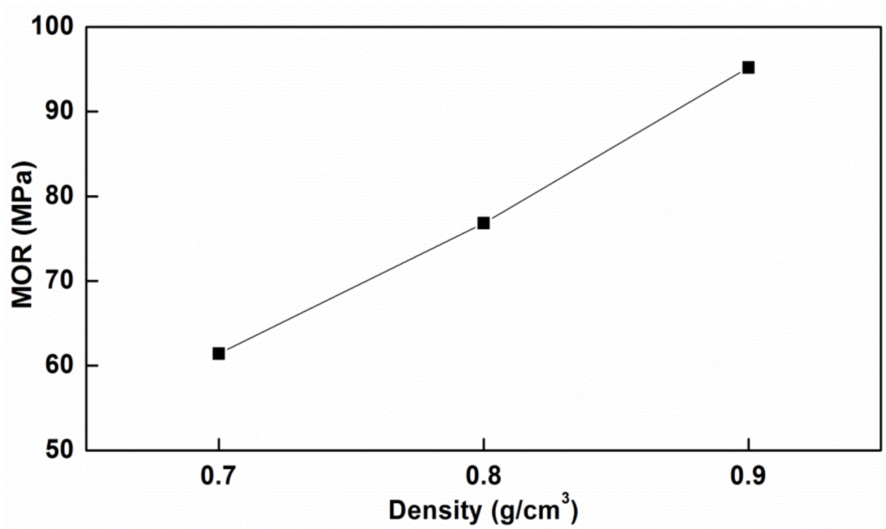


Fig. 5. Relationship between the density and MOR

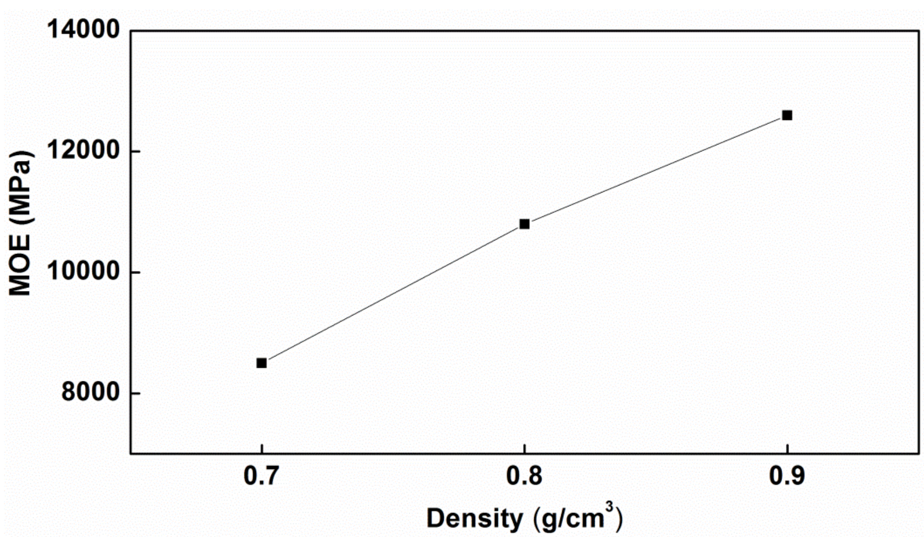


Fig. 6. Relationship between the density and MOE

The MOE and MOR gradually increased as the scrimber density increased. The MOR of the scrimber with densities of 0.8 g/cm^3 and 0.9 g/cm^3 were 25.1% and 55.0% higher than that of the scrimber with a density of 0.7 g/cm^3, respectively. The MOE presented a similar enhancement, increasing by 27.0% and 49.3% with the scrimber densities of 0.8 g/cm^3 and 0.9 g/cm^3, respectively. This illustrated that the density had a substantial effect on the MOE and MOR, and indicated that increasing the density was the most efficient way to enhance both the MOE and MOR of the scrimber. However, the over-condensed scrimber required a high compression ratio and increased PF loading, which would decrease the utilization potential of Chinese fir and increase the production cost. Additionally, a high weight and difficult manufacturing technology were not beneficial for scrimber production. Because the quantity of wood cell wall material is the material basis of determining the strength and stiffness of wood, the strength and stiffness of wood increase with the increase of wood cell wall material. Therefore, the density of Chinese fir scrimber was higher, and the amount of wood cell wall material per unit volume was greater, which led to greater MOR and MOE of Chinese fir scrimber.

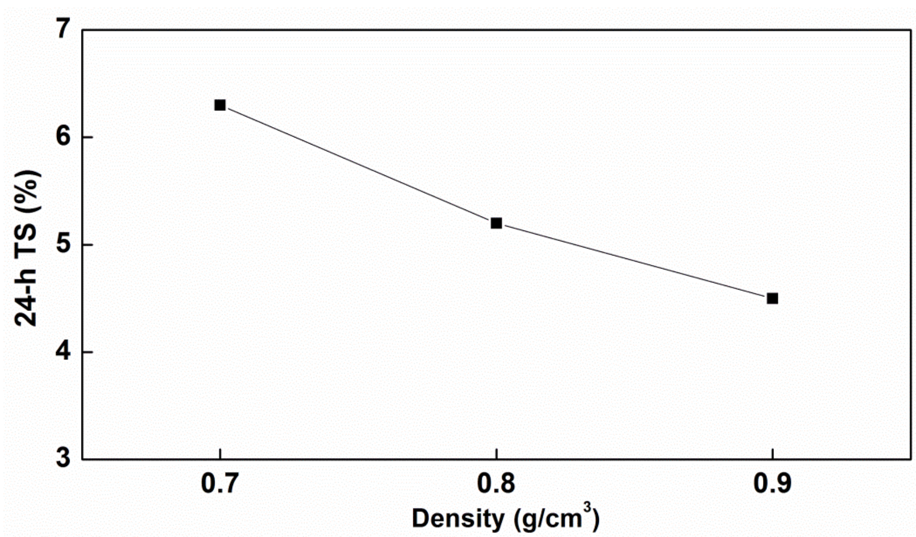


Fig. 7. Relationship between the density and 24-h TS

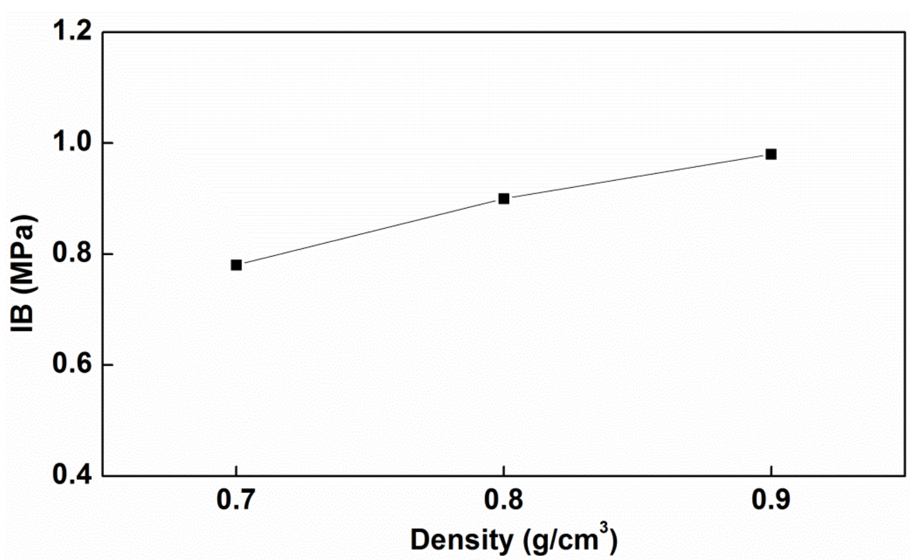
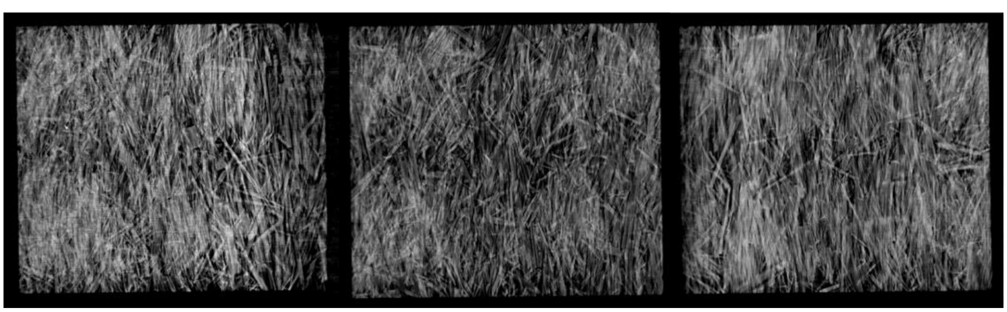


Fig. 8. Relationship between the density and IB

The effects of the density on the 24-h TS and IB of the scrimber are shown in Figs. 7 and 8, respectively. The 24-h TS of the scrimber gradually decreased as the density increased. The 24-h TS of the scrimber with densities of 0.8 g/cm^3 and 0.9 g/cm^3 were 17.5% and 28.6% higher than that of the scrimber with a density of 0.7 g/cm^3, respectively, which implied that a more stable dimension was achieved by increasing the scrimber density. This demonstrated that the density is an important factor when determining the 24-h TS. Because the scrimber was prepared from sawmill slab residues from small-diameter juvenile fir trees with an air density below 0.34 g/cm^3, the compression ratio to prepare the scrimber with densities of 0.7 g/cm^3, 0.8 g/cm^3, and 0.9 g/cm^3 exceeded 100%. A larger compression ratio resulted in a smaller elastic recovery ratio, which led to improved dimensional stability. A compression ratio of 70% results in an optimum elastic recovery ratio (Cheng *et al.* 2005). Therefore, increasing the density of the scrimber is a method to also improve the dimensional stability. Figure 8 shows that the IB of the scrimber increased as the density increased. The IB of the scrimber with densities of 0.8 g/cm^3 and 0.9 g/cm^3 were 15.4% and 25.6% higher than the scrimber with a density of 0.7 g/cm^3, respectively, which indicated that a high density was able to improve the IB. The main reason for this result was that the increased density shrunk the space between the individual bundles while enlarging the contact area of the PF and bundles. In addition, the MOR and MOE of Chinese fir scrimber were lower than this the same density poplar scrimber. When the density of scrimber was 0.8 g/cm^3, the MOR of Chinese fir scrimber was 76.8 MPa, which was 60.0% of that of poplar scrimber 128.0 MPa. The MOE of Chinese fir scrimber was 10750 MPa, which was 76.7 % of poplar scrimber 14010 MPa (Zhang *et al*. 2016). This might be due to the fact that the density of Chinese fir was 0.35 g/cm^3, which was only 72.9% of the density of 0.48 g/cm^3 of poplar (Zhang *et al*. 2016). Therefore, the mechanical properties of the scrimber are related to the density of the tree species in using.

Morphology of the Scrimber

The CT charts of the scrimber showed the horizontal (surface, core, and bottom layer) and vertical faults (front, middle, and tail section) of the scrimber, and are depicted in Figs. 9 and 10, respectively.



a b c

Fig. 9. CT chart of the horizontal faults of the scrimber: (a) surface layer, (b) core layer, and (c) bottom layer

a b c

Fig. 10. CT charts of the vertical faults of the scrimber: (a) front section, (b) middle section, and (c) tail section

During a CT scan, images are presented on the display screen in grayscale. The black shadows represent low absorption areas (low density areas), while the white shadows represent high absorption areas (high density areas) (Cao 2007). Figure 9 shows that the stripe structural characteristic of the scrimber and the joint situations of the wood bundle sticks were apparent in the CT charts for the horizontal faults. The black shadow areas of the scrimber core layer were larger than that of the surface and bottom layers, and the black shadow areas of the wood bundle stick joints were larger than that of the non-joints. Therefore, the densities of the surface and bottom layers of the scrimber were higher than that of the core layer, and the densities of the wood bundle stick joints were lower than that of the non-joints. The main reason for which the densities of surface and bottom layers were higher than that of core layers of Chinese fir scrimber was related to the temperature gradient during pressing. Temperatures of surface layer and bottom layers were higher than that of core layers when the Chinese fir scrimber mats were hot pressed. When the surface and bottom temperatures of the mats were higher, the compressive strengths of the wood bundle sticks decreased, and the compressive rates increased, which these resulting in the densities of Chinese fir scrimber increased. Since the core temperatures of the mats were lower, and the compressive strengths of the wood bundle sticks were higher, and the compressive rates were less, which these led to decreased densities of Chinese fir scrimber. The main reason that the densities of the wood bundle stick joints were lower than that of the non-joints was that the lengths of the wood bundle sticks were different. Hence, they are difficult to form into uniform small mats under the condition of small dimension of the experimental press.

Figure 10 shows that black spots of different sizes were distributed on different parts of the scrimber vertical faults and there were more black spots in the middle of each section. Pores are often shown as black spots in CT images. It was observed that there were a certain number of pores in the scrimber, with more pores in the middle. Because of the large size and strip shape of the wood bundle sticks, it was easy to form pores between them during mat formation. Therefore, the Chinese fir wood bundle sticks needed to be prepared more finely.

In summary, the CT revealed the characteristics of the structural morphology, and density distribution of different sections, and pores distribution of the scrimber, which can provide a theoretical reference for optimizing the manufacturing technology and improving the scrimber product quality. Therefore, CT technology can be used as a supplementary research method and real-time reconstruction tool to reveal the density distribution and internal morphology characteristics of the scrimber.

CONCLUSIONS

1. Sawmill slab residues were combed into individual bundle sticks. These bundle sticks differed considerably from traditional scrimber units (net bundles). The resulting scrimber prepared from the sawmill slab residues can be regarded as a new type of scrimber.
2. The rotary speed of the combing roller and cutting direction remarkably affected the combing process. Rotary speeds of 120 rpm and 360 rpm for the coarse and fine rollers, respectively, combed with the grain were the optimum combing parameters to prepare uniform individual bundles.

3. The MC of the sawmill slab residues had a distinguished effect on the morphology of the resulting combed bundle sticks. It was concluded that the MC of the feeding sawmill residues should be more than 30%.
4. The density of the scrimber from the sawmill slab residues influenced the physical and mechanical properties. As the scrimber density, MOE, MOR, and IB gradually increased, the 24-h TS decreased. This indicated that an increased density improved both the physical and mechanical properties.
5. The CT method was found to be useful in revealing striped structural characteristics, the joint situations of the wood bundle sticks, and the density distribution of different sections of the scrimber.

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