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Research Article

Structure, Mechanical Performance, and Dimensional Stability of Radiata Pine (*Pinus radiata D. Don*) Scrimbers

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Natural wood has certain advantages such as good processability and high specific strength and thus has been used for millennium as a structural material. But the mechanical performance and water resistance, particularly for fast-growing species, are unsatisfactory for high-end applications. In this study, the "new-type" scrimber technology was introduced to radiata pine (*Pinus radiata D. Don*) scrimbers. The structure, mechanical properties, and dimensional stability of the scrimber panels were investigated. Results showed that OWFMs as basic units of scrimber had been very even in size and superior permeability. The scrimbers exhibited a three-dimensional porous structure, and the porosity had a decrease with increasing density. Both OWFMs and densification contributed to the high performance in terms of mechanical properties and water resistance. The flexural, compressive, and short-beam shearing strength were significantly enhanced with increasing density. As the density was 0.80 g cm^{-3}, the flexural strength (MOR) was approximately 120 MPa, much larger than many selected wood-based panels. Moreover, the water resistance and dimensional stability also were closely related to the density. At the density of 1.39 g cm^{-3}, the water absorption rate and thinness swelling rate of the panels in boiled water were only 19% and 5.7%, respectively.

1. Instruction

Natural materials have advantages of sustainability, renewability, and low cost and are gradually overtaking synthetic materials, which suffer from high density, environmental problems, complex processes, and high cost [1]. Wood is recognized as an excellent natural material [2]. It has high specific strength and stiffness, good processability, and favorable aesthetics and has been widely used in the fields of paper [3], package [4], furniture [5], and building [6]. Due to the shortage of high-quality wood, fast-growing wood species such as radiata pine (*Pinus radiata D. Don*) has been attracting attentions over the world [7, 8]. These woods have many advantages such as rapid growth, easy harvesting and processing, and acceptable tolerance to various site conditions. However, they also have inherent disadvantages including low density and natural defects and thus unsatisfactory mechanical properties [9, 10]. They are thus usually used in the fields of paper, package, low-end furniture, and other low-value products. For a broader utilization in high added-value application, those disadvantages need to be overcome.

Various methods, such as chemical modification, heat treatment, and densification, have been developed to obtain better properties, and pronounced effects have been demonstrated [11–16]. Among them, processing fast-growing wood into scrimber is a promising method, in which the logs with small diameters are typically crushed to form interconnected long strands by a scrimming machine [17]. The strands exhibit three-dimensional network structure comprising the dispersed fiber bundles, which not only facilitates adhesive impregnation but also reduces the effects of natural defects on product performance [18]. The scrimber density can be adjusted in the range from 0.85 to 1.2 g cm^{-3} to meet the application requirement, and the mechanical performance is superior to that of many existed wood-based panels [19]. However, those bundles are very uneven in size, which gives rise to many drawbacks for scrimber products. The density variation, for example, leads to poor end-product quality such as curl, deformation, and rough surface.

To address these problems, Yu and his coworkers improved the preparation method [20, 21]. In the new method, round wood was first peeled into thick veneers and then split into the oriented wood fiber mats (OWFMs) by a fluffing machine. The mats had very even fiber strands, which significantly improved the adhesive distribution and the density uniformity [22]. Since a series of uniform linear-shaped cracks were formed on the surface, the mat had better permeability than the bundles prepared by the old method. These improvements contributed to the achievement of excellent performance in terms of mechanical strength and water resistance. In addition, the scrimber panels (named new-type scrimber) preserved the structural characteristics of natural wood (e.g., fiber orientation and appearance), and it could safely be processed as the logs, even with high design strength and availability in large dimensions [23]. The new method has been successfully applied to a hardwood poplar wood (*Populus ssp.*) in China, but few attempts have been made to apply to softwood [20].

Radiata pine is a most widely planted fast-growing softwood in the Southern Hemisphere. It has been a mainstay of the forest economy and reduced cutting pressure on native forests in Australia, New Zealand, Chile, Argentina, Uruguay, Kenya, and the Republic of South Africa [24]. Like other softwoods, it has low density in the range from 0.40 to 0.50 g m^{-3} and unsatisfactory mechanical properties. For example, the pine with a mean density of 0.48 g cm^{-3} has an ultimate bending strength of approximately 75 MPa and modulus of elasticity of approximately 9 GPa [25], which cannot meet the requirement of high-end applications. The emergence of "new-type" scrimber technology has great possibility of improving pine wood performance and extending the application fields.

In this study, the process method of new-type scrimber was used to fabricate pine scrimber. The microstructure, mechanical properties, water resistance, and dimensional stability were investigated, and the effect of density also was discussed. The objective of this study is to explore the extensive applicability of the new-type scrimber technology and to develop high-performance wood materials using inexpensive and abundant pine wood.

2. Material and Method

2.1. Materials. Radiata pine with a diameter of ~ 450 mm and a basic density of 0.42 g cm^{-3} was purchased from Linyi Jinshan Wood Co., Ltd. (China). Phenol formaldehyde (PF) resin with the number-average molecular weight of 596, solid content of 47.49%, viscosity of 41 mPa·s at 25°C, and pH of 10.22 was applied by Dynea Guangdong Co., Ltd. Other reagents were of chemical grade throughout the experiment and purchased from Aldrich Chemical (Shanghai) Co., Ltd.

2.2. Methods

2.2.1. Scrimber Fabrication. The pine log without barks was used as raw material to prepare the oriented wood fiber mats according to the reported method [20], and the scrimbers were obtained through laminating the mats impregnated with PF resin. In brief, round wood was softened in the boiled water and then peeled into the flat veneers with 6 mm in thickness using the spindleless veneer lathe (Xuanjin, China). The veneers were split along the wood growth direction by a fluffing machine into the fiber mats. The mats were dried in an oven at 70°C until the moisture content was approximately 10%. The dried mats were impregnated with dilute PF resin (solid content of 10 wt.%) and the weight gain was 13 wt.% based on the weight of dried mats. The wet mats with resin were air-dried until the moisture content reached 11 wt.%. A certain weight of the dried mats with resin was assembled along the grain direction in the mold. Hot pressing was conducted at 145°C for 30 min on a Model 3856 thermocompressor (CARVER, USA) to obtain the board (300 × 200 × 20 mm^3). By changing the mat weight, a series of scrimber boards were obtained with various densities (i.e., 0.80, 1.01, 1.20 and 1.39 g cm^{-3}). Prior to testing, the scrimber boards were conditioned in a chamber at 65 ± 5% relative humidity (RH) at 20 ± 2°C for two weeks.

2.2.2. Water Loading of OWFMs. The permeability of thick veneers and OWFMs were characterized by the water loading rate (*WLR*). The samples were immersed in water at room temperature for 5 min then taken out and placed vertically for another 5 min. The rate was calculated by

$$WLR = (m_2 - m_1) \times \frac{100\%}{m_1}, \tag{1}$$

where m_1 and m_2 were the weights of samples before and after water impregnation, respectively.

2.2.3. Morphological Observation. Microstructure of transverse sections was observed using a S3400 scanning electron microscope (SEM) (Hitachi, Japan) at an accelerating voltage of 5.0 kV. Samples were made of the same wood at the same position to ensure the comparability. Prior to observation, the surface was smoothed with a sliding microtome and then sputter-coated with a thin layer of gold.

2.2.4. Determination of Porosity. The apparent density (ρ_a) was considered as the ratio between the mass of a sample and the total volume it occupied. The substantial density (ρ_s) was defined as the ratio between the mass of the sample and the actual volume it occupied. ρ_s was measured by an AccuPyc 1330 pycnometer (Micromeritics, USA) at 22 ± 0.5°C. For accuracy, the sample was transversely cut into small slices with 2 μm in thickness and at least five duplicates were measured for each sample. The porosity (ε) was defined as the fraction of the volume of voids over the total volume of the sample, and it was calculated by [26]

$$\varepsilon = \left(1 - \frac{\rho_a}{\rho_s}\right) \times 100\% \tag{2}$$

2.2.5. Mechanical Testing. The flexural and compressive properties of scrimber samples were tested according to the standard of GB/T 17657-2013 and the short-beam shearing

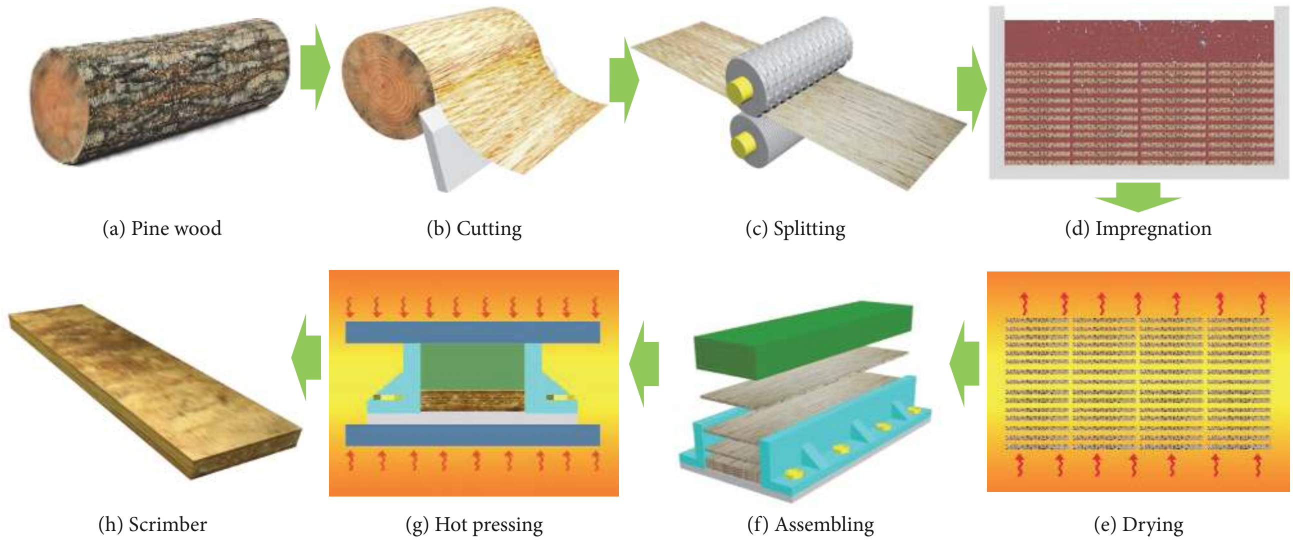


FIGURE 1: Diagrams of scrimber preparation.

according to the standard of GB/T 20241-2006. All tests were performed on a CMT5105 universal testing machine (MTS systems, China). For each density, at least eleven samples were tested to ensure good reproducibility.

2.2.6. Water Resistance. The water absorption rate (*WAR*), thickness swelling rate (*TSR*), and width swelling rate (*WSR*) of scrimber samples were measured according to the standard GB/T 30364-2013. The samples were boiled for 4 hours, dried at 63 ± 3°C for 20 hours and boiled for another 4 hours. *WAR* was calculated by

$$WAR = (w_2 - w_1) \times \frac{100\%}{w_1}, \quad (3)$$

where w_1 and w_2 were the sample weight before and after boiling, respectively. And TSR was calculated by

$$TSR = (t_2 - t_1) \times \frac{100\%}{t_1}, \quad (4)$$

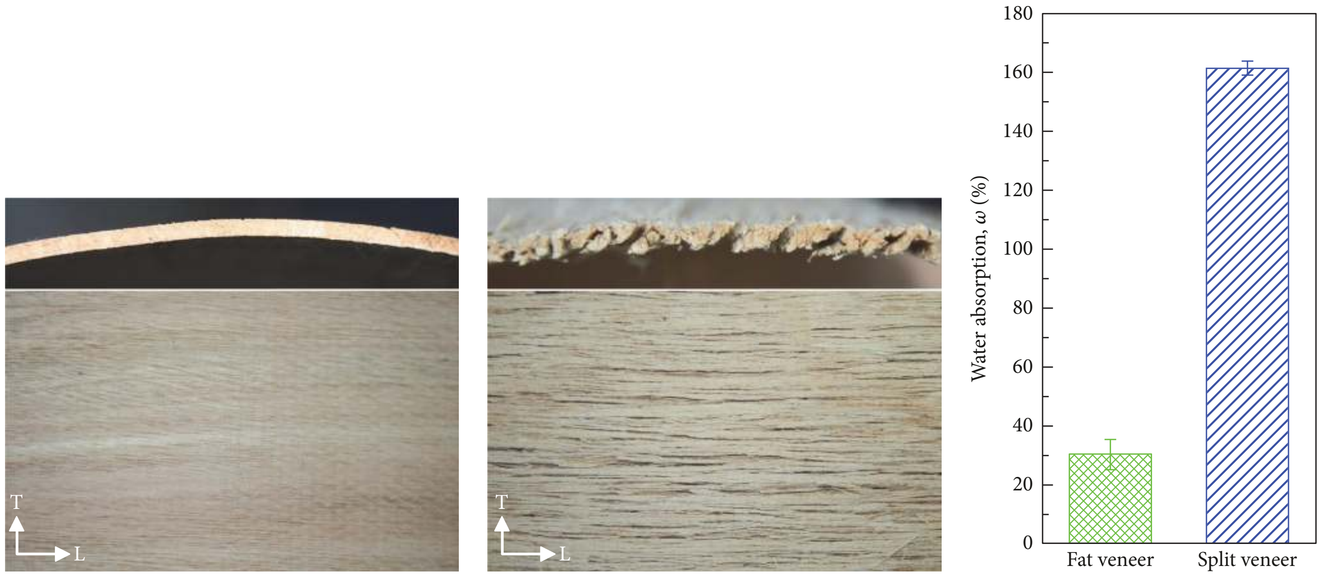
where t_1 and t_2 were the thickness of the sample before and after boiled, respectively. Similarly, WSR was calculated as well.

3. Results and Discussion

3.1. Scrimber Formation. Figure 1 shows the diagrammatical process of pine scrimbers, which mainly involves rotary-cutting of round wood, directional splitting of thick veneers, impregnating with phenolic resin, and hot pressing. The rotary-cut veneers had flat surface and uniform thickness. As directionally split by the fluffing machine, the veneers turned into web-like fiber mats. As like the flat veneer, the mat preserved a whole sheet with well-distributed density. Compared to the strands obtained directly from the crushed log, the mat surface was flatter, and thus it was easier for layup. In addition, there existed a series of dotted and linear-shaped cracks on the mat surface (Figure 2(b)), which offered many paths for liquid impregnation. The water loading rate of OWFMs was 161.34 wt.%, which was four folds more than that of the flat (or split-free) veneers (Figure 2(c)). Apart from enhanced permeability, low-molecular-weight PF resin used in this study allowed more adhesive penetrating into the lumens and cell walls. It has been proven that phenolic resin can prominently soften wood cell walls and decrease the Young's modulus (MOE) of wood fibers [27]. More resin could facilitate the collapse of cell walls at lower pressure. Heat also can effectively soften the wood and make the pressing easier. In comparison with the cold-pressing and hot-curing method, the hot pressing saved more than 90% of the time, which were obtained from the reported literature [28, 29].

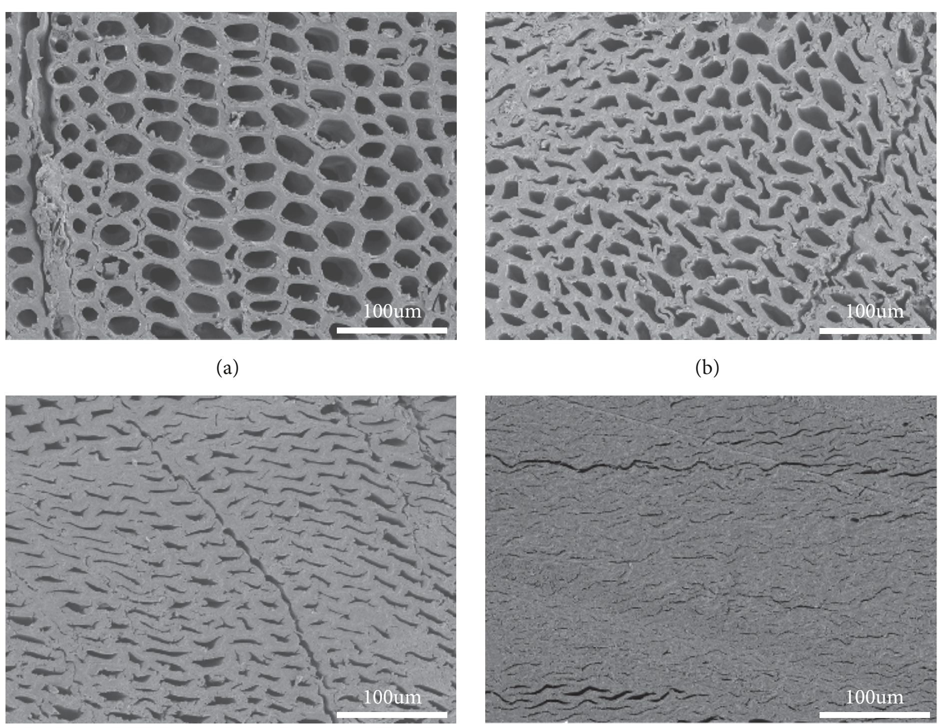
3.2. Microstructure. The cross-section surfaces of scrimbers were observed at microscopic scales, and their micrographs are shown in Figure 3. All scrimbers exhibited a three-dimensional porous structure consisting of axial tracheids with fair dense cell walls. But there still existed the difference between them due to various densities. For the scrimbers with a density of 0.8 g cm^{-3}, the cell walls had less deformation along the pressing direction (Figure 3(a)). Some walls were divided from each other and the narrow gaps were formed, which may arise from the intercellular bonding destruction during the hot pressing. As the density increased, the cell shape became more and more irregular. For the scrimber with 1.2 g cm^{-3}, almost cell walls collapsed layer by layer, accompanied by the walls cracking (Figure 3(c)). When the density reached 1.39 g cm^{-3}, a majority of lumens were filled with the collapsed walls, and most walls had been barely distinguished (Figure 3(d)).

Figure 4 shows that the average porosity of scrimbers sharply decreased with increasing density. The porosity decreased from 68% for the pine wood to 46% for the scrimbers with a density of 0.80 g cm^{-3}. In the case of the scrimbers with 1.39 g cm^{-3}, the porosity reached approximately 2.11%, which was only 3% of that of pine wood.



(a) (b) (c)

FIGURE 2: Surface macrograph of (a) the flat veneer and (b) OWFM, and their water loading rates.



(a) (b) (c) (d)

FIGURE 3: SEM micrographs of scrimbers with density of (a) 0.80, (b) 1.01, (c) 1.20, and (d) 1.39 g cm^{-3}.

Such low porosity may be conducive to the improvement of physical and mechanical properties.

3.3. Mechanical Properties. Figure 5 shows the strength and stiffness of scrimbers as a function of density. The flexural strength (MOR) and modulus (MOE) increased with increasing density. At the density of 0.80 g cm^{-3}, the scrimber had approximately 120 MPa in MOR, which was much larger than most selected wood-based panels as presented in Figure 6, such as pine plywood [30], pine oriented strand board (OSB) [31], kenaf particleboard [32], and wood-polymer composite (WPC) [33]. The strength almost came up to that of poplar scrimbers at the same density, which were prepared by the cold-pressing and hot-curing method [20]. As the density was

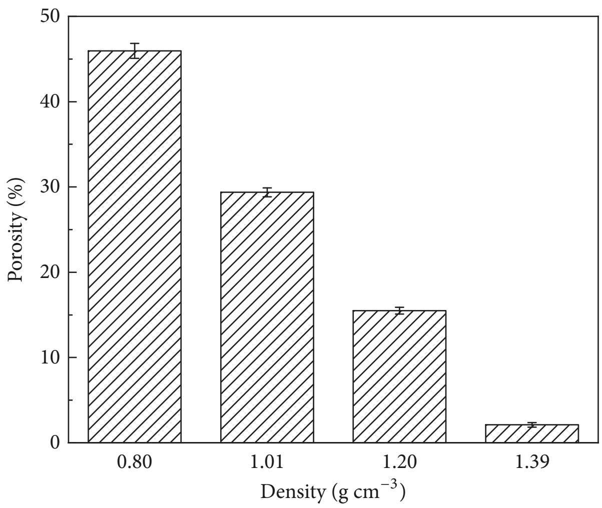


FIGURE 4: Porosity of scrimbers with varying densities.

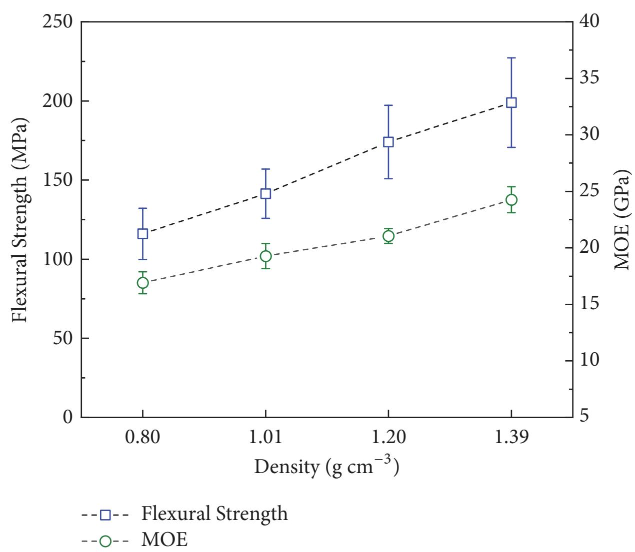


FIGURE 5: Flexural properties of scrimbers with various densities.

1.01 g cm^{-3}, the strength surpassed that of pine compressed wood [34]. When the density was equal to 1.39 g cm^{-3}, MOR was up to 198.92 MPa on average, which was 71% higher than that of scrimers at 0.80 g cm^{-3}. Meanwhile, the modulus had an increase by about 7.5 GPa in comparison with that at 0.80 g cm^{-3}.

Compressive and short-beam shearing properties also were enhanced with an increase of density (Figure 7). The compressive strength was 87 MPa at the density of 0.8 g cm^{-3}, which was 70% larger than that of GluBam prepared by Xiao et al. [35]. As the density reached 1.39 g cm^{-3}, the strength increased to 154 MPa and the specific strength was approximately 110 MPa g^{-1} cm^{3}. Similarly, the short-beam shearing strength, which reflects the bonding quality of laminated panels [36], increased with increasing density, but maintained at 21 MPa as the density was 1.20 g cm^{-3} or more.

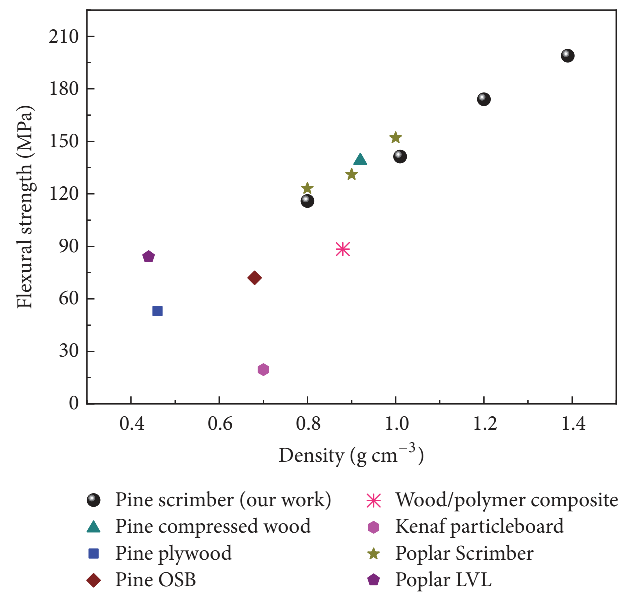


FIGURE 6: Comparison of flexural strength between the scrimbers and selected wood-based panels.

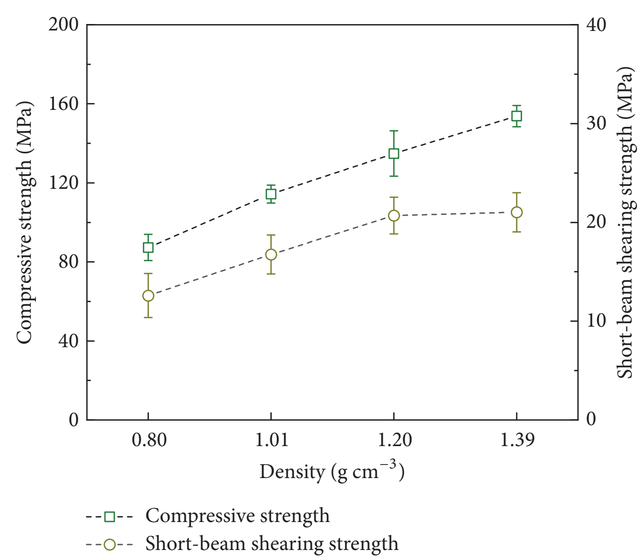


FIGURE 7: Compressive and short-beam shearing properties of scrimbers with various densities.

These remarkable improvements were ascribed to the superior feature of OWFMs and the densified structure of scrimbers. The high permeability of OWFMs facilitated the bonding behavior between wood fibers and PF resin, thus improving the bonding strengths. Besides, the strands increased the contact area between the fiber and PF resin and between each fiber, which benefited the stress transferring. In general, the mechanical properties of lignocellulosic composites manily depended on the structure and strength of cellulosic fibers, which bears the exterior loads [37, 38]. The structural densification increased the fiber content per unit volume, resulting in high endurance capacity for these scrimbers.

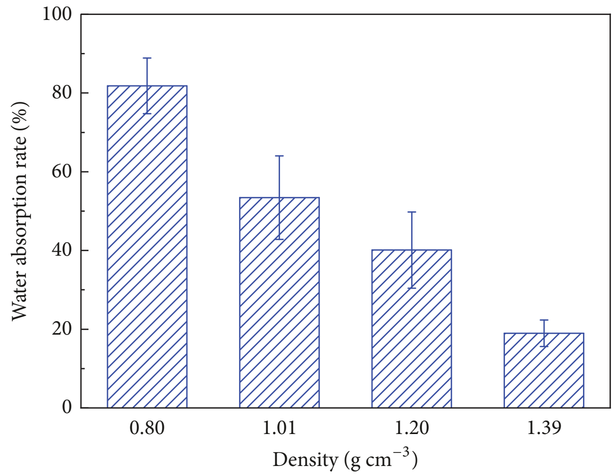


FIGURE 8: Water absorption rate of scrimbers with different densities.

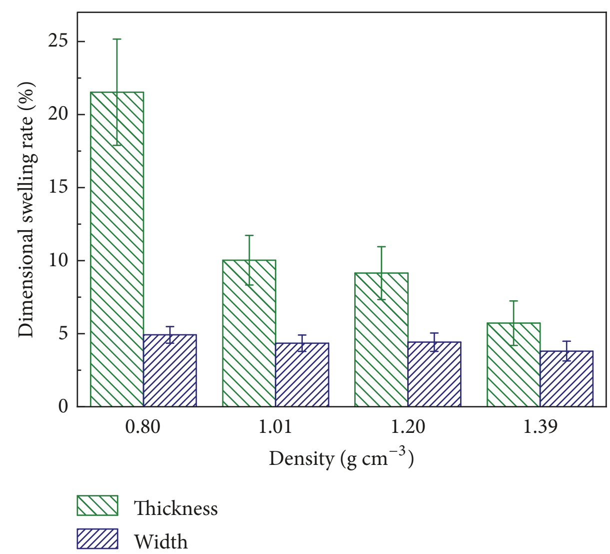


FIGURE 9: Dimensional swelling rate of scrimbers with different densities.

3.4. Water Absorption and Dimensional Stability. The water absorption rate of scrimbers in boiled water is depicted in Figure 8. With increasing density, the absorbed water gradually decreased. When the density was 0.80 g cm^{-3}, the absorbed water was 81.82% based on the weight of oven-dried sample, which was less than half that of pine wood (i.e., 176%). In respect to the scrimbers at the density of 1.39 g cm^{-3}, the water absorption rate was as low as 19%, which was the least value among the scrimbers in this work. Besides the molecular adsorption of cell walls, the pronounced discrepancy can be ascribed to the different porosities. The lumens offered considerable conveying channels and storage space to water [39]. Low porosity reflected fewer channels and space within the scrimber, leading to less absorbed water. Moreover, the lower the density was, the lower the porosity was, followed by less water absorbed by the scrimbers. These results suggested that the scrimbers with high density had better capacity of water resistance.

The absorbed water could cause the deformation recovery of scrimbers. As presented in Figure 9, the thickness swelling rate at the density of 0.80 g cm^{-3} was 22%, which was three times as much as that of pine wood (i.e., 7%). Besides the cell wall swelling, the recovery of compressed wood cells contributed to the great discrepancy. In the preparation process of our case, the wood cells were compressed, accompanied by extra internal stress [40]. When the scrimber was placed in the hygrothermal condition, the compressed cells tended to recover to the initial shape. In the macroscale, the recovery of cell deformations appeared as the thickness swelling. Furthermore, as the density increased, some cell walls crashed, accompanied by tiny cracks on the wall. The rate trended to decline due to the poor ability of cell recovery, confirmed by only 5.7% in thickness swelling the scrimbers at the density of 1.39 g cm^{-3} had.

Compared to the thickness, the width had much less swelling rate under any density. It could be ascribed to the fact that the wood cells were mainly compressed along the thickness direction during the hot pressing, while less deformation occurred in the width direction. In the case, the swelling rate in width was only a little but much lower than that in thickness, no matter how high the density was. It would be seen from these results that the pine scrimbers possessed high dimensional stability.

4. Conclusion

In this study, pine scrimbers were prepared using the "new-type" scrimber technology. The oriented wood fiber mats (OWFMs) as basic units of scrimber exhibited the net-like structure consisting of many sharply oriented fibers. Due to a series of cracks on the surface, the permeability was four folds more than that of the untreated veneers. SEM micrographs revealed that the cell walls were compressed along the thickness direction, resulting in decreasing porosity. Both OWFMs and densification contributed to enhanced performance in the respect of mechanics and dimensional stability. For the scrimber at the density of 0.80 g cm^{-3}, the flexural strength was much larger than that of many existed wood-based panels. As the density reached 1.39 g cm^{-3}, the strength was increased to 198.92 MPa. Meanwhile, the water absorption rate and thickness swelling rate in boiled water were only 19% and 5.72%, respectively. Such remarkable performance could endow the material with great prospects in the fields of high-value applications.

Data Availability

The data supporting the findings of this study have been not available because it is part of the programs being in progress, and it will be further studied.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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