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ORIGINAL ARTICLE

Effects of density and resin content on the physical and mechanical properties of scrimber manufactured from mulberry branches

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Abstract The silk industry in China produces a large amount of mulberry branches as by-product every year. Mulberry branches have high longitudinal toughness and good overall mechanical properties. However, these branches are incinerated because their utility in other industries is limited by their small size. This study determines the feasibility of manufacturing scrimber from mulberry branches by using cold pressing method, followed by thermo-curing with different densities and resin contents. Results show that density [ranging from (0.81–1.24) g/cm^3] exerts a greater effect on the shear strength, modulus of rupture (MOR), and modulus of elasticity (MOE) than resin content (changing from 8 to 20 %). The increase rate slows down when the density exceeds 1.1 g/cm^3 and the resin content reaches more than 12 %. The strength-to-weight ratio analysis shows that the MOR/density and MOE/density maximum at 1.02–1.10 g/cm^3. The density and resin contents of mulberry scrimber with cold compress and heat setting can be set to 1.0–1.1 g/cm^3 and at approximately 12 %, respectively. The mechanical properties of the product meet the maximum requirement indicated in the Chinese national standard for construction. Mulberry scrimber can be a very promising supplement for wood because of its good performance, abundant supply, and renewability.

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Introduction

Mulberry branches are among the most important byproducts of the silk industry because silkworms only eat mulberry leaves for nutrition. Mulberry trees grow quickly,to regulate shoot growth, mulberry trees are trimmed yearly after harvesting the leaves, thus that plenty of mulberry branches are left. According to 2008 statistics, up to 84.6 million hm^2 of mulberry trees occupy China [1], and 1,000 kg of fresh branches can be harvested per 0.089 hm^2. Utilizing these wood resources presents a major problem. Mulberry branches are rich in cellulose [2] and are utilized in medium-density fiberboard manufacturing [3] and paper-making [4]. Scrimber, which is a reconstituted timber product according to the Commonwealth Scientific and Industrial Research Organization, was first discovered by John Douglas Coleman in 1973 [5]. For production of scrimber, the wood is crushed into integrated parallel strips, which are partly connected to one another in the cross section, and then bonded with one another using an adhesive under high pressure. The wood species of *Pinus radiata*, *Eucalyptus* [6], and bamboo have been extensively studied in suitability of manufacturing scrimber [7–10], and studies have shown that the industrialization potentials of these species are promising. Mulberry branches can be used as alternative sources of raw materials for scrimber production because of their excellent longitudinal toughness. However, mulberry branches are quite different from logs and bamboo due to their small diameter, which reduces their application possibilities in material manufacturing. Manufacturing scrimber by mulberry branches will fully utilize the mulberry resources and relieve the shortage of wood supply in the meanwhile.

This study determines the suitability of mulberry trees for scrimber manufacturing and the optimum manufacturing parameters.

Materials and methods

Mulberry branch strip preparation and scrimber manufacturing

The mulberry branches, with a density of 0.497 g/cm^3, a moisture content of 56.8 %, and a diameter of 3–80 mm, were obtained from mulberry trees that have been grown for seven years in Anji, Zhejiang Province, China. The outer skin was manually stripped, cut into 200–250 cm long strips, and crushed into 1–5 mm diameter of the strips by a crusher (with different profiles on both compression rollers) [11].The strips were then bundled together, with each bundle weighing 3 kg to 4 kg. The bundles were immersed in boiling water for 2–3 h for degreasing. After degreasing, the strips were heated in a sealed tank with 0.35 MPa superheated steam medium for 2 h to darken the color and degrade some extractives. Then, the strips were oven dried at 55 °C for 24 h, after which they were stacked for air drying at room temperature for approximately one week.

Phenol formaldehyde resin (PF) was acquired from Beijing Taier Chemical Co., Ltd. PF had a solid content of 46.2 %, viscosity of 36 mP s at 23 °C, pH of 10–11, and was seven to eight times water soluble.

Each dried bundle was impregnated with 13 % PF diluted from the original PF for 7–20 min to achieve different resin contents (8, 12, 16, and 20 %). Resin content was calculated according to the below equation:

$$C = \frac{(m_2 - m_1) \times w}{m_1 \times (1 - x)},$$

where C is the resin content, m_1 and m_2 are the respective mulberry bundle mass before and after immersion in the resin, w is the solid resin content, and x is the wet-basis moisture content before the resin immersion.

The bundles were then dehumidified at approximately 38 °C and then dried until 10 % moisture was reached. The designed density of 1.0 g/cm^3 was achieved by controlling the weight of the dried resin socked strips according to the final dimension of the scrimber (500 mm × 70 mm × 80 mm). After weighing, the resin socked strips were first stacked in a mold and then cold pressed to the target thickness, fixed with an iron plate using pegs, heated in the mold for thermosetting at 110–135 °C for 17 h, unloaded from the mold, and finally conditioned at room temperature

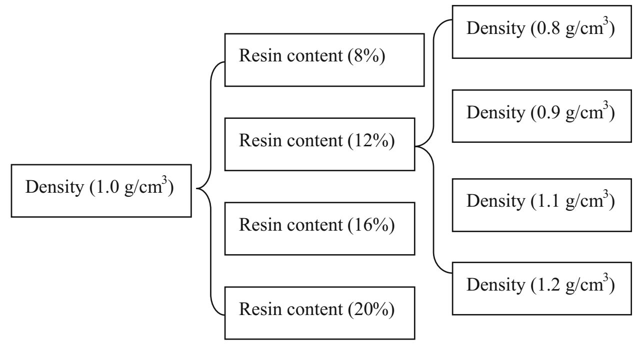

Fig. 1 Scheme of the experiment

(20–25 °C, 60–65 % RH) for two weeks prior to the physical and mechanical testing.

Meanwhile, the scrimber with different densities (0.8, 0.9, 1.0, 1.1, and 1.2 g/cm^3) was prepared with 12 % resin content, following the same procedure above (Fig. 1). Each condition was replicated thrice, and 24 reconstructed boards were manufactured.

Mechanical properties testing

A frame sawing machine, which was a multi-band saw, was used to divide the mulberry scrimber into several 15 mm thick panels. The panels were then cut into smaller specimens [350 mm × 50 mm for the modulus of rupture (MOR) and modulus of elasticity (MOE), 90 mm × 50 mm for the shear strength, and 50 mm × 50 mm for the thickness swelling test]. The tests were performed according to the EN 13986:2010 standard [12] for the MOR and MOE tests with a bending span of 300 mm, the ASTM D2344-13 standard [13] for the shear strength test with a bending span of 60 mm, and the EN 317:1993 standard [14] for the 24 h thickness swelling test. To test the density, 100 mm × 100 mm specimens were used. Each test was replicated six times. The result was the average derived from the six replications.

Results and discussion

Effect of density on the mechanical properties of mulberry scrimber

Table 1 demonstrates that the MOR and MOE increased quickly with the increase of density, especially when the density changed from 0.81 to 1.10 g/cm^3. When the density was higher than 1.10 g/cm^3, both the increase rate of MOR and MOE then declined to less than 5 %. Consequently, density of 1.0–1.1 g/cm^3 was recommended for mulberry scrimber manufacturing.

Table 1 Effect of density on MOR, MOR and shear strength

Density (g/cm^3)	MOR (MPa)	Increase (%)	MOE (MPa)	Increase (%)	SS-PE (MPa)	Increase (%)	SS-PA (MPa)	Increase (%)
0.81	63.9 ± 1.98		8,650 ± 220		5.88 ± 0.48		8.67 ± 0.41	
0.92	80.1 ± 3.62	25.4	10,650 ± 400	23.1	7.66 ± 0.38	30.2	9.26 ± 0.38	8.67
1.02	98.1 ± 5.21	22.5	13,240 ± 365	24.3	11.59 ± 0.60	51.3	9.54 ± 0.45	9.26
1.10	113.4 ± 7.50	15.6	14,120 ± 516	6.6	14.04 ± 0.75	21.2	12.73 ± 0.66	9.54
1.24	118.8 ± 8.60	4.8	14,780 ± 500	4.7	16.36 ± 0.85	16.5	14.42 ± 0.69	12.73
		Total: 85.9		Total: 70.9		Total:178.2		Total: 66.3

MOR modulus of rupture, *MOE* modulus of elasticity, *SS-PE* shear strength perpendicular to the panels, *SS-PS* shear strength parallel to the panels

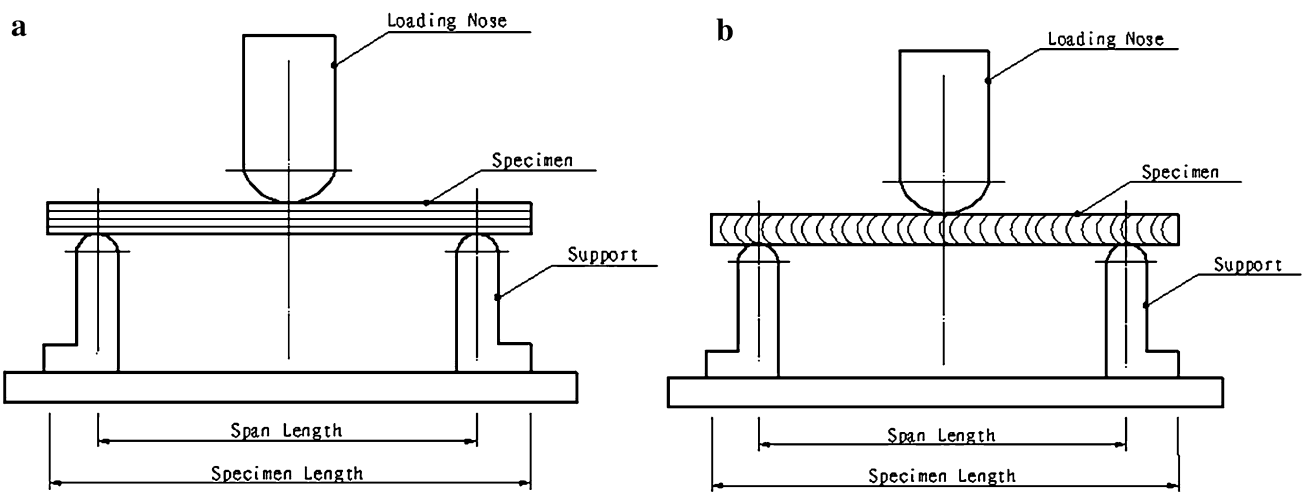

Fig. 2 **a** Shear strength perpendicular to the panels (SS-PE). **b** Shear strength parallel to the panels (SS-PA)

Shear strength is defined as the capability of a material to resist internal slipping of one part on another [15]. Shear strength is one of the most important properties to evaluate the mechanical strength of a construction material. In this study, we evaluated the shear strength in two directions, namely, perpendicular to the panels (SS-PE) and parallel to the panels (SS-PA) (Fig. 2). Table 1 shows that the shear strength that was perpendicular to the panels was more affected by the density than that in the parallel direction. The increase rate of the SS-PE declined when the density changed from 1.02 to 1.10 g/cm^3, whereas the SS-PA maintained a weak increasing trend. At the low density level, the value of the SS-PA was higher than that of the SS-PE. However, the SS-PA value was surpassed by that of the SS-PE when the density was higher than 1.02 g/cm^3. This result was attributed to the fact that in this test, the shear force perpendicular to the panel was toward the opposite direction during manufacturing, thus causing the material to be well compressed and glued [9].

Among the 4 mechanical properties, the SS-PE increased the most (178.2 %) when the density changed from 0.81 to 1.24 g/cm^3, followed by the MOR (85.9 %), MOE (70.9 %), and SS-PA (66.3 %).

Effect of resin content on the mechanical properties of mulberry scrimber

Table 2 shows the effect of resin content on the MOR, MOE, and shear strength. The MOR, MOE, and shear strength all continuously grew rapidly when the resin content rose from 8 to 12 %, and then the increase rate slowed down for the MOE and SS-PE, and the increase rate of the MOR and SS-PA minimized when the resin was above 16 %. The SS-PE value was small when the resin content was 8 % because bamboo scrimber delaminated easily which greatly weakened the shear strength, and then delamination reduced when the resin was above 12 %. The SS-PA easily flexured at a low resin content. However, at the high resin content, the shear strength values of the PE and PA were almost similar because the mulberry branch strips bonded well to one another, and the shear strength represented the whole strength of the scrimber in both directions.

The resin content affected the mechanical properties minimally compared with the density. Among the 4 mechanical properties, the MOR increased the most (59.6 %) when the resin rose from 8 to 20 %, and the MOE and shear strength both increased by 30–40 %.

Table 2 Effect of resin content on MOR, MOR and shear strength

Resin content (%)	MOR (MPa/%)	Increase (%)	MOE (MPa/%)	Increase (%)	SS-PE (MPa/%)	Increase (%)	SS-PA (MPa/%)	Increase (%)
8	80.1 ± 3.62		9,820 ± 298		9.52 ± 0.46		9.01 ± 0.41	
12	98.1 ± 5.21	22.5	13,240 ± 365	34.8	11.59 ± 0.51	21.7	9.54 ± 0.44	5.8
16	122.4 ± 8.65	24.8	13,290 ± 375	0.4	12.38 ± 0.65	6.8	12.04 ± 0.67	26.2
20	127.8 ± 7.65	4.4	13,580 ± 382	2.2	12.72 ± 0.56	2.8	12.10 ± 0.79	0.5
		Total: 59.6		Total: 38.3		Total: 33.7		Total: 34.3

MOR modulus of rupture, *MOE* modulus of elasticity, *SS-PE* shear strength perpendicular to the panels, *SS-PS* shear strength parallel to the panels

Table 3 Strength-to-weight ratio of mulberry scrimber

Density (g/cm^3)	MOR (MPa)	MOR/ density	MOE (10^2 MPa)	MOE × 100/ density	SS-PE (MPa)	SS/ density	SS-PA (MPa)	SS/ density
0.81	63.9	78.9	77.9	96.2	5.9	7.3	8.7	10.7
0.92	80.1	87.1	95.9	104.2	7.7	8.4	9.3	10.1
1.02	98.1	96.2	119.2	116.9	11.6	11.4	9.5	9.3
1.10	113.4	103.1	127.1	115.6	14.0	12.7	12.7	11.6
1.24	118.8	95.8	133.0	107.3	16.4	13.2	14.4	11.6

MOR modulus of rupture, *MOE* modulus of elasticity, *SS* shear strength, *SS-PE* shear strength perpendicular to the panels, *SS-PS* shear strength parallel to the panels

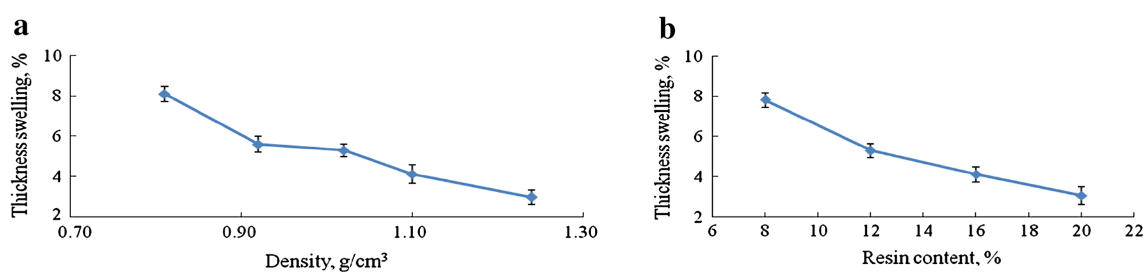

Fig. 3 Density and resin content versus thickness swelling

Based on the results, we recommend that the resin content of the mulberry scrimber that was manufactured through cold compress and heat setting should be set at 12 %.

Strength-to-weight ratio

The mechanical properties of the mulberry scrimber improved as the density increased. The strength-to-weight ratio and the cost are other key points used in evaluating structural materials [15]. Further more, at a high density level, the board was subjected to high pressure, and the cell lumen of the wood may be crushed. Thus, the mechanical strength was lost, which offset the increase rate caused by the higher density.

The strength-to-weight ratios were compared, as listed in Table 3. From Table 3, it can be seen that the MOR/ density and MOE/density reached the maximum ratios when the density ranged from 1.02 to 1.10 g/cm^3, and then the ratios declined. The shear strength/density continued to grow in the perpendicular direction, and the maximum was reached at 1.10 g/cm^3 in the parallel direction.

Thickness swelling (TS)

TS represents the water resistance property of a material by measuring the increase in thickness when the material is immersed in water for a certain period.

Figuer 3a shows that the TS decreased rapidly with the low-level increase of the density, but the TS increase rate

Table 4 Mulberry scrimber mechanical and physical property evaluation

	Density (g/cm^3)	MOR (MPa)	MOE (MPa)	SS-PE (MPa)	SS-PA (MPa)	24 h-TS (%)
Mulberry scrimber	1.02	98.1	11,920	11.6	9.5	5.3
GB/T 20241-2006	/	/	/	6.5(65 V-55H)	5.5(65 V-55H)	12
GB/T 21128-2007	/	90 (A)	9,000(A)	/	/	/

MOR modulus of rupture, *MOE* modulus of elasticity, *SS-PE* shear strength perpendicular to the panels, *SS-PS* shear strength parallel to the panels, *24 h-TS* 24 h thickness swelling

slowed down as the density increased above 1.1 g/cm^3. Although the high-density scrimbers were well compressed and the internal strips were closely connected to one another, the increasing total strip thickness increased the swelling potential. Figure 3b shows that the water resistance of the scrimber improved as the resin content increased because the resin wrapped onto the surface of the mulberry strips, filling in the gaps and eliminating routes where water can penetrate [16].

Compared with the other mechanical properties, the TS was more sensitive to the resin content than the density. The TS improved by 155.6 % when the resin content increased from 8 to 20 %, and the TS improved by 171.8 % when the density increased from 0.81 to 1.24 g/cm^3.

Evaluation of mulberry scrimber as a construction material

The main physical and mechanical properties of mulberry scrimber (1.02 g/cm^3 with 12 % resin content) were evaluated using China's national standard of GB/T 20241-2006 for laminating veneer lumber [17], and GB/T 21128-2007 [18] for structural bamboo and wood composite board.

Table 4 shows that the mulberry scrimber from mulberry branches performed well in the MOR, MOE, and shear strength tests, and the scrimber met the maximum requirement of the Chinese standards for construction materials.

Conclusion

The mulberry scrimber retained the original fiber tissue and grain of mulberry branches and showed high mechanical properties. Based on the studies, we recommend that the optimal density and resin contents of mulberry scrimber could be established through cold compress and heat setting at 1.0–1.1 g/cm^3 and 12 %, respectively. The recommended settings will make the products to meet requirements of the national standard for construction materials of China.

Under wood raw material shortage condition, mulberry scrimber can be a promising substitute for wood resource because of its good mechanical performance and abundance in supply.

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