Influence of Fiber Bundle Morphology on the Mechanical and Bonding Properties of Cotton Stalk and Mulberry Branch Reconstituted Square Lumber

Jing Zhang, Yafang Lei,* Mengmeng Shi, and Xiaozhou Song

The mechanical properties of natural fiber composites can be strengthened in the longitudinal direction if the fiber is formed in a parallel manner. Reconstituted cotton stalk lumber and mulberry branch lumber were fabricated using hot-press technology, and the effects of fiber morphology on their mechanical and bonding properties were investigated. The fiber bundle size had a great influence on the mechanical and bonding properties of the final products. The maximum specific modulus of rupture (MOR) and specific modulus of elasticity (MOE) of the reconstituted lumber were obtained for medium-size fiber bundles, and the maximum MOR and MOE of reconstituted cotton stalk lumber was 130.3 MPa·g^{-1}·cm^{-3} and 12.9 GPa·g^{-1}·cm^{-3}, respectively. The maximum MOR and MOE of the mulberry branch lumber was 147.2 MPa·g^{-1}·cm^{-3} and 14.7 GPa·g^{-1}·cm^{-3}, respectively. Mechanical interlocking structures in the lumber were observed *via* fluorescence microscopy, showing that phenol-formaldehyde adhesive had penetrated into several cell layers of the fiber bundle under heating and pressure. The adhesive penetration capacity was stronger when the fiber bundles were smaller in size and density. The reconstituted lumber fabricated from both materials exhibited excellent mechanical performance in the parallel direction. Therefore, reconstituted cotton stalk and mulberry branch lumber are attractive potential materials for the construction industry.

Keywords: Fiber bundle; Reconstituted square lumber; Mechanical properties; Bonding properties; Cotton stalk; Mulberry branch

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INTRODUCTION

A world-wide shortage of large-diameter lumber is intensifying, which creates a serious imbalance between the global supply and the demand for wood. Agricultural straw material currently represents an interesting potential replacement for wood and has garnered increasing attention from researchers and developers (Reddy and Yang 2005 2007). Wan (1995) analyzed small-diameter lumber and found that its mechanical properties, painting performance, and processing characteristics were nearly the same as mature, larger-diameter wood. The technologies traditionally utilized are not well-suited to small-diameter wood and branches, leading to low utilization and low product qualification rates. Reconstituted lumber represents a potential approach for improving the value-in-use and utilization ratio of renewable, small-diameter wood resources.

Reconstituted lumber is generally made from small-diameter lumber and natural straw materials, which are transformed to scrim-shaped fiber bundles through crushing processes. The scrim-shaped fibers are not fractured along the grain and interconnected in the vertical grain direction. Then they are dried, glued, formed, and hot-pressed into man-made wood with cubic shapes (Wen 2007). Reconstituting lumber does not change the orientation of the fibers, and it retains the fundamental characteristics of the raw materials. In this way, the resulting products retain the aesthetically pleasing texture of solid wood.

Reconstituted lumber, consisting of small-diameter wood and branches, has been investigated by several researchers. Lun *et al.* (2006) investigated the effects of pressure, hot-pressing time, hot-pressing temperature, and resin content on the properties of *Salix* reconstituted lumber and the optimum processing parameters were obtained. Natural agriculture straw and stalk have chemical components and mechanical and physical properties similar to wood, and they can be used to partially replace wood as a raw material. Chen *et al.* (2013) made mulberry branch reconstituted lumber with excellent mechanical properties using phenol-formaldehyde (PF) resin. Song *et al.* (2013) fabricated reconstituted panels using crushed cotton stalk bundles and found that the mechanical properties of the panels met or exceeded the requirements of the Chinese national standard GB/T 4897.2 (2003) for particleboard. Chen *et al.* (2014) studied the effects of the fiber compression ratio and pressure on the physical and mechanical properties of reconstituted poplar panels made by high-frequency hot-pressing technology, and a desirable performance was obtained under a compression ratio of 20% and a hot-pressing pressure of 2.0 MPa. Reconstituted bamboo panels exhibit better mechanical properties than other agricultural stalk reconstituted panels (Qin and Yu 2009). Dai (2012) fabricated hot-pressed reconstituted bamboo panels and found that the hot-pressing pressure and duration have noticeable effects on the mechanical properties.

Other researchers have investigated the influence of fiber morphology on reconstituted panel and lumber performance. Ge (2014) fabricated reconstituted straw lumber using PF adhesive and found that the process parameters were the key factors affecting the material's mechanical properties. Zhang *et al.* (2011) used *Neosinocalamus affinis* as the raw material and investigated the influence of the crushing degree of raw material between rollers on the performance of the resulting reconstituted bamboo-based panels. It was found that crushing 3 times was better to achieve higher compression strength and crushing 7 times was better to reach higher bending strength and water resistance. Jin and Kang (1998) studied the mechanical properties of reconstituted lumber made from different wood species and concluded that the geometrical morphology of the fiber bundles greatly affected the mechanical properties. Rao (2003) observed the effect of bundle morphology on the bending modulus of rupture (MOR) and modulus of elasticity (MOE) of reconstituted poplar and bamboo lumber to find that the overall performance of reconstituted lumber was optimal when the poplar and bamboo bundles are crushed eight times. Gu (2008) studied various approaches for manufacturing wood-bamboo composites and found that increasing the degree of fineness of wood and bamboo bundles enhanced their inner structure uniformity and bonding strength, and ultimately improved the mechanical strength of the composites. In addition, the mechanical properties of fiber bundle/plastic composites are significantly improved by increasing the aspect ratio of fiber bundles (Thamae *et al.* 2008; Migneault *et al.* 2009; Qi *et al.* 2010).

Previous studies have primarily focused on reconstituted composite panels that are relatively thin, while research on thicker reconstituted lumber made of natural agriculture straw and stalks is very limited. The influence of the fiber bundle morphology on its mechanical properties warrants further investigation. In this study, reconstituted square lumber (RSL) samples were manufactured using cotton stalk bundles and mulberry branch bundles of different slenderness (length-to-thickness) ratios after crushing between rollers. The effect of fiber bundle morphology on the mechanical and bonding properties of the reconstituted lumber was determined. The results provide guidance for manufacture process and future applications of thick RSL.

EXPERIMENTAL

Materials

A six-roll crusher machine (Northwest A&F University, Yangling, China; Fig. 1a) was used to crush the cotton stalks and mulberry branches into fiber bundles. A four-side hot pressing machine (Northwest A&F University, Yangling, China; Fig. 1b), modified from two-side hot pressing machine (QD-100, Man-made Board Factory, Shanghai, China), was used to fabricate reconstituted square lumber. Universal testing machine (CMT5504, Xin Sansi, Shenzhen, China) was used to test mechanical properties.

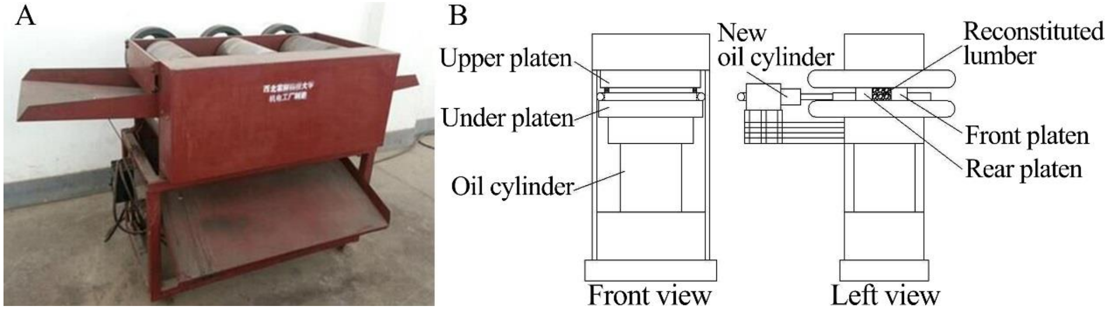

Fig. 1. (a) Six-roll crusher and (b) schematic diagram of the four-side hot pressing machine

Table 1. Fiber Type and Sizes Distribution of Crushed Fiber Bundles

Material	Bundle Size	Abbreviation	Average Width (mm)	Average Thickness (mm)	Average Slenderness (L/T) Ratio [a]
Cotton stalk	Thick	M_1	13.6	6.5	65.3
	Medium	M_2	7.6	4.9	88.4
	Thin	M_3	4.1	2.8	154.4
Mulberry branch	Thick	S_1	11.2	5.5	78.6
	Medium	S_2	6.9	4.8	89.6
	Thin	S3	3.9	3.6	142.2

[a] Note: L/T is Length-to-thickness

Phenol-formaldehyde adhesive with a solid content of 46% was provided by the Tai-er Company in Beijing, China. Cotton stalks and mulberry branches were obtained from a local farmland in Yangling, Shaanxi Province, China. The cotton stalks originated from hybrid cotton and had a culm diameter of 10.6 mm to 17.5 mm and a dry density of 0.3 g/cm^3. Mulberry branches were manually collected with a culm diameter of 10.4 mm to 16.3 mm and a dry density of 0.5 g/cm^3. The average moisture content after air-drying was 11.2% for cotton stalks and 9.1% for mulberry branches. The offshoots and roots of the cotton stalks and mulberry branches were removed before processing. To fit the size limitations of the hot press machine, the raw materials were cut into sections of 400 mm in length with a regular circular saw and then placed into boiling water to steam and soften. The moisture content of the cotton stalks and mulberry branches after cooking was 50.8% and 81.5%, respectively (Shi 2015). The scrim-shaped fiber bundles were prepared by adjusting the crushing times of the roller crusher. The crashed bundles were divided into three groups (thick, medium, and thin) according to crushed degree. Fifty fiber bundles from each group were randomly selected and their thickness was measured using digital caliper, and the average of thickness was used here to calculate length-to-thickness (L/T) when the length of fiber bundle is fixed and is 400 mm (Table 1). Figure 2 shows the finished crushed fiber bundles, and their respective sizes are listed in Table 1.

Fig. 2. Cotton stalk and mulberry branch fiber bundles with different L/T ratios. Thick cotton stalk (M_1), medium cotton stalk (M_2), thin cotton stalk (M_3), thick mulberry branch (S_1), medium mulberry branch (S_2), and thin mulberry branch (S_3)

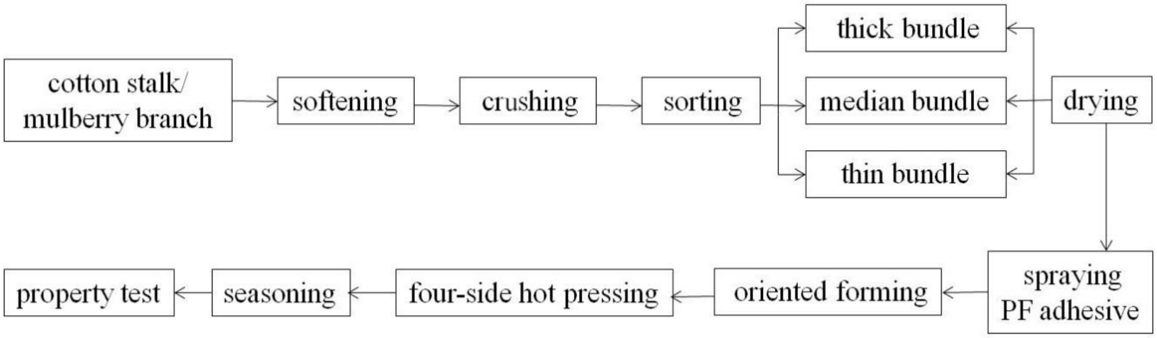

Fig. 3. Schematic diagram of the reconstituted square lumber preparation process

Methods

Reconstituted square lumber preparation process

The manufacture process of reconstituted square lumber is shown in Fig. 3. The bundles were firstly dried at 103 °C until the moisture content was approximately 6%. Cotton stalk or mulberry branch bundles in the same size groups were assembled by oriented forming, and reconstituted square lumber samples with dimensions of 400 × 40 × 50 mm^3 were produced *via* hot-pressing process under the following conditions: density of

0.70 g/cm^3, adhesive content of 10%, and hot pressing temperature of 180 °C. Each mat was pre-pressed for 15 min under 15 MPa to 20 MPa and then compressed for 20 min in front and rear platens under 8 MPa to 13 MPa pressure to ensure the desired width. This process was followed by compression for 20 min in upper and under platens under 5 MPa to 8 MPa to ensure the desired thickness (controlled via a thickness gauge).

Mechanical properties

Chinese national standard methods were employed to test mechanical properties. The density was measured according to GB/T 1933 (2009), the compression strength was referred to GB/T 1935 (2009), and the MOR as well as MOE were tested according to GB/T 1936 (2009). Six duplicates were used for all the test, and analysis of variance (ANOVA) was applied to analyze all the experimental data. The specific strength (strength divided by density) and specific modulus (modulus divided by density) were mean values used to eliminate the potential effect of density on mechanical performance (Rao 2003). Only the mechanical properties parallel to the grain were measured because of the limited size of the square lumber samples. Figure 4 shows the cotton stalk and mulberry branch samples that were subjected to bending property testing.

Fig. 4. Bending test specimens of lumber made from cotton stalks and mulberry branches

Fluorescence microscopy (FM)

Thin cross-sectional and longitudinal sample sections containing whole bond-lines were cut by a blade, and then the bond-line was observed under FM at wavelengths of 330 nm to 380 nm. The examined surface was kept clean during the preparation process to ensure accurate results.

The quantitative indicator of adhesive penetration capacity in this study was effective penetration (EP). The FM images were analyzed by threshold processing, *i.e.*, digital image processing in analysis software (Image-J, National Institutes of Health, Bethesda, USA), and the EP of the PF bond-lines in different types of reconstituted square lumber was calculated in Image-J and Origin programs (OriginLab, Hampton, USA). Effective penetration was defined as the total area of the penetrated adhesive detected in the interphase region divided by the width of the observed bond line (Liu 2014),

$$EP = \frac{\sum_{i=1}^{n} (A_i)}{L_0} \quad (1)$$

where A_i is the area of adhesive in object *i* (μm^2), *n* is the number of adhesive objects, and L_0 is the width of the bond-line (μm).

RESULTS AND DISCUSSION

Analysis of Mechanical Properties

Influence of material types on the mechanical properties of reconstituted square lumber

The mechanical properties of the RSL samples are shown in Table 2 and Fig. 5. The mulberry branch RSL exhibited a higher specific MOR, specific MOE, and specific compressive strength than the cotton stalk RSL.

Microstructural and chemical components of raw materials are major factors that affect mechanical properties of RSL (Jing and Kang 1998). Cotton stalks and mulberry branches were transformed to scrim-shaped fiber bundles using the crushing process to manufacture reconstituted square lumber where the characteristics of the raw materials were successfully retained. Previous study (Song *et al.* 2013) have indicated that the density and strength of mulberry branch are higher than those of cotton stalk. Likewise, the mulberry branch RSL samples in this study showed better mechanical properties than the cotton stalk RSL under the same conditions.

Table 2. Mechanical Properties of Reconstituted Square Lumber

Mechanical Properties	Cotton Stalk RSL			Mulberry Branch RSL		
	M_1	M_2	M_3	S_1	S_2	S_3
Specific MOR (MPa·g^{-1}·cm^{-3})	113.2	130.3	127.9	124.2	147.2	144.5
Standard deviation	6.2	9.6	8.2	6.2	14.1	18.3
Coefficient of variation (%)	5.0	7.0	6.0	5.0	10.0	13.0
Specific MOE (GPa·g^{-1}·cm^{-3})	11.8	12.9	12.9	14.5	14.7	14.3
Standard deviation	0.60	1.15	0.17	0.73	1.11	1.06
Coefficient of variation (%)	5.0	9.0	1.0	5.0	8.0	7.0
Specific compressive strength (MPa·g^{-1}·cm^{-3})	56.6	51.6	55.5	75.4	74.3	71.1
Standard deviation	5.8	4.7	8.0	9.6	9.9	6.7
Coefficient of variation (%)	10.0	9.0	15.0	13.0	13.0	9.0

Table 3. Analysis of Variance Results

Sources of Variation		Df	Specific MOR				Specific MOE				Specific Compressive Strength			
			SS	MS	F	Sig.	SS	MS	F	Sig.	SS	MS	F	Sig.
M	Inter-class variance	2	1026.4	513.2	7.8	**	7.7	3.9	10.4	**	123.0	61.5	5.5	*
	Intra-group variance	15	985.5	65.7			5.6	0.4			169.0	11.3		
	Total variance	17	2011.9				13.3				292.0			
S	Inter-class variance	2	1824.9	912.4	5.8	*	0.8	0.4	0.6	/	616.6	308.3	0.4	/
	Intra-group variance	15	2344.7	156.3			9.4	0.6			10541.2	702.8		
	Total variance	17	4169.6				10.2				11157.8			

Note: $F_{0.10}$ (2, 15) = 2.70, $F_{0.05}$ (2, 15) = 3.68, $F_{0.01}$ (2, 15) = 6.36

*α = 0.05, the variance is a significant difference

**α = 0.01, the variance is a highly significant difference

Degree of freedom (Df), sum of squares (SS), mean square (MS), significance (Sig.), modulus of rupture (MOR), and modulus of elasticity (MOE)

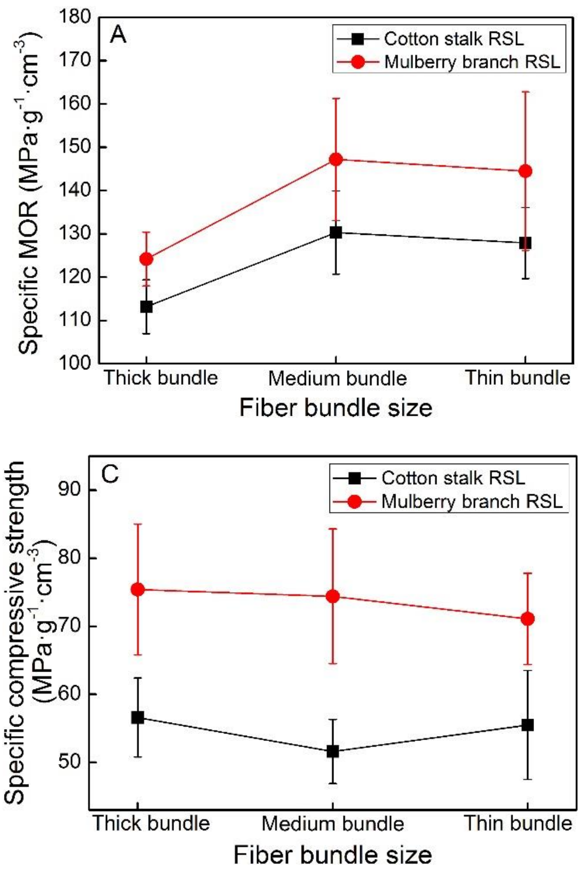

Fig. 5. Effect of the fiber bundle size on (a) specific MOR, (b) specific MOE, and (c) specific compressive strength of reconstituted square lumber

Influence of fiber bundle size on the mechanical properties of RSL

The analysis of variance results are listed in Table 3. The size of cotton stalk bundles significantly affected ($p = 0.005$) the specific MOR of the RSL and highly affected ($p = 0.001$) its specific MOE and had a significant influence ($p = 0.016$) on its specific compressive strength parallel to the grain. The size of mulberry branch bundles also significantly affected ($p = 0.014$) the specific MOR of the resulting RSL and slightly affected its specific MOE and specific compressive strength parallel to the grain.

For both cotton stalk and mulberry branch RSL, the specific MOR and specific MOE were dramatically improved when the bundle size was changed from thick (M1 and S1) to medium (M2 and S2) (Fig. 5a, b). When the material was thin (M3 and S3), the specific MOR and specific MOE slightly decreased compared with the other two groups. Medium and thin bundles had larger surface areas than thick bundles, which enabled better contact between the adhesive and fiber, allowing the adhesive to penetrate the material more easily. The paved bundles made from medium and thin bundles were also more easily compressed and molded, making the resultant structure of the compressed RSL compact and uniform; this effect was apparent in the cross-sectional images of the samples shown in Fig. 4. Because of the large size and rigidness of the thick bundles, plastic deformation was limited during hot pressing and voids/spaces formed between the junction surfaces of the bundles. Because of the relatively small specific bundle area, the adhesive did not readily penetrate the inner structure of the bundle and mostly stayed in the void space between the bundle junction surfaces, forming thick bond-lines between the bundles under compression. The low specific MOR and specific MOE measured in the thick bundle RSL samples were attributed to these void/space and bond-line issues. This phenomenon was more obvious in the mulberry branch RSL.

As shown in Fig. 5c, the specific compressive strength of the mulberry branch RSL minimally decreased as the slenderness ratio of the crushed bundle increased. There was no significant difference ($p = 0.016$) between the specific compressive strength of cotton stalk RSL made from thick or thin bundles, and the specific compressive strength was the lowest in medium-size bundles. The crushed bundle used to produce RSL samples was not fractured in the grain direction; therefore, the original mechanical strength was retained. Consequently, there was less material failure and a higher compressive strength when the bundles were thicker. Conversely, thinner bundles facilitated stronger and more uniformed binding. Thus, the shape and size of bundles had relatively little effect on specific compressive strength.

In summary, RSL made from medium-size crushed fiber bundles have better mechanical properties including specific MOR and specific MOE. The shape and size of the bundle exhibited less of an effect on the specific compressive strength.

Microscopic Structures of Reconstituted Square Lumber

Cross sections of the cotton stalk and mulberry branch RSL samples are shown in Fig. 6 (under 40x magnification). Clearly, the crushed fiber bundles were compressed radially and tangentially in the RSL samples.

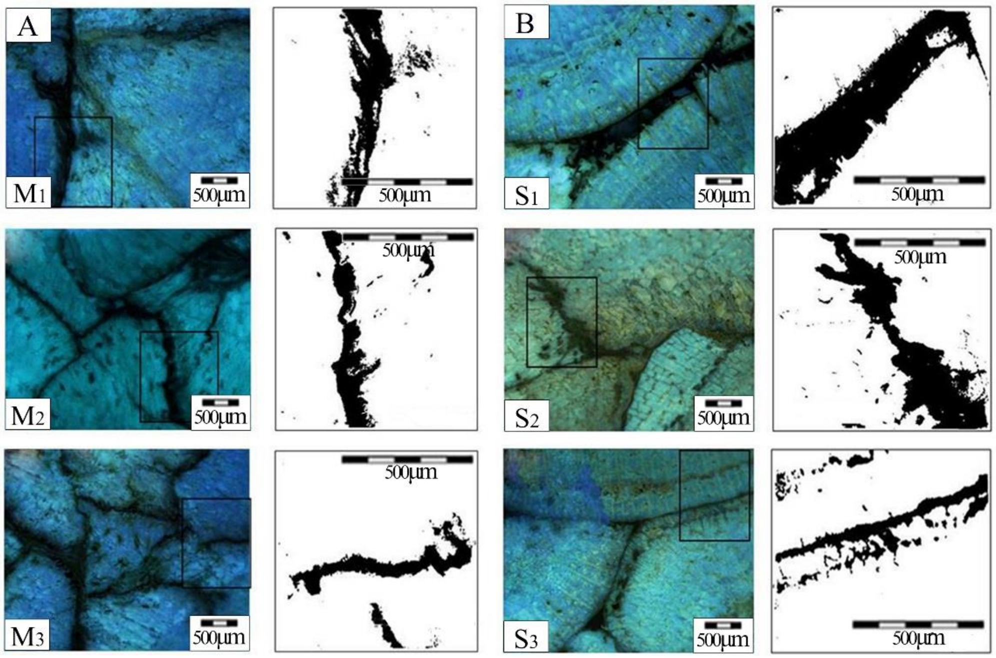

Fig. 6. FM and thresholding images of RSL cross sections of (A) cotton stalk RSL and (B) mulberry branch RSL

Vessels were highly compressed, and wood rays were irregularly distorted. This phenomenon was more obvious as the slenderness ratio of the fiber bundles increased, and it was especially pronounced in the cotton stalk samples. The PF adhesive migrated from the bond-lines to the adjacent layers of cells mostly by infiltration, which enabled larger contact interface and stronger mechanical interlocking between the fiber material and adhesive (Liu 2014). Mulberry branch bundles with lower slenderness ratios tended to retain their shape during hot-pressing, which may have caused voids at the bundle contact interfaces that resulted in thicker adhesive layers and non-uniform structures in the finished RSL.

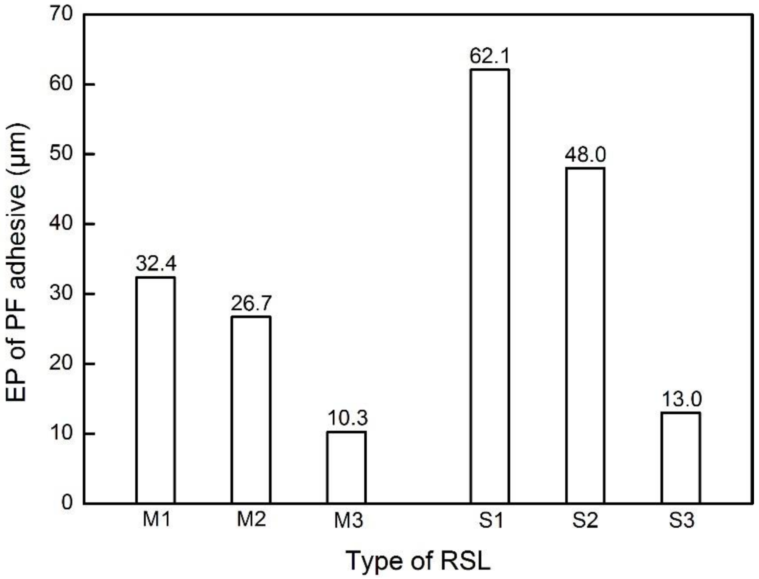

Fig. 7. Effective penetration (EP) of phenol-formaldehyde (PF) adhesive at the bonding interfaces of RSL

Phenol-formaldehyde Adhesive Penetration in RSL

The EP values of PF adhesive at the bonding interfaces of RSL samples are shown in Fig. 7. The EP decreased as the slenderness ratio increased. When fiber bundles of the same shape and size were used, the EPs of the PF adhesive in cotton stalk RSL were significantly thinner than those of the mulberry branch RSL. These differences suggest that thinner fiber bundles and lower density materials promoted effective adhesive penetration. Furthermore, fiber bundles of appropriate size and shape are important for effective distribution of adhesive in RSL to ensure strong bonding and to reduce unnecessary waste of adhesive material.

CONCLUSIONS

1. The size and shape of cotton stalk bundles showed strong effects on the specific modulus of rupture (MOR) and specific modulus of elasticity (MOE) of reconstituted square lumber (RSL) made with cotton stalks and mulberry branches. Better mechanical properties were obtained when medium-size fiber bundles were used as the raw material. During hot press, it was easier for larger *L*/*T* ratio fiber bundles to be compressed, and this effect was pronounced in the cotton stalk material compared to the mulberry branches.
2. Reconstituted square lumber made from mulberry branch bundles showed overall superior mechanical properties. The phenol-formaldehyde (PF) adhesive migrated from the bond-line to adjacent cell layers mostly *via* infiltration, which enabled larger

contacting interface and resulted in stronger mechanical interlocking between the fiber material and adhesive when the fiber bundle was thinner and material density was lower.

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REFERENCES CITED

Chen, M. L., Wang, C. G., Zhang, S. Y., and Wu, H. (2013). "The preliminary study on mulberry branches scrimber," in: *Proceedings from the 5th National Conference on Science and Technology of Biomass Materials*, Fuzhou, China, pp. 564-567.

Chen, Y. P., Wang, Z., Chang, L., and Fang, L. (2014). "Study on preparation and properties of reconstituted lumber of resin impregnated poplar veneer," *Journal of Southwest Forestry University* 34(1), 93-101. DOI: 10.3969/j.issn.2095-1914.2014.01.017

Dai, N. (2012). "Effect of hot-pressing on the properties of recombined bamboo boards," *Forestry Machinery & Woodworking Equipment*, pp. 32-36. DOI: 10.3969/j.issn.2095-2953.2012.05.010

GB/T 4897.2 (2003). "Particleboard-Part 2: Requirements for general purpose boards for use in dry conditions," Standardization Administration of China, Beijing, China.

GB/T 1933 (2009). "Method for determination of the density of wood," Standardization Administration of China, Beijing, China.

GB/T 1935 (2009). "Method of testing in compressive strength parallel to grain of wood," Standardization Administration of China, Beijing, China.

GB/T 1936.1 (2009). "Method of testing in bending strength of wood," Standardization Administration of China, Beijing, China.

GB/T 1936.2 (2009). "Method for determination of the modulus of elasticity in static bending of wood," Standardization Administration of China, Beijing, China.

Ge, L. (2014). *Study on Manufacturing Process and Mechanical Performance Prediction of Reconsolidated Square Materials of Cotton Stalk*, Master's Thesis, Northwest Agriculture & Forestry University, Yangling, China.

Gu, D. L. (2008). *The Key Process and Property Research of Wood-Bamboo Scrimber*, Master's Thesis, Nanjing Forestry University, Nanjing, China.

Jin, W. Z., and Kang, J. (1998). "Experimental research and analysis of mechanical properties of scrimber made from different wood species," *Forest Product Industry* 25(1), 24-26.

Liu, H. L. (2014). *Technology and Mechanism of VTC Modification and Bonding of Low-Density Fast-Growing Wood*, Master's Thesis, Northwest Agriculture and Forestry University, Yangling, China.

Lun, A., Gao, Z. Y., Ma, Y., Gao, F., and Xing, L. P. (2006). "Study on salix scrimber," *Forestry Science and Technology* 31(6),35-37. DOI: 10.3969/j.issn.1001-9499.2006.06.012

Migneault, S., Koubaa, A., Erchiqui, F., Chaala, A., Englund, K., and Wolcott, M. P. (2009). "Effects of processing method and fiber size on the structure and properties of wood–plastic composites," *Composites Part A: Applied Science & Manufacturing* 40(1), 80-85. DOI: 10.1016/j.compositesa.2008.10.004

Qi, C. S., Guo, K. Q., Gu, R., and Liu, Y. Y. (2010). "Preparation technology of oriented cotton stalk bunches/high density polyethylene composite panels," *Transaction of the Chinese Society of Agricultural Engineering* 26(12), 265-270. DOI: 10.3969/j.issn.1002-6819.2010.12.045

Qin, L., and Yu, W. J. (2009). "Status and prospects of reconstituted bamboo lumber," *World Forestry Research*, pp. 55-59. DOI: 10.13348/j.cnki.sjlyyj.2009.06.007

Rao, W. B. (2003). *Research of the Wood-Bamboo Composites Scrimber*, Master's Thesis, Nanjing Forestry University, Nanjing, China.

Reddy, N., and Yang, Y. (2005). "Properties and potential applications of natural cellulose fibers from cornhusks," *Green Chemistry* 7(4), 190-195. DOI: 10.1039/b415102j

Reddy, N., and Yang, Y. (2007). "Preparation and characterization of long natural cellulose fibers from wheat straw," *Journal of Agricultural & Food Chemistry* 55(21), 8570-8575. DOI: 10.1021/jf071470g

Shi, M. M. (2015). *Combing and Drying Technology of Biomass Materials on Reconstituted Square Lumber*, Master's Thesis, Northwest Agriculture & Forestry University, Yangling, China.

Song, X. Z., Li, M., Zhang, B. J, Ge, L., and Zhang, J. J. (2013). "Preparation techniques of reconsolidated square material using crop straw," *Journal of Agricultural Mechanization* 4, 231-234. DOI: 10.13427/j.cnki.njyi.2013.04.053

Thamae, T., Marien, R., Chong, L., Wu, C., and Baillie, C. (2008). "Developing and characterizing new materials based on waste plastic and agro-fibre," *Journal of Materials Science* 43(12), 4057-4068. DOI: 10.1007/s10853-008-2495-3

Wan, Y. J. (1995). "The rational way of trail material," *Guangxi Forestry Science* 11(3), 26-27.

Wen, Y. L. (2007). *Research on Manufacturing Engineering of Scrimber of Sunflower Stalk*, Master's Thesis, Central South University of Forestry and Technology, Changsha, China.

Zhang, Y. H., Meng, F. D., and Yu, W. J. (2011). "Crushing effectiveness on properties of crushed bamboo-mat composites," *China Wood Industry* 5, 1-4. DOI: 10.3969/j.issn.1001-8654.2011.05.001

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