Mechanical Properties of Mulberry Branch Reconstituted Square Lumber

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Reconstituted square lumber (RSL) was fabricated using mulberry branch as the raw material and polymeric diphenylmethane isocyanate (P-MDI) as the adhesive, and its mechanical properties were investigated. By using single factor and orthogonal experiments, the optimal parameters to produce RSL had 10% glue content, 160 °C hot-press temperature, and a 45 min hot-press time. The density distributions along with width, thickness, and length directions were scanned with DENSE-LAB X (density profile measuring system). Density was a significant factor that influenced the performances of mulberry branch RSL. The amount of glue also greatly affected the internal bond strength (IB), modulus of elasticity (MOE), modulus of rupture (MOR), and the 2-h thickness swelling rate of water absorption (TS_{2h}) of RSL. Hot-press time affected the TS_{2h} of RSL, but did not have a significant effect on the MOE, MOR, and IB of RSL. Hot-press temperature had an effect on the MOR of RSL, which significantly influenced the TS_{2h} of RSL and slightly affected its MOE and IB. The density distribution of RSL was steep and flat in the width direction, steep in the thickness direction, and uniform in the length direction.

Keywords: Mulberry branch; RSL; Hot-pressing; Property; Board density

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INTRODUCTION

The demand for construction materials continues to rise, and the short supply of lumber is a common problem in China. The exploration of new types of construction materials is essential for fast growing countries (Tang and Song 2013). The emergence of scrimbing technology can efficiently make use of renewable small-diameter bioresources, such as mulberry and other small bushes. Some scrimbing machines are designed for small-diameter trees, which are crushed. Crushed materials do not have woody tissues along the grain instead of interconnecting in the vertical grain direction (Coleman 2002). The fiber bundles from these materials undergo a series of drying, gluing, paving, and hot-pressing steps until they finally are turned into reconstituted lumber (Zhang *et al.* 2016). Many studies have been done in the preparation of reconstituted lumber from small-diameter trees or crop stalks. Wen and Chen (2007) extensively studied the hot-press process of reconstituted lumber using sunflower stems as raw materials. The operational parameters were obtained under the conditions of 10% (glue), 120 °C (hot-pressing temperature), 4.5 MPa (pressure), and 19 min (hot-pressing time).

Reconstituted square lumber (RSL) is a recently innovated material. Song *et al.* (2013) first prepared RSL using cotton stalks as raw material. The next year, Song *et al.*

(2014) explored machining properties of RSL made from cotton stalk and found that choosing rational processing methods and parameters could improve the RSL quality and efficiency of processing. Ge (2014) modified the two-side hot pressing machine by increasing the lateral pressure apparatus when cotton stalk RSL was fabricated. Zhang *et al.* (2016) studied the influence of fiber bundle morphology on the mechanical and bonding properties of cotton stalk RSL. The dimensional stability and usage of cotton stalk RSL was investigated, and it was found that it can be used as a raw material in furniture manufacture (Zhang *et al.* 2015). Bai (2015) fabricated mulberry branch and cotton stalk RSLs, with phenol-formaldehyde (PF) and P-MDI as adhesives, and compared their physical and mechanical strengths. Mulberry branch RSL has higher mechanical strengths than cotton stalk RSL. Chen *et al.* (2010) prepared scrimber, using high-frequency and contact hot-pressing, to study RSL density distribution. The results showed that under the different hot-pressing techniques, density distribution was different in the directions of length, width, and thickness. Mulberry branches are the by-products in the silk industry in the rearing of silkworms. In 2008 there were 0.8 million ha of mulberry fields and 4.4 million tons of mulberry branch by-products in China alone (Chen *et al.* 2013). Although mulberry branch resources are quite rich, their utilization rate is still quite low. When these branches are put to better use to save wood resources, the economic benefit will be very considerable (Li 2005; Li *et al.* 2011a).

The cellulose content of mulberry branch is 41.5%, which makes it promising as a raw material of RSL (Li and Lei 2016). Meanwhile, the lignin content of mulberry branch is relatively high, making the cohesive force that can be developed by heat-pressure forming favorable (Song *et al.* 2003). Mulberry branches have a beautiful texture and fine mechanical properties, therefore fabricating RSL from mulberry branches is a viable approach for providing a new source of timber (Shang *et al.* 1998).

Hot-pressing is an important process that could affect the quality of scrimber. The density distribution inside the scrimber is a key parameter that influences its physical and mechanical properties (Zhang and Yu 2009). The objective of this study was to analyze the density distribution and performance of mulberry branch RSL using single factor and orthogonal tests to determine the optimal process parameters.

EXPERIMENTAL

Materials

Mulberry branches were collected in the Northwest region of China (East longitude 108.12, north latitude 34.92). The diameters were 10.4 mm to 16.3 mm for the one-year-old branch. The basic density of these branches is 0.49 g/cm^3 and the moisture content (MC) is 9.1%. The branches were cut into segments that were 420 mm in length, and they were softened in boiling water for 12 h. The barks were removed and the branches were crushed for medium fiber bundles by a six-roll crusher (Northwest A&F University, Yangling, China) (Zhang *et al.* 2016). After drying, the fiber's MC was 8%. A P-MDI adhesive (The Novofibre Company, Yangling, China) contained isocyanate radical (-NCO) of 30.5-32.5%. A four-sided hot press machine (Northwest A&F University, Yangling, China; Fig. 1) was used to produce the reconstituted square lumber (RSL).

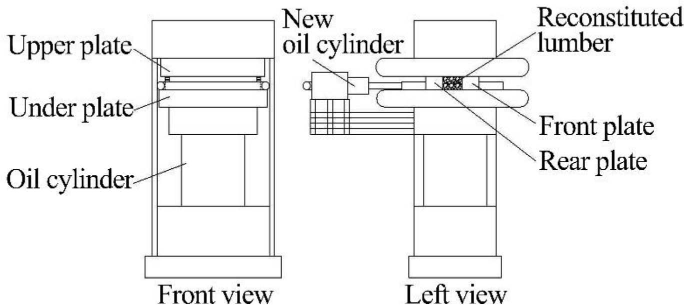

Fig. 1. Schematic diagram of the four-sided hot press machine

Methods

The hot-pressing of mulberry branch RSL

The mulberry branch bundles were assembled in an oriented way, and RSL that were 420 mm × 50 mm × 50 mm in size were produced (Zhang *et al.* 2016). In the four-sided hot-pressing process, mulberry branches were preloaded with the upper and under plates and were then pressed to the target width using front and rear plates. The hot press curve is shown in Fig. 2.

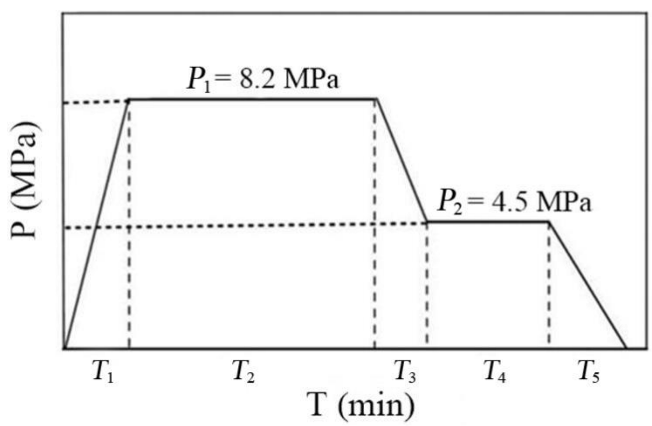

Fig. 2. The hot press curve for producing RSL; T_1 is machine closure time of approximately 40 s, T_2 and T_4 are hot-pressing times within the scope of the test values, T_4 is constant for 5 min, and T_3 and T_5 are the decompression times

Testing procedures

The single factor experiment was used to analyze the parameter influence on the RSL properties. Its scheme is shown in Table 1. Three replications were performed for each group.

Table 1. Single Factor Experiment Scheme Used in the Analysis

Single Factor with 4 Levels					Fixed Factors			
Glue (%)	6	8	10	12	--	0.7	40	160
Density (g/cm^3)	0.6	0.7	0.8	0.9	10	--	40	160
Time (min)	35	40	45	50	10	0.7	--	160
Temperature (°C)	140	150	160	170	10	0.7	40	--

An orthogonal experimental design was used to determine the optimal process parameters. The test scheme is shown in Table 2 and the materials in Fig. 3. The tests were repeated five times. All data were processed by SPSS (IBM, Version 20, Chicago, America), using the analysis of variance (ANOVA).

Table 2. The Orthogonal Experiment Scheme for RSL

Test Number	Glue (%)	Density (g/cm^3)	Time (min)	Temperature (°C)
1	6	0.6	35	150
2	6	0.7	40	160
3	6	0.8	45	170
4	8	0.6	40	170
5	8	0.7	45	150
6	8	0.8	35	160
7	10	0.6	45	160
8	10	0.7	35	170
9	10	0.8	40	150

Fig. 3. The mulberry branch RSL used in the orthogonal experiment

Measurement of RSL mechanical properties

The modulus of elasticity (MOE), modulus of rupture (MOR), internal bond strength (IB), and the 2-h thickness swelling rate of water absorption (TS_{2h}) of mulberry branch RSLs were measured according to the standard method GB/T 17657-2013 (2014). The universal testing machine (CMT5504, Xin Sansi, Shenzhen, China) was used to determine the mechanical properties. The size used for the MOE and MOR measurements was 200 mm × 50 mm × 10 mm, and the size for IB or TS_{2h} measurements was 50 mm × 10 mm × 10 mm.

Measurement of density distribution

The size of test specimen was 50 mm × 50 mm × 50 mm. A DENSE-LAB X (D-31785, Electronic Wood Systems, Hamel, Germany) was used to measure the density distributions. As shown in Fig. 4, the sample was confined in the frame with 0.1 mm increments. Samples passed through the measuring devices, the X-ray tube, and detector, step by step. The test data was then collected.

Fig. 4. The experimental process of density distribution

RESULTS AND DISCUSSION

The Analysis of Single Factor Test Results

The process parameters that affected the performance of mulberry branch RSL are shown in Fig. 5. Density was a significant factor that influenced the performances of mulberry branch RSL. The influence of the amount of adhesive on mechanical properties was positive for any amount of glue less than 10%. For amounts of glue greater than 10%, the influence was negative. Within a certain range, the increased amount of glue made for more contact area with fiber bundles and reduced the void space in the RSL so that the property improved. When there were no more cross-linking reactions occurring, the excessive isocyanate reacted with water, resulting in less influence (Li 2012). An excessive amount of adhesive also can cause overflow. Therefore, the strength would not increase.

The effects of hot-press time on the mechanical properties increased initially, and then decreased. Prolonged pressing under high temperatures would not improve the performance. The hot-pressing temperature usually improves the property when it is less than 160 °C. At any temperature above 160 °C, the strength of RSL fell with the temperature. Although the IB of RSL still increased with the increase of temperature, its increment rate was significantly lower after 160 °C.

After the analysis, it was suggested that the glue amount was between 6% and 10%, hot-pressing time between 35 min and 45 min, and hot-press temperature between 150 °C and 170 °C.

The Analysis of Orthogonal Experiment Results

The results from the orthogonal experiment are shown in Table 3.

Table 3. The Orthogonal Experimental Results

Test Number	MOE (GPa)	MOR (MPa)	IB (MPa)	TS_{2h} (%)
1	8.2	79.1	0.33	3.7
2	11.1	114.7	0.75	2.9
3	12.0	116.0	1.09	1.9
4	8.7	78.5	0.98	3.0
5	11.6	118.8	1.21	2.8
6	12.5	130.1	1.53	2.1
7	9.1	90.5	1.04	2.4
8	11.1	108.0	1.28	2.8
9	12.8	137.3	1.52	2.1

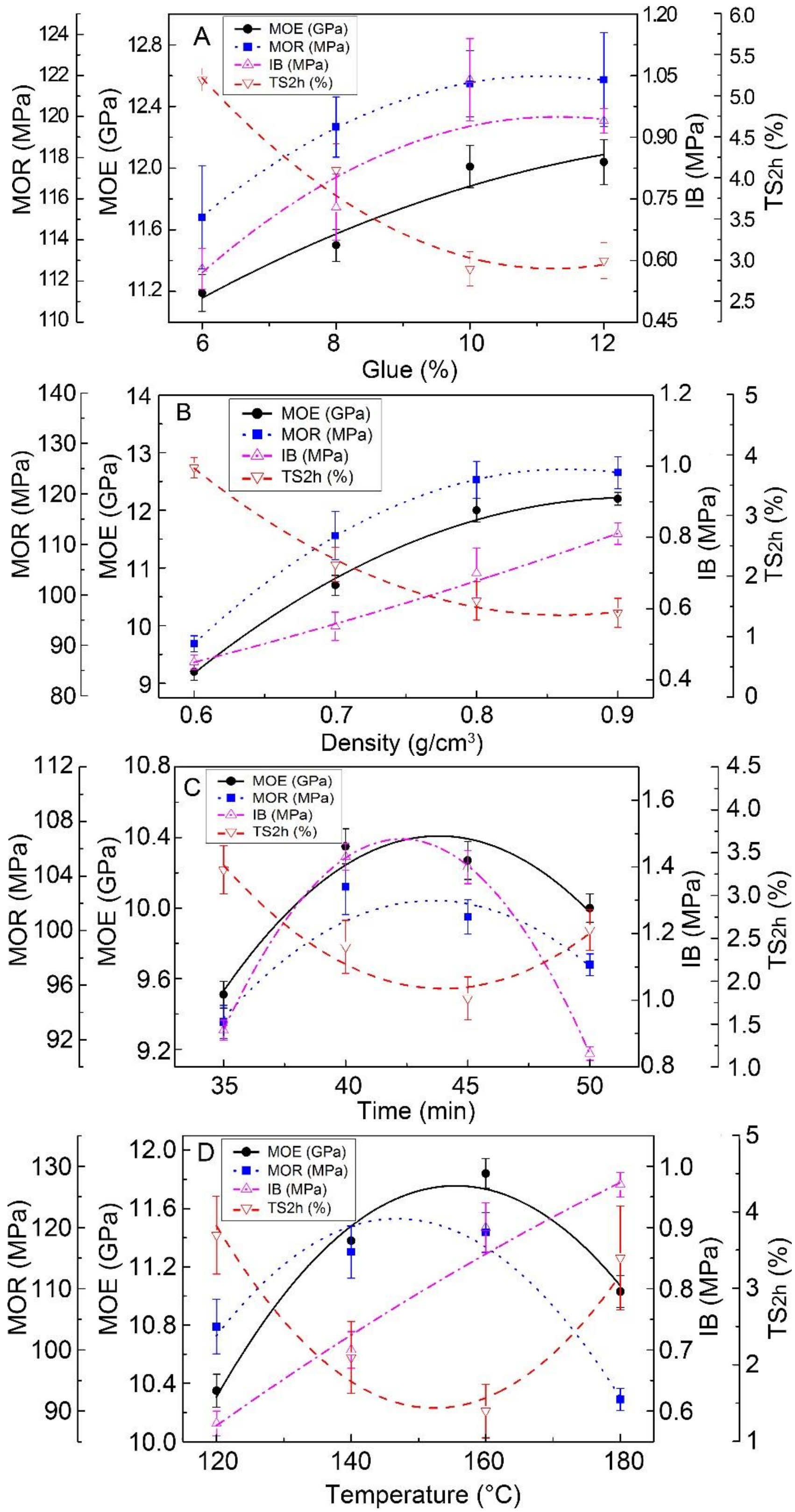

Fig. 5. The effect of process parameters on mulberry branch RSL properties in (a) the effect of glue amount on the RSL properties, (b) the effect of density on the properties, (c) the effect of hot-pressing time on the properties, and (d) the effect of hot-pressing temperature on RSL properties

The effect of parameters on MOE of RSL

The results of variance analysis on the MOE of RSL are presented in Table 4. The density and amount of glue significantly affected the MOEs. However, the hot-press time and hot-press temperature have less effect on the performance.

Table 4. The Analysis of Variance (ANOVA) of MOE

Sources of Variation	SS	DF	MS	f-value	P-value
Amount of Glue	3.0	2	1.5	3.5	0.040
Density	112.2	2	56.1	131.3	0.000
Time	0.8	2	0.4	0.9	0.403
Temperature	0.7	2	0.4	0.8	0.442
Error	15.4	36	0.4	-	-
Total	5381.4	45	-	-	-

Sum of squares (SS), degree of freedom (DF), and mean square (MS)

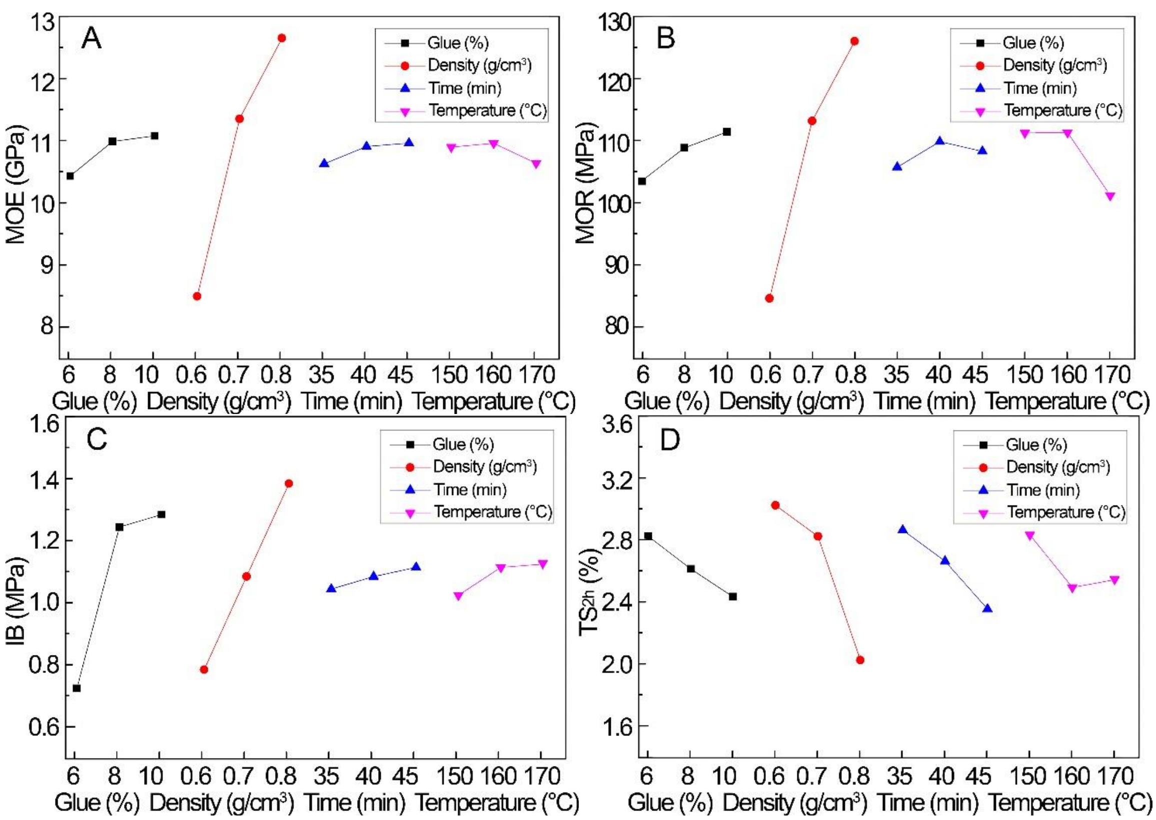

Fig. 6. The effect of parameters on properties of mulberry branch RSL, (a) the effect of parameters on the RSL MOE, (b) the effect of parameters on MOR, (c) the effect of parameters on IB, and (d) the effect of parameters on TS_{2h}

Figure 6a shows the effect of parameters on the MOE of mulberry RSL. The high MOE was achieved at the condition of 10% (glue), 0.8 g/cm^3 (density), 45 min (hot-pressing time), and 160 °C (hot-pressing temperature). The MOE increased significantly when RSL density increased from 0.6 g/cm^3 to 0.7 g/cm^3 because the increase of density leads to more contacts between wood components and the adhesive (Li *et al*. 2011b).

The effect of parameters on MOR of RSL

The results of variance analysis of RSL MOR are shown in Table 5. The density, glue amount, and hot-pressing temperature had a significant effect on MOR. The hot-press time showed the least effect.

Table 5. The ANOVA of MOR

Sources of variation	SS	DF	MS	F-value	P-value
Amount of Glue	584.5	2	292.3	3.7	0.034
Density	15998.7	2	7999.3	101.4	0.000
Time	149.3	2	74.7	0.9	0.398
Temperature	1193.5	2	596.8	7.6	0.002
Error	2841.2	36	78.9	-	-
Total	546864.0	45	-	-	-

Sum of squares (SS), degree of freedom (DF), and mean square (MS)

From Fig. 6b, the optimal MOR was obtained at 10% (glue), 0.8 g/cm^3 (density), 40 min (hot-pressing time), and 160 °C (hot-pressing temperature). The MOR fell dramatically at hot-press temperatures between 160 °C and 170 °C. The high temperature degraded hemicelluloses and reduced the MOR of RSL. At the same time, carbamate, which was the product of -NCO reacting with fiber bundles, turned into substituted urea and CO_2 (Geng 2007) under high temperature for a certain time. This process eventually resulted in the decline of its MOR.

The effect of parameters on IB of mulberry branch RSL

The results of the variance analysis of IB are shown in Table 6. The amount of glue and its density were important factors. Hot-press time and temperature did not show significant effects on the IB.

Table 6. The ANOVA of IB

Sources of Variation	SS	DF	MS	F-value	P-value
Glue	2.9	2	1.5	33.7	0.000
Density	2.7	2	1.3	30.6	0.000
Time	0.04	2	0.018	0.4	0.666
Temperature	0.08	2	0.042	1.0	0.389
Error	1.6	36	0.043	-	-
Total	59.7	45	-	-	-

Figure 6c shows that the high IB was present at 10% (glue), 0.8 g/cm^3 (density), 45 min (hot-pressing time), and 170 °C (hot-pressing temperature). From 6% to 8% glue content, the IB increased significantly. Mulberry branches were not fully contacted with adhesive, which rendered the lower IB when glue was 6% or less. With the increase of glue content, the fiber and adhesive gained more opportunities because of chemical reaction and the depth of the infiltration of the adhesive increased. An isocyanate radical (-NCO) reacted with hydroxyl (-OH) groups on the surface of the wood fiber to improve the cohesive strength (Li 2012), and the IB would be higher.

The effect of parameters on TS_{2h} of mulberry branch RSL

The variance analysis of TS_{2h} of RSL is shown in Table 7. The density and hot-pressing time had a highly significant impact on TS_{2h} ($p < 0.01$). The glue content and hot-pressing temperature had significant effects on TS_{2h} ($0.01 < p < 0.05$).

Table 7. The ANOVA of TS_{2h}

Sources of Variation	SS	DF	MS	F-value	P-value
Glue	1.2	2	0.6	4.1	0.025
Density	8.5	2	4.3	30.0	0.000
Time	2.0	2	1.0	6.8	0.003
Temperature	1.0	2	0.5	3.5	0.041
Error	5.1	36	1.1	-	-
Total	329.2	45		-	-

Figure 6d shows higher TS_{2h} values. These values were achieved at the conditions of 10% (glue), 0.8 g/cm^3 (density), 45 min (hot-pressing time), and 160 °C (hot-pressing temperature). From 0.7 g/cm^3 to 0.8 g/cm^3, the TS_{2h} decreased. The mulberry is a hardwood and its water absorption is inversely proportional to the density (Xu and Liang 1989). With the higher density, the RSL structure was compacted tightly and moisture was difficult to be adsorbed. The TS_{2h} decreased at the higher density.

The amount of glue greatly influenced the IB (P = 0.000) of mulberry branch RSL, and significantly influenced the MOE (P = 0.040), MOR (P = 0.034), and TS_{2h} (P = 0.025). With the glue amount of 10%, the optimal RSL performance was confirmed. Density was a significant factor that influenced the performances of RSL.

The hot-pressing time greatly influenced the TS_{2h} (P = 0.003), and had no significant influence on the MOE (P = 0.403), MOR (P = 0.398), and IB (P = 0.666). By controlling the hot-pressing time at 45 min, the MOR was decreased by 1.5%. The temperature of the four-sided pressing machine excessively affected the MOR (P = 0.002) of mulberry branch RSL, significantly affected the TS_{2h} (P = 0.041), and slightly affected its MOE (P = 0.442) and IB (P = 0.389). At the hot-pressing temperature of 160 °C, the MOE, MOR, and TS_{2h} were satisfactory. From 160 °C to 170 °C, the IB improved slightly.

Through the analysis, the optimum process conditions for RSL were a glue content of 10%, hot-pressing temperature of 160°C, and the hot-pressing time of 45 min.

The Optimal Process

At the densities of 0.6 g/cm^3, 0.7 g/cm3, and 0.8 g/cm^3, the RSL performance is presented in Table 7. Mulberry branch RSL showed excellent performance.

Table 7. The Performance Test Results of RSL

Density (g/cm^3)	MOE (GPa)	MOR (MPa)	IB (MPa)	TS_{2h} (%)
0.6	9.2	90.7	1.1	2.2
0.7	11.7	119.1	1.4	1.9
0.8	12.9	143.2	1.5	1.7

10% (glue), 160 °C (hot-pressing temperature), 45 min (hot-pressing time)

If the density was 0.6 g/cm^3, the MOE (9.2 GPa), the MOR (90.7 MPa), the IB (1.1 MPa), and the TS_{2h} (2.2%) would be far greater than the suggestions of the LY/T 1580-2010 (2010) standard when the oriented strand board (OSB) thickness was less than 10 mm (MOE $\geq$ 3.5 GPa, MOR $\geq$ 22.0 MPa, and IB $\geq$ 0.34 MPa). The mulberry branch RSL properties increased with the increase of density

The Density Distribution in Mulberry Branch RSL

The density distributions in the directions of the width, thickness, and length were determined with a DENSE-LAB X and are presented in Fig. 7.

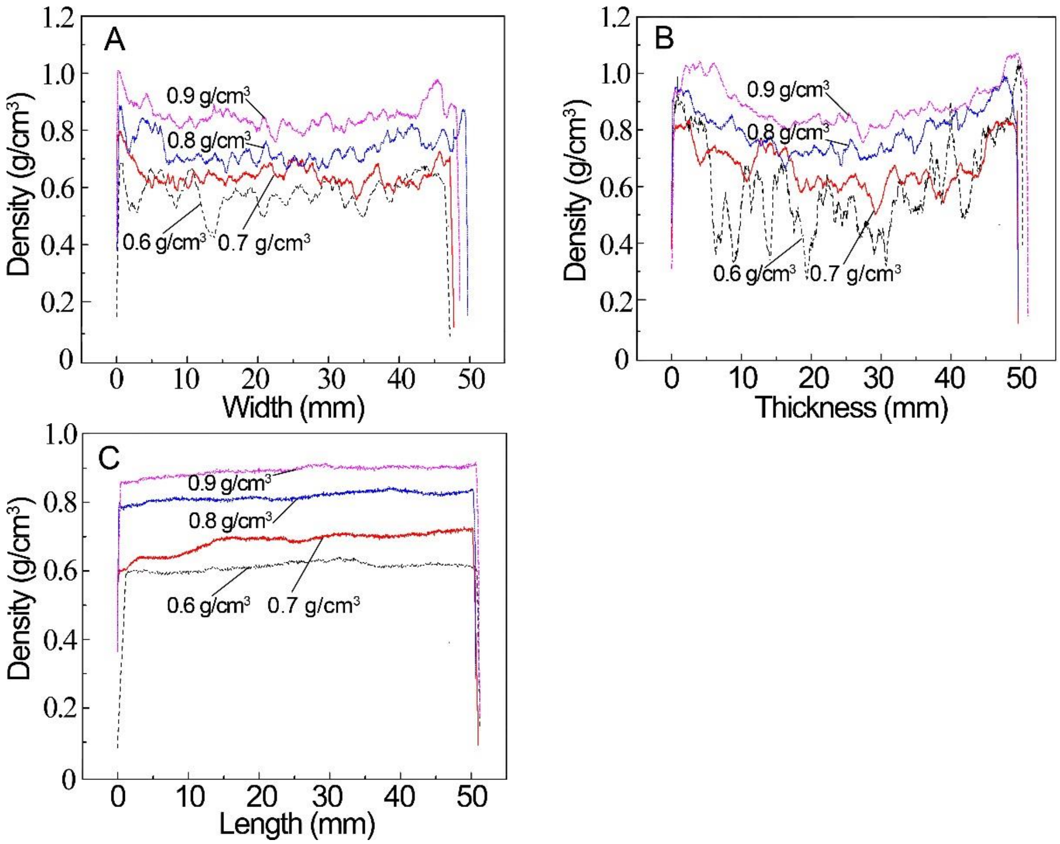

Fig. 7. The density distribution of mulberry branch RSL in (a) the width direction, (b) the thickness direction, and (c) the length direction

Density distribution of RSL in the width direction

In the width direction, the surface-core density ratio of mulberry branch RSL was 1.1. The density distribution was steep and flat from the end to rear surface (Fig. 7a). Due to an oil cylinder behind the press machine (Fig. 1), the pressure at rear plate was slightly higher than the front plate, which made the rear surface density greater. About small density RSL, the difference of surface-core layer density was smaller because its cross-section void ratio was large and the fiber bundles were easy to compress during hot-pressing.

Density distribution of RSL in the thickness direction

In the thickness direction, the surface-core density ratio of mulberry RSL was 1.3. The density distribution was steep from the top to bottom surface (Fig. 7b) because the surfaces experienced a longer hot-pressing process. The surface layer of the high density increasing rate was less than the core layer of low density (Chen 2009). The top surface density of mulberry branch RSL was less than the bottom surface.

Density distribution of RSL in the length direction

In the length direction, the density distribution was more uniform from the front to the back (Fig. 7c). Near the end of the RSL, density was slightly small because some fiber bundles of mulberry branch at the end section had not completely formed in the end. The density variation in RSL was smaller for higher densities of RSL.

CONCLUSIONS

1. The optimal hot press temperature and time for manufacturing mulberry branch RSL were 160 °C and 45 min. The optimum glue content for RSL was 10%. The density was significantly related to the performances of mulberry branch RSL.

2. The amount of adhesive greatly affected the IB of RSL and its MOE (P = 0.040), MOR (P = 0.034), and TS_{2h} (P = 0.025). The hot-pressing time also affected the TS_{2h} (P = 0.003) of RSL. However, the time of hot-pressing did not have a significant influence on the MOE (P = 0.403), MOR (P = 0.398), and IB (P = 0.666). The press temperature excessively affected the MOR (P = 0.002) of RSL and the TS_{2h} (P = 0.041), and slightly affected its MOE (P = 0.442) and IB (P = 0.389).

3. There was steep density gradient near the edges in the thickness and width directions and then stable towards the center. The density distribution of RSL was uniform in the length direction.

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