Effects of Moisture Content on Lap-shear, Bending, and Tensile Strength of Lap-jointed and Finger-Jointed Southern Pine using Phenol Resorcinol Formaldehyde and Melamine Urea Formaldehyde

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The bonding performance of the phenol-resorcinol-formaldehyde adhesive (PRF) and melamine-urea-formaldehyde adhesive (MUF) with southern pine as substrates at various moisture contents (MC) was evaluated. The results showed that bonding shear strength with MUF and PRF was negatively related to wood MC, and bonding shear strength with MUF was higher than that of the PRF. The bending and tensile strengths of finger-jointed lumber decreased with wood MC. The bending strength of finger-jointed lumber was affected more by wood than adhesive. However, both wood and adhesive exhibited the same important contribution to the tensile strength.

Keywords: Bonding behavior; Finger-jointed; Moisture content; Glue line

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INTRODUCTION

Glued Laminated Timber (Glulam) structures have been used worldwide because their dimensions can be much larger than the lumber pieces from which they were made. (Yang *et al.* 2008; Lestari *et al.* 2015). Glulam performance is related to the properties of the individual components (Kilic and Celebi 2006; Ren and Frazier 2012). The performance of the adhesive changes as time is increased, which has an important influence on the performance of the glulam. Moreover, climatic conditions, such as moisture content (MC) and temperature, have an important influence on the performance of products (Yue *et al.* 2017; Liu *et al.* 2019; Očkajová *et al.* 2019; Yue *et al.* 2020). Therefore, it is necessary to investigate the bonding performance of adhesives.

Structural adhesives used in glulam include formaldehyde, epoxy, and isocyanate (Properzi *et al.* 2001). Formaldehyde is widely used. The formaldehyde pollutes the environment, and urea-formaldehyde glulam has poor performance in water (Ringena *et al.* 2006; Park *et al.* 2009). The raw materials of phenolic resin are easy to obtain, and the adhesive has good fire resistance (Stoeckel *et al.* 2013; Klippel *et al.* 2014). However, the phenolic resin products have dark brown color that is not preferred in some applications. Also the glueline is hard and brittle. The phenolic resin demands lower MC of the wood (Na *et al.* 2005; Brunner *et al.* 2010), and its cost is much higher than the urea-formaldehyde resin. In addition to the requirement of high bonding strength and high wood failure percentage, structural adhesives must also have the properties of good durability, room temperature curing, low toxicity, reasonable price, long time storage, and convenient use (Stöckel *et al.* 2010; Clauβ *et al.* 2011; Yue *et al.* 2019).

The humidity in air can affect MC of the wood (Mitchell 2018; Hasburgh *et al.* 2019). The MC is an important factor affecting the strength of the bonded materials because some adhesives are affected by the MC (Bomba *et al.* 2014; Máchová *et al.* 2019), and it also has a certain influence on the curing time of the adhesive (Zhou *et al.* 2017, 2018). Jiang *et al.* (2017) studied Young's moduli of Chinese fir at four different MC values (10.3%, 12.2%, 14.6%, and 16.7%); the result showed that Young's moduli decreased linearly with increasing MC. The 12% MC glulam has a faster cure rate than that of the 22% MC, and it has higher final strength (Properzi *et al.* 2016).

The glue line usually is the weakest section of the glulam structures (Bomba *et al.* 2014). On lap-shear strength of laminated timber, Nadir and Nagarajan (2014) studied the bond strength of polymer vinyl acetate (PVAc) (the hardener was DORUS R 7357) with rubberwood (*Hevea* spp) and found that the wood-adhesive shear strength was 8.59 MPa, which is 64% of the strength of the solid wood. The wood failure percentage remained at 99.7%. Sterley *et al.* (2004) studied European pine shear strength with polyurethane adhesive (PUR) (one-component) in four different pressure conditions (0.5 MPa, 60 min; 1 MPa, 60 min; 0.5 MPa, 120 min; 1 MPa, 120 min) at 35% to 130% MC. The results showed that the higher pressure (1 MPa) and longer time (120 min) gave rise to higher shear strength. Moreover, kiln dry (12% MC) specimens had higher strength than 35% to 130% MC specimens. Bomba *et al.* (2013) studied the dependence of the strength increase in a bonded joint on the curing time. The result showed that the PVAc adhesives (Kleiberit 303, Rhenocoll 3W 4B, and Protovil D4) need 7 days to reach the ultimate strength. On finger joint timber, Hemmasi *et al.* (2014) studied the elastic properties of oak wood finger joints with polyvinyl acetate (one-component) and isocyanate (the hardener was benzoyl chloride) adhesives. The results showed that polyvinyl acetate had better performance than isocyanate and 10 mm length joint had better elastic properties than 5 mm length joints. Piao and Shupe (2016) compared the bending strength of finger joint composite utility poles using resorcinol formaldehyde adhesive. The results showed that the bending strength of composite poles was less than the strength of the solid wood samples but greater than the strength of finger jointed samples. Özçifçi and Yapıcı (2008) studied the influence of adhesives (PVAc, one-component; D-VTKA, one-component), wood species (beech, oak, Scots pine, poplar, and Uludag fir), and finger joint configuration (7 mm, 14 mm, and 21 mm long) on the structural performance of the finger-jointed specimens. The wood species was the greatest factor determining the performance of the finger-jointed specimens, followed by the adhesive used, and the type of joint.

The purpose of this study was to investigate the lap-shear, bending, and tensile strength of southern pine lap-jointed and finger-jointed specimens at the different MC using phenol-resorcinol-formaldehyde adhesive (PRF) and melamine-urea-formaldehyde adhesive (MUF).

EXPERIMENTAL

Materials

Commercially available southern pine (*Pinus* spp.) lumbers of 38 × 89 × 3050 mm^3 (thickness by width by length) was selected for this study because the species is widely used in modern timber construction. The pieces were free of defects. The specific gravity of southern pine wood was 560 kg/m^3 at 12% MC.

The selected lumber pieces were randomly divided into three groups (five replicate

specimens in one group), and they were kept in a condition of 50%, 70%, and 90% relative humidity (RH) at 20 °C for two weeks or more until they reached the equilibrium MC of 10%, 15%, and 20%, respectively (the initial MC was 12%). The chosen test specimens had specific gravity differences among the specimens less than 5% to minimize the effect of the specimen on the bonding and mechanical properties.

The adhesives used in this test were PRF (Shenyang Aikehaobo Chemical Co., Ltd. Shenyang, China) and MUF (Henkel Chemical Technology Co., Ltd. Shanghai, China). The properties of the two adhesives are listed in Table 1. The solid contents of PRF and MUF were 35.7% and 75%, respectively. The adhesive hardeners of PRF and MUF were 100/20 and 100/100, respectively. The hardeners were added into the adhesives and they were homogenized at 200 L/min by a mixer running for 3 min.

Table 1. Parameters of PRF and MUF Adhesives

Adhesive	Color	Main Agent/Hardener Ratio (w/w)	Solids Content (%)	pH (25 ºC)	Viscosity (mPa·s)
PRF	Dark brown	100/20	35.78	7.6	7500
MUF	Milky	100/100	75.0	5.5	1500

Lap-shear Strength Test

The two test specimens of 55 mm × 55 mm × 20 mm were brushed with PRF and MUF of 250 g/m^2 on one face to form the lap-jointed specimens. The glued area was 50 mm × 50 mm (Fig. 1). The test specimens were placed on a flat vulcanizer with a pressure of 1 MPa at room temperature (20 °C). The lap-shear strength was tested for 0.5 h, 1 h, 1.5 h, 2 h, 3 h, 6 h, 9 h, 12 h, 15 h, 18 h, 21 h, and 24 h at 10%, 15%, and 20 MC. Five specimens were used for each condition.

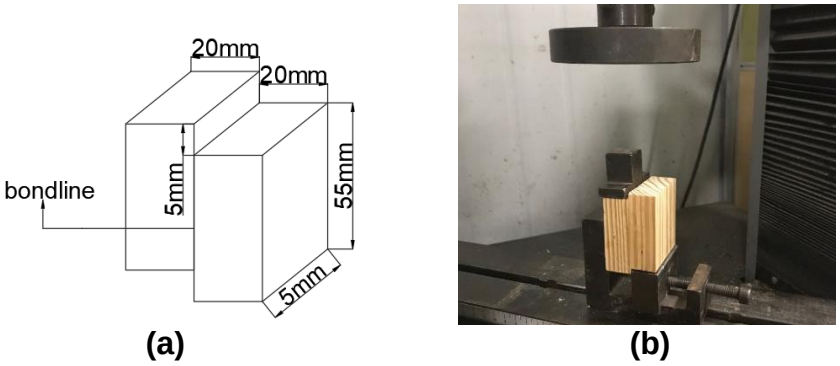

Fig. 1. The specimen dimensions (a) and test set-up in the lap-shear strength test

The mechanical properties of glued specimens were tested with the microcomputer-controlled universal testing machine (MTS Industrial Systems Co., Ltd. Shanghai, China; E45.305E). The displacement loading rate was 5 mm/min. The test was conducted at 23 ± 3 ºC and 65 ± 5% relative humidity. The shear strength was calculated according to Eq. 1,

$$f_v = \frac{Q_v}{b \times t_v} \quad (1)$$

where f_v is the lap-shear strength of the glue line, in Newtons per square millimeter; Q_v is the maximum compressive force applied to the specimens during the test, in Newtons; and b and t_v are the width and depth of the bonded overlap section, in millimeters.

The failure percentage of the lap-shear strength specimens was visually inspected using a magnifying lens. The values were determined at the lowest 10% increment.

Bending and Tensile tests of Finger Joint Lumber

The finger-jointed test specimens were 300 mm × 60 mm × 15 mm (Fig. 2a). The finger-jointed sample was placed at the center of the specimen. The section of tensile specimen was weakened near the finger-jointed area with a cross section of 30 mm × 15 mm (Fig. 2b). The finger profile details were plotted in Fig. 2c. A total of 5 replicate specimens were used for each group. The ultimate strength of finger-jointed specimens was tested at an assembly time of 24 h.

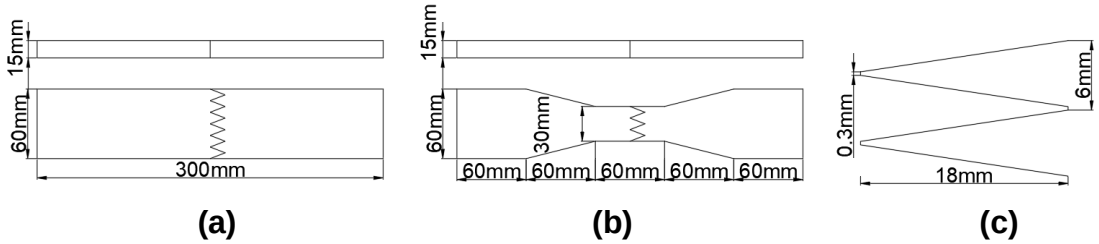

Fig. 2. Dimension of bending (a) and tensile (b) test specimen and finger profile details (c)

The bending test was conducted on the microcomputer-controlled universal testing machine (MTS Industrial Systems Co., Ltd. Shanghai, China; E45.305E). The four-point load was applied to the bending strength test (Fig. 3a). The tensile test machine was WAW-600-G microcomputer-controlled universal testing machine (MTS Industrial Systems Co., Ltd. Shanghai, China; WAW-600-G) (Fig. 3b). The bending tests and tensile tests were conducted with a speed of 5 mm/min. The bending and tensile strengths were calculated according to Eqs. 2 and 3, respectively,

$$f_m = \frac{3 \times a \times F_{\max}}{b \times h^2} \quad (2)$$

$$f_{t0} = \frac{F_{\max}}{b \times h} \quad (3)$$

where f_m is the bending strength, in Newtons/mm^2; f_{t0} is the tensile strength, in Newtons/mm^2; F_{max} is maximum force applied to the specimens during the test, in Newtons; a is the distance between a loading position and the nearest support, mm; and b and h are the width and depth of cross-section, mm.

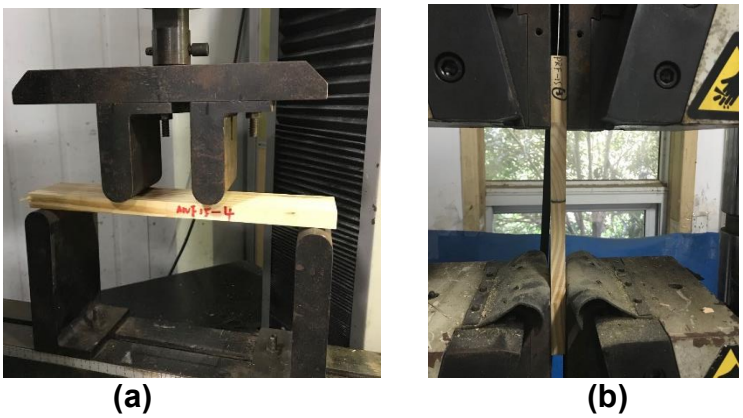

Fig. 3. Four point bending (a) and tensile (b) test

RESULTS AND DISCUSSION

Lap-shear Strength

In order to determine the curves of lap-shear strength *vs.* time, the strength was tested with 30 min intervals for the first 6 h, and then 3 h intervals to 24 h. The shear strengths of PRF and MUF glue line with press time at different MC between 10% and 20% are shown in Fig. 4a and 4b. The fitting formula (Properizi *et al.* (2016) was as follows,

$$\sigma = A_2 + \frac{A_1 - A_2}{1 + e^{\frac{t - t_0}{d}}} \quad (4)$$

where σ is the shear strength at the glue line, in Newtons/mm^2; t is the press time, in hour; and A_1, A_2, t_0, and d are the fitting parameters (Table 2).

The curing progress can be divided into three stages, including initial rapid growth, slow growth phase, and full solidification phase. During the rapid growth phase, the adhesive undergoes a transition from a liquid to a solid. Its curing strength rapidly increases. When the strength reached a certain value, it began to enter a slow growth phase, when its strength was in small increase, the adhesive began to set. After that, the adhesive solidified. The adhesive was fully cured, and its strength reached the maximum.

Table 2. Parameters of the PRF and MUF Fitting at Different Moisture Content

MC (%)	Adhesive types	Parameters				Time (h)
		A_1	A_2	t_0	d	
10	PRF	-11.37	8.25	-0.74	2.69	4.8
	MUF	-38.89	10.40	-3.83	2.99	3.1
15	PRF	-11.16	7.76	-0.95	3.09	6.1
	MUF	-11.73	9.34	-0.47	2.66	4.0
20	PRF	-20.39	7.10	-4.47	4.43	9.6
	MUF	-8.29	7.83	0.02	2.35	4.8

As shown in Fig. 4(a), the glue line shear strength of PRF-glulam increased nonlinearly with time. The finger-jointed wood at 10% MC had the highest strength increase rate as a function of time, followed by wood at 15% MC, and then 20% MC. The ultimate strengths of PRF-glulam at 10%, 15%, and 20% MC were 8.15 MPa, 7.69 MPa, and 7.07 MPa, respectively. The shear strength of wood using PRF adhesive decreased as the MC increased. The strength decrease was attributed to wood MC effects on adhesive penetration into wood and it retarded the adhesive curing. Moreover, high MC made the cell wall soften (Miki *et al.* 2008). As shown in Table 3, the wood failure percentage became higher with increasing time. At 3 h, the wood failure percentage of the PRF-glulam was 20%, indicating that the strength of PRF-glulam mainly depended on the adhesive rather than the wood at this time. At 9 h, the wood failure percentage of 10% MC was 90%, and the wood failure percentage of 15% MC and 20% MC was 80%. Thus, the strength of the PRF-glulam depended mainly on the wood at this time. In order to be used as structural components, the shear strength at the glue line should be higher than 6 MPa (BS EN 386 (2001)). At three MC, The fastest increase in strength occurred at 10% MC and it reached the standard strength requirement in 4.8 h. At 15% MC and 20% MC, the strengths reached the standard strength requirement in 6.1 h and 9.6 h respectively.

In Fig. 4(b), the ultimate lap-shear strength of MUF-glulam at 10%, 15%, and 20%

MC were 10.37 MPa, 9.36 MPa, and 7.94 MPa, respectively. The strengths and wood failure percentages of MUF-glulam were higher than that of PRF-glulam. The MUF had a better bonding performance than PRF. The lap-shear strength of MUF-glulam also decreased as the MC increased. In Table 3, the wood failure percentage of the MUF specimens were similar for each test, indicating the bonding performance of MUF adhesive was hardly influenced by the MC. After 3 h, the wood failure percentage of the MUF-glulam was 30%, higher than that of PRF. The MUF had a higher curing speed than PRF because MUF had higher solid content and higher hardener content compared with PRF (Table 1). After 9 h, the wood failure percentage was 100% at any MC. The strength value of MUF-glulam reached the standard requirements sooner than that of PRF-glulam. The MUF-glulam reached the standard requirement less than 5 h.

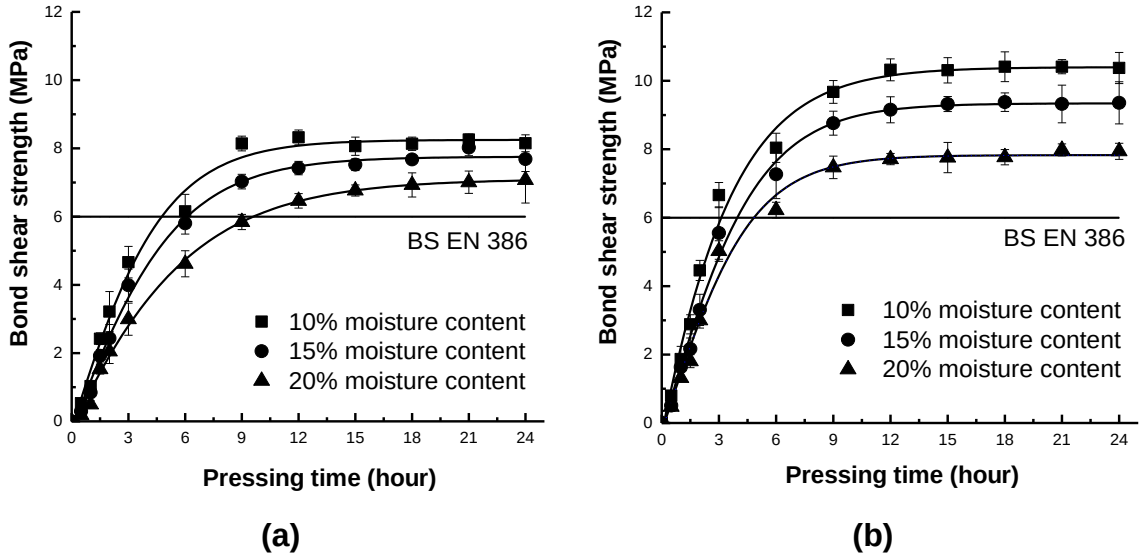

Fig. 4. Relationship between pressing time and lap-shear strength with PRF (a) and MUF (b).

Table 3. Wood Failure Percentage of the PRF and MUF at Different Pressing Time

Adhesive type	MC (%)	Wood failure percentage (%)			
		3h	6h	9h	18h
PRF	10	20	50	90	90
	15	20	50	80	90
	20	20	50	80	90
MUF	10	40	80	100	100
	15	30	80	100	100
	20	30	80	100	100

Strengths of Finger-Jointed samples

Figure 5(a) shows the bending strength of MUF and PRF finger jointed samples at 10%, 15%, and 20% MC. The bending strengths of the MUF finger-jointed samples were 70.58 MPa, 58.6 MPa, and 48.28 MPa at 10%, 15%, and 20% MC, and that of PRF-finger joint were 70.45 MPa, 58.53 MPa, and 50.7 MPa, respectively. As the MC increased, the bending strength of the PRF- and MUF-finger joints decreased linearly. The MUF and PRF had the same strength. Different adhesives resulted in similar bending strength while their wood was the same. This result indicated that the bending strengths of PRF- and MUF-finger joints were determined mainly by the wood components, rather than the adhesive.

Analysis of variation (ANOVA) test with Tukey 95% confidence intervals was used for the statistical analyses. Table 4 shows the ANOVA results of the bending strength. The P-values for PRF and MUF were 0.007 and 0.000, which was smaller than 0.05, indicating that the bending strength had significant difference in different MC.

Figure 5(b) shows the tensile strength of MUF- and PRF-finger joints at 10%, 15% and 20% MC. The tensile strengths of the MUF-finger joint were 53.6 MPa, 52.28 MPa, and 48.31 MPa at 10%, 15%, and 20% MC, respectively. The tensile strength of the PRF-finger joint was 45.83 MPa, 43.7 MPa, and 42 MPa, which were 14.5%, 16.4%, and 13.1% lower than that of MUF-finger joint. Different from bending strength, at three different MC, the MUF had higher tensile strength than PRF. As shown in Table 4, the P-values of PRF and MUF were 0.634 and 0.464, which were higher than 0.05, indicating that that the tensile strength had no significant difference in different MC. This could be attributed to the fact that the parallel to grain tensile strength was insensitive to changed MC, such that the tensile strength changed only 1% when the MC changed 1% (Tsoumis 1991). The strength difference between PRF- and MUF- finger-joint specimens could be that the adhesive was different. The tensile strength of finger-jointed specimens was related to the adhesives and the wood substrate. The adhesive affected the tensile strength. Compared with the bending strength, the adhesives in tensile specimens have stronger influence. The importance of adhesive was higher than that of wood substrate when the finger-jointed wood was subjected to tensile loads.

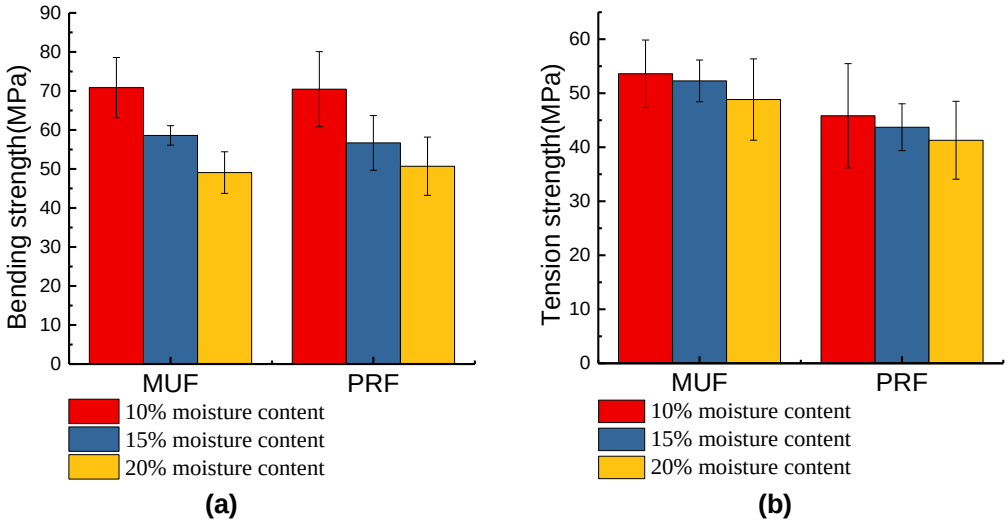

Fig. 5. Bending (a) and tensile strength (b) of finger-jointed lumber

Table 4. Summary of ANOVA Results of the Bending and Tensile Strengths

Adhesive	Treatment (MC %)	Bending strength			Tensile strength		
		Mean ± STD	P value	Remarks	Mean ± STD	P value	Remarks
PRF	10	70.45 ± 9.63	0.007	VS	45.83 ± 9.64	0.634	NS
	15	56.67 ± 7.00			43.70 ± 4.34		
	20	50.70 ± 7.47			41.29 ± 7.21		
MUF	10	70.85 ± 7.73	0.000	VS	53.60 ± 6.25	0.464	NS
	15	58.60 ± 2.49			52.28 ± 3.86		
	20	49.08 ± 5.33			48.84 ± 7.53		

VS: very significant (P＜0.01); S: significant (0.01＜P＜0.05); NS: not significant (P＞0.05)

Fitted Model

Figure 6 shows the model of the wood lap-shear, bending, and tensile strengths with MC because MC had a great influence on its mechanical performance. The strengths decreased linearly with increasing MC. The lap-shear and tensile strengths of MUF were higher than that of PRF, as MUF had a better bonding performance than PRF. However, the MUF and PRF adhesives had similar strength on finger joint bending strength.

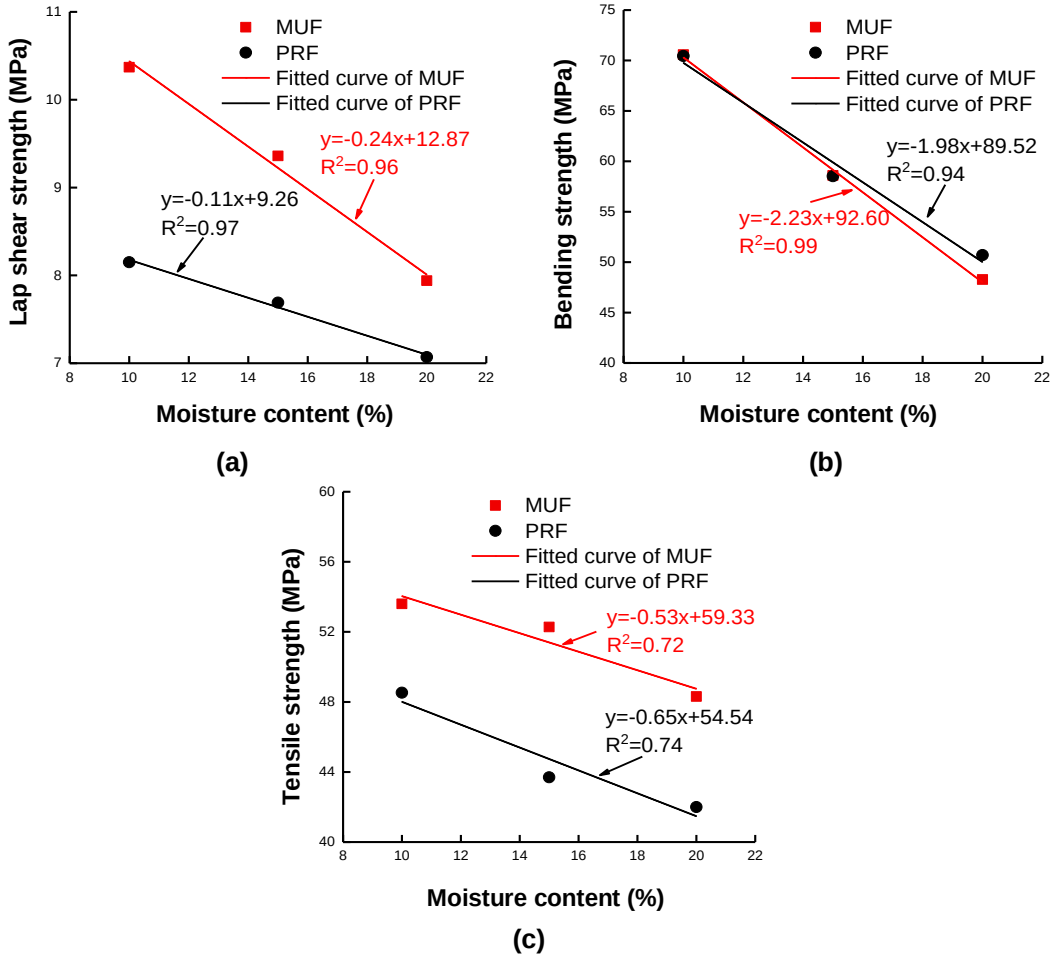

Fig. 6. Lap-shear (a), bending (b), and tensile (c) strengths as a function of MC

CONCLUSIONS

1. The strengths of finger-jointed wood specimens using phenol-resorcinol-formaldehyde (PRF) and melamine urea formaldehyde (MUF) adhesives increased with the press time (0 to 24 h). The increasing rate for MUF was higher than that of PRF at three different levels of moisture content (MC).
2. The ultimate shear strength decreased linearly with the MC, and the MUF generated a higher ultimate lap-shear strength than the PRF.
3. The bending strength of finger-jointed wood specimens using PRF and MUF was affected more by wood rather than by adhesive. However, for lap-shear and tensile strengths, wood and adhesive equally affected the strengths.

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Declaration of Interest

No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

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