PROPERTIES OF PINE SCRIM LUMBER MADE FROM MODIFIED SCRIM

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Abstract. In this study, scrim from small-diameter southern pine bolts was treated with melamine formaldehyde (MF), phenol formaldehyde (PF), and furfuryl alcohol (FA) at different loadings and formed into 25-mm-thick pine scrim lumber (PSL) panels. MOE, MOR, work to maximum load (WML), internal bond (IB), toughness, water absorption, thickness swelling, 5-h tangential dynamic swelling, and termite resistance were evaluated. Results showed that samples treated with 5% MF resin had the highest MOE, MOR, and WML values (15.3 GPa, 54.2 MPa, and 25.4 kJ/m^3, respectively), whereas those treated with 10% MF resin had the highest IB and edgewise toughness values of 390 kPa and 12 N m, respectively. With respect to dimensional stability, samples treated with 20% FA had the lowest swelling values after 24-h submersion in water (anti-swelling efficiency [ASE] = 36.8%), and the lowest water absorption value (27.5%). Five-hour tangential dynamic swelling test revealed much higher dimensional stability for furfurylated samples (ASE >45%). As for termite resistance, both untreated and treated PSL had little weight loss (1.10-1.56%), high visual rating (8-9.3/10), and high mortality (100%) in laboratory tests. MF and FA impregnation proved to be feasible modification methods in this study.

Keywords: Pine scrim lumber, phenol formaldehyde, melamine formaldehyde, furfuryl alcohol, mechanical properties, dimensional properties, termite resistance.

INTRODUCTION

Chemical modification of wood can be defined as a process of bonding a reactive simple chemical to a reactive part of a cell wall polymer, with or without a catalyst, to form a covalent bond between the two (Rowell 2006). This results in lowering of the cell wall water-holding capacity and the fiber saturation point (FSP) (Kumar et al 1991; Militz 1991; Codd et al 1992). The essential requirement is that the reacting chemical should penetrate into the cell wall and react with the available hydroxyl groups of the cell wall polymer, preferably in neutral or mild alkaline conditions at temperatures below 120°C. The major types of linkages formed by reaction with wood are ether, acetyl, ester, etc., of which ester bonds are the weakest and are susceptible to acid or base attack (Kumar 1994).

Impregnation with phenol formaldehyde (PF) resin was first introduced in the 1930s (Stamm and Seborg 1939). Hygroscopicity, shrinking and swelling, and susceptibility to biodeterioration were all reduced (Stamm and Baechler 1960). Higher mechanical strengths were also obtained (Stamm and Seborg 1939). PF resin was located

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mainly in the cell wall (Kumar 1994). A good decay resistance was reported with about 10% polymer loading in the cell wall (Furuno et al 1992). In further study, researchers found that average molecular weight of PF resin affected the performance of impregnation (Ryu et al 1993). Low-molecular-weight (LMW) PF resin could easily penetrate into the cell wall, playing a vital role in dimensional stability and decay resistance; whereas medium and high-molecular-weight resin could only partially penetrate with most depositing within the cell lumen, resulting in negligible contribution to dimensional stability and decay resistance (Furuno et al 2004). Using three different PF resins, Choong and Barnes (1969) showed anti-swelling efficiencies (ASEs) in excess of 75%. Ryu et al (1993) pointed out that molecular weight distribution and pH of the resin also contributed to the decay resistance. PF resin consisting exclusively of monomeric phenol alcohols with two or three reactive alcohol groups and lower alkalinities was less apt to decay.

Similar to PF resin, water-soluble melamine formaldehyde (MF) resin has been utilized to impregnate wood (Gindl et al 2003). The MF resin can penetrate into the wood cell wall (Rapp et al 1999) and amorphous regions of cellulose fibrils (Hua et al 1987a, 1987b), forming covalent bonds with cellulose and lignin (Troughton and Chow 1968; Troughton 1969). Decreased hygroscopicity and biodeterioration have been reported (Minato et al 1993). Improved surface hardness and MOE of wood products can also be obtained when impregnated with LMW MF resin (Gindl et al 2003).

With the development of the adhesive industry, furfuryl alcohol (FA) was recognized as a substitute for PF resin, and furfurylation of wood was introduced in the early 1950s. FA has a low molecular weight, which is preferable to penetrate into wood cell wall (Baysal and Osaki 2004). At that time, researchers' main interests were in durability toward acids and alkali, improved mechanical properties, dimensional stability, and biological durability (Dunlop and Peters 1953). PF, MF, and FA impregnation did not decrease the mechanical properties of wood, which are crucial for structural materials. An excellent review on wood modification has been published by Hill (2006).

However, no research has been done to evaluate the performance of chemically modified pine scrim lumber (PSL). In this study, mechanical, dimensional, and biological properties of PSL were tested, and possible mechanisms are discussed.

MATERIALS AND METHODS

In this initial study, pine scrim was chemically treated and made into panels, followed by the evaluation of mechanical, dimensional, and biological durability properties.

Scrim Preparation

Twenty-five small-diameter southern pine (*Pinus* spp.) bolts (<205 mm) were placed in hot water (>80°C) for 24 h prior to scrimming. The scrimming process has been described previously (Linton and Barnes, 2008, 2010; Barnes et al 2010). Figure 1 shows typical scrim from the scrimming process, the length of the scrim is around 860 mm, the thickness of the scrim is less than 8 mm.

Scrim Treatment

Dried scrim was placed in a stainless steel pan, weighted down to prevent floating, and flooded with the appropriate modification chemical

Figure 1. Typical scrim from the scrimming process (inset is the cross section of the panels).

solution. Treatment was accomplished in a treating retort using a cycle of vacuum at 85 kPa for 30 min, followed by pressure at 1.03 MPa for 1 h. Solution uptake was calculated by weight difference before and after treatment.

Treatment solutions were prepared by dilution with water to yield the desired solution strengths. In this study, solutions of 5%, 10%, 15% PF and MF solutions were used. Solutions of 20%, 30%, 40% FA with 1% citric acid catalyst were used for furfurylation treatments. The curing condition for both PF- and MF-resin-impregnated scrim was 50°C drying for 24 h and 103°C curing for 20 h, respectively. Furfurylated scrim was air-dried for 4 h, wrapped in aluminum foil for 16 h, then unwrapped and post-treatment dried for 8 h. A curing temperature of 103°C was used throughout this study.

Board Fabrication

The treated scrim was resinated with a phenol formaldehyde stage B resole at 16% solids with a final retention of solids content of 14%. The resinated scrim was dried and pressed into panels (860 × 860 × 25 mm) using a Dieffenbacher (Eppingen, Germany) 1 × 1 m laboratory press with Pressman® controls. The pressing cycle consisted of 30 s for press closure, 17 min at 5 MPa, 188°C, and decompression for 55 s. The panels were edge trimmed and conditioned in a conditioning chamber at 20°C and 65% RH until a constant weight was achieved. All panels were unidirectional.

Test Methods

Samples from both treated and control panels were evaluated according to ASTM standards D1037 (2006) for bending, internal bond (IB) strength, thickness swelling and water absorption, and D143 (2007) for toughness. The rate of cross head motion was set to 2.5 mm/min for the bending test. Five-hour tangential dynamic swelling in the thickness direction was determined using linear variable differential transformers (LVDTs) to measure dimensional change when samples were placed under water. Swelling was monitored for 5 h. The dimension of the thickness swelling samples was 100 × 100 × 25 mm and bending samples were tested at a 17:1 span:depth ratio. All other sample sizes conformed to the standards. Density profiles were determined using a QMS density profiler. The termite testing was done in accordance with AWPA Standard E1 (2010). For the termite test, 140 g of sand and 15 mL deionized water were placed into sterilized jars and allowed to set over night. Samples were put into jars the next day, followed by adding 1 g of termites (*Reticulitermes flavipes* Kollar) on the sand while avoiding direct contact with the wood sample. All jars were moved into a conditioning cabinet at 27.8°C for 28 days. A control jar with no samples or termites was also put into the cabin to monitor the moisture loss during the study to assure termites did not die from loss of moisture. The control jar was weighed at 1-week intervals.

Data Analysis

All data obtained from each test were analyzed using statistical analysis software (SAS 2009). Analysis of variance was conducted and Tukey's test with a confidence interval of 95% ($\alpha = 0.05$) was used to analyze the significant differences between groups. The study design is shown in Table 1.

RESULTS AND DISCUSSION

Mechanical Properties

Bending properties. As shown in Table 2, samples treated with all three levels of MF and 30% FA had significantly higher MOE values than the control group, whereas the MOE for samples treated with other levels of chemicals were not significantly different from the control group. For MOR, only samples treated with 5% MF, and 20%, 30% FA were significantly better than the control group. Groups treated with 5%, 10% MF and 30% FA had significantly higher work to maximum load (WML) values than controls. Samples treated with 5% MF performed the best with respect to MOE, MOR, and WML. Lower concentration of the MF and FA solutions

Table 1. Replications by test, treatment, and treatment level.

Treatment	Control	P5	P10	P15	M5	M10	M15	F20	F30	F40
					Test					
Bending	10	14	13	10	14	14	14	12	12	12
Internal bond	10	10	10	10	12	11	12	10	10	10
Toughness	20	20	20	20	20	20	20	20	20	20
Thickness swell	4	4	4	4	4	4	4	4	4	4
5-h tangential dynamic swell	4	4	4	4	4	4	4	4	4	4
Termite	5	5	—	—	5	—	—	—	5	—

P, phenol formaldehyde; M, melamine formaldehyde; F, furfuryl alcohol; numbers represent solution strength %.

Table 2. Mean bending properties for both treated and control groups.

Variable	Weight gain (%)	MOE (MPa)	COV (%)	MOR (MPa)	COV (%)	Work to max load (kJ/m^3)	COV (%)
Control	0.00	10,717C[a]	26	30 DE	27	9.6 D	41
F20	6.35	10,905 C	39	40 BC	45	15.6 BCD	56
F30	7.70	15,146 A	24	48 AB	28	17.6 B	41
F40	8.18	12,783 ABC	26	33 CDE	38	11.4 BCD	51
M5	7.94	15,321 A	25	54 A	32	25.5 A	35
M10	15.15	13,657 AB	32	39 BCD	43	17.3 BC	59
M15	19.04	13,785 AB	21	38 BCD	31	14.2 BCD	39
P5	7.88	10,381 C	26	29 E	40	13.4 BCD	49
P10	17.72	10,331 C	20	27 E	41	10.4 CD	50
P15	23.48	11,263 BC	27	27 E	36	10.7 BCD	40

[a] Means not followed by a common letter are significantly different at $\alpha = 0.05$.
P, phenol formaldehyde; M, melamine formaldehyde; F, furfuryl alcohol; COV, coefficient of variation.

might easily obtain access to the wood cell wall and bond with available functional groups such as hydroxyl groups, making the cell wall structure stronger. However, when the concentration is too high, extra chemicals could be harmful to the wood cell wall structure and have adverse effects on the bending properties.

According to Stamm and Seborg (1939), PF-treated wood should have improved bending properties, whereas in this study, opposite results were observed. The molecular weight of the resin might be a possible reason. As pointed out by Furuno et al (2004), lower concentrations of lower molecular weight PF resin could easily and fully penetrate into the cell wall and form wall polymers. With an increase in molecular weight and solids content, increased fractions of PF resin were found deposited in cell lumen. The PF resin used in this research had a molecular weight of 1300-1400 Da, much higher than the 350-451 Da resins evaluated by Wan and Kim (2008) or those in the 300-400 Da range studied by Choong and Barnes (1969). In this study, since densities of all panels were not significantly different, more resin may have been deposited in the cell lumen. This would indicate a lower proportion of resin in the cell wall, resulting in weaker bending properties.

Results obtained for MF impregnation and furfurylation were as expected. It is possible that the molecular weight of both of MF and FA was so low that the chemicals could easily access the cell wall, thus improving the strength of the products (Gindl et al 2003; Baysal and Osaki

Table 3. Mean internal bond (IB) strength values.[a]

Treatment	IB (kPa)
Control	86.68 E
F20	263.51 ABCD
F30	340.18 AB
F40	303.90 ABC
M5	320.62 AB
M10	389.21 A
M15	210.63 BCD
P5	238.45 BCD
P10	134.35 DE
P15	180.74 CDE

[a] Means not followed by a common letter are significantly different at $\alpha = 0.05$.
P, phenol formaldehyde; M, melamine formaldehyde; F, furfuryl alcohol.

2004). A detailed microscopic study using scanning electron microscopy and transmission electron microscopy may show the distribution of the chemical molecules and the change of morphology of the cell structure, which would facilitate the interpretation of the mechanism of improved properties, but was beyond the scope of this initial study.

Internal bond and density profile. As shown in Table 3, all treated samples had significantly higher IB values than controls except for those

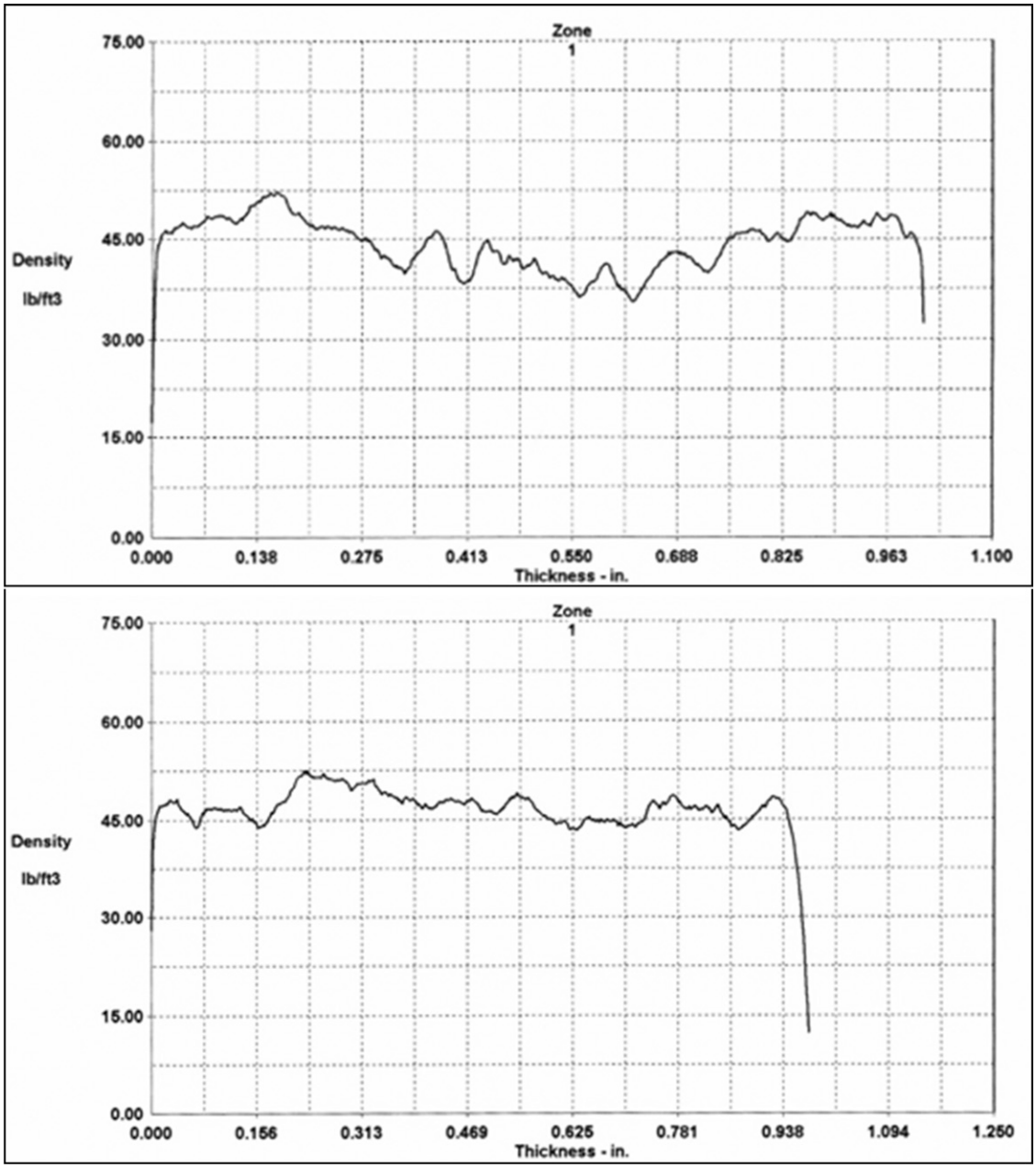

Figure 2. QMS density profile for (top) the control and (bottom) phenolic formaldehyde–treated samples.

treated with 10% and 15% PF solutions. IB strength is related to resin type/content, sample density, and element geometry (Dai et al 2007). In this research, PF resin stage B resole was used as the bonding agent for all panels. The pressing parameters were also the same for each panel. Element geometry and density could not be controlled to be the same because of the variation in scrim size and geometry. According to the output from QMS density profile system (Fig 2), the density profile of controls varied significantly through thickness direction. The loss of bonding strength could start from the weakest point, which would be the lowest density region. Thus, the control group had the lowest mean IB value although the average density was in the medium range. Results show that the IB strength for panels treated with 10% and 15% PF solutions was not significantly higher than that of the controls. Possible reasons could be the scrim size and geometry with larger scrim size leading to less interfacial contact surface area and many more voids among the scrim, thus lowering IB strength. To find detailed reasons for this phenomenon, microscopic techniques should be applied to determine if rupture was due to resin failure. An analysis comparing the pressing parameters and density profiles with IB values and failure modes could also be useful.

Toughness. There appeared to be randomness in toughness in both force directions within each group (Table 4). Statistical results show that panels treated with 10% MF solution had a significantly higher toughness than the controls in the direction parallel to the panel surface, and those treated with 5% and 10% MF solution, and 5% PF solution had a significantly higher toughness than the controls in the direction perpendicular to the panel surface. There was no significant difference between the rest of the treated panels and the controls. Large variation of toughness was also reported by Gerhards (1968) and in the Wood Handbook (FPL 2010), with a coefficient of variation around 30%. Toughness is the most sensitive mechanical property, which can vary sample by sample because of uneven density distributions, differences in resin coverage, annual rings, and MC.

Table 4. Mean toughness properties for treated and control groups.[a]

	Force direction parallel to the panel surface		Force direction perpendicular to the panel surface	
Variable	Mean (N m)	COV (%)	Mean (N m)	COV (%)
Control	8.4 BC	21	5.8 CD	30
F20	7.9 C	13	5.7 D	25
F30	9.0 ABC	24	7.6 BCD	29
F40	6.7 C	24	7.0 BCD	20
M5	8.6 BC	42	9.1 AB	33
M10	12.0 A	45	9.0 AB	32
M15	6.9 C	35	7.1 BCD	25
P5	11.2 AB	28	10.5 A	24
P10	6.8 C	21	8.3 ABC	21
P15	9.5 ABC	25	7.2 BCD	23

[a] Means not followed by a common letter are significantly different at $\alpha = 0.05$.
P, phenol formaldehyde; M, melamine formaldehyde; F, furfuryl alcohol; COV, coefficient of variation.

Dimensional Properties

Water absorption, tangential swelling, and thickness swelling. Results for water absorption, 5-h tangential dynamic swelling (swelling across the grain of the scrim), 24-h thickness swelling, and MC are illustrated in Table 5. None of the treatments included wax to retard water movement. Samples treated with FA solution had smaller water absorption, 5-h tangential swelling, 24-h thickness swelling, and lower MC values than the others. For water absorption, samples treated with 5% PF solution performed significantly worse than controls, whereas those treated with 10% and 15% PF solution and 5% and 15% MF solution had no significant difference

Table 5. Summary statistics for swelling tests of treated and control groups.[a]

	Water absorption	5-h tangential dynamic swelling	24-h thickness swelling	MC
Variable	%			
Control	48.92 BC	5.49 BC	15.50 B	7.48 A
F20	34.15 E	3.49 D	8.23 D	5.36 CD
F30	27.46 F	3.47 D	7.15 D	5.00 D
F40	36.08 E	3.75 D	6.17 D	5.63 BCD
M5	50.73 B	5.49 BC	12.66 BC	6.40 ABCD
M10	41.88 D	4.24 CD	9.47 CD	6.54 ABC
M15	44.64 CD	4.18 CD	8.11 D	7.68 A
P5	60.40 A	7.49 A	20.07 A	6.91 AB
P10	53.15 B	5.93 AB	15.33 B	7.76 A
P15	51.39 B	6.44 AB	14.76 B	6.48 ABCD

[a] Means not followed by a common letter are significantly different at $\alpha = 0.05$.
P, phenol formaldehyde; M, melamine formaldehyde; F, furfuryl alcohol.

from controls. This indicates that MF and PF impregnation did not prevent samples from absorbing water when submerged under water for 24 h, whereas furfurylation did. The reason could be that PF and MF solution did not efficiently react with the available hydroxyl groups in the wood cell wall. The other reason was that treated PSL did not bond well with PF resin stage B resole, since some of the samples fell apart after submersion in water for 24 h.

Anti-swell efficiency (ASE) for 24-h thickness swelling is shown in Fig 3. The ASE values within each group were proportional to the concentration of chemicals used. It is obvious that PF impregnation in this study had little positive effect, and sometimes generates an adverse effect on dimensional stability of PSL. However, according to Wan and Kim (2006), ASE values for PF-impregnated oriented strand board (OSB) were up to 26% and 45%, respectively, for 1.0% and 5.0% resin solids content. Probable reasons for the different results were the geometry of raw material, molecular weight of resin. For OSB, there were larger interfaces between flakes, thus yielding stronger internal bond, whereas for PSL, there is less interface area between scrim as a result of the geometry of scrim. The molecular weight of PF resin used in OSB treatment is 310-451 Da, much lower than that used in this study, which is about 1300 Da. Higher molecular weight of PF resin impedes penetration of resin into the cell wall, thus could not interlock wood polymers effectively. Larger amounts of PF resin deposited in the cell lumen could have a negative effect on bonding. All these reasons could result in weak internal bonding strength of PF-treated samples, which was proved by the fact that the PF-impregnated PSL were loose after treatment, and some of the PF-treated samples

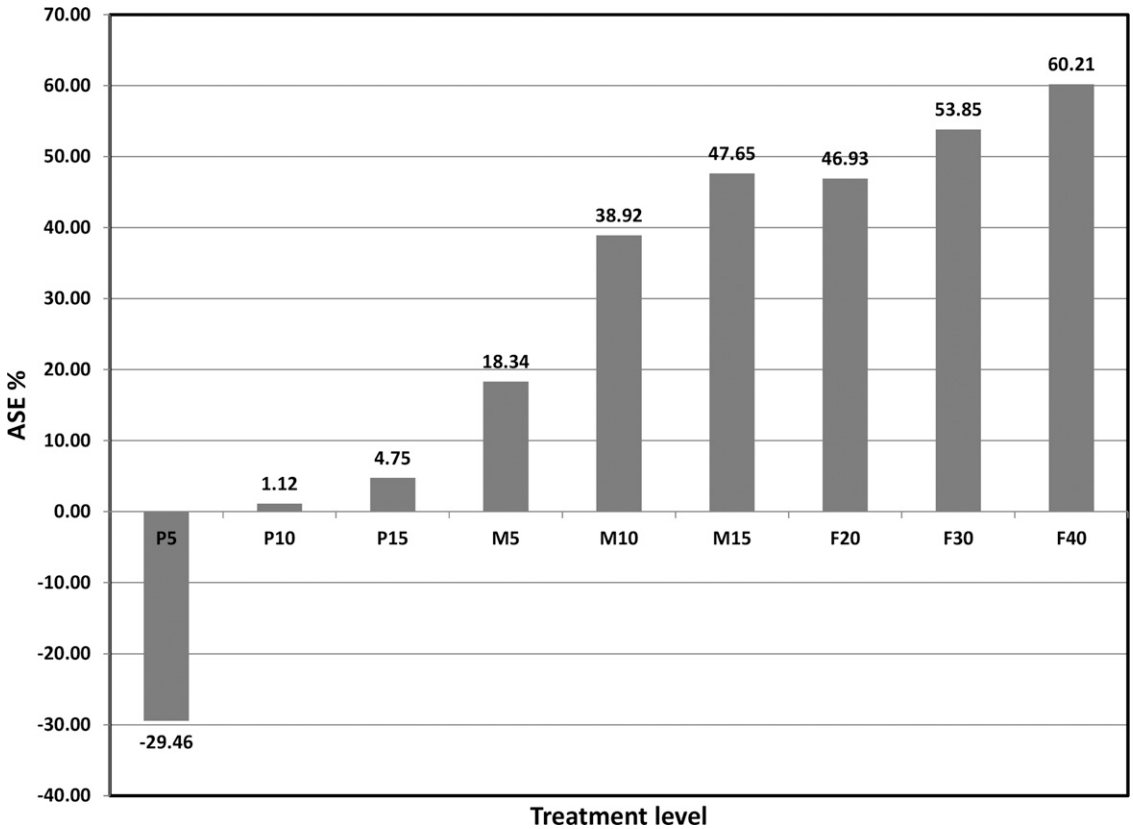

Figure 3. Anti-swelling efficiency for 24-h thickness swelling cross the grain (%).

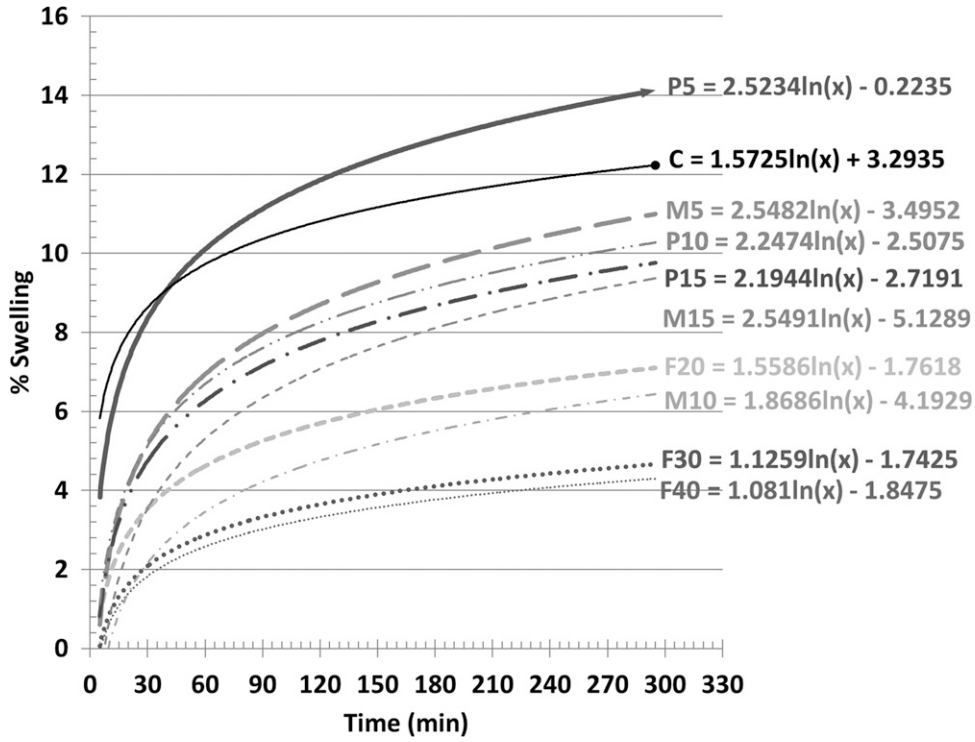

Figure 4. Five-hour tangential dynamic swelling for pine scrim lumber through thickness direction.

fell apart after submerging under water for 24 h. When the PF-treated samples were loose, more voids were created, resulting in greater water absorption and swelling. Low molecular weight PF resin should be studied in the future.

Five-hour tangential dynamic swelling. Five-hour tangential dynamic swelling for all treatments fits a logarithmic regression function, as shown in Fig 4. Similar to the 24-h thickness swelling, the 5-h tangential dynamic swelling for both PF- and FA-treated samples was inversely related to the concentration of chemicals impregnated. However, for MF-treated samples, the 5-h tangential dynamic swelling decreased as the concentration increased from 5% to 10%, then increased as the concentration further increases to 15%.

Termite Resistance

Results of termite resistance for both treated and controls are shown in Fig 5. Visual appearance of the blocks after exposure to termites is shown in Fig 6. For southern pine positive controls (Fig 6, top), the average weight loss was 28.4%, with an AWPA rating of 4 (very severe attack), with no mortality. These results confirm the validity of the termite test. On the other hand, for both untreated and treated PSL tested, the average weight loss ranged from 1.10% to 1.56%, with AWPA ratings from 8 to 9.3 (moderate to trace attack), with 100% mortality.

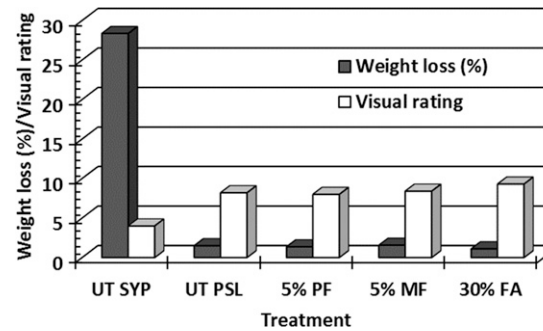

Figure 5. Comparison of visual rating and weight loss after termite test.

Figure 6. Block appearance for (top) southern pine controls and (bottom) untreated and treated pine scrim lumber after 28-da termite test (left to right: untreated controls, 5% phenolic formaldehyde [PF], 5% melamine formaldehyde [MF], 30% furfuryl alcohol [FA]).

This means both untreated and treated PSL are termite resistant. For both untreated and treated PSL, termites were all dead after 3 weeks, indicating that termites do not feed on PSL, whether chemically treated or not. The reason could be that the PF resin stage B resole used for bonding the scrims prevented the termites from eating both treated and untreated PSL samples.

CONCLUSIONS

The bending test results demonstrated that there was no significant difference between PF-treated panels and the controls in this study, whereas MF impregnation and furfurylation significantly improved the bending properties, with the lowest level of MF and medium level of FA performing the best with respect to MOE, MOR, and WML. A low level of chemicalwas preferable to improve the internal bond property. Data from 24-h thickness swelling test show that samples treated with MF and FA were significantly better than the controls. Both untreated and treated PSL were termite resistant in laboratory scale.

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