IMPREGNATION OF SOUTHERN PINE WOOD AND STRANDS WITH LOW MOLECULAR WEIGHT PHENOL-FORMALDEHYDE RESINS FOR STABILIZATION OF ORIENTED STRANDBOARD[1]

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ABSTRACT

Low molecular weight phenol-formaldehyde (PF) resins were impregnated into southern pine wood using a vacuum/pressure method and the specimens were hot-pressed in the radial direction. Anti-swelling efficiency (ASE) values of treated specimens were up to 26% and 45%, respectively, for 1.0% and 5.0% resin solids loading levels in the first water-soak/dry cycle. The high ASE values were due to reduction in the irreversible swelling in radial and tangential directions of wood in spite of some negative effects that occurred in the reversible swelling. In the second and third water-soak/dry cycles, the ASE values were reduced mostly due to increased swelling of irreversible components in the radial direction with the tangential direction components little affected. Vacuum impregnation of southern pine/hardwood strands with 1.0% or 2.0% PF resin solids levels and hot-pressing gave strandboards with ASE values up to 45% in 24-h water-soak tests. ASE and board strength values of boards were higher for 2.0% resin solids loading level, higher hot-pressing temperatures, and longer press times. The high ASE values of boards arose from both irreversible and reversible swelling components and also increased adhesive bonds due to impregnating PF resins. The results would be useful for manufacturing oriented strandboard with reduced swelling if a low-cost resin impregnation process can be found.

Keywords: PF resin impregnation in wood, oriented strandboard, dimensional stabilization of wood composites, wood composites.

INTRODUCTION

Oriented strandboard (OSB) is manufactured from southern pine (SP) and aspen and other low density hardwoods using phenol-formaldehyde (PF) or isocyanate resins as binders. One major problem of OSB is the low dimensional stability, or thickness swelling, in water soak. Various methods have been explored to increase the dimensional stability of OSB, but most methods entail expensive additives and/or processes as discussed in the companion paper (Wan and Kim 2005). Low molecular weight PF resins have shown some success as wood-impregnating materials since they were found to swell wood (Farmer 1967), penetrate wood cell walls (Stamm and Seborg 1936; Stamm and Elwin 1953), and, when cured by heat, form insoluble cross-linked network polymers to reinforce wood structures (Stamm 1959). For example, impregnating SP wood with low molecular

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weight PF resins under vacuum and pressure to 30%–50% resin solids loading levels and curing resulted in an anti-swelling efficiency (ASE) of 70% (Stamm and Baechler 1960). The latter authors also observed that PF resins principally reside in lumens at resin loading levels below 30% and begin to show penetrations into cell walls at higher resin loading levels. These authors suggested that 30% or higher PF resin solids loading levels should be used in impregnation of wood for any significant enhancement of wood properties since resins deposited in lumens would contribute little to ASE. Further, the rate of impregnation of low molecular weight PF resins was found to be faster for green wood than for dry wood (Stamm and Seborg 1939, Haygreen and Gertjejansen 1972). Based on these PF resin impregnation results, veneer-based Impreg and Compreg were developed (Stamm and Seborg 1951; 1955) that have ASE values ranging from 65%–95% at resin loading levels of 25%~30% (Rowell 1999).

Further, Talbott (1959) sprayed dry Douglas-fir flakes with a low molecular weight PF resin at a 35% resin solids loading level and dried and hot-pressed to boards with high strength and very low water absorption. Haygreen and Gertjejansen (1971) sprayed a low molecular weight PF resin on green wood particles at a 10% loading level and dried, applied a PF resin binder at a 5.0% resin solids loading level, and hot-pressed to particleboards that showed thickness swelling being decreased by 86% compared to control. Hujanen (1973) sprayed balsam poplar flakes with a low molecular weight PF resin and then hot-pressed to flakeboards that showed thickness swelling of 14%, 21.3%, and 28.8%, respectively, for 12%, 6%, and 3% resin solids loading levels. Ryu et al. (1993) showed that lower molecular weight PF resins were more effective than higher molecular weight resins in raising ASE as well as that PF resin-impregnated wood shows a substantial increase in resistance to decay fungi and subterranean termites. These results showed the potential of using low molecular weight PF resins in manufacturing wood and wood composites with improved dimensional stability and strength properties.

However, using PF resins at the resin solids loading levels used by most of these authors is prohibitive for current oriented strandboard applications due to the high cost of resin. On the other hand, in impregnating SP wood with various low molecular weight chemicals, it was shown that the flow of liquid chemicals occurs through ray tracheids (Nicholas and Siau 1973), where the pit structures tend to bottleneck the diffusion process. Based on this observation, it would be that depositing PF resins only in ray tracheids and curing them results in blocking the flow of water into wood. Since the volume fraction of ray tracheids is very small in wood, this would provide an approach to improving the dimensional stability of wood and wood composites at low resin solids loading levels.

Further, it has been necessary to clearly define the various low molecular weight PF resins used for wood impregnation purposes with respect to the resin synthesis parameters. Wood adhesive-type PF resins are made by reacting phenol (P) and formaldehyde (F) at F/P mole ratio of about 2.1 with an alkali as catalyst. Various monomeric methylolphenols are initially formed and then they react further to form dimers and trimers, etc., depending on the extent of polymerization carried out to meet particular applications. Polymerization of resins to relatively high molecular weights is normally carried out in manufacturing of wood binder-type PF resins. The reaction products obtained in the early stage of the reaction are referred to as low molecular weight PF resins, but they can vary in molecular weight as well as in reactivity depending on the reaction parameters employed: F/P mole ratio, sodium hydroxide content, reaction temperature and time, and resin solids level in the reaction mixture (Kim et al. 1990).

This study was aimed at improving the dimensional stability of OSB using low levels of low molecular weight PF resins. Three different low molecular weight PF resins with defined molecular weights were synthesized. The PF resins were evaluated by impregnating into SP wood specimens using a vacuum/pressure method, and then two selected PF resins were evaluated by impregnating into SP/hardwood strands using a

vacuum method and hot-pressing them to boards. A vacuum/pressure and low-cost spraying method were briefly investigated as alternative resin impregnation methods.

<div align="center">EXPERIMENTAL METHODS</div>

<div align="center">*Materials*</div>

End-matched wood specimens (40 mm × 19 mm × 5 mm; longitudinal, tangential, radial) were cut from commercial kiln-dried SP lumber, ten specimens for each resin treatment or control. The annual rings of wood specimens were mostly parallel to the top (tangential) surface. Cut specimens were conditioned in a 60% relative humidity room at 25°C for up to 3 weeks to attain constant weights within 1% of variation. The general properties of the SP wood specimens met the requirement of the American Wood-Preservers' Association standard M10-77. For preparation of low molecular weight PF resins, phenol (Aldrich Chemical), 50% formaldehyde solution (Georgia-Pacific Corporation, Louisville, MS), and sodium hydroxide (Aldrich Chemical) were used. Green 60:40 SP/mixed hardwood strands were obtained from Norbord Corporation, Guntown, MS. An OSB core-layer PF resin (GP® 167C09) from Georgia-Pacific Resins, Inc. was used as binder in strandboard manufacture.

Three low molecular weight PF resins were prepared according to a reported procedure (Kim et al. 1990) at an F/P mole ratio of 2.10. Thus, 816 g of phenol (90% concentration) were charged into a 3-L three-neck flask equipped with a stirrer, thermometer, and heating mantle. While the reactor was stirred without heating, 72 g of 50% sodium hydroxide solution were added and then a mild heating was applied to raise the reaction temperature to 65°C. Then, 984 g of 50% formaldehyde solution were added over a period of 45 min while the reaction temperature was kept at about 70°C. The reaction mixture was held at 70°C and the viscosity monitored till it reached A_1 (Gardner-Holdt scale), when 600 g of reaction mixture were taken as resin PF1. When the viscosity reached A_1A, 600 g of reac-

tion mixture were taken as resin PF2; and when the viscosity reached A, the rest of reaction mixture was taken as resin PF3. The entire reaction took about 3 hours. All resins were stored at 2°C until used. The viscosity, pH, specific gravity, gel time, free formaldehyde content, resin solids level, and molecular weight of resins were determined based on standard procedures as follows

Resins	PF1	PF2	PF3
Viscosity (cP)	35	45	57
pH	~10	~10	~10
Specific gravity	1.03	1.03	1.03
Gel time (min) at 100°C	>50	>50	>50
Free CH_2O content (%)	1.91	1.41	0.96
Resin solids level	62.3	62.3	62.3
Molecular weight (Mn)	310	370	451

<div align="center">*Impregnation of resins, drying, and hot-pressing with SP wood specimens*</div>

A set number of wood specimens weighted down in a pan were placed in a wood treatment cylinder, a vacuum of 98 kPa was applied for 15 min, and then a resin solution was introduced into the pan until the wood specimens were fully submerged while under vacuum. The vacuum was then released and an air pressure of 690–828 kPa was applied for 30 min. The air pressure was released and treated wood specimens were taken out, weighed, and dried at 50°C for 24 h. The resin solids loading levels in wood specimens were calculated using the concentration of resin solution and the wet pickup was measured prior to drying of treated wood specimens. Most wood specimens picked up approximately 100% by weight, and therefore a target resin solids loading level of 1.0% required a 1.0% resin solution. Ten resin-impregnated, dried wood specimens were put side by side in a 150-mm × 150-mm Carver laboratory press and hot-pressed in the radial direction to a thickness of 4 mm from the initial thickness of 5 mm using a metal stop at selected press temperatures and press times (20% thickness compression). The compressed, cured wood specimens were equilibrated in a 60% relative humidity room at 25°C for 3 weeks. Control samples were treated in the

same procedure using water instead of resin so-lution for treatment and similarly hot-pressed. The experimental parameters were: resin loading levels of 1.0% and 5.0%, press temperature of 180°C, press times of 5, 15, and 30 min, and resins PF1, PF2, and PF3 for impregnation. A 2 × 3 × 3 factorial design was used with ten replicates.

Measurements of anti-swelling efficiency (ASE) of treated SP wood specimens

ASE measurements based on three consecu-tive water-soak tests (Rowell 1999) were used. It started with drying of test specimens at 103°C for 24 h, cooling them in a desiccator, and de-termining the oven-dry volumes (Vd). The dried wood specimens were then weighted down in a pan and placed in a treatment cylinder, a vacuum of 98 kPa was applied for 15 min, and distilled water was introduced into the pan until speci-mens were fully submerged while under vacuum. The vacuum was then released and an air pressure of 690–828 kPa applied for 30 min. The specimens were taken out and placed in distilled water at 20°C for 24 h. Dimensions of the water-saturated samples were measured to obtain the wet volumes (Vw) and volumetric swelling values (%) of resin-treated (St) and control (Sc) specimens were calculated using Eq. (1). The volumetric anti-swelling efficiency values (ASEv) were then calculated using Eq. (2):

$$\text{Sc or St (\%)} = ((Vw - Vd)/Vd) \times 100 \quad (1)$$

$$\text{ASEv (\%)} = ((Sc - St)/Sc) \times 100 \quad (2)$$

The specimens were then dried at 103°C for 24 h and equilibrated in a 60% relative humidity room at 25°C for 3 weeks to obtain dried vol-umes of specimens (Vd_1). Comparing the dried volumes to original sample volumes gave the irreversible swelling values ($Vd_1 - Vd$) and com-paring to wet dimensions gave the reversible swelling values ($Vw - Vd_1$). Then the entire ASEv determination procedure was repeated two more times, resulting in three consecutive ASEv values, i.e., $ASEv_1$, $ASEv_2$, and $ASEv_3$. Further, since the wood specimens were cut to

have their thickness parallel to the radial direc-tion of wood, thickness and width changes led to the respective ASE values: ASEr for radial and ASEt for tangential dimension changes.

Impregnation of wood strands with resins and manufacturing and testing of strandboards

Green wood strands (60% SP and 40% mixed hardwoods) were impregnated with resin PF1 and PF3 solutions using a vacuum procedure. An 18-kg batch of wood strands was weighted down in a pan and placed in a treatment cylin-der, a vacuum of 98 kPa applied for 15 min, and a resin solution introduced into the pan until the strands were fully submerged while under vacuum. After the vacuum was released, the im-pregnated strands were collected on a strainer and dried in an oven at 80°C for 24 h to 4% moisture content, screened through an 8-mm × 8-mm screen to remove fines, and stored in a sealed plastic bag until use.

For the spraying method of impregnation, a measured amount of aqueous resin solution was sprayed on a batch of green wood strands using a compressed-air sprayer while the strands were tumbling in a blender. The strands taken out were kept in a plastic bag for 24 h to help resin diffuse into wood, dried, screened similarly as above, and kept in a sealed plastic bag until use. For the vacuum/pressure method of impregna-tion, a batch of wood strands was impregnated with resin solutions using the vacuum/pressure method used for the wood specimen impregna-tion experiments described above.

Resin-impregnated, dried wood strands were blended with a commercial PF binder resin (GP®169C09) in a blender equipped with a Coe spinning-disc atomizer at a 4.0% resin solids loading level based on the weight of finished board weight at 8% moisture content. The board mat (533 mm × 560 mm) was formed manually without orientation to have boards at a target thickness of 12.7 mm and density of 641 kg/m³ (42.0 pcf). Two replicate boards for each condi-tion were made in a 2-ft × 2-ft William White hot-press using 45s closing time and a maximum press pressure of about 4.8 MPa. The pressed boards were weighed to verify the materials bal-

ance, kept in an insulated box overnight, and cut into test specimens, which were conditioned in a 60% relative humidity room at 25°C for 3 weeks. Internal bond (IB), modulus of elasticity (MOE), and modulus of rupture (MOR) were measured according to ASTM D1037. Averages of IB test values were calculated by normalizing the measured strengths against densities within the sample group to the target density of board. Volumetric and thickness swelling measurements were carried out by soaking two 75.9-mm × 75.9-mm samples in water for 24 h, followed by drying at 103°C for 24 h and re-equilibrating to 8.0% moisture content. The ASEv values were calculated based on 8.0% moisture-equilibrated sample volumes and the reversible and irreversible swelling values calculated based on the re-equilibrated sample volumes similarly with wood specimen samples.

RESULTS AND DISCUSSION

Wood specimens vacuum/pressure-impregnated with PF resins at 5.0% resin solids level

First water-soak cycle results.—Resin-impregnated wood specimens at 5.0% resins sol-

ids loading level, hot-pressed in the radial direction at 180°C for 5, 10, and 30 min to 20% thickness compression, showed lower swelling compared with control's 22–27% volume swelling (Table 1) that entail 15–18% thickness swelling and 6–8% width swelling (not reported). The $ASEv_1$ values ranged 30~41%, comprised of radial anti-swelling efficiency ($ASEr_1$) values of 32–44% and tangential anti-swelling efficiency ($ASEt_1$) values of 26–32% (Table 1). ASE values varied depending on the press time and resin-type. Overall, considering the thorough water saturation procedure of the first water-soak test cycle in comparison to the commonly used 24-h water-soak test, the relatively large ASE values appear to indicate that PF resins at 5.0%-resin solids levels significantly improve the dimensional stability of wood. Further, the high ASE values were due to the irreversible swelling components. For example, for resin PF1 as a representative of three PF resins the irreversible anti-swelling efficiency, ASE_{ir}, values ranged from 80–97% (Table 2). On the other hand, the reversible swelling values were somewhat higher than control in most cases, indicating that PF resins did

TABLE 1. *ASE values (%) of SP wood specimens impregnated with 1.0% and 5.0% resin solids of resins PF1, PF2, and PF3 and volume expansion of controls (Cv) (%). Both pressed at 180°C for indicated periods of press times.*

Resin solids loading	Resin	Press time (min)	Dry/1st water soak				Dry/2nd water soak				Dry/3rd water soak			
			Cv_1	$ASEv_1$	$ASEr_1$	$ASEt_1$	Cv_2	$ASEv_2$	$ASEr_2$	$ASEt_2$	Cv_3	$ASEv_3$	$ASEr_3$	$ASEt_3$
5.0%	PF1	5	24.1	36.4	39.2	26.1	13.6	−3.6	−25.7	22.2	13.9	0.3	−23.3	25.2
		15	25.7	41.2	41.7	35.1	15.1	14.4	−1.8	33.2	14.8	11.1	−9.6	33.1
		30	24.0	38.6	39.5	32.4	15.5	13.5	2.4	26.6	16.2	15.0	2.9	27.5
	PF2	5	26.3	30.8	32.5	23.0	14.9	−6.7	−37.9	25.6	15.5	−2.4	−31.5	27.4
		15	26.4	34.8	35.2	29.5	16.9	7.0	−11.0	28.5	17.0	5.1	−19.4	32.1
		30	25.7	41.0	43.9	29.7	15.5	10.5	−6.5	29.9	16.0	10.8	−10.5	33.0
	PF3	5	23.3	39.3	41.2	31.6	13.3	5.7	−10.0	23.3	13.1	11.3	−6.7	29.4
		15	24.3	37.1	40.8	24.7	14.9	5.8	−4.5	18.4	14.4	10.5	−4.5	26.9
		30	24.3	36.4	37.8	26.6	15.9	3.3	−9.4	18.6	15.9	9.1	−2.0	21.9
1.0%	PF1	5	25.2	6.0	8.1	−0.1	15.4	−15.7	−28.2	−0.5	15.2	−12.8	−29.8	4.3
		15	24.5	10.5	13.0	4.3	15.6	−10.6	−20.5	2.0	15.9	−7.6	−20.6	8.3
		30	26.8	16.1	17.8	10.7	16.6	−7.2	−16.4	6.6	16.6	−1.8	−11.6	10.8
	PF2	5	22.0	16.0	18.4	8.2	15.0	0.5	−2.6	2.8	14.9	0.5	−2.6	2.9
		15	24.0	9.7	10.8	6.5	15.5	−14.1	−23.8	−1.5	16.3	−13.9	−23.9	0.7
		30	21.6	8.6	7.3	8.8	15.8	−7.4	−16.4	3.8	16.0	−7.4	−16.4	3.8
	PF3	5	25.2	6.9	5.2	7.4	15.4	−9.6	−21.0	4.8	15.5	−4.4	−10.9	4.3
		15	26.6	15.1	17.6	6.2	15.5	−3.7	−14.3	10.0	16.3	6.7	−15.3	27.1
		30	26.2	14.4	18.6	2.3	16.6	−5.8	−13.8	5.1	16.8	−0.1	−6.1	7.7

Note: Each ASE value is an average of 10 samples and the standard deviation values were generally small (detailed data are reported in reference Wan, H). Resin loading levels were calculated from treating solution concentrations and wet pick-up weights and not actual determinations.

TABLE 2. *Irreversible and reversible volumetric swelling values (%) of SP wood specimens vacuum/pressure impregnated with resin PF1 obtained in the first water-soak/dry cycle.*

Press time (min)		5% Resin solids loading				1% Resin solids loading			
		Irreversible swelling	Reversible swelling	ASE_{ir} irreversible	ASE_r reversible	Irreversible swelling	Reversible swelling	ASE_{ir} irreversible	ASE_t reversible
5	Treated	1.90	8.91	97.4	−20.0	5.99	10.40	33.2	−26.3
	Control	8.98	8.02	—	—	9.03	8.34	—	—
15	Treated	2.10	8.54	79.4	−2.3	5.17	10.80	41.8	−16.5
	Control	10.30	8.36	—	—	8.88	9.29	—	—
30	Treated	1.50	8.41	81.5	8.3	5.81	10.70	39.0	−7.4
	Control	6.92	9.44	—	—	9.54	9.95	—	—

Note: Each ASE value is an average of 10 samples and the standard deviation values were generally small, not reported for simplicity. Detailed data are reported in reference H. Wan. Resin loading levels were calculated from treating solution concentrations and wet pick-up weights and not actual determinations.

not reduce but increased the hygroscopicity of wood to small extents, probably due to the sodium hydroxide in PF resins that could soften up wood structures. Overall, the results showed that PF resins impregnated at 5% loading levels were effective in reducing the swelling of wood in both compressed radial and uncompressed tangential directions by decreasing the irreversible swelling components.

Second and third water-soak cycle results.— In these more exhaustive water-soak tests, $ASEv_2$ and $ASEv_3$ values were small positive values, comprised of negative $ASEr$ (radial) and positive $ASEt$ (tangential) values (Table 1). In other words, the large positive $ASEt$ values observed in the first water-soak cycle remain almost unchanged, but the similarly high $ASEr$ values of the first water-soak cycle not only disappeared but became significantly negative. This result means that not only the resin bonds in the radial layers of wood broke loose but also the layers, possibly damaged during compression, swelled more than those of control specimens in the more exhaustive water-soak tests. The effectiveness of PF resins in the tangential direction may be ascribed to the smaller swelling stresses present in the tangential direction of wood since little compression was done in this direction. Microscopic examination of 5% resin-loaded specimens indicated that some cell-to-cell bonds of mechanical interlocking by cured resins occurred through tracheids (Fig. 1), indicating the reinforcement possible in the tangential direction to explain the effectiveness. These interlocking bonds would be in disarray in the radial
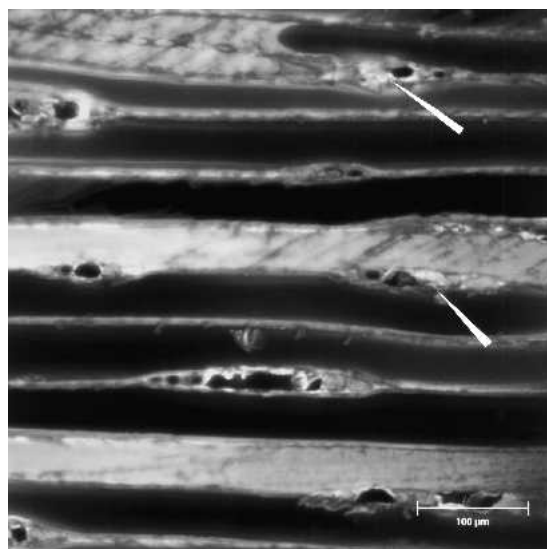

FIG. 1. Light microscopy of a cut specimen showing PF resins in ray tracheids and lumens but not in ray parenchyma.

direction due to compressed layers, and it appears the overall wood/PF resin cured structures did not withstand the swelling stresses. Overall, PF resin-impregnated wood at 5% resin solids levels would show little stabilization effects in an exhaustive water-soak environment. OSB is not expected to be used under such severe water-soak conditions.

*Press time effects.—*Longer press times showed some positive ASE results over shorter press times: for example, the $ASEr_2$ at 15 min increased from −25.7% at 5 min to −1.8% for resin PF1 (Table 1). Furthermore, 30-min press times performed better than 15-min press times.

This trend of press time effects is more clearly distinguished in the second and third water-soak cycle results, especially for radial ASE values. Thus, longer press times appear more useful for more exhaustive water-soak conditions.

PF resin effects.—The effects of impregnating resin were also more clearly distinguished in the second and third water-soak cycle results (Table 1). Resins PF1 and PF2 were similar to each other but performed more poorly than resin PF3 at 5-min press time. On the other hand, at 15- and 30-min press times, resins PF1 and PF2 performed better than resin PF3. Thus, it appeared that PF resins need to be tailored to lower molecular weights for longer press times and to higher molecular weights for shorter press times.

Wood specimens vacuum/pressure-impregnated with PF resins at 1.0% resin solids level

First water-soak cycle results.—The swelling volumes of control specimen ranged from 23–26% (Table 1) with the thickness swelling ranging from 15%–18% and width swelling ranging from 6%~8%. The resin-impregnated specimens resulted in $ASEv_1$ values ranging from 6%~16% with the radial anti-swelling efficiency ($ASEr_1$) values ranging from 5%~19% and tangential anti-swelling efficiency ($ASEt_1$) values ranging from 0%~11%. The ASE values varied depending on the press time and PF resins and, on average, decreased to about one third of 5.0% resin loading level values. ASEt values decreased more drastically than the ASEr compared to the

respective values of 5.0% resin solids loading values, indicating that 1% resin levels were short of giving the interlocking-type bonds through tracheids. Longer hot-pressing times and higher resin molecular weight effects showed minor positive effects on ASE values. The reversible and irreversible swelling components (Table 2) showed similar trends to those of 5.0% resin loading level. Overall, the results showed that a 1.0%-resin solids loading level would show little utility in stabilizing solid wood products but may still have some utility in stabilizing OSB.

Second and third water-soak cycle results.—$ASEv_2$ and $ASEv_3$ values were mostly negative at 1.0% resin solids levels from the negative radial swelling components although the tangential swelling components were positive. Also, the tangential swelling components decreased only slightly compared to the first water-soak cycle values. These results are similar to the 5% resin loading results. Overall, the negative $ASEv_2$ and $ASEv_3$ values indicate that 1.0% resin solids loading would have small negative swelling effects under exhaustive water-soak conditions.

Strandboard vacuum-impregnated with PF resins at 1.0% and 2.0% resin solids levels.

Thickness and volumetric swelling of strandboards in 24 h water-soak tests.—Strandboards, hot-pressed for 3 min and 5 min at 200°C and 220°C with 1.0% and 2.0% resin solids loading levels, showed ASE values of 12%–44% in 24-h

TABLE 3. *Thickness (%), volumetric swelling (%), and ASE (%) values of strandboards made from strands impregnated with PF resins 1 and 3 and pressed at 200° and 220°C for indicated press times.*

		200°C						220°C					
		3 mm			5 min			3 mm			5 min		
	Resin loading level (%)	Thick. swell	Vol. swell	ASEv	Thick. swell	Vol. swell	ASEv	Thick. swell	Vol. swell	ASEv	Thick. swell	Vol. swell	ASEv
Control	0.0	33.9	34	—	27.2	26	—	26.5	27	—	24.5	25	—
PF1	1.0	22.2	22	34	21.4	20	22	20.7	22	20	19.8	20	20
	2.0	18.1	19	45	19.9	20	24	18.2	15	44	15.2	16	36
PF3	1.0	23.3	21	37	22.0	23	12	22.0	22	20	22.3	21	16
	2.0	18.4	19	44	16.5	17	36	18.0	18	33	16.8	17	31

Note: Each ASE value is an average of 2 samples and the standard deviation values were generally small, not reported for simplicity. Detailed data are reported in reference H. Wan. Resin loading levels were calculated from treating solution concentrations and wet pick-up weights and not actual determinations.

water-soak tests (Table 3). Generally, swelling of control boards became less with the longer press time and higher press temperature, and ASE values of resin-impregnated boards were greater for boards pressed for 3 min at 200°C than for boards pressed for the longer time or higher temperature. Boards with 2.0% resin solids levels showed significantly greater ASE values than those with 1.0% resin solids levels. These ASE values appear to be in the practically useful range in manufacture of oriented strandboard especially those of 2% resin loading levels. The ASE values of resins PF1 and PF3 were similar in magnitude to indicate that the molecular weight range selected in this work was relatively narrow for a 24-h water-soak test regime. However, since the molecular weight range covers an ample time length in the resin synthesis operation, the resins would be accurately reproduced in future uses. Statistical analysis of ASE values indicated that press temperature and time, resin solids loading level, interaction of press time and temperature, interaction of press temperature and resin molecular weight, and interaction of press time and resin molecular weight and resin solids loading level were all significant at the 95% confidence level (Wan 2000).

The reversible and irreversible components of thickness swelling of strandboards were approximately in a ratio of 1:2 for both control and resin-impregnated boards (Table 4). Since the similar ratio in wood specimen experiment results was approximately 1:1 for control (Table 2), the increased irreversible swelling components of control boards would be traced to the composite nature of boards. Irreversible ASE values of resin-impregnated boards were gener-

ally higher than their reversible ASE values as expected from the wood specimens results of the first water-soak cycle discussed above. Irreversible ASE values of resin-impregnated boards were higher for the longer press time or higher press temperature, which is expected from a better cure of impregnated and binder resins. Reversible ASE values of resin-impregnated boards were also relatively high and only slightly decreased for the longer press time or higher press temperature. Similarly with the wood specimen results, the reason of these decreases would be traced to the alkali in the impregnating and binder resins that degrade or open up cellulose/lignin structures of wood with increasing severity as the press time or temperature increases, making it easier for water molecules to penetrate.

The high reversible ASE values of strandboards were unlike those observed in the wood specimen experiments. Reversible/irreversible swelling of strandboards would be dictated by strands and adhesion/composite components. The strand components in swelling of resin-impregnated boards would be similar to those observed with the resin-impregnated wood specimen experiments where the impregnating resin's effectiveness was mostly from restraining the irreversible swelling. The adhesion/composite components in swelling of resin-impregnated boards would be similar to those of control boards in the first approximation, not affecting ASE values. On the other hand, the adhesion/composite components would entail irreversible swelling components (broken adhesive bonds) and reversible swelling components (durable adhesive bonds). Therefore, the high

TABLE 4. *Irreversible swelling and reversible volumetric swelling values (%) and the ASE values (%) of strandboards made from strands impregnated with resins PF1 and PF3 and pressed at 200° and 220°C for indicated press times.*

		200°C				220°C			
	Press time	3 mm		5 mm		3 mm		5 min	
	Resin loading	Irrev. swell	Rev. swell	Irrev. swell	Rev. swell	Irrev. swell	Rev. swell	Irrev. swell	Rev. swell
Control	0.0%	27.7	6.2	18.6	9.1	18.6	7.9	16.0	8.5
PF1	1.0% (ASE)	15.9 (42.6)	6.4 (3.2)	13.9 (25.2)	7.5 (17.6)	13.2 (29.0)	7.7 (2.4)	12.4 (22.5)	7.4 (12.9)
	2.0% (ASE)	13.2 (52.4)	4.9 (21.0)	13.4 (28.0)	6.5 (28.6)	13.0 (30.1)	5.2 (34.2)	9.1 (43.1)	6.1 (28.2)
PF3	1.0% (ASE)	18.0 (27.1)	5.3 (14.5)	15.3 (17.7)	6.7 (26.4)	16.0 (17.7)	6.0 (24.1)	14.1 (11.8)	8.2 (3.5)
	2.0% (ASE)	15.1 (45.5)	3.3 (46.8)	11.0 (40.9)	5.5 (39.6)	12.5 (32.8)	5.5 (30.4)	10.6 (33.8)	6.2 (27.1)

reversible ASE values of boards would mean additional, durable adhesive bonds formed due to the impregnating PF resins. Although internal bond (IB) strength values of unsoaked strandboards may not directly reflect the increased amounts of durable bonds, the fact that most IB strength values of resin-impregnated boards were actually higher than control board values points to such a possibility. This conclusion appears reasonable since the low molecular weight PF resins present on the surface of strands would come into contact with binder resin and they would be compatible to each other to result in increased bonding, possibly the durable kind due to the complimentary nature of low molecular weight PF resins to high molecular weight binder PF resins.

All resin-impregnated strandboards met the thickness swelling requirement (25%) of APA standard PS 2-92 and especially 2% resin solids loading levels brought down the swelling to below 20%. It is expected that when wax is added to boards the thickness swelling values will decrease more.

Physical strength values of strandboards.— The physical strength values of resin-impregnated strandboards showed minor increases or decreases although they were generally higher than those of control boards (Table 5). Increasing the press temperature and time increased IB values for both control and resin-impregnated boards. All IB values of resin-impregnated boards passed the minimum IB requirement (345 kPa) of CSA O437.O-93. The MOE values of resin-impregnated boards in most cases were higher than control boards. The influence of molecular weight and resin solids loading levels on MOE values varied, but only slightly. Increasing the press temperature and press time usually resulted in higher MOE values. All MOE values of strandboards met the minimum MOE requirement (1.55GPa) of CSA O437.O-92, and more than half of them met the MOE general property (4.8–8.23GPa) requirement for sheathing-grade OSB (FPL 1999). The MOR values of resin-impregnated boards were slightly higher or lower than control boards depending on the press temperature and time and

TABLE 5. *Physical strength values of strandboards made by impregnating with PF resins 1 and 3 and pressed at 200° and 220°C for indicated press times and % increases (inc.) calculated based on the strength values of control boards.*

Press time		200°C						220°C					
		3 min			5 min			3 min			5 min		
		IB	MOR	MOE	IB	MOR	MOE	IB	MOR	MOE	IB	MOR	MOE
Con.	0.0%	737	36.4	4.8	647	30.4	3.8	803	37.0	4.4	895	31.9	4.5
PF1	1.0%	796	38.0	5.0	808	34.5	4.7	847	33.2	5.1	988	33.4	4.9
	(%inc.)	(8.0)	(4.4)	(4.2)	(24.9)	(13.9)	(24.3)	(5.5)	(−10.3)	(16.9)	(10.4)	(4.7)	(9.6)
	2.0%	1038	33.7	4.6	1008	33.5	4.6	1068	34.0	5.1	966	38.2	5.3
	(%inc.)	(40.8)	(−7.4)	(−4.2)	(55.8)	(10.6)	(23.4)	(33.0)	(−8.1)	(15.3)	(7.9)	(19.7)	(18.5)
PF3	1.0%	950	37.7	4.9	974	26.0	3.9	900	33.3	5.2	875	37.3	5.4
	(%inc.)	(28.9)	(3.6)	(2.9)	(50.5)	(−14.2)	(3.7)	(12.1)	(−10.0)	(17.6)	(−2.2)	(16.9)	(20.8)
	2.0%	1079	33.7	5.2	1121	27.2	4.4	846	30.2	4.9	727	30.0	5.2
	(%inc.)	(46.4)	(−7.4)	(7.3)	(73.3)	(−10.2)	(13.3)	(5.4)	(−18.4)	(11.0)	(−18.8)	(−6.0)	(15.6)

Note: Increases in IB, MOR, and MOE are calculated based on: (Treated−Control)/Control × 100. IB averages are obtained by normalizing the test values at specific gravity of 0.725.

resin molecular weights. All MOR values of resin-impregnated and control boards met the minimum MOR requirement (12.42 MPa) of CSA O437.O-93 as well as the general property requirement (20.7–27.8 MPa) of sheathing-grade OSB (FPL 1999). Overall, physical strength values of resin-impregnated boards increased and when the values decreased the extent of decrease was minor. Although the causes of the small strength variations were difficult to delineate in the current study, optimization of hot-pressing parameters would identify the causes.

Strandboards made by impregnating PF resins with spraying or vacuum/pressure method

Properties of strandboards made by the spraying method with resin PF1 and PF3 at 2% resin solids loading levels showed poor performances in thickness swelling and ASE values (Table 6). It appeared that the resins did not have the chance to uniformly penetrate into the cell walls and rays. The spraying method would offer a significantly lower resin application cost than the vacuum method. On the other hand, the vacuum/pressure method, examined to see if it would offer better ASE values than the simple vacuum method, showed somewhat similar results with those of the simple vacuum method (Table 6), indicating that the additional pressuring step did not help. It is probable that thin wood strands with high surface areas cut in the tangential as well as radial direction allow a rapid penetration of resin molecules in the vacuum impregnation step.

TABLE 6. *Comparison of thickness swelling, ASE values and strength properties of strandboards pressed at 200°C for 3 min for vacuum impregnation (V), spraying (S), and vacuum pressure (VP) treating methods.*

	PF1		PF3	
	2% V	2% S	2% V	2% VP
Thickness swelling (%)	17.9	22.3	18.1	17.3
IB (MPa)	1.0	0.9	1.1	0.8
MOE (GPa)	4.6	4.2	5.2	4.9
MOR (MPa)	33.7	29.6	33.7	30.1
ASE (%)	45.0	6.0	44.0	26.0

CONCLUSIONS

Impregnation of low molecular weight PF resins in SP wood at 1.0% or 5.0% resin solids loading levels using the typical vacuum/pressure method and then hot-pressing in the radial direction to cure the resins significantly decreased the volumetric swelling in the first water-soak test cycle by decreasing the radial as well as tangential swellings. The ASE values reached up to 41% were mostly comprised of irreversible swelling components to indicate the impregnating resins' effectiveness against the compression stresses in wood. In the second and third water-soak test cycles, the ASE values in the radial direction dropped to negative values but the ASE in the tangential direction remained almost unchanged overall, indicating the ineffectiveness of PF resins under exhaustive water exposure conditions. Strandboards made at 1.0% and 2.0% resin solids impregnation levels showed significantly decreased thickness swelling in 24-h water-soak tests with the ASE values reaching up to 45%. The high ASE values were from irreversible as well as reversible components, indicating that impregnating PF resins also contributes to formation of additional adhesive bonding of boards.

ASE values of PF resin-impregnated SP wood and strandboards generally increased with the resin solids loading levels and affected by hot-pressing temperature and time, generally the higher and longer the better. The three low molecular weight PF resins showed only minor differences, but their synthesis procedures used in this work were well defined with the reproducibility being assured. The spraying method of resin impregnation examined as a low-cost method was ineffective. The vacuum/pressure method of resin impregnation of strands did not show any advantage for the additional pressure step. Overall, low molecular weight PF resins were found to significantly reduce the thickness swelling of strandboard at 1.0%–2.0% resin solids loading levels. Further research is needed to resolve the costly nature of the vacuum impregnation method of strands used in this study.

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