PERFORMANCE EVALUATION OF PHENOL FORMALDEHYDE RESIN-IMPREGNATED VENEERS AND LAMINATED VENEER LUMBER

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Abstract. For the past decade, mountain pine beetle infestation in British Columbia, Canada, has substantially changed wood characteristics of vast amounts of the lodgepole pine (*Pinus contorta*) resource. Resin impregnation is one method that could improve the properties of the beetle-affected wood. The key objective of this study was to examine the impact of resin impregnation on dynamic MOE of lodgepole pine veneers and properties of laminated veneer lumber (LVL) made with these treated veneers. A new phenol formaldehyde resin was formulated to treat these veneers using dipping and vacuum-pressure methods. Five-ply LVL billets were made with treated and untreated veneers. Their color, dimensional stability, surface hardness, flatwise bending modulus and strength, and shear strength were evaluated. Good correlation existed between veneer MOE enhancement and resin solids uptake. With the same treatment, stained veneers had higher resin retention and in turn greater MOE enhancement than nonstained (clear) veneers. A 5-min dipping was sufficient for veneers to achieve approximately 7 and 10% resin solids uptake and in turn 5 and 8% enhancement in veneer MOE for nonstained and stained veneers, respectively. LVL made with treated veneers had a harder surface with no discoloration concerns compared with the control. Also, evidence suggested that use of resin impregnation can improve dimensional stability, shear strength, and flatwise bending MOE of LVL.

Keywords: Laminated veneer lumber (LVL), lodgepole pine, mountain pine beetle (MPB), phenol formaldehyde (PF), resin impregnation, veneer.

INTRODUCTION

For the past decade, mountain pine beetle (MPB) infestation in British Columbia, Canada, has substantially damaged vast amounts of the lodgepole pine (*Pinus contorta*) resource and caused significant impact on veneer processing and plywood manufacturing from this resource (Wang and Wharton 2008; Wang et al 2009a, 2009b). MPB-affected lodgepole pine timber has two distinct characteristics: blue stain and dry out. The former causes discoloration in the final product and the latter leads to increased cracks and manual handling and thus decreased material/value recovery. MPB-affected wood, particularly the part with stain, has an exceptionally high permeability, thereby drastically easing chemical treatment, such as resin

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impregnation, which could only be achieved previously through vacuum-pressure treatments (Wang et al 2009b). Such treatment can help mask discoloration and improve physical and mechanical properties of the final product.

Effect of resin impregnation on mechanical properties of wood has been extensively investigated. Resin impregnation of wood could offer a robust solution to improve product appearance and properties such as hardness, stiffness and strength, and dimensional stability (Hare and Kutscha 1974; Nearn 1974; Nicholas and Williams 1987; Brady and Kamke 1988; Troughton and Steiner 1992, 1994; Walser et al 1993; Chui et al 1994; Miroy et al 1995; Gindl et al 2003; Shams et al 2004; Zhang et al 2006; Kamke and Lee 2007; Ors et al 2007). However, the current resin impregnation process is simply not cost-effective. To achieve more resin retention, vacuum-pressure equipment appears necessary (Wan and Kim 2006). Also, when using resin impregnation technology to manufacture laminated veneer lumber (LVL) and plywood, a dual-resin application is generally required: one for impregnation/penetration and the other for interfacial bonding of veneer to veneer after drying (Troughton and Steiner 1992, 1994; Chui et al 1994; Gindl et al 2003; Wan and Kim 2006; Kamke and Lee 2007). As a result, given the relatively high price of resin, none of the plywood and LVL mills in North America are adopting resin impregnation technology to manufacture high-performance and durable engineered wood products.

In this study, a specially formulated phenol formaldehyde (PF) resin consisting of components with a wide range of molecular weight (MW) was used. This eliminated the need to use a dual-resin system. A similar resin was previously used in another study on plywood (Wang et al 2009a). It was shown that with resin impregnation, high-performance plywood made with MPB-affected veneers can have better appearance and greater surface hardness and shear strength. However, because of variation in veneer properties, the effect of resin retention on veneer property enhancement was not quantified properly. However, the British Columbia veneer-based products industry is interested in extending the investigation to another major veneer-based product, LVL. For structural LVL, mechanical properties, such as bending MOE and MOR, directly correlate with properties of veneers, such as density and dynamic MOE, in their lay-up construction. Therefore, the key objective of this research was to explore how MPB-affected veneer dynamic MOE is enhanced by resin impregnation with the new PF formulation and to examine the effects of resin retention level on veneer MOE and resulting LVL properties.

MATERIALS AND METHODS

Sixty dry full-sized (1.2 × 2.4 m) MPB-affected lodgepole veneer sheets were acquired from a plywood mill in British Columbia, Canada. They were cut into 180 subsheets of 405 × 305 mm and then segregated into either stained (95 sheets) or nonstained (85 sheets) groups. Separating into these two groups was necessary because of the difference in permeability. Sap stain (blue color) is often found in MPB-affected logs because of the time lapse between tree death and harvesting. Average moisture content of these sheets was approximately 5.5%. Before resin treatment, thickness, width, length, and weight of each sheet were measured to calculate veneer density. Dynamic MOE along the grain of each veneer sheet was calculated based on gross density and stress wave transit time measured using a stress wave device (Metriguard 1998). Twelve readings were taken from each sheet at a test length of 300 mm and at intervals of 25 mm.

A new PF adhesive formulation (diluted to 30% solids content) was used to treat stained and nonstained veneers using both dipping (or soaking) and vacuum-pressure-soaking methods (Wang et al 2009a). This resin had a broad MW distribution (from 200 to approximately 2000). This resin allows a certain degree of cell wall (cavity) penetration while retaining adequate resin on the veneer surface. In this way, the stain color in MPB-affected wood can be effectively masked, and more adhesive application after veneer drying is not required. As a result, the manufacturing process of MPB-affected LVL using resin impregnation technology can be simplified to become more cost-effective.

To manufacture LVL with different resin loading levels, five treatment procedures (Table 1) were used for each veneer type. These were dipping for 5 min, vacuum-pressure soaking for 5 min, vacuum-pressure soaking for 10 min, dipping for two 30-min periods with a 2-h drying in between, and dipping for 360 min. After treatment, mass of each sheet was measured. Treated veneer sheets were dried in a 50°C oven to achieve a target MC of 7-10%. Then stress wave transit time, thickness, and density of each veneer sheet were measured again. By doing this, the effect of resin impregnation on veneer MOE enhancement can be examined in terms of resin solids uptake. Five-ply LVL billets were manufactured without more resin application after veneer drying using a laboratory minipress (405 × 405 mm). Pressing was performed using a thickness control method with a target thickness of 15 mm. Three replicate billets were made for each group. Press temperature was 155°C, and peak pressure of 2.1 MPa was applied for about 20 s. Pressing time was controlled until temperature of the innermost adhesive line reached 110°C. After unloading, billets were stacked for 48 h before cutting specimens for thickness swell, surface hardness, color, flatwise bending, and shear tests.

Table 1. Treatment procedures applied to mountain pine beetle-affected veneers.

Test	Veneer category	Resin treatment	Time (min)
1	Stained	Dipping (or soaking)	5
2	Stained	Vacuum-pressure (VP)	5[a]
3	Stained	Vacuum-pressure (VP)	10[b]
4	Nonstained	Dipping (or soaking)	5
5	Nonstained	Vacuum-pressure (VP)	5
6	Nonstained	Vacuum-pressure (VP)	10
7	Stained	Dipping (or soaking)	60[c]
8	Stained	Dipping (or soaking)	360
9	Nonstained	Dipping (or soaking)	60[c]
10	Nonstained	Dipping (or soaking)	360

[a] Two and a half min to achieve a vacuum condition and 2.5 min under 0.54-MPa pressure.

[b] Five min to achieve a vacuum condition and 5 min under 0.54-MPa pressure.

[c] Veneer sheets were first dipped in resin for 30 min to evaluate resin solids uptake, then dried for 2 h, and subsequently soaked in resin again for another 30 min.

Flatwise bending tests followed the center loading approach of ASTM (2006) using a span-to-depth ratio of 24. Thickness swell and water absorption tests were conducted according to ASTM (2006). Surface hardness was measured using the Janka ball test specified in ASTM (2006). The shear test followed the short span bending test of JAS (1993) for LVL.

Surface color of the LVL was measured by a spectrophotometer (model CM-600d; Minolta, Osaka, Japan) to obtain color indices L*, a*, and b* (Goktas et al 2008). The L* axis represents lightness and varies from 100 (white) to 0 (black); the a* and b* coordinates represent chromaticity, with + a* for red, – a* for green, + b* for yellow, and – b* for blue. a* and b* ranged from –120 to 120.

RESULTS AND DISCUSSION

Resin Solids Uptake Comparisons

Figure 1 compares resin solids uptake between simple dipping and vacuum-pressure soaking for stained and nonstained veneers. The three treatment procedures compared were dipping for 5 min, vacuum-pressure soaking for 5 min, and vacuum-pressure soaking for 10 min. For all treatments, stained veneers picked up

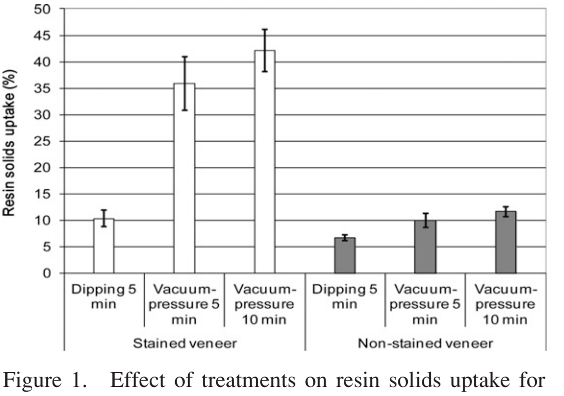

Figure 1. Effect of treatments on resin solids uptake for stained and nonstained veneers.

significantly more resin solids than nonstained veneers. Compared with simple dipping, vacuum-pressure treatment for 5 min significantly improved the resin solids uptake for stained veneers and slightly increased resin solids uptake for nonstained veneers. With an additional 5 min vacuum-pressure treatment, resin solids uptake increased by only 6.3% for stained veneers and 1.7% for nonstained veneers.

Figure 2 compares resin solids uptake of stained and nonstained veneers for the three dipping procedures: dipping for 5 min, dipping–drying–dipping (1-h total dipping time), and dipping for 6 h. For all three treatment procedures, stained veneers had a significantly higher resin solids uptake than nonstained veneers at the $p = 0.05$ level. As expected, longer dipping time led to higher resin solids uptake. Interestingly, for each veneer type, the procedure consisting of dipping (30 min), drying (2 h), and dipping (30 min) produced almost the same resin solids uptake as dipping for 6 h. This result suggests that the dipping–drying–dipping method could be a cost-effective way to achieve a high resin solids uptake compared with a prolonged dipping method.

Veneer MOE Enhancement and Resin Solids Uptake

Stained veneers had on average a 12% higher MOE before resin treatment than nonstained veneers (13,200 and 11,600 MPa). Because of this and because the objective of this study was to determine the level of product property improvement through resin impregnation, it was of interest to understand the relationship between property enhancement and resin solids uptake of veneers after treatment. Therefore, veneer dynamic MOE enhancement was plotted against resin solids uptake for all veneer subsheets in Fig 3. Veneer MOE enhancement ratio was defined as the ratio of dynamic MOE measurements after resin impregnation to initial value before treatment. Figure 3 clearly shows that resin solids uptake of nonstained veneers was restricted because of their lower permeability compared with stained veneers. From a material use perspective, because of their higher initial MOE and higher level of MOE enhancement, the use of resin impregnation to improve mechanical properties of LVL was more effective for stained veneers than for nonstained veneers. Nonetheless, Fig 3 shows that veneer dynamic MOE enhancement generally increased with resin solids uptake in a curvilinear manner regardless of the type of veneer. The rate of increase in MOE enhancement decreased as resin solids uptake increased, A R^2 value of 0.73 was obtained for the overall regression curve. Generally, 10% resin solids uptake yielded an increase of 8% in veneer MOE. A 20% dynamic MOE enhancement was achieved if solids uptake was close to 50%.

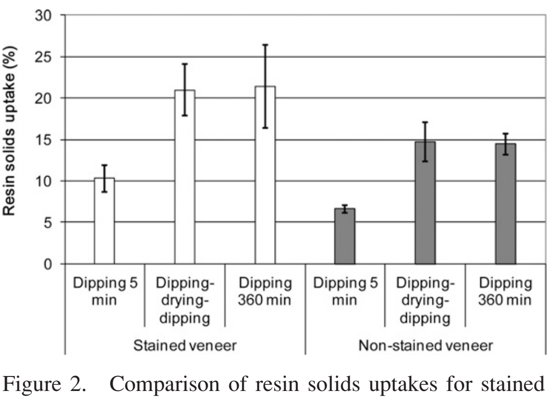

Figure 2. Comparison of resin solids uptakes for stained and nonstained veneers among the three dipping times.

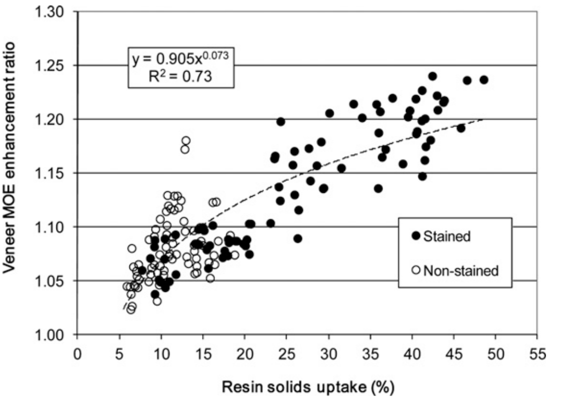

Figure 3. Correlation between veneer modulus of elasticity (MOE) enhancement and resin solids uptake.

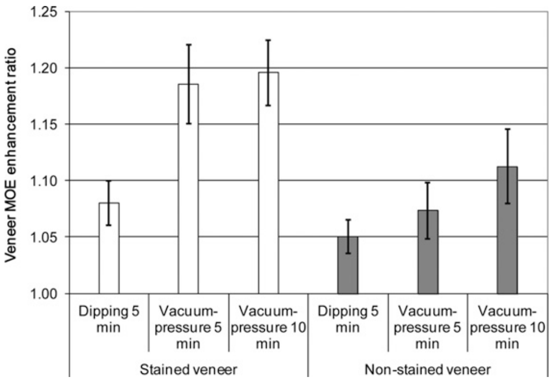

Figure 4. Enhancement of veneer dynamic modulus of elasticity (MOE) from 5-min dipping and vacuum-pressure treatments.

Figure 4 shows how veneer dynamic MOE enhancement was affected by dipping and vacuum-pressure-soaking treatment procedures. Comparison with Fig 1 shows that the higher the resin solids uptake, the greater the veneer MOE enhancement. As was discussed previously, for stained veneers, vacuum-pressure treatment for 10 min yielded 6.3% more resin solids uptake than 5 min vacuum-pressure treatment. Despite the difference in resin uptake, the difference between veneer dynamic MOE enhancement values for the two treatments was not significant at the $p = 0.05$ level. For nonstained veneers, vacuum-pressure treatment for 10 min yielded about 1.7% more resin solids uptake than 5-min vacuum-pressure treatment. Even with this small addition of resin, veneer dynamic MOE enhancement was significant at the $p = 0.05$ level.

Figure 5 shows how veneer dynamic MOE enhancement changes with different dipping procedures. Comparison with Fig 2, as expected, shows longer dipping time led to higher resin solids uptake and greater veneer MOE enhancement. The dipping–drying–dipping method yielded significant improvement in resin solids uptake. However, as shown in Fig 5, its improvement on dynamic MOE was only marginal compared with simple dipping for 5 min. From a productivity point of view, dipping for 5 min appeared to be the most cost-effective for

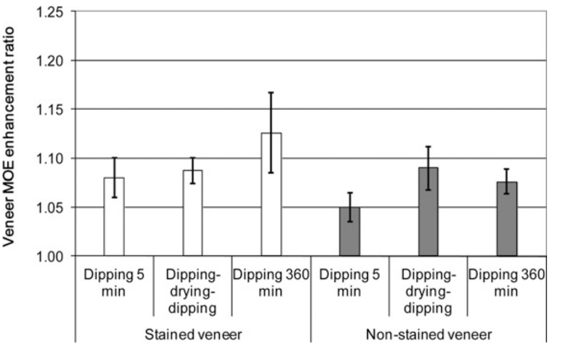

Figure 5. Enhancement of veneer dynamic modulus of elasticity (MOE) from different dipping treatments.

LVL manufacturing using MPB-affected veneers, which agreed with results obtained for 5-ply plywood (Wang et al 2009a). A 5-min dipping was sufficient for MPB-affected veneers to achieve approximately 7 and 10% resin solids uptake and in turn 5 and 8% enhancement in veneer MOE for nonstained and stained veneers, respectively.

These results show that the rate of increase in veneer dynamic MOE was higher at the lower resin retention levels. Figure 3 shows that veneer dynamic MOE enhancement was small when resin retention was greater than 25%. It was speculated that low MW PF could first penetrate into cell walls (Kamke and Lee 2007); however, once resin retention increased to a certain level, the extra resin mainly filled cell cavities instead of cell walls. This part of the resin might not have significantly contributed to veneer MOE enhancement. Further research is deemed necessary to 1) establish the most economical resin retention for veneer MOE enhancement; 2) examine resin penetration in cell walls in terms of resin solids uptake with scanning electron microscopy (SEM) technology; and 3) understand how veneer dynamic MOE relates to product bending performance.

Color Masking of Laminated Veneer Lumber

Figure 6 summarizes the color index L*, a*, and b* of LVL billets made from different veneer categories or treatments. For stained veneers, all treatments masked blue stain effectively.

With 5 min dipping, no significant difference was found in the color components between stained and nonstained LVL at the $p = 0.05$ level.

Laminated Veneer Lumber Performance

Table 2 summarizes the physical properties of 5-ply LVL made from MPB-affected veneers that were subjected to various treatment procedures. The final LVL MC range was approximately 5-8%. The 5-ply LVL compression ratio (CR) was 5.1-8.5%, which was similar to that of 5-ply plywood made with MPB-affected veneers (Wang et al 2009a). CR of each LVL billet was calculated from total initial veneer thickness (t_1) and final product thickness (t_2), such that $CR = (t_1 - t_2)/t_1 \times 100\%$. From a dimensional stability perspective, the short-term (24-h soak) water absorption (WA) and thickness swell (TS) of LVL made with nonstained veneers (Tests 4, 5, 6, 9, and 10) were much lower than those of LVL made of stained veneers (Tests 1, 2, 3, 7, and 8). Compared with the control 13-ply LVL that was made from mixed stained and nonstained MPB-affected veneers, nonstained 5-ply LVL exhibited much smaller WA and TS but the stained counterpart appeared to yield similar levels of WA and TS after 24-h water soaking. This phenomenon can be explained by the higher permeability of stained veneers. Despite the fact that stained veneers absorb more resin, which decreases WA and TS, these properties are probably dominated more by the inherent permeability of veneers. These results demonstrate that dimensional stability of LVL made with MPB-affected veneers can be improved through resin impregnation of the

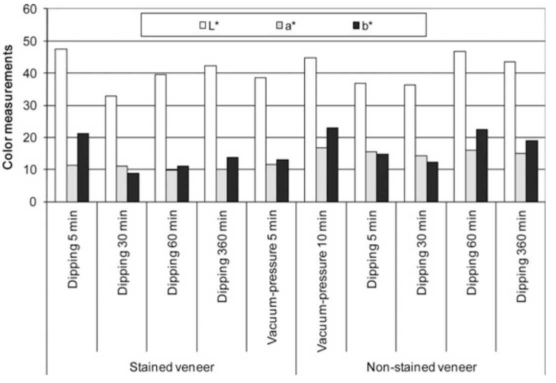

Figure 6. Color components of laminated veneer lumber billets made from veneer with different treatments.

Table 2. Physical properties of 5-ply mountain pine beetle-affected LVL made from veneer with different resin treatments.

			5-ply LVL					
							24-h soak[e]	
Test	Veneer category	Treatment	Thickness[a] (mm)	SG[b]	MC[c] (%)	CR[d] (%)	WA (%)	TS (%)
1	Stained	Dipping 5 min	15.45	0.551	6.0	8.1	42.3	7.1
2	Stained	Vacuum-pressure 5 min	14.52	0.664	6.8	8.1	42.4	5.2
3	Stained	Vacuum-pressure 10 min	14.73	0.679	7.2	7.5	44.8	6.9
4	Nonstained	Dipping 5 min	16.35	0.483	5.2	5.7	33.9	5.3
5	Nonstained	Vacuum-pressure 5 min	15.83	0.546	6.6	5.9	28.0	3.8
6	Nonstained	Vacuum-pressure 10 min	15.83	0.569	6.6	5.1	30.6	3.8
7	Stained	Dipping 1 h	15.44	0.601	7.8	7.3	39.6	7.7
8	Stained	Dipping 6 h	15.07	0.542	7.5	8.5	50.8	7.0
9	Nonstained	Dipping 1 h	15.91	0.556	7.4	7.8	21.6	4.0
10	Nonstained	Dipping 6 h	15.78	0.514	6.9	7.8	27.2	2.8
Control	13-ply MPB LVL	Untreated	37.50	0.496	6.7	10.1	48.5	6.7

[a] Thickness, average of three LVL billets with nine points from each billet measured after trimming to 405 × 305 mm.
[b] SG, specific gravity based on oven-dry mass; average of three specimens in 152 × 76 mm with one specimen from one billet (ASTM 2006).
[c] MC, moisture content (oven-dry basis); average of three specimens (same as SG; ASTM 2006).
[d] CR, compression ratio = $(t_1 - t_2)/t_1$, where t_1 is the sum of initial thickness of veneers, t_2 is final thickness of LVL; average of three LVL billets (405 × 305 mm).
[e] Average of three specimens (152 × 152 mm) with one specimen from each LVL billet (ASTM 2006); WA, water absorption after 24-h soak; TS, thickness swelling after 24-h soak.
LVL, laminated veneer lumber; MPB, mountain pine beetle.

veneers, especially when nonstained veneers are used.

Table 3 summarizes mechanical properties of 5-ply LVL made from veneers that were subjected to different treatments and shows dynamic MOE of the treated MPB-affected veneers for comparison. Flatwise bending MOE of LVL made from veneers with various resin treatments was greater than the veneer dynamic MOE after resin treatment. The ratio of LVL MOE to veneer MOE ranged from 1.01-1.16. With 5-min dipping for veneers, flatwise bending MOE of the resulting 5-ply LVL was 16,893 and 13,445 MPa for stained and nonstained wood, respectively. These met the 2.2 E (15,169 MPa) and 1.9 E (13,101 MPa) LVL market requirements in North America. These MOE results compare favorably with the 1.8 E (12,411 MPa) grade of the 13-ply LVL untreated control. Indeed, the best group for flatwise MOE (Test 2) achieved a 40% MOE improvement compared with the control LVL. LVL made with stained veneers had greater flatwise MOE than that of LVL made from nonstained veneers. The exception was Test 8. This can be explained by the fact that veneer dynamic MOE of Test 8 was low to begin with compared with the other four groups of stained veneers (Tests 1, 2, 3, and 7). For each veneer type, there was no statistical difference in flatwise MOE among the various treatment procedures (except Test 8). This means there would be no significant benefit in adopting more expensive treatment procedures

Table 3. Mechanical properties of 5-ply mountain pine beetle-affected LVL made from veneer with different resin treatments.

				5-ply LVL				
				Flatwise bending[d]		Shear strength (MPa)		
Test	Veneer category	Treatment	Veneer dynamic MOE[c] (MPa)	MOE (MPa)	MOR (MPa)	L-X[e]	L-Y[f]	Hardness[g] (N)
1	Stained	Dipping 5 min	14553 (11.0%)[b]	16898 (3.4%)	99 (14.8%)	5.7 (10.1%)	11.1 (9.4%)	332.4 (21.9%)
2	Stained	Vacuum-pressure 5 min	15587 (6.5%)	17725 (8.2%)	66 (22.1%)	5.1 (19.9%)	10.1 (12.1%)	270.6 (14.9%)
3	Stained	Vacuum-pressure 10 min	15380 (8.1%)	17449 (7.3%)	57 (22.8%)	5.5 (31.1%)	10.9 (17.4%)	326.9 (15.4%)
4	Nonstained	Dipping 5 min	12001 (18.9%)	13449 (10.2%)	66 (21.8%)	5.0 (25.4%)	9.1 (9.9%)	292.2 (14.6%)
5	Nonstained	Vacuum-pressure 5 min	13035 (10.5%)	14484 (8.8%)	92 (28.6%)	6.8 (35.4%)	11.2 (21.8%)	266.1 (13.1%)
6	Nonstained	Vacuum-pressure 10 min	12897 (23.3%)	13035 (17.0%)	80 (10.4%)	6.0 (7.8%)	11.7 (11.2%)	334.4 (18.2%)
7	Stained	Dipping 1 h	15104 (15.1%)	16691 (12.3%)	108 (14.0%)	11.5 (5.4%)	15.8 (10.4%)	291.7 (16.3%)
8	Stained	Dipping 6 h	13587 (22.3%)	14415 (6.0%)	86 (9.0%)	7.0 (24.8%)	11.6 (9.8%)	331.7 (15.3%)
9	Nonstained	Dipping 1 h	13449 (17.4%)	13656 (9.8%)	96 (11.1%)	10.0 (12.7%)	12.3 (7.5%)	380.0 (22.1%)
10	Nonstained	Dipping 6 h	11380 (25.5%)	11932 (11.5%)	83 (21.8%)	8.8 (33.2%)	11.4 (20.5%)	277.8 (19.3%)
Control	13-ply MPB LVL[a]	Untreated	N/A	12622 (9.5%)	67 (15.6%)	5.5 (23.4%)	7.4 (15.4%)	260.0 (34.1%)

[a] Wang and Wharton (2008). LVL was made from mixed MPB veneers without stress grading.
[b] Data in parentheses are coefficients of variation (COV).
[c] Average of veneer dynamic MOE values of five sheets in 405 × 305 mm.
[d] Six specimens in 405 × 76 mm with two specimens from each LVL billet.
[e] Six specimens in 95.3 × 40 × 15.5 mm with two specimens from each billet; load is applied parallel to grain and shear plane is parallel to plane of veneers.
[f] Six specimens in 95.3 × 15.5 × 15.5 mm with two specimens from each billet; load is applied parallel to the grain and shear plane if perpendicular to plane of veneers.
[g] Three specimens in 102 × 102 mm with one from each LVL billet.
LVL, laminated veneer lumber; MPB, mountain pine beetle.

such as vacuum-pressure if the objective is to maximize improvement in MOE. Although improvement in flatwise MOE caused by resin impregnation compared with untreated LVL was clear and followed an expected trend, the influence of resin impregnation on flatwise MOR of LVL was less certain. Whereas seven of the treated groups exhibited higher MOR, three of them had lower MOR than the control group. This could have been caused by the fact that, unlike MOE, flatwise MOR is controlled largely by the outermost veneer. Overall, there is evidence to suggest that flatwise MOR of LVL generally increased after resin treatment of veneers, but this improvement may be inconsistent because of localized influence of veneer quality on this strength property.

Compared with the 13-ply LVL control, L-Y shear strengths of all 5-ply LVL groups (9.1-15.8 MPa) were consistently higher than those of the control LVL (7.4 MPa). Differences are statistically significant at the $p = 0.05$ level. For L-X shear strength, only those groups that had longer dipping times of 1 and 6 h appeared to have higher shear strengths than the control LVL. Also, unlike flatwise MOE, shear strength does not appear to be influenced by veneer type. Reasons for these observations are unknown, and further investigation is required.

In the case of surface hardness, all treated LVL exhibited higher mean hardness values than the 13-ply LVL control. Again, similar to shear strength, there did not appear to be any influence of veneer type on surface hardness improvement. The greatest increase in surface hardness was from Test 9 with a 46% improvement compared with the control.

For typical engineered applications of LVL such as I-joists, product stiffness and strength are primarily governed by the stiffness of face and back veneers (Chui et al 1994). There is potential to manufacture LVL using a partial resin impregnation. As a result, placement of resin-impregnated MPB-affected veneers on the face and back could help further decrease resin consumption and simplify the manufacturing process for LVL as well. This will be addressed in a separate article. For exterior applications such as above-ground or ground contact, durability of MPB-affected LVL (decay resistance) is critical, which will also be examined in a future study.

CONCLUSIONS

In this study, veneers obtained from MPB-affected trees were treated with a new formulation of PF resin using dipping and vacuum-pressure methods. Results demonstrated that there was good correlation between veneer dynamic MOE enhancement and resin solids uptake. With the same treatment, stained veneers had greater MOE enhancement than nonstained. Within the processing conditions adopted in this study, dipping in resin for 5 min appears to be economical for veneers. With this treatment, 7 and 10% resin solids uptake can be attained for nonstained and stained veneers, respectively. These retention levels yielded 5 and 8% enhancement in veneer dynamic MOE, respectively.

Dimensional stability of LVL made with MPB-affected veneers can be improved through resin impregnation of the veneers, especially when clear veneers are used. For LVL made with treated stained veneers, dimensional stability did not deviate significantly from untreated MPB-affected LVL because of the veneers' higher permeability.

LVL made with stained veneers had higher flatwise MOE than that of LVL made with clear nonstained veneers. For flatwise MOR of LVL, there is evidence to suggest that it generally increased after resin treatment of veneers, but this improvement may be inconsistent because of localized influence of veneer quality on this strength property.

Shear strength in the L-Y direction of treated LVL was consistently higher than that of the control group, whereas in the L-X direction, the difference was not significant. Mean surface hardness of treated LVL was higher than that of the untreated control. PF resin was able to mask the staining of MPB-affected veneers.

Results also showed that with further increase in resin solids uptake, veneer MOE enhancement was not as significant as that at lower resin solids uptake. Thus, optimum resin solids uptake should be established to balance manufacturing cost and product performance. Further research is needed to 1) establish the most economical resin solids retention for MOE enhancement based on requirements of final LVL products; and 2) examine resin penetration in cell walls in terms of resin solids uptake with SEM technology.

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REFERENCES

ASTM (2006) D 1037. Standard test methods for evaluating properties of wood-base fiber and particle panel materials. American Society for Testing and Materials, West Conshohocken, PA.

Brady DE, Kamke FA (1988) Effect of hot-pressing parameters on resin penetration. Forest Prod J 38(11/12):63-68.

Chui YH, Schneider MH, Zhang HJ (1994) Effects of resin impregnation and process parameters on some properties of poplar LVL. Forest Prod J 44(6):74-78.

Gindl W, Muller U, Teischinger A (2003) Transverse compression strength and fracture of spruce wood modified by melamine-formaldehyde impregnation of cell walls. Wood Fiber Sci 35(2):239-246.

Goktas OM, Duru E, Yeniocak M, Ozen E (2008) Determination of the color stability of an environmentally friendly wood stain derived from laurel leaf extracts under UV exposure. Forest Prod J 58(1/2):77-80.

Hare DA, Kutscha NP (1974) Microscopy of eastern spruce plywood gluelines. Wood Sci 6(3):294-304.

JAS (1993) JAS SIS-24 Japanese Agricultural Standard for Structural Laminated Veneer Lumber. Ministry of Agriculture, Forestry and Fisheries (MAFF), Tokyo, Japan.

Kamke FA, Lee JN (2007) Adhesive penetration in wood: A review. Wood Fiber Sci 39(2):205-220.

Metriguard (1998) Manual of Metriguard model 239: A stress wave timer, care and instructions, theory and data reduction. Metriguard, Inc., Pullman, WA.

Miroy F, Eymard P, Pizzi A (1995) Wood hardening by methyoxymethyl melamine. Holz Roh Werkst 53:276.

Nearn WT (1974) Application of ultrastructure concept in industrial wood products research. Wood Sci 6 (3):285-293.

Nicholas DD, Williams AD (1987) Dimensional stabilization of wood with dimethylol compounds. IRG/WP 3412. International Research Group on Wood Preservation, Honey Harbour, Ontario, Canada.

Ors Y, Keskin H, Atar M, Colakoglu M (2007) Effects of impregnation with Imersol-aqua on the modulus of elasticity in bending of laminated wood materials. Construct Build Mater 21:1647-1655.

Shams I, Yano H, Endou K (2004) Compressive deformation of wood impregnated with low molecular weight PF resin. I. Effects of pressing pressure and pressure holding. J Wood Sci 50:337-342.

Troughton GE, Steiner PR (1992) Development of high stiffness laminated veneer lumber made from BC softwoods. Submitted to Science Council of British Columbia Grant #196 (T-1). Forintek Canada Corporation, Vancouver, BC, Canada.

Troughton GE, Steiner PR (1994) Development of laminated veneer lumber made from B.C. softwoods using a resin impregnation method. Submitted to Science Council of British Columbia Grant #7 (T-4). Forintek Canada Corporation, Vancouver, BC, Canada.

Walser DC, Troughton GE, Andersen AW (1993) High strength laminated veneer lumber. US patent no 5,234,747.

Wan H, Kim MG (2006) Impregnation of southern pinewood and strands with low molecular weight phenol-formaldehyde resins for stabilization of oriented strandboard. Wood Fiber Sci 38(2):314-324.

Wang BJ, Chui YH, Xie D, He G (2009a) Impregnation of MPB veneers for value-added plywood products. Pages 185-201 *in* Proc 4th International Symposium on Veneer Processing and Products, May 24-27, 2009. Helsinki University of Technology, Espoo, Finland.

Wang BJ, He G, Feng M, Dai C, Xie D, Chui YH (2009b) Manufacturing plywood from MPB veneers impregnated with a low molecular weight PF resin. Pages 171-184 *in* Proc 4th International Symposium on Veneer Processing and Products. May 24-27, 2009. Helsinki University of Technology, Espoo, Finland.

Wang BJ, Wharton S (2008) Benchmarking mountain pine beetle (MPB)-attacked lodgepole pine veneer for plywood/LVL products. Forest Prod J 58(12):87-92.

Zhang Y, Zhang SY, Chui YH, Wan H (2006) Effect of impregnation and in-situ polymerization of methacrylates on hardness of sugar maple wood. J Appl Polym Sci 99(4):1674-1683.