IMPACT OF MOUNTAIN PINE BEETLE–ATTACKED LODGEPOLE PINE LOGS ON PLYWOOD MANUFACTURING

Brad Jianhe Wang†

Composites Research Scientist

Chunping Dai†

Group Leader
Composites Group
FPInnovations - Forintek Division
2665 East Mall
Vancouver, BC, Canada

Steve Wharton

Quality Control Supervisor
Tolko Industries Ltd.
Bag Service 5000
Otter Lake X Road
Armstrong, BC, Canada

(Received November 2007)

Abstract. In this work, the possibility of increasing value recovery from mountain pine beetle (MPB)-attacked lodgepole pine (*Pinus contorta* Dougl.) logs was further investigated, including veneer grading, gluing, panel lay-up, and hot-pressing. This was a follow-up to an earlier study that demonstrated that, by segregating MPB logs, the value recovery could be improved through narrower veneer clipping width, more accurate moisture sorting, and greater drying productivity. Based on pilot plant tests, compared with control veneer of spruce–lodgepole pine–alpine fir (SPF), MPB veneer had various degrees of bluestain, and was significantly denser and stiffer. To minimize manufacturing costs for MPB plywood, glue spread can be kept at the same level as currently used by control SPF plywood. However, the pressing time of 5-ply MPB plywood should be lengthened by about 10% compared with that used by the 5-ply control SPF counterpart. The assembly time should be maintained within 10 to 15 min, keeping veneer temperature as low as possible. Furthermore, the parallel-ply MOE and MOR of 5-ply MPB plywood were approximately 15 and 20% higher than those of 5-ply control SPF plywood, respectively. As a result, MPB veneer was more suitable for making specialty plywood products requiring high stiffness and strength. If manufacturing parameters are properly adjusted in grading, gluing, and hot-pressing, segregating MPB logs from the normal SPF mix also provides an opportunity to manufacture high stiffness plywood with superior dry- and wet-gluebond performance. This could further offset, to a large degree, the reduction in material recovery and the loss in market share for some appearance-based plywood products.

Keywords: Gluing, grading, layup, lodgepole pine, moisture content, mountain pine beetle, plywood manufacturing, pressing, recovery, SPF, veneer.

INTRODUCTION

A large epidemic of Mountain Pine Beetle (MPB) outbreak has changed the nature of the resource available to panel producers in British Columbia (BC). The infestation has resulted in an increased volume of larger diameter, but drier, checked, and stained logs entering plywood and LVL mills (MPBAP 2007). Unlike other panel industries, plywood mills generally do not segregate lodgepole pine logs from the normal white-wood mix consisting of spruce, lodgepole pine, and alpine fir (SPF) to

* Corresponding author: Wang@van.forintek.ca
† SWST member

manufacture standard softwood plywood (CSA O151 2004). This study follows directly from the results of an earlier study (Wang and Dai 2004; Wang and Dai 2005) that investigated manufacturing process adjustments at the early stages of production, from log conditioning and peeling, through to veneer drying, and recommended process changes to optimize manufacturing practices for this altered resource. That study demonstrated that post-MPB attacked wood is drastically different from normal SPF wood in terms of moisture content (MC), log conditioning, veneer peeling, and drying. Once the fraction of MPB logs procured has exceeded about 10% of the total log supply, sorting and processing the MPB-attacked pine logs separately from the normal SPF mix proved cost-effective for the mill. The adjustments resulted in increased productivity and material recovery at the mill through narrower veneer clipping width for full sheets, more accurate moisture sorting, and higher drying productivity. However, the value recovery from the MPB logs remained lower than that from the normal SPF mix, because there was about an 8% greater material recovery loss from veneer peeling, clipping, drying, and composing. This loss was partially from the increased manual handling of random width veneers due to splits (Wang and Dai 2004; Wang and Dai 2005). In the near future, the volume of MPB-attacked wood will be greater than 10% of total log supply with more logs being gray-stage materials. Since gray-stage logs are generally very dry and may contain serious cracks, veneer breakage and recovery loss could be more serious. To increase value recovery from this altered resource, optimization of manufacturing process and product options appears to be essential.

This study was to investigate the possibility of increasing the value recovery from MPB logs farther downstream by optimizing veneer grading, gluing, plywood lay-up, and hot-pressing. Compared with control SPF, MPB veneer has stains, checks, different surface chemistry, and is drier, rougher, more brittle, and more permeable. These characteristic changes can affect veneer grading, gluing, and panel pressing by their impact on surface appearance, wettability, glue penetration, bondability, and heat and mass transfer (Sellers 1985; Shupe et al 1998; DeVallance 2003; Neese et al 2004). To achieve target gluebond quality as measured by percentage wood failure and shear strength for plywood products, gluing and pressing operations may need to be adjusted to avoid glue dry-out and ensure full glue cure. To address possible concerns in the marketplace, the plywood lay-up may need to be adjusted by placing stained veneer in center plies and crossbands. To maximize manufacturing productivity and material recovery, the effect of using the MPB veneer on plywood hot-pressing, and resulting panel gluebond quality and bending performance should be investigated. Field trials were conducted at the same plywood mill as the first study (Wang and Dai 2004) to permit a practical assessment of the processing adjustments and ensure that the impact on overall value recovery can be quantified.

The key objectives of this project were to: 1) investigate the effects of MPB logs on veneer grading, gluing, panel lay-up, and hot-pressing, and resulting panel gluebond quality and bending performance; and 2) through pilot plant tests and mill trials, quantify the costs and benefits of adjusting manufacturing processes.

MATERIALS AND METHODS

Pilot Plant Tests

In the same plywood mill (Wang and Dai 2004; Wang et al 2005), 180 sheets (2.4- × 1.2-m) of dried 3.2-mm-thick MPB veneer and 120 sheets (2.4- × 1.2-m) of dried control SPF veneer were randomly selected from those peeled from segregated MPB logs and normal control SPF mix, respectively. Note that the MPB veneer sheets were peeled from the typical mixture of different stages of MPB logs being received by the mill, with green stage being 85% and red stage 15% in volume breakdown. To make the veneer samples representative, those sheets were sampled from three shifts in one operation day and then delivered to FPInnovations - Forintek's composites pilot plant.

In the pilot plant, each 2.4- × 1.2-m veneer sheet was trimmed into two halves (1.2- × 1.2-m, Fig 1). Then two 81.3- × 40.6-cm and two 40.6- × 40.6-cm subsheets were further cut from each 1.2- × 1.2-m sheet for plywood manufacture. In total, about 650 and 400 veneer subsheets of 81.3- × 40.6-cm were generated from the MPB and control SPF veneer, respectively. Also, about 500 and 300 veneer subsheets of 40.6- × 40.6-cm were generated from the MPB and control SPF veneer, respectively, to use as crossbands. In addition, about 500 63.5- × 63.5-mm and 80 30- × 30-mm veneer pieces were randomly cut from the remainder of the MPB and control SPF veneer, respectively, for image analysis and compression tests.

Veneer transverse permeability. The air permeability of wood has a remarkable effect on wood treatment efficiency, drying, and panel hot-pressing productivity. To date, comparative tests on air permeability of MPB wood and control wood have been conducted by several authors (Oliveira et al 2005; Woo et al 2005). However, comparative tests of air permeability of the MPB and control veneer have not been done. During gluing and hot-pressing of plywood and LVL products, the veneer transverse air permeability, rather than lateral permeability, determines the degree of glue penetration and diffusion of hot air and high temperature vapor from surface layers to the core at the stages of panel consolidation and curing, and the ease of evaporation at the stage of decompression. The air permeability of veneers is the rate of air flow through a unit cube of the wood with a unit pressure differential between two parallel faces that can be measured using a standard permeability measurement device as described by Wang et al (2006).

Thirty 60-mm-dia MPB veneer disks and thirty 60-mm-dia control SPF veneer disks were randomly cut from 10 representative MPB and control veneer sheets, respectively. Among the 30 disks of the MPB veneer, 15 were stained sapwood and 15 were nonstained heartwood veneer. The *t*-tests were performed to identify whether there was a significant difference in transverse air permeability between the MPB stained, MPB nonstained, and control SPF veneer.

Since the control SPF veneer was a mixture of lodgepole pine, spruce, and alpine fir, in order to determine the effect of bluestain on veneer air permeability, 6 representative lodgepole pine sapwood and heartwood veneer sheets were selected from the control SPF veneer for tests. Ten 60-mm-dia disks were randomly cut from each sapwood and heartwood veneer sheet. To minimize the effect of lathe checks on air permeability, two-ply glued disk pairs were prepared for the MPB stained veneer, MPB nonstained veneer, and control lodgepole pine sapwood and heartwood veneer. The permeability measurements were then performed.

FIGURE 1. Dried MPB and control SPF veneer sheets sampled from a plywood mill.

Veneer stress grading. Thirty-six dry veneer sheets (81.3- × 40.6-cm) were randomly selected from each of the two categories: MPB and control SPF veneer. They were placed in plastic bags until measured for length, width, thickness, and weight to calculate the mean density. The MC of each sheet was also checked. As shown in Fig 2, a portable Metriguard Model 239 stress-wave timer was used to measure veneer stress-wave time. For this measurement, 11 straight lines were drawn along the grain on the loose (lathe-checked) side of each veneer sheet with a lateral separation of 3.8 cm. The distance between the sending transducer and receiving transducer was 76.2 cm. Based on the mean density and stress-wave time of each veneer sheet, the mean dynamic modulus of elasticity (MOE) was calculated for each veneer sheet. The t-tests were conducted to compare whether there was a significant difference in veneer density and MOE between the MPB and control SPF veneer.

Veneer visual grading. Current machine vision technology used by some plywood/LVL mills cannot differentiate veneer defects within the bluestained area, hence it is unable to sort the MPB veneer in its current configuration (Wang and Dai 2004). Due to this reason, plus some current market issues, a study on visual characteristics of bluestain was required. Five hundred 63.5- × 63.5-mm MPB veneer pieces cut for the image analysis contained various levels of bluestain, knots, resin pockets, and cracks. As shown in Fig 3, an image system was used to determine the visual characteristics of the MPB veneer, especially stained veneer, and its effect on visual grading (Groves 2000). To perform optical scanning, 150 pieces each were further selected from the total 500 MPB pieces and 500 control SPF veneer pieces. One image (1- × 1-cm area) each was taken from the stained area of each MPB veneer piece and central area of each control SPF veneer piece. The mean values of Red, Green, and Blue (RGB) (from 0 to 255) and Hue (0 to 360°), Saturation (0 to 100%), and Luminance or Lightness (0 to 100%) in HSL color space of each image were extracted. The frequency distribution of RGB values and HSL indexes was then established for both MPB-stained and control SPF veneer.

Lap-shear tests. As shown in Fig 4, 200 small veneer strips (100 × 20 mm) were randomly cut from the MPB and control SPF veneer for lap-shear tests. The purpose of the tests was to examine the effect of veneer side (loose or tight) on wettability and glue penetration (Shupe et al. 1998), and, in turn bondability, and then establish an optimum panel lay-up scheme. Six different lay-ups involving three panel lay-up options (stained-stained, stained-control, and control-control), and two veneer constructions (loose-to-loose and loose-to-tight) were considered. The Automated Bonding Evaluation System (ABES), originally designed for bonding tests of thin wood pieces (strands), was extended to test the effect of lay-up on dry-shear strength for this nominal 3.2-mm-thick veneer. The glue spread was 174 g/m^2 per single glueline using a normal plywood phenol-formaldehyde (PF) glue

FIGURE 2. Pilot plant veneer stress wave testing.

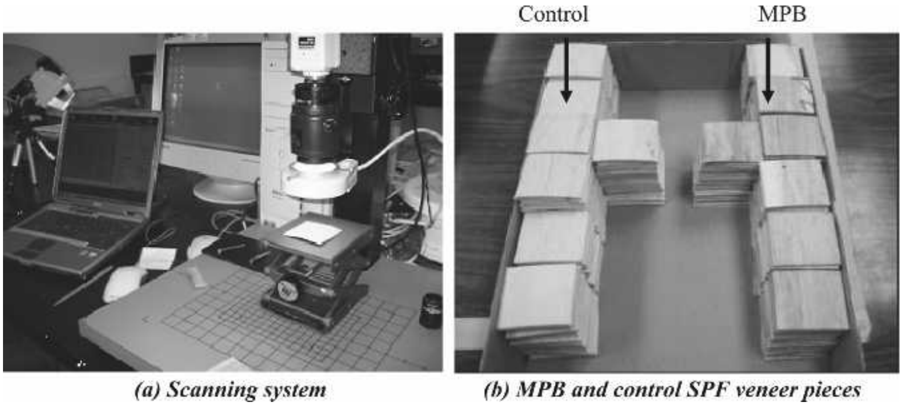

FIGURE 3. Pilot plant systems for scanning MPB and control SPF veneer.

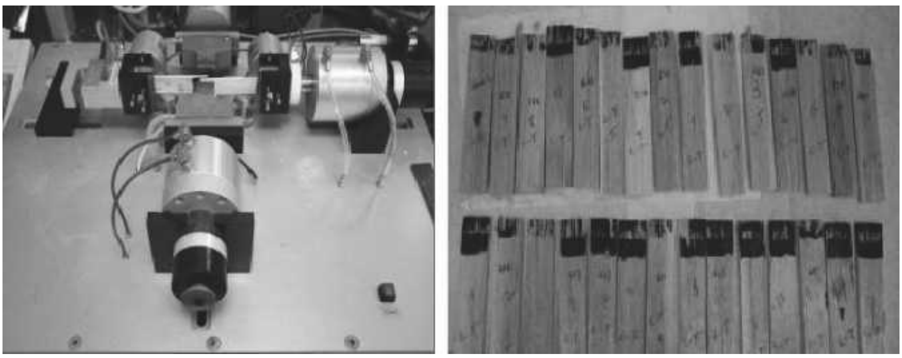

FIGURE 4. The ABES system for measuring dry shear (bond) strength.

mix with 45% solids content. The contact area between the two strips was 10 × 20 mm. The total force applied was about 325 N, equivalent to 1.62 MPa on the contact area. The heating temperature and time were 155°C and 180 s, respectively, to cure the PF. The glueline temperature was monitored with a thermocouple during heating. After heating, the cooling time for glued adherents (veneer strips) was 100 s. Subsequently, the glued adherents were pulled apart. The load was recorded accordingly to calculate the shear strength, and the failure mode of each sample was examined. Additional tests were conducted with 240-s heating time to ensure a full cure of the PF. The loose-to-tight construction was used for both stained and control SPF veneer. Fifteen replicates were used for each test.

Plywood gluing, lay-up, and hot-pressing. An experimental design was devised to study the effect of veneer temperature, glue-spread level, and panel assembly time on gluebond quality of plywood panels made from the MPB and control

TABLE 1. *Experimental design on effects of glue spread, veneer temperature, panel assembly time on plywood gluebond quality and bending performance.*

Test no.	Glue spread (g/m^2)	Veneer temperature (°C)	Assembly time (min)
1	159	21.1	10
2	159	32.2	15
3	159	43.3	20
4	174	21.1	15
5	174	32.2	20
6	174	43.3	10
7	189	21.1	20
8	189	32.2	10
9	189	43.3	15

SPF veneer. As shown in Table 1, 27 5-ply plywood panels (81.3- × 40.6-cm) each were made with different combinations of glue-spread level, veneer temperature, and assembly time using the MPB and control SPF veneer. The assembly time was defined as the time interval between completion of assembly of lay-ups and the application of heat and full pressure. To simulate the effect of veneer temperature, veneer sheets were put into the oven at the preset temperature for 300-s of heating. Then veneer sheets were covered with a target level spread with a rotary glue spreader. During pressing, the platen pressure was maintained at 1.21 MPa, and the temperature rise of the innermost glueline was monitored with two thermocouples. Once the temperature reached the 110°C target, a 30-s decompression cycle started. After unloading, panels were hot stacked for 48 h. Subsequently, 4 (43.2- × 7.6-cm) parallel-ply bending specimens and 24 (80.0- × 25.4-mm) shear test specimens were cut from each panel. Among the 24 shear specimens, 12 received vacuum pressure treatments and 12 were subjected to boiling-dry-boiling treatments. Panel parallel-ply bending MOE, MOR, shear strength, and percentage wood failure were examined following standard test methods (CSA O325 1988; CSA O151 2004).

Mill Trials

Approximately 2000 m^3 of MPB logs were segregated from the normal SPF mix in the mill before the trial. The mill trial was focused on panel gluing, lay-up, and hot-pressing. Based on mill daily quality control records, the process parameters, and relevant information on the control SPF veneer from lay-up, hot-pressing, and gluebond quality tests were captured. The difference in gluing and pressing behavior found in the pilot plant tests between 5-ply MPB and 5-ply control SPF plywood was examined in the mill in making 2.4- × 1.2-m panels. Panel gluebond quality was evaluated in terms of shear strength and percentage wood failure.

A jet dryer was used to dry the MPB and control SPF veneer. The target drying temperature and relative humidity were set at 196°C and 75% for three zones. The drying outputs were monitored for the MPB and control SPF veneer. For three sorts of green veneer, the drying times for heavy-sap, light-sap, and heart were about 8, 7, and 5 min for the MPB veneer, and 10.5, 9.0, and 6.5 min for the control SPF veneer. As a result, compared with the control SPF, the MPB veneer drying time was reduced by 23.8, 22.0, and 23.1% for the heavy-sap, light-sap, and heart sorts, respectively. In general, veneer drying yielded 75–80% of normal dry veneer (level 0) with a peak MC of 0–6% for both the MPB and control SPF veneer by setting the total volume of redry and stacking at a target of 25%. To effectively tackle the MPB veneer, this mill upgraded the Raute Mecano VDA Grader to differentiate physical defects from bluestain after the first mill trial (Wang and Dai 2004).

For both MPB and control SPF plywood, total assembly time and veneer temperature were also recorded. A 30-opening hot press was used to press 5-ply MPB and 5-ply control plywood. The panel hot-pressing parameters were: platen temperature (140.5°C) and platen pressure (1.33 MPa). During pressing, the innermost glueline temperature was monitored with a thermocouple linked with a digital pyrometer (EETh501) with a 112°C target. For 5-ply control SPF plywood, the current mill pressing schedules were used with a pressing time of 255 s. One press load was manufactured at each of the following four glue-spread levels: 144, 149, 154, and 159 g/m^2 (per single glueline). Then two plywood panels (2.4- × 1.2-m) at each glue-spread level were randomly sampled from 30 panels for gluebond quality tests. For 5-ply MPB plywood, as shown in Table 2, there were six combinations of manufacturing parameters: three glue-spread levels: 144, 152, and 159 g/m^2 (per single glueline) and two pressing time levels, 255 and 285 s. Four loads were pressed for each manufacturing condition. Nine plywood panels (2.4 × 1.2 m) were randomly sampled for gluebond quality tests.

For each panel sampled, one 122.0- × 30.5-cm

TABLE 2. *The experimental design for manufacturing 5-ply MPB plywood in the mill.*

5-ply MPB plywood	Glue spread (g/m^2)	Pressing time (s)	Press loads	Number of panels sampled
1	144	285	4	9
2	144	255	4	9
3	152	285	4	9
4	152	255	4	9
5	159	285	4	9
6	159	255	4	9

sample strip was cut and shipped to Dynea Canada Ltd, for gluebond quality tests (CSA O151 2004), and the remaining 213.4- × 122.0-cm was shipped to FPInnovations - Forintek's composites pilot plant. For each panel, 12 80- × 25.4-mm shear specimens were cut for vacuum pressure tests at Dynea, and 6 43.2- × 7.6-cm parallel-ply bending specimens were cut for measuring MOE and MOR at FPInnovations - Forintek (CSA O325 2007). The results helped to determine if glue spread and pressing time should be adjusted for the MPB plywood, and whether the MPB plywood is stronger than the control SPF plywood.

RESULTS AND DISCUSSION

Pilot Plant Tests

Veneer air permeability. As shown in Table 3, t-tests indicated that for the MPB veneer, the transverse air permeability between the stained and nonstained veneer was significantly different. On average, the air permeability of the stained veneer (sapwood) was about 2.8 times that of nonstained veneer (heartwood). This was consistent with other studies showing that the permeability of sapwood was generally higher than that of heartwood (Wang et al 2006). On average, the MPB sapwood veneer was about 21% higher in air permeability compared with the control SPF veneer, however, they were not statistically different at the $p = 0.05$ level. Neither was between the MPB and control SPF veneer. The results indicated that during hot-pressing of MPB plywood panels, the rate of heat convection could still be limited as commonly experienced in the hot-pressing of control plywood made from normal SPF veneer. However, veneer density could be the key factor affecting heat transfer efficiency. As also shown in Table 3, the air permeability of the two-ply MPB heartwood panels was significantly higher than that of the two-ply control lodgepole pine heartwood panels at the $p = 0.05$ level. While not statistically different at the $p = 0.05$ level, the air permeability of the two-ply MPB sapwood panels was about 1.5 times that of the two-ply control lodgepole pine sapwood panels. The implication is that the permeability of the MPB veneer increased compared with that of control lodgepole pine veneer. The drying rate, rate of heat convection, and preservative uptake of the MPB veneer would be relatively higher compared with those of the control lodgepole pine veneer segregated from the normal SPF mix.

TABLE 3. *Comparison of air permeability of the MPB and control veneer.*

	Comparison between	Air permeability (10^{-13} m^2) Mean	Std.	Number of samples	Significance
Case 1	MPB sapwood veneer (stained)	3.75	1.23	15	$\|t\| > t_{critical}$, $P < 0.05$*
	MPB heartwood veneer (nonstained)	1.33	1.24	16	
Case 2	MPB sapwood veneer (stained)	3.75	1.22	15	$\|t\| < t_{critical}$, $P > 0.05$
	Control SPF veneer	3.10	2.41	13	
Case 3	MPB veneer	2.50	1.73	31	$\|t\| < t_{critical}$, $P > 0.05$
	Control SPF veneer	3.10	2.41	13	
Case 4	Two-ply MPB sapwood panels (stained)	2.62	2.09	23	$\|t\| < t_{critical}$, $P > 0.05$**
	Two-ply control lodgepole pine sapwood panels	1.74	1.47	22	
Case 5	Two-ply MPB heartwood panels (nonstained)	1.81	1.02	22	$\|t\| > t_{critical}$, $P < 0.05$*
	Two-ply control lodgepole pine heartwood panels	1.04	1.79	11	

Note: * significantly different at the $p = 0.05$ level; ** significantly different at the $p = 0.10$ level.

In summary, the stained MPB sapwood veneer was more permeable than nonstained MPB heartwood veneer. There was no significant difference in permeabilities between the MPB and control SPF veneer. The permeability of MPB panels was about 1.5–1.7 times that of control lodgepole pine panels. Although the transverse air permeability of the MPB veneer increased compared with that of the control lodgepole pine veneer, the rate of heat convection during panel hot-pressing could be similar between the MPB and control veneer with or without lodgepole pine segregation considering their difference in the magnitude of air permeability.

Veneer stress grading. About 50% of the 36 dried MPB veneer sheets (average MC = 3.5%) had long cracks or splits, which was probably due to: 1) dryout of logs after beetle attack; and 2) over-drying of veneer. There were 13 full-stained, 12 partially-stained, and 11 nonstained veneer sheets. The cracks or splits were present on both stained and nonstained veneer. As shown in Table 4, the t-test results showed that the dry density and dynamic MOE of the MPB veneer were significantly higher than those of the control SPF veneer at the $p = 0.05$ level. Quantitatively, the dry density and MOE of the MPB veneer were 14.6 and 7.9% greater than those of the control SPF veneer, respectively.

Veneer visual grading. There were different levels of bluestain on the stained MPB veneer. Similarly, the whiteness of the control SPF veneer also varied from piece to piece. As shown in Fig 5, the frequency distribution of RGB values is plotted for both MPB and control SPF

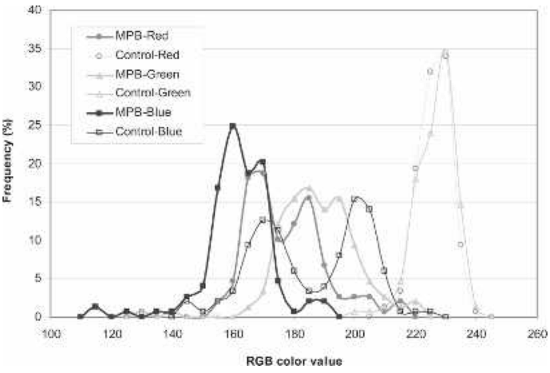

FIGURE 5. The frequency distribution of RGB values for the MPB and control SPF veneer.

veneer. A small overlapping in both Red and Green existed between the MPB and control SPF veneer, but a significant overlap existed in Blue color between the MPB and control SPF veneer. The results indicated that the stained veneer could be segregated from the normal control SPF veneer based on either Red or Green color values or a combination. To further identify the unique color characteristics of the stained veneer, the frequency distribution of the three alternative color indexes (HSL) was plotted for both MPB and control SPF veneer, as shown in Fig 6. The results showed that the degree of overlapping between the MPB and control SPF veneer decreased from Luminance to Hue, and then to Saturation. Compared with the Red and Green color values, the Saturation Index resulted in the least overlapping between stained MPB and control SPF veneer. This demonstrated that the Saturation Index could be more effectively

TABLE 4. *The t-test results for comparing dry veneer density and dynamic MOE.*

Comparison	Dry veneer density[a] (kg/m^3) Average per sheet		Veneer MOE (MPa) Average per sheet	
	MPB	Control SPF	MPB	Control SPF
Mean	447	390	11300	10438
Variance	1.8	2.0	462	386
Observations	36	36	36	36
Hypothesized mean difference	0		0	
df	35		35	
t Stat	5.26	$\|t\|>t_{critical}$	11.03	$\|t\| > t_{critical}$
P(T<=t) two-tail	7.30E-06		6.10E-13	
t Critical two-tail	2.03		2.03	

[a]Oven-dry mass/oven-dry volume

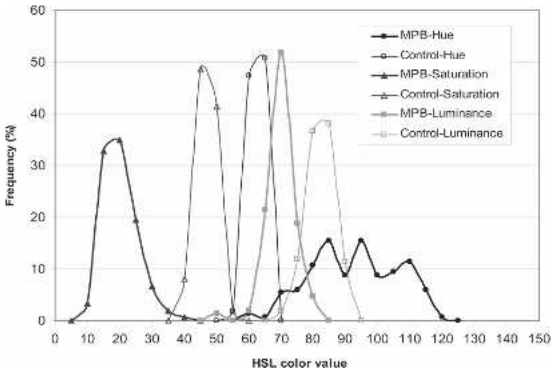

FIGURE 6. The frequency distribution of HSL indexes for the MPB and control SPF veneer.

used to segregate the stained MPB from the non-stained MPB and control SPF veneer. As shown in Fig 7, using the Saturation Index was also effective to differentiate stain from other veneer characteristics such as dark knots, cracks, and knot perimeters. The results demonstrated that the stained veneer had the lowest color Saturation Index with values from 5 to 65 by which stain could be isolated from veneer defects, non-stained veneer, and normal control SPF veneer. In addition, the combination of Saturation and Hue, or Red and Green could also be tested for more effective differentiation of stain from other defects. As a result, by adjusting the color detection algorithm or color threshold in the software, the current machine vision systems used by some plywood/LVL mills can be upgraded to sort for stained veneer or mask bluestain during veneer visual grading.

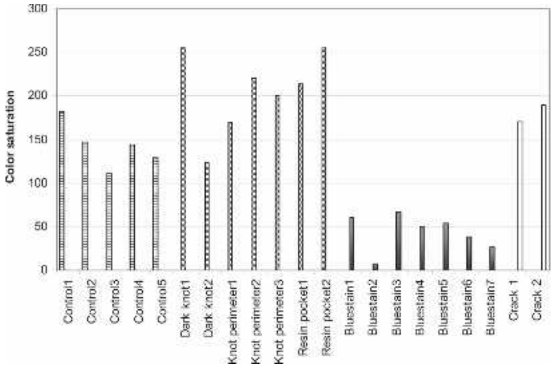

FIGURE 7. Color saturation index (%) for different veneer characteristics.

Lap-shear tests. Table 5 shows the results from shear strength testing with the ABES system. It was found that the glueline temperature ranged 115–125°C after heating for 180 s. After 100-s cooling, the glueline temperature was about 100°C when the tensile loading in the ABES machine commenced. In the additional tests with 240-s heating, maximum airflow was introduced to reduce the postpressing temperature as quickly as possible. The corresponding glueline temperature at the time of tensile pulling was about 85–95°C. With 180-s heating time, among 6 lay-ups from A to F, lay-up types B and D had higher shear strength. Compared with the loose-to-loose construction, gluing veneer loose-side to tight-side resulted in higher shear strength for both stained-to-stained and stained-to-control lay-ups. The difference in shear strength was found to be statistically different at the $p = 0.1$ level for the above two lay-ups. Additional lay-up tests BB* and FF* demonstrated that: 1) by gluing loose side to tight side using the stained veneer resulted in significantly higher shear strength compared with using the control SPF veneer at the $p = 0.05$ level; and 2) the longer heating time and lower temperature at the tensile pulling contributed to the higher shear strength. As a result, veneer loose-to-tight construction improved the panel dry shear strength for both MPB and control SPF veneer, or their combination. Gluing veneer loose side to tight side using the stained veneer, resulted in significantly higher dry-shear strength compared with using the control SPF veneer. Therefore, the MPB-stained veneer appeared to have a positive effect on the dry gluebond strength.

Plywood gluebond quality and bending performance. Table 6 shows the comparison of pressing time and physical properties of 5-ply MPB and control SPF plywood. In general, for the innermost glueline temperature to reach 105 and 110°C, the pressing time needed was longer with 5-ply MPB than 5-ply control SPF plywood. On average, the pressing times of MPB plywood should be lengthened by about 7.6 and 9.6%, respectively, for the above target temperatures. Apparently, higher transverse air permeability in

TABLE 5. *The pilot plant testing results of shear strength from different panel lay-up options and veneer constructions.*

			Shear strength (MPa)	
Lay-up type	Panel lay-up option	Veneer construction	Mean	Std.
A	Stained - stained	Loose-to-loose	1.60	0.43
B	Stained - stained	Loose-to-tight	1.92	0.56
C	Stained - control	Loose-to-loose	1.58	0.41
D	Stained - control	Loose-to-tight	1.88	0.66
E	Control - control	Loose-to-loose	1.68	0.49
F	Control - control	Loose-to-tight	1.65	0.44
BB*	Stained - stained	Loose-to-tight	3.25	0.72
FF*	Control - control	Loose-to-tight	2.42	0.63

Note: * additional lay-up tests with long heating time (240 s) and maximum cooling

TABLE 6. *Comparison of panel pressing time and physical properties between 5-ply MPB plywood and control SPF plywood from pilot plant tests.*

	Pressing time (s) for the innermost glueline to reach target temperature				Panel thickness		Panel density[a]		Panel MC	
	MPB		Control		MPB	Control	MPB	Control	MPB	Control
Test no.	105°C	110°C	105°C	110°C	(mm)		(kg/m^3)		(%)	
1	279.3	341.7	231.7	283.3	14.9	15.0	476	451	7.1	7.3
2	221.7	285.0	196.7	251.7	15.3	15.1	452	429	6.8	7.5
3	223.3	289.3	208.3	260.0	15.0	15.1	484	419	7.2	7.6
4	246.7	310.0	226.7	276.7	15.1	14.7	477	408	7.6	7.8
5	215.0	274.3	228.3	282.7	14.9	14.9	478	405	7.4	7.9
6	210.0	261.7	200.0	249.3	15.0	15.2	470	414	7.7	7.9
7	253.3	325.0	241.7	295.0	14.8	15.0	470	421	7.8	7.9
8	233.3	293.3	201.7	256.7	15.0	14.5	488	399	7.8	8.3
9	223.3	279.3	221.7	271.7	15.3	15.2	494	409	7.6	8.2
Average	234.0	295.5	217.4	269.7	15.04	14.98	477	417	7.4	7.8

[a] Oven-dry mass/oven-dry volume

the MPB veneer did not contribute to more rapid heat transfer, and in turn, shorter pressing time, since heat conduction, rather than heat convection, was generally the dominant transfer mechanism during plywood and LVL pressing (Wang et al 2006). Note that the pressing time, or temperature rising speed, is governed by veneer diffusivity, a combination of both veneer conductivity and density. Although higher veneer density is generally associated with more rapid heat conduction, more mass, in this case, needs to be heated. As also shown in Table 6, the MPB plywood was heavier, drier, and slightly thicker compared with the control plywood. The average compression ratio (CR) was 7.2% for 5-ply MPB and 7.5% for control SPF plywood under the same platen pressure of 1.21 MPa. These values appeared to be slightly higher, which was mainly caused by the rougher veneer peeled or received by this mill.

Table 7 shows the comparison of gluebond quality and bending performance between the 5-ply MPB and 5-ply control SPF plywood. For examining plywood gluebond quality, the shear specimens were required to receive both vacuum pressure and boiling-dry-boiling cycle treatments (CSA O151 2004). Based on the vacuum pressure tests, under various combinations of glue spread, veneer temperature, and assembly time, the t-test results for paired two samples for means demonstrated that the shear strength of the MPB plywood was consistently and statistically higher than that of the control SPF plywood at the $p = 0.05$ level. Although not significantly different at the $p = 0.05$ level, the average percentage wood failure of the MPB plywood was about 10% higher than that of the control plywood. Similarly, based on the boiling-dry-boiling cycle tests, under various gluing and lay-up conditions, the average shear strength

Table 7. *Comparison of panel gluebond quality and bending performance between 5-ply MPB and control SPF plywood from pilot plant tests.*

	Vacuum pressure				Boiling-dry-boiling				Panel parallel-ply bending			
	MPB		Control		MPB		Control		MPB		Control	
Test no.	Shear strength (MPa)	Wood failure (%)	Shear strength (MPa)	Wood failure (%)	Shear strength (MPa)	Wood failure (%)	Shear strength (MPa)	Wood failure (%)	MOE (GPa)	MOR (MPa)	MOE (GPa)	MOR (MPa)
1	1.003	86.2	0.909	49.3	0.911	89.5	0.914	48.9	8.31	69.6	6.70	47.6
2	0.882	75.0	0.813	84.7	0.750	60.3	0.788	83.6	6.78	44.4	7.18	57.6
3	0.940	69.7	0.826	76.2	0.798	76.6	0.838	67.2	8.20	54.2	6.96	55.2
4	0.928	81.1	0.883	66.0	0.800	90.6	0.856	46.3	8.58	68.1	6.80	52.1
5	1.021	84.9	0.904	70.4	0.799	95.9	0.824	47.4	7.77	55.3	6.43	47.5
6	0.994	79.3	0.795	78.8	0.840	81.8	0.793	73.2	7.79	54.5	6.06	38.8
7	0.892	90.3	0.802	91.5	0.763	92.3	0.775	81.0	7.69	62.7	6.72	47.9
8	0.891	73.6	0.761	66.2	0.758	84.0	0.802	73.4	7.87	53.5	6.31	39.9
9	0.891	85.5	0.742	77.5	0.751	83.2	0.751	73.4	8.10	53.5	6.36	44.7
Average	0.938	80.6	0.826	73.4	0.796	83.8	0.816	66.0	7.90	57.3	6.62	47.9

Note: * a span to depth ratio of 24 was used. A conversion is needed to compare the values of MOE and MOR between different testing standards.

of the MPB plywood was close to that of the control. However, the t-test results indicated that the percentage wood failure of the MPB plywood was significantly higher than that of the control plywood at the $p = 0.05$ level. Note that for both treatments, the average percentage wood failure of the MPB plywood exceeded the 80% standard requirements under various manufacturing conditions. In contrast, the average percentage wood failure of the control SPF plywood did not meet the standard requirements. Note that excessive roughness of veneers peeled in the mill was one of the main causes of low percentage wood failure for both plywood types. The reason why the MPB plywood had a relatively higher percentage wood failure could partially be explained by the higher glue penetration in the MPB veneer. The results demonstrated that the wet gluebond quality of the MPB veneer was also better than that of the control SPF veneer. To increase both shear strength and percentage wood failure, the optimum glue spread appeared to be at the middle level of 174 g/m^2 per single glueline. The best combination of the three variables under the scope of this experiment was: 174 g/m^2 glue spread per single glueline, 21.1°C veneer temperature, and 10-min assembly time. However, to reduce the glue consumption, and in turn the manufacturing cost, glue spread could be reduced to 159 g/m^2 per single glueline as normally used by the control SPF plywood meeting a minimum of 80% wood failure requirement (CSA O151 2004).

As far as bending performance is concerned, on average, the parallel-ply bending MOE and MOR of the MPB plywood were significantly greater by about 20% than those of the control plywood. Recall that from the veneer stress-wave testing, the MOE of the MPB veneer was only about 7.9% higher than that of the control SPF veneer. The reason for this discrepancy could be due to the fact that the MPB veneer had cracks and splits that would be repaired and reinforced during panel gluing and hot-pressing.

In summary, the MPB and control SPF veneer displayed dramatic differences in gluing and wet bonding properties. The MPB plywood required longer pressing time than the control SPF plywood, indicating that the current pressing schedules used for the control SPF plywood need to be adjusted. Compared with using the control SPF, the MPB veneer not only resulted in higher dry shear strength, but also higher wet gluebond quality. It seemed that the changes in MPB plywood bondability are from a change of surface chemistry. A separate study indicated that following MPB attack, wood morphology and chemistry undergo significant changes due to the defensive mechanism of trees. The MPB-attacked sapwood had lower hemicellulose/lignin contents and contained significantly lower concentrations of extractives when compared with the control lodgepole pine sapwood. Stained MPB-attacked wood also contains higher fatty and resin acid proportions (Woo et al 2005). Although increased resin acids in MPB-attacked wood could have a negative effect on pulping and aquatic ecosystems (Chow and Shepard 1996; Woo et al 2005), it might help increase the dry- and wet-bonding strength for MPB plywood. In addition, with MPB veneer, the glue might penetrate into the cell wall easier than in the control SPF veneer, resulting in reinforcement to the cell walls and even stronger bonding. The reasons why the percentage wood failure was higher with the MPB than the control SPF veneer could be 2-fold: 1) the chemical components of the MPB veneer were different from those of the control SPF veneer; and 2) the green MC sorting of the MPB veneer was more accurate than that of the control SPF veneer (Wang and Dai 2004). Although veneer over-drying could easily occur with the MPB veneer in the mill drying conditions, there could be more veneer being overdried with the control SPF than with the MPB veneer due to the larger within-sort MC variation of the control SPF veneer. Further, MPB plywood had about 20% higher MOE and MOR than control SPF plywood. Aside from the narrower clipping width, more accurate moisture sorting, and higher drying productivity previously identified (Wang and Dai 2004), segregating MPB logs also provides an opportunity to manufacture higher stiffness plywood with superior dry and wet gluebond quality. This could further offset the reduction in material recovery and some appearance-based plywood products in the specialty market.

Mill Trials

During the mill trial, the ambient temperature was 19°C. Although efforts were made to control the total assembly time between 10 and 15 min, the actual total assembly time for 5-ply MPB plywood was from 12.5 to 19.5 min, which was longer than the 11.0 to 12.5 min used for 5-ply control SPF plywood. This was due to additional time for adjustment of glue-spread level and pressing schedules. Thus, glue dryout could become more significant with MPB compared with control SPF plywood. Pilot plant results indicated that for 5-ply MPB plywood, the total assembly time should be within 10–15 min with a shorter time yielding better gluebond quality.

For MPB plywood, when pressing time was increased to 285 s, the average innermost glueline temperature was about 111°C, essentially at the 112°C target. Table 8 summarizes the results for gluebond quality and panel parallel-ply bending performance for both 5-ply MPB and 5-ply control SPF plywood. For the control SPF plywood panels sampled, the average percentage wood failure was 74.1%, which was below the target (80%). This was largely due to the combined effect of veneer surface roughness, glue dryout, relatively shorter pressing time, and/or inadequate panel compression experienced in the mill. Note that the control SPF veneer had excessive localized veneer roughness, resulting in a reduced average percentage wood failure with larger variation. To improve the gluebond quality for the control plywood, actions need to be taken to peel smoother veneer and adjust the gluing and pressing parameters.

The effect of glue spread and pressing time on gluebond quality of the 5-ply MPB plywood, as measured by panel shear strength and percentage wood failure, was statistically analyzed using the testing results from Dynea. A JMP statistical software program was used (SAS Institute Inc.

TABLE 8. *Comparison of panel gluebond quality and bending performance between 5-ply MPB plywood and control SPF plywood from mill trials.*

5-ply plywood		Glue spread (g/m^2)	Pressing time (s)	Panel gluebond quality		Panel parallel-ply bending***	
				Shear strength (MPa)	Wood failure (%)	MOE (GPa)	MOR (MPa)
Control SPF	1	144	255*	0.54	55.0	5.37	38.0
	2	149	255*	0.79	78.5	7.90	50.6
	3	154	255*	0.77	74.0	5.87	38.6
	4	159	255*	0.68	79.5	7.53	53.8
Average		152	255*	0.72	74.1	6.67	45.2
MPB	1	144	285	0.82	84.8	7.52	53.8
	2	144	255*	0.65	72.9	7.82	59.1
	3	152	285	0.79	85.8	7.88	53.9
	4	152	255*	0.70	77.8	7.42	56.0
	5	159	285	0.79	83.5	7.42	58.6
	6**	159	255*	0.71	80.5	7.52	53.6
Average		152	270	0.74	80.9	7.60	55.8

Note: * pressing time used in the mill for 5-ply control SPF plywood;
** one panel was undercured;
*** a span to depth ratio of 24 was used. A conversion is needed to compare the values of MOE and MOR between different testing standards.

1995). Table 9 shows the variance analysis of shear strength and percentage wood failure for the 5-ply MPB plywood. The results show that pressing time has a significant effect on both shear strength and percentage wood failure at $p = 0.05$ and 0.10, respectively. Based on the screening effect provided by the software, the relative importance of the two variables to each gluebond quality criterion can also be determined by comparing the maximum differences in magnitude of responses from the criterion, with respect to the designated levels of each variable. In general, the larger the difference, the more important the variable. For the MPB plywood, within the ranges tested, pressing time was more important than glue spread.

Based on the analysis from the JMP program, the prediction profiles of gluebond quality for the 5-ply MPB plywood were plotted with regard to the glue-spread level at pressing times of 255 (Fig 8) and 285 s (Fig 9). The prediction model gave R^2 of 0.90 for the shear strength and R^2 of 0.83 for the percentage wood failure. When 255-s pressing time was used, the percentage wood failure increased with increasing glue-spread level, but the average value still failed to achieve the 80% target. By comparison, when 285-s pressing time was used, the percentage wood failure reached the minimum 80% target at the three different glue-spread levels. For manufacturing the 5-ply MPB plywood, a glue-spread level from 144.0 to 153.0 g/m^2 seemed to be sufficient. Note that one MPB plywood panel with pressing time of 255 s was undercured. As a result, as far as the gluebond quality is concerned, the 5-ply MPB plywood required a pressing time of 285 s compared with the 255 s used for 5-ply control SPF plywood in the mill, which translated to an increase of the pressing time by about 11.8%. Based on the pilot plant results for the 5-ply MPB plywood, an increase of the pressing time by 9.6% was needed for the

TABLE 9. *The analysis of variance (ANOVA) of shear strength and percentage wood failure for 5-ply MPB plywood.*

MPB plywood	Source	Degree of freedom	Sum of squares	F ratio	Prob > F
Shear strength	Glue spread	2	4.3	0.1	0.91
	Pressing time	1	400.2	18.1	0.05**
Percentage wood failure	Glue spread	2	12.4	0.6	0.61
	Pressing time	1	87.4	8.8	0.098*

Note: * pressing time is significant at the $p = 0.10$ level;
** pressing time is significant at the $p = 0.05$ level.

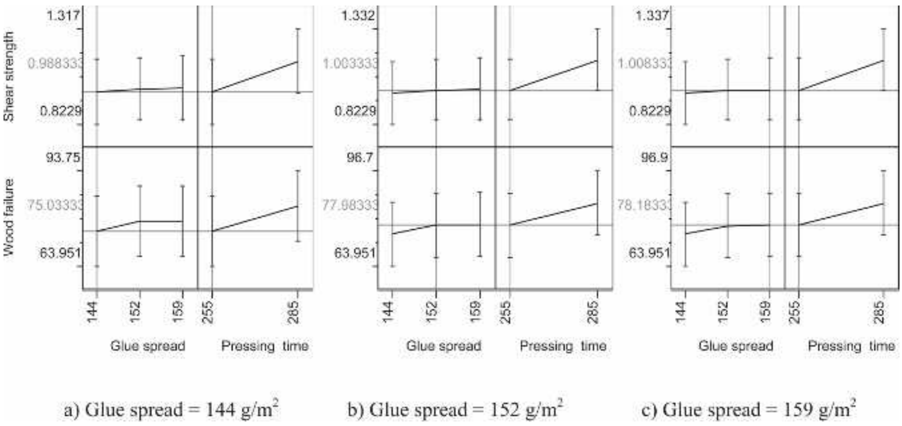

FIGURE 8. Prediction of the gluebond quality at 255 s pressing time.

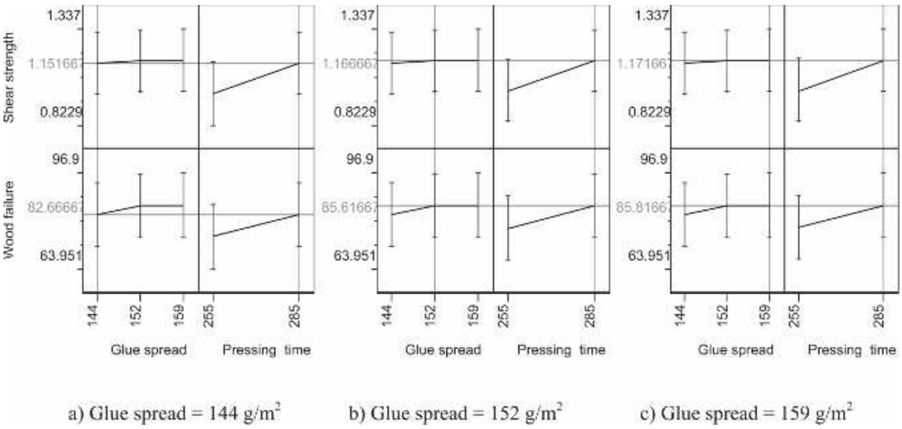

FIGURE 9. Prediction of the gluebond quality at 285 s pressing time.

innermost glueline temperature to reach 110°C. Therefore, it was confirmed that compared with the 5-ply control SPF plywood, the pressing time should be lengthened about 10% for manufacturing the 5-ply MPB plywood to achieve the target gluebond quality.

As also shown in Table 8, the mill trial results demonstrated that 5-ply MPB plywood was about 14.0 and 23.5% higher in parallel-ply bending MOE and MOR, respectively, compared with 5-ply control SPF plywood. The results were in conformation with those from the pilot plant tests in which about 20% difference in MOE and MOR was identified. For manufacturing the 5-ply MPB plywood in the mill, the optimum gluing and pressing parameters were as follows: assembly time, 10–15 min; glue-spread level, 144–152 g/m^2 per single glueline; and pressing time, 285 s, while minimizing veneer temperature.

CONCLUSIONS

Based on the results from pilot plant tests and mill trials, the dry MPB veneer was denser and stronger than the dry control SPF veneer. The parallel-ply bending MOE and MOR of 5-ply MPB plywood were about 14 and 20% higher than those of 5-ply control SPF plywood, respectively. As long as manufacturing parameters are properly adjusted in drying, grading, gluing, and hot-pressing, segregating MPB-attacked logs provides an opportunity to manufacture higher stiffness specialty plywood products with superior dry and wet gluebond quality. This could further offset to a large degree the reduction in material recovery and the loss in some appearance-based plywood markets. As well, this practice of segregation could become more important for recovering the highest value possible since the MPB wood will be greater than 10% of total log supply with more logs being gray-stage materials. Since gray-stage logs are generally very dry and may contain serious cracks, sorting of MPB logs at the woodlands or log yards for different panel products appears to be essential.

The MPB veneer had various degrees of bluestain. To improve veneer visual grading, existing camera-based vision systems used by some plywood mills can be upgraded by adjusting the color detection algorithm to segregate the stained veneer or mask the effect of bluestain. Veneer loose-to-tight construction improved the panel dry shear strength for both MPB and control SPF veneer, or their combination. Compared with the control SPF, the MPB veneer had positive effects on both dry and wet gluebond quality. Compared with control SPF, MPB plywood more easily achieved 80% or greater wood failure requirements. It was therefore believed that changes in MPB plywood bondability were due to a change of surface chemistry of the MPB veneer. To increase gluebond quality while minimizing manufacturing costs for the MPB plywood, glue spread can be kept at the same level as currently used by the control SPF plywood. However, the pressing time should be lengthened by about 10% compared with that used for the control SPF plywood, and the assembly time should also be maintained within 10 to 15 min, while minimizing veneer temperature.

ACKNOWLEDGMENTS

This project was funded by the Government of Canada through the Mountain Pine Beetle Initiative (MPBI), a 6-yr, $40 million program administered by Natural Resources Canada, Canadian Forest Service. The authors would also like to thank personnel at Tolko-Armstrong plywood operation and Dynea Canada Ltd. for their help in the mill trial and plywood gluebond tests, and Mr. Kevin Groves for conducting the image tests.

REFERENCES

CHOW S, SHEPARD D (1996) High performance liquid chromatographic determination of resin acids in pulp mill effluent. Tappi J 79(10):173–179.

CSA O151(2004) Canadian softwood plywood. Canadian Standards Association.

CSA O325 (2007) Test methods for construction sheathing. Canadian Standards Association.

DEVALLANCE DB (2003) Influence of veneer roughness, lathe check, and annual ring characteristics on glue-bond performance of Douglas-fir plywood. MS thesis, Oregon State Univ, Corvallis, OR.

GROVES K (2000) Development of the GluScan image analysis system for measuring resin distribution in OSB. Forintek Canada Corp.-Report 2287. 13 pp.

MPBAP (2007) The Mountain Pine Beetle Action Plan (2006-2011). The Government of British Columbia. http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/.

NEESE JL, REEB JE, FUNCK JW (2004) Relating traditional surface roughness measures to gluebond quality in plywood. Forest Prod J 54(1):67-73.

OLIVEIRA L, WALLACE J, CAI L (2005) Optimizing drying of mountain pine beetle wood. Natural Resources Canada Pacific Forestry Centre, Victoria, BC. Mountain Pine Beetle Initiative Working Paper 2005-12. 30 pp.

SAS INSTITUTE INC (1995) JMP user's guide, Version 3. Gary, North Carolina.

SELLERS T (1985) Plywood and adhesive technology. Marcel Dekker. NY. 661pp.

SHUPE TE, HSE CY, CHOONG ET, GROOM LH (1998) Effect of wood grain and veneer side on loblolly pine veneer wettability. Forest Prod J 48(6):95-97.

WANG BJ, DAI C (2004)Maximizing value recovery from mountain pine beetle-attacked pine for veneer products. Natural Resources Canada Pacific Forestry Centre, Victoria, BC. Mountain Pine Beetle Initiative Report. 33 pp.

———, ——— (2005) Maximizing value recovery from mountain pine beetle-killed pine for veneer products. Mountain Pine Beetle Initiative (MPBI) working paper 2005-9. Canadian Forest Service, Natural Resources Canada.

———, ——— (2005) Optimization of gluing, lay-up and pressing for Mountain Pine Beetle (MPB) plywood. CFS Mountain Pine Beetle Initiative Reports. 58 pp.

———, ZHOU X, DAI C, ELLIS S (2006) Air permeability of aspen veneer and glueline: experimentation and implications. Holzforschung 60:304–312.

WOO KL, WATSON P, MANSFIELD SD (2005) The effects of mountain pine beetle attack on lodgepole pine wood morphology and chemistry: implications for wood and fibre quality. Wood Fiber Sci 37(1):112–126.