Effect of Blue Stain on Bond Shear Resistance of Polyurethane Resins Used for Cross-Laminated Timber

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Abstract

The effect of blue stain on shear strength of cold-set polyurethane resin (PUR) bonds was investigated using lodgepole pine lumber with varying degrees of stain and two different wood grain orientations. While blue stain was associated with definite differences in wood permeability, it had no negative effect on shear strength or wood failure percent. The results indicate that blue stain will not adversely affect bond strength of PUR bonds.

Lodgepole pine (*Pinus contorta* L.) grows in a wide swath across the western United States and Canada, including the central and eastern parts of Oregon and Washington (Koch 1996). Decades of fire suppression have resulted in overstocked stands that are increasingly susceptible to attack by the mountain pine beetle (*Dendroctonus ponderosae* Hopkins). This beetle can overcome natural tree defenses, causing large-scale stand mortality leading to increased risks of catastrophic fires (Furniss and Carolin 1977).

One way to reduce the risk of beetle infestation and reduce fire risks is to thin overstocked stands as well as salvage and utilize beetle-killed trees. Forest restoration operations can be costly, but commercial utilization of the harvested timber helps offset some of the costs.

One potential outlet for beetle-killed pine (BKP) is in core layers of cross-laminated timber (CLT). CLT is a prefabricated solid engineered wood product made of at least three orthogonally bonded layers of solid-sawn lumber or structural composite lumber (SCL) that are laminated by gluing of longitudinal and transverse layers with structural adhesives to form massive panels intended for roof, floor, or wall applications (Van de Kuillen et al. 2011). The current CLT product standard ANSI/APA PRG 320 (American National Standards Institute [ANSI] 2012) specifies the grade for face layers as No. 2 or Better, while No. 3 and Better materials may be used for the core. The latter allowance creates the potential for using substantial volumes of BKP for CLT. One concern with this material, however, is the potential effect of existing blue stain on adhesive bond integrity.

BKP is susceptible to colonization by a variety of fungi, including the Ascomycetes that cause blue stain (Byrne et al. 2005). Blue stain fungi utilize sugars and other nutrients stored in the rays (Lindgren and Scheffer 1939; Scheffer 1940) and produce brown-pigmented melanins in their hyphae that give the colonized wood a bluish color (Zink and Fengel 1988).

Fungal hyphae moving through the cells also degrade the pit membranes, increasing the ability of the wood to absorb liquids, although the overall effects on the mechanical properties of wood are considered to be minor (Saling 1930; Chapman and Scheffer 1940; Scheffer 1941). Blue-stained lumber is often used in construction, but it is prohibited in some high-value structural applications, such as utility poles and cross arms (ANSI 2015a, 2015b).

Permeability changes in areas affected by blue stain may also negatively affect the development of effective adhesive

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bonds. The concern is that resins applied to the wood surface at prescribed uniform spread rates may be more likely to penetrate into more permeable blue-stained areas, reducing the amount of resin available at the wood interface and interfering with the formation of adequate bonds (Kamke and Lee 2007). This effect has been studied extensively on composites such as plywood that are bonded with thermoset adhesives (Byrne et al. 2005, Zaturecky and Chiu 2005, Lam et al. 2007, Wang et al. 2007). A number of studies have suggested that shear strength of plywood made from blue-stained veneer is greater than in panels made from normal veneers, possibly as a result of better adhesive penetration into the surrounding cell lumens. However, there appears to be little information on the effects of blue stain on cold-setting resins (5°C to 30°C) typically used for CLT.

Understanding the effects of increased permeability associated with blue stain on the ability of a resin to move into the wood and create acceptable adhesive bonds in CLT is important for determining if blue-stained lumber can be successfully utilized in CLT cores. Use of these materials could reduce the overall cost of producing CLT, making the product more competitive against alternative materials while creating further incentives to reduce fire risks through restoration forestry on overstocked timber stands.

The objective of this work was to determine the effects of varying levels of blue stain on the shear resistance of adhesive bonds produced using a polyurethane resin (PUR) in parallel and cross-laminated billets.

Materials and Methods

Creating uniformly stained lumber would be one approach for this process; however, blue stain is rarely uniformly distributed, and the affected wood is often colonized by other fungi that may not cause discoloration. Thus, we chose to use naturally stained material from an area located near Klamath Falls, Oregon, to establish more realistic test conditions. Lodgepole pine boards (19 mm thick by various widths and lengths) were obtained from Collins Co. (Klamath Falls). The material had been kiln dried following sawing, but a number of boards were heavily blue stained. The boards containing stain were then cut into 19 by 44.4 by 50.8-mm pieces. The degree of stain coverage on each sample was visually assessed on a scale from 0 percent (no stain) to 100 percent (complete stain coverage). The samples were then allocated to groups based on the following range of staining:

- Free of visible fungal attack
- Stain on 10 to 50 percent of the wide face of the board
- Stain on 51 to 90 percent of the wide face of the board
- Stain on 91 to 100 percent of the wide face of the board

No effort was made to track samples to an original parent board because the degree of stain also varied within individual boards. The pieces were conditioned to constant weight at 23°C and 65 percent relative humidity according to procedures described in ASTM Standard D905 (ASTM International 2016). Sixty samples from each stain category were paired to produce 30 pairs in each category for testing. One set of 15 pairs with a given degree of stain was tested with the samples arranged with the grain oriented parallel and the other with the grain oriented perpendicular to one another for each of the four stain categories.

For resin application, a 44.4 by 44.4-mm section on the wide face of one half of a test pair was coated with a single-component PUR (Purebond HB E452; Henkel Adhesives International, Düsseldorf, Germany) at a rate of 180 g/m^2. The coated sample was paired with its noncoated mate so that the samples were aligned either perpendicular to the grain or parallel to the grain, and the samples were pressed for 24 hours at 0.97 N/mm^2 at 20°C to 23°C.

The cured samples were reconditioned to constant weight at 23°C and 65 percent relative humidity prior to testing. The resistance to shear was assessed by the block shear method following ASTM Standard D905 (ASTM International 2016). Samples were set in a test jig and loaded in shear parallel to the glue line at a rate of 5 mm/min to failure. Load was continuously recorded, and the resulting maximum load was used to calculate maximum shear strength in megapascals. While no qualification criteria are specified for shear strength, the values are useful for assessing the potential effects of blue stain on the shear resistance of the bonds.

After testing, the fractured surfaces were visually examined to determine the amount of wood failure expressed as the percentage of the bond area to the nearest 5 percent. ANSI/APA PRG 320 (ANSI 2012) specifies that mean wood failure cannot be less than 85 percent.

While visual assessment of the degree of stain in the area that was tested for bonding was useful, it did not allow for quantification of the degree of change in permeability of the wood as a result of fungal growth. The effect of stain on wood permeability was quantified using a procedure for assessing changes in wood permeability during fungal decay in aboveground exposures (Carey et al. 1981). Briefly, the 10.4-mm-long portion that had not been part of the glue bond test was cut from each end of the test pair. These sections were oven-dried at 50°C for 24 hours and weighed (nearest 0.01 g). The samples were then immersed in dekalin (decahydronaphthalene) at room temperature for 10 seconds, quickly blotted dry, and weighed. The weight gain from dekalin immersion served as an indirect measure of wood permeability via liquid absorption.

The resulting shear strength and dekalin uptakes were subjected to a 1-way analysis of variance and Tukey pairwise comparisons ($\alpha = 0.05$).

Results and Discussion

Average glue line shear strength ranged from 9.32 to 10.42 MPa when the samples were aligned parallel to the grain, but there were no significant differences between nonstained controls and samples with varying degrees of discoloration (Table 1). Average glue line shear strength of samples oriented perpendicular to one another were much lower, ranging from 3.19 to 3.92 MPa, but there were no significant differences between treatments (Table 2). The lower shear values for the samples oriented perpendicular to one another are consistent with the lower shear strength of wood in this direction (i.e., rolling shear; Panshin and DeZeeuw 1980). The results suggest that the presence of fungal stain had no significant effect on bonding strength, nor did the stained wood negatively affect shear stress in either direction.

Bond quality was also assessed by estimating the wood failure percent in the fractured areas of the specimens. The average wood failure percentages ranged from 92.7 to 97.6 percent of the glued zone, and there were no significant differences in wood failure levels with either degree of stain or wood orientation (Table 1). The results would be consistent with a well-bonded composite.

Table 1.—Effect of degree of blue stain on dekalin uptake of wood, bond strength, and percent wood failure in lodgepole pine lap shear samples bonded with a polyurethane resin.[a]

	Samples parallel to the grain			Samples perpendicular to grain		
Degree of stain (%)	Dekalin uptake (kg/m^3)	Shear stress (MPa)	Wood failure (%)	Dekalin uptake (kg/m^3)	Shear stress (MPa)	Wood failure (%)
No stain	51.72 (16.27) B	10.42 (1.84) A	97.5 (3.5) A	42.12 (14.73) C	3.26 (1.00) A	95.1 (5.4) A
10–50	142.10 (100.00) A	9.88 (1.99) A	97.0 (4.8) A	176.64 (107.66) A	3.19 (0.94) A	93.4 (8.3) A
51–90	82.67 (36.78) AB	9.83 (2.39) A	97.0 (4.8) A	122.55 (80.17) AB	3.92 (1.04) A	97.2 (3.2) A
>90	90.59 (52.15) AB	9.32 (1.72) A	97.6 (3.2) A	93.26 (32.38) BC	3.46 (0.87) A	92.7 (7.0) A

[a] Values represent means of 15 replicates per grain orientation and degree of discoloration. Values in parentheses represent one standard deviation. Values followed by the same letters are not significantly different by a Tukey pairwise comparison at $\alpha = 0.05$.

Table 2.—Summary statistics for the 1-way analysis of variance comparing blue stain percentage and glue line shear strength.

Source	Degrees of freedom	Adjusted sum of squares	Adjusted mean square	*F* value	*P* value
Treatment	4	1.680	0.4200	1.75	0.148
Error	73	17.490	0.2396		
Total	77	19.170			

Visible stain assessment is useful but somewhat imprecise because fungi may have grown through wood and altered permeability without discoloring the wood. Percent dekalin uptakes did not differ significantly between specimen halves for a given treatment except between samples with no stain and those with 10 to 50 percent stain in the sets tested parallel to the grain. The implication of these differences is unclear because dekalin uptake did not differ significantly in samples from the sets with the same degree of stain tested perpendicular to the grain.

Samples with no visible discoloration had the lowest dekalin uptakes, indicating that the visual selection of this material was reasonably accurate. Dekalin uptakes for the remaining groups varied widely, with the samples with 10 to 50 percent discoloration having the highest uptakes. The dekalin results were extremely variable for the stained materials, even within a given treatment, suggesting that the fungi may have altered permeability in areas that were not discolored. The high variability made it difficult to clearly separate treatments; however, the results do indicate that liquid uptake was greater in stained samples.

The lack of effect on shear strength was not surprising given the high wood failure percentage ratios observed in our tests.

Conclusions

The presence of varying levels of blue stain in lodgepole pine lumber had no significant effect on initial bonding properties using a cold-set PUR. The results suggest that these materials could be used in the core of CLT panels without adversely affecting adhesive bond properties.

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