Effect of Treatment Pressure on Treatment Quality and Bending Properties of Red Pine Lumber

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Abstract

Although higher treatment pressures have the potential to improve preservative penetration, higher pressures may possibly result in greater reduction in mechanical properties. The present study evaluated the effect of treatment pressure on the treatment quality and mechanical properties of red pine (*Pinus resinosa* Ait.) lumber. End-matched sections of red pine lumber were treated with an ethanolamine copper preservative at pressures of 1,207 kPa (175 psi), 1,379 kPa (200 psi), or 1,551 kPa (225 psi). Preservative uptake and penetration were measured, and small clear specimens were subsequently cut from the specimens for evaluation of bending properties. The average percentage of sapwood penetration increased slightly with increasing pressure, and this difference was statistically significant between the 1,207-kPa (175-psi) and 1,551-kPa (225-psi) pressures. In comparison to untreated specimens, treatment at all pressures caused small reductions in modulus of rupture and work to maximum load. However, there were no significant differences in bending properties between the pressures evaluated, indicating that higher pressures can be used without additional sacrifice of wood properties. These treatments were conducted at ambient temperature, and the findings do not necessarily apply to treatments conducted at elevated temperatures.

Red pine (*Pinus resinosa* Ait.) represents an important softwood resource in portions of the upper Midwest and northeastern United States and eastern Canada. In comparison with other softwood species native to these areas, red pine is well suited for preservative-treated applications because it is generally treatable and has relatively high strength properties. Red pine is recognized as a treatable wood species by the American Wood Protection Association (AWPA) and has penetration and assay zone requirements similar to the southern pine species group and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.; AWPA 2009). However, commercial pressure-treatment personnel have expressed concern about occasional inconsistencies in the treatability of red pine sapwood. A recent study indicated that these inconsistencies were caused by anatomical characteristics related to geographic source (Lebow et al. 2006), and that they could be partially overcome by the use of longer initial vacuum and pressure periods. However, longer initial vacuum and pressure periods also slow production.

An alternative approach to improving penetration is the use of higher treatment pressures, and in 2005 the allowable maximum pressure for treatment of red pine was raised from 1,241 kPa (180 psi) to 1,551 kPa (225 psi) in AWPA Standard T, Section 8.1. Previous studies have indicated that preservative uptake and penetration does increase with increases of pressure within the range of 100 to 250 psi (MacLean 1924, 1952; Siau 1970; Walters and Whittington 1970). However, with the exception of Walters and Whittington (1970), these studies have generally indicated that improvements in treatment quality were less than proportional to increases in pressure. It is also apparent from these studies that the relationship between pressure intensity on treatment quality is dependent on length of pressure period, temperature, type of preservative, and wood species. Not surprisingly, most of the previous research has focused on species with low permeability, such as Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco), and it is possible

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that increases in pressure may be more beneficial in more permeable wood species such as red pine.

A potential negative consequence of increasing treatment pressure is damaging the wood structure, causing a decrease in mechanical properties. Numerous studies have been conducted to evaluate the effects of preservative treatment on mechanical properties of treated wood (MacLean 1952, Walters and Whittington 1970, Bendtsen et al. 1983, Barnes et al. 1993, Winandy and Lebow 1997), and much of this research has been previously summarized (Winandy 1995). In general, these studies have indicated that pressure treatment with waterborne preservatives or water alone causes slight reductions in modulus of rupture (MOR) and work to maximum load (WML) but little, if any, reduction in stiffness (modulus of elasticity [MOE]). Fewer studies have evaluated the effect of pressure intensity within the range typically used commercially (1,034 to 1,379 kPa [150 to 200 psi]), but two have noted negative impacts with pressure increases from 690 to 1,379 kPa (100 to 200 psi; MacLean 1952, Walters and Whittington 1970). In those studies, however, the effects appear to be at least partially attributable to the use of heated treatment solutions.

The potential benefits in treatment quality with increasing pressure have not been reported for red pine, nor have the effects of higher pressure on mechanical properties. This article presents the results of a study to evaluate the effect of pressure intensity on both treatment quality and mechanical properties of red pine lumber.

Materials and Methods

Specimen preparation

This study was conducted by pressure treating 38 by 140-mm (nominal 2 by 6-in.) lumber, and then cutting small clear specimens from the lumber specimens after treatment. A packet (128 pieces) of No. 2 grade, 3.66-m (12-ft) lumber was obtained from a mill in the upper Midwest. The lumber had been kiln dried to below 19 percent moisture content using a conventional kiln schedule. The packet was sorted to obtain 60 pieces from which the desired sections and specimens could be obtained. Each 3.66-m-long (12-ft-long) piece was numbered and marked to obtain four 914-mm-long (3-ft-long) treatment specimens labeled A, B, C, or D. The location for subsequently cutting a 25 by 25 by 406-mm (1 by 1 by 16-in.) small clear sapwood specimen was also marked on each section. Although the small clear specimens were shorter than the treatment specimens and thus not directly end-matched, an effort was made to remove the small clear specimens from approximately the same location for each set of matched A, B, C, and D treatment specimens. The experiment conducted was a type of randomized block design in which the four pressure treatment groups, untreated, 1,207 kPa (175 psi), 1,379 kPa (200 psi), or 1,551 kPa (225 psi), were run in a set of four blocks. Each board was assigned to a block and then cut into four pieces, with each piece randomly assigned to one of the pressure treatment groups. This design allowed for a test of a block by pressure interaction (which would be an indication that charges at the same pressure behaved differently over time).

Preservative treatment

The 914-mm (3-ft) specimens were treated using a modified full cell treatment schedule. All treatment parameters were held constant with the exception of the intensity of the pressure:

- Preservative: an ethanolamine copper solution containing 1.1 percent copper (expressed as CuO)
- Initial vacuum: 10 minutes at 61 kPa below atmospheric pressure (18 in. Hg by gauge)
- Pressure: 40 minutes at either 1,207 kPa (175 psi), 1,379 kPa (200 psi), or 1,551 kPa (225 psi)
- Final vacuum: 55 minutes at 78 kPa below atmospheric pressure (23 in. Hg by gauge)
- Temperature: indoor ambient

Each specimen was weighed immediately before and after treatment to determine the uptake of preservative solution. Copper retention (expressed as CuO) was calculated by multiplying the uptake retention by the solution concentration (Table 1).

Penetration and mechanical properties evaluation

Following treatment, the specimens were examined for visual evidence of collapse and then stickered for 1 week with forced air movement to speed initial drying. Each 914-mm-long (3-ft-long) section was then cut to obtain a cross section for penetration measurement, as well as the 25 by 25 by 406-mm (1 by 1 by 16-in.) small clear bending specimen. The small clear bending specimen was cut from along an edge of each 914-mm (3-ft) section to maximize the extent of preservative penetration. An effort was made to remove the small clear specimens from approximately the same location for each set of matched A, B, C, and D treatment specimens. The cross section was first sprayed with a heartwood indicator (AWPA Standard M2-07, Section 4.3.1.1, AWPA 2009), and then sprayed with chrome azurol–S copper indicator solution prepared in accordance with AWPA Standard A3-08, Section 2 (AWPA 2009). Penetration measurements similar to those determined commercially (by removal of increment cores) were obtained by measuring penetration at the midpoint of both narrow faces of each specimen (AWPA Standard M2-07, AWPA 2009). The two measurements from each specimen were averaged to obtain a single penetration value. Sapwood depth was measured at the same locations, and the percentage of sapwood penetrated was calculated.

The small clear bending specimens were conditioned at 23°C (74°F) and 65 percent relative humidity until their weight stabilized at approximately 13 to 14 percent moisture content. After conditioning, mechanical and physical properties of the small clears were evaluated in general accordance with ASTM Standard D143 (ASTM International 2005). Because the bending specimens were cut from the edges of the larger treatment specimens, the growth ring orientation was not controlled, and the growth rings were not necessarily parallel to the tangential face. However, because the specimens were end-matched, each pressure-treatment group had specimens with similar grain orientation. Static bending tests were used to determine MOR, MOE, and WML. The specimens were tested with center point bending using a span of 356 mm (14 in.) and a crosshead speed of 2.5 mm (0.1 in.) per minute. Immediately after testing, a small section of each specimen was removed and used to determine ovendry moisture content and specific gravity.

Table 1.—Summary of treatment characteristics for each pressure treatment group.

Pressure	Statistic	Solution uptake, kg/m^3 (lb/ft^3)	CuO retention, kg/m^3 (lb/ft^3)[a]	Percentage of sapwood penetrated[b]
1,207 kPa (175 psi)	Arithmetic avg	319.0 (19.9)	3.51 (0.22)	63
	SD	87.3 (5.4)	0.96 (0.06)	32
	Median	322.6 (20.2)	3.55 (0.22)	62
1,379 kPa (200 psi)	Arithmetic avg	361.8 (22.6)	3.98 (0.25)	68
	SD	88.9 (5.6)	0.98 (0.06)	32
	Median	357.9 (22.4)	3.94 (0.25)	66
1,551 kPa (225 psi)	Arithmetic avg	360.4 (22.5)	3.96 (0.25)	75
	SD	107.8 (6.7)	1.19 (0.07)	32
	Median	359.1 (22.4)	3.95 (0.25)	100

[a] Based on solution uptake.
[b] Current AWPA standards require that 80% of cores removed from a charge have at least 85 percent sapwood penetration (AWPA 2009).

Data analysis

The study was set up as a replicated, randomized complete block design, and statistical analyses were performed in SAS V9.2 (SAS Institute Inc., Cary, North Carolina) using a mixed effect modeling procedure. This allowed estimating the treatment effects as well as estimating various variance components, such as variations due to charges, an interaction of charge by pressure treatment, and boards within charges. Pairwise mean (and median, where appropriate) comparisons were conducted to determine if pressure intensity had a significant effect on preservative uptake or penetration or on the mechanical properties of the specimens.

Results and Discussion

Effects of pressure on preservative uptake and penetration

Increasing the treatment pressure caused a slight increase in percentage of sapwood penetration (Table 1; Fig. 1). Because charges at the same pressure appeared to behave consistently over time with no detectable charge effect or charge by treatment interaction, the data for replicate charges at the same pressure were combined.

Pairwise median and mean comparisons indicated that the increase in percentage of sapwood penetrated was statistically significant between the 1,207-kPa (175-psi) and 1,551-kPa (225-psi) pressures. However, preservative uptake was not significantly different for the three pressures evaluated. These findings generally agree with those of previous researchers (MacLean 1924, 1952; Siau 1970), who also noted slight increases in penetration or preservative uptake with increases in treatment pressure. Although the increase in average percentage of sapwood penetration at higher pressures was relatively modest, the increase in median sapwood penetration at the highest pressure was more striking. At the 1,551-kPa (225-psi) pressure level the median sapwood penetration was 100%, indicating that at least half of the specimens had complete sapwood penetration (Table 1). This increase may be sufficient to have practical significance when viewed in the context of the large number of pieces treated in commercial charges. For example, AWPA standards require that 85 percent of the sapwood be penetrated in 80 percent of cores removed from a charge of red pine lumber. At the lowest pressure, only 35 percent of the specimens achieved this 85 percent of sapwood criteria. The proportion of specimens meeting the penetration criteria increased to 47 percent and 55 percent for the 1,379-kPa (200-psi) and 1,551-kPa (225-psi) treatments, respectively. Thus, although in this trial none of the charges would have met the 80 percent passing

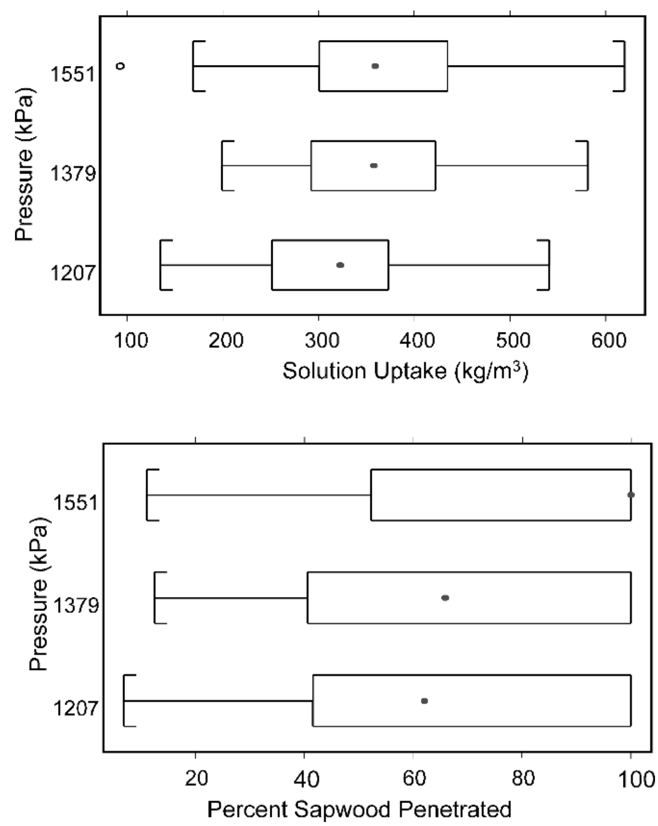

Figure 1.—Distribution of solution uptake and percentage of sapwood penetrated values for specimens in each pressure treatment group. The solid dot within each box represents the median, the left-hand side of the box represents the lower quartile (25th percentile), and the right-hand side represents the upper quartile (75th percentile). The difference between the upper and lower quartiles is the interquartile range. The whisker on the left side of the box represents the minimum observation greater than or equal to the lower quartile minus 1.5 times the interquartile range, while the right whisker represents the maximum observation less than or equal to the upper quartile plus 1.5 times the interquartile range. Any observation that is more than 1.5 times the interquartile range beyond the third quartile or below the first quartile is a suspected outlier and identified by an open circle.

criteria, the use of higher pressure did notably increase the proportion of adequately treated specimens.

Effects of pressure on mechanical properties

No collapse or other treatment-related defects were noted for any of the samples treated in this study. Table 2 summarizes the physical and mechanical properties for each treatment group. It should be noted that these estimates ignore imbalance within a blocked experiment; least squares means are model-based means that adjust for imbalance and are listed in Table 3. Because charges at the same pressure appeared to behave consistently over time with no detectable charge effect or charge by treatment interaction, the data for replicate charges at the same pressure were combined. Boxplots of MOR, MOE, and WML by control and pressure treatment groups are shown in Figure 2. Although the boxplots indicate the presence of outliers, these data points had no associated cause that could make them different and were not considered sufficiently flawed to warrant exclusion from the statistical analyses.

Statistical analyses were conducted to evaluate the effects of treatment pressure on mechanical properties (Table 3). The least squares means accommodate the lack of balance resulting from a missing observation, and the standard error represents the standard deviation of the estimate of the mean. Table 3 also summarizes pairwise mean comparisons based on the mixed effect models. If two means have the same letter in the pairwise mean comparison columns, then that pair is not declared significantly different based on a comparison-wise error rate of 0.05.

For MOR, the overall test of a difference in treatment means indicates that at least one of the groups has a different mean ($P = 0.0264$). Based on the pairwise comparisons, the untreated controls have a significantly higher MOR, but no differences were detected between mean MOR for the three pressure treatments.

For MOE, no overall significant differences in treatment means were observed ($P = 0.5743$). In addition, P values for all pairwise mean comparisons exceeded 0.20, further indicating a lack of significant differences.

For WML, the overall test of a difference in treatment means was highly significant ($P < 0.0001$) indicating that at least one of the groups has a different mean WML. The pairwise comparisons revealed that the untreated controls had a significantly higher WML than all the pressure-treated groups. However, no differences in mean WML were detected between the three pressure levels.

Components of variation associated with charges, charge by pressure treatments, and boards were tested for significance with likelihood ratio tests. Variations resulting from charge effects and/or a charge by pressure treatment interaction were not detectable. Variation because of boards within charges, however, was highly significant indicating that significant gains in precision were achieved by end-matching specimens and blocking on boards in the statistical analysis.

The slight reduction in MOR and WML with pressure treatment was expected and has been reported in the past (Winandy 1989, Barnes et al. 1993, Winandy and Lebow 1997, Forest Products Laboratory [FPL] 1999). As noted both in the present study and by previous researchers, WML

Table 2.—Summary of physical properties for specimens in each pressure treatment group.[a]

Pressure	Statistic	Moisture content (%)	Specific gravity	MOR (kPa)	MOE (MPa)	WML (kJ/m^3)
Untreated[b]	Arithmetic avg	13.2	0.39	59,467	8,940	63
	SD	0.49	0.03	6,831	1,521	14
	Median	13.3	0.38	58,502	8,818	62
1,207 kPa (175 psi)[c]	Arithmetic avg	14.5	0.39	56,974	9,179	47
	SD	0.32	0.03	6,981	1,687	12
	Median	14.4	0.39	57,544	9,008	47
1,379 kPa (200 psi) [b]	Arithmetic avg	14.5	0.39	57,462	9,000	50
	SD	0.33	0.03	6,704	1,431	12
	Median	14.6	0.39	57,726	8,774	51
1,551 kPa (225 psi)[d]	Arithmetic avg	14.3	0.39	57,151	9,084	51
	SD	0.33	0.03	7,076	1,705	13
	Median	14.3	0.39	57,130	9,142	51

[a] Conversions to English units: MOR (kPa) × 0.145 = lbf/in^2; MOE (MPa) × 1.45 × 10^{-4} = ×10^6 lbf/in^2; WML (kJ/m^3) × 0.145 = in-lbf/in^3.
[b] $n = 60$ for all properties.
[c] $n = 59$ for MC and SG, otherwise $n = 60$ for mechanical properties.
[d] $n = 59$ for all properties.

Table 3.—Pairwise mean comparisons of the effects of pressure on mechanical properties.[a]

	MOR (kPa)		MOE (MPa)		WML (kJ/m^3)	
Pressure	LS mean (SE)	Mean test[b]	LS mean (SE)	Mean test	LS mean (SE)	Mean test
Untreated	59,463 (922)	A	8,940 (214)	A	63 (2)	A
1,207 kPa (175 psi)	56,938 (922)	B	9,174 (214)	A	47 (2)	B
1,379 kPa (200 psi)	57,469 (922)	B	8,994 (214)	A	50 (2)	B
1,551 kPa (225 psi)	57,147 (924)	B	9,073 (215)	A	51 (2)	B

[a] Conversions to English units: MOR (kPa) × 0.145 = lbf/in^2; MOE (MPa) × 1.45 × 10^{-4} = ×10^6 lbf/in^2; WML (kJ/m^3) × 0.145 = in-lbf/in^3.
[b] Mean test = pairwise mean comparisons. If two means have the same letter, that pair is not declared significantly different based on a comparison-wise error rate of 0.05.

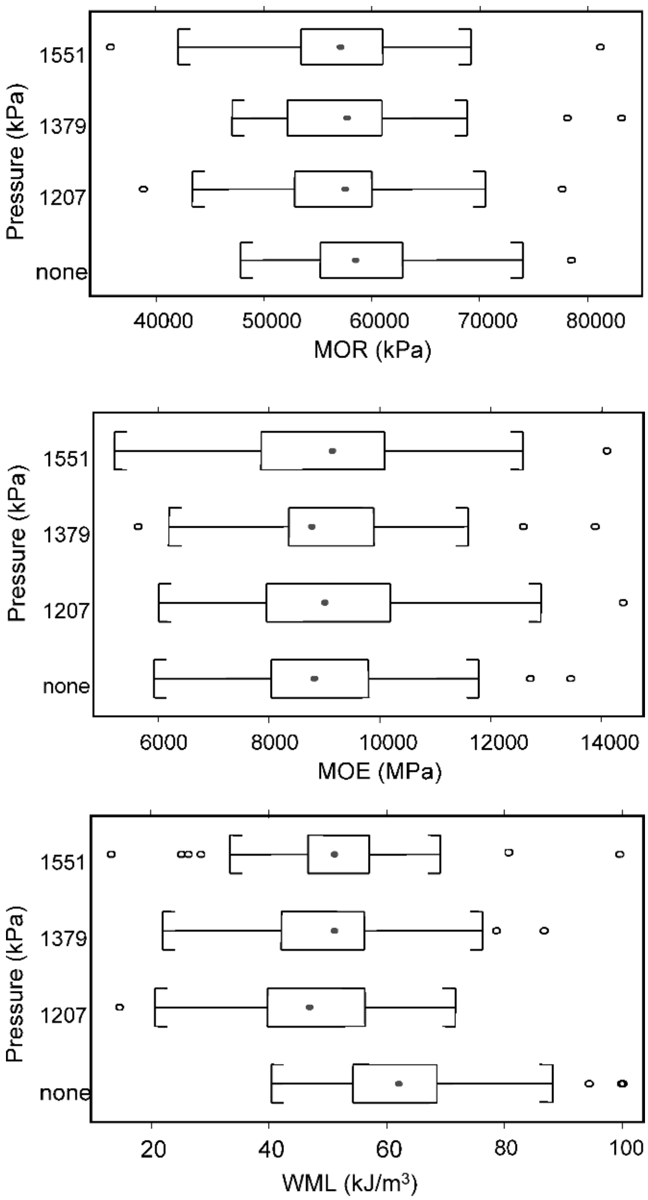

Figure 2.—Distribution of modulus of rupture (MOR), modulus of elasticity (MOE), and work to maximum load (WML) values for specimens in each pressure treatment group. See Figure 1 caption for explanation of box plots.

appears to be the property most affected (Barnes et al. 1993, Winandy and Lebow 1997). These reductions were associated with both the treatment process itself, and chemical properties of the preservative (FPL 1999).

It is noteworthy that all treatments evaluated in this study were conducted at room (ambient) temperature. The use of heated treatment solutions can increase the potential for damage to the wood structure (MacLean 1924, 1952; Walters and Whittington 1970; Barnes and Winandy 1986; Lebow et al. 2005), and it is possible that more significant reductions in mechanical properties would have been observed if these experiments had been conducted using heated treatment solution.

The mechanical properties for the untreated specimens in this study were lower than values reported for red pine in the *Wood Handbook* (FPL 1999) but were comparable to those obtained by Shukla and Kamdem (2008). This may be partly attributable to the lower specific gravity of these specimens (0.39) compared with those reported in the *Wood Handbook* (0.46). However, within the specimens in this study, specific gravity did not appear to be a key parameter. Specific gravity was considered as a covariate, but its inclusion resulted in only minor adjustments to estimated mean property values and no differences in experimental conclusions. The lower mechanical properties observed in this study may also be a function of growth rate and growth ring orientation. Properties reported in the *Wood Handbook* were determined with the load applied parallel to the growth rings (i.e., load applied to the tangential face), and other orientations may produce lower properties in some species (FPL 1999). In this test, grain orientation varied, with many specimens evaluated at an intermediate grain orientation. Specimens in this study also were not selected to meet specific growth rate (ring width) criteria. Growth ring width and other potential sources of variation in red pine properties were discussed in detail in Deresse and Shepard (1999). Experimental designs that take into account these and other possible sources of variability between boards will likely result in more efficient experiments for detecting treatment differences.

Conclusions

Raising the treatment pressure from 1,207 kPa (175 psi) to 1,551 kPa (225 psi) increased the average percentage of sapwood penetrated. Although this increase was not great, it was statistically significant. The increase in median sapwood penetration with higher pressure was more notable and indicates that the use of the higher pressure may have value in commercial charges. Uptake retention appeared to marginally increase between the 1,207-kPa (175-psi) and 1,379-kPa (200-psi) pressure levels, but did not increase when the pressure was raised from 1,379 kPa (200 psi) to 1,551 kPa (225 psi). In comparison with untreated specimens, pressure treatment did cause a statistically significant decrease in MOR and WML for the treated specimens. However, there was no significant difference in MOR, MOE, or WML for the three pressures evaluated, indicating that the increases in treatment pressure within the range of 1,207 kPa (175 psi) to 1,551 kPa (225 psi) will not significantly affect the mechanical properties of the treated material. It should be noted, however, that this study did not evaluate the potential effects of treatments conducted at elevated temperatures.

Literature Cited

American Wood Protection Association (AWPA). 2009. Book of Standards. AWPA, Birmingham, Alabama.

ASTM International. 2005. Standard test methods for small clear specimens of timber. ASTM D143-94. ASTM International, West Conshohocken, Pennsylvania.

Barnes, H. M., D. E. Lyon, A. R. Zahora, and F. Muisu. 1993. Strength properties of ACQ-treated southern pine lumber. *In:* Proceedings of the American Wood-Preservers' Association Annual Meeting, Newport Beach, California. 89:51–60.

Barnes, H. M. and J. E. Winandy. 1986. The effect of seasoning and preservatives on the properties of treated wood. *In:* Proceedings of the American Wood-Preservers' Association Annual Meeting, Philadelphia. 82:95–105.

Bendtsen, B. A., L. R. Gjovik, and S. P. Verrill. 1983. Mechanical properties of longleaf pine treated with waterborne salt preservatives. Research Paper FPL-RP-434. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 17 pp.

Deresse, T. and R. K. Shepard. 1999. Wood properties of red pine (*Pinus resinosa* Ait.). CFRU Information Report 412. US College of Natural Sciences, Forestry, and Agriculture, Maine Agricultural and Forest Experiment Station, University of Maine, Orono. 17 pp.

Forest Products Laboratory (FPL). 1999. Mechanical properties of wood, chap. 4. *In:* Wood Handbook—Wood as an Engineering Material. General Technical Report FPL-GTR-113. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 463 pp.

Lebow, S. T., C. A. Hatfield, and W. Abbott. 2005. Treatability of SPF framing lumber with CCA and borate preservatives. *Wood Fiber Sci*. 37(4):605–614.

Lebow, S. T., C. A. Hatfield, and S. Halverson. 2006. Effect of source, drying method and treatment schedule on treatability of red pine. *In:* Proceedings of the American Wood-Preservers' Association Annual Meeting, Austin, Texas. 102:39–43.

MacLean, J. D. 1924. Relation of temperature and pressure to the absorption and penetration of zinc chloride solution into wood. *In:* Proceedings of the American Wood-Preservers' Association Annual Meeting, Kansas City, Missouri. 20:44–71.

MacLean, J. D. 1952. Preservative treatment of wood by pressure methods. Agricultural Handbook No. 40. US Department of Agriculture, US Government Printing Office, Washington, D.C. 160 pp.

Shukla, S. R. and D. Pascal Kamdem. 2008. Physical and mechanical properties of red pine (*Pinus resinosa* Ait.) from three provenances. *Wood Fiber Sci*. 40(1):103–110.

Siau, J. F. 1970. Pressure impregnation of refractory woods. *Wood Sci*. 3(1):1–7.

Walters, C. S. and J. A. Whittington. 1970. The effect of treating pressure on preservative absorption and on the mechanical properties of wood. II. Douglas-fir. *In:* Proceedings of the American Wood-Preservers' Association Annual Meeting, Chicago. 66:179–193.

Winandy, J. E. 1989. CCA preservative treatment and redrying effects on the bending properties of 2 by 4 southern pine. *Forest Prod. J*. 39(9): 14–21.

Winandy, J. E. 1995. Effects of waterborne preservative treatment on mechanical properties: a review. *In:* Proceedings of the American Wood-Preservers' Association Annual Meeting, New York. 91:17–33.

Winandy, J. E. and S. T. Lebow. 1997. Effects of ammoniacal copper citrate preservative treatment and redrying on bending properties of two grades of southern pine 2 by 4 lumber. *Forest Prod. J*. 47(7/8): 91–99.