A COMPARISON OF THE TREATABILITY OF SOUTHERN YELLOW PINE TO FIVE APPALACHIAN HARDWOODS

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ABSTRACT

The preservative treatment variability of many hardwood species is one of the key stumbling blocks to their wider use in high biodeterioration situations, except for railway ties treated with creosote. The home-use or do-it-yourself market is dominated by southern yellow pine treated with chromated copper arsenate (CCA). Recent work performed to determine the treatability of Appalachian hardwoods with CCA, ammoniacal copper quaternary compound Type B (ACQ-B), creosote, and berates allowed for some direct comparison of the hardwoods (red oak beech hickory, yellow-poplar, and red maple) to southern yellow pine. The treatability of southern yellow pine sapwood with CCA was as good or better, when compared to yellow-poplar and red maple sapwood treated with CCA. Southern yellow pine heartwood was consistently in the middle range of treatability when compared to the heartwood of the five hardwoods. Creosote treatment results reaffirmed the well-accepted treatability of hardwoods and explains the dominance in certain industrial markets. Although treatment of hardwoods with CCA, ACQ, and berates was better than southern pine for some hardwoods, the level of penetration and retention overall, was not sufficient to meet any existing standards.

There is an extensive and wide-ranging body of work investigating the preservative treatment of hardwoods. One of the most referenced works, MacLeans' preservative treatment of wood by pressure methods manual (9), classifies different species into treatability groups based on penetration of preservative. Thompson and Koch's review (13) is an excellent source of information on preservative treatment of hardwoods. More recent work germaine to the effect of moisture content (MC) on treatability, would include Kumar and Morrell (7), Lebow, Morrell, and Milota (8), and Morns (10).

Of crucial importance in any explanation of treatability differences between species are the relevant anatomical differences. The most obvious difference in this work is the difference between the main cellular components of hardwoods and softwoods. The main cell type of southern pine is the tracheid, serving support as well as transport functions. Hardwoods are far more complex in this aspect, with several types of cells performing specialized functions. In his review of the influence of structural anatomy on liquid penetration into hardwoods, Greaves (4) concluded that the anatomical diversity of hardwoods is the key factor in the more variable results of liquid penetration and distribution in hardwoods as compared to softwoods. Behr et al. (2) investigated a variety of hardwoods and softwoods treated with creosote and pentachlorophenol. One of the conclusions of this paper was that, while ray tissue in softwoods was an important transport venue, it was often a hindrance to penetration into hardwoods.

Work done by Slahor et al. (12) and Hassler et al. (6) investigated the treatability of yellow-poplar *(Liriodendron tuliplfera* L.), red maple *(Acer rubrum* L.), hickory *(Carya* spp.), beech *(Fagus grandifolia* Ehrh.), and northern red oak *(Quemus rubra).* These studies included six preservative treatments, including: chromated copper arsenate Type C (CCA), ambient ammoniacal copper quaternary compound Type B (ACQ-B), heated ACQ-B, creosote, unwrapped borate, and wrapped borate. In addition, the treatments were conducted at two MCs (12% and either 17.5 or 24%), with sapwood and heartwood and at three different pressure periods (60, 90, and 120 min.). Southern yellow pine obtained from western Virginia (most likely *Pinus echinata* Mill.) was simultaneously evaluated for comparison purposes.

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TABLE 1. — Overall experimental design indicating where southern pine comparisons were made.

Preservative	CCA		A-ACQ[a]		H-ACQ[a]		Creosote		W-Borate[b]		U-Borate[b]	
	12%[c]	17.5%[c]	12%[c]	17.5%[c]	12%[c]	17.5%[c]	12%[c]	17.5%[c]	12%[c]	25%[c]	12%[c]	24%[c]
Y-poplar sap	X[d]	X	NC[e]	NC	NC	NC	NC	NC	NC	NC	NC	NC
Y-poplar heart	X	X	X	X	X	X	X	X	X	X	X	X
Red maple sap	X	X	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Red maple heart	X	X	X	X	X	X	X	X	X	X	X	X
Beech sap	X	X	X	X	X	X	X	X	X	X	X	X
Beech heart	X	X	X	X	X	X	X	X	X	X	X	X
Hickory sap	X	X	X	X	X	X	X	X	X	X	X	X
Hickory heart	X	X	X	X	X	X	X	X	X	X	X	X
Red oak heart	X	X	X	X	X	X	X	X	X	X	X	X
S. pine sap	X	X	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
S. pine heart	X	X	X	NC	X	NC	NC	X	NC	X	NC	X

[a] A = ambient; H = heated.
[b] W = wrapped; U = not wrapped.
[c] Sample moisture content.
[d] X = included in comparisons.
[e] NC = not included in comparisons.

TABLE 2 — Mean treatment results for southern yellow pine, red maple, and yellow-poplar sapwood treated with CCA.

Species	No. of samples	MinX	MaxX	Rating[a]	MinY	MaxY	Retention
		------- (in. (mm)) -------			------- (in. (mm)) -------		(pcf (kg/m³))
Yellow-poplar	38	0.58 (15)	0.75 (19)	2.84[b]	1.32 (34)	1.69 (43)	0.59[b] (9.4)
Red maple	39	0.49[b] (12)	0.75 (19)	2.85[b]	1.18 (30)	1.61[b] (41)	0.66[b] (10.6)
Southern yellow pine	50	0.65 (17)	0.75 (19)	3.00	1.75 (44)	1.75 (44)	0.83 (13.3)

[a] 0 = 0 to 25 percent; 1 = 25 to 50 percent; 2 = 50 to 75 percent; and 3 = 75 to 100 percent.
[b] Statistically less than pine at $\alpha = 0.05$.

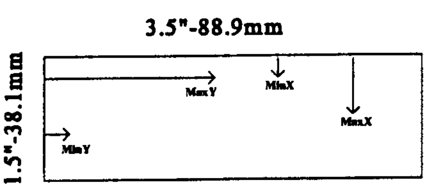

Figure 1, — Penetration measurements.

However, the pine was subjected to only a subset of the total hardwood treatment combinations investigated as can be seen in **Table 1.** This paper details the results of those available comparisons.

MATERIALS AND METHODS

Nominal 2-by-4-inch samples, 6 inches in length were produced from rough-cut material of all sapwood or all heartwood. The opening cuts on the hardwood logs were made to leave as much wane as possible and still produce a rough-cut 2-inch board. The wane was used as an indicator of hardwood sapwood. The remaining boxed-heart cant was the source of the heartwood samples using proximity to pith and wood color as indicators of hardwood heartwood.

The southern yellow pine logs obtained for this work were primarily sapwood with heartwood/sapwood being differentiated according to AWPA Standard M2-91 (1). The limited number of heartwood samples restricted the ability for direct comparison to the hardwoods in all treatments. The following comparisons were made: 1) yellow-poplar, red maple, and pine sapwood at 12 and 17.5 percent MC treated with CCA; 2) the heartwood of all of the hardwoods and pine heartwood at 12 percent MC with CCA and both treatments of ACQ-B; and 3) the heartwood of all the hardwoods and pine heartwood at either 17.5 or 24 percent MC treated with creosote and borates, respectively.

The aforementioned sample MCs were achieved using conditioning chambers maintained at appropriate temperature and relative humidity. All the samples (southern pine and all hardwoods it is compared to) of all the treatments described in this paper were treated in the same respective charge. Treatment cycles consisted of a 30-minute vacuum of 28 inch Hg, followed by 60-, 90-, or 120-minute pressure periods. Pressure for the CCA and ACQ-B treatments was 200 psi (0.141 kg/mm²) and 150 psi (0.105 kg/mm²) for creosote and borate treatments. Creosote was heated to 120°F (48.9°C) and ACQ-B treatment solutions (1% active ingredient) were heated (180°F/82.2°C) or ambient (80°F/26.7°C). The CCA solution (2% active ingredient) and the borate solution (2% active ingredient) were at ambient (80°F/26.7°C) temperature. Samples were end-sealed before treatment. Borate-treated samples consisted of two subgroups: the first group was spaced on wire grills to allow airdrying immediately atler treatment while the second group was immediately dead stacked and wrapped in plastic and stored at room temperature for 6 weeks. Following the 6-week period the samples were unwrapped, open stacked and allowed to dry.

Preservative penetration measurements were taken according to **Figure 1** (Min(imum)X, Max(imum)X, Min(imum)Y, Max(imum)Y) and a percentage rating of cross section penetrated. Percentage of cross section penetrated was given a rating of 0, 1, 2, or 3, where: 0 = 0 to 25 percent 1 = 25 to 50 percent; 2 = 50 to 75

TABLE 3. — Mean treatment results for heartwood of southern yellow pine and five hardwood species treated with CCA at 12 percent MC.

Species	No. of samples	MinX	MaxX	Rating[a]	MinY	MaxY	Retention
		------- (in. (mm)) -------			------- (in. (mm)) -------		(pcf (kg/m^3))
Yellow-poplar	30	0.12[b] (3)	0.60[b] (15)	1.57[b]	0.13 (3)	0.92[b] (23)	0.44[b] (7.0)
Red maple	30	0.25[b] (6)	0.54[b] (14)	1.67[b]	0.52[b] (13)	1.07[b] (27)	0.47[b] (7.5)
Red oak	30	0 (0)	0.20[c] (5)	0.03	0 (0)	0.20 (5)	0.18[c] (2.9)
Beech	30	0.04 (1)	0.63[b] (16)	1.47[b]	0.10 (3)	1.07[b] (27)	0.32 (5.1)
Hickory	30	0 (0)	0.13[c] (3)	0	0 (0)	0.10 (3)	0.14[c] (2.2)
Southern yellow pine	30	0.04 (1)	0.32 (8)	0.17	0.03 (1)	0.36 (9)	0.31 (5.0)

[a] 0 = 0 to 25 percent; 1 = 25 to 50 percent; 2 = 50 to 75 percent; and 3 = 75 to 100 percent.
[b] Statistically greater than pine at $\alpha = 0.05$.
[c] Statistically less than pine at $\alpha = 0.05$.

TABLE 4. — Mean treatment results for heartwood of southern yellow pine and five hardwood species treated with ambient ACQ-B at 12 percent MC.

Species	No. of samples	MinX	MaxX	Rating[a]	MinY	MaxY	Retention
		------- (in. (mm)) -------			------- (in. (mm)) -------		(pcf (kg/m^3))
Yellow-poplar	30	0.14 (4)	0.48 (12)	1.10	0.20 (5)	0.63 (16)	0.11 (1.8)
Red maple	30	0.22[b] (6)	0.66[b] (17)	2.10[b]	0.44[b] (11)	1.28[b] (33)	0.13[b] (2.1)
Red oak	30	0[c] (0)	0.38[c] (10)	0.67[c]	0.02 (1)	0.47 (12)	0.10 (1.6)
Beech	30	0.24[b] (6)	0.64[b] (16)	2.37[b]	0.41[b] (10)	1.04[b] (26)	0.17[b] (2.7)
Hickory	30	0.01 (0)	0.25[c] (6)	0.33	0.01 (0)	0.30[c] (8)	0.06[c] (1.0)
Southern yellow pine	30	0.08 (2)	0.49 (12)	1.20	0.01 (0)	0.30 (8)	0.10 (1.6)

[a] 0 = 0 to 25 percent; 1 = 25 to 50 percent; 2 = 50 to 75 percent; and 3 = 75 to 100 percent.
[b] Statistically greater than pine at $\alpha = 0.05$.
[c] Statistically less than pine at $\alpha = 0.05$.

percent; and 3 = 75 to 100 percent penetration.

Chemical retention of CCA (total oxide basis) and ACQ-B (CuO) was determined by x-ray fluorescence (ASOMA). An entire cross section was ground for analysis. The densities used for retention determination, based on 0 percent MC, were as follows: yellow-poplar, 26.2 pcf; red maple, 33.7 pcf; beech, 39.9 pct red oak, 39.3 pcf; hickory, 44.9 pcf; and southern pine, 32 pcf (11). Weight retention of creosote and borate was calculated by gross uptake of treating solution.

Treatability results were tested statistically using analysis of variance (ANOVA). For sapwood comparisons, a two-way ANOVA with interaction was used and the experimental factors were species and MC (12% vs. 17.5%). In all heartwood comparisons, a one-way ANOVA was used with species as the treatment factor.

Results

Sapwood

Table 2 shows the sapwood treatment results (regardless of MC) using CCA. The overall treatment of all three species was excellent, with the pine achieving statistically higher mean penetration on a fairly consistent basis. MaxX results were not statistically different since all three species were at their physical maximums (i.e., 0.75 in.). Retention was also significantly higher in pine (0.83 pcf), well above the 0.40 pcf (pound per cubic foot) specified in AWPA Standard C2-Lumber, Timber, and Ties Preservative Treatment by Pressure Process. Penetration results for pine were also well above AWPA standards. Similarly, if the same standards applied to yellow-poplar, then the penetration and retention results would meet the minimum standards as specified in AWPA Standard C2. The retention results for red maple would also meet the minimum requirements of C2, but the penetration results would not.

The interaction between species and MC was also significant in all treatability parameters (except MaxX, where all means were at their physical maximum of 0.75 in.). The 17.5 percent MC for pine was statistically greater than the 12 percent MC for MinX, MinY, and retention (MaxX, MaxY, and % rating were not statistically different since the maximum possible values were obtained for both MCs). The interactions further indicated that the 17.5 percent MC for pine consistently outperformed all species at either MC.

Heartwood

It is generally well documented that the heartwood of southern yellow pine is refractory. Slahor et al. (12) and Hassler et al. (6) also found that the heartwood of hardwoods was generally difficult to treat. **Tables 3** through **7** contain the treatability results for all hardwood species compared to pine. These results support the refractory nature of heartwood, regardless of species studied here. The best penetration and retention occurred with creosote at 17.5 percent MC and borate wrapped in plastic at 24 percent MC.

Comparing the pine treatability results to the treatability of various hardwood species indicated a mix of results. Yellow--poplar and red maple, treated with CCA at 12 percent MC, showed significantly higher penetration and retention than southern pine **(Table 3).** Beech also showed improved penetration in the MaxX, MaxY, and percent rating values. Red oak and hickory were generally comparable to southern pine, but did show significantly lower retention. In all cases, the results would be well below the minimum AWPA standards applicable to pine.

TABLE 5. — Mean treatment results for heartwood of southern yellow pine and five hardwood species treated with heated ACQ-B at 12 percent MC.

Species	No. of samples	MinX	MaxX	Rating[a]	MinY	MaxY	Retention
		------- (in. (mm)) -------			------- (in. (mm)) -------		(pcf (kg/m^3))
Yellow-poplar	30	0.23 (8)	0.66[b] (17)	2.20[b]	0.37[b] (9)	1.00[b] (25)	0.14 (2.2)
Red maple	30	0.04[c] (1)	0.54[b] (14)	0.70	0.07 (2)	0.71 (18)	0.09[c] (1.4)
Red oak	30	0[c] (0)	0.30 (5)	0.33[c]	0 (0)	0.34 (5)	0.20[b] (2.9)
Beech	30	0.07[c] (2)	0.46 (12)	0.77	0.11[b] (3)	0.64 (16)	0.09[c] (1.4)
Hickory	30	0.04[c] (1)	0.41 (10)	0.83	0.04 (1)	0.45 (11)	0.08[c] (1.3)
Southern yellow pine	30	0.12 (3)	0.38 (10)	0.97	0.01 (0)	0.48 (12)	0.12 (1.9)

[a] 0 = 0 to 25 percent; 1 = 25 to 50 percent; 2 = 50 to 75 percent; and 3 = 75 to 100 percent.
[b] Statistically greater than pine at $\alpha = 0.05$.
[c] Statistically less than pine at $\alpha = 0.05$.

TABLE 6. — Mean treatment results for heartwood of southern yellow pine and five hardwood species treated with creosote at 17.5 percent MC.

Species	No. of samples	MinX	MaxX	Rating[a]	MinY	MaxY	Retention
		------- (in. (mm)) -------			------- (in. (mm)) -------		(pcf (kg/m^3))
Yellow-poplar	30	0.58[b] (15)	0.74 (19)	2.93[b]	1.10[b] (28)	1.37 (35)	6.82 (109.2)
Red maple	30	0.39 (10)	0.71 (18)	2.43	0.73 (19)	1.06 (27)	6.29 (100.8)
Red oak	30	0.63[b] (16)	0.75 (19)	2.93[b]	1.29[b] (33)	1.61[b] (41)	4.38[c] (70.2)
Beech	30	0.32[c] (8)	0.73 (19)	2.23[c]	0.59 (15)	1.10 (28)	4.70[c] (75.3)
Hickory	30	0.23[c] (6)	0.66[c] (17)	1.80[c]	0.38 (10)	0.61[c] (15)	3.55[c] (56.9)
Southern yellow pine	30	0.45 (11)	0.74 (19)	2.63	0.80 (20)	1.22 (31)	8.29 (132.8)

[a] 0 = 0 to 25 percent; 1 = 25 to 50 percent; 2 = 50 to 75 percent; and 3 = 75 to 100 percent.
[b] Statistically greater than pine at $\alpha = 0.05$.
[c] Statistically less than pine at $\alpha = 0.05$.

Depending on the type of ACQ-B treatment different results were evident. For the ambient solution **(Table 4),** both red maple and beech showed improved results over pine, in all treatability parameters. Both red oak and hickory showed a trend toward poorer treatability than pine in three of six treatability categories. Yellow-poplar showed no differences with southern pine.

The heated ACQ-B solution had better treatability results in four of six treatability pammeters for yellow-poplar **(Table 5).** No significant trend was evident in the other species.

Creosote treatability results were also mixed **(Table 6).** Southern pine generally exhibited better treatability than beech and hickory. No statistical treatability differences were found between red maple and southern pine, while yellow-poplar was statistically greater than pine in percent rating and minimum penetration. Red oak treatability was statistically better in MinX, MinY, and MaxY, but poorer in retention than pine.

The unwrapped borate treatment showed very few treatability differences between southern pine and the hardwoods **(Table 7).** Yellow-poplar had the most definitive results, having better penetration in MinX and MinY and better retention. Red oak and hickory both exhibited statistically poorer mean retention than southern pine.

The wrapped borate treatment samples also showed little evidence of any treatability differences between species **(Table 8).** Red maple showed statistically improved reds in MinX, MinY, and MaxY. Yellow-poplar also had better retention than southern pine, while red oak and hickory had significantly lower retention.

Discussion

The treatability of southern yellow pine is well established in relation to waterborne preservatives (especially CCA), as evidenced by its market dominance in spite of having a refractory heartwood. Results of this investigation indicate that southern pine does not similarly dominate the hardwoods tested, with respect to treatability. Although southern pine sapwood treatability was as good in all treatment parameters and better in several as compared to yellow-poplar and red maple sapwood, such was not the case for heartwood. For CCA and ACQ-B, depending on the preservative, yellow-poplar, red maple, and beech heartwood showed better treatability. Yellow-poplar and red oak heartwood showed improved treatability with creosote, while the borate treatments showed little difference in treatability between hardwoods and southern pine.

Although yellow-poplar sapwood treatability using CCA (and to a lesser extent red maple sapwood) is comparable to southern pine sapwood treatability, very little progress has been made in penetrating the southern pine treated product market for a number of reasons. Traditionally, hardwoods have been marketed and sold as appearance-graded lumber in non-structural markets. There is very little incentive to convert the high quality outer portions of logs, where the very treatable sapwood exists, to less valuable structural applications. Further, the hardwood industry, in general, is not currently consolidated sufficiently to allow for surfacing, trimming, structural grading, drying, and treating in a single location. The increased handling costs to accomplish these tasks in the hardwood industry may not be economically competitive at this time.

Similarly, hardwood heartwood despite some potentially improved treatability over southern pine in certain species, has not made many inroads into the southern pine treated product market.

TABLE 7. — Mean treatment results for heartwood of southern yellow pine and five hardwood species treated with borate (not wrapped) at 24 percent MC.

Species	No. of samples	MinX	MaxX	Rating[a]	MinY	MaxY	Retention[b]
		------- (in. (mm)) -------			------- (in. (mm)) -------		(pcf (kg/m^3))
Yellow-poplar	30	0.25[c] (6)	0.60 (15)	1.23	0.48[c] (12)	0.84 (21)	0.40[c] (6.4)
Red maple	30	0.14 (4)	0.70 (18)	1.40	0.20 (5)	0.89[c] (23)	0.30 (4.8)
Red oak	30	0.17 (4)	0.55 (14)	1.23	0.17 (4)	0.46 (12)	0.12[d] (1.9)
Beech	30	0.09 (2)	0.61 (15)	1.00	0.11 (3)	0.81 (21)	0.20 (3.2)
Hickory	30	0.21 (5)	0.55 (14)	1.57	0.22 (6)	0.54 (14)	0.17[d] (2.7)
Southern yellow pine	30	0.16 (4)	0.62 (16)	1.20	0.24 (6)	0.54 (14)	0.26 (4.2)

[a] 0 = 0 to 25 percent; 1 = 25 to 50 percent; 2 = 50 to 75 percent; and 3 = 75 to 100 percent.
[b] As B_2O_3.
[c] Statistically greater than pine at $\alpha = 0.05$.
[d] Statistically less than pine at $\alpha = 0.05$.

TABLE 8 — Mean treatment results for heartwood of southern yellow pine and five hardwood species treated with borate (wrapped in plastic) at 24 percent MC.

Species	No. of samples	MinX	MaxX	Rating[a]	MinY	MaxY	Retention[b]
		------- (in. (mm)) -------			------- (in. (mm)) -------		(pcf (kg/m^3))
Yellow-poplar	15	0.56 (14)	0.72 (18)	2.60	1.06 (27)	1.21 (31)	0.43[c] (7.4)
Red maple	15	0.63[c] (16)	0.73 (19)	2.87[c]	1.37[c] (35)	1.37 (35)	0.25 (4.0)
Red oak	15	0.43 (11)	0.68 (17)	2.40	0.61 (15)	0.95 (24)	0.15[d] (2.4)
Beech	15	0.28[d] (7)	0.73 (19)	2.20	0.55 (14)	1.06 (27)	0.23 (3.7)
Hickory	15	0.42 (11)	0.68 (17)	2.20	0.61 (15)	1.04 (26)	0.18[d] (2.9)
Southern yellow pine	15	0.46 (12)	0.70 (18)	2.40	0.82 (21)	1.11 (28)	0.28 (4.5)

[a] 0 = 0 to 25 percent; 1 = 25 to 50 percent; 2 = 50 to 75 percent; and 3 = 75 to 100 percent.
[b] As B_2O_3.
[c] Statistically greater than pine at $\alpha = 0.05$.
[d] Statistically less than pine at $\alpha = 0.05$.

Treatability aside, susceptibility of CCA-treated hardwoods to soft-rot decay (2, 3,5) is also a factor relative to this lack of use. The lower quality log hearts of hardwoods have traditionally been marketed to industrial applications where strength is important. Railroad ties and pallet materials, among others, have provided readily available markets for hardwood hearts. The necessary effort to redirect this material to treated markets dominated by southern pine has not been thoroughly investigated.

The ACQ-B and borate treatments are not widely used for treated products, again due in part to the dominance of CCA-treated southern pine, as well as their specialty marketing or end-use specification. Conversely, creosote-treated hardwood railroad ties have a long history of excellent serviceability and are dominant in that market segment.

In the final analysis, the refractory nature of both southern pine heartwood and hardwood heartwood is a technical barrier to increased volumes of CCA-, ACQ-B-, and borate-treated hardwoods. If hardwood heartwood is to become competitive in preservative-treated end-use lumber markets, further development of efficient, cost-effective preservative system(s) is essential. If successful treatment of hardwood heartwood, the weak link in the treatability issue of hardwoods, can bring a sufficient premium to the lower grades of lumber (i.e., No. 2 and No. 3 Common) or pallet stock of species such as beech and hickory, additional market opportunities may become available.

Literature Cited

1. American Wood Preservers' Association. 1995. Standard for inspection of treated timber products. M2-91(1), section 5.3.1. AWPA, Granbury, Tex.
2. Behr, E.A., I.B. Sachs, B.F. Kukachka, and J.O. Blew. 1969. Microscopic examination of pressure treated wood. Forest Prod. J. 19(8):30-40.
3. Butcher, J.A. 1979. Soft-rot control in hardwoods treated with chromated copper arsenate preservatives. Part 5. A reason for variable performance of CCA-treated hardwoods. Material und Organismen 14(3): 215-234.
4. Greaves, H. 1974. A review of the influence of structural anatomy on liquid penetration into hardwoods. J. of the Inst. of Wood Sci. 6(6):37-40.
5. _________. 1977. An illustrated comment on the soft rot problem in Australia and Papua New Guinea. Holsforschung 31(3): 71-79.
6. Hassler C.C., J.J. Slahor, R.C. DeGroot, and D.J. Gardner. 1998. Preservative treatment evaluation of five Appalachian hardwoods at two moisture contents. Forest Prod. J. 48(7/8):37-42.
7. Kumar, S. and J.J. Morrell. 1989. Moisture content of western hemlock: Influence on treatability with chromated copper arsenate type C. Holzforschung 43(4):279-280.
8. Lebow, S.T., J.J. Morrell, and M.P. Milota. 1996. Western wood species treated with chromated copper arsenate: Effect of moisture content. Forest Prod. J. 46(2):67-70.
9. Maclean, J.D. 1952. Preservative treatment of wood by pressure methods. Agriculture Handbook No. 40. Reprinted with corrections Sept. 1960. USDA, Washington, D.C. pp. 81-82.
10. Morris, P.I. 1991. Improved preservative treatment of spruce-pine-fir at higher moisture contents. Forest Prod. J. 41(11/12):29-32.
11. Simpson, W.T. 1973. Specific gravity, moisture content, and density relationship for wood. Gen. Tech. Rept. FPL-GTR-76. USDA Forest Serv., Forest Prod. Lab., Madison, Wis. 13 pp.
12. Slahor, J.J., C.C. Hassler, R.C. De Groot, and D.J. Gardner. 1997. Preservative treatment evaluation with CCA and ACQ-B of four Appalachian wood species for use in timber transportation structures. Forest Prod. J. 47(9):33-42.
13. Thompson, W.S. and P. Koch. 1981. Preservative treatment of hardwoods: A review. Rept. FO-35. USDA Forest Serv., Southern Forest Expt. Sta., New Orleans, La. 47 pp.