ISSN impresa 0717-3644
ISSN online 0718-221X

Maderas. Ciencia y tecnología 2022 (24): 41, 1-14

DOI: 10.4067/s0718-221x2022000100441

EXPLORATORY STUDIES ON EFFECTS OF GROWTH LOCATION AND CONDITIONING ON TREATABILITY AND PERMEABILITY OF SOUTHERN PINE LUMBER

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ABSTRACT

Southern pine lumber is often treated with preservatives, but issues related to initial kiln-drying conditions and geographic source across the wide southern pine growth range have been suspected to negatively affect subsequent permeability and treatability. These effects remain poorly understood. In this series of exploratory studies, southern pine from across part of the growing range subjected to different kiln-drying regimes was evaluated in three phases exploring the effects of geographic source and initial kiln-drying conditions on permeability, pit structure and eventual preservative treatment of southern pine lumber. The results suggest that elevated temperatures coupled with poor humidity control at the start of the kiln drying process may negatively influence permeability and preservative penetration, but had only negligible effects on several other wood properties.

Keywords: Drying, growing range, lumber, permeability, southern pine, treatability.

INTRODUCTION

Southern pine sapwood is generally considered to be highly permeable and easily treated, but variations in permeability lead to variations in treatability. This variability is further complicated with southern pines because the term refers not to a single, genetically distinct species, but to a species group consisting of four major species, loblolly, slash, longleaf and shortleaf pine (*Pinus taeda, P. elliotti, P. palustris* and *P. echinata*, respectively), with commercially similar physical properties that are difficult to identify to species once the wood has been processed (SPIB 2014).

Each of the four major species has subtly different native growth zones (Bendtsen and Ethington 1972) related to the six differing physiographic regions across the southeast United States: Gulf-Atlantic coastal flats, Gulf-Atlantic rolling plains (i.e., Piedmont), Appalachian highlands, Eastern Interior upland and basin, Lower Mississippi alluvial plain and the Ozark-Quachita highlands (USGS 1970). Each of these species also has distinct physical property differences (Bendtsen and Ethington 1972, Larson *et al.* 2001). Over the

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Received: 08.09.2021 Accepted: 29.05.2022

last 50 years, the proportional growing zone of loblolly and slash pine has increased due to intensive tree-improvement research (McKeand *et al.* 2003). Loblolly pine now represents over 50% of the standing pine in the Southeast U.S. due to its efficient regenerative properties and rapid growth (Schultz 1997, Shiver *et al.* 2000, Eberhardt *et al.* 2017). Despite their similarities in terms of many commercial timber properties, southern pine species differences and geographic source are often suspected of influencing treatability (Jewell *et al.* 1990). Complicating these issues even further are potential differences in permeability and, hence treatability, associated with juvenile wood which become challenging to quantify on a large scale in the final sawn products.

No systematic practical attempts appear to have been undertaken to identify the multitude of issues defining differential treatability of the southern pine lumber group. The issue is complicated because it involves differences in species within the commercial group, genetic provenances, growing conditions on a given site, drying conditions of the sawn product as they affect permeability and finally, preservative treatment processes. It is beyond the scope of nearly any research laboratory to fully address the issue across the entire species range nor would it be easy to justify such a project without some preliminary data. The objective of the series of studies reported in this paper was to use commercially obtained timbers to explore various facets of the problem (geographic source and kiln drying regimes) in order to better define future research directions. The results should, therefore, be viewed as more qualitative than quantitative due to the limited sample sizes in any phase of the studies.

Together, loblolly, slash, longleaf and shortleaf pine represent approximately 90 % of the Southern pine growing stock (Koch 1972). Additionally, the group can sometimes also include the locally important minor species Virginia pine, pitch pine, pond pine, sand pine and spruce pine (*P. virginiana, P. rigida, P. serotina, P. clausa* and *P. glabra*, respectively) (SPIB 2014). These five minor species generally have lower density, strength and stiffness (FPL 2010). There have been extensive efforts to improve the form, growth rates and wood quality of the southern pines, especially loblolly pine, through both breeding and enhanced silvicultural practices (Eberhardt *et al.* 2017, Schimleck *et al.* 2018, Dahlen *et al.* 2018, Adhikari *et al.* 2021, Gräns *et al.* 2021). These efforts have concentrated on more easily measured characteristics such as growth rates, density, modulus of elasticity, juvenile wood content, and microfibril angle.

An often overlooked wood quality factor is permeability which, while more difficult to measure, plays important roles in both drying and preservative treatment. While the southern pines generally contain thick bands of easily treated sapwood, receptiveness to treatment can also vary between species and affect preservative treatment. For example, shortleaf pine was reported to be more difficult to treat than loblolly pine possibly due to differential permeability although the authors did not explore that possibility (Jewell *et al.* 1990). Older data suggests that longitudinal permeability of sapwood under vacuum can vary between the four major species of southern pine by a 4x factor when green and 3x when air-dried to 10% moisture content (MC) (Erickson *et al.* 1937). The lack of species differentiation under current southern pine grading rules may account, in part, for reports that southern pine treatability varies by species and across the growing region (SPIB 2014, Winandy *et al.* 2001, Donn Keefe, Personal communication, 2001).

Similar regional differences in treatability have been found with Douglas-fir (Miller and Graham 1963). Such differences are not surprising given the biological nature of wood but understanding the causes and extent of these differences can be important for proper processing. Sapwood cells in living coniferous trees are connected via pits that are essentially semi-permeable membranes that allow fluids to move across cells. Pits can be simple, half-bordered or bordered depending on the species and cellular arrangements. Pits in the sapwood are generally open allowing ready passage of fluids between cells. While coniferous structure is dominated by longitudinal tracheids whose lumens vary in diameter and might be expected to have major effects on fluid flow, the pits are the primary limiting factor in fluid flow. *Poiseuille's* Law describes fluid flow in porous materials and notes that the diameter of the smallest pore (i.e. generally the pits) is raised to the fourth power in the numerator meaning that it dominates flow. Pits in living trees can become blocked for a number of reasons, including encrustation of the membrane with cellular contents or debris, or in the case of bordered pits, movement of the torus to block the pit opening. These activities may occur in response to drought stress, wounding or fungal attack, but most sapwood pits remain open and receptive to flow. Permeability, which is most often related to pit condition has also been shown to vary with position in the tree and in juvenile vs mature wood (Milota *et al.* 1995). Pits also sometimes close or become clogged during sapwood conversion to heartwood, helping to explain why the heartwood of most species is impervious to fluids. Permeability variations can produce inherent difficulties in processing timber from some species or regions, although there is little that can be done to alter the material once the pits have closed.

There have been suggestions that drying conditions can affect pit structure and alter permeability. Rapid drying or exposure to elevated temperatures may lead to closing or aspiration of the pits, resulting in a sharp decrease in permeability (Langrish and Walker 2006). High temperature drying between 110ºC to 140 ºC with kiln times of 24-36 hours has become common in the Southern United States (FPL 2010).

Several studies have examined the potential effects of various drying processes on wood permeability. Increased pit aspiration resulting in decreased longitudinal permeability in red pine (*Pinus resinosa*) and eastern hemlock (*Tsuga canadensis*) sapwood was associated with using higher initial kiln-drying temperatures (Comstock and Côté 1968). Conversely, radial permeability of heartwood and sapwood of *Pinus radiata* increased as drying temperatures increased (Booker and Evans 1994). Sapwood permeability was nearly double for high-temperature-dried timber compared to air-dried, while heartwood permeability increased about 280%. They concluded that this higher radial permeability of high temperature-dried wood was responsible for improved preservative impregnation. Conversely, Leggate *et al.* (2021) found that both gas and liquid permeability and preservative retention and copper penetration tended to be noticeably reduced, but not statistically, as maximum kiln-drying temperatures progressively increased from 40 to 115ºC to 180ºC.

Other studies have examined the potential effects of drying processes on wood permeability and their relationship with treatability. Gas permeability of subalpine fir (*Abies lasiocarpa*) lumber experienced no significant change after 4 hr of steaming in either the green condition or at the fiber saturation point (Cai and Oliveira 2007). Bordered pit damage and aspiration were more prevalent in *Cryptomeria japonica* sapwood lumber dried at 100ºC to 120ºC than similar lumber dried at far lower temperatures, but permeability measurements were similar (Sakagami *et al.* 2016). Anecdotally, some southern pine kiln operators have found improved treatment results when lowering initial kiln-drying temperature by 5ºC to 10ºC or limiting venting to achieve higher wet-bulb temperatures early in the kiln-drying process to produce more rapid heating of the wet wood while delaying early rapid drying (Winandy *et al.* 2001, Donn Keefe, Personal communication, 2001). Similar anecdotal results have been reported with restricted-vent control during the early stages of kiln-drying Australian slash and mixed slash/Caribbean pine (Morrell 2021). Another factor that can affect subsequent treatability is the target moisture content with a suggestion that lower moisture contents reduce receptiveness to preservative penetration in some species. For example, Lebow *et al.* (1996) found that treatability of hem-fir lumber declined as moisture contents fell below 25 % which is above the target moisture levels used for kiln-dried lumber in the U.S.

While there are numerous carefully controlled studies of permeability, there are few full scale trials that encompass the myriad of practical processing effects on treatment. The objective of the exploratory trials described herein was to assess the effects of elevated initial kiln-drying temperatures and differing growing locations on pit structure, permeability and preservative treatment of mixed southern pine lumber. The three phases were iterative with the results of one phase helping to form the goals of the next. Results of Phase I and parts of Phase II were reported earlier (Winandy *et al.* 2001). It is important to emphasize that these studies were intended to be preliminary and to stimulate more comprehensive research into this important issue.

MATERIALS AND METHODS

The research was conducted in three phases. In Phase I commercially dried southern pine lumber from one mill that was reported to be difficult to penetrate was treated with chromated copper arsenate (CCA) and characterized for wood properties and conformance to treatment standards. In Phase II, a small number of boards obtained from 7 mills located across the southern pine growing region were evaluated for wood characteristics and treatability. In Phase III, samples were collected from six mills and characterized by kiln schedule and treatability. More complete details of each phase are given in the following three sub-sections.

Phase I: Two hundred fifty-six pieces of wane-free No 2 Prime nominal 2 by 6 southern pine lumber (38mm by 140mm by 4,88m) were obtained from a mill located southwest of Atlanta, GA. This was commercially produced material and there was no way to determine tree source or original position in the tree. No 2 Prime (SPIB 2014), a special grade of No 2 lumber with stricter wane limitations, is intended primarily for use as decking. The focus of Phase I was to better understand how treatability correlated with physical/anatomical characteristics, such as juvenility, growth rate, and/or chemical composition.

Each 4,88m long, nominal 2 by 6 southern pine board was cut in half and one 2,44 m long half was allocated for commercial preservative treatment while the other half was shipped to Forest Products Laboratory

(FPL) in Madison, WI for further evaluation. The 2,44 m long half to be treated was commercially treated using a modified full-cell treatment (5 min at -60kPa, 15 min at 1000kPa, and 10 min at -80kPa) with CCA Type C. The 256 treated boards were each individually inspected for preservative penetration by Mr. Donn Keefe, former Vice-president and Chief Inspector of the American Wood Preservers' Bureau by removing increment cores from the narrow faces and staining with chrome azurol S to indicate the presence of copper to determine if penetration met American Wood Protection Association (AWPA) Standard T1 (AWPA 2001a, AWPA 2001b, AWPA 2001c).

Twenty-four of the 256 2,44-m nominal 2x6 untreated halves shipped to FPL were randomly selected to examine relationships between growth rate, anatomical factors and chemical composition with treatment penetration failures. Seventeen pieces were selected from the 102 boards that failed to meet penetration, along with 7 randomly selected untreated pieces from the 154 boards where penetration was acceptable were tested for chemical analysis. The selection of just 24 samples was required because of limitations for the carbohydrate composition test procedures. The matched twenty-four (17 failed and 7 meeting penetration requirements) untreated 2,44 m long halves were then further cut into six knot-free, clear grained sections: one 25 mm long section for chemical analysis, one 25 mm long section for specific gravity determination (ASTM D2395-02 2003), and four 100 mm long sections for assessing growth rate, presence of blue stain, heartwood percentage, and presence of pith and/or juvenile wood (AWPA 2001c). Juvenile wood is considered to include wood within the first 3 to 18 growth rings (Larson *et al.* 2001); for these studies juvenile wood was defined as the first 10 growth rings from the pith. The matched 25mm carbohydrate test samples were then ground to 40mesh and individually analysed for total carbohydrates following the chromatographic methods of Davis (1998).

Phase II: Two randomly selected untreated southern pine boards each (38 mm by 89mm by 4,88m) were obtained from seven mills located in Georgia, Florida, South Carolina, and Arkansas (Figure 1). The focus of Phase II was to compare southern pine lumber from several distinct geographic regions across the growing range and then begin to identify how different treatment schedules might affect penetration and treatment. A 1,22 m long section was cut from one end of each 4,88 m long board and used for further study while the remainder was discarded. The longer boards were initially selected for sampling to ensure that the shorter 1,22 m cut-off sample was representative of commercial production. It was anatomically impossible to distinguish between the various species in the southern pine group after conversion to lumber nor was it possible to determine original position in the parent tree.

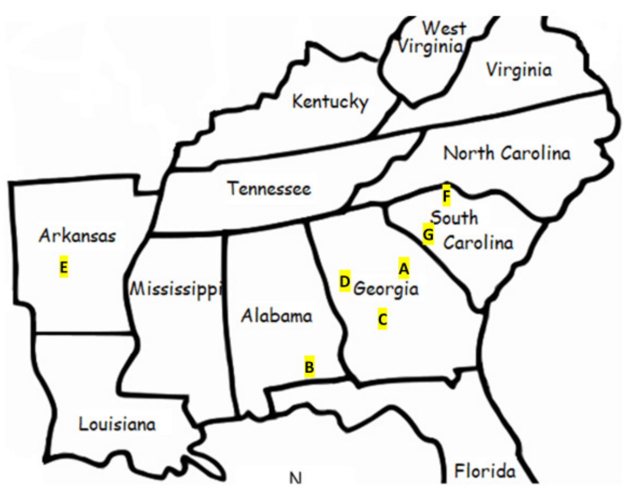
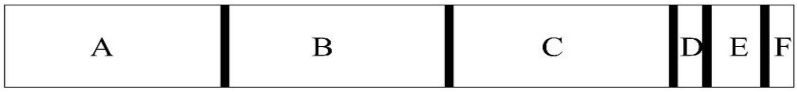


Figure 1: Locations of the seven mills from which lumber was obtained for Phases II.

Each of these fourteen 1,22 m pieces was further cut to produce three 305 mm long sections for treatment trial specimens, two 25 mm long sections for chemical analysis and specific gravity determination and one 100 mm long section for assessment of general anatomical characteristics (Figure 2).



A - 305 mm Treatability A (ends were sealed)
B - 305 mm Treatability B (ends were sealed)
C - 305 mm Treatability C (ends were sealed)
D - 25 mm Chemical Analysis
E - 100 mm Anatomy Specimen
F - 25 mm Specific Gravity/Moisture Content

Figure 2: Example of Phase II cut-up pattern to obtain six samples from each of the 14 untreated 1,22 m long nominal 2x4 (38 x 89 mm) matched halves of Southern pine lumber.

Both ends of each305 mm long treatment sample were end-sealed with a commercial elasto-polymeric end-sealing formulation and weighed before being allocated to be treated with CCA using either a:

a) full cell (15 min at -80 kPa, 30 min at 1000 kPa, and 10 min at -80 kPa),

b) modified full-cell (6 min at -60 kPa, 15 min at1000 kPa, and 10 min at-80 kPa), or

c) low-weight gain (15 min at -80 kPa, 10 min at 1000 kPa, and 15 min at -80 kPa).

Immediately after treatment, the samples were wiped clean and weighed to determine net solution absorption. The samples were then cut in half and sprayed with chrome azurol S to visually assess copper penetration and photographed. Penetration was expressed as a proportion of the total cross-sectional area.

Samples for chemical analysis were ground to 25mesh in a Wiley mill. Ground wood from the two samples from each of the 7 original mills were combined before being extracted and chromatographically analysed using previously described procedures (Davis 1998). The other 25 mm long section was used to determine specific gravity on an oven-dry basis by water displacement (ASTM D2395-02 2003).

Phase III: Twenty pieces of 38 mm by 140mm by 4,88 m kiln-dried southern pine lumber were randomly collected from each of six sawmills located in Georgia and Florida representing three Coastal and three Piedmont growth zones. Two of the three mills sampled that used direct-fired kilns were from Coastal zones and one was from a Piedmont zone. For the three that used steam-heated kilns with secondary humidity control, one was from a Coastal zone and two were from Piedmont zones. Once again, the pine samples could not be anatomically identified to species or location within the parent tree and will be discussed as southern pine. The samples were labelled at each end and cut in half. One 2,44 m sample was kept for further evaluation and the other discarded.

The 2,44 m test samples were further cut up as described above in Phase II taking care to ensure that the ensuing seven samples (three for treatment and individual samples for measuring specific gravity/moisture content (SG/MC), heartwood/growth rate, chemical analysis and permeability) were straight-grained and clear of defects and that the treatment samples did not contain any knots or other obvious defects that might affect treatment. The moisture content samples were always taken inward from the end of the boards to minimize the effect of any excessive drying that might have occurred on the cross-sectional face exposed during drying.

The 305 mm long treatment samples were end-sealed and pressure treated using the same end-sealer and 3 treatment schedules described in Phase II except that the pressure period for the low-weight gain treatment was 14 minutes instead of 10 minutes. The samples were weighed before and after treatment then the sections were cut in half and preservative penetration was measured at five equidistant locations each on the upper and lower wide faces and at the mid-point on each narrow face for all 20 boards from each mill. The results were averaged for each board.

Longitudinal-and radial-gas permeability were then determined by cutting 12 mm diameter plugs oriented both longitudinally and radially from the 127 mm long untreated cut-up sections using procedures described by Comstock (1967) and modified by Milota *et al*. (1995) (Figure 3). The remaining sub-sections from each board were used to determine growth rate, percent latewood, moisture content at time of treatment, and pre-treatment specific gravity as described earlier.

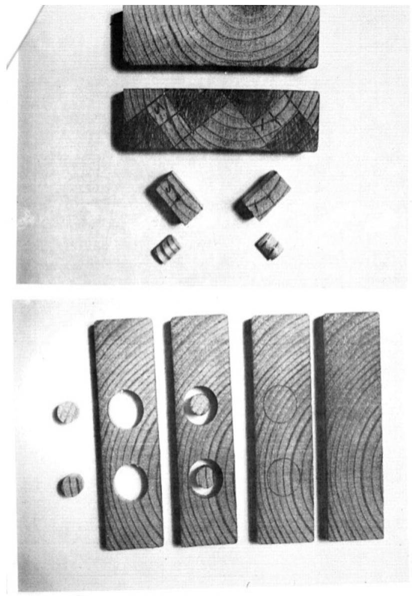


Figure 3: Examples of 12mm diameter plugs cut from the 127mm permeability specimen and used to determine longitudinal- (upper) and radial- (lower) gas permeability.

Data analysis

The limited replication and the inability to sort samples prior to collection limited statistical analysis. Instead the data were summarized using means and standard deviations/coefficients of variation for comparison.

RESULTS AND DISCUSSION

Phase I: Nearly 40 % (102 out of 256) of samples failed to meet the AWPA T-1 penetration requirement of 63 mm or 85 % of the sapwood for CCA treatment of southern pine lumber (AWPA 2001a). Light-microscopic examination of stained, thin transverse sections cut from the 2,44 mm untreated pieces matching the 17 boards selected from those that failed preservative penetration showed that a majority of the pits were aspirated, suggesting that they would impede preservative flow (data not shown). Similar microscopic examination of thin sections cut from the matched untreated halves of 7 selected boards that had passed the CCA penetration required for proper treatment showed no evidence of pit aspiration.

The Phase I CCA penetration evaluations also suggested the presence of a one to two growth increment wide zone of "intermediate wood" between true sapwood and heartwood. This visibly recognizable transition zone often existed between growth rings rapidly penetrated compared to the visible border of non-penetrated growth rings. Booker (1990) defined this intermediate wood (also sometimes termed a "transition zone") as differing from heartwood in that it has living ray parenchyma cells without polyphenols while differing from sapwood because it has lower moisture content and permeability. Sano and Nakada (1998) observed a similar intermediate zone between sapwood and heartwood for *Cryptomeria japonica*. The transition zones observed between true heartwood and sapwood in the current study showed indications of debris on the pit membranes that might impede CCA penetration. Pit encrustations could have been present in the living tree or their formation was influenced by temperature and relative humidity conditions within the kiln that affected moisture flux and internal vapor pressures that were found to be critical by Comstock and Côté (1968).

While it was not clear why the pit membranes in nearly all failed specimens were aspirated, initial kiln-drying at the primary sawmill could be one explanation. The kiln-drying facility reportedly subsequently lowered their direct-fire kiln temperatures by 5°C to 10°C and also closed their top-vents to encourage heating, rather than drying, during the initial stages of kiln-drying. The cooperating treating facility, as well as a second nearby treating plant using the same lumber resource, subsequently reported dramatically fewer treatment penetration failures for lumber from that particular sawmill (Keefe 2001).

Evaluation of other wood properties on samples cut from the 24 boards that either met or failed to meet the AWPA T-1 Standard suggested that there were few differences between the two populations in terms of percent heartwood, percent juvenile wood, or growth rate (Table 1). Interestingly, boards that failed penetration had slightly higher levels of blue stain, which would normally be expected to increase preservative penetration (Scheffer and Lindgren 1940). However, the levels of blue stain in the poorly treated boards were so slight that this factor was considered negligible.

Chemical analysis of samples cut from the untreated sections of boards that met or failed the penetration requirement also showed little difference in the levels of various hemicellulose sugars as well as glucan or total carbohydrates between the two groups (Table 2). Exposure to elevated temperatures has been shown to affect hemicelluloses although both the failed and the boards that met treatment penetration requirements in this Phase I were exposed to the same temperatures, thereby reducing the likelihood of differences between the two groups.

Table 1: Wood characteristics of CCA treated southern pine boards that either met or failed the AWPA Standards for treatment from Phase I.

Treatment	Reps	Juvenile Wood (%)	Pith (%)	Heartwood (%)	Rings/cm	Blue Stain (%)
Pass	7	45,7 (32,6)	8,1 (5,6)	10,7 (22,4)	3,08 (1,40)	0
Fail	17	44,7 (34,7)	10,1 (9,5)	11,2 (20,2)	2,72 (0,92)	0,4 (0,5)

Values in parentheses represent one standard deviation.

Table 2: Sugar content of southern pine cut from boards that met or failed the AWPA Standards for CCA treatment from Phase I.

Treatment	Reps	Sugar Content (%)						
		Arabinan	Rhamnan	Galactan	Xylan	Mannan	Glucan	Total Carb
Pass	7	1,21 (0,07)	0,10 (0,01)	2,15 (0,38)	6,30 (0,57)	10,61 (0,46)	41,57 (1,14)	61,96 (0,99)
Fail	17	1,18 (0,09)	0,10 (0,02)	1,85 (0,45)	5,98 (0,58)	11,32 (0,84)	42,52 (1,37)	62,95 (1,08)

Values in parentheses represent one standard deviation.

In summary, the results from Phase I suggested that there were anatomical differences in pit structure between boards that met or failed the AWPA treatment requirements, but the other wood parameters measured did not help explain these differences.

Phase II: Treatment quality in this phase was assessed on the basis of preservative penetration primarily examined preservative penetration in order to better understanding effects of treatment process variables, chemical composition and anatomical characteristics on treatment. Samples were all virtually completely penetrated, regardless of the treatment process, except near the pith or near areas having radial grain dislocations such as above or below branching structures (Figure 4). Specific gravity and growth rates were similar for most samples, with the exception of the samples from Arkansas (Table 3). The Arkansas samples had higher specific gravities and also contained the most heartwood, and were associated with untreated gaps near the pith. However, treatability seemed similar to southern pine from other locations.

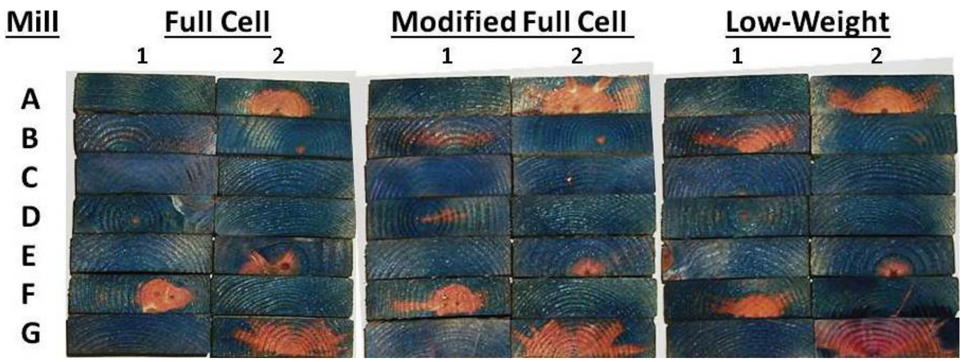


Figure 4: Matched treated lumber samples from Phase II showing CCA penetration patterns of two replicate 2x6 southern pine pieces from seven different Mills after either a full-cell, modified full-cell, or low-weight treatment. Locations of the seven mills sampled are given in Table 3.

Table 3: Average anatomical and physical characteristics of Phase II southern pine lumber from seven different mills (two sample replicates/mill) across the southern pine growth range.

Location	Region	Mill ID	MC (%)	Specific Gravity	Heartwood (%)	Growth Rate (rings/cm)
Georgia	Coastal	A	14,4	0,480	15	2
Florida	Piedmont	B	13,5	0,473	0	2
S,Carolina	Piedmont	C	13,8	0,461	0	1,8
Georgia	Coastal	D	17,9	0,407	0	2,6
Georgia	Coastal	E	12,8	0,483	7,5	1,6
Georgia	Coastal	F	13,1	0,475	12,5	2,6
Arkansas	Ozark Highland	G	13,6	0,532	30	2,4

As with the samples in Phase I, there were no noticeable differences in sugar content or growth rate between the board sources suggesting that other anatomical factors accounted for any treatment differences (Table 4).

Phase III: Samples obtained from six different mills in Georgia and Florida were segregated by whether the lumber was dried using direct-fired or steam-heated kilns (Table 5). Samples from Mills A, D, and F had slightly higher specific gravities than those from the other three mills. Mills A and F used direct fired kilns while Mill D used steam. Samples from Mills A and F also had higher percentages of latewood. Latewood tends to be more easily treated with CCA than earlywood (Hunt and Garratt 1967), although the degree of treatment in these materials would suggest that the permeability of both portions of the ring were high.

Table 4: Average sugar content of southern pine lumber from seven different mills (two sample replicates/ mill) collected in Phase II.

State	Region	Sugar Content (%)						
		Arabinan	Rhamnan	Galactan	Xylan	Mannan	Glucan	Total Carb
Georgia	Coastal	1,11	0,10	1,42	6,16	11,98	43,15	63,8
Florida	Piedmont	1,21	0,13	2,53	6,41	9,65	40,37	60,3
S. Carolina	Piedmont	1,34	0,11	2,42	6,98	11,06	40,35	61,9
Georgia	Coastal	1,19	0,09	2,98	6,14	10,00	37,47	57,9
Georgia	Coastal	1,17	0,12	1,63	5,99	11,94	42,83	63,7
Georgia	Coastal	1,16	0,11	2,05	6,51	10,56	42,41	62,8
Arkansas	Ozark Highland	1,28	0,10	2,13	6,05	11,78	41,18	62,5

Table 5: Wood characteristics of southern pine lumber obtained from six mills located in Georgia and Florida[a] in Phase III.

Mill	U.S. State	Region	Kiln Type	Growth Rate (rings/cm)	Latewood (%)	Moisture Content at Treatment (%)	Specific Gravity
A	Georgia	Coastal	Direct	2,12 (0,78)	32,5 (8,5)	9,6 (1)	0,60 (0,06)
B	Florida	Coastal	Direct	2,52 (1,08)	23,6 (9)	11,2 (0,7)	0,51 (0,05)
F	Georgia	Piedmont	Direct	2,96 (1,24)	30,2 (7)	11,3 (0,6)	0,56 (0,10)
C	Georgia	Coastal	Steam	2,52 (1,08)	23,6 (9,9)	10,4 (0,8)	0,51 (0,06)
D	Georgia	Piedmont	Steam	3,20 (2,85)	22,1 (9,1)	10,4 (0,5)	0,55 (0,08)
G	Georgia	Piedmont	Steam	2,56 (0,79)	24,6 (9,6)	10,1 (0,7)	0,52 (0,06)

[a]Values represent means of 20 measurements per mill; values in parentheses are one standard deviation

CCA retentions for full-cell treated lumber from the 6 different mills were virtually the same (Table 6). However, retentions were noticeably lower (~ 45 % to 55%) when treated using modified-full cell or low-weight processes. An analysis of variance indicated that there were no significant ($p<0,05$) differences in CCA retention based on either mill source or initial kiln-drying process when comparing the data based on individual treatment process. However, that analysis showed that CCA retentions from the full-cell process were significantly higher than those from the other two treatment processes. CCA retentions were 2-3x more variable for modified-full cell or low-weight treatments illustrating the risk of varying process to reduce up-takes.

Table 6: Average CCA retention measured at 12 locations per piece for 20 pieces of CCA-treated southern pine lumber obtained from 6 different Phase III mills using either direct fired or steam kilns.

Mill	Drying	Growth Location	Retention (kg/m^3)					
			Full Cell		Modified Full Cell		Low Weight	
			Mean	COV	Mean	COV	Mean	COV
A	Direct	Coastal	5,63	10	2,83	22	3,12	18
B	Direct	Coastal	6,21	6	2,70	13	3,15	9
F	Direct	Piedmont	6,13	6	2,67	11	3,20	15
Avg.	Direct		5,99	7,3	2,74	15	3,16	14
C	Steam	Coastal	5,57	12	3,01	15	3,22	20
D	Steam	Piedmont	5,63	14	2,80	16	2,86	26
G	Steam	Piedmont	5,54	20	2,78	17	3,28	16
Avg.	Steam		5,58	15	2,86	16	3,12	21

COV is coefficient of variation (Standard Deviation/Mean)

CCA penetration in lumber dried in direct fired kilns was consistently better than lumber dried using steam fired kilns, regardless of treatment process (Table 7). Total cross-sectional penetration when data from mills using the same drying system were combined was 10 % to 13% lower for wood dried using steam fired kilns. While all of these averages would have met the minimum AWPA penetration requirements, penetration was much more variable in lumber from steam fired kilns. The Standards require a minimum of 16 out of 20 samples meet the minimum penetration. The increased penetration variability associated with steam fired kilns increases the likelihood that more individual samples will fail resulting in retreatment of an entire charge.

As noted earlier, geographic source has been reported to influence treatability within the same species. Mill source had no consistent effect on CCA penetration in the current study although average penetration tended to be slightly better in material from Coastal mills (Table 8). However, penetration tended to be more variable in material from Piedmont mills. As noted with drying process, slight differences in penetration can have major effects when assessing quality control; however, it is important to note that the same treatment processes were used regardless of timber source. Treatment facilities routinely adapt process conditions to ensure proper treatment of their resource. In this case, that might include using either a higher pressure or holding pressure for a longer period. While these adaptations might reduce plant efficiency in terms of the number of charges possible in a given period of time, they would help reduce the proportion of retreatments that interfere with normal production schedules.

Table 7: Proportion of CCA penetration on cross section of southern pine lumber obtained from 6 different Phase III mills dried using either direct fired or steam kilns.

Treatment Process	Proportion of Cross Section Penetration[a]								Difference (%) Direct/Steam
	Direct Fired			Steam Fired			Avg Direct Fired	Avg Steam Fired	
	Mill A	Mill B	Mill F	Mill C	Mill D	Mill G			
Full Cell	0,97 (0,07)	0,99 (0,03)	1 (0,01)	0,89 (0,16)	0,93 (0,10)	0,89 (0,18)	0,99 (0,04)	0,90 (0,15)	10
Modified	1,00 (0,01)	0,99 (0,04)	0,98 (0,06)	0,89 (0,16)	0,89 (0,15	0,84 (0,18)	0,99 (0,04)	0,87 (0,16)	13,8
Low Wt	0,99 (0,03)	0,98 (0,05)	0,98 (0,07)	0,86 (0,19)	0,88 (0,22)	0,89 (0,16)	0,99 (0,05)	0,88 (0,19)	12,5

[a]Values represent means of 20 samples per mill/treatment process; values in parentheses represent one standard deviation. Penetration was measured at 12 location on each sample.

Table 8: Proportion of CCA penetration on cross sections of southern pine lumber obtained from 6 different Phase III mills from either Coastal or Piedmont growing regions.

Treatment Process	Proportion of Cross Section Penetration[a]								Difference (%) Coastal/ Piedmont
	Coastal Mills			Piedmont Mills			Avg Coastal	Avg Piedmont	
	Mill A	Mill B	Mill C	Mill D	Mill F	Mill G			
Full Cell	0,97 (0,07)	0,99 (0,03)	0,89 (0,16)	0,93 (0,10)	1 (0,01)	0,89 (0,18)	0,95 (0,09)	0,94 (0,10)	1,10
Modified	1 (0,01)	0,99 (0,04)	0,89 (0,16)	0,89 (0,15)	0,98 (0,06)	0,84 (0,18)	0,96 (0,07)	0,91 (0,13)	5,50
Low Wt	0,99 (0,03)	0,98 (0,05)	0,86 (0,19)	0,88 (0,22)	0,98 (0,07)	0,89 (0,16)	0,95 (0,09)	0,92 (0,15)	3,30

[a]Values represent means of 20 samples per mill/treatment process while values in parentheses represent one standard deviation. Penetration was measured at 12 locations on each sample.

Wood permeability

Longitudinal permeability of samples removed from the untreated portions of boards from each mill ranged from 0,26353 µm^2 to 1,09152 µm^2 for samples from lumber dried in a direct fired kiln compared to 0,00389 µm^2 to 0,04277 µm^2 for those from steam fired kilns (Table 9). While permeability values were extremely variable (COV's 42 % to 67 %), there was a definite trend towards increased longitudinal permeability in wood dried using direct fired kilns. Average longitudinal permeabilities in samples from steam fired kilns were all lower than the lowest value for a direct fired kiln. While there were large differences in longitudinal permeability with geographic source, there were no consistent trends.

Table 9: Longitudinal and radial permeability of samples cut from southern pine sapwood boards in Phase III.

Mill	Replicates	Kiln Type	Geographic Source	Permeability (µm^2)			
				Longitudinal		Radial	
				Mean	COV (%)	Mean	COV (%)
A	12	Direct	Coastal	1,0915	42	0,04277	51
B	18	Direct	Coastal	0,4349	45	0,01181	76
F	18	Direct	Piedmont	0,4992	50	0,00521	43
C	18	Steam	Coastal	0,2683	54	0,00563	71
D	18	Steam	Piedmont	0,2899	67	0,00514	73
G	24	Steam	Piedmont	0,2635	53	0,00389	73

Radial permeability of samples from Coastal Mills A and B were 2 to 8 times higher than those from the other mills, again suggesting that these differences in radial permeability could be related to improved treatability which in turn could be related to kiln process. However, samples from Mill F which also used a direct fired kiln had an average radial permeability similar to those for samples dried in steam heated kilns at Mills C and D. Radial permeability of lumber from Coastal Mill C was nearly 10 % higher than from Piedmont mills D, F or G. COV's for radial permeability were almost all higher than those for longitudinal permeability. It is important to note that the lumber used in these tests was not specifically selected and represented a limited population. However, the treatment results suggest that kiln type as related to the ability to limit rapid drying during the early heating phase has the potential to improve permeability and, as a result, preservative penetration.

The treatment results, along with the permeability data suggest a link between kiln control of initial temperature and relative humidity through reduced venting and treatment that merits further study (Winandy *et al.* 2001, Keefe 2001) Maintaining higher humidity in the early stages of kiln drying results in more rapid lumber heating while also slowing the early drying rate by avoiding excessive vapour pressure differentials that can lead to pit aspiration (Simpson 1991).

CONCLUSIONS

Geographic source had little effect on treatment quality within the parameters tested, while kiln type was closely related to both treatment results and permeability. These effects may be related to humidity control to minimize drying in the early stages of drying; however, further studies are needed to better define the nature of the differences. Modifying kiln processes would represent a relatively simple method for improving receptivity to preservative treatment.

ACKNOWLEDGEMENTS

This work is dedicated to our deceased friend and colleague, Donn Keefe, former Chief Inspector, American Wood Preservers Bureau. We believe he knew more about the species-to-material processing-to-treatability relationships of Southern Pine than anyone we have ever worked with.

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