PENETRATION INDICES OF HARDWOODS: A QUANTITATIVE APPROACH TO DEFINE TREATABILITY

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ABSTRACT

Fluid accessibility of various structural components of 15 hardwoods belonging to different treatability classes was studied by using water-soluble and organic solvent stains. Penetration was found to vary even among the species categorized under the same treatability class indicating large-scale variation within the existing treatability classes. A quantitative estimation of this behavior was obtained in the form of a penetration index. This approach indicates that treatability class needs a change for 5 of the 15 species studied.

Keywords: Hardwoods, flow path, penetration, creosote, wax, water-borne salts, treatability, penetration index.

INTRODUCTION

In India nearly 12 million cubic meters of industrial wood are harvested annually from the forests, while the rest of the demand is met from plantations on private land and from imports (Anon. 1987). Currently over 160 wood species, mostly hardwoods available in merchantable quantities, are used (Sagar and Ansari 1983). Many of these species being nondurable, it is necessary to impregnate them with preservatives before use.

Although wood is cellular and porous, most wood species are not easy to treat. Indian wood species have been divided into five treatability classes, *a* to *e*, according to their increasing resistance to impregnation with preservatives as determined empirically from the gross uptake and depth of penetration (Anon. 1982). This classification provides a basis for choosing species for a particular end-use, but supplies few guidelines for preservative treatment under pressure. Not only have vast differences in preservative retention and gross penetration been observed in species in the same treatability class (Kumar and Sharma 1982), but also different hardwood species with equivalent gross retention of preservatives have often been observed to perform differently (Purushotham et al. 1967). Early failure in some species has been reported (Aston and Watson 1976; Greaves 1977) and attributed to nonuniform distribution of the chemicals in various cells—especially in the fibers, a major constituent of hardwoods (Dickinson and Sorkhoh 1976).

Fluid flow within wood, which is controlled by the continuity of the wood's porous structure, is fundamental to the impregnation process. Hardwoods have a structure which, owing to the large variety of tissue types, is more complex than that of softwoods. The variation in size and distribution pattern of structural tissues is considered to be the main cause of variation in flow/penetration patterns, even within a species (Greaves 1974).

In a previous work (Chaubey et al. 1986), six easy-to-treat hardwoods were studied for the penetration of various tissues with different stains at the microstructural level. Differences in performance of the various types of wood preservatives were also found to be related to differences in penetration of various cell types. It was observed that qualitatively defined treatability based on gross absorptions and penetration sometimes overstated the expect-

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ed performance of treated wood. A penetration index (PI), computed from data on penetration of different structural components, was considered a better yardstick for defining treatability, and a method for arriving at such an index was reported (Kumar et al. 1990). The method has also been used to evaluate treatability of bamboo with different types of fluids (Kumar and Dobriyal 1992). The present paper extends the study to wood species in different treatability classes and to different types of solvent carriers; its purpose is to further quantify the entire range of treatability in terms of penetration indices.

EXPERIMENTAL PROCEDURE

Fifteen hardwood species of Indian origin were studied: aini (*Artocarpus hirsutus* Lam.), chilauni (*Schima wallichii* Korth.), dhaman (*Grewia tiliifolia* Vahl.), gurjan (*Dipterocarpus indicus* Gaertn.), hollock (*Terminalia myriocarpa* Heureck & Mull.), horse chestnut (*Aesculus indica* Colebr.), jaman (*Syzygium cumini* (Linn.) Skeels), kathal (*Artocarpus heterophyllus* Lam.), kokko (*Albizia lebbeck* Benth.), kumbi (*Careya arborea* Roxb.), lampati (*Duabanga grandiflora* Walp.), machilus (*Machilus macrantha* Nees.), maharukh (*Ailanthus excelsa* Roxb.), toon (*Toona ciliata* Roem.), and udal (*Sterculia villosa* Roxb.). These species belong to different families, and their classifications of treatability vary widely (Table 1).

Samples (35 × 15 × 15 mm, with the largest dimension along the grain) were cut from heartwood stakes previously removed from logs of the above species. All samples were free from physical or mechanical damage and from fungal and insect attack. One sample was obtained from each stake. One of three staining reagents—coal-tar creosote, an oil-soluble red dye dissolved in paraffin wax, or 5% silver nitrate (aqueous solution) was applied to a different set of 10 samples of each species. All samples were conditioned to 12% moisture content and then treated with the staining reagent under vacuum in a desiccator according to techniques reported earlier (Kumar and Dobriyal 1983).

After air-drying, the samples were cut or split at the middle, and 12- to 15-micron-thick sections were microtomed in the three principal directions. The sections were temporarily mounted in glycerol and examined under a microscope. Each section was viewed at five random locations. A four-scale numerical rating was used to quantify the degree of penetration (P) for each cell type: 3 (+++) indicating heavy penetration (more than 60% of the cells), 2 (++) indicating moderate (between 30 and 60% of the cells), 1 (+) indicating sparse (between 10 and 30% of the cells), and 0 (−) indicating less than 10% of the cells penetrated (Chaubey et al. 1986). In addition, each cell type was assigned a weight factor (W) of 3, 2, or 1, depending on its importance in flow or structural support as described earlier (Kumar et al. 1990).

The penetration index (PI) for each species and with each stain was calculated as follows:

$$PI = \sum_{i=1}^{4} W_i P_i / 27$$

The values obtained with the three stains were averaged so that an overall treatability class could be assigned for each wood species.

RESULTS AND DISCUSSION

Penetration pattern

Penetration of various cell types in the 15 different wood species studied is summarized in Table 1.

Vessels.—For species such as chilauni, kumbi, and machilus with small vessels filled with tyloses, there was hardly any penetration in the vessels or other tissues, indicating that these species are extremely impermeable. Tyloses diminished flow in dhaman and jaman despite their large vessel size. Because of deposits in many of the vessels, aini and kathal were only slightly permeable. Maharukh was an exception to this trend: despite the absence of tyloses or deposits, its vessels showed no sign of penetration. Detailed study of the perforation plates connecting the vessel segments in maharukh seems necessary, as this species has

TABLE 1. *Summary data on penetration and penetration indices for the 15 wood species studied.*

Wood spp. and old treatability class (IS:401)	Stain[1]	Degree of penetration[2] Vessels [W = 3]	Fiber [W = 3]	Rays [W = 2]	Parenchyma [W = 1]	PI	New treatability class
Aini	C	++	+	++	++	0.55	
	D	−	−	−	−	0	
	S	−	−	−	−	0	
*						0.18	d
Chilauni	C	+	−	−	−	0.11	
	D	+	−	−	−	0.11	
	S	+	−	−	−	0.11	
d						0.11	d
Dhaman	C	+	+	−	−	0.22	
	D	+	+	−	−	0.22	
	S	+	−	+	−	0.19	
d						0.21	c
Gurjan	C	++	++	++	++	0.67	
	D	++	++	+	−	0.52	
	S	++	++	++	++	0.67	
a						0.62	b
Hollock	C	+++	++	++	+++	0.81	
	D	+++	++	++	+++	0.81	
	S	+++	++	+++	+++	0.89	
a						0.84	a
Horse chestnut	C	++	+++	+	+++	0.74	
	D	++	+++	+	+++	0.74	
	S	+	+++	+	+++	0.70	
*						0.73	a
Jaman	C	+	+	−	+	0.26	
	D	+	−	−	−	0.11	
	S	+	+	−	+	0.26	
e						0.21	c
Kathal	C	+	−	−	−	0.11	
	D	+	−	−	−	0.11	
	S	+	−	+	+	0.22	
d						0.15	d
Kokko	C	+++	+++	+++	+++	1.00	
	D	+++	++	+++	+++	0.89	
	S	+	−	+	++	0.26	
a						0.72	a
Kumbi	C	−	−	−	−	0	
	D	−	−	−	−	0	
	S	−	−	−	−	0	
e						0	e
Lampati	C	+++	+++	+++	+++	1.00	
	D	+++	+++	+++	+++	1.00	
	S	+++	+++	+++	+++	1.00	
c						1.00	a

TABLE 1. *Continued.*

Wood spp. and old treatability class (IS:401)	Stain[1]	Degree of penetration[2] Vessels [W = 3]	Fiber [W = 3]	Rays [W = 2]	Parenchyma [W = 1]	PI	New treatability class
Machilus	C	–	–	–	–	0	
	D	+	–	–	–	0.11	
	S	–	–	–	+	0.04	
e						0.05	e
Maharukh	C	–	–	–	–	0	
	D	+	–	–	–	0.11	
	S	–	–	–	+	0.04	
*						0.05	e
Toon	C	++	–	–	++	0.30	
	D	++	–	–	++	0.37	
	S	++	+	++	+++	0.59	
c						0.42	b
Udal	C	+++	++	+++	+++	0.89	
	D	+++	++	+++	+++	0.89	
	S	+++	+	+++	+++	0.78	
*						0.85	a

[1] C, creosote; D, dye-wax; S, silver nitrate.
[2] +++, more than 60% of the cells penetrated; ++, between 30 and 60% of the cells penetrated; +, between 10 and 30% of the cells penetrated; –, less than 10% of the cells penetrated. W, weight factor.
* Treatability class unknown (not reported/studied). Averages for each species appear between ruled lines.

also exhibited very low gas permeability in axial flow (Jain et al. 1991).

Fibers.—Structural data on bordered pits connecting vessels to fibers in these hardwoods are lacking, making predictions on the accessibility of fibers to penetration from vessels difficult. Anatomical details about the size and distribution of vessels in the growth ring as well as the existence of tyloses and other deposits and the pitting pattern with rays in most of the species are, however, documented (Pearson and Brown 1932). Data on fiber-fiber pitting are also available for some of the species. The fibers in species having abundant pitting were well penetrated (aini, gurjan, horse chestnut, jaman, lampati). Vessels, however, seemed to be the primary flow routes; wood species in which vessels were not penetrated because of the presence of tyloses or deposits also had low penetration in fibers despite the presence of fiber-fiber pits (kumbi, machilus, maharukh). Lack of penetration of rays in these species also leads to the same conclusions, as the rays are well-connected to the vessels. In chilauni and kathal, fiber penetration was less than 5% despite partial penetration of the vessels, indicating poor vessel-fiber communication. In toon, the fibers were not penetrated except with silver nitrate in the vicinity of vessels (Kumar and Dobriyal 1983), indicating poor fiber-fiber communication. Fiber pits in toon are limited to radial walls (Pearson and Brown 1932), a configuration that probably affects penetration. Fiber penetration was also deficient in hollock despite good penetration in vessels and axial parenchyma mainly because of sparse fiber-fiber pitting (Pearson and Brown 1932).

Rays.—Lateral transport of fluids in the wood structure is accomplished mainly through the radially oriented ray cells. Rays are reported to be connected to vessels via pits and were invariably penetrated where these were void of any gummy deposits (aini, gurjan, horse chestnut, kokko, lampati, and udal). The presence of gummy deposits totally blocked (or reduced) penetration in chilauni, dhaman, jaman, kathal, and toon. Similar results have been reported previously for tropical hardwoods (Mackay 1971).

Axial parenchyma.—Axial parenchyma cells

TABLE 2. *Penetration criteria for new classification of treatability.*

Penetration pattern (visual observation)	Penetration index	Treatability class
Heartwood easily treatable (complete penetration)	≥0.66	a
Heartwood treatable but complete penetration not always obtained	≥0.33 and <0.66	b
Heartwood only partially treatable (mottled penetration)	≥0.21 and <0.33	c
Heartwood refractory to treat	≥0.10 and <0.21	d
Heartwood untreatable no penetration even from the ends	<0.10	e

in aini, gurjan, hollock, horse chestnut, jaman, kokko, lampati, toon, and udal were penetrated in proportion to the penetration of their vessels. In all these species except horse chestnut, jaman, and toon, parenchyma cells are predominantly paratracheal and well-connected with the vessels through pits (Pearson and Brown 1932). Metatracheal (jaman and toon) and terminal (horse chestnut) parenchyma cells were penetrated from the fibers. Axial parenchyma cells in chilauni, dhaman, and kathal were unpenetrated indicating lack of communication with the vessels, which were partly penetrated. Although axial parenchyma tissues have a limited role in fluid conduction, they are considered important in stress distribution (Winandy and Rowell 1984). Their penetration may, therefore, be important to retaining structural integrity by eliminating any possible decay-prone untreated zones.

Stain/solvent differences.—Penetration obtained with different stains in aqueous and nonaqueous solvents for the 15 species studied is shown in Table 1. Such information on penetration becomes highly useful in selecting preservative formulations for a particular wood species and for modifying properties of preservative formulations. Penetration in kumbi, machilus, and maharukh was scanty (even in the vessels) by any of the stains used and are thus the most refractory species studied. Organic fluids invariably provided better access than the aqueous solutions, probably because the wood being an organic substance is wetted better by organic solvents. Such differences were more evident in aini and kokko, which were relatively less penetrated by silver nitrate, indicating that these species would be difficult to treat with waterborne wood preservatives. Kathal and toon, on the other hand, had the greatest penetration with waterborne solutions. Creosote and wax also differed in penetration. Wax-dye showed up better under the microscope because it solidified in the cells and was not dislocated during sectioning, whereas creosote being a liquid sometimes got flushed out during sectioning and was not evident if the vessel walls or the parenchyma cells surrounding such vessels failed to be stained. In the latter case, additional information was obtained by incident light microscopy.

Penetration indices

Table 1 also reports the penetration indices calculated from the data on penetration. A PI of more than 0.66 indicates more-or-less uniform distribution of the chemicals in all the structural elements and corresponds to easy-to-treat class *a* (Table 2). PIs falling between 0.33 and 0.66, classified as *b*, invariably showed some deficiency in penetration of fibers or partial blocking of the flow paths (i.e., vessels); however, it is possible to overcome this problem by increasing the pressure or prolonging the pressure period (Kumar et al. 1990). Treatability class *c* is equated with mottled penetration when observed in cross-section (Anon. 1982). For this class, penetration is limited to cells contiguous to vessels and is indicated by index values between 0.21 and 0.33. Treatability classes *d* and *e* refer to refractory wood species. In the latter class, penetration is negligible even from the ends, indicating that even the vessels do not conduct flow. Index values of less than 0.10 correspond to class *e* and those between 0.10 and 0.21 correspond to class *d*.

This new approach indicates that the treatability classes of the following five species need to be changed:

Dhaman, *d* to *c*
Gurjan, *a* to *b*
Jaman, *e* to *c*
Lampati, *c* to *a*
Toon, *c* to *b*

CONCLUSIONS

1. In hardwoods, vessels virtually control the flow of fluids to other structural components, and when they are blocked with tyloses or deposits, render the wood impermeable.
2. Ease of treatability is indicated by good penetration of the fibers from the vessels.
3. The penetration pattern obtained with different types of fluids/carrier solvents gives a good estimate of the treatability of the species with preservatives incorporated into those types of fluids.
4. Penetration index not only defines the treatability in quantitative terms but also indicates the penetrability of different cell types.

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