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SWELLING CHARACTERISTICS OF CONVENTIONAL AND ORGANIC PRESERVATIVE-TREATED POROUS TROPICAL UTILITY HARDWOOD [CEIBA PENTANDRA (L.) GAERTN.]

*Charles Antwi-Boasiako** & *Kwadwo Boakye Boadu*

Department of Wood Science & Technology, Faculty of Renewable Natural Resources, Kwame Nkrumah University of Science & Technology, Kumasi-Ghana

*Address all correspondence to Charles Antwi-Boasiako E-mail: cantwiboasiako@gmail.com

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Overexploitation of endangered timbers necessitates utilization of chemically treated nondurable species. Ceiba pentandra is porous, dimensionally stable in dry service conditions, and has regular export of treated products. Swelling characteristics of treated woods are hardly studied. This work provides a scientific bridge to this gap. Influence of Maneb/Lambda mixture and Erythrophleum suaveolens bark extract on the swelling of C. pentandra was investigated by water immersion for 24 h. Directional swelling was greatest tangentially (1.4–2.5 times greater than radial swelling) and least along longitudinal directions (90–360 times less than tangential surfaces) depending on solvent type. Untreated stakes soaked in the three solvents swelled more than treated stakes in water. Tangential swelling was greater for untreated stakes in E. suaveolens (9.20 ± 0.02%) and Maneb/Lambda (9.32 ± 0.02%) than in water (8.10 ± 0.01%); the contrary occurred for longitudinal and radial swellings. Maneb/Lambda-treated stakes swelled more tangentially in water (7.36 ± 0.13%) but less at radial directions (2.89 ± 0.01%) than those treated with E. suaveolens (7.10 ± 0.00% and 3.28 ± 0.02%, respectively). Volumetric swelling was greater for untreated stakes in all solvents (12.66 ± 0.60% in water/14.74 ± 0.66% in Maneb/Lambda) than for Maneb/Lambda- and E. suaveolens-treated stakes in water (10.51 ± 0.14% and 10.62 ± 0.02% respectively). Thus, preservative-chemicals would protect nondurable timbers against biodeterioration with the added advantage of reducing moisture-absorption capacity of engineered products in service conditions.

KEY WORDS: *dimensional stability, Maneb/Lambda mixture, moisture content, organic preservative, porous medium, shrinkage, volumetric swelling*

1. INTRODUCTION

Tropical forests contain numerous wood species. However, few are used to manufacture valuable products due to lack of comprehensive information on their properties including physical characteristics (e.g., dimensional stability), which are paramount in maximizing value addition (Mantanis et al., 1994; Shukla and Kamdem, 2010). Wood cell walls comprise mainly polymers with hydroxyl and other oxygen-containing groups that attract moisture through hydrogen bonding (Rowell and Banks, 1985; Cetin and Ozmen, 2011). In engineering applications, wood moisture absorption capacity should be properly considered since failure to control it within a building envelope leads to chemical leaching, increased energy usage, building material degradation, and drying defects including case-hardening, collapse, and honeycombing (Eckelman, 1998; Wallström, 1998; Williamson, 2002; Aleksander, 2012). Wood undergoes dimensional changes when its moisture fluctuates around the fiber saturation point (FSP), which results in shrinkage and swelling (Mantanis et al., 1994; Eckelman, 1998). Wood moisture exerts its own vapor pressure determined by maximum size of the capillaries filled at any time until a stage when that within equals that in the ambient space above it or water loss from the capillaries and absorption from the ambient cease. Moisture content (mc), which now remains within, is in equilibrium with water vapor pressure outside. This equilibrium moisture content (emc) varies with wood species, relative humidity and temperature of surrounding air, mechanical stress, drying history, density, and extractive content (Desch and Dinwoodie, 1996). To minimize changes in wood mc or movement of wooden objects in service, wood is usually dried to mc close to the average emc conditions to which it will be exposed (Walker et al., 1993). If wood were an isotropic material (Faouel et al., 2012) and its moisture absorption equal in all directions, the problem associated with swelling might be less serious (Kollman and Côté, 1968). However, wood dimensional changes are characteristically anisotropic or different in all three faces. Longitudinal swelling between the FSP and oven-dry state of wood is between 0.1 and 0.2%, which is of no practical significance except in reaction or juvenile wood where these values may be significantly higher (Winandy, 1994). Generally, swelling is greatest tangentially (i.e., 5.1–10.9%) and about half as much (i.e., 2.1–6.5%) in the radial faces (Walker et al., 1993; Mantanis et al., 1994).

The amount of swelling is approximately proportional to changes in wood mc, extractive content, density (heavier woods contain more moisture and swell more than lighter types) (Williamson, 2002; Yoichi et al., 2009), and its porosity. Mantanis et al. (1995) and Eckelman (1998) confirmed that wood swelling rate in water increased considerably after extractive removal, while the maximum tangential swelling increased averagely by 5–10%. Extractives or chemical impregnation reduce pore spaces within cell walls, which otherwise could be occupied by water; moisture absorption increases on removal of extractives (Eckelman, 1998). Swelling of wood could be minimized by chemical treatment to replace the hydroxyl groups with other hydrophobic functional groups in the chemicals (Stamm, 1964; Rowell, 1991; Kumar, 1994; Haque, 1997). Opoku (2007) observed that wood treated with teak and decking oils, prior to immersion, absorbed less water than its control. When dry, *Ceiba pentandra* (L.) Gaertn. is porous but stable in service, swells and shrinks less, which makes it ideal for plywood core stock, lightweight joinery, insulation, and particle board manufacturing. However, it is not durable, especially when exposed to moisture (Duvall, 2009). Organisms which cause decay and stain thrive well in timbers with little natural resistance on exposure to water (Walker et al., 1993; Edlich et al., 2005; Desch and Dinwoodie, 1996). Nevertheless, their durability is enhanced with preservatives (Baechler, 1956; Kollman and Côté, 1968; Bolza and Keating, 1972; Beckwith, 1998; Townsend and Solo-Gabriele, 2006; Tsunoda et al., 2006). All treatment types affect certain wood properties (Davids and Thompson, 1964; Cihat et al., 2002; Waldemar et al., 2003; Yildiz et al., 2004). Information on the influence of preservative treatment on the swelling behavior of tropical hardwoods is not existent. Wood swelling characteristics are understood by studying its dimensional changes in different relative humidity and temperature regimes or in contact with water and other liquids (Mantanis et al., 1994). To optimize utilization of treated woods with an array of chemicals as outdoor structural materials, which are liable to moist conditions, this work examined the influence of organic and inorganic water-borne preservatives on the swelling properties of *C. pentandra*.

This work has been presented to include, besides the introduction, the main body (i.e., methodology, results and discussion), conclusion and recommendation, acknowledgments, references, and figures.

2. MATERIALS AND METHODS

2.1 Preparation of Water-Borne Preservative Chemicals

A pesticide, Lambda-cyhalothrin (2.5%), was standardized at 1.5% by serially diluting the stock solution (Florence and Attwood, 2006; Stoker, 2010). Maneb 80WP (15 g), a fungicide, was mixed with distilled water (1000 ml) to 1.5% (Nwoye et al., 2009). Their mixture (1:1 v/v) produced 1.5% Maneb/Lambda solution (Organic Materials Review Institute, 2006). Extract from the bark of *Erythrophleum suaveolens* (Guill. & Perr.), previously proven potent against biodegraders (Ngounou, et al. 2005; Antwi-Boasiako and Damoah, 2010), was employed as organic preservative. The bark was collected 50 cm above diameter at breast height of three trees from the Demonstration Farm of the Faculty of Renewable Natural Resources, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi in the Ashanti Province of Ghana. The flakes were washed, air-dried to 14% mc, and milled to powder (40–60 mesh sieve) with the Wiley Mill. The powder (40 g) was added to distilled water (400 ml) and heated on water bath to 75°C for 8 h, while stirring. On cooling, the solution was sieved with a 0.5 mm mesh and centrifuged (1400 × g for 45 min) to obtain the supernatant extract. Concentration of the extract (10 ml) was determined [Eq. (1)] after the content in a known mass Petri dish was heated in an oven at 105 ± 2°C (Nwoye et al., 2009):

$$C = \frac{(Wo - Wi)}{V} \times 100\% \qquad (1)$$

where C = concentration of bark extract; Wi = initial weight of Petri dish; Wo = oven-dried weight of Petri dish with bark extract; V = volume of bark extract.

Concentration of the extract was standardized at 1.5% using the dilution formula provided by Florence and Attwood (2006) and Stoker (2010). The stakes were impregnated with the two chemical solutions.

2.2 Preparation of Wood Samples for Swelling Test

Thirty stakes (152 × 76 × 5 mm, longitudinal, tangential, and radial, respectively) were prepared based on ASTM D 1037-06a 24 (2006) from defect-free, air-dried *C. pentandra* (to 12% mc). Dimensions were measured at room temperature with a jaw-type Vernier caliper (at ±0.02 accuracy). Five measurements were each made at 15 and 30 mm intervals at the same points of the opposite surfaces of the longitudinal and radial directions, respectively, and also at 1 mm interval along the two tangential surfaces. Subsequent measurements for swelling were done at these points. To reduce error, 10 replicate stakes (Rowell and Young, 1981; Mantanis et al., 1994; Meier et al., 2005; Tsunoda et al., 2006) were pressure-impregnated with 1.5% *E. suaveolens* extract (at 124°C and 120 kPa for 3 h), another set with 1.5% Maneb/Lambda, while the 10 untreated samples served as controls. The dimensions of the stakes were again determined immediately after treatment with the respective preservatives and their swellings calculated. Treated and untreated stakes were air-dried to 12% mc, conditioned at 50 ± 2% relative humidity, and 25°C for 1 h. Their thicknesses (millimeters) and lengths (centimeters) were remeasured and thereafter submerged at least 10 cm below the water level in porcelain desiccators for 24 h using the water-soak test method [ASTM D 1037-06a (24), 2006]. The discolored solvents caused by extractives from the stakes were changed for fresh samples after 8 h. Measurements from all three directions were quickly made (i.e., within 30 s) upon removal from water to prevent water loss to the atmosphere or avoid humidity uptake from the air (Meier et al., 2005). Swelling at each direction was calculated (Kollman and Côté, 1968; Mantanis et al., 1994; ASTM D 1037-06a24, 2006) [Eq. (2)]:

$$\text{swelling}\,(\%) = \frac{Wda - Wdb}{Wdb} \times 100 \qquad (2)$$

where Wda = wood dimension after immersion (i.e., wet dimension); Wdb = wood dimension before immersion (i.e., dry dimension).

Volumetric swelling for each stake was determined from values for its longitudinal, radial, and tangential faces (Rowell and Young, 1981; Mantanis et al., 1994) [Eq. (3)]:

$$\text{volumetric swelling}\,(\%) = \frac{Sl \times St \times Sr - Dl \times Dt \times Dr}{Dl \times Dt \times Dr} \qquad (3)$$

where Sl, St, and Sr = longitudinal, tangential, and radial dimensions, respectively, of stakes in swollen condition; Dl, Dt, and Dr = longitudinal, tangential, and radial dimensions, respectively, of stakes in dry condition.

2.3 Analysis of Results

The data were statistically subjected to analysis of variance (ANOVA) and Duncan's multiple range test.

3. RESULTS

3.1 Directional Swelling

Directional swelling was greatest for tangential surfaces and least along the longitudinal directions for all stakes. Tangential swelling was generally 1.4–2.5 and 90–360 times greater than radial and longitudinal swellings, respectively. However, swelling at the directions was solvent-specific (Fig. 1). Untreated stakes immersed in the three solvents swelled greater in all directions than their treated counterparts kept in water. Tangential swelling was also greater for the controls dunked in the water-borne preservatives [*E. suaveolens* (9.20 ± 0.02%) and Maneb/Lambda (9.32 ± 0.02%)] than in water (8.10 ± 0.01%). However, longitudinal and radial swellings were greater for untreated stakes submerged in water (i.e., 0.12 ± 0.03% and 5.67 ± 0.13%, respectively) than for their water-soaked treated stakes with *E. suaveolens* (i.e., 0.02 ± 0.01% and 3.28 ± 0.02%, respectively) and Maneb/Lambda (i.e., 0.01 ± 0.01% and 2.89 ± 0.01%,

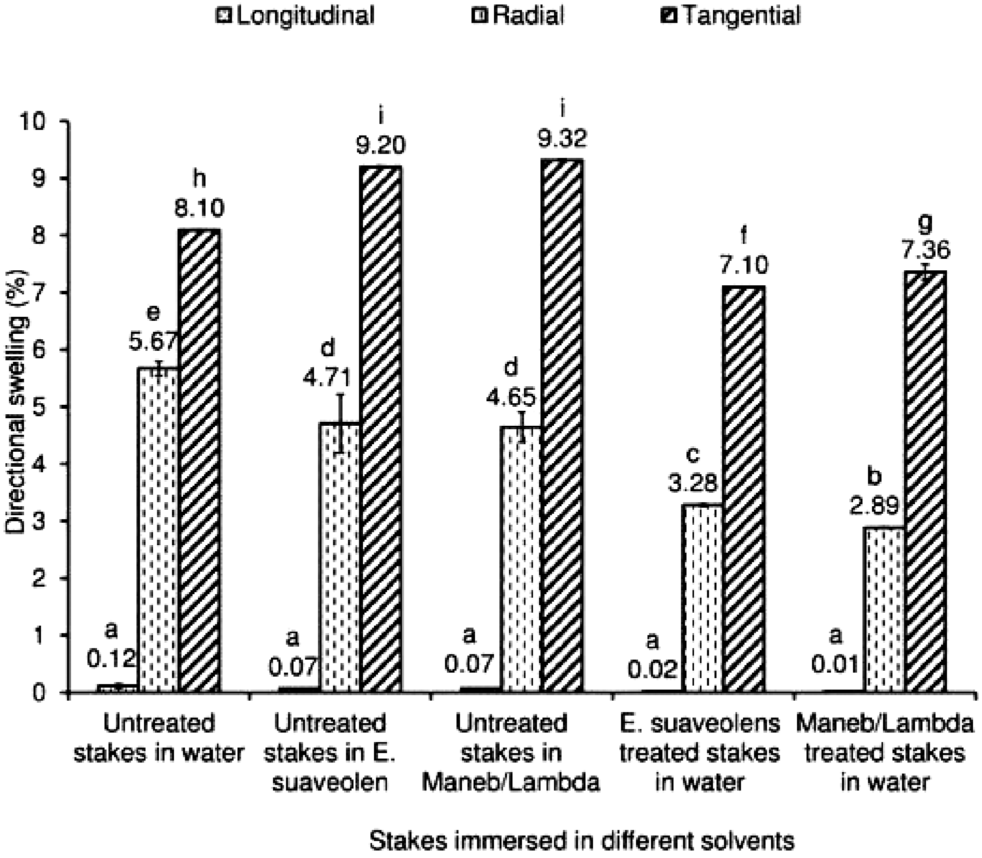

FIG. 1: Directional swelling of treated and untreated *C. pentandra* stakes in different solvents after 24 h (bars = SE; n = 10).

respectively). The differences, besides those for the longitudinal directions, were significant ($p < 0.05$). For treated stakes soaked in water, those impregnated with Maneb/Lambda swelled more along the tangential surfaces but less in radial directions (i.e., 7.36 ± 0.13% and 2.89 ± 0.01%, respectively) than those treated with *E. suaveolens* (i.e., 7.10 ± 0.00% and 3.28 ± 0.02%, respectively).

3.2 Volumetric Swelling

The swelling extent of each stake, determined from the final volumetric increase, shows that swelling was highest among all the untreated stakes immersed in the three solvents (ranging from 12.66 ± 0.60% to 14.74 ± 0.66% in water and Maneb/Lambda, respectively) than for the treated stakes immersed in water (10.51 ± 0.14% and 10.62 ± 0.02% for Maneb/Lambda and *E. suaveolens*, respectively) (Fig. 2). The differences between the volumetric swellings of the untreated stakes in the three solvents were not significant ($p < 0.05$), as well as between the treated stakes immersed in water.

4. DISCUSSION

The wood–moisture relationship is one of its important properties which needs a full understanding since shrinkage and swelling cause several structural problems in engineered products in use. Wood swells when the walls of its cell pipes absorb water, which constraints its service use due to dimensional stability glitches at different temperature and moisture regimes. Wood being anisotropic (Faouel et al., 2012) varies in structure and properties at its three directions and hygroscopic for having the ability to attract moisture from air along these surfaces. Thus, according to Meier et al. (2005), wood swelling in liquids

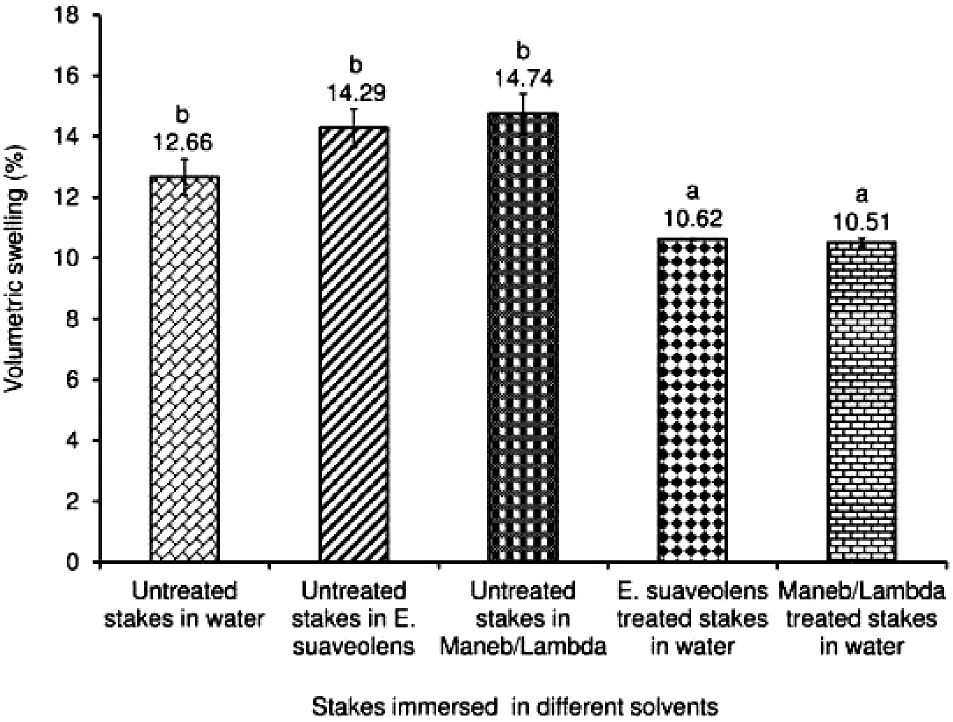

FIG. 2: Volumetric swelling of treated and untreated *C. pentandra* stakes in different solvents after 24 h (bars = SE; n = 10).

is of fundamental importance from a scientific standpoint and in the context of commercial processes involving dimensional stabilization, chemical modification, preservation, pulping, and removal of extractives. Swelling is a complex process affected by wood type and the solvent substrate. However, the influence of each is difficult to predict. Wood swelling in water has been investigated much more than its behavior in organic solvents, which is ever so important for water-borne preservatives and coating materials. For some reason, wood behavior studies in such solutions have been avoided, including the effect of binary mixtures of substances in aqueous solutions (Meier et al., 2005). Thus, the swelling profile of *C. pentandra* is a good index of its dimensional stability in binary mixtures of inorganic chemicals and in extracts from organic materials.

4.1 Swelling along Stake Directions

The greater swelling ability in all directions for the untreated *C. pentandra* stakes than their treated counterparts confirms the assertion by Gryc et al. (2008) that in overcoming the swelling effect, several woods are impregnated with appropriate hydrophobes and other chemicals, as compounds introduced into them often reduce their pores for water ingress and swelling in the various directions (Kumar, 1994; Haque, 1997; Opoku, 2007; Tarmain et al., 2012). Stability can also be improved by bulking the cell wall with chemicals to reach its elastic limit such that additional moisture does not cause swelling. The void space (lumen) could be filled with a monomer that is polymerized *in situ* to exclude moisture, reduce the moisture penetrating rate of the cell wall, and improve the elastic properties if the polymer is hard. Cell-wall polymers could be changed chemically to decrease moisture sorption through reduced hydroscopicity by modifying hydroxyl groups in the polymers to avoid bonding with water to improve the dimensional stability and elastic properties of wood (Rowell, 1995). Many reactive chemicals have been used to bond to cell-wall hydroxyl groups to produce modified wood with reduced FSP and emc, which shows that its hydroscopicity is reduced. Such treatments result in a filled structure that greatly reduces the rate of water entry and acts as a plasticizer and a finish outside and throughout the entire wood structure. From the foregoing, the implication is that preservative chemicals applied to wood (e.g. Maneb/Lambda and *E. suaveolens* extract to *C. pentandra*) offer them protection against biodeterioration and, on exposure to moisture, lower its swelling in all directions.

This study confirms earlier works by Rowell and Banks (1985), Usta and Guray (2000), and Meier et al. (2005) that variations exist in swelling associated with the three wood directions. Mantanis et al. (1994) found tangential swelling of Sitka spruce, Douglas fir, sugar maple, and quaking aspen to be greatest, followed by radial and then longitudinal swellings. Nazerian et al. (2011) reported the same for *Populus deltoids* and *Tamarix aphylla*. When dry wood gets soaking wet, it swells 8% in the direction of the annular rings (tangentially to the trunk), 4% radially, and not at all or very little lengthwise. It also shrinks when drying through the same moisture scale and percentages (i.e., 1.5–2.0 times greater tangentially than radially, while that for longitudinal surface ranges 1/1000–1/10 that of either tangential or radial direction). Thus, this negligible longitudinal measurement is often not made (Ashton, 1973). The anisotropic variation in swelling is caused by wood anatomical structure (Mantanis et al., 1994; Nazerian et al., 2011) since fibrilar orientation in the cell wall S_2 layer is a decisive factor for the process (Gryc et al., 2008). In normal wood, deflection angle of fibrils is small and causes little longitudinal swelling, as water molecules cannot penetrate between the fibrils into the valence chain. Greater swelling in the tangential and radial planes was due to the parallel orientation of the microfibrils along the axis of the cell wall (Perstorper et al., 2001; Williams et al., 2001; Gryc et al., 2008; Shukla and Kamdem, 2010). Meanwhile, variation in the degree of transverse swelling between tangential and radial planes could be due to the restraining effect of the rays on the radial plane, increased thickness of the middle lamellae on the tangential direction compared with the radial surface, and the difference in degree of lignification between the radial and tangential cell walls (Wilson and White, 1986; Usta and Guray, 2000; Dinwoodie, 2000; Antwi-Boasiako and Bimpong, 2010). The cell pipe walls in the three directions are not uniform in thicknesses, which cause uneven dimensional changes (Meier et al., 2005; www.swst.org/teach/teach2/properties2.pdf; koti.kapsi.fi/hvartial/wood/wood3.htm). All these contribute in causing water movement along the grain to be many times faster than across. Directional swelling was greatest for untreated stakes immersed in Maneb/Lambda (1:1 v/v) compared to those retained in *E. suaveolens* and water. Meier et al. (2005) confirmed that different organic substances affect different cell-wall components such that wood swells more in binary compounds (e.g. Maneb/Lambda) through synergism than in a pure compound (e.g., water or *E. suaveolens* extract). This implies that it is important to protect wood in service with a pure compound (e.g., *E. suaveolens* extract) to minimize the dimensional stabilization effects associated with swelling, particularly at the tangential surfaces.

4.2 Volumetric Swelling

Volumetric swelling derived from the three directions of wood lies between 7.5 and 18.1%, which is important when comparing swelling in different liquids (Kollman and Côté, 1968; Shukla and Kamdem, 2010). Values obtained for the treated and untreated *C. pentandra* stakes (i.e., 10.51 ± 0.14%–14.74 ± 0.66%) fall within this range. Treated stakes immersed in water had lower values (i.e., 10.62 ± 0.02% and 10.51 ± 0.14% for *E. suaveolens* and Maneb/Lambda, respectively) than for the untreated stakes kept in the three solvents (i.e., 12.66 ± 0.60%, 14.29 ± 0.62%, and 14.74 ± 0.66% for water, *E. suaveolens*, and Maneb/Lambda, respectively). Cell walls of the treated stakes were likely filled partially with components of the preservative chemicals leaving small intercellular spaces and cell cavities for less water into the cells (Stamm, 1964; Rowell, 1991; Kumar, 1994; Haque, 1997; Shukla and Kamdem, 2010; Nazerian et al., 2011; Tarmain et al., 2012). Wood swells differently in various chemicals, especially in the form of mixtures (Meier et al., 2005). Volumetric swelling was greater for untreated stakes immersed in Maneb/Lambda than in either *E. suaveolens* or water due, as previously explained, to the synergistic effect of binary mixtures of inorganic preservatives, which usually causes greater swelling than pure solutions (Mantanis et al., 1994; Meier et al., 2006). Stakes immersed in *E. suaveolens* had greater volumetric swelling than those kept in water. Although the difference was not significant ($p < 0.05$), this could be due to the extracts contained in *E. suaveolens*.

As solvent uptake also depends on the void volume or wood porosity, which is related to the intercellular spaces and cell cavities (Shukla and Kamdem, 2010), the light and highly porous nature of C. *pentandra* with basic density of 420 kg/m^3 (Kumar et al., 2009) offered it less moisture resistance and a faster swelling capacity especially in the more effectively reactive solutions (i.e., *E. suaveolens* and Maneb/Lambda) than in water. One problem of treating wood is to react it with sufficient reagent under normal conditions of temperature and pressure to change its surface and other properties. Since cellulose is a high molecular weight polysaccharide, it is probable that these solvents would improve wood treatment by swelling it to a greater extent than previously possible and by improving the desired reactions with its functional groups (Ashton, 1973). An understanding of water movement will help to minimize dimensional stability problems such as internal stresses, which cause splitting and warp as wood shrinks or swells by different amounts in these directions (Eckelman, 1998; Wallström, 1998; Williamson, 2002; www.swst.org/teach/teach2/properties2.pdf). Swelling leads to leaching of preservatives applied to wood. The minimal swelling obtained with the water-borne preservatives would mean that bulk of the chemicals would remain in the treated wood to resist it against biodeterioration, while dimensional stability of the porous structural material in service would also be improved (Meier et al., 2006). Thus, the present swelling profile of *C. pentandra* is a general indication of its dimensional stability indices in different (i.e., organic and inorganic) solutions.

5. CONCLUSION

Being anisotropic, *C. pentandra* swelled the greatest in its tangential directions and the least longitudinally. Greater swelling occurred in all three wood directions for untreated stakes immersed in the three solvents than for treated stakes that were kept in water. Preservative chemicals introduced into the treated stakes reduced their pores for water uptake and reduced directional swelling. Volumetric swelling of untreated *C. pentandra* was greater in Maneb/Lambda mixture (i.e., the binary compound) than in *E. suaveolens* and water (i.e., the pure solutions). Impregnation with water-borne preservative (i.e., Maneb/Lambda and *E. suaveolens*) reduced its directional and volumetric swellings in water. This implies that preservatives (especially the organic types) would protect nondurable timbers with the added advantage of reducing swelling or improving the dimensional stability of their treated products in service where they are usually exposed to wet conditions.

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