SWELLING PROPERTIES OF HARDWOODS AS AFFECTED BY THEIR EXTRANEOUS SUBSTANCES, WOOD DENSITY, AND INTERLOCKED GRAIN

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ABSTRACT

Samples of nine tropical hardwoods from Peru and sugar maple wood from Quebec were selected to perform moisture sorption tests associated with swelling tests using a multiple step procedure at 25°C. Cold-water and hot-water extractives, sequential cyclohexane, acetone, and methanol extracts, ash content, wood density, and interlocked grain also were evaluated on matched samples. Swelling properties were highly variable within and among wood species. The wood density corrected for the extraneous substances was the most significant variable positively affecting the transverse and volumetric swelling of tropical hardwoods. Sequential extraction with organic solvents was the most suitable method for evaluating the effect of extractives on swelling properties of tropical hardwoods. The extractives soluble in cyclohexane were the more accessible, but they virtually did not contribute to wood swelling. The substances dissolved in acetone appeared to be located within cell walls. After wood density, these compounds were the most significant variable negatively affecting the radial swelling. The substances dissolved in methanol were located within cell walls. After wood density, this extracted fraction was the most significant variable negatively affecting the tangential swelling. The acetone and methanol extracted fractions positively affected the dimensional stability of tropical hardwoods. Finally, the effect of the interlocked grain on swelling was only indirect given that this grain pattern reduces the equilibrium moisture content.

Keywords: Ash content, density, extractives, interlocked grain, swelling, tropical woods.

INTRODUCTION AND BACKGROUND

Variation in relative humidity (RH) causes wood to change in dimensions when its moisture content is below the fiber saturation point (FSP). Swelling occurs when wood gains water vapor, while shrinkage takes place when it loses moisture. For a given density, tropical woods show a lower degree of shrinkage than temperate woods (Wangaard 1951). Stamm and Loughborough (1942) reported that woods containing great amounts of extractives exhibit less shrinkage.

Previous research has indicated that shrinkage can increase after cold- or hot-water extraction (Nearn 1955). Such increases were greater for the wood of species such as redwood (*Sequoia sempervirens*) and mahogany (*Swietenia macrophylla*), which contain high extractives contents. Nearn (1955) noted that the ratio of shrinkage to moisture content (MC) for extracted woods was relatively constant and changed only as MC approached saturation. As a result, the lower maximum shrinkage observed in unextracted woods was attributed to a reduction in the FSP produced by the extractives. Similar results have been also found for redwood (Hart 1984) and for southern pines (Choong 1969). However, other researchers have suggested that wood extractives also affect the slope of the shrinkage-MC curve, but they did not demonstrate it experimentally (Torelli and Cufar 1979; Chafe 1987).

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Taylor (1974) and Kryla (1980) have indicated that extractions lead to an increase in the green volume of wood, which also increases the number of sorption sites in the cell walls. The change in volume was principally due to an increase in the tangential dimension at the saturated state. This increase would be compensated to some degree by a commensurate decrease in the radial dimension. However, other researchers have reported that the removal of extractives increases shrinkage in the two principal directions of wood (Choong and Achmadi 1991; Adamopoulus 2002).

Other experimental results go against those cited earlier. Wood swelling of black walnut (*Juglans nigra*) decreased after hot-water extraction (Cooper 1974) while that of spruce wood was not affected by an alcohol-benzene extraction (Krutul 1983).

Most of the studies mentioned earlier were made using extracted samples. Extraction treatments are usually conducted using various combinations of solvents, temperature, and exposure times. Mantanis et al. (1994) have confirmed that solvents used for removing extractives are themselves disruptive to the cell walls. Substantial quantities of sugars were removed even with a mild procedure (80% ethanol for two hours). These sugars are derived primarily from hemicelluloses in the cell walls, which implies that the whole internal structure of the cell walls was probably disrupted (Mantanis et al. 1994). It follows that little information on the different functions of wood extraneous substances *in situ* can be obtained from extracted samples. Another approach considering the characterization of wood extractives from material matched to swelling unextracted specimens should be considered. As suggested by Shupe et al. (1996), more detailed studies involving several species are required, while focusing on the location and distribution of these substances within wood. This would contribute to a better understanding of the effect of these substances on swelling and other wood properties.

A number of tropical tree species exhibit interlocked grain patterns in their wood. For example, Aróstegui (1982) tested 60 Peruvian tropical hardwoods and found that 33 had this type of grain. From 258 tropical hardwoods studied by Kribs (1950) about 75 percent were prone to interlocked grain. The influence of the interlocked grain on wood properties has long been recognized, but data are not available on the effect of interlocked grain on swelling properties of wood.

The main objectives of this study were to evaluate the effects of extraneous substances, wood density, and interlocked grain on the swelling properties of nine tropical hardwoods from Amazonian forests and sugar maple from eastern North America. Changes in dimensions were measured on unextracted samples under five moisture conditions, which were obtained during the first full sorption cycle at 25°C. Matched material was used for interlocked grain measurements and chemical analyses. A series of extraction procedures were used to ascertain the location and distribution of extractives within wood.

MATERIALS AND METHODS

This paper is a part of an extensive study concerning the effects of extraneous substances, wood density, and interlocked grain on physical and mechanical properties of tropical hardwoods. The experiment reported here consisted of moisture sorption tests associated with swelling measurements on unextracted wood samples. Matched material was used to determine the interlocked grain and the proportion of extraneous substances. Results of the interlocked grain and of the individual chemical analyses obtained from a same board were assigned to each one of the physico-mechanical specimens prepared from the same board. Chemical analyses included cold-water (CW) and hot-water (HW) extractions, sequential extractions with cyclohexane (CYC), acetone (ACE) and methanol (MET), as well as determination of ash content (ASH). According to Morgan and Orsler (1969), the first solvent must remove cell cavity material and the latter two, mainly cell-wall constituents. Detailed descriptions of the experiments are given in Hernández (2007a).

The experiments were carried out with nine Peruvian tropical hardwoods: caoba or mahogany (*Swietenia* sp.), cedro (*Cedrela* sp.), ishpingo negro (*Amburana cearensis* A.C. Smith), pumaquiro (*Aspidosperma macrocarpon* Mart.), copaiba (*Copaifera* sp.), palisangre negro (*Pterocarpus* sp.), estoraque (*Myroxylon* sp.), tahuarí (*Tabebuia serratifolia* Nichols), and palosangre (*Brosimum* sp.). Sugar maple (*Acer saccharum* Marsh.) was also included to represent a temperate hardwood having low amounts of extraneous substances.

Ten flatsawn boards were selected per species and stored at 20°C and 60% RH until EMC was reached. After conditioning, the boards were cut according to a pattern that yielded at least five parallel samples and three tangential samples. These two types of matched samples were used to determine the EMC, the parallel-to-grain and perpendicular-to-grain tangential compression strength, swelling, and oven-dry density. Five moisture sorption conditions were studied with the parallel samples. Three of these were repeated with the tangential samples. The longitudinal matching yielded eight comparable groups of 100 samples each, with every species represented by ten replicate samples. The test material was all heartwood, except for sugar maple, which was sapwood.

Sample dimensions were measured in all principal directions with a micrometer to the nearest 0.01 mm. These measurements were made on wood in the oven-dry state and as soon as each point of sorption was completed. The test results were used to calculate the percent swelling in the tangential (α_{TH}), radial (α_{RH}), and longitudinal (α_{LH}) dimensions of the wood. Volumetric swelling was estimated as the sum of these three directional measurements ($\alpha_{TH} + \alpha_{RH} + \alpha_{LH} + \alpha_{TH}\,\alpha_{RH}$). Swelling was obtained for five EMCs for the parallel samples and three EMCs for the tangential samples.

Exploratory analysis

Multiple regression models were developed for percent swelling properties after first identifying sources of collinearity in the data sets. As one precautionary measure, a new wood density corrected for the extraneous substances (D_{oc}) was used instead of the oven-dry wood density (D_o), and was defined as follows:

$$D_{oc} = \frac{M_{oc}}{V_o} = \frac{M_o}{V_o}(1 - e) = D_o(1 - e) \qquad (\mathrm{t\ m^{-3}}) \tag{1}$$

where M_{oc} is the oven-dry mass without extraneous substances, V_o is the oven-dry volume, M_o is the overall oven-dry mass, and e is ash content (ASH) plus extractives soluble in organic solvents (TOT) (i.e., ASH + TOT). Five different multiple regression models were applied using a stepwise technique, as described in Hernández (2006a). Four common independent variables were included in each regression: corrected oven-dry density (D_{oc}), ash content (ASH), the maximum angular deviation of the interlocked grain (IG), and EMC. The other independent variables were:

- model 1: substances soluble in cold water (CW).
- model 2: extractives soluble in cold water (CW), and substances soluble in hot water minus those soluble in cold water (HW-CW).
- model 3: substances soluble in hot water (HW).
- model 4: extractives soluble in a sequence of cyclohexane (CYC), acetone (ACE), and methanol (MET).
- model 5: extractives soluble in the organic solvents when taken together (TOT).

RESULTS AND DISCUSSION

The means and coefficients of variation (CV) of swelling properties for all woods and moisture sorption conditions are shown in Tables 1 to 3. Means were calculated from ten replicate samples. For a given RH, the EMCs varied among species, due to the presence of variable amounts of extractives in the wood. Detailed discussion about hygroscopicity is given elsewhere (Hernández 2006a). For this reason, direct comparisons between percent swelling values

TABLE 1. *Percent tangential swelling (α_{TH}) for all woods as a function of sorption conditions at 25°C. Means (percent) and coefficients of variation (percentages in italics).*

	First adsorption					Second desorption		
	33% RH	76% RH		100% RH		58% RH		33% RH
Wood species	PS[1] a33P[2]	PS[1] a76P[2]	TS[1] a76T[2]	PS[1] a100P[2]	TS[1] a100T[2]	PS[1] d58P[2]	TS[1] d58T[2]	PS[1] d33P[2]
Caoba	1.05	2.79	2.83	6.68	6.60	3.76	3.72	2.83
	6.0	*9.5*	*7.1*	*17.4*	*17.5*	*23.1*	*23.3*	*30.4*
Cedro	1.31	3.49	3.38	7.37	7.16	3.75	3.59	2.45
	10.0	*10.9*	*11.4*	*12.9*	*13.2*	*12.6*	*12.8*	*12.1*
Ishpingo negro	0.72	2.42	2.55	5.05	5.17	2.88	3.23	2.21
	7.5	*8.6*	*6.5*	*5.6*	*4.9*	*8.4*	*6.9*	*9.1*
Pumaquiro	1.08	3.65	3.61	7.42	7.38	3.89	3.84	2.39
	2.3	*4.5*	*4.0*	*4.1*	*3.1*	*4.2*	*3.0*	*2.1*
Sugar maple	1.18	4.08	4.05	10.90	10.98	4.31	4.13	2.56
	2.9	*4.6*	*2.8*	*6.3*	*4.8*	*10.3*	*7.4*	*12.3*
Copaiba	1.20	3.25	3.23	6.63	6.52	3.77	3.71	2.38
	9.9	*10.3*	*9.8*	*16.3*	*16.1*	*9.2*	*11.3*	*10.7*
Palisangre negro	1.14	3.32	3.29	6.26	6.21	3.58	3.47	2.26
	7.2	*5.8*	*4.7*	*7.4*	*8.1*	*4.0*	*4.1*	*5.9*
Estoraque	1.33	4.07	4.13	7.88	7.81	4.43	4.45	2.89
	5.9	*4.2*	*4.0*	*5.4*	*4.5*	*3.6*	*3.0*	*3.1*
Tahuarí	1.62	5.14	5.02	10.77	10.28	5.18	5.01	3.12
	4.3	*2.1*	*2.0*	*7.0*	*5.9*	*3.3*	*2.8*	*4.7*
Palosangre	0.93	3.10	3.30	5.91	6.13	3.44	3.46	2.09
	13.8	*10.7*	*4.7*	*12.1*	*9.3*	*8.1*	*4.2*	*5.0*

[1] PS: Parallel sample; TS: tangential sample.

[2] Notation used in Tables 4 to 7.

are not possible except for the maximum swelling of the wood (from the oven-dry condition to the saturated state). In this case, tangential swelling ranged from 5.1% for ishpingo negro to 10.9% for sugar maple (Table 1), radial swelling ranged from 2.1% for ishpingo negro to 6.5% for tahuarí (Table 2), and volumetric swelling ranged from 7.5% for ishpingo negro to 18.1% for tahuarí (Table 3). These data confirm the wide variation in swelling properties previously observed in tropical hardwood species.

Two types of matched specimens were used for the parallel and tangential compression tests (not shown). A comparison between such types of samples showed similar swelling values for the three common moisture sorption conditions that were studied (Tables 1 to 3). Tangential specimens that were at least 60 mm in length came from large trees and exhibited growth rings with negligible curvature, which likely contributed to these results. On the other hand, wood species also played an important role in the precision of the measurements. Greatest variability in volumetric swelling properties was associated with copaiba and palosangre woods (Table 3). These species were among those having the highest extractives contents (Hernández 2006a). In contrast, species as sugar maple, tahuarí, and pumaquiro, which contain lower amounts of wood extractives, were among those exhibiting the least variation in swelling properties.

Tangential swelling of caoba was highly variable, even though the extractives content of this species was not very high (Table 1). However, anatomical analysis showed that caoba wood presented two groups of samples having different structure. Five samples presented storied rays, which were three to four cells wide, and had a mean oven-dry density of 0.49 t m^{-3}. Five other samples exhibited unstoried but larger and more abundant rays and, as a result, had a mean oven-dry density of 0.44 t m^{-3} The presence of these two populations significantly affected the

TABLE 2. *Percent radial swelling (α_{RH}) for all woods as a function of sorption conditions at 25°C. Means (percent) and coefficients of variation (percentages in italics).*

	First adsorption					Second desorption		
	33% RH	76% RH		100% RH		58% RH		33% RH
	PS[1]	PS[1]	TS[1]	PS[1]	TS[1]	PS[1]	TS[1]	PS[1]
Wood species	a33P	a76P	a76T	a100P	a100T	d58P	d58T	d33P
Caoba	0.95	2.16	2.18	3.74	3.78	2.18	2.28	1.36
	5.1	*7.5*	*6.7*	*7.2*	*6.5*	*7.2*	*7.0*	*9.6*
Cedro	0.99	2.44	2.33	4.60	4.54	2.58	2.56	1.64
	2.1	*3.4*	*4.9*	*4.6*	*6.0*	*5.2*	*7.5*	*7.2*
Ishpingo negro	0.53	1.36	1.48	2.13	2.32	1.23	1.44	0.71
	5.0	*4.8*	*3.9*	*8.0*	*4.9*	*7.4*	*6.3*	*8.6*
Pumaquiro	0.81	2.41	2.31	4.30	4.19	2.50	2.44	1.47
	5.4	*5.5*	*5.4*	*6.7*	*8.0*	*8.2*	*5.1*	*6.4*
Sugar maple	0.90	2.60	2.64	5.59	5.67	2.78	2.72	1.64
	5.2	*5.6*	*6.6*	*6.2*	*8.6*	*5.0*	*6.8*	*7.6*
Copaiba	1.00	2.32	2.45	3.76	3.92	2.49	2.52	1.56
	9.0	*10.6*	*13.1*	*15.8*	*16.0*	*16.5*	*14.6*	*14.8*
Palisangre negro	0.99	2.59	2.59	4.23	4.21	2.61	2.60	1.53
	7.6	*8.8*	*8.3*	*13.0*	*12.7*	*11.3*	*11.7*	*12.7*
Estoraque	1.10	2.99	3.06	5.05	5.11	2.96	3.07	1.83
	6.6	*8.6*	*8.9*	*8.5*	*9.8*	*9.3*	*9.5*	*9.6*
Tahuarí	1.23	3.46	3.62	6.46	6.64	3.52	3.59	1.92
	3.3	*3.4*	*4.0*	*6.7*	*8.3*	*4.4*	*5.6*	*7.0*
Palosangre	0.74	2.10	2.33	3.21	3.56	1.93	2.18	1.07
	16.2	*17.9*	*8.7*	*27.5*	*21.0*	*24.8*	*13.3*	*27.3*

[1] PS: Parallel sample; TS: tangential sample.

means and variances of the tangential swelling. Redistribution of samples of this wood into two groups gave more precise means, even though the number of replications was reduced.

Swelling in both principal transverse directions was evaluated with similar precision (Tables 1 and 2). However, tangential swelling was slightly best evaluated on the tangential samples, given their larger dimension in this direction.

Exploratory analysis

The results of the exploratory analysis, in terms of coefficients of determination (R^2) and CV for the five models studied, are summarized in Table 4. The CV is useful for evaluating a regression for predictive purposes; a value lower than 15% is normally acceptable. All models used to explain the percent swelling variation were statistically significant at the 0.01 probability level. It was previously reported that EMC was very sensitive to the different models of regression (Hernández 2007a). The swelling properties studied here are less sensitive than EMC to the different models but show the same trends. Model 4, which involves the substances soluble in organic solvents taken separately, best explained the swelling variation of tropical hardwoods under study. Model 5, which takes the same extractives together, gave generally similar results. Therefore, only model 4 will be considered in the following discussion. It is clear that any studies for tropical hardwoods based on extractions using either cold or hot water as solvents would not give such good results. The swelling properties that resulted were clearly affected by the presence of organic solvent-soluble extractives in these woods.

Parameters of swelling

Differential swelling.—There is a close relationship between MC of wood and its swelling at equilibrium. As already noted, variable EMCs were obtained at a given RH for the different

TABLE 3. *Percent volumetric swelling (α_{VH}) for all woods as a function of sorption conditions at 25°C. Means (percent) and coefficients of variation (percentages in italics).*

	First adsorption					Second desorption		
	33% RH	76% RH		100% RH		58% RH		33% RH
Wood species	PS[1] a33P	PS[1] a76P	TS[1] a76T	PS[1] a100P	TS[1] a100T	PS[1] d58P	TS[1] d58T	PS[1] d33P
Caoba	2.14	5.18	5.27	10.87	10.96	6.20	6.35	4.36
	3.0	*3.0*	*2.3*	*9.4*	*9.4*	*12.4*	*12.5*	*17.7*
Cedro	2.45	6.20	5.99	12.58	12.41	6.63	6.60	4.31
	5.9	*7.6*	*8.3*	*9.5*	*10.2*	*9.5*	*9.7*	*9.7*
Ishpingo negro	1.36	3.97	4.26	7.54	8.00	4.30	4.98	3.02
	5.3	*4.1*	*3.8*	*3.1*	*4.1*	*5.0*	*7.0*	*6.9*
Pumaquiro	2.01	6.30	6.18	12.24	12.21	6.60	6.60	3.99
	3.4	*3.1*	*3.1*	*4.6*	*4.4*	*3.1*	*2.5*	*2.7*
Sugar maple	2.24	7.01	7.09	17.40	17.78	7.43	7.40	4.43
	1.6	*2.8*	*2.0*	*4.5*	*3.7*	*6.3*	*5.1*	*8.0*
Copaiba	2.37	5.81	5.96	10.86	11.00	6.49	6.52	4.09
	8.3	*10.1*	*10.6*	*15.6*	*16.2*	*11.9*	*12.3*	*11.7*
Palisangre negro	2.26	6.13	6.12	10.94	10.91	6.39	6.32	3.90
	7.2	*6.8*	*6.1*	*9.5*	*9.6*	*6.2*	*6.5*	*4.5*
Estoraque	2.55	7.34	7.51	13.55	13.67	7.69	7.89	4.9
	5.4	*5.4*	*5.6*	*6.1*	*5.9*	*5.1*	*4.0*	*5.1*
Tahuarí	2.98	8.93	9.05	18.14	17.93	9.04	9.06	5.23
	3.5	*2.4*	*2.6*	*7.0*	*6.6*	*3.1*	*2.6*	*4.5*
Palosangre	1.79	5.43	5.94	9.56	10.22	5.59	5.92	3.27
	13.4	*13.1*	*6.1*	*16.9*	*12.6*	*13.3*	*7.3*	*11.4*

[1] PS: Parallel sample; TS: tangential sample.

hardwoods. To take the EMC variation into account, analysis of changes in dimensions within the hygroscopic range was not made on the percent swelling parameter (α_{UH}) but rather on the differential swelling ratio or hygroexpansion ratio (g_{UH}). This ratio was defined as follows:

$$g_{UH} = \frac{\alpha_{UH}}{EMC} \qquad (2)$$

A dimensional stable wood is one that shows small changes in size due to changes in moisture. Thus, a given wood can have a high total shrinkage (from green to oven-dry conditions), and yet the dimensional change between two hygrothermal conditions may be relatively small and therefore exhibit high dimensional stability. The swelling ratio was hence calculated for all moisture conditions. A similar index has been used by several authors for evaluating hygroexpansion properties of wood (Noack el al. 1973; Skaar 1988; USDA 1999). For the groups equilibrated in adsorption over distilled water, g_U was calculated with EMC (FSP) estimated by the volumetric swelling intersection point method (Hernández 2007b). The regression equations for the g_{UH} ratios were obtained by stepwise techniques and are given in Tables 5 to 7. They include only the statistically significant variables, tested at the 0.10 probability level. To evaluate the relative importance of each independent variable on g_{UH} variation, the regression coefficients were standardized by calculating the beta coefficients. These coefficients were calculated for each individual regression, and therefore they are not comparable from one moisture sorption condition to another. On the other hand, the order of importance of each variable was verified by systematic elimination of the more influential points of measurement, which were chosen from Cook's distances, as proposed by Draper and Smith (1981).

The retained models explained from 26% to 87% of the total variation in g_{TH}, from 81% to

TABLE 4. *Coefficients of determination (R^2) and variation (CV) of the five regression models that explained variation in percent swelling for woods under study.*

Moisture sorption condition[1]	Regression model 1 R^2 (%)	1 CV (%)	2 R^2 (%)	2 CV (%)	3 R^2 (%)	3 CV (%)	4 R^2 (%)	4 CV (%)	5 R^2 (%)	5 CV (%)	N
Percent tangential swelling α_{TH}											
a33P	80.0	9.6	80.0	9.6	79.7	9.7	81.9	9.1	80.7	9.5	100
d33P	26.6	15.5	22.1	15.9	25.4	15.6	28.0	15.2	27.4	15.3	100
d58P	60.5	11.5	62.8	11.3	62.3	11.3	63.3	11.1	63.9	11.1	100
d58T	46.3	12.0	45.0	12.1	46.3	12.0	48.9	11.7	48.7	11.7	100
a76P	81.2	9.6	81.8	9.5	80.6	9.8	83.9	8.9	81.6	9.5	100
a76T	83.0	8.4	83.0	8.4	82.3	8.5	86.0	7.5	83.3	8.3	100
a100P	70.1	14.8	73.4	14.1	72.7	14.2	75.8	13.4	75.9	13.3	100
a100T	70.3	14.1	74.1	13.2	73.3	13.4	77.3	12.4	76.7	12.5	100
Percent radial swelling α_{RH}											
a33P	91.5	6.3	92.2	6.0	91.1	6.5	91.7	6.2	91.5	6.3	100
d33P	81.7	11.1	81.7	11.1	81.5	11.2	87.9	9.2	87.0	9.4	100
d58P	87.2	9.3	87.2	9.3	86.6	9.6	89.4	8.5	89.2	8.6	100
d58T	83.3	9.6	83.3	9.6	83.0	9.6	85.9	8.8	85.5	8.9	100
a76P	90.2	7.4	90.2	7.4	89.9	7.5	91.2	7.1	90.4	7.3	100
a76T	89.6	7.5	89.6	7.5	88.9	7.6	90.3	7.2	89.7	7.4	100
a100P	70.5	16.2	84.0	12.0	78.6	13.8	85.2	11.5	85.2	11.5	100
a100T	68.5	16.1	81.7	12.3	76.4	13.9	82.6	12.0	81.5	12.2	100
Percent volumetric swelling α_{VH}											
a33P	88.3	6.9	88.3	6.9	87.8	7.0	90.3	6.3	88.9	6.7	100
d33P	63.5	10.8	63.5	10.8	63.2	11.0	68.9	10.1	68.7	10.1	100
d58P	81.6	8.6	81.6	8.6	80.9	8.7	84.8	7.8	83.9	8.0	100
d58T	70.2	9.6	68.4	9.9	70.2	9.6	74.6	8.9	74.5	8.9	100
a76P	88.5	7.4	88.5	7.4	88.1	7.5	90.3	6.8	89.2	7.1	100
a76T	89.2	6.8	89.2	6.8	88.8	6.9	91.4	6.0	89.4	6.7	100
a100P	73.8	14.1	80.3	12.3	78.4	12.8	83.2	11.4	82.8	11.4	100
a100T	73.2	13.6	80.5	11.7	78.0	12.3	83.5	10.8	82.6	11.0	100

[1] Refer to Table 1 for a description of the various moisture conditions.

90% of the total variation in g_{RH}, and from 60% to 92% of the total variation in g_{VH}. The coefficients of variation (from 5% to 15%) suggest that all equations may be used for predictive purposes. The analyses of differential swelling gave better regressions than those obtained for the corresponding percent swelling parameter (Table 4). Contrary to results of EMC variation (Hernández 2006a), copaiba wood was included in calculations because its swelling behavior did not differ from that of the other species. This confirms the hydrophilic character of the acetone solvent-soluble extractives in this wood, independently of their location and distribution within the cell walls (Hernández 2006a).

Results also show that correlations were less precise in desorption than in adsorption conditions (Tables 5 to 7). This was due to the fact that the residual swelling in the dry state (Goulet and Fortin 1975) was not taken into account when calculating the g_{UH} ratio in the desorption state. Therefore, regression equations describing swelling under adsorption conditions must be considered as the more appropriate ones.

In tangential swelling (Table 5), the low coefficient of determination ($R^2 = 26\%$) in desorption above 33% RH was likely attributed to the caoba specimens having unstoried structure. When these specimens were excluded, R^2 increased to 53%. In radial swelling (Table 6), the

TABLE 5. *Regression equations of the differential tangential swelling at 25°C as a function of the corrected oven-dry density (D_{oc}), interlocked grain (IG), ash content (ASH), as well as the extractives obtained successively in cyclohexane (CYC), acetone (ACE), and methanol (MET).*[1]

Moisture sorption condition[2]	Equations	R^2 (%)	CV (%)
a33P	$g_{TH} = 0.129 + 0.21\ D_{oc} - 0.0046\ MET$ (0.80) (−0.26)	76.1	8.2
d33P	$g_{TH} = 0.275 + 0.16\ D_{oc} + 0.011\ CYC - 0.0067\ MET$ (0.40) (0.25) (−0.24)	25.8	14.9
d58P	$g_{TH} = 0.226 + 0.25\ D_{oc} - 0.0076\ MET$ (0.67) (−0.29)	58.4	10.6
d58T	$g_{TH} = 0.182 + 0.30\ D_{oc} - 0.0067\ MET$ (0.76) (−0.26)	67.0	9.8
a76P	$g_{TH} = 0.127 + 0.33\ D_{oc} - 0.0076\ MET$ (0.84) (−0.27)	83.1	8.3
a76T	$g_{TH} = 0.122 + 0.33\ D_{oc} - 0.0091\ MET + 0.0015\ ACE + 0.0008\ IG$ (0.87) (−0.35) (0.13) (0.09)	87.1	7.0
a100P	$g_{T} = 0.134 + 0.41\ D_{oc} - 0.0090\ MET$ (0.85) (−0.27)	84.9	8.2
a100T	$g_{T} = 0.149 + 0.38\ D_{oc} - 0.0079\ MET - 0.0018\ ASH$ (0.82) (−0.24) (−0.08)	87.1	7.6

[1] The terms in parentheses are the beta coefficients of the regression.
[2] Refer to Table 1 for a description of the various moisture sorption conditions.

correlations are better than for tangential swelling, except at the saturated state. In this case, the estimation of FSP by the volumetric swelling intersection point method would not be appropriate since use of radial swelling instead of volumetric swelling normally led to lower FSPs

TABLE 6. *Regression equations of the differential radial swelling at 25°C as a function of the corrected oven-dry density (D_{oc}), interlocked grain (IG), ash content (ASH), as well as the extractives obtained successively in cyclohexane (CYC), acetone (ACE), and methanol (MET).*[1]

Moisture sorption condition[2]	Equations	R^2 (%)	CV (%)
a33P	$g_{RH} = 0.073 + 0.17\ D_{oc} - 0.0015\ ACE + 0.022\ ASH + 0.00042\ IG$ (0.92) (−0.27) (0.24) (0.09)	85.1	6.0
d33P	$g_{RH} = 0.134 + 0.17\ D_{oc} - 0.045\ ACE - 0.0051\ CYC$ (0.55) (−0.49) (−0.14)	80.6	10.2
d58P	$g_{RH} = 0.105 + 0.22\ D_{oc} - 0.0045\ ACE$ (0.69) (−0.47)	85.8	8.6
d58T	$g_{RH} = 0.072 + 0.27\ D_{oc} - 0.0027\ ACE + 0.021\ ASH - 0.0028\ MET$ (0.91) (−0.27) (0.16) (−0.15)	87.7	6.7
a76P	$g_{RH} = 0.051 + 0.25\ D_{oc} - 0.0025\ ACE + 0.015\ ASH + 0.00058\ IG$ (0.87) (−0.30) (0.11) (0.08)	88.8	7.2
a76T	$g_{RH} = 0.035 + 0.28\ D_{oc} - 0.0015\ ACE + 0.0027\ CYC + 0.010\ ASH$ (0.94) (−0.17) (0.08) (0.07)	90.2	6.8
a100P	$g_{R} = 0.040 + 0.29\ D_{oc} - 0.0032\ ACE$ (0.80) (−0.30)	84.4	11.0
a100T	$g_{R} = 0.029 + 0.30\ D_{oc} - 0.0027\ ACE$ (0.82) (−0.25)	83.0	11.6

[1] The terms in parentheses are the beta coefficients of the regression.
[2] Refer to Table 1 for a description of the various moisture sorption conditions.

TABLE 7. *Regression equations of the differential volumetric swelling in the radial direction at 25°C as a function of the corrected oven-dry density (D_{oc}), interlocked grain (IG), ash content (ASH), as well as the extractives obtained successively in cyclohexane (CYC), acetone (ACE), and methanol (MET).*[1]

Moisture sorption condition[2]	Equations	R^2 (%)	CV (%)
a33P	$g_{VH} = 0.209 + 0.40\ D_{oc} - 0.0060\ MET + 0.040\ ASH - 0.0014\ ACE + 0.0011\ IG$ (0.92) (−0.20) (0.20) (−0.11) (0.10)	85.1	5.7
d33P	$g_{VH} = 0.415 + 0.37\ D_{oc} - 0.0143\ MET - 0.0034\ ACE + 0.049\ ASH$ (0.63) (−0.35) (−0.20) (0.18)	60.4	9.7
d58P	$g_{VH} = 0.352 + 0.49\ D_{oc} - 0.0107\ MET - 0.0036\ ACE$ (0.75) (−0.23) (−0.19)	82.0	7.2
d58T	$g_{VH} = 0.308 + 0.56\ D_{oc} - 0.0048\ ACE - 0.0084\ MET$ (0.84) (−0.21) (−0.19)	86.0	6.2
a76P	$g_{VH} = 0.208 + 0.59\ D_{oc} - 0.0091\ MET - 0.0015\ ACE$ (0.87) (−0.19) (−0.08)	90.1	6.2
a76T	$g_{VH} = 0.180 + 0.63\ D_{oc} - 0.0095\ MET + 0.0056\ CYC$ (0.93) (−0.20) (0.07)	92.3	5.4
a100P	$g_{V} = 0.182 + 0.74\ D_{oc} - 0.0119\ MET - 0.0023\ ACE$ (0.86) (−0.20) (−0.09)	89.9	7.3
a100T	$g_{V} = 0.180 + 0.74\ D_{oc} - 0.0120\ MET - 0.0022\ ACE$ (0.86) (−0.20) (−0.09)	89.8	7.4

[1] The terms in parentheses are the beta coefficients of the regression.

[2] Refer to Table 1 for a description of the various moisture sorption conditions.

(Kelsey 1956; Sekhar and Rajput 1967; Skaar 1988; Choong and Achmadi 1991).

The regression analysis shows that wood density is the most important variable of the transverse swelling, positively affecting it (Tables 5 and 6). The negative effect of wood extractives on such swelling was notable. Compounds soluble in methanol affected the differential tangential swelling, while those soluble in acetone affected radial swelling. However, the beta coefficients indicate that the effect of wood density on differential swelling is about threefold greater than that exerted by extractives.

As expected, differential volumetric swelling shows an average behavior in relation to both principal transverse directions of wood. Wood density has a principal positive effect, whereas the methanol and acetone extractives have negative effects on dimensional changes (Table 7). The beta coefficients show the contribution of both compounds to be similar, which is especially noted in the group where ishpingo was excluded (d58T group). Acetone and methanol are polar solvents and can swell wood structure. Thus, these solvents should dissolve material located within cell walls, while the extractives dissolved in cyclohexane did not contribute to the differential swelling. Cyclohexane is a non-polar solvent and probably incapable of opening up and penetrating cell walls. Therefore, this solvent would remove the non-polar substances distributed either in the cell cavities or in the intercellular spaces.

The effect of the interlocked grain on swelling was not significant in the regression analyses. This anatomical feature would affect only the EMC (Hernández 2006a). The internal stresses probably induced by the interlocked grain appear to decrease EMC. This indirectly affects wood swelling, but there should not be an additional effect associated with this grain pattern.

Swelling ratio.—Figure 1 clearly shows how the relationship between differential swelling and wood density is improved when the oven-dry mass used in wood density calculation is corrected for extraneous substances. The slope of this relationship is called the R-ratio (Chafe 1986), dimensional hygroexpansion coefficient (Skaar 1988), or specific moisture expansion coefficient MX (Skaar 1988; Choong and Achmadi

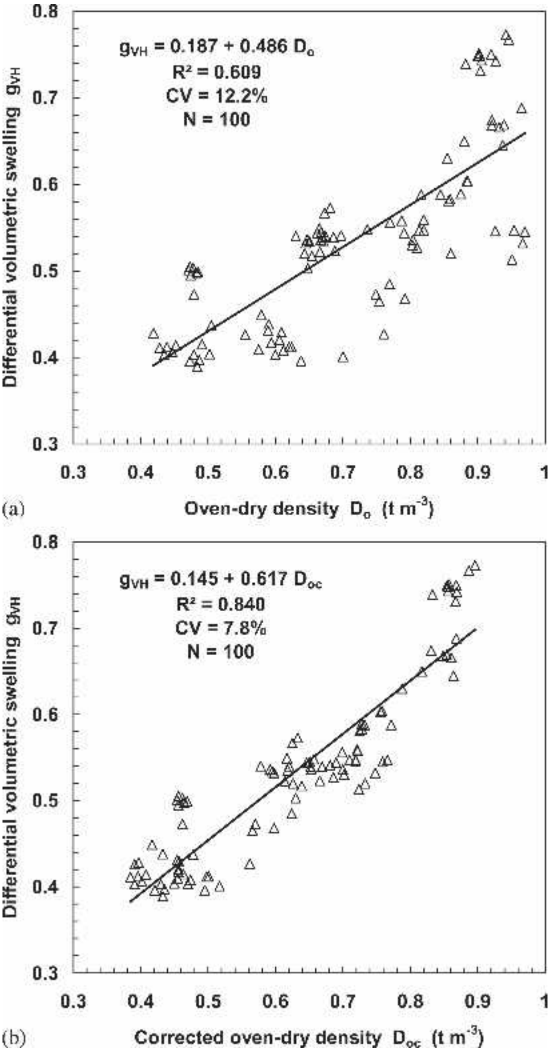

FIG. 1. Effect of the correction of the oven-dry mass by extraneous substances on the relationship between differential volumetric swelling and wood density. Adsorption at 25°C and 76% RH with parallel samples. a) Uncorrected oven-dry density (D_o), b) Corrected oven-dry density (D_{oc}).

1991). This parameter, which describes the increase in wood volume per unit volume of liquid water added, is defined as:

$$R = \frac{g_V}{D_o} = \frac{\alpha_{VH}}{D_{oc}EMC_c} = \frac{\alpha_{VH}}{D_oEMC} = \frac{\alpha_V}{D_oFSP} = \frac{V_H - V_o}{M_H - M_o} = \frac{\Delta V}{\Delta M_{H_2O}} \qquad (m^3t^{-1}) \qquad (3)$$

The R-ratio is at unity if the cell cavity remains constant in size and if the swelling (or shrinkage) of cell wall is equal to the volume of liquid water added (or removed). In swelling conditions, a value higher than one implies that the cell cavity expands, while a value lower than one means that cell cavity contracts (Skaar 1988). Chafe (1986) suggested that this R-ratio might be used as a general index of dimensional stability.

The mean R-ratios for adsorption between 33% and 76% RH and for desorption between 33% and 58% RH were calculated. Matched samples coming from the same original board were used for this purpose (Table 8). The R-ratio under adsorption ranged from 0.67 m^3t^{-1} for copaiba to 1.06 m^3t^{-1} for cedro. It should be kept in mind that both terms of this ratio are obtained by subtraction. The effect of oven-drying for obtaining the dry condition on later swelling therefore is eliminated or avoided. Hence, it is possible to study the effect of wood extractives on swelling without reference to the oven-dry state. On the other hand, because swelling is divided by EMC and wood density in the calculation of the R-ratio, these two properties could not be included as independent variables in the multiple regression analysis of R-ratio.

Multiple regressions of the R-ratio for both sorption states are presented in Table 9. The retained models explained from 68% to 72% of the total variation in R-ratio. Again, the low coefficients of variation (9%) indicate that these equa-

TABLE 8. *R-ratio as a function of the sorption state and wood species for parallel samples at 25°C.*

Wood species	Adsorption from 33% to 76% RH, R_{ads} (m^3t^{-1})	Desorption from 58% to 33% RH, R_{des} (m^3t^{-1})
Caoba	0.94	0.89
Cedro	1.06	1.08
Ishpingo negro	0.74	0.69
Pumaquiro	0.91	0.92
Sugar maple	0.87	0.96
Copaiba	0.67	0.70
Palisangre negro	0.73	0.77
Estoraque	0.81	0.79
Tahuarí	0.94	0.92
Palosangre	0.68	0.71

TABLE 9. *Regression equations of the R-ratio, calculated between 33% and 76% RH under adsorption, and between 58% and 33% RH under desorption, as a function of the interlocked grain (IG), ash content (ASH), as well as the extractives obtained successively in cyclohexane (CYC), acetone (ACE), and methanol (MET). Parallel samples at 25°C.*[1]

Equations	R^2 (%)	CV (%)
R_{ads} = 0.98 − 0.032 MET − 0.012 ACE (−0.52) (−0.49) + 0.09 ASH (0.21)	67.8	9.3
R_{des} = 1.02 − 0.035 MET − 0.011 ACE (−0.54) (−0.41) − 0.019 CYC + 0.08 ASH (−0.18) (0.17)	71.6	9.1

[1] The terms in parentheses are the beta coefficients of the regression.

tions may be used for predictive purposes. The beta coefficients show that the effects of methanol and acetone extracted fractions accounted for about 80% of the R-ratio variation explained by the regression equations (two regressions pooled). The contribution made by both categories of substances seems similar. The relationships between R-ratio obtained in adsorption between 33% and 76% RH, and the sum of methanol and acetone extractives is given in Fig. 2. It is therefore established that wood extractives contribute greatly to the dimensional stability of tropical hardwoods. This conclusion confirms the suggestions advanced by Torelli and Cufar (1979) and Chafe (1987), but it is contrary to those proposed by Nearn (1955) and Spalt (1979).

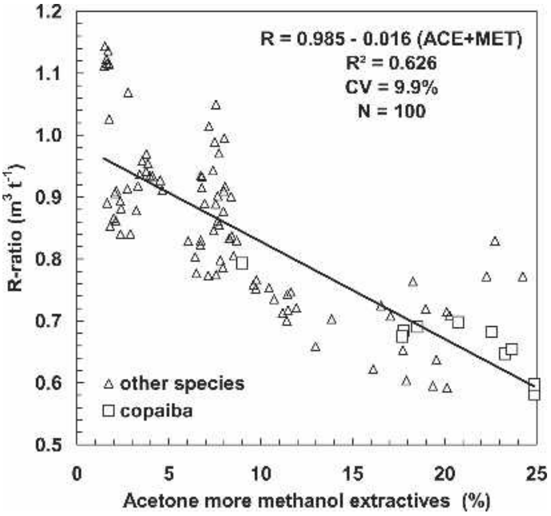

FIG. 2. Swelling R-ratio as a function of the acetone more methanol extractives contents, during adsorption at 25°C, between 33% and 76% relative humidity.

The ash content and the cyclohexane extractives also affected the variation in R-ratio, but their participation was somewhat lower. This would be related to their presence in the cell cavities, intercellular spaces, and lining of the lumen wall surfaces.

In summary, the study of the differential swelling and the R-ratio has demonstrated that acetone and methanol extractives are responsible for the dimensional stability of tropical hardwoods. These types of compounds would be principally distributed within cell walls bulking the structure.

SUMMARY AND CONCLUSIONS

Experiments of cold-water and hot-water solubilities, sequential extractions with cyclohexane, acetone, and methanol solvents, ash determination, wood density, as well as interlocked grain measurements, were conducted with specimens of nine tropical hardwoods and sugar maple wood. Results of these measurements were associated with those of moisture sorption and swelling properties obtained from unextracted but matched specimens using a multiple step procedure at 25°C. The main conclusions of this work may be summarized as follows:

1. There was high variation in swelling properties within and among wood species.
2. Wood density corrected for the extraneous substances was the major factor affecting positively the transverse and volumetric swelling of tropical hardwoods.
3. Sequential extraction with organic solvents was the most suitable method for evaluating the effect of extractives on swelling properties of tropical hardwoods.
4. The extractives soluble in cyclohexane were the more accessible and probably located in the cell cavities and intercellular spaces.

They contributed virtually nothing to wood swelling.

5. The substances dissolved in acetone appeared to be located within cell walls. After wood density, these compounds were the most significant variable negatively affecting radial swelling.
6. The substances dissolved in methanol were located within cell walls. After wood density, this extracted fraction was the most significant variable negatively affecting the tangential swelling.
7. The acetone and methanol extracted fractions positively affected the dimensional stability of tropical hardwoods.
8. The effect of the interlocked grain on swelling was only indirect, given that this grain pattern reduces EMC.

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