

SHRINKAGE OF THREE TROPICAL HARDWOODS BELOW AND ABOVE THE FIBER SATURATION POINT

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ABSTRACT

Two experimental techniques were used to perform moisture sorption tests at 25°C on samples of three tropical hardwood species: tornillo (*Cedrelinga cateniformis* Ducke), pumaquiro (*Aspidosperma macrocarpon* Mart.), and huayruro (*Ormosia coccinea* Jackson) woods. The first technique used saturated salt solutions at a relative humidity from 0% to 90%, and the second one used the pressure membrane method at above 96% relative humidity. These sorption tests were combined with shrinkage measurements. The fiber saturation point (FSP), estimated by interpolation to zero volumetric shrinkage, was 28%, 22.5%, and 21.5% for tornillo, pumaquiro, and huayruro, respectively. Results confirmed that at equilibrium moisture content, radial, tangential, and volumetric shrinkage occur above the actual FSP. This behavior can be explained by the effect of hysteresis at saturation on wood properties. This hysteresis indicates that loss of bound water takes place in the presence of liquid or capillary water, which contradicts the traditional concept of FSP. The initial equilibrium moisture content at which bound water starts to leave cell walls varied largely among the species: 52%, 36%, and 77% for tornillo, pumaquiro, and huayruro, respectively. The liquid water remaining in wood could be principally located in the least permeable flow paths of these wood species.

Keywords: Equilibrium moisture content, fiber saturation point, shrinkage, *Cedrelinga cateniformis*, *Aspidosperma macrocarpon*, *Ormosia coccinea*.

INTRODUCTION AND BACKGROUND

The fiber saturation point (FSP) is a very important property of wood as it governs the changes in its properties (Stamm 1964; Siau 1984; Skaar 1988). The FSP was initially defined by Tiemann (1906) as the moisture content (MC) at which the cell walls are saturated with bound water with no free water in the cell cavities. It is assumed that the FSP is the MC below which the physical and mechanical properties of wood begin to change as a function of MC

(USDA 1974; Siau 1984). Therefore, the FSP is used in models to adjust the mechanical properties of wood as a function of its MC (Bodig and Jayne 1982), as well as in wood shrinkage and density adjustment models (Siau 1984; Skaar 1988).

However, several studies show that this assumption is not realistic. Stevens (1963) indicated that shrinkage in beech wood begins taking place above the FSP. The MC gradient effect advanced by his study for explaining this behavior appears invalid because shrinkage values were obtained at equilibrium moisture content (EMC). Goulet and Hernández (1991) reported a

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large hysteresis effect on the EMC and on the perpendicular-to-the-grain tangential tension strength of sugar maple wood at high relative humidities (RH). The difference for the tangential tension strength between adsorption and desorption states was 20% at 26% EMC. This effect was attributed to the hysteresis at saturation phenomenon, which affected the wood moisture sorption above 63% RH (Hernández 1983). This hysteresis implies that during desorption the loss of bound water begins before the removal of all liquid water from the wood.

Even though desorption curves had 26% EMC as an upper limit, Goulet and Hernández (1991) suggested that the effect of EMC on sugar maple wood properties could be extended beyond the FSP, estimated to be 31% MC. To this end, two studies focusing on high humidities (above 90% RH) were performed on sugar maple (Hernández and Bizoñ 1994) and yellow birch woods (Almeida and Hernández 2006a). The results confirmed that at the EMC, changes in shrinkage and in transverse strength occur above the FSP for both species. The initial EMC, at which bound water starts to leave the wood, was 42.5% for sugar maple and about 41% for yellow birch. This occurs even in the presence of liquid water within the wood structure. The results of Hernández and Bizoñ (1994) were taken into account by Siau (1995) when describing the fiber saturation point. However, more research on wood species with different structures is needed in order to corroborate these conclusions.

The purpose of this investigation was to study the effect of EMC on shrinkage properties of three tropical hardwoods below and above the cell-wall saturation. Two moisture sorption techniques, combined with shrinkage measurements, were applied to large specimens at 25°C.

MATERIAL AND METHODS

The experiments were carried out on three tropical hardwood species: tornillo (*Cedrelinga cateniformis* Ducke), pumaquiro (*Aspidosperma macrocarpon* Mart.), and huayruro (*Ormosia coccinea* Jackson). The specimens for moisture sorption tests had a cross-section of 20 mm (R)

by 20 mm (L) and a height of 60 mm (T). The choice of dimensions was limited by the matching techniques used, by the length of the sorption experiments and to reduce the effect of the growth ring curvature.

One hundred twenty-two green defect-free flatsawn pieces were carefully selected and stored in a conditioning room maintained at 20°C and 60% RH. After reaching equilibrium moisture content (13% for tornillo and 11% for pumaquiro and huayruro), the pieces were cut to obtain boards of 20 mm (R) by 60 mm (T) and 500 mm (L). The twenty best boards were selected for each species on the basis of their growth ring orientation, growth ring uniformity as well as reduced wood density variation among boards (by eliminating the heavier and lighter boards). Each board was then cross-cut to yield 20-mm-thick specimens. Thirteen adjacent specimens were chosen from each board to investigate thirteen moisture conditions. This longitudinal matching yielded thirteen comparable groups of twenty specimens each. An additional group of matched specimens was used to study the anatomical structure of these species (Almeida and Hernández 2006b).

The average basic wood density (oven-dry mass to green volume) was 490 kg/m³ for tornillo (coefficient of variation (CV) of 3.5%); 585 kg/m³ for pumaquiro (CV of 2.8%), and 640 kg/m³ for huayruro (CV of 3.5%).

Experiments

The experiments consisted of moisture sorption tests associated with shrinkage measurements. Dimensions of specimens were taken as soon as the EMC was reached. The sorption conditions studied are summarized in Table 1. Prior to the desorption tests, specimens were saturated in three steps until their full moisture content was reached. This was done in order to avoid internal defects caused by a rapid moisture adsorption (Naderi and Hernández 1997). The full saturated masses were then taken to the nearest 0.001 g using a digital balance, and dimensions in all principal directions to the nearest 0.001 mm were measured with a digital micrometer.

TABLE 1. Characteristics of the moisture sorption conditions.

State of sorption	Chemical or saturated salt solution	Nominal relative humidity (%)	Water potential (Jkg ⁻¹)	Radius of curvature of the air-water meniscus ¹ (μm)
Full saturation under distilled water				
Saturation	H ₂ O	100	0	∞
Equilibrium under a pressure membrane at 25°C				
Desorption	—	99.927	-100	1.44
Desorption	—	99.782	-300	0.480
Desorption	—	99.492	-700	0.206
Desorption	—	98.557	-2 000	0.072
Desorption	—	96.431	-5 000	0.029
Equilibration over saturated salt solutions at 25°C				
Adsorption	H ₂ O	≈100	—	—
Desorption	ZnSO ₄	90	-14 495	—
Desorption	KCl	86	-20 750	—
Desorption	NaCl	76	-37 756	—
Desorption	NaBr	58	-74 941	—
Desorption	MgCl ₂	33	-152 526	—
Desorption	P ₂ O ₅	0	-950 346	—

¹ $r = \frac{-2\gamma \cos\theta}{\psi}$; where: γ is the surface tension of water (0.072 N m⁻¹ at 25°C); θ is the contact angle between the liquid and the surface of the capillary (0°). Under about 92% RH, equation is not applicable.

The group to be conditioned in adsorption over distilled water was kept at 20°C and 60% RH prior to the test.

The sorption experiment was performed according to Almeida and Hernández (2006a). Briefly, this sorption required two experimental techniques. The first technique involved saturated salt solutions, and the second involved conditioned specimens using a pressure membrane procedure. The first technique was carried out at between 0% and 90% RH, as well as over distilled water, using sorption vats equilibrated at 25°C. For the saturated salt solutions, the time of conditioning varied between 105 days (tornillo in desorption at 33% RH) and 249 days (tornillo in desorption at 90% RH). For each point of sorption, control specimens were weighed weekly, without being removed from the desiccator. It was assumed that the equilibrium moisture content (EMC) was reached when the loss in MC was under 0.007% per day.

The pressure membrane procedure was used to determine five additional points of desorption between 96.431% and 99.927% RH (Table 1). A series of studies has shown the suitability of the technique used for this humidity range (Stone and Scallan 1967; Griffin 1977; Fortin 1979;

Hernández and Bizoñ 1994; Almeida and Hernández 2006a). The procedure introduces the concept of water potential (ψ or WP), which is derived from classical thermodynamics and is defined as the difference between the specific Gibbs free energies of water in the state under study and in a standard reference state (Siau 1995). A detailed description of the apparatus used for the pressure membrane method is given by Cloutier and Fortin (1991). For each point of longitudinal desorption, twenty fully saturated specimens were placed into the pressure extractor on a saturated cellulose acetate membrane. Pressure was then gradually applied until the required level was reached. Flow of water was collected in a burette. EMC was considered as reached when outflow became negligible (no outflow during seven successive days). These experiments required between eight and seventy days of desorption, depending on the ψ considered and the wood species tested.

As soon as each sorption test was completed, the sample mass was measured to the nearest 0.001 g. Dimensions in all principal directions were taken to the nearest 0.001 mm with a micrometer. Differences in dimensions of specimens after full saturation and as soon as the

equilibrium was reached were used to estimate partial percent shrinkage in the tangential (β_{TH}) and radial (β_{RH}) directions of the wood. Volumetric shrinkage was estimated to be the summation of these two directional shrinkages ($\beta_{TH} + \beta_{RH} - \beta_{TH} \cdot \beta_{RH}$). The mass of the specimens at equilibrium and their mass measured after oven-drying were used to calculate the EMC, expressed as a percentage of oven-dry mass.

RESULTS AND DISCUSSION

Wood hygroscopicity

The relationship between water potential and EMC for the three tropical hardwoods is given in Fig. 1. Previous results obtained for sugar maple wood (Hernández and Bizoñ 1994) are also added for comparative purposes. This figure displays only the desorption curve obtained by using either the pressure membrane or the saturated salt solution methods. The point obtained

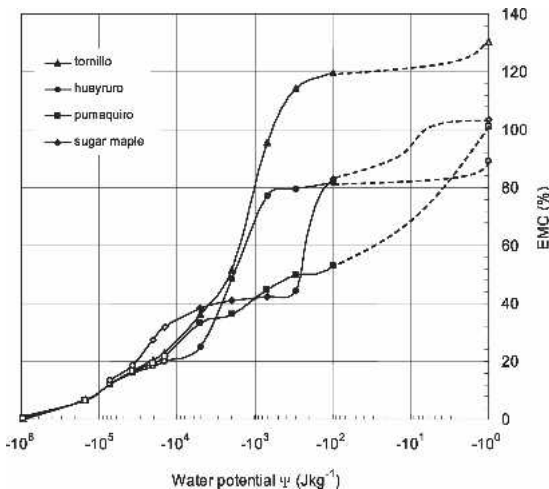


FIG. 1. Equilibrium moisture content as a function of the water potential for tornillo, pumaquiro, and huayruro hardwoods at 25°C and for sugar maple at 21°C (maple from Hernández and Bizoñ 1994). Gray symbols represent full saturation under distilled water; black symbols are the values obtained by the pressure membrane method and white symbols are the values obtained under the saturated salt solution method (standard errors do not exceed the symbol size shown).

at full saturation is also shown. An excellent continuity is apparent between the results obtained by the two sorption methods. This confirms the suitability of the pressure membrane method for determining EMC in wood under high relative humidity conditions, which is consistent with several earlier reports (Stone and Scallan 1967; Cloutier and Fortin 1991; Hernández and Bizoñ 1994; Defo et al. 1999; Almeida and Hernández 2006a).

The hysteresis at saturation has been described by Goulet and Hernández (1991) as the difference between the equilibrium obtained in desorption when starting from the FSP and that reached in desorption when starting from wood having liquid water. Some researchers have indicated that high EMCs in desorption are obtained using never-dried specimens (Higgins 1957; Spalt 1958). Skaar (1988) ascribed such behavior to an initial irreversible loss in hygroscopicity after the initial drying of green or water-soaked wood. However, many studies have shown that this effect is apparent during subsequent desorptions (Fortin 1979; Hart 1984; Goulet and Hernández 1991; Cloutier and Fortin 1991; Hernández and Bizoñ 1994; Almeida and Hernández 2006a). Experimental data for second desorption above 76% RH show an equilibrium higher than the one expected when starting from the FSP of each species (about 28% MC for tornillo, 22.5% for pumaquiro, and 21.5% for huayruro). This confirms that the hysteresis at saturation is not limited to the first drying, but rather to any desorption made in the presence of liquid water.

The importance of this hysteresis will vary according to the initial MC of the wood. In this study, desorption was carried out beginning from the fully saturated state, and the curve obtained corresponds to the maximum EMC expected for each RH condition. The term boundary desorption curve is therefore used to describe this feature. Thus, any desorption curve obtained from a lower initial MC would be located below this boundary desorption curve (Defo et al. 1999).

The region between 96% and 100% RH (WP higher than -10^4 Jkg $^{-1}$) is greatly expanded

when using the water potential concept to represent sorption isotherms. This region is very important when studying the wood-water interactions given that it is mainly controlled by the capillary forces and consequently by the microstructure of wood species. Since wood is a porous material, an important effect to be considered in the interpretation of Fig. 1 is the "ink-bottle effect." The capillary system of wood consists of cavities interconnected by narrow channels. The variation in dimensions between the different types of cavities connected in series suggests that desorption tends to be governed by a lower water potential, which is determined by the narrower sections of the pores. In contrast, adsorption tends to be governed by a higher water potential that depends on the larger sections of the pores. Thus, the desorption isotherm will depend on the size of channels connecting the lumina, whereas the adsorption isotherm will depend on the size of these lumina (Fortin 1979).

The boundary desorption curves presented in Fig. 1 show that a great variation exists among the three species of wood. This variation is more pronounced as WP increases. Pumaquiro wood exhibited a more distinct drainage behavior than the other hardwoods, especially at high values of WP. Figure 1 shows that the loss of EMC between full saturation and -100 Jkg^{-1} WP was 48% for pumaquiro, 11% for tornillo, and 7% for huayruro. In terms of mass units within a specimen, this corresponds to a loss of 7.43 g, 1.60 g, and 1.16 g liquid water for pumaquiro, tornillo, and huayruro, respectively. This water would have occupied a volume within the wood specimen of about 31% for pumaquiro, 7% for tornillo, and 5% for huayruro (mean volume of the specimens at 12% EMC was 24 cm^3). According to previous studies, this water should have been removed from the larger capillaries, especially the vessel lumina (Hernández and Bizoñ 1994; Almeida and Hernández 2006a). Quantitative anatomical measurements performed from matched samples showed that the proportion of vessel lumina within the wood volume was 28% for pumaquiro, 8% for tornillo, and 5% for huayruro (Almeida and Hernández 2006b). Table 1 shows that at -100 Jkg^{-1} WP,

capillaries with radius larger than $1.44 \mu\text{m}$ are already empty. The tangential radius of vessel elements was $45 \mu\text{m}$ for pumaquiro, $128 \mu\text{m}$ for tornillo, and $86 \mu\text{m}$ for huayruro (Almeida and Hernández 2006b). Therefore, it is apparent that the majority of vessel elements were already empty at this stage of desorption. However, the presence of some vessels that terminate within the samples (Petty 1978), the cut cells at the transverse faces, as well as deposits of extractives in the vessels can also affect the flow in wood. For instance, it is known that huayruro wood possesses some deposits of gum within its vessels (JUNAC 1981).

The boundary desorption curve of pumaquiro shows a constant decreasing EMC rate between -100 Jkg^{-1} and -2000 Jkg^{-1} WP, with a plateau occurring between -2000 Jkg^{-1} and -5000 Jkg^{-1} WP (Fig. 1). This plateau indicates that pore openings controlling the retention and flow of water are scarce within this WP range. Below this WP region, the water remaining in wood would be localized in capillaries having a radius equal to or smaller than $0.029 \mu\text{m}$ (Table 1). As discussed later, this would correspond to the transition between the drainage of the fiber cavities and that of the ray parenchyma as noted by Hart (1984).

The boundary desorption curves presented in Fig. 1 change abruptly at about -300 Jkg^{-1} WP for tornillo and at -700 Jkg^{-1} WP for huayruro. Below these WP values, curves show a quite constant EMC decreasing rate up to -5000 Jkg^{-1} WP, without presence of a plateau as occurring for pumaquiro wood (Fig. 1). A more uniform distribution of pore openings in wood may explain the absence of a plateau for these species. Another possibility is that the intervals of WP used were too large for detecting it. For softwood species, Fortin (1979) and Tremblay et al. (1996) also observed a drainage curve without an intermediate plateau. Such results confirm that at high humidities, the EMC-WP relationship is strongly dependent on species. For tornillo and huayruro, it should be more difficult to determine the location of liquid water within the wood elements at these WP levels. For instance, these species have an important proportion of

axial parenchyma (12% for tornillo and 34% for huayruro; Almeida and Hernández 2006b). The drainage of the liquid water could even occur simultaneously among different elements of the wood. In this case, the range of dimensions of the openings connecting the different wood elements could be overlapped.

Figure 1 also shows that a high proportion of drainage occurs at lower values of WP for tornillo and huayruro (curves shifted to the left) as compared to drainage for pumaquiro and sugar maple woods. The pore openings connecting the lumina at these levels of WP are smaller for the later species than for pumaquiro and sugar maple. The difference among the boundary desorption curves could also indicate the facility of a given wood species to reach full impregnation. In fact, tornillo and huayruro were least permeable and hence more difficult to impregnate up to full saturation. These species exhibited a very low loss of EMC at higher ranges of relative humidity (Fig. 1). In contrast, pumaquiro and sugar maple are more permeable woods and were saturated up to full moisture very easily. Therefore, these species showed a higher loss of EMC even at the beginning of the desorption (Fig. 1).

The boundary desorption curves of the three species nearly join below 58% RH (Fig. 1). A similar result was observed between yellow birch and sugar maple woods (Almeida and Hernández 2006a). This was expected given that desorption of liquid water at this level of RH is almost achieved. For sugar maple, Hernández (1983) reported that loss of liquid water was accomplished at about 63% RH. Thus, the bound water desorption was quite similar for the three hardwoods studied (values at 33% and 58% RH).

For the three hardwood species, it was not possible to determine the FSP by the adsorption over distilled water method (Table 1). Equilibrium was not reached because condensation of water occurred simultaneously with bound water adsorption (Hernández 2006). For this reason, the FSP was determined by the volumetric shrinkage intersection point method. In this method, the FSP is defined as the MC at which

the extended straight linear portion of the shrinkage-MC curve intersects the line of zero shrinkage (Stamm 1964; Skaar 1988; Siau 1995). For this estimation, only volumetric shrinkage values obtained between 33% and 76% RH were used. This was done because of the non-linearity of the shrinkage-MC curve at low moisture contents (Stamm 1964) and the effect of the hysteresis at saturation on shrinkage at high moisture contents (Hernández and Bizoñ 1994). The estimated FSP were 28%, 22.5% and 21.5%, for tornillo, pumaquiro and huayruro, respectively. The FSP values estimated by extrapolation to zero volumetric shrinkage (actual FSP) are used in the discussion that follows.

Wood shrinkage—EMC relationships

The relationships between the EMC and the radial, tangential, and volumetric shrinkages for the three hardwoods are shown in Fig. 2. Free-hand curves were drawn taking into account the sorption state, in such a way that the actual FSP is not linked to the others. The standard errors of the shrinkage values do not exceed the symbol size shown. As expected, the three tropical hardwoods showed a low degree of shrinkage when compared to temperate woods having a similar density. This behavior can be explained by the presence of extractives in the woods studied (Choong and Achmadi 1991).

For the three hardwoods, Fig. 2 shows that radial, tangential, and volumetric shrinkages started before the FSP was reached. In order to determine the EMC at which shrinkage starts to take place, the differences between the dimensions at full saturation and those at each EMC studied were calculated. This was made for the tangential and radial dimensions of specimens. Since the dimensions at full saturation and at each EMC studied were taken on the same specimen, a paired t-test (one-tail) was performed (SAS Institute 2002–2003). This test determined if changes in dimensions between these two MCs are statistically larger than zero at the 0.01 probability level. The results of the paired t-tests indicating the EMC at which shrinkage

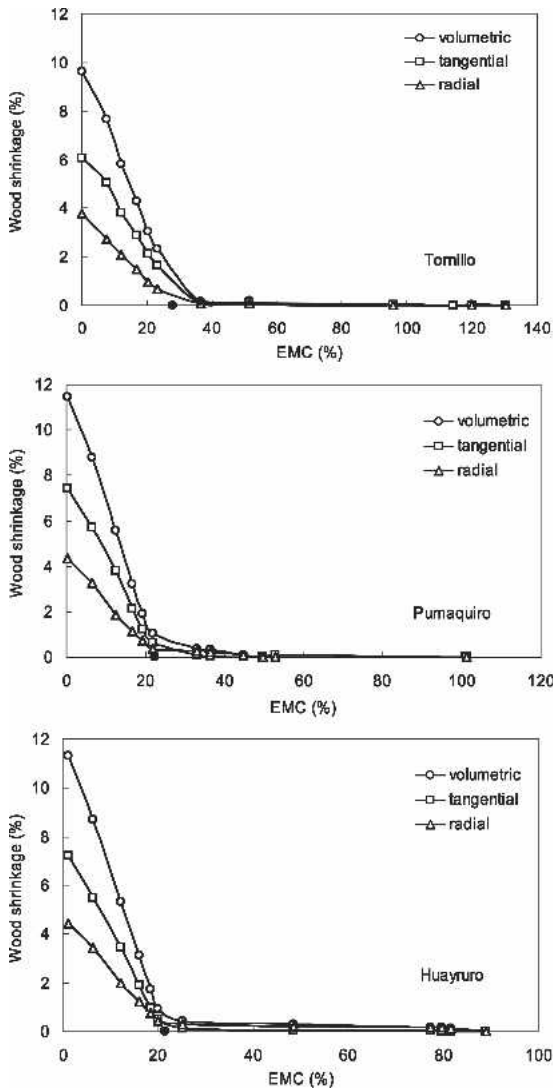


FIG. 2. Shrinkage of tornillo, pumaquiro, and huayruro hardwoods as a function of the EMC at 25°C. The symbol • represents the FSP estimated by the volumetric shrinkage intersection method (standard errors do not exceed the symbol size shown).

begins to take place in both principal directions of wood are shown in Table 2.

The EMC at which shrinkage was larger than zero varied among wood species (Table 2). This was expected since water drainage at high moisture contents is highly dependent on wood structure. Table 2 shows that in tornillo wood tangential and radial shrinkages started at 51.5%

EMC, which corresponds to $-2000 \text{ Jkg}^{-1} \text{ WP}$. Since the actual FSP for tornillo was estimated to be 28%, shrinkage started before the FSP was reached. It is clear that, even at equilibrium, loss of bound water within the cell walls provokes shrinkage of wood before all liquid water has evaporated. This implies that about 23.5% MC in liquid form is still retained in the wood when shrinkage of tornillo starts taking place at $-2000 \text{ Jkg}^{-1} \text{ WP}$ (51.5%–28.0% EMC). In terms of mass units, this corresponds to 3.06 g of liquid water that would have occupied a volume of about 13% within a wood specimen (mean volume of the specimens at 12% EMC was 24 cm^3). This remaining liquid water could be entrapped in the ray elements, given that these wood elements are considered as the least permeable flow path in hardwoods (Siau 1995). Wheeler (1982) noted that the parenchyma-parenchyma pit membranes are thicker than both the intervessel pit membranes and the fiber-fiber pit membranes, and consequently are less efficient pathways for liquid flow. This entrapped water could in fact fill the 14% volume of ray tissue measured on matched specimens of tornillo wood by Almeida and Hernández (2006b). The entrapment of liquid water in ray tissue reported by Hart (1984) for hickory and oak adds further support to this hypothesis. Menon et al. (1987) studied the water location during drying of Douglas-fir and western red cedar woods using proton magnetic resonance techniques. Under unequilibrated conditions, they noted that liquid water remained in the ray and tracheid compartments when bound water begins to leave the cell walls. The liquid water was completely lost when the MC reached values as low as 9%.

For the other species, shrinkage was statistically different from zero at 36.3% EMC for pumaquiro and at 77.3% EMC for huayruro (Table 2). These EMCs are also larger than the actual FSP of these species (22.5% EMC for pumaquiro and 21.5% for huayruro). About 13.8% MC in liquid form is still retained in pumaquiro wood when shrinkage starts taking place at $-2000 \text{ Jkg}^{-1} \text{ WP}$ (36.3%–22.5% EMC). For huayruro, 55.8% MC in liquid form is still retained in the wood when shrinkage starts taking

TABLE 2. Statistical analysis of the difference in dimensions of specimens after full moisture saturation and at a given EMC for the three wood species.

Wood species	EMC ¹ (%)	Tangential direction ²			Radial direction ³				
		T _{FS} (mm)	T _{EMC} (mm)	Diff T (mm)	t Value	R _{FS} (mm)	R _{EMC} (mm)	Diff R (mm)	t Value
Tornillo	52	62.407	62.344	0.063 (0.014) ⁴	4.56**	20.709	20.691	0.019 (0.009)	2.01 ns
Pumaquiro	36	62.502	62.463	0.039 (0.005)	7.80**	20.603	20.552	0.051 (0.008)	6.34**
Huayruro	77	62.341	62.320	0.021 (0.004)	6.04**	20.667	20.636	0.032 (0.008)	4.01**

¹ Equilibrium moisture content where Diff T (difference between T_{FS} and T_{EMC} dimensions) and Diff R (difference between R_{FS} and R_{EMC} dimensions) were statistically higher than zero (**).

² Average of 20 measurements: T_{FS} = tangential dimension at full saturation, T_{EMC} = tangential dimension at EMC.

³ Average of 20 measurements: R_{FS} = radial dimension at full saturation, R_{EMC} = radial dimension at EMC.

⁴ Values between parentheses represent the standard error.

place at -700 Jkg^{-1} WP (77.3%–21.5% EMC). In terms of mass units, this corresponds to 2.07 g for pumaquiro and to 9.11 g for huayruro of liquid water that would have occupied a volume of about 9% (pumaquiro) and 38% (huayruro) within a specimen (mean volume of the specimens at 12% EMC was 24 cm^3). The volume of ray tissue in pumaquiro wood was 9% (Almeida and Hernández 2006b). As was the case for tornillo wood, the liquid water in pumaquiro wood appears to be trapped principally in the ray tissue.

The case of huayruro was different: even though having a high density, this species exhibits a high proportion of aliform and confluent parenchyma (34%) and ray parenchyma (20%; Almeida and Hernández 2006b). Shrinkage of this wood started earlier (77.3% EMC) at a high WP (-700 Jkg^{-1}). The capillary tension forces at this level of WP could be too low to cause a loss of bound water in wood. However, these could be enough to provoke some localized collapse on the thin cell walls of axial parenchyma (Hart 1984). Localized collapse in parenchyma cells above FSP has been reported previously (Hart 1984; Demanet et Morlier 2000; Wu et al. 2005). Furthermore, the action of the capillary tension could be combined with hydrostatic tension forces occurring at the interface between the confluent parenchyma and fibers of huayruro (Bariska 1992; Demanet and Morlier 2000). In fact, this species exhibited fibers with very thick cell walls and very small lumina. This should

contribute to increase the gradient of drying stresses between these two wood elements (as noted between earlywood and latewood in temperate woods). However, judging by the total shrinkage measured for this wood (11.3%), the magnitude of this localized collapse can be considered as negligible. Thus, the occurrence of a localized collapse from cavity water loss for some heterogeneous hardwoods can not be discarded. However, the hypothesis of a cell-wall shrinkage from bound water loss taking place in presence of liquid water appears as more plausible for homogeneous hardwoods. It is hence postulated that these two mechanisms occurred simultaneously in huayruro wood. Additional work is, therefore, needed in order to better understand the mechanisms releasing the beginning of shrinkage at equilibrium.

General discussion

The results show that, for the three tropical woods, shrinkage started before the FSP was reached as a result of the loss of bound water in the presence of liquid water (Fig. 2). Such behavior in shrinkage has been also reported for tangential compression strength in previous studies. The changes in physical properties started at about 42.5% EMC for sugar maple (Hernández and Bizoñ 1994) and at 41% EMC for yellow birch (Almeida and Hernández 2006a). In the present study, wood species presenting more variable anatomical structures

showed that changes in wood properties began at different EMC values: at nearly 52% EMC for tornillo, 36% EMC for pumaquiro, and 77% EMC for huayruro. These values do not correspond to any abrupt transition from bound water to liquid water as currently stated. It is henceforth established that during boundary desorption a region exists where the loss of bound water takes place in the presence of liquid water. The FSP or cell-wall saturation can not be directly determined from desorption experiments. The range of EMC of this region depends on the size distribution of wood capillaries, which will vary among wood species. The occurrence of localized collapse above FSP for highly heterogeneous woods must also be considered in this kind of studies.

CONCLUSIONS AND RECOMMENDATIONS

Moisture adsorption and desorption experiments were performed in specimens of tornillo, pumaquiro, and huayruro woods at 25°C. Special attention was paid to the fiber saturation zone. Once equilibrium was reached, shrinkage measurements were undertaken. The results of these tests lead to the following main conclusions:

1. At equilibrium, the radial, tangential shrinkage, and consequently the volumetric shrinkage begin well above the actual fiber saturation point for the three species studied. The EMC at which shrinkage begins to take place varied among species.
2. In the desorption phase, loss of bound water begins at nearly 52% EMC for tornillo, 36% EMC for pumaquiro, and 77% EMC for huayruro in the presence of liquid water. The volume of liquid water that remains in wood at the beginning of shrinkage was estimated to be 24% EMC for tornillo, 14% EMC for pumaquiro, and 56% EMC for huayruro. This volume of entrapped water depended on the micro-structure of each wood species.
3. The cell-wall saturation or FSP can be determined sufficiently by interpolation to zero

shrinkage from the linear portion of the volumetric shrinkage-EMC relationships.

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