INFLUENCE OF MOISTURE SORPTION ON THE COMPRESSIVE PROPERTIES OF HARDWOODS

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ABSTRACT

Samples of nine tropical hardwoods from Peru and sugar maple wood from Quebec were selected to undergo moisture sorption tests associated with either a parallel to grain compression test or a perpendicular to grain tangential compression test at 25 C. Results indicated that, for a given equilibrium moisture content, the transverse strength is lower after desorption than after adsorption. The magnitude of this phenomenon, called second-order effects of moisture sorption, varied with the species and with the mode of measurement of the strain. Hence, it seems that the distribution of deformation influences the second-order effects in tangential compression. Also, it was shown that second-order effects of moisture sorption associated with parallel to grain compression strength are explained by those related to the transverse swelling of wood. These effects are thereby proportionally greater in the perpendicular to grain direction of wood than in the parallel to grain direction.

Keywords: Moisture sorption, adsorption, desorption, mechanical properties, compliance coefficient, ultimate compression stress, tropical woods, sugar maple.

INTRODUCTION

It is known that the moisture sorption state of wood has an effect on some of its properties. At a given equilibrium moisture content (EMC), such properties will differ, depending on whether the wood is in the state of adsorption or desorption. Goulet (1968) has called these changes in behavior "second-order effects of moisture sorption."

Laforest and Plamondon (1976) further established the existence of this phenomenon while measuring the deformation of sugar maple in radial compression. These researchers confirmed previous results obtained by Goulet (1968), who found that for a given moisture content, the wood was stiffer when equilibrium was reached by gaining moisture rather than by losing it. A study conducted at temperatures between 5 and 50 C by Djolani (1970) showed that a temperature increase will decrease the EMC and increase the hysteresis between moisture content values at a given relative humidity, but have no effect on the second-order effects of wood in radial compression.

Goulet and Hernández (1991) performed an analogous study in tangential tension. For the compliance coefficient s_{33}, these effects seem to be only half of those measured in radial compression. They have also shown that second-order effects could be present in wood up to the point of failure.

Similar experiments were carried out to investigate the deformation of sugar maple wood in the longitudinal direction (Laforest 1981). The results indicated that, with regard to the compliance coefficient s_{11}, the second-order effects of moisture sorption are so small as to be negligible in tension as well as in compression.

The research described above has considered only one species, namely sugar maple. Little information is available in the literature on the second-order effects of moisture sorption for other woods as concerns their strength properties. As a consequence, it was considered suitable to establish the presence of these effects and estimate their importance for other woods. The purpose of this paper is to provide

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TABLE 1. *Peruvian hardwood test material.*

Native name/Botanical name/Family	Wood density* (t/m³)	Porous type
Caoba/*Swietenia* sp./Meliaceae	0.463	diffuse
Cedro/*Cedrela* sp./Meliaceae	0.476	semi-ring
Ishpingo negro/*Amburana* sp./Papilionaceae	0.592	diffuse
Pumaquiro/*Aspidosperma* sp./Apocynaceae	0.660	diffuse
Sugar maple/*Acer saccharum* Marsh./Aceraceae	0.668	diffuse
Copaiba/*Copaifera* sp./Caesalpiniaceae	0.710	diffuse
Palisangre negro/*Pterocarpus* sp./Papilionaceae	0.806	diffuse
Estoraque/*Myroxylon* sp./Papilionaceae	0.900	diffuse
Tahuari/*Tabebuia serratifolia* Nichols/Bignoniaceae	0.913	diffuse
Palosangre/*Brosimum* sp./Moraceae	0.915	diffuse

* Based on weight and volume in the oven-dry condition.

such information for nine tropical hardwoods in addition to sugar maple, when tested in parallel to grain and perpendicular to grain tangential compression. This research reports the compliance coefficient (s_{11}), the ultimate crushing stress parallel to grain (σ_{Lu}), and the compliance coefficient perpendicular to grain in tangential compression (s_{33}). These properties are presented under five (longitudinal direction) and three (tangential direction) equilibrium moisture contents obtained during the first full sorption cycle at 25 C.

MATERIALS AND METHODS

Besides sugar maple wood, experiments were carried out with nine Peruvian tropical hardwoods (Table 1).

These species were selected as a representative sample of tropical hardwoods of a wide range of density, type and amounts of extraneous substances, and different anatomical structures.

Shape and dimensions of the samples for mechanical tests are shown in Fig. 1. Dimensions of samples differ from those recommended by ASTM D143. Matching techniques used and moisture sorption tests were limiting factors in determining these dimensions. For the parallel to grain compression test, a length-to-width ratio of 4 was used to preclude buckling during the test (Bodig and Jayne 1982). For the pure perpendicular to grain tangential compression test, a ratio of 3 was used to limit the curvature of growth rings. Both types of samples had cross sections of 20 mm × 20 mm.

Ten flatsawn boards per species were selected and allowed to dry slowly in a conditioning room at a relative humidity (RH) of 60% and a temperature of 20 C. Once the boards reached equilibrium, each was cut according to a pattern that yielded at least five parallel to grain and three perpendicular to grain tangential specimens. Eight samples for compression tests were selected from each board, five for the parallel to grain compression test and three for the perpendicular to grain tangential compression test. Five moisture conditions were studied with the parallel to grain specimens being subjected to three of the moisture conditions used for the perpendicular to grain specimens. This matching yielded eight comparable groups of 100 samples each, consisting of ten samples from each of the ten species examined. All test material was heartwood, except for the sugar maple, which was sapwood.

EXPERIMENTS

The experiments consisted of a moisture sorption test associated with a mechanical test. Wood samples were mechanically tested as soon as the desired EMC was reached. In order to ensure uniformity between groups, all samples had been previously oven-dried together. This preliminary drying, to be considered as the first desorption, was slow (377 hours) in order to minimize the formation of drying

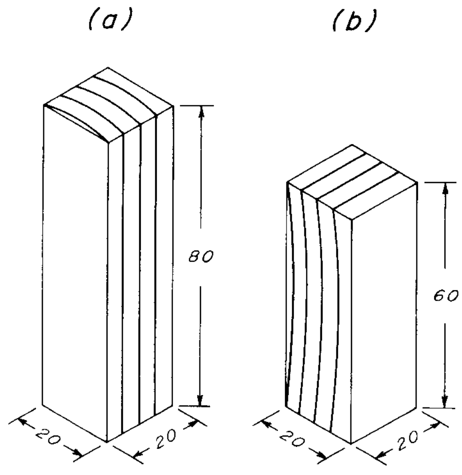

FIG. 1. Schematic representation of specimens for (a) parallel to grain compression and (b) perpendicular to grain tangential compression (mm).

stresses in the wood. Temperature was gradually increased up to 100 C to reach a final wood moisture content of approximately 0%. After drying, all specimens were kept in desiccators containing phosphorus pentoxide at 25 C for 46 days. This treatment eliminated any residual moisture and minimized probable effects of some internal drying stresses. After this period of relaxation, all specimens were weighed to 0.001 g, and their oven-dry dimensions in all principal directions were measured to the nearest 0.01 mm.

Later, the sorption tests were conducted simultaneously on all samples, using sorption vats described earlier by Goulet (1968). These vats provided a temperature control of ±0.01 C during extended periods, thus allowing control of the relative humidity in the various desiccators serving as small sorption chambers. For each point of sorption (100 samples), five desiccators (parallel to grain compression) or four desiccators (perpendicular to grain tangential compression) were used, each containing twenty specimens for the parallel compression test or twenty or thirty for the tangential compression test. All final sorption conditions were realized over saturated salt solutions or distilled water, in a multiple step procedure (Table 2) which lasted between 167 days (adsorption 33% RH) and 450 days (adsorption ≃ 100% RH). The number of steps was kept between 1 and 5 to realize a mild sorption that was without, or at most with minimal, internal tensions. This long period of time was adequate to reach equilibrium in both adsorption and desorption, assuming that the equilibrium process is an exponential function of time (Laforest 1981). For each step of conditioning, control specimens of each species were weighed periodically, without being removed from the desiccator, using a method described by Suchsland (1980). To avoid the effect of the hysteresis at saturation on the mechanical strength (Goulet and Hernández 1991), desorption tests were made in the presence of bound water only. Final desorptions were hence preceded by an adsorption step over distilled water (Table 2).

As soon as each point of sorption was completed, mechanical tests were carried out on an Olsen machine (parallel to grain compression) or a Riehle machine (perpendicular to grain tangential compression). For the parallel to grain compression test, strain was measured over a span of 50 mm of the central part of the specimen, using a two-side clip gauge provided with a Sangamo linear displacement sensor. This same clip gauge was used to measure the strain for the tangential compression test, but the span was adjusted to 40 mm. In addition, complete deformation of the specimen during this test was measured by the displacement of the cross-head, using a Heidenhain 3010 linear displacement sensor. In all cases, hygrothermal changes during the mechanical test were controlled by wrapping the specimen in cotton that had been previously conditioned above a corresponding saturated salt solution. As per Sliker (1978), the cross-head speed was adjusted in order to ensure a similar strain rate for all species. In the elastic range, these strain rates were of 0.15 mm/mm/min for the parallel specimen and of 0.40 mm/mm/min for the tangential sample.

These tests permitted the establishment of the compliance coefficient in the longitudinal direction s_{11} of the wood, the reciprocal of this

TABLE 2. *Sequence of moisture sorption conditions.*

Experience	Number of the group[1]	Chemical or saturated salt solution	Nominal relative humidity (%)	State of sorption	Length of each step (days)	Step
Adsorption	1	$MgCl_2$	33	Adsorption	167	1
	2 6	NaBr	58	Adsorption	44 19	1
	2 6	NaCl	76	Adsorption	175 150	2
	3 7	NaBr	58	Adsorption	39 22	1
	3 7	KCl	86	Adsorption	27 21	2
	3 7	H_2O	≃100	Adsorption	384 384	3
Desorption	4 8	NaBr	58	Adsorption	41 22	1
	4 8	KCl	86	Adsorption	30 27	2
	4 8	H_2O	≃100	Adsorption	160 148	3
	4 8	NaCl	76	Desorption	43 36	4
	4 8	NaBr	58	Desorption	161 154	5
	5	NaBr	58	Adsorption	40	1
	5	KCl	86	Adsorption	28	2
	5	H_2O	≃100	Adsorption	140	3
	5	NaCl	76	Desorption	44	4
	5	$MgCl_2$	33	Desorption	133	5

[1] Groups 1 to 5, parallel to grain compression; groups 6 to 8, perpendicular to grain tangential compression.

parameter being Young's modulus. The maximum load at failure and cross-sectional area yielded the ultimate crushing stress in the longitudinal direction (σ_{Lu}). On the other hand, the transverse compression test yielded the compliance coefficient in the tangential direction, s_{33}. In all cases, the cross-sectional area used for the calculations was that measured at the time of testing.

Finally, the mass of the samples just before the mechanical test and their oven-dry mass measured just before the sorption test was used to estimate the EMC, expressed as a percentage of oven-dry mass.

RESULTS AND DISCUSSION

The main results of ten hardwoods studied here are summarized in Figs. 2 to 5. These graphs illustrate the relationships between the EMC and the compressive properties for all species at 25 C in both the adsorption and desorption states. Despite the long conditioning period, four species (cedro, ishpingo negro, pumaquiro, and palisangre negro) did not reach their equilibrium in adsorption over distilled water. An analysis of their compressive properties as well as their swelling behavior (Hernández 1993a) showed that these woods reached their minimum strength and maximum swelling at the time of testing. All freehand curves shown in these figures were therefore drawn taking into account the swelling intersection point, which was used as an indicator of fiber saturation point for each species (Choong and Achmadi 1991). This intersection point was derived from the volumetric

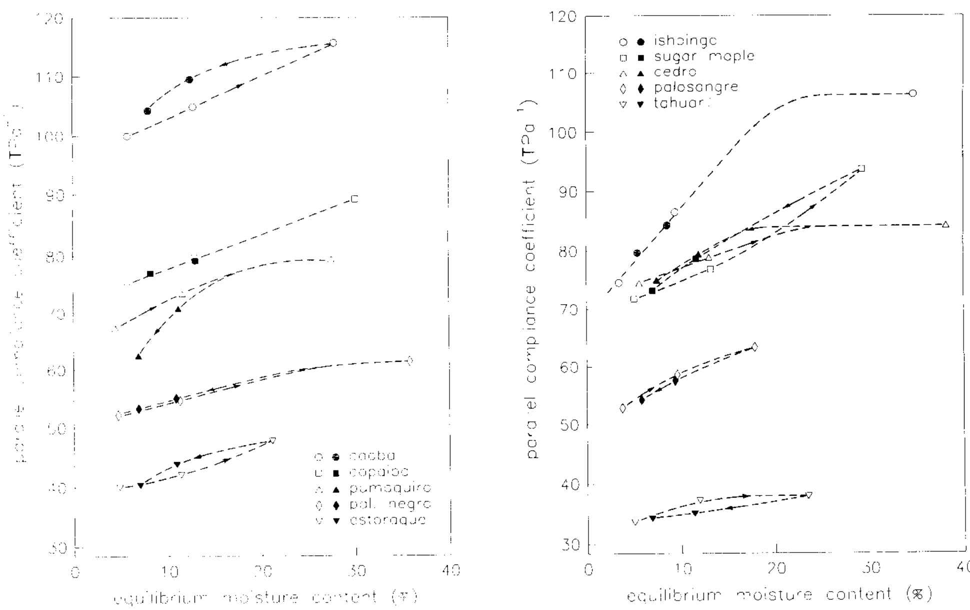

FIG. 2. Compliance coefficients s_{11} in parallel to grain compression for all species as a function of EMC at 25 C. Open and filled points correspond to the adsorption and desorption states respectively.

swelling of these woods (Hernández 1993a). Consequently, the curves for the four species mentioned above were leveled-off at the swelling intersection point rather than at a point obtained over distilled water.

These figures show that for a given RH, the EMCs varied greatly between species for all moisture conditions. This variation has principally been attributed to the presence of variable amounts of extraneous substances in the wood and will be discussed in a subsequent paper (Hernández 1993b).

Second-order effects of moisture sorption on parallel to grain compression

Compliance coefficient s_{11}.—Relationships between the EMC and the compliance coefficient s_{11} for all species are shown in Fig. 2. These results show that for a given EMC, the differences between adsorption and desorption curves are less than 5% for all species. Therefore, with regard to the compliance coefficient s_{11}, the second-order effects of moisture sorption, between 6% EMC and the saturated state, must be considered as negligible from a practical standpoint. These findings confirm previous results reported by Laforest (1981) for sugar maple wood and extend his conclusion to nine other species.

Ultimate compression stress.—Relationships between the EMC and the maximum compression stress in the parallel direction for all species are shown in Fig. 3. This graph shows that, within the range of about 6% EMC and the saturated state, the curves for adsorption and desorption are close. If the stress is calculated from oven-dry dimensions thereby taking the swelling differences into account, the majority of the differences between the curves would be eliminated. This was also the case for the compliance coefficient s_{11}. Hence, the second-order effects of moisture sorption on swelling of wood (Hernández 1993a) explain the similar effects found for the compliance coefficient s_{11} and the ultimate parallel compression stress.

Pumaquiro wood shows a peculiar behavior concerning the second-order effects. In this species, the adjusted ultimate compression stress was about 6% greater after desorption than after adsorption at 10% EMC. It is probable that its pronounced interlocked grain could

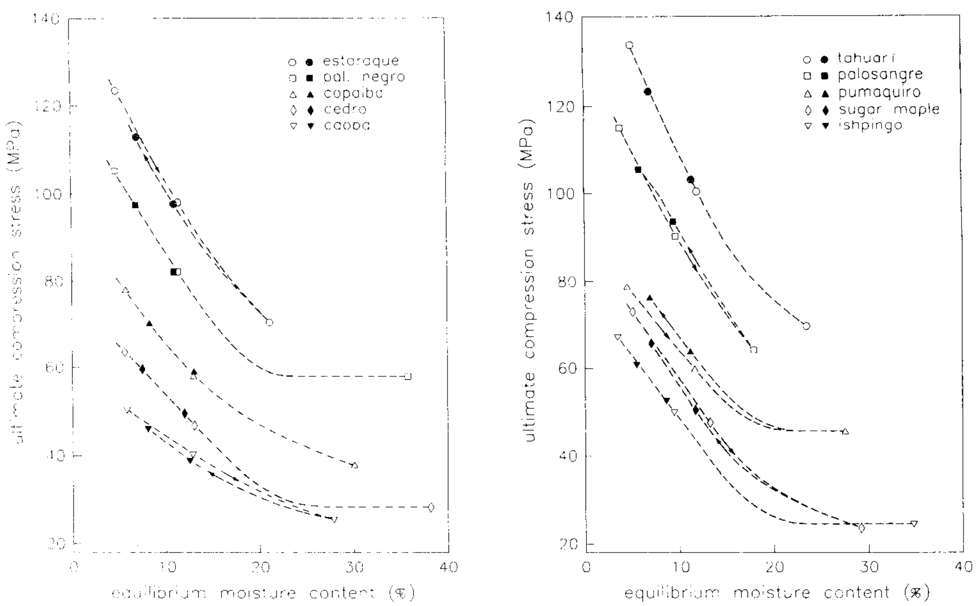

FIG. 3. Ultimate stress in parallel to grain compression (σ_{Lu}) for all species as a function of EMC at 25 C. Open and filled points correspond to the adsorption and desorption states respectively.

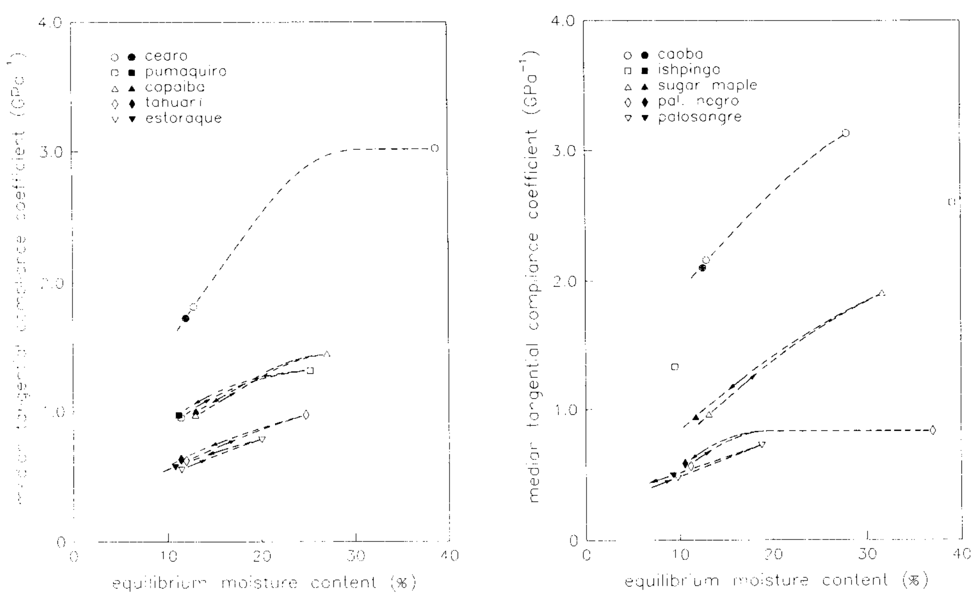

FIG. 4. Compliance coefficients s_{33} in perpendicular to grain tangential compression, measured in the central part of specimens (40 mm), for all species as a function of EMC at 25 C. Open and filled points correspond to the adsorption and desorption states respectively.

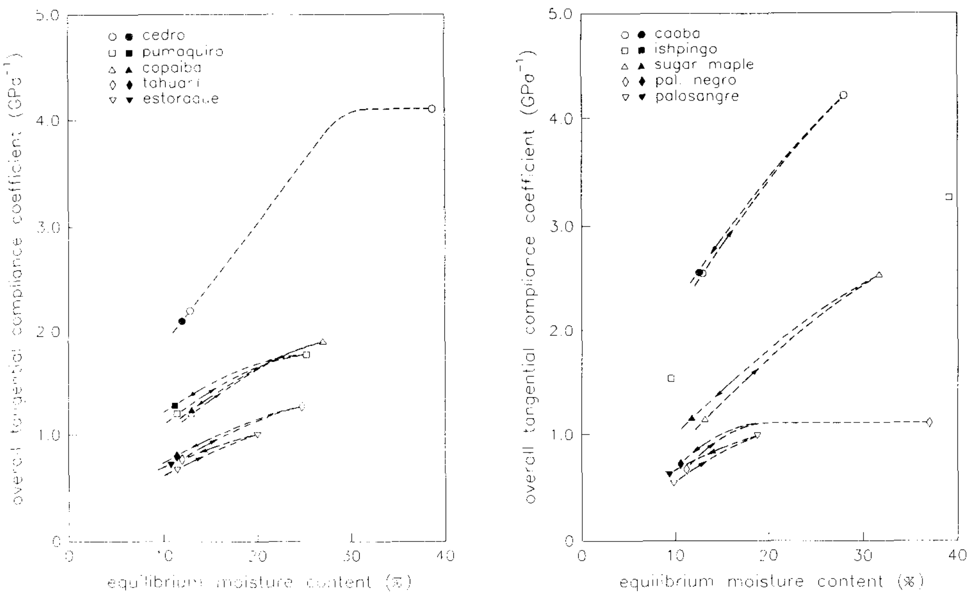

FIG. 5. Compliance coefficients s_{33} in perpendicular to grain tangential compression, measured over the entire length of specimens (≈60 mm), for all species as a function of EMC at 25 C. Open and filled points correspond to the adsorption and desorption states respectively.

play a role in this abnormal behavior where isotherm curves are inverted.

These results establish the limited practical importance of second-order effects on the strength of wood in its longitudinal direction. Conclusions given by Laforest (1981) for the compliance coefficient s_{11} of sugar maple wood between 13% and 18% EMC are further extended to the rupture behavior of nine additional hardwoods and to EMCs that range from 6% to the saturated state. It seems that the second-order effects of moisture content found in parallel to grain compression are directly related to the second-order effects of the swelling of the wood, which occur essentially in the transverse plane.

Second-order effects of moisture sorption on tangential compression

Relationships between EMC and the compliance coefficient s_{33} for all species are shown in Figs. 4 and 5. Figure 4 presents the compliance coefficient measured over the central part of the specimen (40 mm), whereas Fig. 5 depicts the same coefficient measured over the entire length of the same sample.

Although these results might be considered limited with only three sorption points, these were chosen to have an equivalent EMC in each one of the isotherm curves besides the saturated state. In this way, adsorption at 76% RH and desorption at 58% RH yielded generally close EMCs, which permitted direct comparison between both sorption states. Results corresponding to the ishpingo samples in desorption above 58% RH are not shown because their EMC were lost, and only two sorption points are plotted for this species. It is deduced from these graphs that, at a given EMC, there are two different transverse strain ratios depending on the way the hygroscopic equilibrium was reached. Moreover, it seems that the magnitude of the second-order effects is dependent on species. While its presence is not discernible for caoba and cedro, it is perceptible for pumaquiro, copaiba and tahuarí, and it clearly appreciable for the remaining species, that is sugar maple, palisangre negro, estoraque, and palosangre. Given these results, it appears that wood density is not a principal factor affecting the second-order effects of moisture sorption, at least in transverse compression.

As for the parallel to grain compression test, a correction was made to express the compliance coefficient s_{33} from the oven-dry dimensions, taking into account both the cross-sectional area and the span where strain was measured. In this case, the consideration of the swelling of wood in the compliance coefficient calculation does not eliminate the difference between both curves.

For sugar maple, the difference between curves at 12% EMC was estimated to be around 12% (Fig. 4) and 14% (Fig. 5). It is noted that this difference of the compliance coefficient s_{33} is lower than that of 20% estimated for the compliance coefficient s_{22} in radial compression (Goulet 1968; Djolani 1970). On the other hand, this same difference is nearly double that previously calculated for the same compliance coefficient (s_{33}), but measured in tangential tension (Goulet and Hernández 1991). Because experimental techniques used in both studies were similar (level of stress, measurement of the strain), it is probable that the mode of loading (compression or tension) may partially explain this discordance of results.

A comparison between Figs. 2 and 4 confirms that second-order effects of moisture sorption are proportionally greater in the transverse plane of wood than in its parallel plane. Analysis of previous works shows that, for sugar maple wood this trend is also maintained (Goulet 1968; Laforest 1981; Goulet and Hernández 1991).

A comparison between Figs. 4 and 5 shows that there is probably a heterogeneous distribution of the second-order effects into the wood specimen. Curves are generally more widely spaced for the overall compliance coefficient than for the median compliance coefficient. Thus, considering all species except ishpingo negro, the estimated mean extent of these effects at 10% EMC was about 5% in the central part of the specimens and 8% over the entire length of the samples. This discordance between the two deformation measurement methods applied to the same sample indicates that comparison with previous works is somewhat limited and difficult.

Variables of the second-order effects identified for the transverse deformations of sugar maple wood are essentially the type of stress (compression and tension), and the cycle of sorption (first or second cycle). The present work indicates that the species of wood is an additional important parameter. It follows that the method of the measurement of deformation should be better understood in order to be able to explain the role of the variables of the second-order effects of moisture sorption on the transverse mechanical behavior of wood.

It is believed from the results and from previous works that second-order effects of moisture sorption on mechanical behavior of wood could be associated with a creep phenomenon occurring either in the saturated state or in its vicinity (Djolani 1970; Goulet and Fortin 1975). This hypothesis remains probable given the present level of knowledge concerning the second-order effects. An analogous interpretation had been advanced by Barkas (1949) concerning swelling hysteresis only. The difference between the desorption and adsorption treatments and the resulting curves is that the desorption tests were conducted after an earlier adsorption, which had been carried out in three steps up to entire saturation of the cell walls (Table 2). The second-order effects are likely a response to factors that generate a structural reorientation of wood, manifesting itself by creep at the saturated state or close to it. Consequently, a greater compliance coefficient s_{33} of wood in desorption for a same EMC would imply a lower cohesion between its components, at least in the transverse plane as proposed by Djolani (1970). Additional work however is required to validate this theory.

SUMMARY AND CONCLUSIONS

Experiments of moisture adsorption and desorption were performed with nine tropical hardwoods and sugar maple wood in a multiple step procedure at 25 C. Once equilibrium was reached, parallel to grain compression tests and perpendicular to grain tangential compression tests were undertaken. The results of these tests lead to the following main conclusions:

1. At a given equilibrium moisture content, the compliance coefficient s_{33} is lower when equilibrium is reached by adsorption rather than by desorption. The magnitude of this second-order effect of moisture sorption varied with the species of wood and with the mode of measurement of specimen deformation.
2. For the parallel to grain compression strength, the second-order effects of moisture sorption may be considered as limited from a practical standpoint. In all species, except pumaquiro, a correction that takes into account the swelling of wood eliminated this small difference between adsorption and desorption curves.
3. The second-order effects of moisture sorption are proportionally greater in the perpendicular to grain direction of wood than in its longitudinal direction.

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