

INFLUENCE OF MOISTURE SORPTION ON THE STRENGTH OF SUGAR MAPLE WOOD IN TANGENTIAL TENSION¹

Marcel Goulet and Roger Hernández

Professor and Assistant Professor
Département des Sciences du Bois
Université Laval
Ste-Foy, Québec G1K 7P4, Canada

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ABSTRACT

This research confirms that, at a given equilibrium moisture content, the strength perpendicular to the grain is less after desorption than after adsorption. This behavior, called second-order effects of moisture sorption, has been established for sugar maple wood in tangential tension. For the compliance coefficient s_{33} , these effects only halve those measured in radial compression (s_{22}). Also, it is shown that second-order effects could be present, though to a lesser extent, up to failure. Near the oven-dry condition, some internal tensions were responsible for a decrease of the ultimate tensile stress in the adsorption state. A subsequent remoisturing eliminated those tensions, seemingly built up during the preliminary drying of samples. Finally, near the fiber-saturation point, a loss of bound water may take place in the presence of free water and thus affect significantly the strength of wood across its grain.

Keywords: Moisture sorption, moisture changes, mechanical properties, compliance coefficient, ultimate tensile stress, fiber-saturation point, sugar maple.

INTRODUCTION AND BACKGROUND

At a given equilibrium moisture content (EMC), some wood properties will differ, depending on whether the wood is in the state of adsorption or desorption. Goulet (1968) has designated these changes in behavior as second-order effects of moisture sorption.

The observations of Laforest and Plamondon (1976) are in agreement with those of Goulet (1968), who established the existence of this phenomenon while measuring the deformation of sugar maple in radial compression. For a given moisture content, the wood is stiffer when equilibrium is reached by gaining moisture rather than by losing it. A similar study, conducted at temperatures between 5 and 50 C by Djolani (1970), showed that second-order effects and sorption hysteresis are parallel but independent phenomena. In this way, a temperature increase will increase the hysteresis ratio of the moisture contents at a given relative humidity, but it does not affect the second-order effects in radial compression.

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

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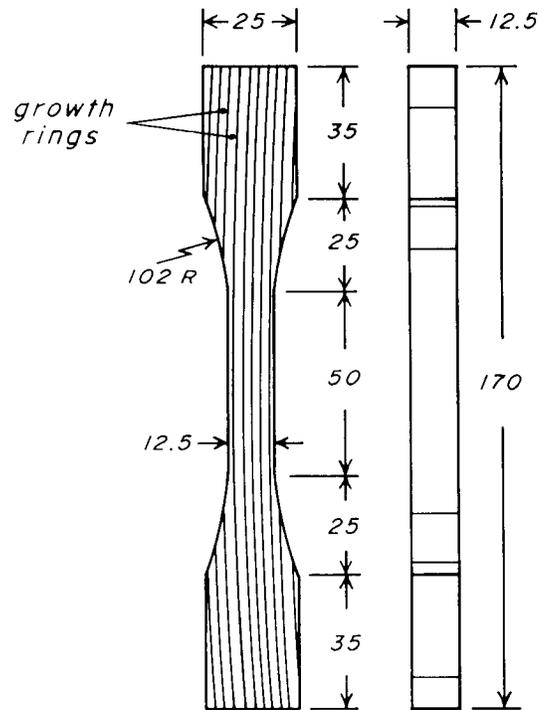


FIG. 1. Schematic representation of specimen (dimensions in mm).

Yet, for the tangential direction, no information about second-order effects is available, either concerning the strain behavior of wood or its rupture. The purpose of this investigation was to provide such information for sugar maple wood in tangential tension. The properties evaluated and reported here are the compliance coefficient (s_{33}), the ultimate tensile stress in the tangential direction (σ_{Tu}), and the equilibrium moisture content obtained during the first adsorption-second desorption cycle at 21 C.

MATERIALS AND METHODS

Experiments were carried out with sugar maple wood (*Acer saccharum* Marsh.). Profile and dimensions of the samples are shown in Fig. 1. This necked-down type of specimen allows both the measurement of deformation and the induction of failure in the reduced central section. As a preliminary step, thirty carefully selected flat-sawn boards were allowed to dry slowly in a conditioning room at a relative humidity of 60% and a temperature of 20 C. At about 14% moisture content, the boards were machined and cross-cut to samples 12.5 mm thick. Twelve adjoining tension specimens were then selected from each board, in order to comply with twelve test environments. This longitudinal matching yielded twelve comparable groups of 30 samples. The test material was all sapwood with average oven-dry density and growth ring thickness of 669 kg/m³ and 2.1 mm, respectively.

TABLE 1. *Relative humidities and number of samples.*

Chemical or saturated salt solution	Nominal relative humidity %	Number of samples	
		First adsorption	Second desorption
P ₂ O ₃	≈0	30	30
MgCl ₂	33	20	30
NaBr	58	30	30
NaCl	76	30	30
KCl	86	30	30
ZnSO ₄	90	30	
H ₂ O	≈100	30	

EXPERIMENTS

The experiment consisted of a moisture sorption test associated with a mechanical test. In order to ensure uniformity between the groups, all material was previously oven-dried together. This preliminary drying, to be considered as the first desorption, was slow in order to reduce the formation of drying stresses in the material. It lasted eighteen days, at gradually increasing temperatures up to 95 C, the final moisture content of the wood being between 0% and 1% of its dry weight. After drying, all specimens were kept in desiccators containing phosphorus pentoxide. Later, those to be conditioned by desorption were immersed in distilled water for twenty hours and then kept in a saturated atmosphere prior to the desorption test. In all cases, the moisture content of this material was well above 70%.

The first adsorption and second desorption tests were carried out simultaneously on all samples, using sorption vats described in detail by Goulet (1968). These vats provided a temperature control of ± 0.01 C during extended periods, thus allowing the control of the relative humidity in the various desiccators serving as small sorption chambers. For each point of the sorption three desiccators were used, each one containing ten specimens. However, the material for the adsorption above 33% RH had to be reduced to twenty specimens only, following the breakage of a desiccator. All sorption conditions were realized over saturated salt solutions (Table 1) in a single step that lasted 91 days. This 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). Control specimens in adsorption over distilled water were weighed periodically on an analytical balance, without being removed from the desiccator, using a method described by Suchsland (1980).

Once this step was completed, mechanical tests were carried out on an Instron TT-BM machine. To transfer stress to a specimen, straight wedge-type grips were used. Strain was measured over a span of 30 mm located in the central straight part of the specimen, using a two-side clip gauge provided with a Heidenhain 3010 linear displacement sensor. Hygrothermal changes during the mechanical test were minimized by wrapping the specimen in cotton that had been previously conditioned above the same saturated solution used by the particular sorption condition. The load was applied at a nominal cross-head speed of 2 mm per minute. Finally, all samples were dried in an oven maintained at 103 ± 2 C until a nearly constant weight was attained.

TABLE 2. Equilibrium moisture content (EMC), compliance coefficient (s_{33}) and ultimate stress (σ_{Tu}) in tangential tension of sugar maple wood as a function of sorption conditions at 21 C. Average values and coefficient of variation (percent of average in italic numbers).

Relative humidity (%)	Equilibrium moisture content (%)		Compliance coefficient s_{33} (GPa ⁻¹)		Ultimate tensile stress σ_{Tu} (MPa)	
	A ¹	D ¹	A	D	A	D
0	0	0.26	0.82	0.85	11.11	12.42
	—	<i>11.20</i>	<i>7.6</i>	<i>10.0</i>	<i>10.4</i>	<i>10.3</i>
33	5.52	8.40	0.85	0.97	11.86	11.75
	<i>1.36</i>	<i>2.81</i>	<i>7.1</i>	<i>10.0</i>	<i>11.5</i>	<i>9.5</i>
58	9.72	12.99	0.95	1.11	11.75	10.39
	<i>1.10</i>	<i>0.76</i>	<i>9.9</i>	<i>10.4</i>	<i>8.9</i>	<i>9.1</i>
76	13.46	18.31	1.07	1.30	10.49	8.76
	<i>0.88</i>	<i>0.62</i>	<i>9.0</i>	<i>9.5</i>	<i>6.9</i>	<i>5.9</i>
86	16.55	26.42	1.24	1.59	9.08	7.37
	<i>1.30</i>	<i>3.87</i>	<i>9.0</i>	<i>8.1</i>	<i>6.7</i>	<i>5.8</i>
90	18.52		1.40		8.16	
	<i>0.93</i>		<i>8.2</i>		<i>7.3</i>	
100	30.27		2.04		5.70	
	<i>2.13</i>		<i>8.9</i>		<i>6.1</i>	

¹ A: adsorption; D: desorption.

These tests permitted the establishment of the compliance coefficient in the tangential direction s_{33} of the wood, the opposite of this parameter being known as the Young's modulus in tangential direction (E_T). Therefore:

$$s_{33} = \frac{1}{E_T} = \frac{\epsilon_T}{\sigma_T}$$

where:

ϵ_T = strain in tangential direction

σ_T = stress in tangential tension below the proportional limit

The maximum load obtained at failure (L_m) gave the ultimate tensile stress in the tangential direction (σ_{Tu}) as follows:

$$\sigma_{Tu} = \frac{L_m}{A}$$

where A is the cross-sectional area of the specimen at the time of each test.

Finally, the weight of the samples just before the mechanical test and their oven-dry weight after the test served to estimate the equilibrium moisture content (EMC), expressed as a percentage of oven-dry weight.

RESULTS AND DISCUSSION

The main results of this work are summarized in Table 2. The following four items will be discussed: dispersion of the measurements, wood hygroscopicity, second-order effects of moisture sorption, desorption at saturation.

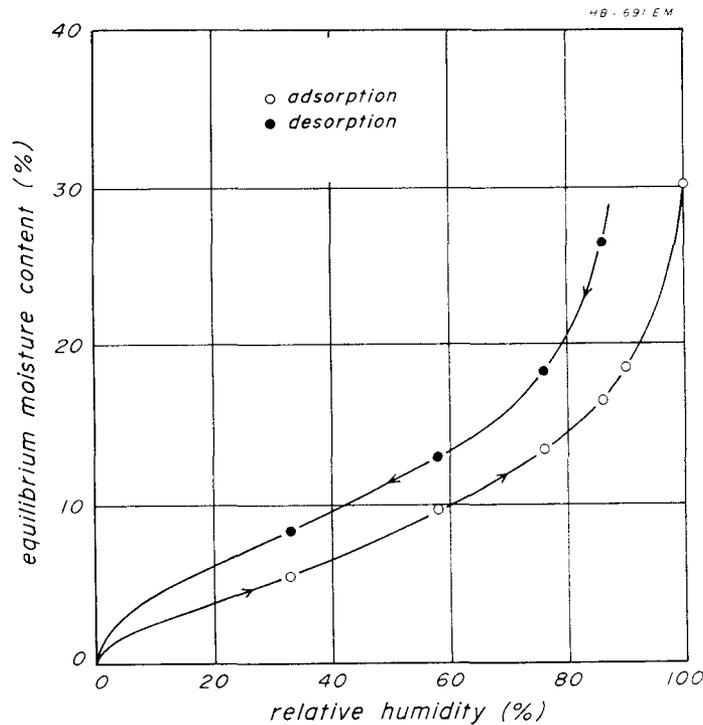


FIG. 2. Equilibrium moisture content for sugar maple wood as a function of relative humidity at 21 C.

Dispersion of the measurements

The relative standard deviation or coefficient of variation of the results is shown in Table 2. With the selection of high-quality material, it was possible to obtain a relatively low dispersion of the experimental data. Thus, for the moisture content (EMC), the use of 30 specimens per group gave a standard error of the mean, expressed as a percentage of the mean, that was generally less than 0.40%, while for the mechanical properties, it was almost always under 2%. Moreover, for the compliance coefficient s_{33} , the dispersion remained constant over the entire hygroscopic range, while for the ultimate stress values the dispersion was inversely proportional to the moisture content, in adsorption as well as in desorption. This behavior might be related to the variation of density within each of the twelve groups. In fact, Siimes (1967) found that changes in the transverse tensile strength due to changes in moisture content were greater in heavy than in light wood belonging to the same species. The matching used in the present study led to the same overall wood density for all groups of specimens. Thus, the effect exerted by decreasing moisture content on strength appears to be more pronounced in heavy wood than in light wood. Such behavior will produce a more important dispersion in dry wood. Hence, it would be useful to introduce wood density as an additional variable in similar experiments on the hygrothermal behavior of the rupture strength across the grain.

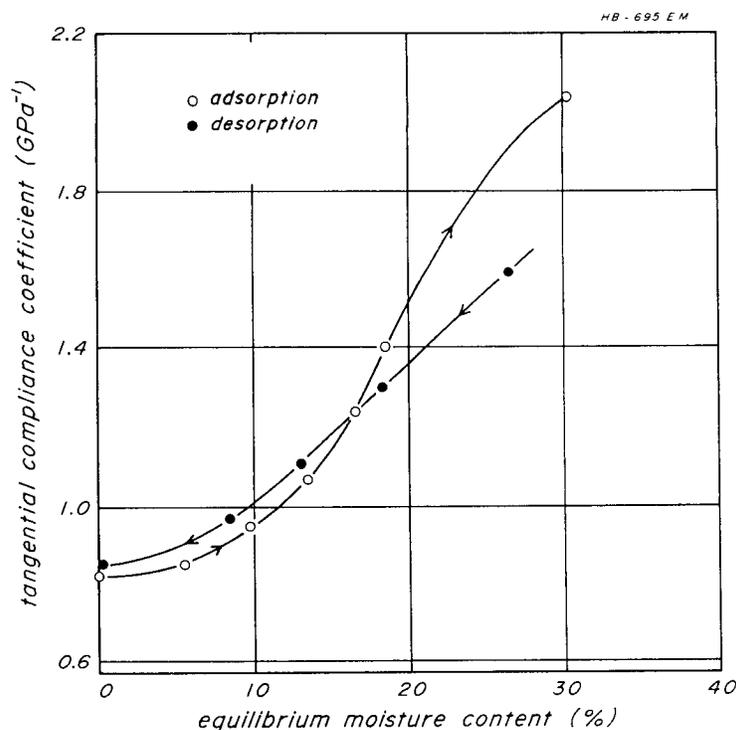


FIG. 3. Compliance coefficient s_{33} in tangential tension of sugar maple wood as a function of EMC at 21 C.

Wood hygroscopicity

Sorption isotherms illustrated in Fig. 2 are similar to those known from previous studies (Goulet 1968; Djolani 1970; Goulet and Fortin 1975). Moreover, many researchers have established that when the isotherms are obtained by starting the measurements with never-dried wood, the initial desorption is always appreciably above subsequent desorption curves at relative humidities above 60% (Higgins 1957; Spalt 1958). This behavior, sometimes called "hysteresis at saturation," remains largely unexplained. There is a tendency to ascribe such behavior to an initial irreversible loss in hygroscopicity after the initial drying of green or water-soaked wood (Skaar 1988), but many authors have shown its presence during subsequent desorptions (Goulet 1968; Fortin 1979; Hart 1984). This behavior may be related, at least partially, to the entrapment of water in the parenchyma cells as noted by Hart (1984). In this study, the experimental data for second desorption at relative humidities of 76% and 86% offer an equilibrium higher than the one expected when starting from the fiber-saturation point (about 30% MC). The coefficient of variation of 0.62% obtained in desorption at 76% RH turned out to be the lowest for all sorption conditions (Table 2). From all this, it follows that the hysteresis at saturation is not only limited to the first drying, but rather to a desorption in the presence of free water.

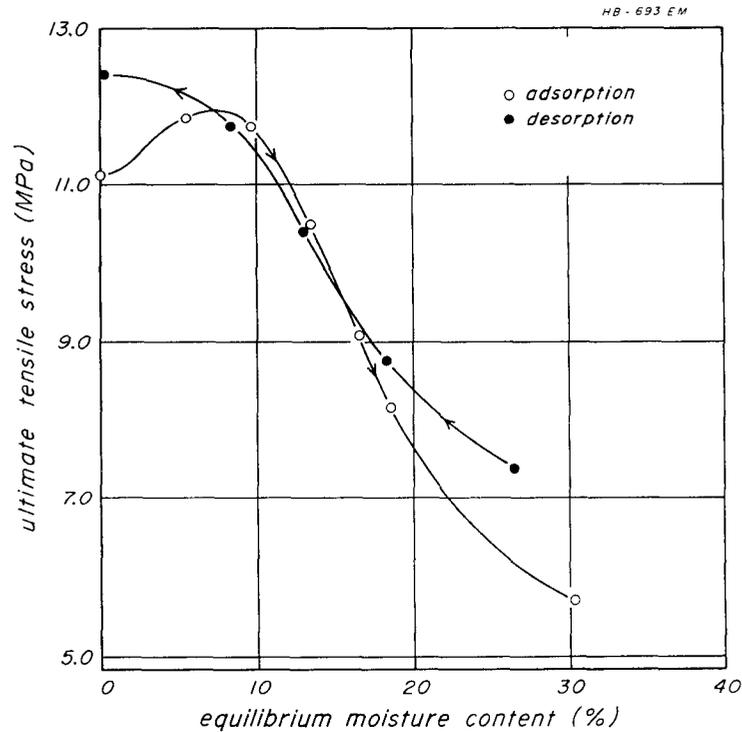


FIG. 4. Ultimate stress in tangential tension of sugar maple wood as a function of EMC at 21 C.

Second-order effects of moisture sorption

Compliance coefficient s_{33} .—Relationships between the EMC and the compliance coefficient s_{33} are shown in Fig. 3, with the state of sorption as a parameter. At a given moisture content, there are two different strain ratios depending on the way the hygroscopic equilibrium was reached. Also, the hysteresis at saturation is apparent by the crossing of the adsorption and desorption curves at about 17% EMC.

The results indicate that below 17% EMC, the largest difference between isotherms is 6.7%, near 12% EMC. This difference is statistically significant at the 95% probability level. The method for establishing the strain coefficient did not affect this difference either, since a comparison that took into account the viscoelastic component of the stress-strain curve, according to Sliker (1978), produced similar results. It is noted that the difference obtained for the compliance coefficient s_{33} is half of that obtained for the compliance coefficient s_{22} in radial compression (Goulet 1968; Djolani 1970). However, direct comparisons between these two coefficients are difficult because of the different rates and modes of loading, different levels of stress, and different techniques used to measure strain in both experiments. On the other hand, Fig. 3 also illustrates that the adsorption and desorption curves do not reach the same point in the oven-dry condition, a

fact already observed in similar experiments concerning the swelling of wood (Seifert 1972; Goulet and Fortin 1975).

Ultimate tensile stress.—Relationships between the EMC and the maximum tensile stress in the tangential direction are shown in Fig. 4. Within the range of about 7% and 17% EMC, the curves for adsorption and desorption come near to one another, the difference at 12% EMC being about 2.7%. Thus, the second-order effects in tangential tension are of lower magnitude for the ultimate tensile stress than they are for the corresponding compliance coefficient s_{33} . Moreover, as the sampling was designed to detect differences of 5% or more, these differences in Fig. 4 are not statistically significant. If they do exist, though, they would correspond to a weakening of the wood tissue in desorption with regard to the preceding adsorption, as was the case above for the compliances.

Nevertheless, the results near the oven-dry state in Fig. 4 are worth discussing because they present a difference of about 12% between the adsorption and desorption values, significant at the 99% probability level. Thus, the remoisturing ("first adsorption") apparently led to the disappearance of internal tensions induced during the preliminary drying, in such a way the following desorption ("second desorption") was realized without the same tensions. As can be seen in Fig. 4, this tension reduction was progressive and completed at about 9% EMC in adsorption. Therefore, in the vicinity of the oven-dry condition, an adsorption after a mild drying, particularly without thermal treatment, should lead to higher rupture values.

On the other hand, drying did not affect the compliance coefficient s_{33} to the same extent: in Fig. 3 the curves do not intersect at low moisture contents. The drying tensions mentioned above could have been located in weak zones, for example, near wood rays where the ruptures in tangential tension originate. Consequently, the importance of these drying tensions should vary with sample dimensions, type of drying, and wood species. This phenomenon may explain, at least partially, the discordance reported in the literature concerning the moisture content at which wood reaches its maximum strength in transverse tension (Bodig and Jayne 1982). Under ideal conditions, higher strength in tangential tension could be reached at the oven-dry state.

A complementary test was performed on a matched group that remained six more months in the oven-dry state over phosphorus pentoxide at 21 C. Results show no difference from those indicated in Table 2 for adsorption. Thus the time, within the range studied, is not a variable of the drying tensions mentioned above near the anhydrous state.

Desorption at saturation

The desorption isotherms for the mechanical properties appear to be affected by the hysteresis at saturation (Figs. 3 and 4): above 17% EMC, the adsorption and desorption isotherms significantly diverge from each other, the differences being about 20% at 26% EMC for both properties. Although the desorption curves have 26% EMC as an upper limit, such differences should not be reduced significantly as the fiber-saturation point is approached. To support this point of view, a similar behavior has already been reported up to 37% EMC for data on sugar maple in radial compression (Goulet 1968). Thus the results obtained above in desorption indicate that within the range of "hysteresis at saturation," the loss of

bound water had begun before all free water had evaporated from the wood. The same interpretation can be given to shrinkage curves published for European beech by Stevens (1963), showing that dimensional changes started taking place in drying at about 45% EMC.

It seems inappropriate to generalize results obtained for transverse properties only and on small samples, i.e., with 10 to 15 mm along the grain. Nevertheless, moisture sorption is a bulk property of wood and one should be aware of its possible consequences especially for test material labeled "green" or "water-saturated" but whose moisture content approaches the fiber-saturation point.

CONCLUSIONS

Simultaneous experiments of moisture adsorption and desorption were realized in a single step at 21 C on sugar maple wood. Associated at equilibrium with tangential tension tests, they led to the following main conclusions:

1. At 12% EMC, the compliance coefficient s_{33} is nearly 7% less when equilibrium is reached by adsorption rather than by desorption. This effect seems present, though to a much lesser degree, up to failure.
2. In the vicinity of the oven-dry condition, internal stresses were responsible for a decrease of the ultimate stress in the adsorption state. These tensions, attributed to the preliminary drying of the samples, were reversible.
3. Hysteresis at saturation is not limited to the first or initial desorption, but rather to a loss of bound water in the presence of free water.
4. Near the fiber-saturation point, the hysteresis at saturation has affected significantly the strength of wood across its grain.

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