

# Experimental study of the mechanosorptive behaviour of softwood in relaxation

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**Abstract** In softwood material, the coupling between mechanical loading and hydric state is known as the mechanosorptive effect. However, the coupling with viscoelastic effect remains unclear so far, especially when the loading is controlled by strain. In this context, the present paper is focused on the process of creation and recovery of ‘hygrolock’ behaviour, i.e. a stress locking effect which occurs in a phase of drying under load. For this purpose, several relaxation tests were first performed on small-scale silver fir specimens in order to express the relaxation function in terms of the ambient humidity. Then, two mechanosorptive tests were carried out in order to induce hygrolock stresses in the same sample loaded in sustained strain condition, and subjected to cyclically varying humidity. Based on the assumption of stress partition, the analysis of the test results clearly shows the existence of a hygrolock stress. From these experimental evidences, a law is finally proposed to describe the evolution of the hygrolock stress in terms of the hydric state of the softwood material.

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## Introduction

The phenomenon of coupling between hydric and mechanical effects in wood is known as the mechanosorptive behaviour. This unconventional behaviour was first described in the early 1960s for timber wood subjected to variable loading and humidity (Armstrong and Kingston 1960). Since then, a number of experiments have been carried out in order to investigate this complex behaviour. Most of them concern creep tests under variable humidity (e.g. Hearmon and Paton 1964; Ranta-Maunus 1975; Hunt 1984, 1986, 1997; Mohager and Toratti 1993; Hanhijärvi 2000; Toratti and Svensson 2000). Only a very few of them concern relaxation tests under variable humidity (Pittet 1996).

It is generally assumed that the mechanosorptive behaviour consists of two complementary phenomena. The first one is an instantaneous effect; it relies on a difference in the mechanical response of wood during drying or moistening period under load. Ranta-Maunus (1993) has proposed distinct coefficients to distinguish drying and wetting phases in order to reflect the existence of an irreversible strain. The second one is a delayed effect, known as mechanosorptive creep (Grossman 1971); it consists of accelerated creep caused by humidity changes, as opposed to normal time-dependent creep. Several authors have proposed to represent this effect as a function of water content rate (Leicester 1971; Bazant 1985; Salin 1992), while others have related it to the number of drying–moistening cycles (e.g. Hunt and Shelton 1988; Hunt 1989, 1997). The mechanosorptive creep may lead to premature failure (Hearmon and Paton 1964) or to a creep limit (Hunt and Shelton 1987), depending on the rate of loading. Toratti (1992) summarized the approaches; he has proposed a global model which takes into account both effects.

An alternative approach for the analysis of the mechanosorptive behaviour of wood is based on the assumption of the existence of a recoverable locking phenomenon, i.e. a part of the mechanical strain is temporarily blocked during a period of drying under stress, before being recovered during a subsequent moistening period under the condition of sufficient moisture content. This phenomenon was depicted from experimental evidences by Gril (1988) who named it ‘hygrolock strain’. Based on this assumption, a model was developed where this effect is coupled with creep (Dubois et al. 2005). Later on, this effect was represented by means of a ‘hygrolock spring’ connected to a Kelvin generalized model (Husson et al. 2010; Dubois et al. 2012). Besides, an alternative model was developed where the mechanism of creation of the hygrolock strain is represented by an ‘active box’ in which the elastic behaviour of wood is progressively tuned during a drying–moistening cycle (Colmars et al. 2009). It was recently found that these two approaches were equivalent (Colmars et al. 2014). These approaches were developed under the assumption of partitioned strain, i.e. the total strain is the sum of hydric, elastic, viscoelastic and hygrolock strain parts in the course of time. However, given the limited number of experimental work available in literature, this hygrolock behaviour is still not very well known. In particular, it seems that almost nothing is known about its existence and evolution in relation to the relaxation behaviour of wood under variable loading and humidity.

In the present paper, the issue of the hygrolock behaviour is addressed with the assumption of the existence of a ‘hygrolock stress’ in the case of softwood tested in relaxation under cyclic humidity, i.e. a recoverable stress locking phenomenon in analogy with the hygrolock strain discussed above. For this purpose, a series of preliminary tensile and relaxation tests were first carried out on silver fir samples under various humidity conditions, aiming at determining their basic hydric and mechanical behaviour. The use of a specific testing device enables the possibility of precisely controlling mechanical loading and strain, relative humidity, and temperature during the tests. Relaxation test results give a basis for proposing a linear law to express the relaxation function in terms of the ambient humidity in the frame of linear viscoelasticity. Then, two complementary mechanosorptive tests specially designed for this purpose were carried out in order to induce hygrolock stress in the same silver fir sample tested in blocked strain condition under cyclically varying humidity. Based on the assumption of stress partition, a meticulous analysis of the test results demonstrates the existence of a hygrolock stress and it provides valuable details about the process of its creation and recovery.

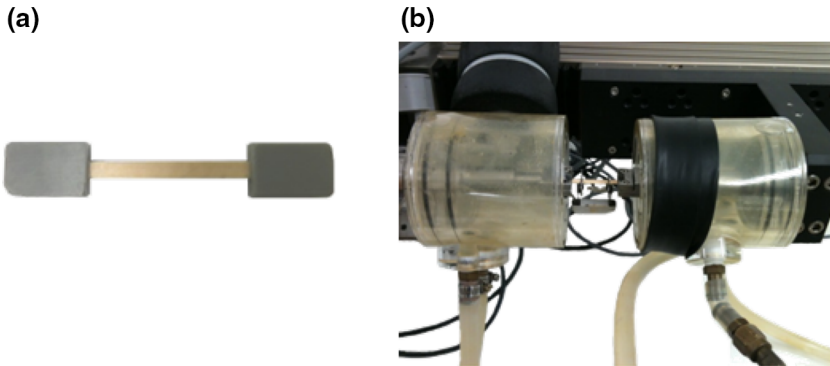
## Experimental setup

The experimental programme consists of two series of tests. At first, a series of preliminary tests were devoted to the determination of the hygromechanical properties of the softwood under consideration, including its relaxation behaviour under steady humidity conditions. Then, a second series consisted of two mechanosorptive tests specially designed to induce hygrolock stresses in small samples subjected to repeated humidity cycles in controlled strain condition.

The rectangular-shaped specimens were prepared from silver fir softwood (*Abies alba* Mill.), with the longitudinal direction parallel to the grain. A precision table saw was used to carefully cut the specimens parallel to the grain from the same piece of wood, with the following cutting dimensions: 50 mm in the longitudinal direction, 3 mm in the radial direction, 1 mm in the tangential direction. The small size of the specimen cross-section was especially chosen to limit hydric gradient effects in the transverse directions, and to minimize the transient time necessary for the moisture content to reach equilibrium within the specimen cross-section under changing ambient humidity. Preliminary tests at zero stress, where the longitudinal strain was monitored by means of an extensometer, showed that a stabilized state was obtained after a period of 45 min.

The specimens were selected according to the number of annual rings within their width (between 4 and 6). Each specimen end was embedded in a resin block over a length of 10 mm. This aimed at facilitating the setting up and clamping in the machine’s jaws, and at limiting stress concentrations at specimen ends (Fig. 1a).

The tests were carried out by means of a specific testing device (Fig. 1), specially designed to perform tensile/compression tests under tuneable ambient conditions: air relative humidity and temperature (Pittet 1996; Navi et al. 2002; Froidevaux et al. 2010). The device consists of a tensile machine with a maximum capacity of 500 N, equipped with a hygrothermal cell with a double wall. Water at a controlled



**Fig. 1** a Silver fir specimen with both ends embedded in resin blocks; b tensile testing machine equipped with a double-walled hygrothermal cell

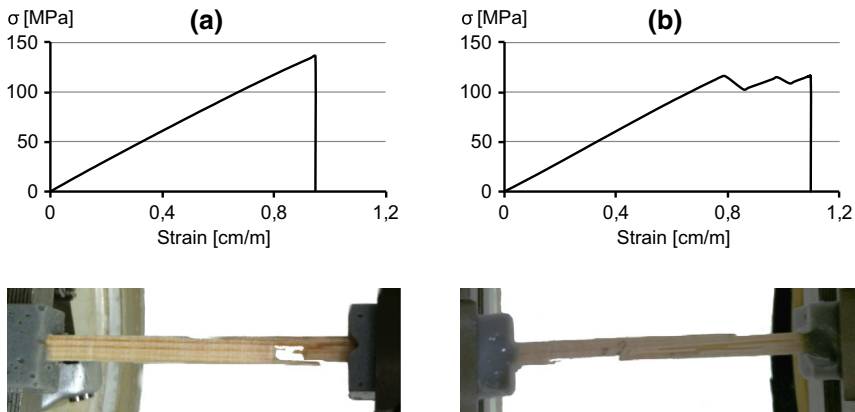
temperature is circulated between the two walls, thus allowing maintaining a steady temperature inside the cell. The relative humidity within the cell is controlled by mixing two flows of dry and humid air. Electronic sensors were used to monitor the relative humidity and the temperature inside the climatic cell during the tests. The applied load was controlled with an accuracy of  $\pm 0.05$  N. The mechanical stress was estimated by dividing the applied force by the cross-sectional area, which was calculated for each tested specimen from its width and depth precisely measured by means of an electronic digital calliper.

The experimental programme consisted of a total of 31 tests, with the following repartition: 17 tensile tests, 12 relaxation tests and 2 mechanosorptive tests. As already mentioned before, all tests were carried out with similar specimens in order to minimize errors. When possible, the tests were performed on the same specimen. In any case, every specimen was stored for several hours at the specified relative humidity before testing until stabilization of the monitored strain, i.e. the humidity equilibrium was reached within the sample. The tensile, relaxation and mechanosorptive tests were all carried out in controlled strain. All tests were performed at a constant temperature within the cell, equal to  $20.8 \pm 0.3$  °C. Details about the testing procedures and results are presented and discussed below for every type of test.

## Preliminary tests

### Tensile tests

The objective of the preliminary tensile tests was to determine the ultimate tensile strength at different humidity levels. For this purpose, 17 specimens were loaded up to failure at a steady relative humidity ranging between 5 and 75 %. As already mentioned, every specimen was stored at a stabilized relative humidity and temperature during several hours before testing. The tests were conducted in



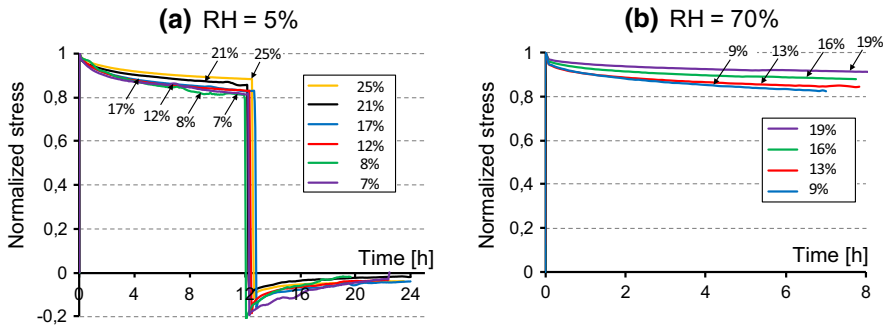
**Fig. 2** Examples of typical tensile test curves and alternative failure modes obtained for two specimens tested at RH = 50 %

controlled displacement condition, with a fixed elongation rate equal to 0.3 %/min, identical for all tested specimens. This rate was chosen in order to limit viscoelastic effects during the tests.

Figure 2a, b shows typical results obtained for two specimens tested at a stabilized relative humidity (RH) equal to 50 %. Two alternative modes of failure are clearly observed in these figures, confirmed by visual inspection of the broken specimens: the first one corresponds to a brittle fracture of all grains within a given cross-section; the second one corresponds to a progressive delaminating process between longitudinal fibres, accompanied by a failure of the grain, leading finally to the failure of the specimen. It is worth noticing that in each case, the first part of the curve is linear, i.e. the short-term mechanical behaviour can be considered as elastic linear up to failure, with a longitudinal Young's modulus equal to  $16.1 \times 10^3$  and  $14.6 \times 10^3$  MPa, respectively. The average value obtained for the tensile ultimate strength is  $115 \pm 22$  MPa, with no clear influence of the humidity level. This result will be used in the following to express the loading level as the ratio between the applied stress and the ultimate tensile strength.

### Relaxation tests

The main objective of the relaxation tests is to determine the limit of linearity for various relative humidity levels and then to derive a reliable expression for the relaxation function in terms of the ambient humidity. With this aim, two series of tests were performed, each series corresponding to a given relative humidity with several relaxation tests under various loading conditions: six tests at RH = 5 % with an initial stress ranging from 7 to 25 % of the ultimate tensile strength for the first series; four tests at RH = 70 % with an initial stress ranging from 9 to 19 % of the ultimate tensile strength for the second one. In order to limit the scatter, two specimens only were used for the relaxation tests and indeed the same specimen was used for all tests in each series. As already mentioned in 'Experimental setup'



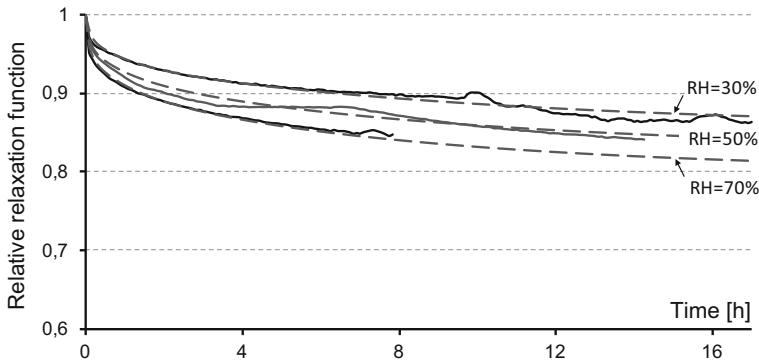
**Fig. 3** Normalized stress curves for different initial stress levels. **a** For RH = 5 % (12 h of relaxation followed by 12 h of stress recovery after return to zero strain state); **b** for RH = 70 % (pure relaxation)

section above, the specimen was kept in the testing cell under zero force at the specified relative humidity in order to ensure hydric equilibrium before testing. Moreover, this resting period was maintained for at least 12 h to make sure that the residual stress was totally released before starting the next test. In each series, the relaxation tests were carried out in stepwise increasing order of initial stress level. The loading was applied at a constant strain rate equal to 0.3 %/min. The time duration necessary to reach the peak load was between 10 and 40 s. During the tests, the load was measured at a frequency of four points per second.

The results are plotted in Fig. 3 as normalized stress curves (or relative relaxation curves, i.e. actual tensile stress divided by the peak value of the stress at the beginning of the relaxation period) in terms of elapsed time. For RH = 5 % (Fig. 3a), the relative relaxation curves are coincident in the first four cases (i.e. for normalized stress equal to 7, 8, 12 and 17 %), leading to the conclusion that the viscoelastic behaviour is not affected by the loading level. In other words, linearity is ensured for the viscoelastic behaviour until the initial stress reaches about 17 % of the tensile ultimate strength. For RH = 70 % (Fig. 3b), the linearity limit drops below 16 % (i.e. situated between 13 and 16 %). Therefore, the loading levels will be limited to 13 % in the following, in order to ensure the applicability of linear viscoelasticity.

Figure 4 presents the results of relaxation tests carried out for three fixed levels of relative humidity: 30, 50 and 70 % on three different samples (result for RH = 70 % previously shown in Fig. 3b). The tests were performed with a fixed strain corresponding to an initial stress slightly below 13 % of the ultimate tensile strength, i.e. the limit of linearity determined above. It is worth noticing that the relative relaxation functions plotted in Fig. 4 are dimensionless, i.e. all test values were divided by the instant Young's modulus (equal to the initial value of the measured relaxation function). As a consequence, all curves are starting from unity at time  $t = 0$ .

The dependence of the relaxation behaviour of softwood in relation to the ambient humidity is obvious in this figure. It is clearly observed that the stress is relaxing more quickly and in a magnified way in a wet environment than in a dry



**Fig. 4** Relative relaxation functions for three fixed levels of relative humidity—from tests (solid lines) and from Eq. (4) (broken lines)

one. To allow for this well-known feature, it is assumed letting the relaxation function be linearly dependent on the relative humidity. Hence, it is proposed to express the dimensionless relaxation function  $R_{RH}(t)$  at a given humidity as follows

$$R_{RH}(t) = \beta_{RH}R_{70}(t) + (1 - \beta_{RH})R_{30}(t) \tag{1}$$

where  $R_{30}(t)$  and  $R_{70}(t)$  are the dimensionless relaxation functions at RH = 30 and RH = 70 %, respectively.  $\beta_{RH}$  is a parameter which depends on the relative humidity, as follows

$$\beta_{RH} = 0.025(RH - 30\%) \tag{2}$$

In the frame of linear viscoelasticity, a relaxation function can be expressed as a Dirichlet’s series (Bazant and Wu 1974; Jurkiewicz et al. 1999). In the present case, the dimensionless nature of the relaxation function corresponds to the additional boundary condition  $R(0) = 1$ , hence

$$R(t) = 1 - \sum_{\mu=1}^r \rho_{\mu}(1 - e^{-\alpha_{\mu}t}) \tag{3}$$

where  $R(t)$  stands for  $R_{30}(t)$  or  $R_{70}(t)$ , respectively, depending on the ambient relative humidity. Given a set of  $\alpha_{\mu}$  parameters, the  $\rho_{\mu}$  parameters are determined by means of the mean square method from the relaxation test results presented above (refer to Appendix A in Electronic Supplementary Material for further details). Finally, it comes for the dimensionless relaxation function  $R_{RH}(t)$ , in terms of the relative humidity

$$R_{RH}(t) = (0.8893 - 0.0554\beta_{RH}) + (0.0669 + 0.0250\beta_{RH})e^{-0.25t} + (0.0187 + 0.0116\beta_{RH})e^{-2.5t} + (0.0251 + 0.0188\beta_{RH})e^{-25t} \tag{4}$$

where  $\beta_{RH}$  is given by Eq. (2). This expression is plotted as broken lines in Fig. 4, where the values are compared with the experimental data for three relative

humidity levels 30, 50 and 70 %, respectively. The experimental and the analytical curves are in a fair agreement, which confirms the validity of Eq. (4). This equation will be used in the following to estimate the pure viscoelastic effects during the mechanosorptive tests.

## Mechanosorptive tests in relaxation

It is well known that mechanosorptive effects occur in loaded wood with changing humidity. In the previous section, the viscoelastic behaviour of softwood has been analysed for fixed ambient humidity. The aim in the present section is to create mechanosorptive effects in the form of hygrolock stresses. For this purpose, two complementary relaxation tests were carried out under variable humidity conditions. These two tests are complementary in the sense that the humidity is varied cyclically from ‘dry’ to ‘wet’ in the first case, while it is varied cyclically from ‘wet’ to ‘dry’ in the second case. In order to minimize the scatter, the same specimen was used for the two tests (same specimen previously used for relaxation tests under 30 % RH in ‘[Relaxation tests](#)’ section), which are described and analysed in the following subsections.

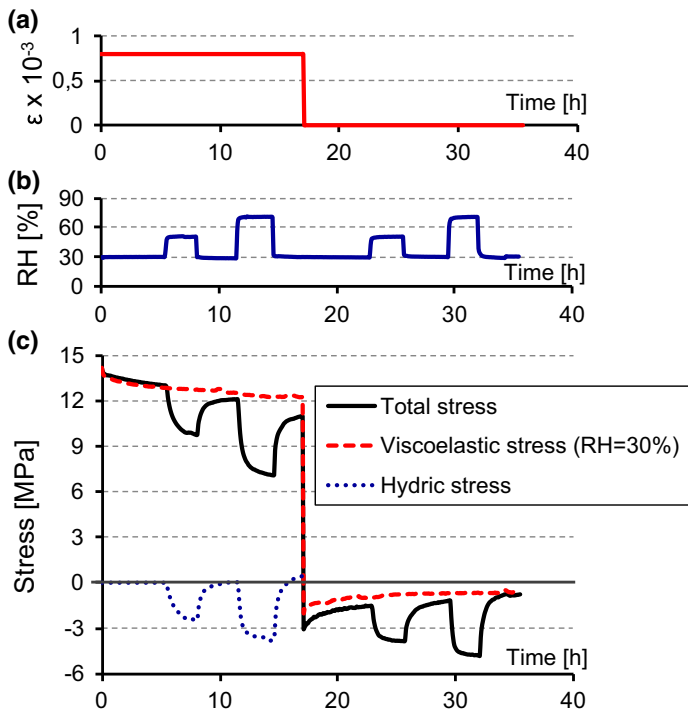
### Mechanosorptive test 1: ‘dry-to-wet’ repeated humidity cycles

The experimental procedure was as follows.

- First, the specimen was stored at zero stress in the testing cell under constant RH = 30 % until stabilization of the strain value given by the extensometer, i.e. the humidity equilibrium was reached within the sample (see ‘[Experimental setup](#)’ section).
- Then, the specimen was exposed to a fixed strain over a period of 17 h. This strain was initially produced by applying a stress equal to about 12 % of the tensile ultimate strength. Finally, the strain was cancelled for the next 19 h (Fig. 5a).
- Simultaneously, the specimen was exposed to two ‘dry-to-wet’ humidity cycles with a length of 2.5–3.0 h during each period, with RH ranging from 30 to 50 % for the first cycle and from 30 to 70 % for the second one (Fig. 5b).
- Besides, the same specimen was tested separately in blocked zero strain condition under the same relative humidity cycles in order to measure the hydric stress, i.e. the stress evolution induced in the specimen by the same humidity cycles.

In Fig. 5c, the evolution of the resulting total stress measured during the test is plotted as a solid line, while the dotted line represents the hydric stress evolution. The measured total stress evolution is compared with the one previously obtained for the same specimen under constant humidity RH = 30 % (broken line). It is seen that every humidity cycle causes a decrease of the total stress followed by a trend of the stress to retrieve its initial evolution when the humidity is returned to its initial



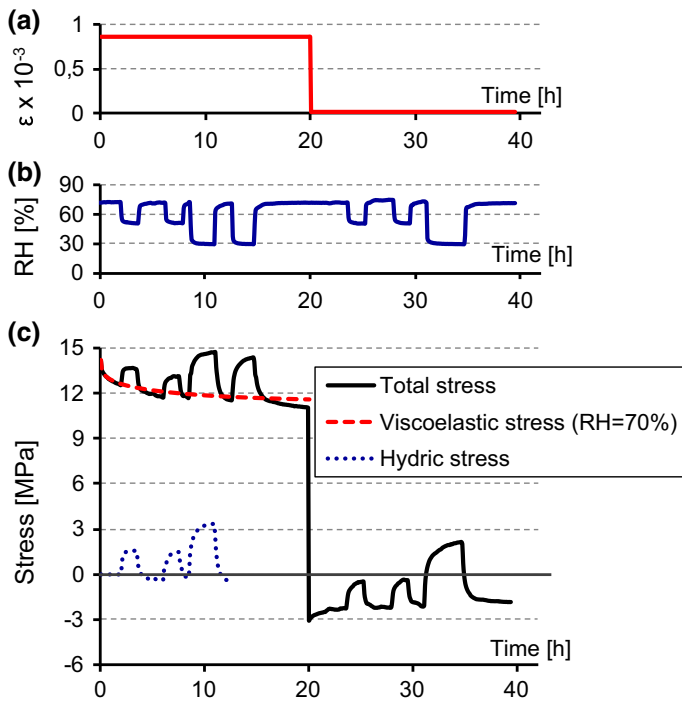


**Fig. 5** Mechano-sorptive test 1. **a** Longitudinal strain imposed to the specimen; **b** relative humidity cycles imposed during the test; **c** response of the specimen: viscoelastic stress at constant RH = 30 % (*broken line*); stress evolution under ‘dry-to-wet’ repeated humidity cycles (*solid line*); hydric stress in blocked zero strain condition (*dotted line*)

level. However, it is noted that the reference relaxation curve under constant humidity is not completely retrieved after every humidity cycle. Indeed, the distance between the two curves increases with the amplitude of the drying cycle. This distance is preserved upon cancelling of the strain. In contrast, it progressively vanishes when the humidity cycles are repeated during the phase of stress recovery. As it will be seen hereafter, this distance denotes the existence of a mechano-sorptive effect. The fact that it finally disappears shows the ability of the material to cancel the mechano-sorptive effect which has recently been considered as a kind of memory effect by some authors (Husson et al. 2009; Dubois et al. 2012).

### Mechano-sorptive test 2: ‘wet-to-dry’ repeated humidity cycles

As in the previous test, the specimen was first stored at zero stress at constant RH = 70 % in order to ensure hydric equilibrium. Then, the specimen was subjected to a fixed strain over a period of 20 h, before being cancelled for the next 20 h (Fig. 6a). During the first period, the specimen was exposed to two couples of ‘wet-to-dry’ humidity cycles, with RH ranging from 70 to 50 % for the first couple of



**Fig. 6** Mechanosorptive test 2. **a** Longitudinal strain imposed to the specimen; **b** relative humidity cycles imposed during the test; **c** response of the specimen: viscoelastic stress at constant RH = 70 % (*broken line*); stress evolution under ‘wet-to-dry’ repeated humidity cycles (*solid line*); hydric stress in blocked zero strain condition (*dotted line*)

cycles and from 70 to 30 % for the second one (Fig. 6b). Compared with the previous test, each cycle of humidity has been duplicated in order to check the repeatability of the mechanical response. These humidity cycles were repeated during the second period after cancellation of the strain. Besides, the same specimen was tested separately in order to measure the hydric stress evolution induced by the same humidity cycles in blocked zero strain condition (dotted line in Fig. 6c).

The evolution of the resulting total stress (solid line) is compared with the pure relaxation stress (broken line) previously obtained for the same specimen under constant humidity RH = 70 % in Fig. 6c (available for the first half of the test only).

In contrast to the results of the previous test, it is observed that the relaxation curve at constant humidity is almost retrieved after every humidity cycle during the first period. In the second period, the stress recovery is not complete; a residual stress is observed and it persists after 20 h of recovery. Obviously, in qualitative terms, the global behaviour of the sample is different between the two mechanosorptive tests. This will be analysed and discussed hereafter.

## Discussion

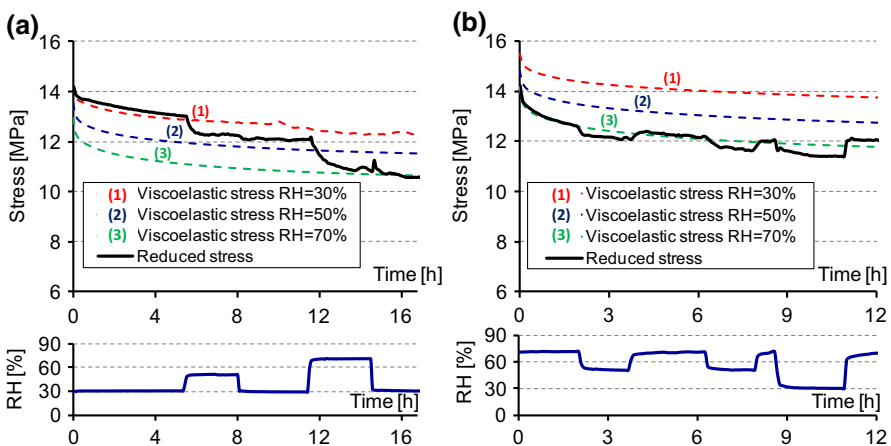
A classic approach used by several authors to analyse creep mechanosorptive test results is to compare the creep strain at constant RH with a ‘reduced strain’ obtained by subtracting the hydric strain from the total measured strain (e.g. Navi et al. 2002). In analogy, a ‘reduced stress’ is used hereafter; it is derived from the test results by subtracting the hydric stress from the total stress measured during the test, as follows

$$\sigma_r = \sigma - \sigma_w \quad (5)$$

Figure 7a, b shows the reduced stress evolutions as solid lines and the viscoelastic stress evolutions at various constant RH as broken lines during the first half of each mechanosorptive test, respectively.

In the first case (Fig. 7a), the reduced stress evolution obviously switches from the viscoelastic curve at RH = 30 % to that at RH = 50 % when the humidity is increased from 30 to 50 %. However, there is no trend for the reduced stress to return towards the initial viscoelastic curve when the humidity retrieves its 30 % initial value. The same trend is observed during the second humidity cycle. This behaviour is not in accordance with the principle of linear viscoelasticity. Indeed, this shows the existence of a cumulative irrecoverable effect in the case of ‘dry-to-wet’ repeated cycles.

On the contrary, the previous effect is not observed in the case of ‘wet-to-dry’ repeated moisture cycles (Fig. 7b). However, the stress evolution during every humidity cycle is opposite to what is expected. As a matter of fact, the stress should increase towards the viscoelastic curve corresponding to RH = 50 or 30 %, instead of decreasing as it is in the figure. This shows that an additional effect occurs upon drying that causes the specimen behaviour to diverge from a pure linear viscoelastic



**Fig. 7** Evolutions of the reduced stress (*solid line*) and viscoelastic stress (*broken lines*) versus time; **a** in the case of ‘dry-to-wet’ repeated moisture cycles; **b** in the case of ‘wet-to-dry’ repeated moisture cycles

response. This effect vanishes upon moistening after each humidity cycle, which shows that it is recoverable in this second case.

Finally, it is clearly observed that the global response of the specimen is not solely governed by pure linear viscoelasticity. A temporary stress locking effect occurs upon drying, which is recovered upon moistening. In analogy with the concept of hygrolock strain previously introduced by other authors (Gril 1988; Husson et al. 2010), this stress locking effect will be analysed in the following under the hypothesis of the existence of a hygrolock stress.

## Evidence of the existence of a hygrolock stress

### Bases for the analysis

The aim in this section is to discuss the existence of a hygrolock stress in loaded softwood subjected to variable moisture conditions. For this purpose, the test results are analysed on the basis of stress partition, i.e. the total stress is assumed to be the sum of a hydric part ( $\sigma_w$ ), a viscoelastic part ( $\sigma_{ve}$ ) and a hygrolock part denoted hereafter as  $\sigma_{HL}$ , as follows

$$\sigma = \sigma_w + \sigma_{ve} + \sigma_{HL} \quad (6)$$

This approach is motivated by the fact that the analysis is performed on the basis of mechanosorptive tests in relaxation, where the strain is applied as a whole.

In Eq. (6), the evolutions of  $\sigma$  and  $\sigma_w$  are known from the test measurements: solid lines in Figs. 5c and 6c for the total stress  $\sigma$ , and dotted lines in Figs. 5c and 6c for the hydric part  $\sigma_w$ , respectively. It is worth noticing that  $\sigma_w$  is resulting from a complex combination of hydric (swelling/shrinkage), elastic and viscoelastic effects. Anyway, according to the principle of stress partition, these effects are assumed to be additive, and hence the reduced stress  $\sigma_r = \sigma - \sigma_w$  defined by Eq. (5) is not affected by the peculiar nature of  $\sigma_w$ .

In order to derive the evolution of  $\sigma_{HL}$  from the test results on the basis of Eq. (6), it is necessary to estimate the evolution of the viscoelastic part  $\sigma_{ve}$  under variable humidity on the basis of the relaxation function established in ‘Preliminary tests’ section in the case of steady relative humidity. This is done by using the principle of superposition (see Appendix B in Electronic Supplementary Material for further details). Accordingly, the viscoelastic stress  $\sigma_{ve}(t)$  evolution caused by a constant strain loading  $\varepsilon_0$  for a number of successive humidity levels  $HR_i$  occurring from intermediate times  $t_i$ , writes

$$\sigma_{ve}(t) = \tilde{R}(t)\varepsilon_0 \quad (7)$$

where

$$\tilde{R}(t) = R_1(t_1, t) + \sum_{i>1} [R_i(t_i, t) - R_{i-1}(t_i, t)], \forall t \in [t_i, t_{i+1}] \quad (8)$$

In this equation,  $R_i(t_i, t)$  is given by Eq. (4) where  $t$  is substituted for  $(t - t_i)$ . The estimated evolutions of the viscoelastic part of the stress given by Eq. (8) are shown in Appendix B (Figure B2a, b in Electronic Supplementary Material) for the two mechanosorptive tests.

### Existence of a hygrolock stress

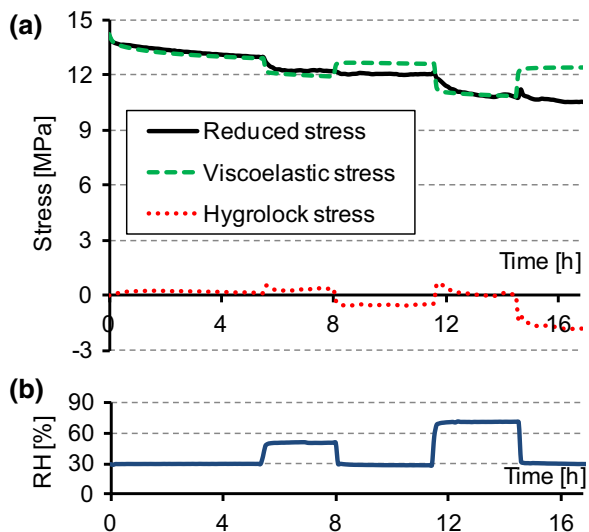
Given Eqs. (5) and (6), the evolution of the hygrolock stress can be easily derived from the test results as follows

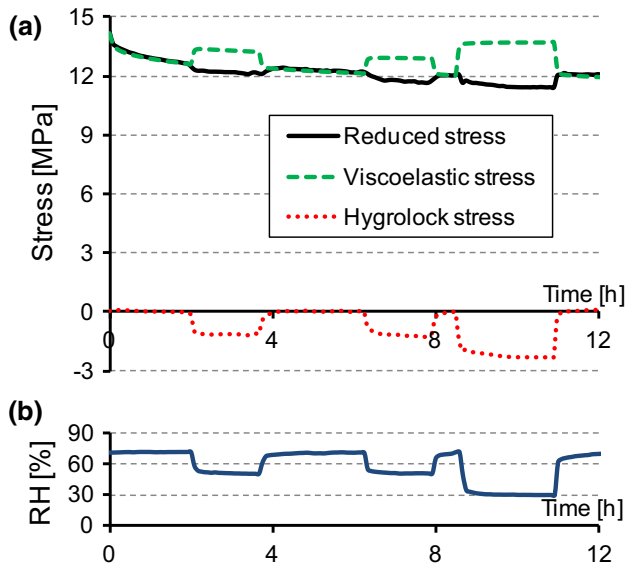
$$\sigma_{HL}(t) = \sigma_r(t) - \sigma_{ve}(t) \quad (9)$$

where  $\sigma_r(t)$  is given in Fig. 7 for each mechanosorptive test and  $\sigma_{ve}(t)$  is derived from Eqs. (7) and (8). The resulting values are presented in Figs. 8 and 9. In each figure, the solid line is the reduced stress, while the broken line is the viscoelastic stress. According to Eq. (9), the difference between these two lines is the hygrolock stress  $\sigma_{HL}(t)$ ; its evolution during the test is represented by the dotted line in each figure.

In the case of ‘dry-to-wet’ repeated humidity cycles (Fig. 8), no significant evolution is observed for the hygrolock stress as far as the humidity level is maintained or increased:  $\sigma_{HL}(t)$  can be therefore considered as equal to zero during this first period. Then, it is observed that the hygrolock stress suddenly appears when the first drying step occurs (i.e. RH drops from 50 to 30 % at time 8.1 h), before vanishing upon the next wetting step (increase of RH from 30 to 70 % at time 11.5 h). It appears again upon the second drying step (i.e. RH drops from 70 to 30 % at time 14.6 h), with magnified amplitude. It is worth noticing that the peak observed at the beginning of each wetting step is resulting from the fact that the transient hydric gradient is not considered in the present analysis.

**Fig. 8** Mechanosorptive test 1—**a** reduced stress (solid line), viscoelastic stress (broken line), hygrolock stress (dotted line); **b** relative humidity





**Fig. 9** Mechanosorptive test 2—**a** reduced stress (*solid line*), viscoelastic stress (*broken line*), hygrolock stress (*dotted line*); **b** relative humidity

In the case of ‘wet-to-dry’ repeated moisture cycles (Fig. 9), it is noted that the reduced stress and the viscoelastic stress are equal in ‘wet’ condition, while they evolve separately in ‘dry’ condition. As a consequence, the hygrolock stress appears upon drying and vanishes upon wetting for each humidity cycle. Similarly to the previous case, its amplitude is magnified when the amplitude of the humidity cycle is increased.

This analysis clearly shows the existence of a hygrolock stress parallel to the grain. Based on the results above, it is concluded that the hygrolock stress appears upon drying and recovers upon moistening. Its evolution follows the humidity changes: it evolves instantly with any increase or decrease of humidity, with no obvious time dependence. It is clear that the magnitude of the hygrolock stress and the amplitude of the humidity cycle are in a strong correlation. These observations will be used in the following to propose a model of evolution for the hygrolock stress.

### Model of evolution for the hygrolock stress

Based on the previous conclusions, it is possible to introduce the following assumptions for the evolution of the hygrolock stress. From Eq. (9), the instant evolution of the reduced stress for any sudden change of humidity writes

$$\Delta\sigma_r = \Delta\sigma_e + \Delta\sigma_{HL} \quad (10)$$

since the instant variation  $\Delta\sigma_{ve}$  reduces to a pure elastic stress change  $\Delta\sigma_e$  which is caused by the sudden change in the Young’s modulus due to the humidity change at a fixed strain  $\varepsilon_0$ .

Looking at Fig. 8, it is obvious that the hygrolock stress evolves in a sudden manner from an initial zero value to a constant negative value after every drying step. Simultaneously, the reduced stress evolution is obviously not affected by the humidity change. This observation is taken into account by setting  $\Delta\sigma_r = 0$  in Eq. (10). It comes

$$\Delta\sigma_{HL} = -\Delta\sigma_e = -\Delta E\varepsilon_0 \quad (11)$$

This equation gives the evolution of the hygrolock stress caused by a drying step.  $\Delta E$  is the Young's modulus increase due to the loss of moisture content in the softwood sample. It is worth noticing that Eq. (11) expresses a relationship between the magnitude of the hygrolock stress and the amplitude of the humidity cycle, which is in accordance with the experimental results discussed in 'Evidence of the existence of a hygrolock stress' section.

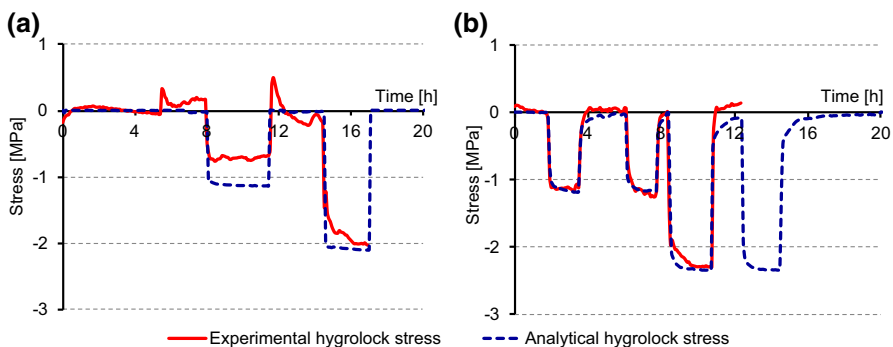
Looking again at Fig. 8, it is obvious that the reduced stress and the viscoelastic stress evolve in a similar manner during the period of time following each wetting step. Therefore, the hygrolock stress is returned to a zero value. In order to satisfy this condition, the instant evolution of the hygrolock stress caused by a wetting step must write

$$\Delta\sigma_{HL} = -\sigma_{HL} \quad (12)$$

where  $\sigma_{HL}$  is the value gained by the hygrolock stress just before the wetting step occurs.

Finally, Eqs. (11) and (12) depict the evolution of the hygrolock stress in an incremental form for a succession of drying and wetting steps. According to observations reported above, this evolution is not time dependent.

In Fig. 10, the values given by these two equations are compared with the experimental values previously derived from the two mechanosorptive tests. It is seen that their evolutions given by the model are fairly similar to those derived from the tests. It is worth noticing that the peak observed at the beginning of each wetting step is resulting from the fact that the transient hydric gradient is not considered in the present analysis. This comparison asserts the existence of the hygrolock stress; it



**Fig. 10** Evolution of the hygrolock stress derived from the two mechanosorptive tests—derived from tests (*solid line*); given by Eqs. (11) and (12) (*broken line*)

validates the assumptions introduced above for the analysis (principle of stress partition) and for the model of evolution.

## Conclusion

An extensive experimental programme was carried out in order to investigate the relaxation behaviour of softwood in variable humid environment. A series of preliminary tests was first devoted to the determination of the relaxation function in terms of steady relative humidity. Then, two mechanosorptive tests—consisting of relaxation tests under cyclic ambient humidity—were conducted aiming at evidencing the existence of a hygrolock stress in softwood loaded in a cyclically changing humid environment. The main conclusions are as follows.

- The loading level must be limited to 13 % of the ultimate tensile stress in order to ensure the applicability of linear viscoelasticity to silver fir softwood when loaded in the longitudinal direction.
- A linear formulation is proposed for the relaxation function over a period of 17 h, in terms of the relative humidity. A specific procedure, based on the mean square method, is given to determine the material parameters in this formulation.
- The existence of a hygrolock stress is clearly evidenced by comparing results obtained from relaxation tests in steady ambient humidity with results obtained from same relaxation tests in cyclic ambient humidity.
- The main features of this hygrolock stress are as follows: it appears during drying and vanishes during the next phase of moistening. The hygrolock stress evolves instantaneously upon any humidity change.
- Finally, a model is proposed for the evolution of the hygrolock stress: upon drying, it progressively increases in such a way as to compensate for the pure elastic stress induced by the stiffening effect due to the humidity decrease; it progressively recovers upon a phase of moistening until the material is returned to its initial humidity state. This model is validated by a comparison with values derived from the two mechanosorptive tests.

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