Study of the hygric inertia of a vegetal fibre material

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ABSTRACT. Hygroscopic inertia is defined as the material capacity to adsorb and reject moisture and dampen indoor relative humidity variations. Moisture buffering capacity of different materials such as gypsum and brick, have been widely studied. In this paper, authors investigate moisture transfer under isothermal conditions in a hemp concrete specimen subjected to static variations of air relative humidity. Only one face of the specimen is in contact with indoor air of a climatic chamber. Other faces are made impermeable to water by adding an alumina sheet. The specimen is weighted each hour. Experimentation is also compared to numerical results that take into account hysteresis phenomenon of the sorption curve under the simulation environment SPARK. Results are also compared to data found in literature for gypsum and brick.

KEY WORDS: hemp concrete, moisture buffering capacity, modeling, moisture, hysteresis, SPARK.

1 Introduction
The sustainable world’s economic growth and people’s life improvement greatly depend on the use of alternative products in the architecture and construction, such as vegetal fibres conventionally called green materials. Among these materials, hemp is widely used in building construction. When mixed to lime, it gives hemp concrete a porous ecomaterial with low thermal conductivity. Researches done until this day [1-4] allowed us to determine its physical properties and its performances regarding the energy consumption and hygrothermal comfort in buildings. In this paper, we are interested experimentally and numerically by its moisture buffering capacity. First we present experimental results concerning the behaviour of such material under periodical step change of relative humidity. Then results are compared numerically using the simulation environment SPARK, which allows studying coupled heat and moisture transfer through material using Umidus [5] model modified in order to take into account sorption isotherm hysteresis [6]. Results are compared to other materials from literature.

2 Experimental study
In order to determine moisture buffering capacity, experiments has been done at laboratory of GRESPI/ LTM of Reims University. It considers two samples which surfaces are (10 cm x 11 cm) and (12 cm x 12 cm) and their thicknesses are 3 cm and 6 cm respectively. The test specimens are exposed to a periodical step change in ambient relative humidity chamber between 75% during 24 hours and 35% during 24 hours (Fig. 1). The temperature is held constant at 20°C. In order to ensure one-dimensional water vapour transfer between the specimen and ambient air, five faces of samples were sealed with an aluminium tape keeping only one face exposed to indoor environmental chamber conditions.

Fig. 1: View of the samples placed in the climatic chamber.

The weight change of specimen was measured by a balance with a resolution of 0.01g. Initially, the specimens are in equilibrium state at 20°C temperature and 35% relative humidity. For reasons
of availability of the chamber, the period of the tests is 5 days. In order to better determine the behaviour over a longer period, other tests are actually running.

Figure 2 shows the variation of the mass in the samples. One can see that for sample 2 thickness 6 cm, the variation of mass are more important than that of sample 1. This means that for over one period of 24:00, the penetration depth in material is higher than 3 cm. The experimental study is accompanied by a numerical study whose equations of the model are clarified in the following part.

![Fig. 2. Mass variation of specimens over a period of 5 days.](image)

### 3 Physical Model

We find in the literature several works concerning modeling the hygrothermal transfer. Most of the research is still carried out by using phenomenological macroscopic models, introducing heuristic laws relating thermodynamic forces to fluxes through moisture and temperature dependent transport coefficient. In this way, one of the most used and accepted macroscopic models for studying heat and moisture transfer through porous material is the Phillip and de Vries model [7] which uses as driving potentials the temperature and moisture content gradient. While most studies on heat transport processes largely agree, no consensus in the choice of driving potentials for describing moisture transport phenomena exists at present and some authors modified the Phillip and de Vries model by using other driving potentials instead of the moisture content. We should cite Perdesen [8] who used the capillary pressure, but in practice it is difficult to be directly measured. Künzel [9] used the relative humidity as a potential. The calculation methodology employed by them is correct since it takes into account the discontinuity phenomenon at the interface.

However, in many circumstances, the direct use of the moisture content as the driving forces can be appropriate since it can be more computationally viable and, most of time moisture content is more useful parameter as it has a simple and direct physic meaning. Consequently, in this paper, we use the Umidis model [5] in which the moisture in porous material can be transported under liquid and vapor phases. The liquid phase is supposed to move by capillary pressure, while the vapor phase is supposed to be diffused due to partial pressure gradients. Considering these hypotheses, the governing moisture balance equation within the wall is given by

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left( D_T \frac{\partial T}{\partial x} + D_\theta \frac{\partial \theta}{\partial x} \right) + \frac{\partial}{\partial x} \left( D_v \frac{\partial \theta}{\partial x} \right)
\]  

(1)

The boundary conditions for this equation are given by (x=0 and x=L):

\[
- \rho_i \left( D_T \frac{\partial T}{\partial x} + D_\theta \frac{\partial \theta}{\partial x} \right) \bigg|_{x=0,i} = h_{M,i} \left( \rho_{we,i,e} - \rho_{we,i,s} \right)
\]

(2)

\[
- \rho_i \left( D_T \frac{\partial T}{\partial x} + D_\theta \frac{\partial \theta}{\partial x} \right) \bigg|_{x=L,j} = h_{M,j} \left( \rho_{we,j} - \rho_{we,i,j} \right)
\]

(3)

The governing energy balance equation states that the temporal variation of energy is due to the net amount of heat received/lost by conduction and the phase change within pores:

\[
\rho_0 C_P = \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \lambda_{app} \frac{\partial T}{\partial x} \right) + L_v \rho_1 \left( \frac{\partial}{\partial x} \left( D_T \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial x} \left( D_\theta \frac{\partial \theta}{\partial x} \right) \right)
\]

(4)

where

\[
C_P = C_{P_o} + C_{P_i} \frac{\rho_i}{\rho_o} \theta
\]

(5)

And the boundary conditions for this equation are given by (x=0 and x=L):

\[
- \lambda_{app} \frac{\partial T}{\partial x} - L_v \rho_1 \left( D_T \frac{\partial T}{\partial x} + D_\theta \frac{\partial \theta}{\partial x} \right) \bigg|_{x=0,i} = h_{T,e} \left( T_{a,e} - T_{s,e} \right) + L_v h_{M,e} \left( \rho_{we,e,i,e} - \rho_{we,i,s} \right) + \alpha_i \Phi_{ray,e}
\]

(6)
\[
\lambda = 0.1058 + 0.77 \theta
\] (8)

### 3.1 Determination of transport coefficients

Hemp concrete transport coefficients were calculated using relations suggested by Philip et al. [7] and Kunzel [8]. For the transport coefficient associated to a gradient of moisture content, it is computed from dry vapour permeability \( \delta_0 \) (kg.m\(^{-1}\).s\(^{-1}\).Pa\(^{-1}\)) \( \delta_0 = \frac{\delta_a}{\mu} \) where \( \delta_a \) is air vapour permeability which is equal to 2.10\(^{10}\) kg.m\(^{-1}\).s\(^{-1}\).Pa\(^{-1}\) at 23°C and \( \mu \) is material vapour diffusion resistance factor and the specific hygric capacity \( \xi \) which is the slope of moisture retention curve:

\[
D_\theta = \frac{\delta_a}{\mu} \frac{P_{VS}}{\rho_s \xi}
\] (9)

Vapour transport coefficient under a temperature gradient is given by the relation:

\[
D_{T,ve} = \phi \frac{\delta_a}{\rho_l \mu} \frac{dP_{VS}}{dT}
\] (10)

To simplify the problem, vapour transport coefficient under moisture gradient is assumed equal to moisture transport coefficient under moisture gradient:

\[
D_{\theta,ve} = D_\theta
\] (11)

Thermomigration of liquid phase is also neglected and thus thermomigration coefficient \( D_T \) is also equal to \( D_{T,ve} \).

### 3.2 Sorption isotherm

In this study we use the analytical model of adsorption/desorption proposed by Merakeb [6]. In this model, the relation between the water content and the relative humidity is written in the form:

\[
\ln \left( \frac{\theta}{\theta_s} \right) = a \cdot \ln(\phi) \cdot \exp(b\phi)
\] [12]

Where \( a \) and \( b \) are parameters determined experimentally.

Referring to [1-2], hemp concrete sorption curves are determined for values of relative humidity varying from 0 to 100%.

For the adsorption curve (from 0 to 100%):

\[
\theta = 0.151 \cdot \exp \left[ 1.1 \cdot \ln(\phi) \cdot \exp(2.3 \cdot \phi) \right]
\] (13)

For the desorption curve (from 100% to 0%):

\[
\theta = 0.151 \cdot \exp \left[ 0.75 \cdot \ln(\phi) \cdot \exp(2.3 \phi) \right]
\] (14)

In the general case, between these two curves, the sorption curve is given by:

\[
\ln \left( \frac{\theta}{\theta_s} \right) = a \cdot \ln(\phi) \cdot \exp(b\phi) + \Delta a \cdot \ln(\phi) \cdot \exp(\Delta b \phi)
\] (15)

\( \Delta a \) and \( \Delta b \) are defined by equations that depend on the sorption state (whether it is adsorption or desorption).

### 4 Simulations

To solve the previous system of equations we used the Simulation Problem Analysis and Research Kernel (SPARK), a simulation environment allowing to solve efficiently differential equation systems [10-11]. Equations (1) and (4) are discretized using the finite difference method.

We compared simulation results with experimental data for the specimen 1. Two cases are considered with and without taking into account sorption hysteresis.

Fig. 3 compares numerical results with hysteresis to experimental data. It can be seen that there is a good agreement between both curves.
Fig. 3: Comparison between numerical and experimental data for specimen 1.

Fig. 4 shows mass variation when neglecting sorption hysteresis. Three cases are considered: taking the adsorption curve as the sorption isotherm, taking the desorption curve or taking the mean curve between the adsorption and desorption. We notice that none of the three cases is in agreement with the dynamical variation of the specimen mass variation.

Fig. 4. Comparison between numerical and experimental data when neglecting hysteresis.

Fig. 5 compares moisture content in the material at 6 mm depth from the surface with and without hysteresis. It can be seen that for the model using hysteresis the curve tends toward the model neglecting hysteresis and using the mean curve between adsorption and desorption. However, as shown in fig. 6, mass variation of specimen for the two cases is different. This is mainly due to initial moisture content which is different for both cases.

Fig. 5. Moisture content variation at 6mm depth for the 4 sorption isotherm cases and for a period of two weeks.

Fig. 6. Specimen mass variation for a period of two weeks with and without sorption hysteresis.

Fig. 6 shows specimen mass variation for a period of two weeks with and without sorption hysteresis. When neglecting hysteresis, periodic variation is reached after 4 days whereas it needs two weeks to reach equilibrium when sorption hysteresis is considered. These results are in agreement with those found in literature for a hemp concrete with similar properties [12].

Comparing hemp concrete other material such as brick and gypsum, we notice it has a very high moisture buffering capacity. After 10h and under a static step of 75% of relative humidity, specimen mass increases about 118 g/m². For gypsum, under the same conditions, mass increases about 26 g/m² and for 1 cm of brick mass growth is about 19 g/m². [13].

5 Conclusion

In this paper, we investigated experimentally and numerically the hydric behaviour of a mixture of hemp and lime (hemp concrete) under periodical static step change of air relative humidity.
Compared to gypsum and brick, our results suggest that hemp concrete has a higher moisture buffering capacity. In parallel a numerical model using the simulation environment SPARK showed the importance of taking into account sorption isotherm hysteresis in order to predict material dynamical behaviour. These results are actually completed with experimental data for longer periods.

### NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
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<tbody>
<tr>
<td>C</td>
<td>Specific heat</td>
<td>J kg⁻¹. K⁻¹</td>
</tr>
<tr>
<td>C₀</td>
<td>Specific heat of dry material</td>
<td>J kg⁻¹. K⁻¹</td>
</tr>
<tr>
<td>C₁</td>
<td>Specific heat of water</td>
<td>J kg⁻¹. K⁻¹</td>
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<td>Dᵣ</td>
<td>Mass transport coefficient associated to a temperature gradient</td>
<td>m².s⁻¹.°C⁻¹</td>
</tr>
<tr>
<td>Dᵣᵥ</td>
<td>Vapor transport coefficient associated to a temperature gradient</td>
<td>m².s⁻¹.°C⁻¹</td>
</tr>
<tr>
<td>D₀</td>
<td>Mass transport coefficient associated to a moisture content gradient</td>
<td>m².s⁻¹</td>
</tr>
<tr>
<td>D₀ᵥ</td>
<td>Vapor transport coefficient associated to a moisture content gradient</td>
<td>m².s⁻¹</td>
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<tr>
<td>g</td>
<td>Gravity acceleration</td>
<td>m³.s⁻¹</td>
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<tr>
<td>hₘ</td>
<td>Mass transfer convection coefficient</td>
<td>kg.m⁻².s⁻¹</td>
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<tr>
<td>hᵣ</td>
<td>Heat transfer convection coefficient</td>
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<td>Lᵥ</td>
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<tr>
<td>t</td>
<td>Time</td>
<td>s</td>
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<tr>
<td>α</td>
<td>Solar radiation absorption coefficient</td>
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<tr>
<td>θ</td>
<td>Moisture content</td>
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<td>λ</td>
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<td>ρᵥ</td>
<td>Mass density of vapor water</td>
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### References


