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Modeling the moisture buffering behavior of a coated biobased building material by including hysteresis

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Abstract

To investigate the influence of plastering on the moisture buffering behavior of hemp concrete, experiments are performed on two samples, one uncoated and one coated with less hygroscopic lime-based plasters. Global mass variations were monitored and results indicate in this case that coating reduces the MBV of hemp concrete. In addition, local temperatures and relative humidities are also measured at several depths within the samples in the view of validating a heat and mass transfer model. Results show that including the hysteretic behavior of each layer (hemp concrete and plasters) leads to a better agreement between numerical and experimental results, but also plays a significant role in the prediction of stored energy.

Keywords: Hemp concrete; Lime-based plasters; Moisture Buffer Value; Relative humidity measurement; Hysteresis; Heat and moisture transfer;

1. Introduction

In a context of building energy efficiency and indoor comfort, using hygroscopic materials in building envelopes may moderate the variations of indoor humidity and, thus, may positively affect HVAC system energy consumption or indoor air quality [1][2]. To characterize and compare the moisture buffering capability of materials, the Nordtest project developed a protocol to determine a standardized quantity, namely the Moisture Buffer Value MBV [3]. Concretely, a sample is exposed to cyclic step-changes in RH between high and low values for 8 and 16 hours respectively and MBV indicates the amount of water that is transported in or out of a material per open surface area.

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To date, MBV of numerous building materials is well characterized. However, building envelopes are made of several layers, only few studies are dealing with the influence of surface coating on the moisture buffering behavior [4][5][6]. Experimental works of Ramos et al. [4] and Hameury [5] showed respectively that moisture buffering capacity of gypsum and wood could be reduced up to the half when painting layers were applied. Roels et al [6] observed that the hygric response of coated gypsum boards could not be accurately simulated with a finite element model, but also that the prediction of could be improved by modifying the moisture capacity. More generally, hysteresis model should be used for analyzing the moisture buffering behavior of multilayered building envelope.

In this work, the moisture buffering behavior of uncoated and coated biobased building materials is analyzed experimentally and numerically by including hysteresis. Section 2 introduces the experimental device used to assess MBV and temperature and relative humidity fields in uncoated and coated hemp concrete samples. A model accounting for phase change effects and hysteresis is presented in Section 3. In Section 4, the performance and accuracy of the model is evaluated against experimental data in the view evaluating the influence of finishing layers.

2. Materials and experimental facility

The investigated material is hemp concrete (defined as a mix of hemp shives and lime-based pre-formulated binder) since it presents a low environmental impact [7], interesting thermal properties [8] and an “excellent” moisture buffering capacity [9,10]. When used in building, hemp concrete is coated with lime-based plasters. All material hygrothermal properties were measured in the laboratory and are gathered in Table 1. Dry thermal capacity $c_p$ is determined by DSC measurement and thermal conductivity $\lambda$ is measured by the guarded hot plate technique according to the standard EN ISO 12667 [8]. Dry cup vapor resistance factor $\mu_{dry}$ were measured according to ISO 12572. The main sorption isotherms were determined gravimetrically at 23 °C using salt solutions to generate relative humidity according to ISO 12571 and fitted with a GAB model (eq. (1)). It should be noted that lime-based plasters are less hygroscopic and permeable, but also less insulating than hemp concrete. Furthermore, we observe hysteresis in the sorption curves whatever the material.

$$w = \frac{w_m \times C \times K \times \Box}{(1-K\Box)(1+K(C-1)\Box)}$$

(1)

Table 1. Hygrothermal properties of hemp concrete and lime-based plasters.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ [kg.m$^{-3}$]</th>
<th>$c_p$ [J.kg$^{-1}$.K$^{-1}$]</th>
<th>$\lambda$ [W.m$^{-1}$.K$^{-1}$]</th>
<th>Adsorption</th>
<th>Desorption</th>
<th>$\mu_{dry}$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemp concrete</td>
<td>450</td>
<td>1000</td>
<td>0.1</td>
<td>0.02</td>
<td>0.86</td>
<td>0.08</td>
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<td>5</td>
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<tr>
<td>Lime-sand plaster</td>
<td>1730</td>
<td>830</td>
<td>0.4</td>
<td>0.0017</td>
<td>0.94</td>
<td>0.0126</td>
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<td>1000</td>
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<td>0.55</td>
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<td>16</td>
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<tr>
<td>Lime hemp plaster</td>
<td>930</td>
<td>1000</td>
<td>0.2</td>
<td>0.012</td>
<td>0.65</td>
<td>0.0375</td>
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</table>
Fig. 1. Experimental set-up and measured air relative humidity (right) and temperature in the ambient air and at the bottom of the sample (left).

In this work, a sample was cored directly from the indoor side of a wall [11], resized with a parallelepipedic shape of $152 \times 123 \times 115$ cm$^3$ (L x l x h) and is made of $\approx 105$ mm of hemp concrete, $\approx 5$ mm of coarse plaster (lime-based plaster) and $\approx 5$ mm of finishing plaster (lime-hemp plaster). Its hygrothermal behavior when subjected to environmental change is investigated by monitoring continuously the global mass variations with a weight-scale (resolution of $\pm 0.01$ g) and temperature and relative humidity at different depths (at the interface between the coarse plaster and hemp concrete and at $x = 40$ mm, $x = 60$ mm, $x = 80$ mm and $x = 115$ mm) with capacitive humidity sensor (uncertainties of $\pm 0.5 ^\circ$C and $\pm 2$ % respectively). To ensure 1D heat and moisture transfer within the sample, the sample is sealed on all its surfaces except the top one with aluminum tape and insulating material.

Before running the experiments, the instrumented sample is first conditioned in sorption at $23 ^\circ$C / 50 % in a climatic chamber, so that initial moisture content of each layer is well known. Then, it is subjected to cyclical relative humidity conditions between 33 % and 75 % at a fixed temperature of $23 ^\circ$C. Here, two experiments are performed: in the first one, a long time scheme is imposed (20 days adsorption + 20 days desorption), so that a quasi steady state can be reached, which is useful for validating the hygrothermal model [10]. In the second one, a daily time scheme is imposed according to the Nordtest protocol. Whatever the experiment, temperature and relative humidity is monitored in the air (as shown in Figure 1 in the case of the long cycling test). As a fan is used to ensure good air homogeneity, relative humidity set points are rapidly reached whereas temperature remains constant. In addition, the temperature measured at the bottom presents similar variation as that of air temperature, except small variations of about $0.2 ^\circ$C observed at each relative humidity set point change.

3. Numerical model

Heat and moisture transfers are modeled in hygroscopic building materials under the following main assumptions: materials are regarded as continuous, homogeneous, stabilized (e.g. no chemical reactions) and non-deformable (e.g. no shrinkage); Local thermodynamic equilibrium is assumed at every point of materials; Moisture storage is independent of temperature; No air transfer and no liquid transfer due to thermal gradients occur.

Last, investigating heat and moisture transfer through multilayered building materials requires focusing on the interface for choosing the state variable and driving potential. Generally speaking, we refer to “Perfect contact” when there is contact with or without interpenetration of both layers’ porous structure and “Unperfect contact” when there are small air pockets between each layer [12]. In this work, even if there are some air pockets, they have approximately the same size than the porosity of hemp concrete, and thus, we assume a perfect contact between each layer. As a consequence, thermal and moisture flows as well state variables $T$ and $\phi$ are continuous between layers, which imply that vapor and capillary pressures are continuous across the interface. On the other hand, when two layers of materials having different moisture storage properties are considered, moisture contents of the respective contacting surfaces are different, leading thus to a discontinuity in the moisture content profile at the interface [13].
Under these considerations, energy and moisture conservation equations are written in each material as:

\[
\frac{\partial}{\partial t} \left( c_{p,s} + w_c p_{s} \right) \frac{\partial T}{\partial T} = - \nabla \cdot \left( \nabla T \right) + \nabla \cdot \left( \left( D_v \nabla + D_c \nabla \right) \left( T - T_{\text{ref}} \right) \right)
\]  

(2)

\[
\frac{\partial}{\partial t} \left( c_{p,l} + w_c p_{l} \right) \frac{\partial T}{\partial T} = - \nabla \cdot \left( \left( D_v + D_l \right) \nabla \right) \left( T - T_{\text{ref}} \right)
\]  

(3)

where vapor and liquid diffusion coefficients \( D_v \) and \( D_l \) are determined as follows, while liquid transfer coefficient \( D_l^w \) was set empirically [10]:

\[
D_v = \frac{\partial}{\partial p_v} \frac{\partial p_{\text{sat}}}{\partial T} \quad \text{and} \quad D_l \frac{\partial}{\partial T} D_l^w
\]  

(4)

Because of hysteresis, the sorption capacity \( \theta \) cannot be described by a unique function. In this work, we use a model based on the Mualem’s work [14] to evaluate the sorption capacity during adsorption and desorption phases:

\[
\theta_{\text{ad,hyd}} = \frac{w_f - w_{\text{des}} \left( \phi_j \right)}{w_f - w_{\text{ad}} \left( \phi_j \right)} \theta_{\text{ad}}
\]  

(5)

\[
\theta_{\text{des,hyd}} = \frac{w_f - w_{\text{ad}} \left( \phi_j \right)}{w_f - w_{\text{des}} \left( \phi_j \right)} \left( \theta_{\text{ad}} - \theta_{\text{des}} \right)
\]  

(6)

where \( w_{\text{ad}} \) and \( \theta_{\text{ad}} \) (resp. \( w_{\text{des}} \) and \( \theta_{\text{des}} \)) are the moisture content and the sorption capacity of main adsorption (resp. desorption) isotherms, \( w_f \) is the free water saturation moisture content and \( \phi_i \) and \( \phi_j \) are the minimal and maximal level reached by the relative humidity during an adsorption-desorption cycle.

At the bottom, impermeable condition is assumed for moisture whereas the temperature is set to the experimental one. The heat flux \( q \) and the mass flux \( g \) are evaluated at the interface between the air and the material as:

\[
q = h_c \left( T_{\text{air}} - T_{\text{surf}} \right) + h_r \left( T_{\text{wall}} - T_{\text{surf}} \right)
\]  

(7)

\[
g = \beta \left( p_{v,\text{air}} - p_{v,\text{surf}} \right)
\]  

(8)

Convective and radiative heat transfer coefficients \( h_c \) and \( h_r \) and convective mass transfer coefficient \( \beta \) are respectively set to 3 W.m\(^{-2}\).K\(^{-1}\), 5 W.m\(^{-2}\).K\(^{-1}\) and 1.7 \(10^8\) m.s\(^{-1}\).

4. Results and discussion

4.1. Model validation

Simulations were performed by solving the coupled nonlinear partial differential equations in the “PDE Modes” of COMSOL Multiphysics® and using a mesh size of 0.6 mm and a time step of 600 s. The results for mass, relative humidity and temperature variations are presented respectively in Figures 2a, 2b and 2c and compared with the experimental results for the long cycling test.
During the adsorption stage, $\phi$ increased from 50 to 75% and no hysteresis modeling is required: mass variations are well predicted, particularly during the 5 first days. We noted differences between simulated and measured relative humidity during the transient phase that were previously observed for the uncoated hemp concrete [10] and explained by moisture dynamics effects [15]. Nevertheless, a better agreement is found in quasi steady state giving confidence in the moisture transport properties. Last, temperature variations are well caught. In particular, we note a peak in the temperature variations, which is more attenuated and delayed deeper within the material, indicating that condensation phenomenon occurred when the moisture front passed the location of the sensor. After 20 days, a primary desorption experiment started: $\phi$ decreases from 75 to 33% and hysteresis model is required in the simulation. As shown in Figures 2, the model could capture the mass, relative humidity and temperature variations. Last, even if they are not shown, sensitivity analyses indicate that the thickness of each plaster has a greater influence on the mass variations than their hygrothermal properties. Since plasters are applied manually, it can provide large difference in the hygrothermal response from a wall to another.

### 4.2. Moisture buffering of uncoated and coated samples

Figure 3a show the measured MBV as function of the number of cycles for the coated sample, but also for each material and a mean MBV is calculated for the 5 last cycles. A value of 1.9 g/(m².%RH) is found for hemp concrete which is similar to the one measured by Collet et al. [9]: uncoated hemp concrete is classified as an « excellent hydric regulator ». When reducing the amount of hemp shives in the composite, MBV decreases to 1.4 g/(m².%RH) for the lime-hemp plaster. When substituting hemp by sand in the plaster, MBV decreases to 0.9 g/(m².%RH). Consequently, compared to uncoated hemp concrete, MBV of coated hemp concrete is reduced by 40% to a value of 1.2 g/(m².%RH) and the assembly is classified as « moderate hydric regulator ». It confirms that the coating with less hygroscopic and permeable materials reduces moisture buffer value of building materials.
Since boundary conditions are not strictly identical, theoretical Nordtest Protocol was simulated for coated and uncoated samples. Attention is paid in the temperature, the heat flux and the accumulated energy (see Figure 3b) at the sample surface. One can observe a great influence of coating on these parameters: surface temperature of coated sample is about 0.2 °C lower than the uncoated one, while the maximal heat flux is reduced by about 25%. As a consequence, less energy is accumulated at the material surface of coated sample during the adsorption phases. Since the plastering reduces the moisture transfer within coated sample, condensation phenomena are less important, explaining thus the results. Similar trends are also observed for the desorption phases. Furthermore, the influence of hysteresis is investigated: neglecting this phenomena lead to a temperature difference of about 0.1 °C whereas a difference of 10% is observed in the accumulated energy. Therefore, accounting for hysteresis is of great importance when evaluating the moisture exchange of hygroscopic building material with its environment, but also when evaluating the heat transfer through the surface.

5. Conclusion

In the present work, a coupled heat and moisture transfer 1D-model was developed to simulate the hygrothermal behavior of a coated hemp concrete sample. The hysteretic behavior of each layer (hemp concrete and plasters) was included in the modeling whereas a perfect hygrothermal contact was assumed between each layer. The comparison of numerical results with experimental data gives satisfactory results, in terms of mean mass variation, as well of relative humidity and temperature variations. Therefore, the model was globally validated in spite of the materials heterogeneity (in terms of composition and thickness), of the experimental uncertainty (location and sensitivity of the sensors) and of the uncertainties of the hygrothermal properties.

Then, the influence of plastering was investigated. On the one hand, measurements indicate that the moisture buffering capacity of coated hemp concrete is reduced by 40% compared to uncoated hemp concrete. On the other hand, simulations show that plastering have a great influence on the thermal behavior, particularly on the surface temperature and on the accumulated energy. In conclusion, we recommend accounting for the finishing layers when investigating the hygrothermal behavior of hygroscopic building materials.

References