Hygrothermal modelling of Lime-Hemp concrete used as building material and indoor climate buffering characterization

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Abstract:

Hygroscopic building materials can affect the indoor air by exchanging moisture with it and buffering the ambient humidity variations. The *Nordtest* protocol and the concomitant *Moisture Buffer Value (MBV)* parameter definition has been one of the first attempt to characterize this moisture regulation performance. This paper present an attempt to confront this well-established experimental protocol with a mathematical model implemented in the *Comsol* multiphysics solver. The power of the simulation will be showed with a good correlation between the modelling and the experimental phase for the *MBV* determination of a lime-hemp concrete bloc.

Key words: HAM modelling, humidity regulation, lime hemp mixes, adsorption, moisture buffer.

1. Introduction

The indoor humidity is an important air quality parameter that determines the comfort for the occupants. When too high it will also potentially cause the phenomena of microbial growth on the walls. It is often stated that the adsorption/desorption of water on hygroscopic materials in contact with the inside air of a building can be used as a passive means to moderate the variations of indoor humidity. This is called the "moisture buffering" effect. The goal of the research presented in this paper is to study the performance offered by agro-sourced materials in controlling building indoor conditions.

Our work is based on one of the first experimental protocol aiming to characterize the moisture buffer performance of hygroscopic materials with a single parameter, the *Nordtest* protocol. This protocol answered to the need for a parameter which could combine all the properties of the material in one value and indicates the rate of moisture exchange in a dynamic variation of its surrounding climate (Peuhkuri & Rode, 2005). Because of its growing success among the eco-construction promoters, the Lime-Hemp concrete (LHC*)* has been chosen here to study the performance of vegetal aggregates as building materials. The reader should find information about this product in Evrard (2008).

2. Material and methods

2.1. The *Moisture Buffer Value* characterization protocol

2.1.1. Principles

The moisture buffer capacity of the tested LHC is measured experimentally in accordance with the *Nordtest project* protocol (Rode et al. 2005) and expressed as the *Moisture Buffer Value (MBV).* The samples are subject to isothermal cyclic step-changes in relative humidity (RH): 8 hours at 75% followed by 16 hours at 33% and are weighted regularly. The same 24 hours cycle is repeated as long as the mass variation during a absorption/desorption phase doesn't vary more than 5% during three consecutive cycles (stable cycle condition). The experimental *MBV* is then given by Eq.1 in $kg/(m^2 \cdot \%RH)$.

$$MBV_{practical} = \frac{\Delta m}{A \cdot \Delta RH} \quad (1)$$

where Δm is the mass variation during the 8 hours absorption phase or the 16 hours desorption phase in one cycle, A $[m^2]$ is the total exchange surface and ΔRH is the difference between the high and low relative humidity of the cycle. This value can be compared to an ideal value, called MBV_{ideal}, which is the theoretical buffer capacity computed using semi-infinite solid theory and Fourier series without transfer resistance at exchange surface :

$$MBV_{ideal} = 0.00568 \cdot p_{sat} \cdot b_m \cdot \sqrt{24 \cdot 3600} \quad (2)$$

with $p_{sat}[Pa]$ the saturation vapour pressure equal to 3145 Pa at 298.15 K. This value is proportional to the moisture effusivity b_m $[kg/(m^2 \cdot Pa \cdot s^{0.5})]$, a parameter based on standard steady-state material parameters :

$$b_m = \sqrt{\frac{\delta_v \cdot \rho_l \cdot \frac{\partial \theta}{\partial \varphi}}{p_{sat}}} \quad (3)$$

where δ_v $[kg/Pa.m.s]$ is the vapor permeability of the material, θ $[m^3/m^3]$ the volumetric water content, ρ_l $[kg/m^3]$ the mass density of water and φ the relative humidity. The slope of the moisture storage curve, $\partial\theta/\partial\varphi$, is generally called the moisture capacity ξ, expressed here in $[m^3/(m^3 \cdot \%RH)]$. A detailed explanation about the *MBV* protocol and it's theoretical basis is found in Rode et al. (2005).

2.1.2. Experimental set-up

A *HPP749* (*Memmert)* climatic chamber was used to carry out the humidity cycles in an isothermal closed environment. This device was upgraded with an additional dehumidification stage consisting of a *AD 21-138 (Aircraft)* refrigerating dryer in order to improve its performance.

The tested material is a LHC wall-mix (Evrard, 2008) experimental bloc produced in 2008 for comparability trials. The LHC sample bloc has an unique exchange surface of 150x150 mm and a thickness of 75mm, which is stated sufficient given the theoretical moisture penetration depth. The lateral and back faces are isolated from water exchange with polyethylene film and tape (Fig. 1).The sample is placed on a *Sartorius M-Power* laboratory scale with a 0-3100g range and 0.01g resolution which is monitored every 5 minutes trough its RS232 output via a *Labview* acquisition program. Two *SHT75* (*Sensirion*) sensors are also implemented in order to monitor the evolution of humidity and temperature at different positions. The first one is placed in the Lime-Hemp mix, at 1cm from the exchange surface, the other is place 10cm above the exchange surface to monitor the conditions in the chamber.

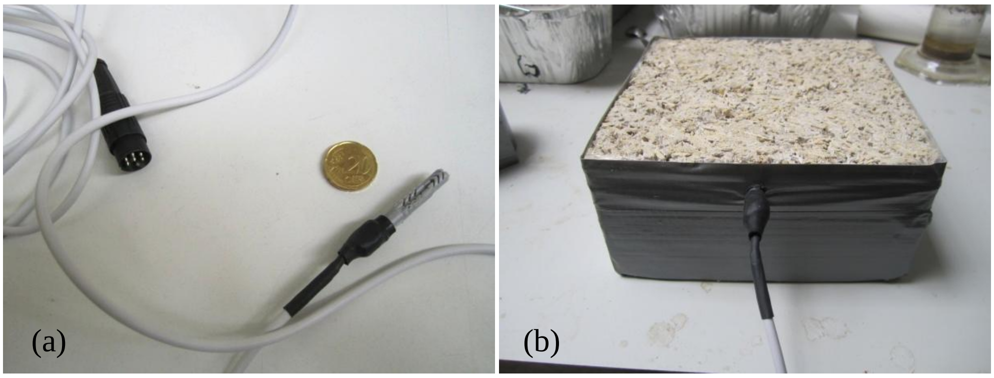

Figure 1: *Sensirion SHT75* sensor with protective shell (a) and bloc with sealed faces (b)

2.2. A model to simulate the *MBV* experiment

2.2.1. Conservation equation

The goal is to compare direct results from the *MBV* experiment with a mathematical model able to characterize moisture transfers in porous building materials for an isothermal case. Considering the experimental conditions, the modelling of moisture transfer can be expressed by a conservation equation (Eq. 4) on an elementary representative volume.

$$\rho_l \frac{\partial \theta}{\partial \varphi} \frac{\partial \varphi}{\partial t} = -\nabla \cdot \left[\vec{j}_d^{M_v} \right] \tag{4}$$

where $\vec{j}_d^{M_v}$ $[kg/m^2 s]$ is the diffusion flow density of vapour. The advection of vapour (transport with air advection) is not considered here as the phenomenon should not occur in the MBV experimental protocol. Liquid transport plays a secondary role, given the relatively low moisture content of the LHC in this experimental RH range. The latter is therefore neglected. The vapour flow density that remains is expressed as the product of its driving potential, the vapour pressure, and a transfer coefficient, the vapour permeability (Eq. 5)

$$\begin{aligned} \vec{j}_d^{M_v} &= -\delta_v \cdot \nabla p_v \\ \left(\vec{j}_d^{M_v}\right)_{isothermal} &= (-p_{sat} \cdot \delta_v) \cdot \nabla \varphi \end{aligned} \tag{5}$$

The vapour permeability of the tested material was measured to $\delta_v = 3.7 \cdot E^{-11}\ kg/(Pa \cdot m \cdot s)$ (Evrard, 2008).

2.2.2. Moisture storage

The moisture storage function $\theta(\varphi)$ has yet to be defined in order to reduce the number of unknowns. We will use the analytical description proposed by Haüpl and Fechner (2003) which is based on actual pore size distribution parameters. It's a perfect illustration of the 'bundles of capillaries' pore space description type, and quite close to a multimodal van Genuchten formulation. The porous material is in fact described in the form of a sum of several storage functions, each describing a compartment of the total pore size distribution and containing 3 parameters (Eq. 6).

$$\theta(p_c) = \sum_{i}^{N} \theta_i \cdot \left(1 - \left(1 + \left(\frac{2\sigma}{p_c \cdot R_{in}}\right)^2\right)^{1-n_i}\right) \tag{6}$$

where θ_i $[m^3/m^3]$ is the volumetric water content of the i^th pore size compartment, R_i $[m]$ is the main radius of the pore size compartment and n_i is the shape factor of the pore size compartment. The storage is expressed in terms of capillary pressure p_c, which is linked to relative humidity through de Kelvin's relation (Eq. 7).

$$p_c(\varphi) = -\rho_l \cdot R_v \cdot T \cdot \ln \varphi \tag{7}$$

where R_v $[J/kg \cdot K]$ is the vapour specific gas constant and T $[K]$ the temperature. The multimodal moisture storage function is thus fitted on pressure plate and sorption isotherm experimental points from Evrard (2008) using a *Matlab* specifically designed software. Literature data from mercury intrusion porosimetry on LHC (Samri, 2008) helped to select main pore radii, $R1$, $R2$ and $R3$ in accordance with real pore size distribution. The selected parameters are given in Table 1 and Fig. 2 shows the resulting storage curves.

Table 1: Moisture storage function parameters

Main radius			Partial volume			Shape parameter		
R1	R2	R3	θ_1	θ_2	θ_3	n_1	n_2	n_3
5.6e-10	8e-8	5e-7	0.11	0.133	0.33	1.09	1.32	1.20

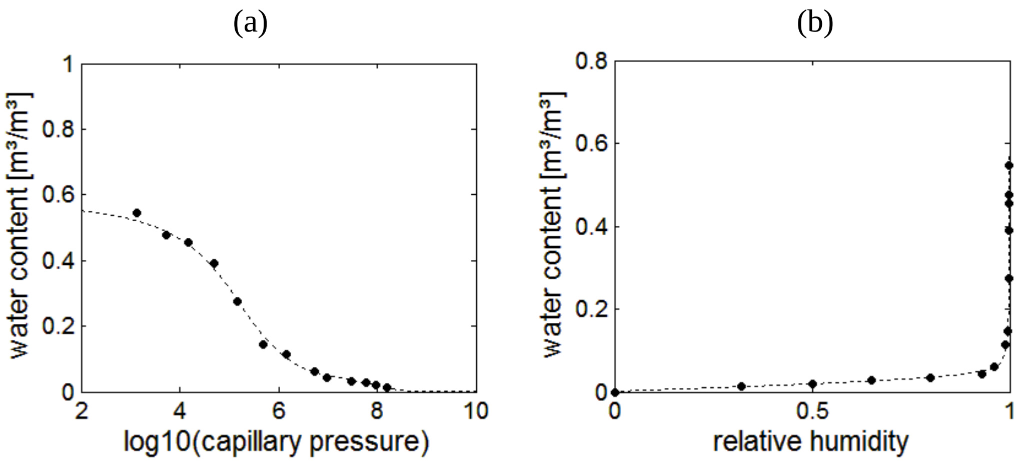

Figure 2: Fitted moisture storage as a function a capillary pressure (a) and relative humidity (b); • experimental points --- multimodal function

2.2.3. Boundary conditions

Ultimately the boundary conditions have to be defined so that the problem can be solved in the finite-element multiphysics solver. Only one face of the bloc can exchange water with the environment. A Newton type boundary condition is then applied to this face :

$$\left(\vec{j}_d^{M_v}\right) \cdot \vec{n} = \frac{p_{sat}(\varphi_1 - \varphi)}{Z_{surf}} \quad (8)$$

where φ_1 is the ambient relative humidity (in the chamber), φ is the relative humidity at the material surface and Z_{surf} $[Pa/(kg \cdot m^2 \cdot s)]$ is the vapour diffusion resistance factor which characterize the moisture transfer resistance that exists on the material surface and slows down the moisture exchange. Its value is generally fixed to $5 \cdot E^{-7} Pa/(kg \cdot m^2 \cdot s)$ for environments with an ambient air velocity around 0.1 m/s (Rode et al., 2005).

3. Results

3.1. Experimental curves

Fig. 3 shows the *MBV* humidity cycles and the measured weight of the sample. The climatic chamber is capable of reaching a 33-70% HR transition in 20 minutes and 75-50% in 30 minutes. The ends of the two transitions are really slow and need further improvement to get closer to a step solicitation. The actual humidity values are also higher than excepted, with an average of 40% during the low humidity phase (6.20PM-10.20AM) and 75.3% during the high humidity phase (10.20AM-6.20PM). This is partly due to poor calibration of the humidity sensors regulating the chamber. It is then necessary to take into account these conditions during the following computer simulation and the *MBV* determination. Therefore the choice has been made to use the actual RH values as input during the modelling phase presented in the next section.

The absorption/desorption dynamics can be seen trough the weight variation of the sample. The first phase is a desorption phase from the initial stabilization humidity of 50% RH. Actually the initial measured relative humidity is higher and closer to 55% with an average of 55,1% on the hour preceding the beginning of the test.

The average air velocity in the chamber is necessary to determine the vapour diffusion resistance factor Z_{surf}. It was measured in the horizontal direction with an hot-wire anemometer *TSI 8465-300*. It showed an average value of $0.135 \pm 0.03\ m/s$.

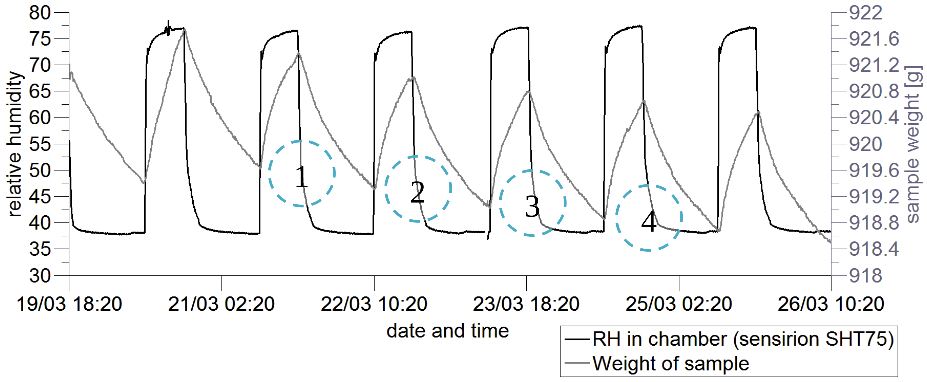

Figure 3: The *MBV* protocol experimental curves and cycles numbers

3.2. Predicted moisture transfer from simulation

Two sets of ambient air variations will be used as boundary solicitation in the model. The first one, called *real cycle*, is the measured RH from the experimental cycle, which as mentioned before is quite different from the ideal step cycle. The second set is the ideal cycle of the *Nordtest* protocol (with perfect step changes), called *ideal cycle*. The initial value of relative humidity inside the bloc is fixed to 55% RH to match the real initial condition.

The conservation equation along with the selected parameters and boundary conditions are the encoded in the *Comsol* environment, a multiphysics partial differential equation solver. The resulting weight curves for the two simulated cycles are shown on Fig. 4.

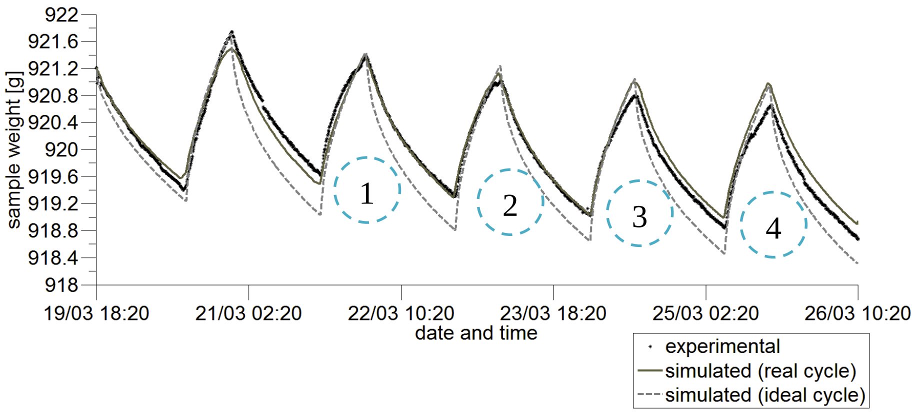

Figure 4: The *MBV* protocol experimental/simulated curve comparison

A really good correlation between the experimental and simulated data on the actual chamber RH values is observed. The ideal simulated cycle shows a greater desorption phase which can be explain by the problems encountered with the chamber to reach to low relative humidity value.

3.3. Simulated, experimental and ideal *MBV* comparison

The MBV_{ideal} of the LHC wall-mix can be easily estimated. First the moisture effusivity of the material is calculated with Eq. 3, based on Evrard's parameters and taking $\xi = 0.05\ m^3/(m^3 \cdot \%RH)$. The obtained effusivity is $b_m = 7.67 \cdot E^{-7} kg/(m^2 \cdot Pa \cdot s^{0.5})$. Knowing this, MBV_{ideal} is valued at $4.03\ g/(m^2 \cdot \%RH)$ (Eq. 2). This is the theoretical maximal buffer capacity of the LHC material for wall-mix proportions, with no surface transfer resistance.

Table 2 shows the comparison between experimental and simulated results for $MBV_{practical}$ determination (Eq. 1). The results are expressed for the four cycles on Fig. 4, with a value for absorption phase, another for desorption phase and the mean on the cycle.

Table 2: $MBV_{practical}$ $[g/m^2 \cdot \%RH]$ results for the experimental and the two simulated data sets

	ΔRH	Cycle 1			Cycle 2			Cycle 3			Cycle 4		
		Abs.	Des.	Mean	Abs.	Des.	Mean	Abs.	Des.	Mean	Abs.	Des.	Mean
Experimental	~35.3%	2.23	2.62	2.43	2.17	2.51	2.34	2.23	2.47	2.35	2.28	2.49	2.39
Simulated (real cycle)	~35.3%	2.40	2.65	2.53	2.31	2.64	2.48	2.46	2.52	2.49	2.51	2.63	2.57
Simulated (ideal cycle)	42%	2.54	2.78	2.66	2.57	2.75	2.66	2.54	2.74	2.64	2.62	2.78	2.70

As expected, the practical buffer capacity value is lower to the ideal value, due to surface resistance effects. There is a good accordance between the simulated and measured results with a global mean on the 3 last cycles giving $2.36\ g/(m^2 \cdot \%RH)$ for experimental, $2.51\ g/(m^2 \cdot \%RH)$ for simulation on real solicitation conditions, and $2.67\ g/(m^2 \cdot \%RH)$ for simulation on ideal step cycle.

4. Conclusions and future work

First this study showed that LHC can be classified as having an excellent moisture buffer performance, based on the measured $MBV_{practical}$ and the *Nordtest* classification categories. It confirms the general idea of agro-sourced material being good indoor climate regulators. Moreover, the model presented seems able to characterize rightly the hygrothermal behaviour of such materials, opening perspective for further studies. In the future, we will focus on studying different mixes to show the influence of their components and proportions on obtained *MBV*. The solicitation cycle will also be studied, showing the influence of RH step value and duration on moisture storage and transfer.

Bibliography

Evrard, A. (2008). *Transient hygrothermal behaviour of Lime-Hemp Materials*. Ph.D. Thesis. Ecole Polytechnique de Louvain, Université catholique de Louvain Belgique.

Haüpl, P., Grunewald, J. and Fechner, H. (1997). *Coupled Heat Air and Moisture Transfer in Building Structures*. International Journal of Heat Mass Transfer, 40, 1633-1642.

Haüpl, P., Fechner, H. (2003). *Hygric material properties of porous building materials*. Journal of thermal envelope and building science vol. 26, 3, 259-284.

Padfield, T. (1999). *The role of absorbent building materials in moderating changes of relative humidity*. Ph.D. Thesis (Report no. 54) Department of Structural Engineering and Materials, Technical University of Denmark.

Peukhuri, R., Rode, C. (2005). *Moisture buffer value: Analytical determination and use of dynamic measurements*. Working paper. IEA Annex 41 Meeting, Trondheim.

Rode, C. et al. (2005). *Moisture buffering of building materials*. Department of Civil Engineering, Technical University Denmark. Report BYG.DTU R-126

Samri, D. (2008). *Analyse physique et caractérisation hygrothermique des matériaux de construction : approche expérimentale et modélisation numérique*. Ph.D. Thesis. ENTPE France.