HYGROTHERMAL BEHAVIOUR OF A HEMP CONCRETE WALL: EXPERIMENTAL AND NUMERICAL APPROACH

Timéa Béjat[1], Arnaud Jay[1], Anais Lagesse[1], and Amandine Piot[1]
[1] CEA, LITEN, Laboratoire Energétique du Bâtiment, at INES, Le Bourget Du Lac, France

ABSTRACT

Alternative products such as green materials are either back or newly implemented in the construction field. The low environmental impact of hemp concrete and its thermo-hydric behaviour show the possibilities of healthier construction and let obtain a better comfort of users. In contrast with usual concrete, the hemp concrete has huge hygroscopic buffer capacity.

The aim of this work is to study the hempcrete with prompt natural cement, which is a concrete block made of a mixture of hemp shivs and “Prompt natural cement”. For that, its behaviour in energy consumption and comfort at a wall and building size level are analysed thanks to simulation and experimental measurements, which are conducted in parallel.

Experimental tests have been run at wall scale in two PASSYS test facilities. Test walls are subject to weather solicitations outside and hydrothermal regulation inside. For numerical study, a 2D coupled heat and moisture transport model is defined. Numerical analysis gives results in the same trends as experimental data.

INTRODUCTION

High environmental quality buildings are nowadays required and some alternative products such as green materials are either back or newly implemented in the construction field. Since 1986, hemp concrete came back on the construction area in France. Its low environmental impact and its thermo-hydric properties still mostly unknown show the possibilities of healthier construction and let obtain a better comfort of users. In contrast with usual concrete, the hemp concrete has huge hygroscopic buffer capacity and hemp gives to it a porous structure more complete with several pore sizes, which increase the hydrothermal exchange with building inside. Most of the time, hemp concrete (hempcrete) is a mixture of lime and shiv, the non-fibered part of hemp. In this work, a prompt natural cement binder is used.

The aim of this work is to understand the behaviour of the hempcrete in energy consumption and comfort at a construction size level. For this, both simulation and experimental measurements are done simultaneously. The paper is divided into four parts. First, a state of the art will be given, and then two parts will discuss the experimental setup and the numerical study. A comparison between experimental data and numerical results is presented.

STATE OF THE ART

Since the eighties different research have been done on the hemp concrete. The research programs mainly focus on three different scales: Material, Wall and Building, to better characterize its physical (mainly thermo-hydric) properties, to be able to predict its behaviour in real conditions and to highlight its pros and cons compared to other materials.

For this material, one finds mostly experimental studies on the matrix and material properties. (Cérezo (2005), Magniont (2010), Glouannec et al. (2011)). The objectives are mainly to characterize the physical properties of the material and quantify the impact of hempcrete characteristics (density, relative humidity, …) on the thermal properties (thermal conductivity, -capacity and -diffusivity). For example the different authors highlight that the variation of the thermal conductivity can be double depending on the relative humidity and that can increase of 50% depending on the density.

At the wall scale, both experimental and numerical analysis are run in parallel by different authors: Holcroft et Rhydwen (2011) Gourlay et al. (2011) Colinart et al. (2011), Ait et al. (2011). Experimental studies are usually conducted in controled ambient (temperature and relative humidity) test cells. Their objectives are to understand the behaviour of hempcrete under different conditions of temperature and humidity. Thanks to these experiments they all emphasized the impact of the moisture transfer on the thermal behavior of the wall, sometimes due to phase change inside the wall. Gourlay et al. (2011) conclude that an optimal hempcrete porosity might exist to be the best compromise between convective transfer and phase change inside the material. These experimental data have been analyzed and helped to calibrate some numerical models. Ait et al (2012) put in evidence the importance of taking into account the hysteresis phenomenon of the sorption curve and of the initial water content gradient in the hempcrete.

At building scale, numerical and experimental analysis are done separately. [GRE (2005) follow energy consumption and thermal comfort of some real hemp concrete buildings behavior thanks to light monitoring. Yates (2002) records that with the same energy production in two different houses, the temperature is 1°C higher in the hempcrete house in comparison of a brick house. Maalouf et al. (2011) describe the behavior of a hempcrete cell for both winter and hot summer conditions with a detailed heat and mass transfer code, developed in SPARK environment. The hempcrete is compared to traditional construction materials such as brick and concrete. The hempcrete mitigate more the exterior temperature amplitude than the others.
The work presented here allows going further than these works in two points. First it allows to characterize hempcrete with natural cement instead of lime and then to test hempcrete at a wall scale under real weather conditions as we will describe it in the following paragraph.

EXPERIMENTAL APPROACH

Experimental campaign Description

Figure 1 : Passys cells with hempcrete walls

In the experimental study, two PASSYS test cells are used as shown in Figure 1. They are parallelepiped test cells of around 30 m^3 volume each. For each cell, one test wall is built with the studied material while the five other walls are highly insulated (40 cm of polystyrene) and are non-tested walls (Figure 2).The two test cells are next to each other. Tested walls are south oriented and are subject to weather solicitations outside and hydrothermal regulation inside.

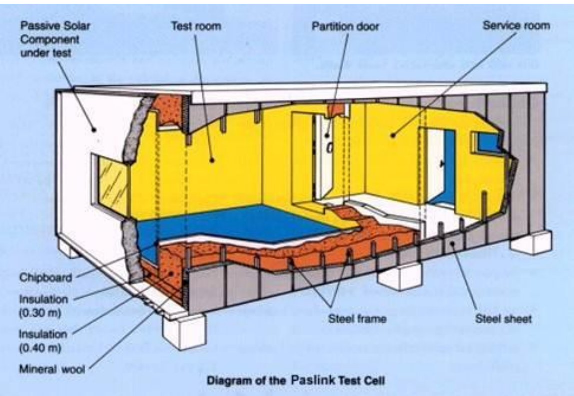

Figure 2 : Passys test cell structure

The tested wall compositions are the same with few differences in physical properties. They are composed of prefabricated hempcrete blocks with structural concrete beams (of 15 cm size) as illustrated in Figure 3. This structure allows the simultaneous analysis of two different parts of the same structure, one with a concrete beam and one only with hempcrete. The wall is then finished with plasters on both sides.

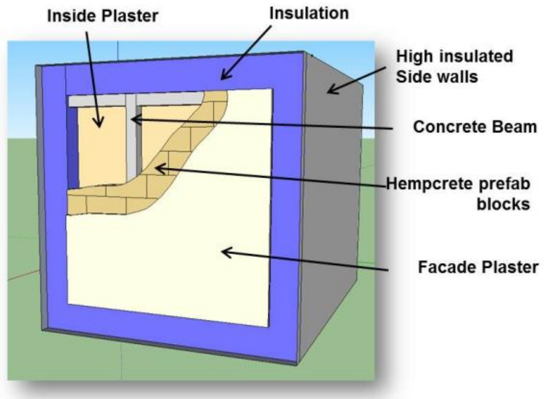

Figure 3 : Wall structure view

Indoor conditions scenarios

Indoor temperature is controlled by an air conditioning unit and moisture can be generate by an ultrasonic humidity generator which is linked to a recording system to save the generated water weight. Air change is possible in the system but in order to reduce this impact, the system was turned off during measurements. These systems enable to impose scenarios to test physical phenomena. On the first 5 scenarios, the relative humidity in both cells has been let in free evolution. Figure 4 shows the evolution of temperature through these 5 scenarios.

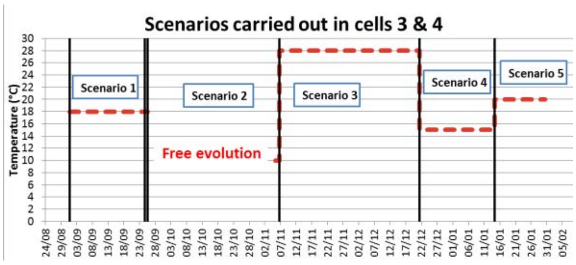

Figure 4 : Temperature evolution in scenarios

These evolutions have been chosen according to the need of the numerical analysis.

Monitoring system

Sensor mapping

More than one hundred sensors are set to record the wall and cell behaviour as illustrated in *Figure **5***. The instrumentation enables to collect temperature, relative humidity, heat flux data from the wall and the test room, consumptions of HVAC systems. Weather conditions are recorded for the whole experimental site.

Sensirion SHT75 sensors are used to record relative humidity and temperature for the air and in the material. A special protection around sensor head was applied to avoid deterioration of sensor sensible element. The impacts of the protection on sensor accuracy and on sensor response time were verified by preliminary tests. Results show a good performance of the protection. In order to follow the transfer inside the wall, they are set at different depth: at the interfaces between air and interior plaster, interior plaster and hempcrete blocks, hempcrete blocks and external plaster and in the middle of the hempcrete blocks. This wall mapping allows having different vertical and horizontal gradient measurement. Some sensors have been set in the concrete beam in order to quantify its impact on the thermo hydric transfer.

Captec sensors are used to record heat flux. Four of them are set in each cell, two of them at the interface between the interior plaster and the hempcrete blocks and two others at the interface of hempcrete blocks and the exterior plaster. For each side, one is set in front of the concrete beam the other in the middle of the concrete blocks face. This will allow quantifying the impact of the concrete beam on the thermal transfer.

Weather station based on the platform records outdoor conditions (100m from the experiments) which include global and direct radiation, dry bulb temperature, wind speed and direction, pluviometry.

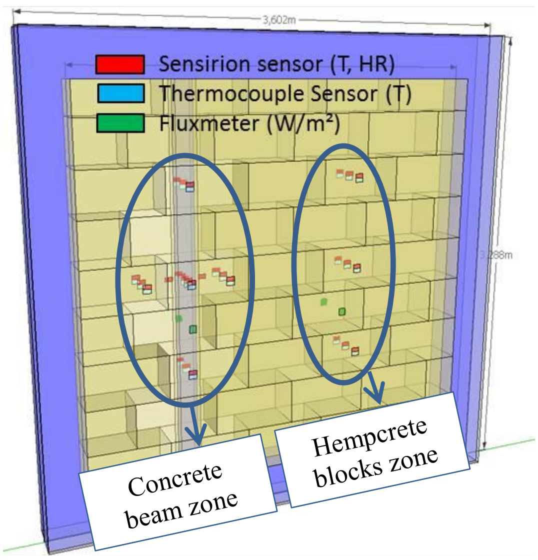

Figure 5 : Sensors mapping

Sensors validation

To validate the relative humidity acquisition, some preliminary tests have been run in different configurations for sensor inter-comparison. Our sensors give satisfying results (*Figure **6***).

To consolidate temperature acquisition and reliability, it is also measured by thermocouple at the same points.

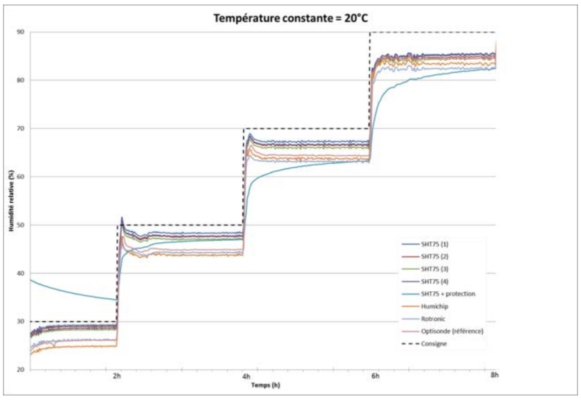

Figure 6 : Sensirion SHT75 validation

Experimental campaign results

Impact of initial conditions

As a first observation, it can be noted that the different hempcrete blocks were not at the same level of moisture conditions at the construction stage, so that their behaviour highly depend on their initial conditions. This is illustrated on *Figure 7*, which shows the evolution of the relative humidity in the middle of the hempcrete blocks for 3 different points in each cell. Early September (2 months after the wall construction), relative humidity varies from 60% to 100% in the middle of the different blocks. It has been choosed to used hempcrete blocks in their usual state and not have a initial phase in a climate chamber to be sure of the initial conditions. This illustrates uncertainties that can be expected on real conditions. Thanks to the first scenario, where the indoor conditions are set to 18°C with a free evolution of relative humidity, we can see that the hempcrete blocks relative humidity trends to converge to the same values. The dry block has an increasing relative humidity while the wetter have a decreasing relative humidity.

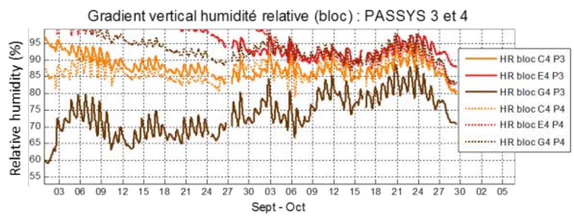

Figure 7 : Relative humidity evolution at the middle of different hempcrete blocks.

Beam concrete influence

The impact of the concrete beam on the thermal loss can be quantified thanks to the heat flux sensors. Regarding the thermal conductivity of hempcrete and concrete, and the size of the beam (15cm x15cm), the thermal resistance is half when there is the concrete beam compared to the full hempcrete blocks. This can be verified on Figure 8, which represents the heat flux recorded. We notice that the internal heat flux in front of the concrete beam is twice the one in front of the full hempcrete blocks. The impact of the concrete beam on the moisture transfer still needs to be investigated.

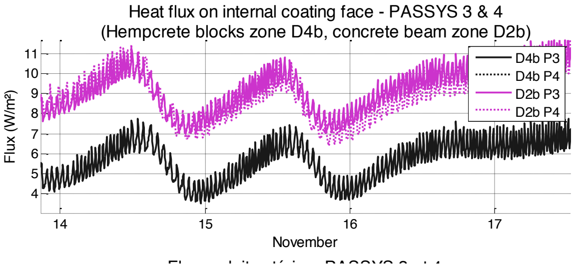

Figure 8 : Heat flux data

Scenario 3 for simulation

We now concentrate on scenario number 3, which was run from November the 7th for 50 days. This will be the one used to compare the numerical model with the experiments. On the 7th of November, the internal conditions were changed from a free temperature (which vary between 15 and 20°C the days before) to a steady temperature of 28°C. It implies an evolution on the relative humidity, which is left free inside the cells from 80-90% to 25-35%. If we look at two horizontal gradients, the concrete beam zone and the hempcrete blocks zone, a decrease of the relative humidity at the middle of the block and at the interface between the interior coating and the block is observed as shown on Figure ***9***. These results will help to calibrate the numerical models.

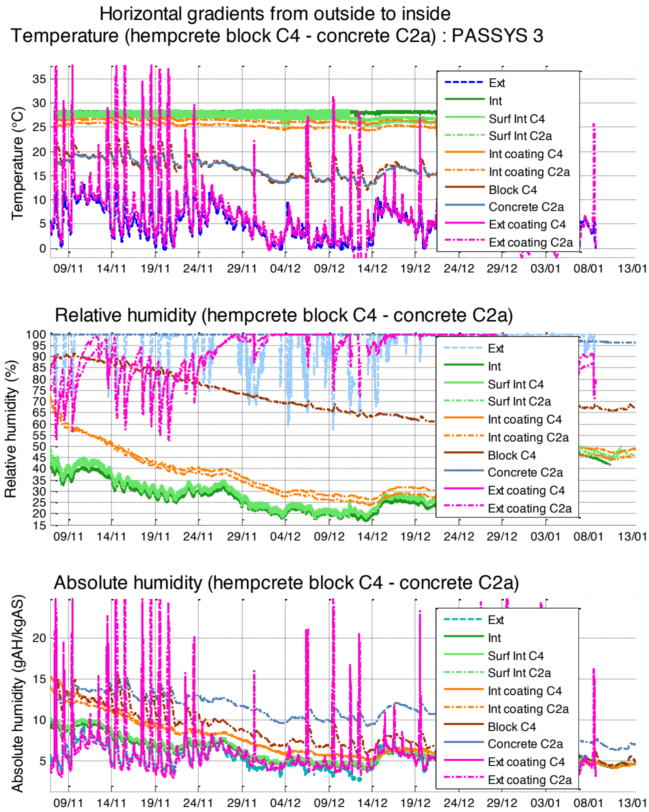

Figure 9 : Horizontal gradient for scenario Tint = 28°C

NUMERICAL APPROACH

Numerical model description

In parallel to the experimental campaign presented in the last paragraph, numerical simulations are set up to go further in the hempcrete characterization and try to generalize the conclusion to other configurations. In a first step, a 2D model in COMSOL 4.3a is defined to take into account thermal and hydric coupled transfer.

The geometry considered is a 2D horizontal cut of the presented hempcrete wall. At this stage, the model includes only the hempcrete blocks and the concrete beam without the interior and exterior plasters (yellow dash line in *Figure **10***)

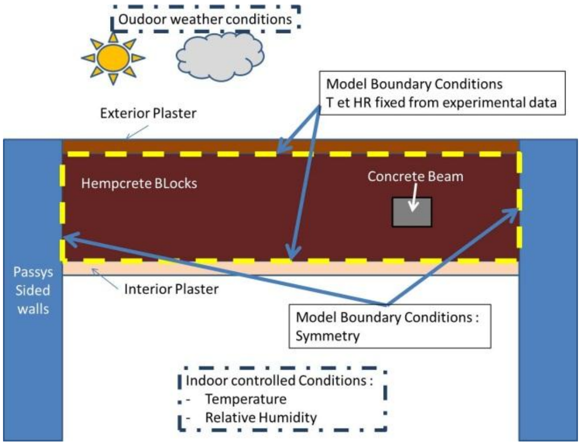

Figure 10: Model domain and boundary conditions

The generated mesh has 2454 triangular elements. The boundary conditions considered, shown on Figure 10, are the measured data for both temperature and relative humidity at the interface of the hempcrete blocks and the plasters. It let us overcome on first physical properties of plasters that are not defined at this stage of the study and also on radiation on the exterior façade. This method takes into consideration the radiation indirectly by its thermal effect. For the same reasons convective exchange with indoor and outdoor are neglected at this stage of the study as we took boundary conditions recorded under a first plaster layer on both sides of the wall.

The phenomena considered here are conduction and storage of heat, diffusion and storage of moisture. Künzel (1994) developed the following original model where the driving potentials are temperature and relative humidity. Both depend on space coordinates and time.

$$\frac{dH}{dT}\frac{\partial T}{\partial t} = \nabla(\lambda \nabla T) + h_v \nabla[\delta_p \nabla(\varphi p_{sat})] \quad (0.1)$$

$$\frac{dw}{d\varphi}\frac{\partial \varphi}{\partial t} = \nabla[D_\varphi \nabla \varphi + \delta_p \nabla(\varphi p_{sat})] \quad (0.2)$$

Both equations with adequate boundary conditions are implemented into Comsol on the following frame:

$$\begin{bmatrix} c11 & c12 \\ c21 & c22 \end{bmatrix} \begin{bmatrix} \nabla^2 T \\ \nabla^2 HR \end{bmatrix} = \begin{bmatrix} d_a 11 & d_a 12 \\ d_a 21 & d_a 22 \end{bmatrix} \begin{bmatrix} \dfrac{\partial T}{\partial t} \\ \dfrac{\partial HR}{\partial t} \end{bmatrix}$$

The final form of the equation is

$$\begin{bmatrix} \lambda + h_v \dfrac{2{,}0 \cdot 10^{-7} T^{0{,}81}/P_L}{\mu} \varphi \left(\dfrac{M_w h_v}{RT^2} p_{sat} \right) & h_v \dfrac{2{,}0 \cdot 10^{-7} T^{0{,}81}/P_L}{\mu} p_{sat} \\ \dfrac{2{,}0 \cdot 10^{-7} T^{0{,}81}/P_L}{\mu} \varphi \left(\dfrac{M_w h_v}{RT^2} p_{sat} \right) & D_w \dfrac{dw}{d\varphi} + \dfrac{2{,}0 \cdot 10^{-7} T^{0{,}81}/P_L}{\mu} p_{sat} \end{bmatrix} \begin{bmatrix} \nabla^2 T \\ \nabla^2 HR \end{bmatrix}$$
$$= \begin{bmatrix} c_s \cdot \rho_s + c_w w & 0 \\ 0 & \dfrac{dw}{d\varphi} \end{bmatrix} \begin{bmatrix} \dfrac{\partial T}{\partial t} \\ \dfrac{\partial HR}{\partial t} \end{bmatrix}$$

Nusser and Teibinger (2012) show the transformation steps for theses equations. They present also the validation of this model on two benchmark cases for Heat Air Moisture (HAM) simulation.

The different parameters of the models are set thanks to experimental measurements or data found in the literature. For the water vapour permeability of the material (δ_p) the following expression is used:

$$\delta_p = \frac{\delta}{\mu}\,.$$

where δ is the water vapour permeability of stagnant air [kg/m.s.Pa] and μ is water vapour diffusion resistance factor of the building material.

We chose the third measurement period as boundary condition for the coupled simulation (data recorded at every 5 minutes during 50 days). Initial conditions was set constant in the whole computational domain for both temperature and moisture. In order to determine the numerical resolution time step, several simulations were done. In a first step, a time step dependence is run in order to choose a compromise between accuracy and computing time. Four resolution time steps have been tested : 5 min, 10 min, 30 min and 1hour. The time choosed is 30 min since there is only a few difference with 5 and 10 min but is much more accurate than 1 hour as illustrated in *Figure* ***12*** and let significantly reduce computational time.

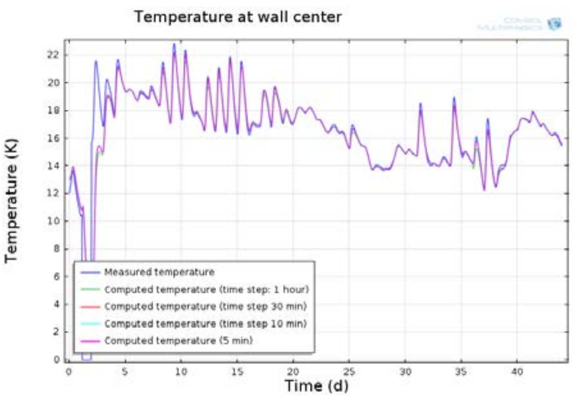

Figure 11 : Time step dependence

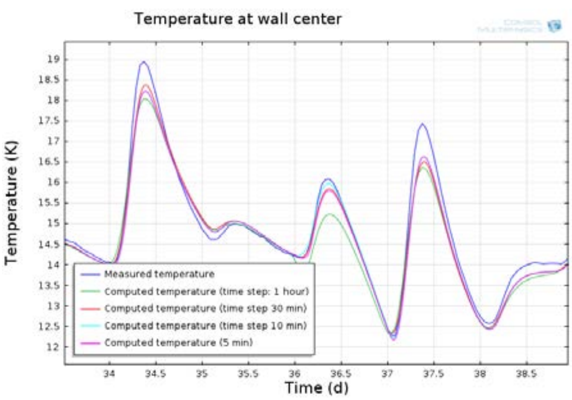

Figure 12 : Time step dependence - zoom

Numerical model results

In a first step, a non coupled version of the model have been run without taking into account the terms of the coupling the 2 equations which imply water vapour saturation pressure and water vapour permeability of the material (δ_p).

In a second step, the coupled equations have been solved.

The synthetic way to observe the advantages of the coupled model is to analyse temperature and humidity data separately. Thus on temperature data one can observe the difference between the two models with the measured data in support on the same figure; and the same analysis for the humidity. In the following, on figure 11, we present temperature data with a zoom on the right hand side of the figure.

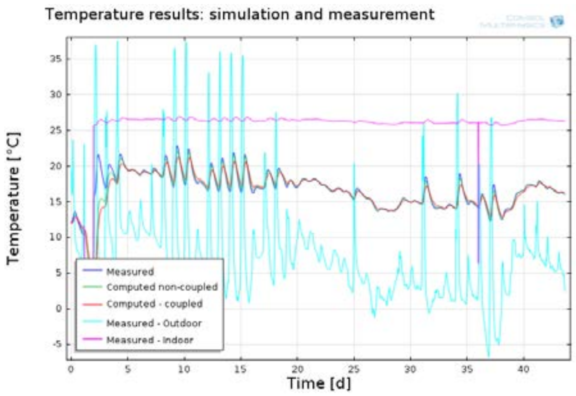

Figure 13 : Temperature evolution - Comparison between experimental, non-coupled and coupled model

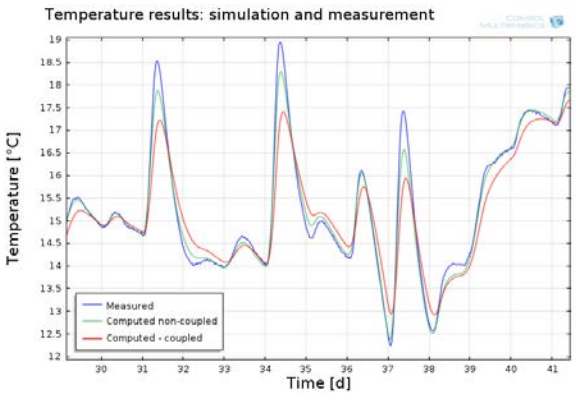

Figure 14 : Temperature evolution - Comparison between experimental, non-coupled and coupled model - zoom

For both models, non-coupled and coupled, the temperature evolution is in good concordance with the measured data. The difference in the temperature is lower than 0,5°C after a first initiation period where discrepancies are more important due to assumption done at the initialization. A general remark is that the pure heat model is more accurate that the coupled model for temperature values. Thus, a parametric analysis on material characteristics' influence is necessary to find which values have dominant impact on results.

For the relative humidity evolution, coupled model is able to reproduce data variation tendencies quite well (Figure 12). In the same time, non-coupled model gives results less accurate and its computed values are further from measured data than the coupled one (Figure 13.). Everyday variations are not reproduced but tendencies are, thus, a longer validation period is necessary to see the impact of building materials characteristics on results.

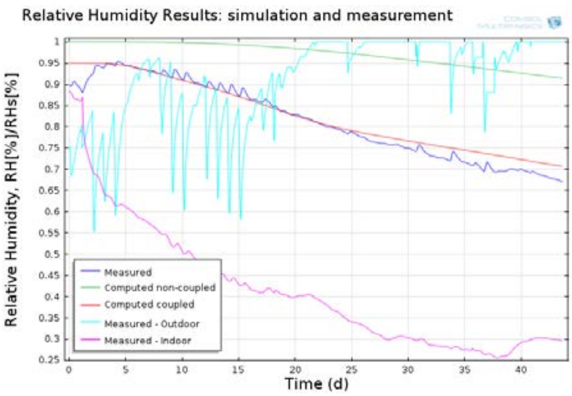

Figure 15 : Relative Humidity evolution - Comparison between experimental, non-coupled and coupled model

CONCLUSION

An experimental campaign testing hempcrete with natural prompt cement facades has been set up on two Passys cells. On one side, these facilities allow to control thermal and hydric ambient air and on the other side receive outdoor conditions. The walls and cells are mapped with sensors including temperature, relative humidity and heat flux. In the first part of this study, different scenarii have been set up to control the inside temperature and highlight the behaviour of the hempcrete wall. Interior relative humidity is left free during these first scenarii. Experimental data show some consistent results regarding the literature with other hempcrete tests. In parallel, a 2D coupled heat and moisture transport model has been developed and numerical results are in a good agreement with the experimental data.

Next steps will be for the experimental parts to generate water vapour in the different cells in order to force vapour transfer in the hempcrete wall. For the numerical models it will be necessary to go further in the comparison with the experimental data thanks to other scenarii which have been set up, and then to adapt and improve the numerical model with more physics. Some examples are to increase accuracy in the thermal properties definition with some function of relative humidity impact and to go further in the sorption curves definition. The integration of plasters will then follow to have the real wall as a whole. Another step will finally be to go from wall scale model to building scale, based on the 2D model validation and quantify the real impact of hempcrete bricks on hydrothermal comfort and energy consumption in comparison to other materials.

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