**First International Conference on
Bio-based Building Materials**

June 22nd - 24th 2015
Clermont-Ferrand, France

HYGROTHERMAL BEHAVIOR OF A HEMP CONCRETE WALL: EXPERIMENTAL AND NUMERICAL STUDY OF COATING

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Abstract

The aim of this work is to understand the hygrothermal behaviour of hempcrete based on cement at a wall size level. For this both simulation and experimental measurements are conducted in parallel. In the experimental study two Passys test cells are used to compare 2 test walls, subjected to weather solicitations outside and hygrothermal regulation inside. The only difference between walls is the coating, in order to analyse its effect on moisture transfer: one cell is supplied with traditional lime render and the other one with industrial, cement based render. The ability of the coating to regulate relative humidity is shown in this paper. Simultaneously the numerical study is used to calibrate a model to this material in order to have a more complete understanding than the experimental study. A parametric study on material parameters is done to emphasize the impact of coatings, and to analyse the effect of material characteristics' variation on global behaviour. For this, a coupled heat and moisture transport model is applied with boundary condition from the monitored data (outside and inside). This study show that the hempcrete is sensitive to the applied coating's properties: in particular, the exterior coating must protect from rain absorption, and be permeable to vapour, otherwise the moisture inside the hempcrete rises, which can reduce the wall performances.

Keywords:

Hempcrete; Hygrothermal behaviour; coupled heat and moisture model; field experimentation; cement

1 INTRODUCTION

To limit the impact of human activity on environment sustainable development concept was established. In this frame bio based building materials gain more and more application as they use renewable materials and have a less environmental footprint. In this scope hemp became more popular in France nowadays than it was before the 80'. Its low environmental impact and its interesting 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 large hygroscopic buffer capacity and hemp gives to it a porous structure more complete with several pore sizes, which increases the hygrothermal exchange with indoor air. 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, then the experimental setup will be presented. The numerical model used will be described in a third part. Then the results presented in this paper will focus on the hygrothermal behaviour of the coatings and its influence on the long term behaviour of the walls.

2 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 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 by 50% depending on the density. [Walker 2014] focuses on the effect of binder on the hygrothermal properties of hempcrete, and shows that the main effect is on capillary absorption of water, more than vapour diffusion or thermal characteristics.

At the wall scale, both experimental and numerical analysis are run in parallel by different authors: [Holcroft 2011], [Gourlay 2011], [Colinart 2011], [Ait 2011]. Experimental studies are usually conducted in controlled 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 behaviour of the wall, sometimes due to phase change inside the wall. [Gourlay 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 analysed and helped to calibrate some numerical models. [Ait 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. [Grelat 2005] follow energy consumption and thermal comfort of some real hemp concrete buildings behaviour 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 2011] describe the behaviour 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. [Shea 2012] describes a small test-building made of hempcrete and shows its ability to strongly buffer the moisture level inside the room.

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.

3 EXPERIMENTAL SET-UP

3.1 Test walls

In the experimental study, two PASSYS test cells are used as shown in Fig. 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. The two test cells are next to each other. Tested walls are 3.3m wide and high, and are south oriented. They are subjected to weather solicitations outside and hygrothermal regulation inside.

Fig. 1: Passys cells with hempcrete walls

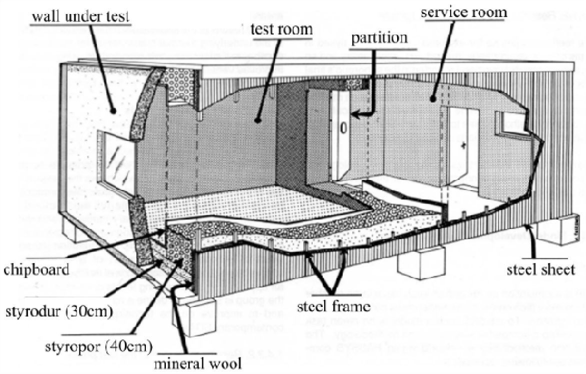

Fig. 2: scheme of a Passys test cell

The tested wall compositions are the same with few differences in physical properties. They are composed of Precast Interlocking Blocks (PIB) system with structural concrete beam and post (thickness 15 cm). The concrete was cast directly into a cavity foreseen inside the blocks. The thickness of the wall is 30cm. In this construction, there is no mortar joint between the blocks, they are put together through tongue and groove keys. Most of the time, hemp concrete (hempcrete) is a mixture of lime and hemp but here a Prompt Natural Cement binder is used as part of the collaboration between the CEA at INES and the cement industrial VICAT. The wall is then finished with plasters on both sides. On the inside, both walls have a lime-based plaster; on the outside, one wall is covered with traditional lime-based coating, while the other wall is covered with an industrial product, based on cement, the coating is composed of two products : TRADI MORTIER 400 *©VPI* and RENOJET FGT *©VPI,* supplied by VPI (Vicat Produits Industriels). Fig. 3 gives the cross section and dimention of the wall.

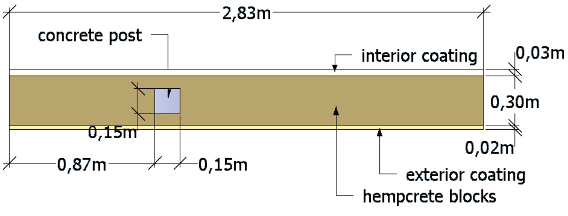

Fig. 3 : cross section of the wall

3.2 Indoor and outdoor conditions

Indoor temperature is controlled by an air conditioning unit and moisture can be generated 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. Indoors, 3 kinds of temperature control were used: constant heating, free floating temperature or step-wise cooling, and 2 kinds of humidity control: free floating or step-wise humidification. The walls are exposed to real weather on the outside; they are oriented towards South. The air temperature and relative humidity, the solar radiation, wind speed and direction as well as rain are recorded continuously.

3.3 Monitoring system

More than one hundred sensors are set to record the wall and cell behaviour as illustrated in Fig. 4. 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. In order to follow the transfer inside the wall, they are set at different depth:

- at the surface of interior plaster,
- at the interface between interior plaster and hempcrete blocks,
- in the middle of the hempcrete blocks
- and at the interface between hempcrete blocks and external plaster.
- After a few months, additional sensors have been placed à 7.5cm (1/4 of thickness) from the coatings, at the top of the wall.

This set-up is installed at 3 heights in the wall, close to the concrete post (on the left-hand side of Fig. 4) and in the regular part of the hempcrete blocks (on the right-hand side of Fig. 4).

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. Thermocouples and heat flux sensors have also been used. The experimental set-up is more detailed in [Bejat 2013]. At the end of the experiment we have one whole year of measured data, with a time step of 5 minutes.

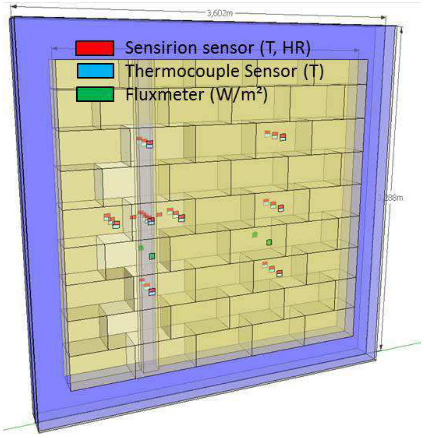

Fig. 4: Sensors mapping: in yellow, the hempcrete blocks; in grey the concrete post; in purple the insulation around the wall.

4 NUMERICAL MODEL

4.1 Numerical model description

The phenomena considered here are conduction and storage of heat, vapour diffusion, liquid flow and storage of moisture. [Künzel, 1995] developed the following original model where the driving potentials are temperature (T) and relative humidity (φ). Both depend on space coordinates and time.

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = \nabla(\lambda \nabla T) + h_v \nabla\left[\delta_p \nabla(\varphi \cdot p_{sat})\right] \tag{4.1}$$

$$\frac{dw}{d\varphi} \cdot \frac{\partial \varphi}{\partial t} = \nabla\left[D_\varphi \nabla \varphi + \delta_p \nabla(\varphi \cdot p_{sat})\right] \tag{4.2}$$

The material properties are the thermal conductivity (λ), the bulk density (ρ), the specific heat capacity of the moist material (c), the vapour permeability (δ_p) and a liquid transport coefficient (D_φ). Those parameters can vary with the moisture content (w) of the material. The vapour flux is responsible for an additional energy flux, due to the latent heat flux h_v. Those equations are therefore strongly coupled.

The different parameters of the models are coming from data found in the literature for part of them or set to fit experimental measurements for the other part.

We used this model (in the software Wufi®), to reproduce our experiments and determine the material properties, in particular those of hempcrete and of the exterior coating. We focused on the part of the wall without the concrete beam, in order to have 1D transfers.

We have had a "step-by-step" approach to validate our model:

1. The properties of hempcrete were first fitted by using the measures between the coatings and the hempcrete as boundary conditions.
2. Then the calculations were made with indoor climate as boundary condition on the inside, to determine the properties of the indoor coating.
3. In the end, real weather was used as boundary conditions to determine the properties of the exterior coating. Only this part of the work is presented here.

4.2 Properties of the coatings

A usual way to describe the moisture-properties of the coatings, instead of D_w and δ_p, is to use a A-value (liquid water absorption coefficient), and Sd-value (diffusion-equivalent air layer thickness). Those coefficients are for example used to classify the coatings in the French standard NF EN 15824.

The Sd value describes what thickness of stagnant air would have the same resistance to vapour flow as the material (the lower the Sd-value, the greater the permeability to vapour diffusion) ; it depends on the thickness of the material:

$$S_d = thickness \cdot \frac{\delta_{air}}{\delta_p} \tag{4.3}$$

This value is often used to characterize thin materials, such as films and membranes. The absorption coefficient A can be linked to the liquid transport coefficient as a function of the actual water content (w) and of the water content at saturation (w_{sat}) [KRUS 1996]:

$$D_w(w) = 3.8 \cdot \left(\frac{A}{w_{sat}}\right)^2 \cdot 1000^{\left(\frac{w}{w_{sat}}-1\right)} \tag{4.4}$$

This relationship is used in our model to calculate the D_w, the latter being very difficult to determine experimentally. On the contrary, a simple absorption test allows to determine the A-value. The thermal properties of the coatings have no significant influence, except the solar absorption of the exterior coating. This one is similar on both cells.

5 RESULTS

5.1 Behaviour of interior coating

In order to evaluate the impact of the indoor moisture on the wall, a humidifier was used to generate steps of moisture 6h/day every day during 1 month. During this period, the temperature was kept constant at 25°C. *Fig. 5* shows the measured relative humidity between the 18th and 24th of May, that is 1 month after the beginning of the humidification tests. Although the humidifiers of the 2 cells are independent of one another, the humidity is very similar.

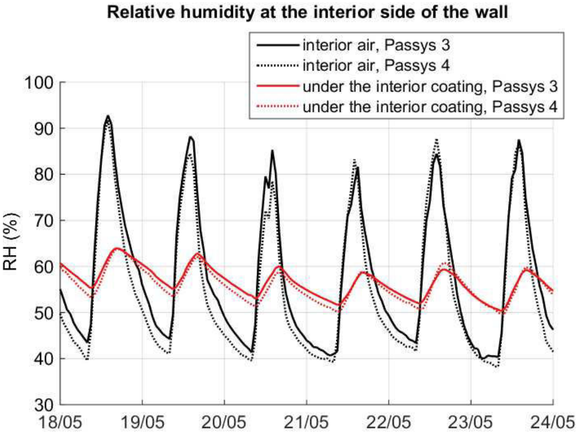

Fig. 5 : relative humidity of indoor air and in the wall

The relative humidity inside the room volume raises up to more than 90%, and falls down every night at around 40%. In both cells, the moisture in the wall, under the interior coating remains much more stable, oscillating between 50% and 60%. The variations are reduced by the coating and dampened by the hygroscopicity of the hempcrete. We can therefore conclude that for short term solicitations, such high levels of moisture don't propagate into the hempcrete.

5.2 Behaviour of exterior coating

Experimental results

In order to evaluate the ability of the coatings to protect the wall from liquid water penetration (for example rain), a small test was carried out. The walls were sprinkled with water during a period of sunny weather. *Fig. 6* illustrates this. 4L of water were sprayed on the exterior coating within a few minutes, in front of a set of sensors.

Fig. 6: Passys cells after absorption test

Fig. 7 shows the relative humidity measured just before and a few days after the test (test was done July, 17th). It can be seen clearly that the industrial coating on Passys 3 (right-hand on *Fig. 6*) is water-tight, whereas the traditional coating on Passys 4 (left-hand on *Fig. 6*) allows the water to enter the wall. This will have a significant influence on the long term moisture of the walls (see §5.3). We can notice that, although the weather was sunny during the following days, the moisture level remains very high during more than 3 days. During the following week, the moisture continues to rises more at that position than at the other places at night. This indicates that the wall has stored moisture, which is confirmed by the moisture recorded by the sensors placed in the centre of the wall (*Fig. 8*).

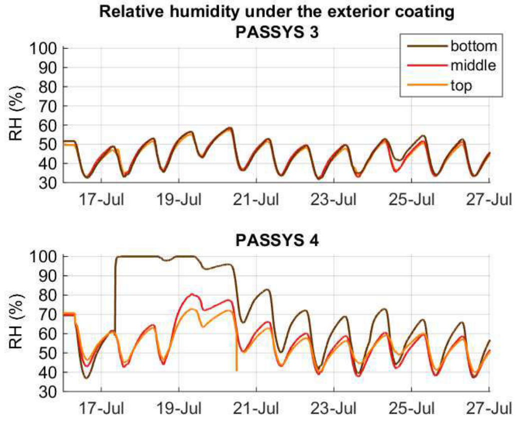

Fig. 7: relative humidity under the coating before and after the absorption test

In the days following the sprinkling on the surface, the moisture in the centre of the block (*Fig. 8*) increases in Passys 4 in front of the humidified zone (bottom, dotted yellow line), whereas at the other places the moisture remains stable. Although the moisture level at the bottom was lower as the 2 other places, it becomes higher a few days after the test.

On Passys 3, no modification is visible in the evolution of moisture.

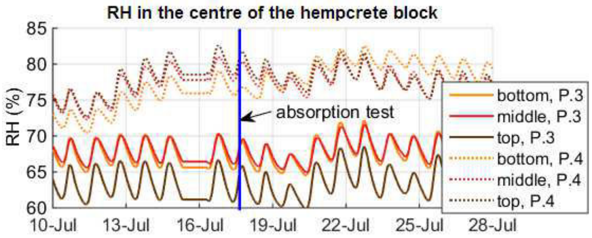

Fig. 8: relative humidity inside the wall before and after the absorption test

Numerical simulations

Simulations were carried out in order to determine the properties of the coatings used in the experiment. *Table* lists the cases studied. The two main properties to determine were the ability to absorb liquid water (absorption coefficient A) and the vapour permeability (Sd value). The experiment had proven that the coating on Passys 3 did not absorb liquid water, therefore we tested values of $A=0.01\ kg/m^2s^{0.5}$ and $A=0.001\ kg/m^2s^{0.5}$. Conversely on Passys 4 the coating was much more absorbent, we used A=0.05 kg/m²s$^{0.5}$. We tried for both coatings 3 different Sd values (Table 1). Those values were chosen to have coatings from the different categories defined in the standard NF EN 15824.

Table 1

	Sd=0,1m	Sd=0,5 m	Sd=2m
A=0,05 kg/m²s^{0,5}	A	B	C
A=0,01 kg/m²s^{0,5}	D	E	
A=0,001 kg/m²s^{0,5}	F		

The calculations were run for a period of 1 year (whole data acquisition period). *Fig. 9* shows the results for 3 coatings for Passys 3 and 4, with a zoom on a period of 1 month. The best combination for Passys 3 (industrial coating) is the coating F, with a very small rain absorption and a large vapour permeability. If one chooses a greater rain absorption, the humidity rises too high after a rain event (for example June, 29th, or July, 11th). If one chooses a smaller vapour permeability (greater Sd, coating E), the average level of moisture remains too high, as the wall can't dry out. For Passys 4, the coating that fits best the measured data is also the one with the largest vapour permeability (A). With smaller vapour permeability, the wall dries out much more slowly and remains too humid. We also compared the calculations with measurements at 7.5cm from the coating, they confirm this choice. This is not presented here.

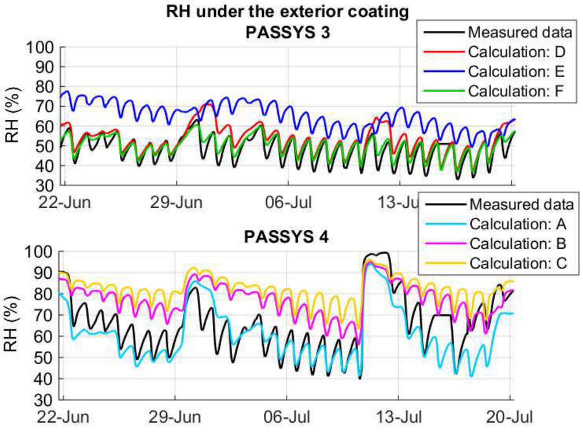

Fig. 9: relative humidity under the coating, measured and calculated (zoom on 1 month)

5.3 Long term behaviour

Experimental results

The relative humidity was measured during one year under the coating and at the centre of the hempcrete wall, at 3 different heights. *Fig. 10* shows the measured data averaged on 24h-basis for better readability. The relative humidity under the coating in Passys 4 reaches 100% several times, and remains at 100% for a very long period in winter. This is the consequence of the absorption of rain (see §5.1).

In the centre of the block, the relative humidity is similar in both cells at the beginning of the experiment (even if we can notice a strong discrepancy between the blocks of one Passys cell). During the winter, we see that the moisture in Passys 4 begins to be higher than in Passys 3; this lasts during the whole experience. The difference decreases in late spring (this corresponds to lower humidity levels under the coating), and increases again afterwards, when the moisture under the coating in Passys 4 is high again.

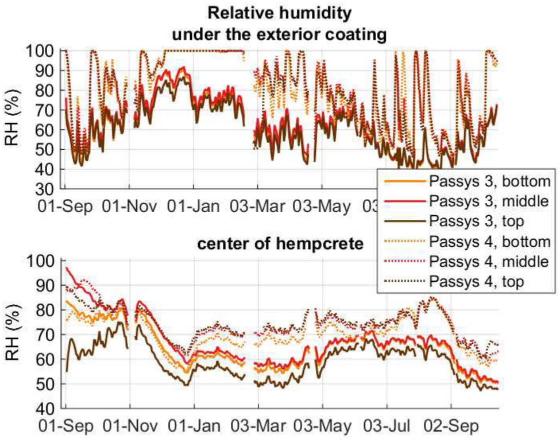

Fig. 10: relative humidity at different positions for the 2 Passys cells, one year data

Numerical modelling

Fig. 11 and *Fig. 12* show results on 1 year (for better readability, the measured data was averaged on 24h-basis and on the 3 heights) in the middle of the hempcrete block and next to the exterior coating. *Fig. 11* confirms that the coating F (very water-tight, very vapour permeable) represents correctly the industrial coating used on Passys 3. The general tendency of relative humidity in the centre of the hempcrete is well reproduced by the model.

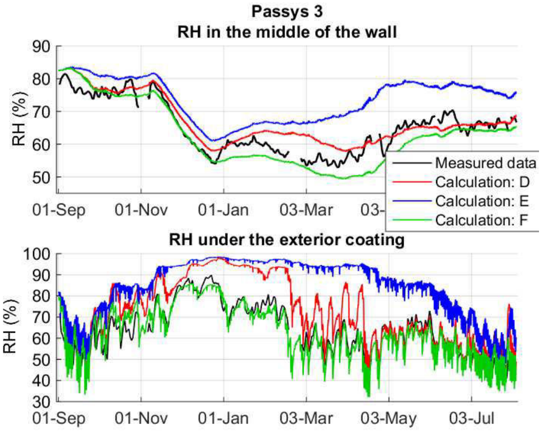

Fig. 11: model compared to measured data, 1 year, Passys 3

For Passys 4 (Fig. 12), we can see that the coating A (very vapour permeable) gives the best amplitude in the variations of the relative humidity under the coating. We also notice that the model underestimates the humidity inside the block; this can be due to the fact that the model doesn't remain at 100% RH under the coating in winter, in contrast to the measurements (this is the case for all tested coatings). This can be due to a lack of rain data (difficulty to measure continuously this parameter) or/and to model the high moisture levels (properties highly variable in this range).

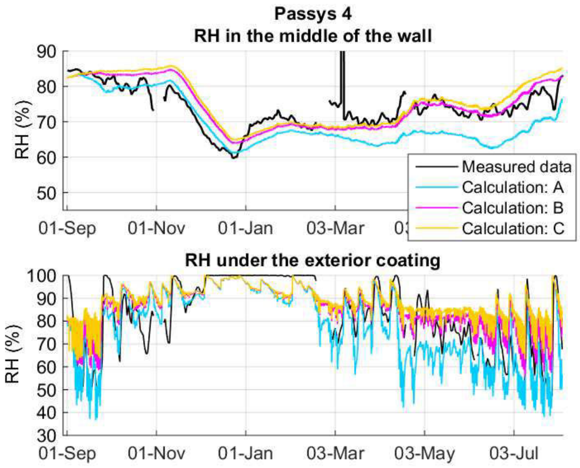

Fig. 12: model compared to measured data, 1 year, Passys 4

The simulations carried out have shown that a large vapour permeability of the exterior coating is necessary so that the wall can dry out when humidified. Otherwise the moisture level increases and the risk is to diminish the wall performance (thermal conductivity, mould growth…). Another critical point is to prevent the entry of liquid water, either by using a water-tight coating, or by appropriate architectural design.

6 CONCLUSION

An experimental campaign testing hempcrete with natural prompt cement facades has been set up on two Passys test 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 parallel, a 1D coupled heat and moisture transport model has been used and numerical results are in a good agreement with the experimental data.

The experiment on the one hand, and the comparison between calculation results and measured data on the other hand allows to determine materials properties. This study shows that a hempcrete wall is very sensitive to the moisture-related properties of the exterior coating:

- If the coating is not liquid-water tight, the wall will absorb a large quantity of rain and remain moist for a long period of time
- If the coating is not permeable enough to vapour, the humidity rises over the long run.

Those 2 situations lead to defects in the hempcrete, for example increase of thermal capacity or risk of mould growth.

Further work is planned to up-scale this study to the building size: the construction of a real house is planned in order to evaluate the behaviour of a whole building in real-life conditions.

7 ACKNOWLEDGEMENT

This work is carried out in the scope of a Research Program done in Collaboration between the French cement Company VICAT and CEA at INES (French Alternative Energy and Atomic Commission – French National Solar Energy Institute). The authors wish to thank VPI which supplied the coating

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