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EXPERIMENTAL HIGHLIGHT OF HYGROTHERMAL PHENOMENA IN HEMP CONCRETE WALL

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Abstract

This study investigates the hygrothermal behaviour of a timber-framed hemp concrete wall made of precast blocks. Measurements are performed on an uncoated wall as well as on a coated wall. The experimental device consists in two air-conditioned rooms where ambient conditions are selected to induce temperature and/or vapour pressure gradient between the two sides of the wall. The monitoring deals with temperature and relative humidity within the wall. Kinetics of temperature and of vapour pressure are given. Profiles are drawn at several times of the transient phase. In the regular part of the wall, several kinds of hygric behaviours are highlighted such as homogeneous vapour diffusion and huge vapour pressure variations due to evaporation-condensation and/or sorption-desorption phenomena. The results in the line of frame show that the frame doesn't induce disturbances in the hygrothermal behaviour of the wall. It is also shown that the coating reduces and delays vapour diffusion.

Keywords: bio-based material, hygrothermal behaviour, sorption-desorption, evaporation-condensation.

1 Introduction

Nowadays, responsible construction should be energy efficient and made of environmentally friendly materials. Bio-based materials avoid depletion of raw material and exhibit low impact on environment (carbon storage, low embedded energy...) [1]. Hemp concrete is a bio-based building material made of lime and hemp shiv. This material can be used for several applications (wall, floor and roof) adjusting the composition. It is implemented by casting, spraying or pre-casting. Due to its low mechanical performances, hemp concrete is used with a framework that can be made of steel, concrete or wood. Usually, hemp concrete walls are coated on both sides but hemp concrete can occasionally be naked on the indoor side.

The experimental characterization of hygrothermal behaviour of hemp concrete is widely investigated at material scale. Measurements provide thermal and hydric properties that are available in the literature.

Hemp concrete is a lightweight building material. Its thermal conductivity depends both on its formulation, its density and its water content. It ranges from 0.07 to 0.3 W.m⁻¹.K⁻¹. Hemp concrete is therefore a good, not exceptional, thermal insulator [2] [3] [4] [5] [6] [7] [8]. Like all bio-aggregate based building materials, hemp concrete is strongly hygroscopic. Its water uptake is much higher than in usual building materials, as shown in [9] by comparing hemp concrete with Aerated Autoclaved Concrete and with Vertical Perforated Bricks. The water content at equilibrium at very high relative humidity (95 %RH) is much lower than the water content at saturation [10]. This is linked to the macroporosity due to the bio-based aggregate. Moreover, its sorption curves show hysteresis which extends all over the range of relative humidity [11] [12] [13] [14]. The mainly open high porosity of bio-aggregate based building materials gives them high moisture vapour permeability (ie low water vapour diffusion resistance). The water vapour diffusion resistance, at dry point, ranges from 5 to 12 for hemp concrete [7] [11] [15] while it is equal to 130 for solid concrete, 50 for light weight aggregate (natural pumice stone) concrete, and 10 for aerated autoclaved concrete [16]. Finally, the moisture buffering quality of hemp concrete was studied by several authors [14] [17] [18] [19] [20] [21] [22]. The experimental investigations are generally performed following the Nordtest protocol [23]. It is shown that hemp concrete is an excellent hygric regulator with moisture buffer values globally higher than 2 g/(m².%RH).

The hygro and thermal properties of bio-aggregate based building materials give them a particular hygrothermal behaviour which allows reducing the energy demand of buildings while maintaining indoor relative humidity [24] [25]. The investigations of the hygrothermal behaviour of building materials at large scale, found in literature, are generally performed numerically. Experimental studies are also performed at large scale (1 m², wall or building).

It was shown in [25] and in [26] that hemp concrete wall performs better than traditional wall assembling on a phase shift point of view. For example, in the simulation of [25] the phase shift was 15 h in the hemp concrete wall while it was 5 h in the mineral wool wall. These performances are correlated with hygro behaviour of hemp concrete. Actually, Shea et al. [26] underline that, after a sudden drop in temperature on one side of the experimental wall, the steady state is reached at approximately 240 h while it is reached within 72 h in simulations ignoring the effects of relative humidity. Thus, relative humidity has a strong effect on the hygrothermal behaviour of the wall. The experimental study reported by Arnaud, Samri and Gourlay in [9] shows that an internal source (or well) of heat and/or the presence of another flow of heat (notably by convection) exists in hemp concrete and directly impact the heat balance equation.

Mlakar and Strancar compared hygrothermal behaviour of small-scale test houses with several kinds of materials [27]. Among their results, the lack of moisture buffering materials leads to higher level and larger oscillation of indoor relative humidity. The authors underline that high moisture loads could have an impact on the durability of buildings and also on its energy performance. At building scale, Woloszyn et al. [28] studied the effect of combining relative-humidity-sensitive ventilation with moisture buffering materials on relative humidity and energy consumption. They show that the use of moisture buffering materials allows reducing the amplitude of daily moisture variation and that energy savings are realised, thanks to SRH ventilation. Tran Le et al. compare hemp concrete behaviour to that of cellular concrete [24]. They found that hemp concrete induces a reduction ranging from 15% to 45% in energy consumption, depending on ventilation strategy. More, Maalouf et al. compare hemp concrete with other building materials (cellular concrete, earth block, solid brick, concrete)[29]. They show that hemp concrete has the lowest thermal diffusivity and the highest time lag which means that it can better reduce the propagation of outdoor weather conditions through building envelope. However, these authors also

show that, in South France, there is a risk of indoor superheating due to low effusivity of hemp concrete. Besides, they underline that hygric properties are high affecting parameters.

The aim of this study is to learn more about the practical behaviour of hemp concrete wall. This study is performed at wall scale in order to respect the usual implementation. The studied hemp concrete wood-framed wall is made of precast blocks. The experimental device is made of two air-conditioned rooms. The monitoring deals with temperature and relative humidity within the wall in the regular part of blocks and in the front of wood framework. The experimental device and the implementation of the wall are first presented. Then the results obtained under several ambient conditions in the rooms are given. These conditions are selected to have vapour transfer, heat transfer or simultaneous heat and vapour transfer. Kinetics of temperature and vapour pressure are given and profiles are drawn at several times of the transient phase.

2 Experimental method

2.1 Experimental device

This study focuses on the hygrothermal behaviour of a hemp concrete wall under hygrothermal stresses. The aim is to study the wall response under temperature gradient only, vapour pressure gradient only and finally under both temperature and vapour pressure gradients. So, in order to well control ambient temperature and relative humidity on both sides of the wall, the experimental device involves two adjacent air-conditioned rooms separated by the studied test-wall.

Each room is 2.35 m deep, 2.78 m wide and 2.4 m high. The floor is made of concrete and all the other walls of the rooms are well insulated by polyurethane panels ($U = 0.40 \text{ W.m}^{-2}.\text{K}^{-1}$) and are air and moisture tight. One of the air-conditioned rooms reproduces the indoor climate of common buildings (“indoor room”) while the other one simulates outdoor climatic conditions (“outdoor room”). Table 1 gives the ranges of temperature and relative humidity for each room. The regulation of each parameter (T and RH) is ensured by universal controllers DR4020 used to define the set point and a bandwidth that governs the switch-on and the switch-off of the devices of the chambers. Each controller has two outputs: heating / cooling for the temperature regulation and humidification / dehumidification for the humidity

regulation. Heating is provided by convectors, cooling and dehumidification by a refrigeration group and humidification by steam humidifiers. When systems are operating, fans with low rotational speed are employed. This induces low level of air movement, with mean vertical velocity lower than 0.1 m.s⁻¹ in the studied part of the wall. This is not higher than the value commonly met in buildings. Hence, the rate of evaporation and moisture movement are not enhanced by the fan use.



Figure 1. Experimental device: bi-climatic rooms

Table 1: Ranges of temperature and relative humidity

	Room 1 (indoor)		Room 2 (outdoor)	
	Range	Bandwidth	Range	Bandwidth
Temperature (°C)	18 - 27	± 0.2	-5 - 35	± 0.5
Relative humidity (%RH)	30 - 60	± 0.3	30 - 90	± 0.8

2.2 Test wall and metrology

The test wall is built with precast hemp concrete blocks (see the dimensions of blocks in figure 6) and a wooden frame. The precasting consists in mixing binder and hemp shiv and then forming blocks. The binder is made of 72% in mass of CaO and 28% of hydraulic binder (lime and pozzolan). The hemp to binder mass ratio is 65% and the water to binder ratio is 120%. Firstly, CaO is mixed with water to obtain slaked lime. Then hydraulic lime and hemp shiv are added. The mixture is then poured into moulds and blocks are formed by compaction in the moulds under vibrations (figure 2). These blocks show holes to

introduce the wood frame ($17 \times 8 \text{ cm}^2$) and holes for networks ($\varnothing 5 \text{ cm}$) (figure 3). The apparent density of these blocks is 320 kg.m^{-3} , their thermal conductivity (at 23°C , 50%RH) is $0.12 \text{ W.m}^{-1}.\text{K}^{-1}$ and their water vapour permeability is $1\text{E}^{-10} \text{ kg.m}^{-1}.\text{s}^{-1}.\text{Pa}^{-1}$ [30]. The wood frame is made of semi-heavy pine wood. According to [16], this kind of wood shows dry density from 435 to 520 kg.m^{-3} , thermal conductivity about $0.15 \text{ W.m}^{-1}.\text{K}^{-1}$ and water vapour permeability about $0.4 \text{ E}^{-10} \text{ kg.m}^{-1}.\text{s}^{-1}.\text{Pa}^{-1}$.

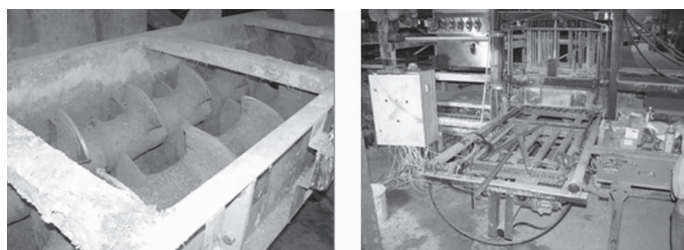


Figure 2. Device for precasting hemp concrete – mixer; forming process.

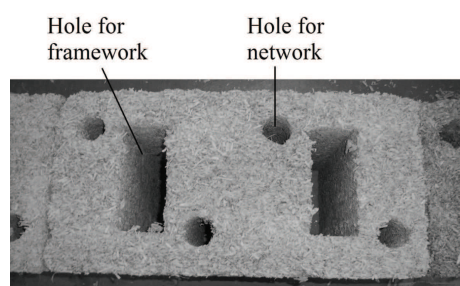


Figure 3. Hemp concrete block

The test wall is 2.30 m long, 0.30 m thick and 2.1 m high (figure 4). The horizontal joints between the rows of pre-cast blocks are narrow joints made of a few millimetres of milk of lime (25 kg of natural hydraulic lime with 10 l of water). The vertical joints between blocks are filled with a mixture made of hemp shiv and lime, as best as possible. The cross section of the frame is $15 \times 5 \text{ cm}^2$. The space between the wood and the hemp concrete is filled with a milk of lime. This wall is highly heterogeneous (regular part of the block, joints, timber frame, reservation holes...).



Figure 4. Building of the test wall

The aim of the monitoring is to measure the hygrothermal response of the wall to environmental conditions (temperature and relative humidity). Temperature is measured with thermocouples (type K) on the one hand, and with sensirion SHT75 sensors on the other hand. These sensors also measure relative humidity. The accuracy of thermocouples is $\pm 0.1^\circ\text{C}$. They were checked at 0°C , 10°C , 20°C and 30°C . The accuracies of sensors SHT75 are $\pm 0.3^\circ\text{C}$ at 25°C and $\pm 1.8\%\text{RH}$ at 10 - 90%RH. In order to quantify the absolute quantity of moisture, vapour pressure is calculated from temperature and relative humidity with the usual relationship:

$$p_v = \varphi \cdot 100 \exp\left(18.986 - \frac{4052}{235.89 + T}\right) \quad (1)$$

The measurements are carried out on ambient air, on the surface of the wall and within the wall. Due to the heterogeneity of the wall, several profiles are studied. Figure 5 shows the numbering of blocks (1 to 31) and columns (1 to 8) and the location of sensors. Profiles are measured in the regular part of blocks 17 and 20 and in the line with the timber frame (columns 3 and 6). In order not to disturb each other, the sensors are installed with an angle of 45° and distributed at different levels (figure 6).

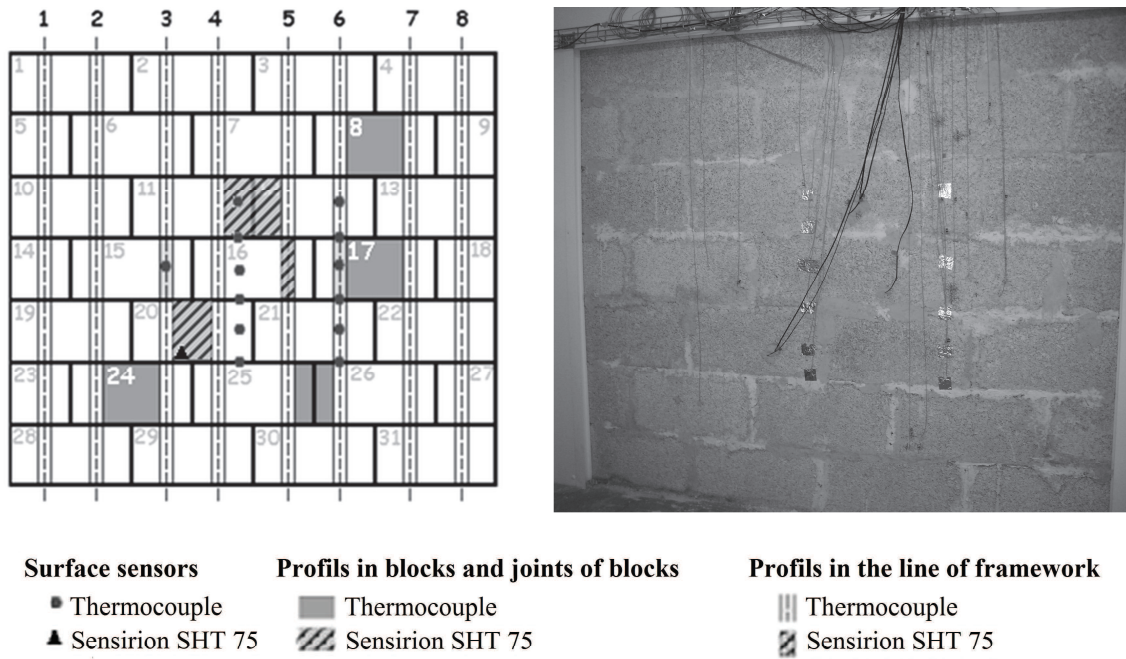


Figure 5. Instrumentation of the test wall for the monitoring of temperature and relative humidity

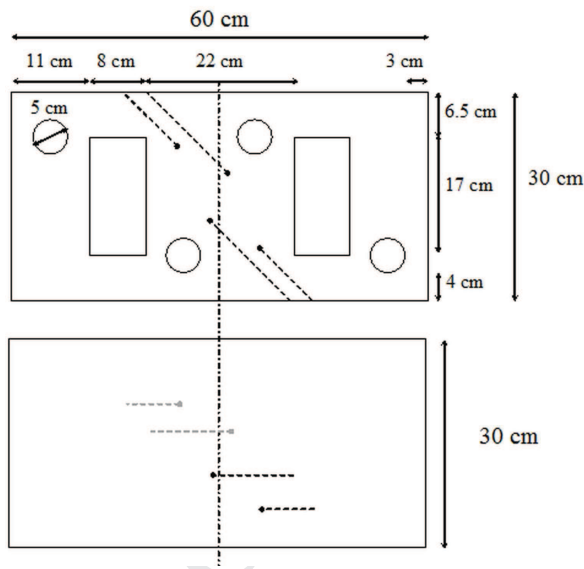


Figure 6. Sensors location in a block (up : top view, down : front view)

2.3 Methodology

Four months later the construction (drying of the wall), the whole device is stabilized with the same setpoint for indoor and outdoor climates: 23°C, 40% RH. Then, the set points of the ambient conditions are chosen in order to ensure uncoupled or coupled heat and mass transfer. Temperatures and relative

humidities considered are in the range of the values met in temperate climate. They are chosen in order to ensure a high enough gradient to provide meaningful results.

Both during the stabilization phase and during the test phase, the time step between measurements is five minutes.

Firstly, measurements are performed on uncoated wall. Then both sides of the wall are coated with a breathable commercial lime based coating (water vapour diffusion factor lower than 35). This coating is made of hydrated lime, low quantity of hydraulic binders, silicate and calcareous sand and mineral pigment. It is applied in two five-millimetre thick layers. Then, sensors are added on the surface of the coated wall.

3 Results and discussion

The response time of air conditioning is firstly considered. Then, the hygrothermal response of the wall under hygrothermal stress is detailed for uncoated wall and then for coated wall. In both cases, the study is performed under temperature gradient only, vapour pressure gradient only and finally simultaneous temperature and vapour pressure gradients.

3.1 Performance of air conditioning

Several ambient conditions are considered. For all cases, the response time of air conditioning is short. For example, figure 7 shows the ambient temperature and relative humidity values of each room after stabilization at 23°C 40% on both sides of the wall when the ambient conditions of the outdoor room are set to 9°C, 75%RH. The setpoints are quickly reached as well for the temperature as for the relative humidity. This is mainly due to the low inertia of the bi-climatic rooms. The curves show small fluctuations around the setpoints due to the power of the air conditioning system and to its on/off regulation.

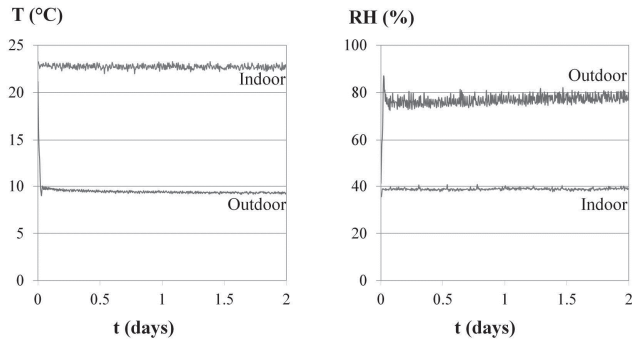


Figure 7: Kinetics of the ambient temperature and relative humidity for the following setpoints: indoor 23°C 40% RH - outdoor 9°C 75% RH.

3.2 Hygrothermal behaviour of uncoated hemp concrete wall

3.2.1 Hygrothermal behaviour in the regular part of hemp concrete blocks

In the first case studied, the setpoints are chosen to ensure only a vapour pressure gradient between the two rooms. After stabilization at 23°C, 40%RH, the outdoor temperature and relative humidity are set to 23°C, 80%RH while the indoor ones are kept at 23°C, 40%RH. Such conditions lead to a vapour transfer from the outdoor to the indoor side. Figure 8 gives the kinetic of vapour pressure at several depths within the wall.

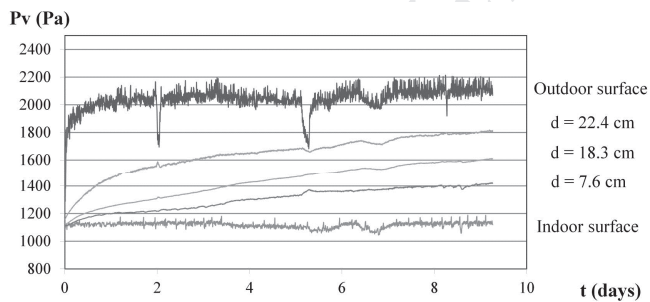


Figure 8: Kinetics of vapour pressure in a block after stabilization at 23°C 40%RH when outdoor setpoint is set to 23°C 80%RH and indoor is kept at 23°C 40%RH.

The steady state is reached after seven days all over the thickness of the wall. At initial time, the vapour pressure is almost the same in the whole thickness of the wall because the ambient values in the rooms are similar. After changing the setpoints, the vapour pressure increases through the wall. The closer to the solicitation (outdoor side), the greater and quicker the increase is. For example, the vapour pressure

increases by 302 Pa at 7.6 cm depth from indoor side and by 643 Pa at 22.4 cm depth. After one day, these increases are respectively 20% and 30% of the final variation. Finally, the vapour pressure profile tends towards a linear profile (figure 9). It is characteristic of homogeneous moisture diffusion through the wall.

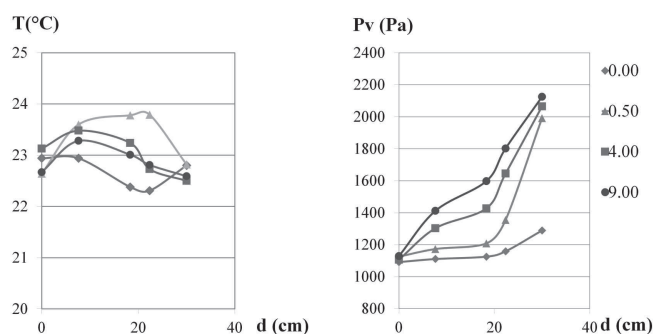


Figure 9: Temperature and vapour pressure profiles obtained at several times, when outdoor setpoint is changed from 23°C 40%RH to 23°C 80%RH

In the second case, the wall is initially exposed to temperature and vapour pressure gradients (indoor at 23°C, 40%RH and outdoor at 15°C 45% RH). Then the setpoints are changed such as the vapour pressures are nearly the same on both sides of the wall whereas a temperature gradient appears: the outdoor room is changed to 30°C 27% RH while the indoor is kept at 23°C 40% RH. The outdoor setpoint is not exactly reached and the test is held under outdoor conditions of 28°C 32% RH. Figure 10 gives the kinetics of temperature and vapour pressure within block 20. Figure 11 gives the profiles of temperature and vapour pressure at several times. This figure shows the good agreement between the measures on the two blocks and underlines that this is representative of the hygrothermal behaviour in the regular part of the wall. The monitoring shows that the temperature evolves quickly: 90% of the final variation of temperature is reached after 2.5 days at a 22.6 cm depth from interior side (figure 10). The steady state is reached after 5 days. Obviously, initial and final time temperature profiles are linear with opposite slope (figure 11). This is correlated with the heat transfer flow. Initially, the temperature gradient in the wall induces a thermal flux from the indoor to the outdoor side. When the outdoor setpoint is changed, a thermal flux occurs from outdoor to indoor. These two fluxes are simultaneous until the temperature within the wall reaches the indoor one. Then only the thermal flux from outdoor to indoor occurs. Regarding vapour transfer, the vapour pressure inside the wall evolves quickly. Less than one

hour after changing the setpoint, a pressure peak is observed through the material. The vapour pressure observed is higher than those measured in the rooms. This highlights sorption-desorption phenomena in the material. These phenomena induce heat of sorption-desorption exchange simultaneously with thermal transfer, this impacts the global energy balance of the wall. Finally, the vapour pressure tends towards a constant value that is nearly reached after 10 days (figure 11).

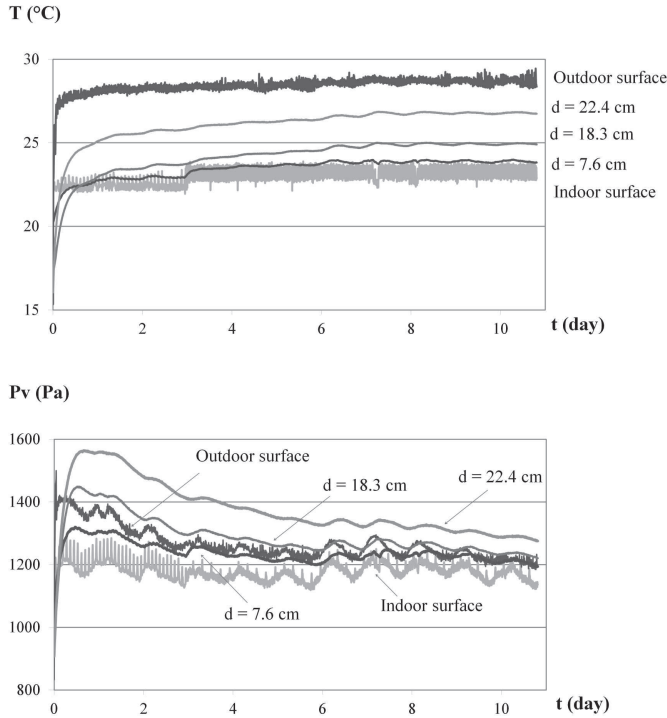


Figure 10: Temperature and vapour pressure kinetic when the outdoor setpoint is set from 15°C 45%RH to 28°C 32%RH.

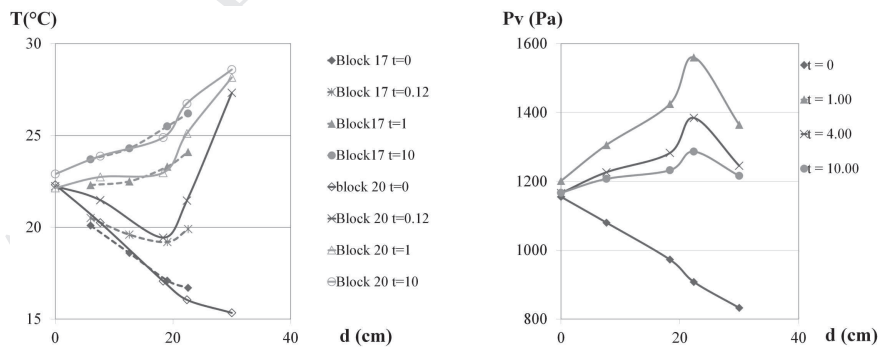


Figure 11: Temperature and vapour pressure profiles when the outdoor setpoint is set from 15°C 45%RH to 28°C 32%RH.

The third case investigates simultaneous heat and mass transfers under temperature and vapour pressure gradients. Both fluxes occur from the indoor to the outdoor side of the wall. The studied system is first stabilized at 23°C 40%RH. After that, the setpoint of the outdoor side is changed to 9.5°C 77% RH while

the indoor side is kept at 23°C 40% RH. Temperature and vapour pressure kinetics are plotted on figure 12. The vapour pressure decreases quickly near the outdoor side of the wall before increasing slightly until stabilization. The same phenomenon occurs within the material with a phase shift, a damping and with greater time constants for the fall and rise in vapour pressure. The vapour pressure reaches lower values than the stabilized ones that shows sorption-desorption and/or evaporation- condensation phenomena.

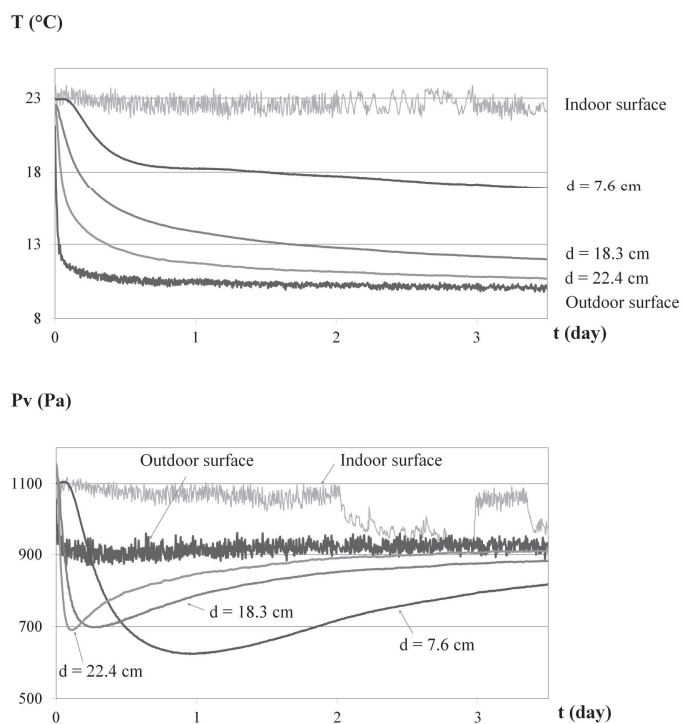


Figure 12. Temperature and vapour pressure kinetics when the outdoor setpoint is set from 23°C 40%RH to 9.5°C 77%RH.

3.2.2 Hygrothermal behaviour in line with the timber frame

The hygrothermal behaviour in line with the timber frame is presented for an indoor setpoint equal to 23°C 40%RH whereas the outdoor one is set from 15°C 45%RH to 28°C 32 %RH (figures 13 and 14). The wall is thus initially exposed to temperature and vapour pressure gradients and finally to temperature gradient only. The kinetics measured in contact with the timber frame change in the same trend as those measured in the regular part of the blocks as well for the temperature as for the vapour pressure. Thus, the

timber frame does not seem to induce high phase shift in the propagation of heat and moisture fluxes. Temperature profiles in front of the timber frame are similar to those measured in the regular part of the block all along the transient phase. So, the timber frame does not disturb significantly the heat transfer and storage in the wall. No thermal bridges occur because the hemp concrete and wood have similar thermal conductivities. Furthermore infrared thermographic imaging was performed with a Flir B50 camera. The difference of ambient temperature between the interior and the exterior side of the wall was about 10°C for several days before the imaging begins. This gradient ensures high enough thermal transfer to induce surface temperature differences in case of thermal bridge. The air velocity is low enough to not disturb the measurement. Infrared thermographic images show a uniform temperature field on the surface of the coated wall. The vapour pressure profiles in line with the timber frame are also similar to those measured in the regular part of the block. Thus, the influence of the timber frame on the moisture transfer and storage within the wall is limited.

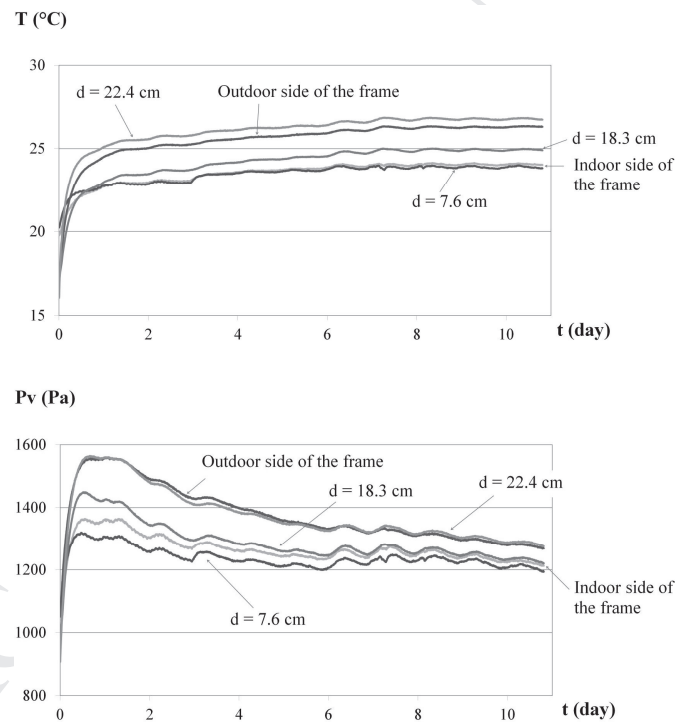


Figure 13. Temperature and vapour pressure kinetics when the indoor setpoint is kept at 23°C 40%RH and the outdoor setpoint is set from 15°C 45%RH to 28°C 32%RH.

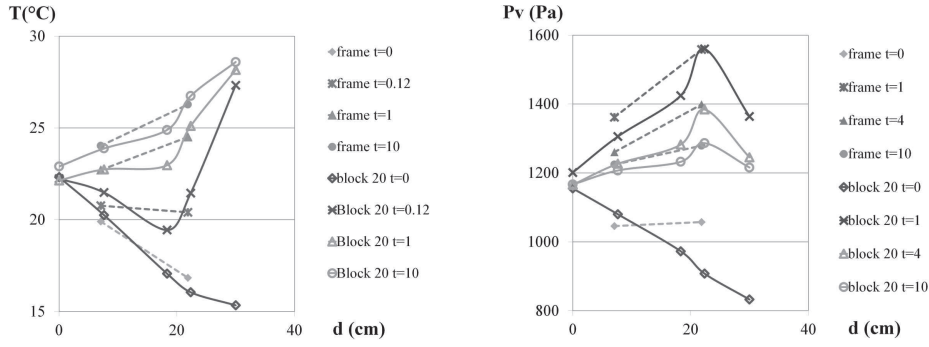


Figure 14. Temperature and vapour pressure profiles when the indoor setpoint is kept at 23°C 40%RH and the outdoor setpoint is set from 15°C 45%RH to 28°C 32%RH.

3.3 Hygrothermal behaviour of coated hemp concrete wall

Figure 15 shows the kinetics in the coated wall exposed to vapour flux. The outdoor setpoint is set from 23°C 40%RH to 23°C 80%RH while the indoor setpoint is kept at 23°C 40%RH. The outdoor relative humidity reached is slightly higher than the setpoint.

At initial state, the vapour pressure profile shows constant value through the wall as indoor and outdoor conditions are the same. Once outdoor setpoint is changed, vapour pressure shows higher gradient near the outdoor side of the wall. The vapour pressure within the coated wall tends to a linear profile.

However, after 6 days of exposure, this profile is less linear than the one observed without coating after 4 days of exposure. This is probably due to slower vapour diffusion through the wall.

In order to compare kinetics with and without coating, figure 16 shows the plot of the ratio $(P_v - P_{v_{indoor}}) / (P_{v_{outdoor,average}} - P_{v_{indoor,average}})$. This shows that the slopes for the uncoated wall are lower than the slopes for the coated wall. Moreover, vapour pressures are lower within the coated wall than within the uncoated one. This is particularly obvious near the outdoor side of the wall. So, the coating induces an additive vapour resistance that reduces and delays the vapour transfer through the wall. Such effect was also observed in [31] measuring the moisture buffer value of naked and coated hemp concrete. So, coating highly impacts the vapour transfer through the wall. However, it does not stop the sorption-desorption and/or evaporation-condensation phenomena in hemp concrete.

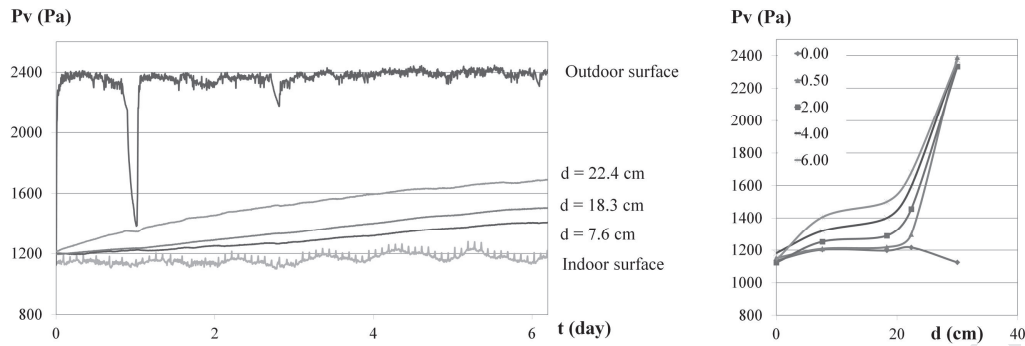


Figure 15. Vapour pressure kinetics and profiles of the coated wall when the outdoor setpoint is set from 23°C 40%RH to 23°C 80%RH

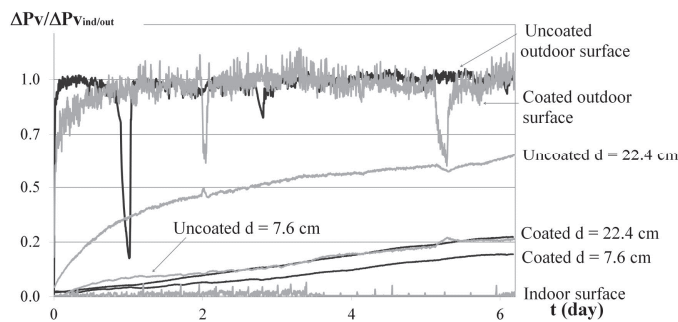


Figure 16. Comparison of kinetics of the coated and of the uncoated wall when the outdoor setpoint is set from 23°C 40%RH to 23°C 80%RH

4 Conclusion

The experimental device is well adapted to study hygrothermal behaviour of a representative building wall. Moreover, the registered curves are of great interest in order to validate numerical codes.

The study shows that the response time of the uncoated wall is short as well as for temperature as for humidity. Depending on initial and final setpoints, various phenomena are highlighted:

- under isothermal conditions with vapour pressure gradient, an homogeneous vapour diffusion is shown,
- under constant vapour pressure with a decrease of ambient temperature, huge variations of vapour pressure are observed within the wall. This underlines sorption-desorption and/or evaporation-condensation phenomena.

The investigation, performed under moderate climate, could be carried on under severe conditions too. It could be interesting to study the response to low temperature to analyse the possibility of occurrence of frost in the wall.

The results in the line of frame show that the frame doesn't induce disturbances in the hygrothermal behaviour of the wall. Besides, the frame is not a thermal bridge as the thermal conductivity of wood is similar to the one of hemp concrete.

The study on coated wall, under vapour pressure gradient and for isothermal conditions, shows that the coating reduces vapour pressure through the wall and delays the vapour diffusion due to an additional moisture resistance. However, it does not stop the sorption-desorption and/or evaporation-condensation phenomena in hemp concrete.

Finally, such hygric phenomena directly impact the heat balance equation in correlation with latent heat of phase-change or sorption heat. It is thus necessary to consider the contribution of hygric behaviour in the whole energetic performance of these materials. In order to highlight this contribution, it is necessary to develop new experimental benches.

Acknowledgements

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- We report the construction of a hemp concrete test-wall as separating wall of bi-climatic rooms.
- The hygrothermal behaviour of the wall is investigated under several hygrothermal stresses.
- Vapour diffusion, evaporation-condensation, sorption-desorption phenomena are shown.
- It is shown that the frame doesn't disturb the hygrothermal behaviour of the wall.
- It is also shown that the coating reduces and delays vapour diffusion.