Study of a hempcrete wall exposed to outdoor climate: Effects of the coating

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Study of a hempcrete wall exposed to outdoor climate: Effects of the coating

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HIGHLIGHTS

- Cement based hemp concrete walls exposed for one year to indoor controlled and outdoor climate.
- 2 different exterior coatings were compared.
- Modelling was used to determine material properties and for extrapolation of results.
- Results show that the wall is sensitive to the fact that the exterior coating absorbs rain or not.
- Results show that drying can last several month.
- Results show that model with properties determined in steady-state presents some limitations.

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ABSTRACT

Hemp concrete is becoming a popular building construction material, as it has a low environmental impact and helps reducing the heat conductivity of walls. The generally used binder is lime, but in this study a prompt natural cement binder was used. The objective of this study was to analyse the behaviour of a hempcrete wall in realistic conditions. 2 test walls made of prefabricated hemp concrete blocks were built. Those walls were exposed to the outdoor climate on the one side, and to a controlled indoor climate on the other side. 2 different exterior coatings were applied. The experiment lasted one year. In addition, numerical simulations were carried out. The model was used to determine the material properties and to help understand the behaviour measured.

The results show that an important humidification of the wall can occur if the coating is not well chosen. The exterior coating must be very permeable to water vapour, but it seems to be important to prevent the absorption of rain as well, otherwise, the humidity inside the wall can lead to degradations such as mould growth or increased thermal conductivity. Both numerical simulation and measurements show that applying a vapour permeable coating on the blocks does not slow down the drying process, the hempcrete itself being the limiting factor.

1. Introduction

Since the increase in the energy costs and the awareness of the impact of human activities on the climate, there has been done a huge effort of both research and policies to reduce the energy consumption of the building sector. Further work is still necessary, as the European union has recently committed itself to a reduction in the greenhouse gases emission of 40% by 2030 in comparison with 1990 [13].

This has led to an increase in the insulation level of building envelopes in order to reduce energy consumptions for heating and cooling buildings. Therefore, it has become more and more important to take into account the environmental impact of the construction materials in the design of eco-friendly buildings, as they take an increasing proportion of the total impacts in the life cycle analyses, as shown in Blengini and Carlo [6]. In this regard, the so-called bio-based materials have much interests (renewable resource, eventually locally grown, CO_2 sink…). However, risks are also associated with bio-based products, such as the sensitivity to

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mould or insects. Such risks have to be taken into account when one studies this kind of materials.

Ip and Miller [16] show that hemp is an important greenhouse gas sink potential. The review carried out by Ingrao et al. [15] shows that many reasons can explain why the hemp based products are more and more popular: the cultivation of hemp has a good yield, and needs only few fertilization and herbicide. As a vegetal material, it has a high level of CO_2 sequestration during its growing phase, therefore being very efficient in term of reducing climate change indicators, and uses only a few non-renewable resource.

The hemp concrete or hempcrete is a mixture of hemp shives and of a binder, cement or lime for example. Hempcrete benefits from the porous structure of the shives, giving a lightweight product with a low thermal conductivity, a good acoustical insulation, and making it a hygrothermal responsive material.

Numerous studies on the matrix and material properties can be found in the literature, either experimental characterisation or numerical studies [7,8,11,20,21]. 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). Walker and Pavia [26] focus on the effect of binder on the hygrothermal properties of hempcrete. The moisture buffer value (MBV) of hempcrete is also investigated, together with the impact of coating or wall rendering on this MBV [18]. Collet and Pretot [12] conducted experimental studies in controlled climate (temperature and relative humidity) test chambers, showing that applying coating did reduce the vapour diffusion through the wall.

Only few authors report the behaviour of a hempcrete wall exposed to real outdoor conditions. Shea et al. [25] describes a small test-building made of hempcrete and shows its ability to strongly buffer the moisture level inside the room. Latif et al. [19] studied 2 walls, one with and one without vapour barrier, made of wood-hemp insulation exposed to real climate. No significant difference was found between walls' experimentally determined U-values.

In this paper we present the study of 2 hempcrete walls exposed during one year to outdoor climate on one side and to controlled climate on the other side. The binder used to make the hempcrete is a natural Prompt cement. PROMPT is a natural hydraulic binder manufactured from a single raw material without additives. It results from firing an argillaceous limestone of regular composition extracted from homogeneous rock strata, between 800 °C and 1200 °C in a vertical kiln, followed by very fine grinding. The walls are coated on both side, the exterior coating differs between the 2 walls. The measurements are analysed to see how the walls respond to different solicitations (indoor humidification, outdoor humidity, rain loads) with the help of numerical modelling. The article outlines the importance of the choice of coatings on the long term performance of the hempcrete.

The first part of the paper will present the experimental set-up, then the numerical model used is introduced. This model is compared to the measurements to determine the material properties, in particular of the coatings. The following paragraphs of the paper present the analysis of the role of the interior coating, and in the end the role of the exterior coating.

2. Experimental set-up

2.1. Test walls

Two test walls were built on the outdoor exposure site of CEA at INES (Le Bourget du Lac, France, 45°38′ N, 5°52 E). They are composed of precast hempcrete blocks (31 cm × 60 cm, thickness of 30 cm), and were assembled on site by the end of June 2012.

The blocks used here are prefabricated and the binder used is a natural Prompt cement which has the property to be fired at lower temperatures than ordinary Portland Cement. They are assembled through a dry mortarless construction (with tongue and groove keys [1]). The hemp-concrete blocks are self-bearing but not structural, therefore a concrete post and beam structure was used (size of the post $15 * 15\ cm^2$). The composition of the concrete is described in Bessette and Sommain [4].The dry density is of $350\ kg/m^3$.

On the interior side, both walls are covered with traditional, commercially available lime-based render. The exterior coating differs between the 2 constructions. On one wall, the coating applied is an industrial, pre-mixed, lime- and cement-based, and containing additives; on the second one, a hand-mixed (prepared on site) lime- and cement-based coating is used. Both coatings have a similar colour (which is unfortunately not well depicted by Fig. 1), in order to have a comparable behaviour towards solar radiation. The experiment has shown that the industrial coating did not absorb rain, as opposite to the hand-mixed coating. This is shown in paragraph 5.

The walls have a square shape (3.3 m side). Fig. 1 gives some pictures of the walls and a cross section.

Those walls were installed on "PASSYS" test cells, which allow one face of the wall to be exposed to indoor climate (indoor temperature varied between 15 °C and −28 °C while humidity emission varied between 170 g/h and 200 g/h), the other to real outdoor climate. The PASSYS test cells outer dimensions are 8.44 m long, 3.61 m wide and 3.8 m high. The cells are made of a metallic frame with 5 walls strongly insulated ($U = 0.09\ W/m^2\ K$), also water- and vapour proof. The 6th face is reserved for a wall of maximum $3.6 * 3.3\ m^2$ to be tested. The studied wall is exposed to outdoor conditions on one side and to controlled indoor conditions on the other side. Each cell is placed on a raised support which allows free air circulation under the floor.

The tested walls are oriented towards South. The indoor air volume of the test room is of $30\ m^3$. Indoor temperature is controlled by a small blowing air-conditioning unit (either cooling or heating). Moisture can be generated by an ultra-sonic generator. The flow-rate of moisture is measured by weighing continuously. Different indoor conditions were imposed: free-floating temperature, heating, cooling, with or without moisture generation (see Table 1). No mechanical ventilation is used.

2.2. Monitoring system

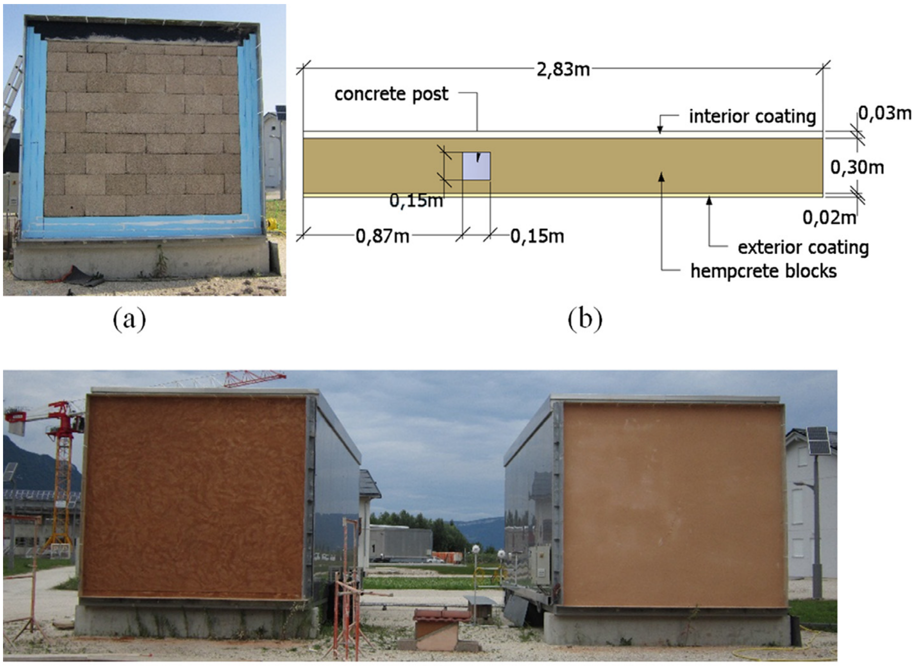
The set-up enables to collect temperature, relative humidity, heat flux data inside the wall and the test room.

Sensirion SHT75 sensors are used to record relative humidity and temperature for the air and in the material. Accuracy of those sensors is 1.8%-RH and 0.5 °C.

In order to follow the transfer inside the wall, they are set at different depths (see Fig. 2):

- 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.

The sensors were placed inside the blocks through a hole drilled from the top of each block, the wire going down perpendicular to the main heat- and moisture fluxes, in order not to disturb the latter. This set-up is installed at 3 heights in the wall, close to the concrete post (on the left-hand side of the wall depicted in Fig. 2 and in



(a)

(b)

(c)

Fig. 1. Picture and schemes of the experimental walls: (a) before exterior coating, (b) cross section, (c) the 2 cells with exterior coating.

Table 1
Indoor conditions in both test cells.

Begin	End	Duration	Temperature set-up	Humidity control
31st Aug.	24th Sept.	25 days	18 °C (cooling) ± 1 °C	Free evolution
25th Sept.	5th Nov.	42 days	Free evolution	Free evolution
6th Nov.	21st Dec.	45 days	28 °C (heating) ± 1 °C	Free evolution
21st Dec.	21st Jan.	31 days	15 °C (heating) ± 1 °C	Free evolution
21st Jan.	4th Mar.	42 days	20 °C (heating) ± 1 °C	Free evolution
19th. Mar.	15th. Apr.	27 days	20 °C (heating) ± 1 °C	170 g/h, 2 h/day
15th. Apr.	21st. Jun.	67 days	25 °C (heating) ± 1 °C	200 g/h, 6 h/day
21st. Jun.	23rd. Jul.	33 days	18 °C (cooling) ± 1 °C	Free evolution
29th. Jul.	23rd. Aug.	26 days	18 °C ± 1 °C from 8 am to 8 pm, free floating during the night	Free evolution
23rd. Aug.	1st Sept.	10 days	28 °C (heating) ± 1 °C	Free evolution

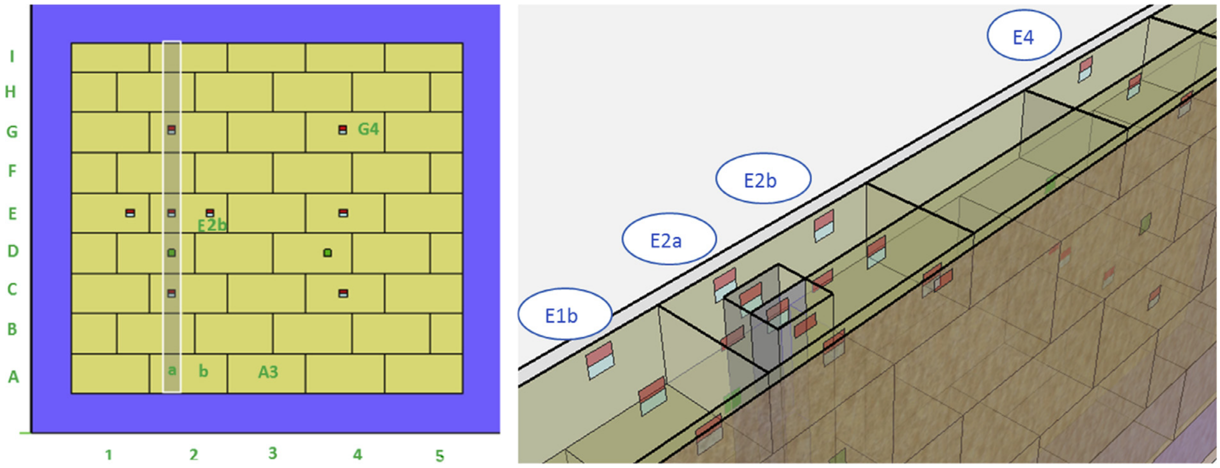


Fig. 2. Sensors mapping with nomenclature related to position in the wall.

the regular part of the hempcrete blocks (on the right-hand side in Fig. 2. Some sensors have been set in the concrete beam in order to quantify its impact on the thermo-hydric transfer.

After a few months, additional sensors have been placed à 7.5 cm (1/4 of thickness) from the coatings, at the top of the wall. Thermocouples and heat flux sensors have also been used. The experimental set-up is more detailed in Bejat et al. [2].

The acquisition time step is of 5 min. A special protection around sensor head was applied to avoid deterioration of sensor sensible element by chemicals of the concrete and of the plasters. The impacts of the protection on sensor accuracy and on sensor response time were verified by preliminary tests. They showed that the response time of the material was much lower than that of the sensor including its protection case.

The weather was also monitored on site; the following parameters were recorded every 5 min:

- Dry bulb temperature
- Relative humidity
- Wind speed and direction
- Rain gauge
- Solar irradiation on horizontal surface (direct and global)
- Longwave radiation on horizontal surface.

Fig. 3 shows the humidity to which the walls were exposed: relative humidity indoors and outdoors, and rain gauge. Unfortunately, a lack of data exists in April–May for the rain gauge.

3. Numerical model

3.1. Model description

The phenomena considered here are conduction and storage of heat, vapour diffusion, liquid (capillary) flow and storage of moisture. Künzel [17] developed the following formulation where the potentials used are temperature (T) and relative humidity (φ). Both vary in space and time. Relative humidity was chosen as driving potential for the moisture fluxes as it has the advantage to be continuous at the interface between 2 materials. The choice of this potential is also interesting for validation purposes as it can be directly measured.

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = \nabla(\lambda \nabla T) + h_v \nabla[\delta_p \nabla(\varphi \cdot p_{sat})] \tag{3.1}$$

$$\xi \cdot \frac{\partial \varphi}{\partial t} = \nabla[D_w \cdot \xi \cdot \nabla \varphi + \delta_p \nabla(\varphi \cdot p_{sat})] \tag{3.2}$$

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, the slope of the sorption curve ξ and a liquid transport coefficient D_w. 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. No hysteresis is considered.

In practice, 2 liquid transport coefficients can be defined: one for the absorption phase, one for the redistribution of the moisture into the material. Those coefficients being difficult to measure directly, a correlation is used to determine them based on a more simple measurement, the liquid water absorption coefficient A [17].

We used this model (in the commercial software Wufi®), to reproduce our experiments. We focused on the part of the wall without the concrete beam, and therefore made one dimensional calculations.

Some properties of the hemp concrete were measured by an external laboratory: dry density, thermal conductivity and heat capacity. The vapour permeability and sorption curve up to 97% RH were determined with samples of a slightly different mixture than the one used in the experiment described in this paper. Those values were also compared with data from the literature and a parametric study was done to find out which values fitted better the measurements [8,9,14].

For the coatings we had no value at all, and the numerical simulation has been used to identify their properties.

We have had a "step-by-step" approach to determine the material properties:

1. The properties of hempcrete were first fitted by using the measures (T, RH) between the coatings and the hempcrete as boundary conditions and the measure in the middle of the wall as a comparison point.
2. Then the calculations were made with indoor climate (T, RH) as boundary conditions on the inside, to determine the properties of the indoor coating by comparing T and RH both in the middle of the coating and at the interface between the interior coating and the hempcrete.
3. In the end, real weather was used as boundary conditions to determine the properties of the exterior coatings. The input data used are air temperature and relative humidity, rain, wind speed and direction, solar radiation, long wave radiation. We compared the measures and calculation in the middle of the wall and at the interfaces between both coatings and the hempcrete.

In the following, we present only the results of this last step.

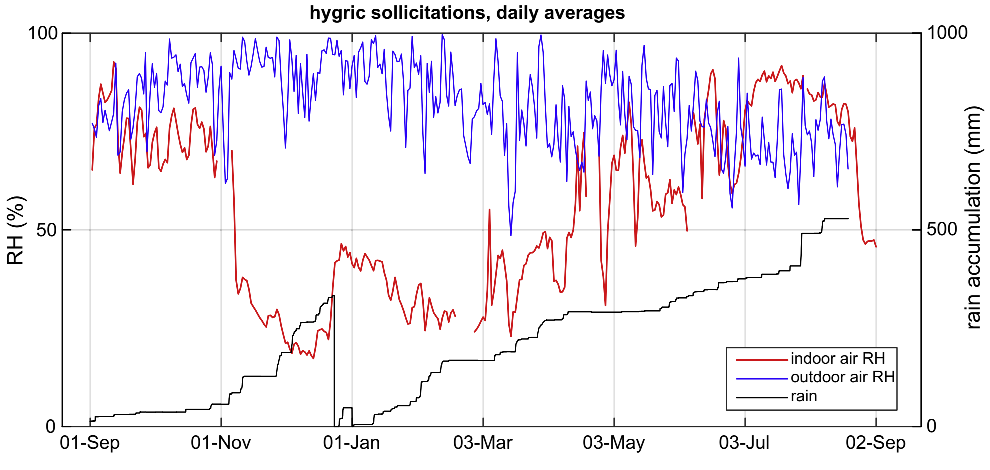


Fig. 3. Daily average of relative humidity in the test cells and outside, rain accumulation (with reset on January, 1st).

3.2. Model validation

3.2.1. Long term trends

Fig. 4 presents the results between September 2012 and August 2013; the measured values plotted here are the relative humidity averaged over the 3 heights of the wall and over 24 h. On the left, data for test cell PASSYS 3 (with industrial, pre-mixed coating), on the right data for test cell PASSYS 4 (with on-site mixed coating).

The calculations fit correctly the measures under the interior coating for both test walls, as can be seen from the bottom graphs.

In the middle of the wall, the experimental behaviour is well replicated during the first 4 months. From the end of December onwards, when the humidity increases in the walls, the calculated RH remains under the measurements. Afterwards the humidity remains lower during the next months in the calculations, but the trends are correctly followed. This phenomenon was already visible when only the hempcrete was modelled (with T and RH under the coatings as boundary conditions, see Bejat et al. [3]. Even though there is a difference of about max 7–10% RH between calculations and measures in the middle of the wall, the difference between the walls is reproduced.

Under the exterior coating, the measurements in PASSYS 3 are quite correctly reproduced; the general level of humidity is correct, although some discrepancies can be seen. In winter and spring, the model slightly underestimates the humidity, whereas in autumn and summer the humidity tends to be overestimated.

We can see more discrepancy between calculation and measures under the coating of the test wall "PASSYS 4" (which absorbs rain). However the overall level of humidity is correct and significantly higher than in the other test wall (PASSYS 3). A major difference with the measurements is that in the calculation the coating always dries out and does not remain at 100% RH.

As input data for the calculations, we used rain gauge measured on site, but some data miss. In April–May, no rain was recorded at all, whereas weather service [22,23] indicates more than 270 mm of accumulated rain during this period; this is equivalent to the rain fall of December 2012 (see Fig. 3). This can explain the discrepancy between the measures and calculations under the exterior coating in this period. However, on the period January–February, there is no lack of data, this cannot explain the difference between calculations and measures on this period.

The humidity calculated under the coating is lower than the measurements in the test wall of PASSYS 4; this can explain why the humidity is underestimated in the middle of the wall. Indeed, the difference between measures and calculations is bigger (around 10%) in test wall of PASSYS 4 than in test wall of PASSYS 3 (around 7%).

3.2.2. Properties of the exterior coating

Simulations were carried out in order to determine the properties of the coatings used in the experiment. The two main properties to determine were the ability to absorb liquid water (absorption coefficient A) and the vapour permeability (Sd value). Table 2 lists the cases studied. Those values were chosen to have coatings from the different categories defined in the standard NF EN 15824.

The experiment shows (see Section 5.1) that the coating on PASSYS 3 did not absorb liquid water, therefore we tested values of $A = 0.01\ \text{kg}/(\text{m}^2\ \text{s}^{0.5})$ and $A = 0.001\ \text{kg}/(\text{m}^2\ \text{s}^{0.5})$. Conversely on PASSYS 4 the coating was much more absorbent, we used $A = 0.05\ \text{kg}/(\text{m}^2\ \text{s}^{0.5})$. We tried for both coatings 3 different Sd values (see Table 2).

The calculations were run for a period of 1 year (whole data acquisition period). Fig. 5 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

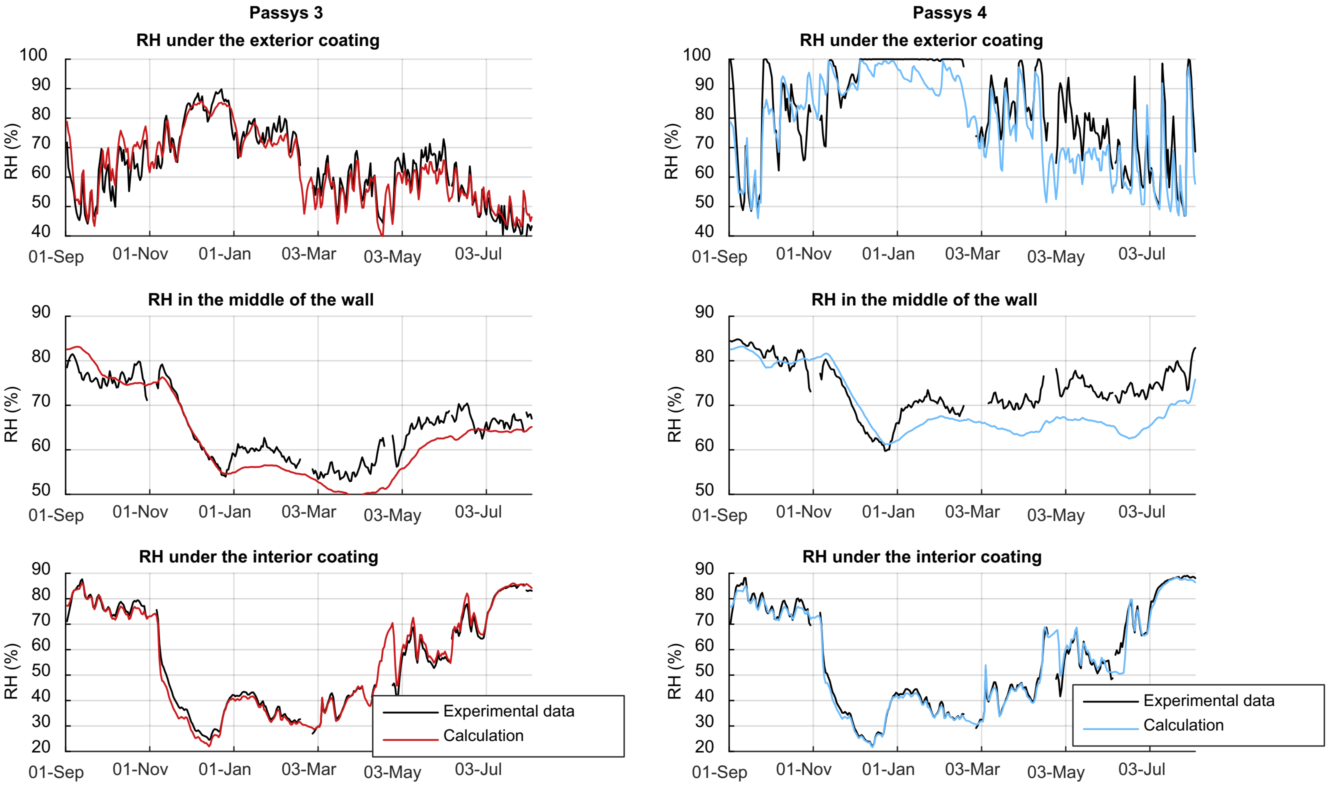


Fig. 4. measured and calculated relative humidity in the walls, all over the year.

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Table 2
Properties of the coating compared.

	Sd = 0.1m	Sd = 0.5 m	Sd = 2m
A = 0.05 kg/(m^2 s$^{0.5}$)	A	B	C
A = 0.01 kg/(m^2 s$^{0.5}$)	D	E	
A = 0.001 kg/(m^2 s$^{0.5}$)	F		

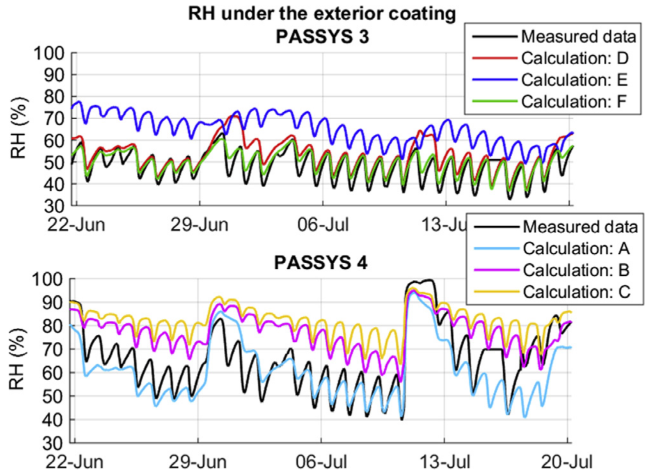

Fig. 5. Variation of the properties of the outer coating.

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 7.5 cm from the coating, they confirm this choice. This is not presented here.

This step allowed to adjust the material properties of the hempcrete based on laboratory measurements and to determine roughly those of the coatings which were unknown. In the following, we will use both calculation results and measurements to analyse the effect of the interior and exterior coatings.

4. Effect of interior coating

4.1. Drying process

4.1.1. Initial drying of different blocks

The blocks were fabricated at different dates (mostly in January 2012) and stored in different conditions for a few months before the wall construction in June 2012. Fig. 6 shows the water vapour pressure in the middle of different hempcrete blocks located far from the concrete post. The plotted values are averaged over 24 h for readability purposes. The indoor and outdoor vapour pressure is represented in light grey. When the measurements begin (September), the walls were built since already 2 months. During this period, and until the end of October, they are exposed to outdoor climate and no indoor climate variation was fixed (one can see that the vapour pressure inside both cells is rather similar to the exterior vapour pressure). Although all blocks are exposed to the same conditions, the vapour pressure in the middle still differ when the data acquisition begins, with a vapour pressure between 1000 Pa for the drier block and 1600 Pa for the moister one. The discrepancy between the blocks has been reduced to less than 100 Pa of pressure difference except for one block (Top – P3) which remains almost 100 Pa lower than the other blocks by the end of October, i.e. 4 months after the construction of the walls.

At the beginning of November the indoor temperature was increased by turning on the heating system (set-point 28 °C). This lead to a faster and regular decrease of the relative humidity. The moisture content of the material can be directly related to relative humidity via the sorption curve; we can therefore consider that the decline of RH corresponds to the drying of the blocks. One can notice that the drying slope of all blocks are parallel. The humidity level decreases of 20% RH within 2 months, thanks to a very low indoor RH.

Those results show that the hempcrete can remain moist once installed as long as the building is not heated. However it is possible to accelerate the drying if necessary. We can also see that the differences remain between blocks even after several months under similar exposure which emphasise the importance of good initial conditioning of blocks during the manufacturing process.

4.1.2. Effect of the coating on the drying capacity of the wall

The coatings were applied shortly after the wall was built. This could have prevented the blocks from drying faster. To analyse this effect, we carried out numerical simulation with and without the interior coating. In the calculations we always assumed that the exterior coating was applied, as it is necessary to protect the wall from weather solicitations.

Fig. 7 shows the results on the relative humidity in the middle of the blocks. We can see that in the absence of indoor coating, the blocks dry out only a bit faster than in the case with a coating (comparable to our measurements). This shows that a coating can be applied on the interior side of blocks that have not yet dried out, without compromising the drying process, provided that this coating be vapour permeable as it is in our experiment (see Section 3.2.2).

Fig. 8 presents measured values of the humidity in the room air, under the interior coating and in the middle of the walls. We can notice that the relative humidity under the coating decreases nearly as fast and as much as the humidity in the indoor air. On the contrary, the humidity in the middle of the blocks decreases much more slowly and remains much higher. This implies that the actual limiting factor in the drying process is the hempcrete itself, and not the coating applied on it.

4.2. Indoor humidification

In order to evaluate the impact of the indoor moisture on the wall, a humidifier was used to generate moisture loads 6 h/day every day during 2 months (see Table 1). During this period, the indoor temperature was kept constant at 25 °C. Fig. 9 shows the measured relative humidity between the 18th and 24th of May, that is 1 month after the beginning of the humidification tests.

The relative humidity inside the room volume raises up to more than 90% while the temperature is kept constant (25 °C), and falls down every night at around 40%, leading to variations of the vapour pressure between 1500 Pa and 3000 Pa. A part of the moisture is absorbed by the tested walls, another part is removed by air leakages.

In both cells, the moisture in the wall, under the interior coating (Fig. 9, top) remains much more stable, oscillating between 1800 Pa and 2200 Pa.The variations are reduced by the coating and the hygroscopicity of the hempcrete. Collet and Pretot [12] had shown that coating reduces and slows down the moisture penetration in hempcrete walls. (Latif et al. [18] also presented results showing that the moisture buffer potential of a coated hempcrete

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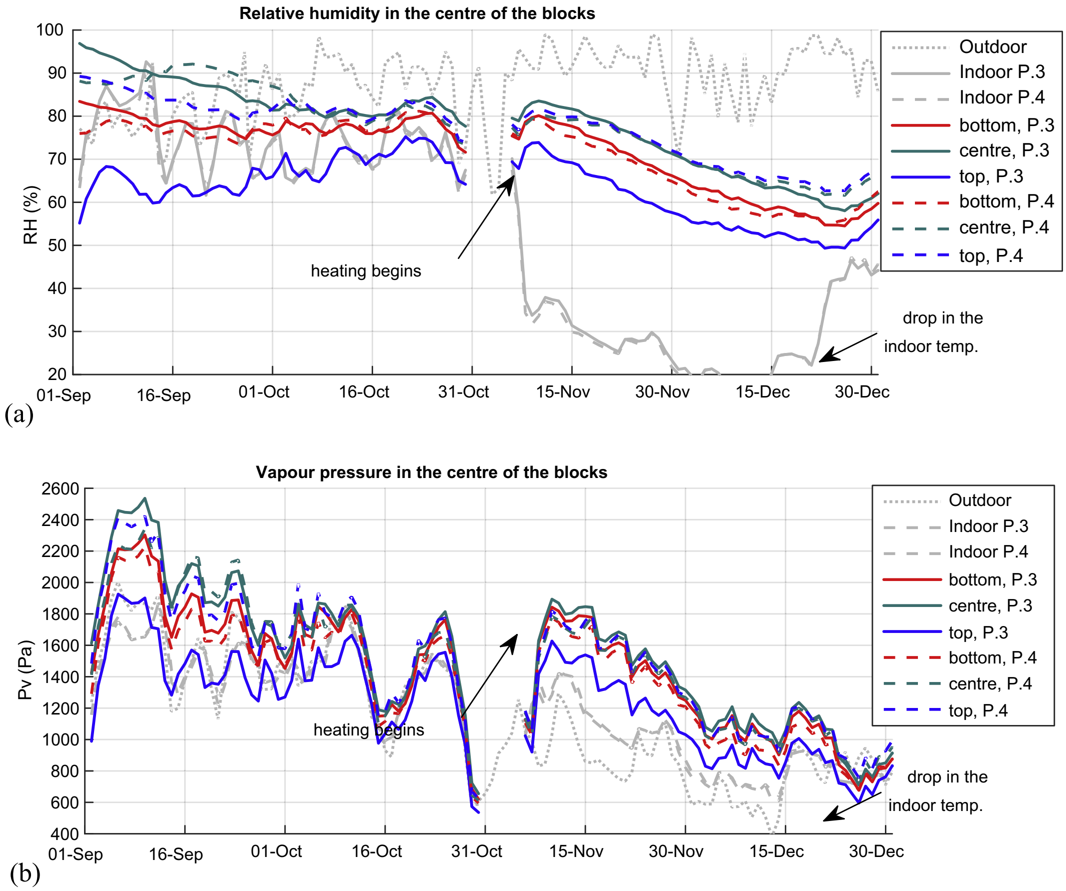

Fig. 6. Humidity inside the blocks during the first months of the experiment; a: relative humidity, b: vapour pressure.

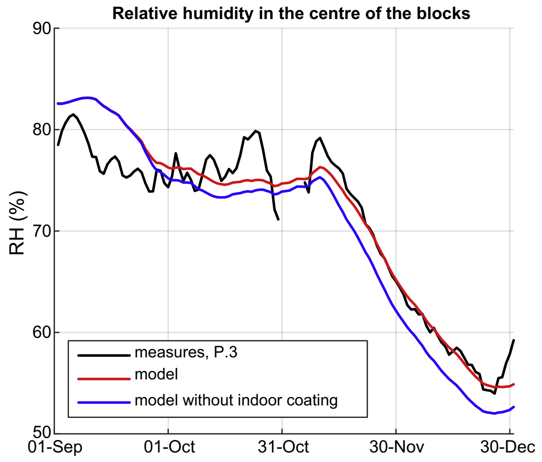

Fig. 7. Drying of the blocks with and without interior coating.

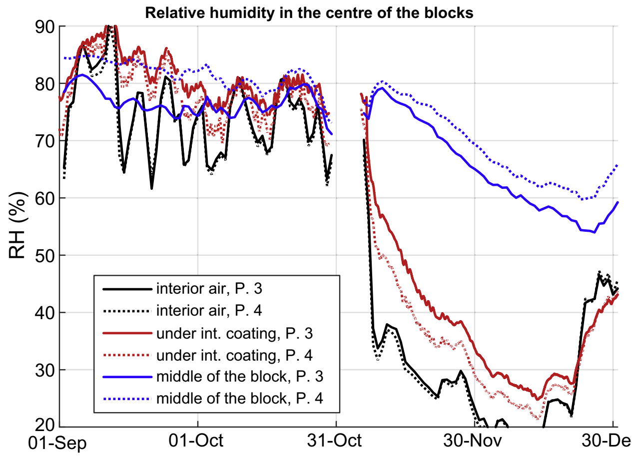

Fig. 8. average over 3 heights and 24 h of relative humidity in the walls during the drying phase.

was reduced in comparison with an uncoated hempcrete, however only slightly. In the middle of the wall (Fig. 9, bottom), the relative humidity varies very few due to the high hygric inertia of the hempcrete.

We can therefore conclude that for short term solicitations, such high levels of moisture don't propagate deeply into the hempcrete. This is in line with the works of Collet and Pretot [10], that found of a penetration depth of 5.8 cm for daily solicitations of an uncoated hempcrete.

5. Exterior coating effect

5.1. Effect of rain loads

The 2 test walls were submitted to real weather during more than 1 year, and thus to rain loads. One objective of this study was to compare the effect of the 2 exterior coatings used (industrial, pre-mixed coating versus on-site, hand-mixed coating, with a different composition). Fig. 10 shows the measurements of

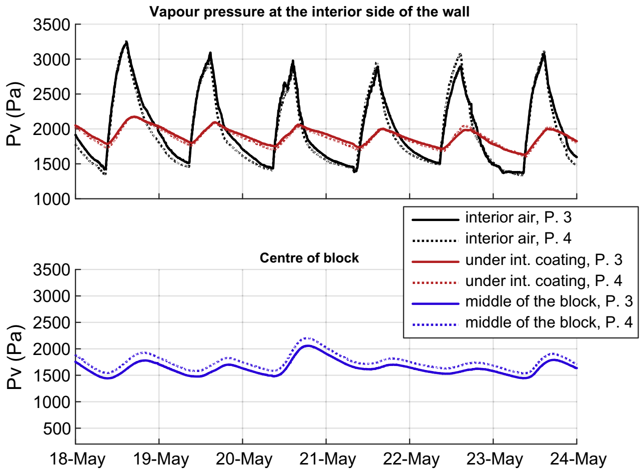

Fig. 9. relative humidity of indoor air and in the wall.

relative humidity under the exterior coatings and in the middle of the 2 walls over a period of 18 days. During this period, the weather was nice and sunny, except for 2 days: on June, the 21st and June, the 29th, when rain has occurred. The 2 walls being at the same temperature, the comparison can be done in relative humidity rather than in vapour pressure.

At the beginning of the period, both walls behave similarly. Then, after the big rain event of June, 21st, the vapour pressure under the two coatings differ. On the upper graph, we can clearly see a major difference in the behaviour of the 2 coatings: under the coating of test cell PASSYS 4 (dashed lines), the relative humidity increases suddenly during the rain events, whereas no reaction is observed under the coating of test cell PASSYS 3. A test was carried out, detailed in, that proved that the coating of test cell PASSYS 3 (industrial, pre-mixed) did not absorb liquid water, whereas the handmade, mixed on site coating did absorb instantaneously great quantities of water [24]. This was confirmed by numerical simulation (see Section 3.2.2), that has also shown that this difference did not come from the vapour permeability of the coatings, as both coatings are vapour permeable.

The relative humidity remains higher under the coating of PASSYS 4 during several days. The drying process seems to be inhomogeneous, as we observe discrepancy between the 3 sensors. Conversely, the relative humidity under the coating of test cell PASSYS 3 is very similar for the 3 sensors.

The second graph shows the relative humidity in the middle of the blocks; as previously observed, the amplitude of variations of relative humidity is very small; on this short term period, no direct effect of the rain penetration can be seen. At this depth, we observe a certain heterogeneity of the relative humidity inside the blocks in both walls. The average level of humidity is higher in the wall of test cell PASSYS 4, the coating of which absorbs rain. On this short period, no major trend can be seen, however one can distinguish that the difference between the two walls increases slightly after the first rain event. This effect will be confirmed in the following section:

We can also notice that relative humidity variations are strongly dampened in comparison with the exterior relative humidity, as was seen on the indoor side of the wall (see Section 4.2), although numerical simulations have shown that the exterior coating is very vapour permeable (see Section 3.2.2).

5.2. Long term impact

The results here are presented both in vapour pressure and relative humidity, as the relative humidity is correlated with the actual moisture content of the material (sorption isotherm) and to the risks (see Section 5.3). Fig. 11(a) shows the relative humidity measured during the whole year, averaged over 24 h and at the 3 heights, for the blocks placed far from the concrete post. The upper graph shows the humidity between the exterior coating and the hempcrete block. We notice here a very strong difference between the two test walls. The humidity of the wall coated with the hand prepared coating ("PASSYS 4") is higher as the humidity of the wall with industrial coating ("PASSYS 3"). Several peaks can be observed up to 100% (although those are 24 h-averaged values), and one can even see that the humidity remains at 100% RH during 3 months in winter. This phenomenon was observed by all 8 sensors placed under this coating. This is the consequence of the absorption of rain by the coating of test cell PASSYS 4. The test mentioned previously and described in Piot et al. [24] showed that the sensors could be saturated by a rain event but were able to dry out within 2–3 days.

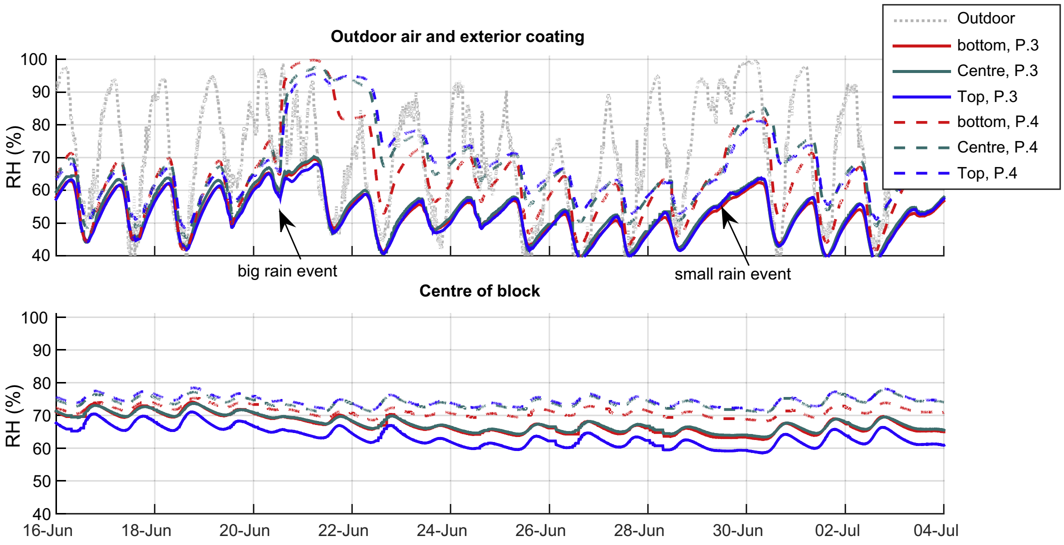

Fig. 10. relative humidity during 2 weeks under the exterior coating (top) and in the center of the bloc (bottom).

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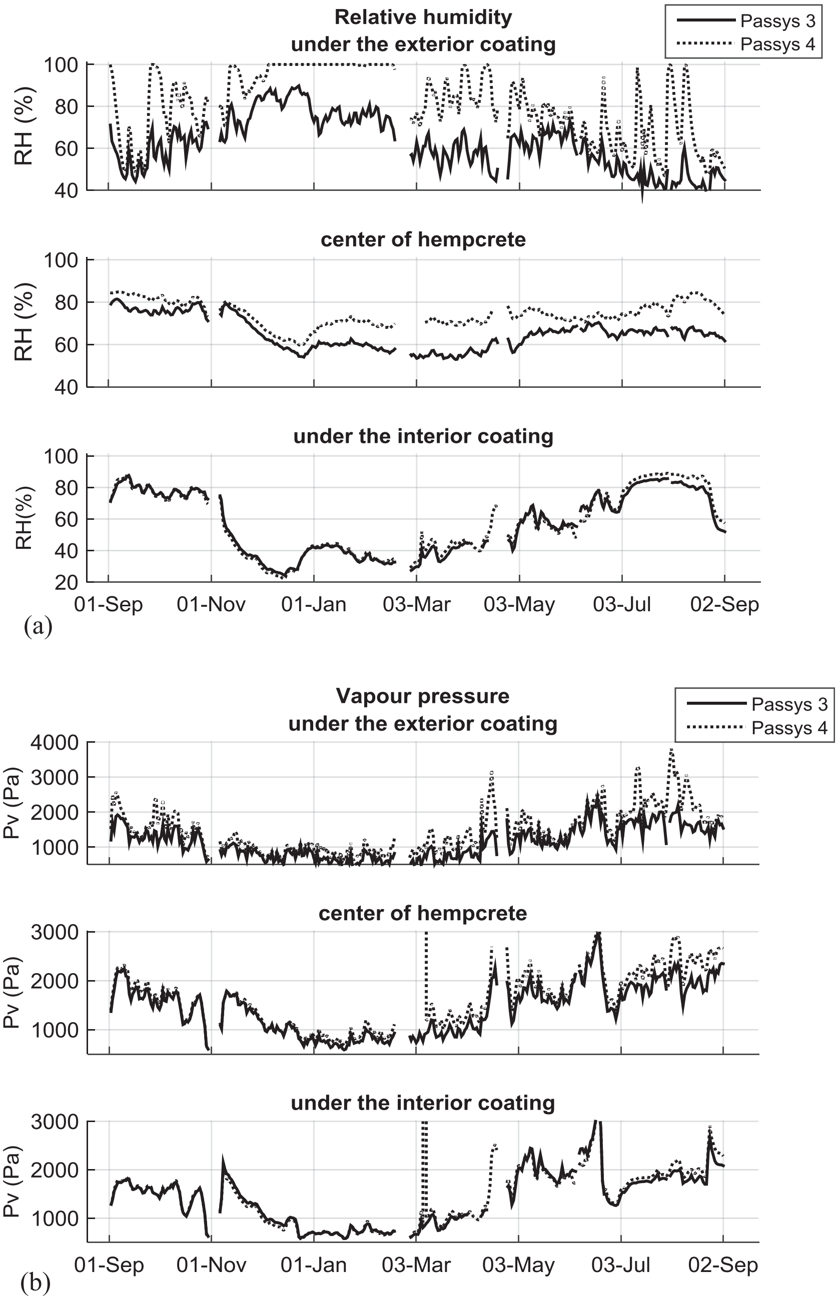

Fig. 11. Relative humidity (a) and vapour pressure (b) at different depths in the wall; values averaged over 24 h and at 3 heights.

This has an impact on the humidity in the middle of the wall. Indeed, the relative humidity is higher in the wall on “PASSYS 4” than in the wall of “PASSYS 3”. During the first drying phase (until November), the moisture level in both walls tends to converge to the same value. But during the winter, the difference begins to increase and remains around 20% RH. It decreases in May, we can notice that it follows a period where the RH is less high under the exterior coating in PASSYS 4. In July, the difference in the RH in the middle of the 2 walls increases again, following a period where RH has reached high values in PASSYS 4.

Apart from rain, we can see that the moisture in the wall is strongly influenced on the long run by the variations of the indoor humidity (see Fig. 3); indeed in the centre of the hempcrete the humidity follows the trend of the indoor air humidity, presenting a slow increase between March and July.

On the interior side of the wall no major difference is to be seen between the two test walls. The relative humidity under the coating follows closely the indoor relative humidity.

The Fig. 11(b) confirms the difference between the 2 walls: the vapour pressure in Passys 4 (hand mixed coating) becomes more humid than the Passys 3 wall (industrial coating) after the winter.

5.3. Associated risks

5.3.1. Risks of mould growth

At the end of the experiment, samples were removed from the 2 walls at different depths: under the exterior coating, in the middle of the wall, and under the interior coating, at mid-height of the wall. An additional sample was taken in the middle of the block, close to the concrete post. This experiment is detailed in Bessette

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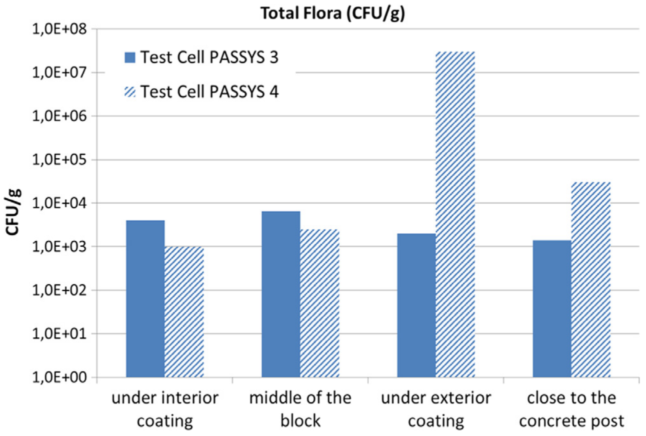

Fig. 12. Microbial growth after incubation in the different samples.

et al. [5]. Fig. 12 shows the total microbial growth in colony forming units per grams after incubation.

The results showed that the risk of mould growth is negligible (inferior to 10^4) in the middle of the walls and near the interior coating for both walls after one year of exposure to real outdoor climate. The difference between the various locations can come from the initial moisture content of the different blocks, it seems not to be significant. On the contrary, the risks differ under the exterior coating depending on its composition. The risk of mould growth was found not significant under the industrial, pre-mixed coating (test cell PASSYS 3), whereas there exists a significant risk of mould growth (>10^6) under the hand-mixed coating (test cell PASSYS 4), where the relative humidity was very high during several months. Close to the concrete post, there is a small difference between the 2 cells, but the risk remains small (<10^5). Here too, the difference can come from the initial moisture of the different blocks. We can thus conclude that the fresh concrete cast seems not to increase the risk of mould growth.

5.3.2. Thermal performance

Another effect of the humidification of the wall is related to the thermal conductivity. At the material scale [7,8], suggest that an increase of 10% up to more than +50% in thermal conductivity can be seen between dry and moist state (75% RH). From Cerezo [8], the change of thermal conductivity between 50% RH and 75% RH is of +20%. The works of Evrard [14] on a hempcrete slightly more dense than the one used here indicate an increase of 8% in the thermal conductivity between 50 and 65% RH. An additional source of energy loss could be also the energy necessary to evaporate and dry out the moisture at the exterior surface. The heat fluxmeters installed on the interior of the walls recorded indeed a difference between the 2 walls. However, on the heating period, the difference between the energy losses through the walls was only 6%, which is not sufficient to conclude to a significant effect.

6. Conclusions and recommendations

In this article, the behaviour of hemp concrete walls in realistic conditions has been studied. For that, two tests walls, made of prefabricated hemp concrete blocks were built. The binder used was prompt natural cement. Two different external coatings were applied. Those walls were exposed to the outdoor climate on one side and to a controlled climate on the other side during one year. In parallel a numerical model based on Künzel's equations was developed and numerical results were compared to experimental data.

Thanks to the numerical model and experimental data, the material properties have been calibrated. They were tuned for the hemp concrete materials and roughly estimated for the coatings. The experimental campaign highlights that the drying process of blocks is long and last more than 4 months in the conditions applied.

Regarding the interior coating, it has been proved that it was permeable to vapour. In spite of this, short term interior humidification did not impact the hemp concrete blocks behaviour. Furthermore, numerical simulation shows that internal coating did not slow down significantly the drying process of the hempcrete blocks.

Regarding the exterior coating, both numerical simulation and experimental results highlight that industrial coating did not absorb rain (water liquid) contrary to the hand mixed one. The effect of this absorption strongly impacts the RH under the coating in the short term and its impact is even detected in the middle of the blocks in the long term. This could lead to possible problem of mould growth over the long run as first measurements suggest.

To continue this work, a longer period with a real case (house with people living in) will complete this study and improve the knowledge on this material behaviour. Regarding the numerical model, some improvement can be done to be more accurate, especially in short term dynamic.

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