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MOISTURE PROPERTIES OF RAPE STRAW CONCRETE AND HEMP CONCRETE

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Abstract

The renewable and less impacting materials are more and more involved with science research. The bio-based materials can replace the traditional ones in order to reduce greenhouse gases emission produced by the building sector. This article presents the moisture properties of new bio-based material called "straw lime concrete" and of “hemp lime concrete”, which is considered as the reference material. The tests are performed to establish the experimental measure of sorption isotherm, water vapor permeability and moisture buffer capacity, which is estimated from the moisture buffer value determined under equilibrium conditions. The results showed that hygric performance of the materials studied is particularly interesting and both exhibit an excellent moisture buffer capacity.

Keywords: Rape straw concrete; Hemp concrete; Hygric properties; Moisture buffer capacity

1 INTRODUCTION

Over the last few decades, there has been an increasing in the use clean and durable materials in order to reduce the building sector pollutants, which acting on the environment. Using vegetable particles as building material aggregates can contribute effectively to reduce greenhouse gas emissions thanks to its ability to capture carbon dioxide during its life cycle. Currently, hemp lime concrete (HLC) has been extensively studied in many researches [1-4]. Indeed, this material enables to store approximately 35 kg of CO_2 per m² of wall built with a thickness of 25 cm over 100 years stores [5].

Hemp concrete, is mainly used to cover the walls of masonry, or to fill the timber-framed structures in new and old buildings and, it can be used to isolate the roofs or floors. The physical and hygrothermal characteristics have shown that this material has a low conductivity which reduces heat diffusion and a high moisture buffering capacity which can maintain indoor hygrothermal comfort [6, 7, 8, 9]. Regarding its low thermal conductivity (it about 0.1 W/(m.K)) [9, 10], this material can be used without adding insulation material.

In hygric case of view, hemp concrete has a high water vapor permeability which is approximately 2.5×10^{-11} kg/(Pa.m.s) [2]. At whole building scale, numerical and experimental results showed that hemp concrete can decrease the daily indoor relative humidity variations and reduce energy consumption [8, 11], thanks its high moisture buffer capacity (2.02 g/(m^2.%RH)) [7].

This paper presents a new bio-based material called "rape straw lime concrete" by combining the rape straw with a lime-based binder. The choice of other resources such as rape straws as aggregates has its wide availability. In France rapeseed cultivated is the fourth most cultivated species. Indeed, using rape straw for green materials will help to promote new economic prospect for straw rape.

This paper deals with the analysis of the moisture properties of bio-based concrete materials. The new material is investigated: the "rape straw concrete". The performance of the "rape straw concrete" and the "hemp lime concrete" with respect to their moisture properties were compared based on experiments.

Also, the comparison of these two materials intended to provide more information about the straw concrete which is a new bio-based material and the main subject of this study. These materials were tested for moisture properties (sorption isotherm and water vapor permeability) and moisture buffer values inspired by the Nordtest project [12], which represent their ability to dampen the indoor relative humidity variations thanks to their moisture sorption capacity.

2 MATERIALS

2.1 Manufacturing

Hemp land straw concretes are comprised of water, lime-based binder and plant particles such as hemp shivs for hemp concrete (HLC) case and rape straw for rape straw concrete (SLC). Hemp shivs and rape straw have a relatively constant size distribution (5x5x15 mm for hemp shivs and 0.5x3x15 mm for rape straw case).

The binder used, in this present work, for the formulation is Tradical PF 70 which contains around 75 % of rich lime (Ca(OH)2), 15 % of hydraulic lime and 10 % of puzzolon binders. The proportion of lime binder, hemp/rape straw and water by mass (%) is presented in Tab. 1.

Table 1: Proportion of lime binder, hemp/straw and water by mass for concretes.

Material	Granular	Lime	Water
HLC	16	36	48
SLC	14	36	50

The concretes were manufactured by the molding method. It consists in mixing the aggregates, the water and binder. The mixture was manually filled in the mould and then damped in order to avoid the empty zone. The concrete specimens were removed from the mould after three days. In order to ensure the total carbonation of the concrete, samples have been stored in the same location for 9 months.

2.2 Density and porosity

The dry density, matrix density and porosity of concretes and aggregates were carried out and presented in Tab. 2. The matrix density is measured experimentally according to the pycnometer method involving filling air spaces in material with toluene. The total porosity is calculated from the matrix density and dry bulk density of material. Concerning the open porosity, it is determined according to the vacuum saturation method.

The results shown that hemp shivs and rape straw present an important porosity which are 90% and 89% respectively. The physical proprieties of both materials are very close. Compared to HLC, SLC shows a slightly lower total porosity and higher dry density (487 compared to 478 kg/m^3) and higher open porosity.

Table 2: Density and porosity of studied concretes and aggregates.

	Dry density [kg/m^3]	Matrix density [kg/m^3]	Total porosity [%]
HLC	478 ±7	2030 ±30	76.4 ±0.1
Hemp shivs	125 ±9	1259 ±21	90.1 ±0.5
SLC	487 ±6	1954 ±36	75.1 ±0.7
Rape straw	125 ±5	1140 ±32	89.0 ±0.5

3 THEORY AND METHOD

3.1 Sorption isotherm

The sorption isotherm or the hygroscopic curve describes the equilibrium between the water content and relative humidity. These curves can be measured under quasi-equilibrium conditions according to continuous or discontinuous methods [13].

The specimens were placed in desiccators contending salts solutions in order to keep relative humidity at desired levels which have been chosen: 0 %, 33 %, 51 %, 81 % and 95 %. To control the temperature, the desiccators were stored in test room where the indoor temperature is maintained at 23 °C by an air conditioner. For each measuring point, three samples were used. Before testing, the samples were dried in an oven at 70 °C until the weight loss between two successive measurements, with a time interval of at least 24 h, remained less than 0.1 %. The water content was obtained by weighing the specimen with one balance that has an accuracy of 0.1 mg. The specimen was considered to be in steady-state when the mass variation after weighting at three consecutive intervals of 24 h (or more) is less than 0.1 % of the mass of the wet sample. The water content was calculated from following equation:

$$w = \frac{m - m_0}{V} \qquad (1)$$

Several mathematical models have been suggested to represent the relationship between equilibrium moisture content and relative humidity [14, 15]. Among the existing models, BET and GAB models can be cited. An experimental study comparing two models showed that, in the case of a porous medium, the GAB model has much wider application, it also allows to find the results of BET model [16]. Therefore, the GAB model was chosen and it is expressed as:

$$w = \frac{\varphi}{\alpha.\varphi^2 + \beta.\varphi + \gamma} \qquad (2)$$

Where α, β and γ are GAB model constants to determine.

3.2 Moisture diffusivity

Moisture diffusivity is widely used for investigating the moisture transport within building materials under a vapor pressure gradient. This transport property is calculated from the vapor permeability measured experimentally and specific hygric capacity, which is the slope of moisture retention curve. Moisture diffusivity is expressed as follows:

$$D_w = \frac{\delta_p . P_s}{\frac{dw}{d\varphi}} \qquad (3)$$

3.3 Moisture buffering capacity

The relative humidity is one of most important factors to consider for evaluating the hygric building comfort. High indoor humidity can cause the degradation of a building structure and significantly shorten its life [17]. Many authors showed that the hygroscopic materials can contribute to moderate the indoor relative humidity variations (so improve comfort for occupants) and reduce energy consumption [8, 12, 11].

Currently, the moisture properties of materials have been presented which are measured under steady state and equilibrium conditions of relative humidity and temperature. However, it is more realistic to study the hygric behavior of materials under dynamic conditions. The Nordtest project [12] proposed an experimental protocol to evaluate the moisture buffer capacity of hygroscopic materials via the definition of Moisture Buffer Value (MBV). There is notice that the

MBV value takes into account the mass transfer resistances at the boundary, so this is not an intrinsic property of the material. The aim of this part is to determine the MBV values of studied materials and to experimentally investigate the impact of specimen thickness on the moisture buffer capacity.

3.4 Moisture penetration depth and ideal MBV

The penetration depth is defined as the depth where the amplitude of moisture content variations does not exceed 1 % of the surface amplitude. Further details can be found in [12]. The penetration depth ($d_{p,1\%}$) provides a referential value which can be used to evaluate the thickness of the sample for measuring the MBV value. The moisture penetration depth is calculated using the following:

$$d_{p,1\%} = 4,61\sqrt{\frac{D_w \cdot t_p}{\pi}} \quad (4)$$

Nordtest defined also the ideal moisture buffer value (MBV_{ideal}) which is calculated based on the Fourier analysis when relative humidity variation at boundary of material is a sinusoidal form. The MBV_{ideal} value is derived from the material properties and is given by:

$$MBV_{ideal} \approx 0.00568 \cdot P_s \cdot b_m \cdot \sqrt{t_p} \quad (5)$$

Moisture effusivity bm allows to describe the ability of a material to absorb or release moisture and can express theoretically, the rate of moisture absorbed by a material when it is subjected to a sudden increase in surface humidity [12]. Moisture effusivity is expressed as follows expression:

$$b_m = \sqrt{\frac{\delta_p \cdot \frac{\partial w}{\partial \varphi}}{p_s}} \quad (6)$$

3.5 MBV experimental protocol

The practical MBV, as defined in Nordtest project, indicates the amount of water vapor uptake or release by material per open surface area, during a certain period of time when it is subjected to variations in relative humidity of the surrounding air. The unit of this global parameter is kg/(m².%RH). Experimentally, the sample is subjected to cyclic step-changes in relative humidity between 75 % RH during 8 h and 33 % RH during 16 h respectively at a constant temperature of 23°C. The MBV value is calculated at steady-state by the following equation:

$$MBV = \frac{\Delta m}{A \cdot \left(HR_{high} - HR_{low}\right)} \quad (7)$$

Where Δm is the moisture uptake/release during the period, $RH_{high/low}$ the high/low relative humidity level and A is the exposed surface.

The MBV value is determined in steady state, which is supposed to reach, when between three consecutive cycles, the test satisfies the following two conditions:

- The change in mass Δm [g] is less than 5 % between the last three cycles. Δm is the average between the weight gain during the moisture uptake and the weight loss during drying.
- The difference between the weight gain and weight loss within each cycle should be less than 5 % of Δm.

The Moisture buffer values of HLC (for validation of experimental setup) and SLC are measured experimentally according to the Nordtest protocol [12]. In order for this to be conducted, a climate chamber (CL2 Biaclimatic Type -25) was used. This device can control the temperature and the relative humidity in the range of 8-65 °C with an accuracy of ± 0.3 °C and 10-98 %RH, with an accuracy of ± 2 %RH respectively. The temperature is kept constant at 23°C. The regulation of the relative humidity (75%, 33%) in the climate chamber according to the 8/16 h scheme carried out manually. The regulation of temperature and relative humidity can be verified using the sensor of the climate chamber.

Based upon the penetration depths calculated above, thicknesses of samples (with the area of 100 cm^2) are 3, 5 and 7 cm. For each thickness, three samples were prepared. The side lengths of exposed which are higher than the value recommended in the Nordtest protocol. The back and edges of samples were sealed with aluminum tape as shown in Fig. 1. These were then placed in the climatic chamber. The gravimetrical determination of the moisture absorption/desorption was made outside the climate chamber using a balance with 0-750 g and 0.001 g resolution. To minimize the perturbation of temperature and relative humidity in the climate chamber, the specimens were weighed three times during the absorption period and two times during desorption period.

Fig. 1: Specimens for MBV measurement.

4 RESULT AND DISCUTION

4.1 Sorption isotherm

Fig. 2 and 3 present the kinetics of sorption curves of HLC and SLC. In order to reduce the measurement time for SLC case, the measurement for 95 % point was carried out from the samples stabilized at 81 %. As it can be seen in these figures, the sorption process was very slow, particularly under high relative humidity levels. It required more than 400 and 200 days for respectively HLC and SLC concretes to reach equilibrium when the relative humidity of atmosphere is 95 %RH. Furthermore, as can be seen in these figures unexpected behavior of the HLC kinetics of adsorption was observed at 90 days and 75 %RH case and at 150 or 250 days for 95 %RH case. That should be explained by the disruption of relative humidity regulation in the desiccators. Concerning kinetics curves of desorption, the water content decreases rapidly at the beginning and then it decreases slowly until the equilibrium state which is reached after about 200 days for both materials. Despite mold not being detected during experimentation, special attention must be taken care to prevent it due to the exposure time.

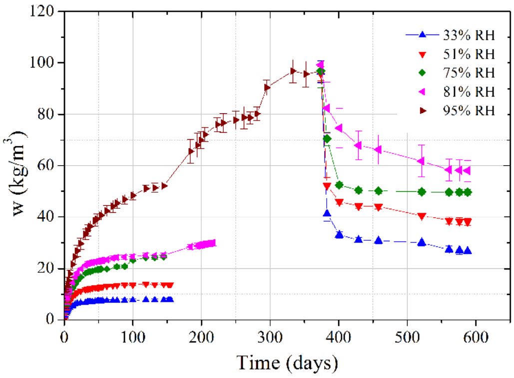

Fig. 2: Kinetics of adsorption of hemp lime concrete.

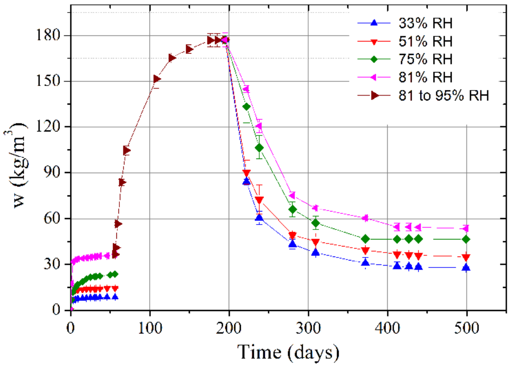

Fig. 3: Kinetics of adsorption of straw lime concrete.

Fig. 4 shown the sorption isotherms obtained from experimental adsorption and fitting curves with GAB model (GAB model constants are given in Tab. 3). The GAB model equation leads to satisfactory prediction of the adsorption equilibrium moisture content of both materials. The curves are most familiar to type II, according to the IUPAC adsorption isotherms classifications [18]. This type of curve characterizes the mesoporous and macroporous material media.

It can be observed that the adsorption isotherms of the two materials display a similar pattern, which is to be expected because they have similar microstructure. As the relative humidity increases, the moisture content increases, due to more water vapor being adsorbed, when relative humidity exceeds 75 %, moisture content of SLC increases more rapidly and higher than the one of HLC. At 95 %RH, the moisture content of SLC is 160 kg/m^3 compared to 95 kg/m^3 for HLC. This difference may be associated with microstructure of aggregate of lime shivs and rape straw. Indeed, it is apparent from scanning Electron Microscopy (SEM) analysis of hemp and straw particles (see Fig. 4) where rape straw has a finer and more homogeneous porosity compared to hemp. The pores are of different sizes in which their diameters of the hemp shivs and straw rape are respectively 10-40 µm and 10-30 µm.

Table 3: GAB model constants.

	α	β	γ
HLC	-0.085	0.058	0.030
SLC	-0.083	0.056	0.028

Furthermore, at the same relative humidity value, the moisture content of adsorption was smaller than the one of desorption. The average of moisture content difference between adsorption and desorption curves at 33, 51, 75 and 81 %RH for HLC and SLC are about 20 kg/m^3. As the adsorption isotherms, the desorption isotherm curve of SLC is similar than the one of HLC. Current physical explanations for the existence of hysteresis are, capillary condensation hysteresis, contact angle hysteresis and the ink-bottle effect due to entry pores with small diameter [19]. After drying out, the desorption curve did not return to the initial condition, the moisture content at 0-2 %RH for HLC and SLC are 9.2 kg/m^3 and 10 kg/m^3, respectively. This residual moisture content was also observed in [2] and it may be due to the carbonation occurred during the sorption test.

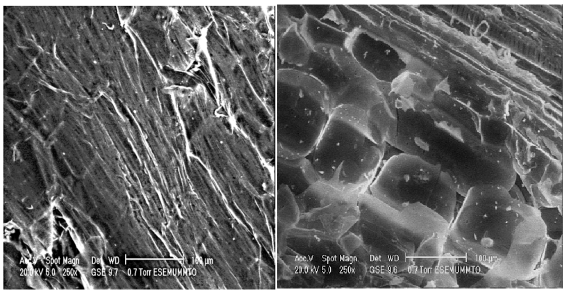
(A) (B)

Fig. 4: (A) SEM Image of hemp particle. (B) SEM Image of straw rape particle.

For sorption isotherms of HLC, it can be compared to the one obtained by Collet [20] and Evrard [3]. In comparison with the present study, the curves found by these authors have a similar shape; however, the moisture content was relatively low.

4.2 Water vapor diffusion

The moisture diffusivity as a function of water content calculated from equation 3 is presented in Fig. 5. The specific hygric capacity was derived from GAB model curve. Whereas, the water vapor permeability is experimentally in Codem Laboratory, which is determined, follow the dry-cup method [13].

It can be seen that curve shapes are in accordance with the one proposed by De Vries theory [21]. For HLC case it has similar shape compared to the one obtained by Collet [20]. When moisture content is low ($w < 6.84$ kg/m^3 for HLC and $w < 6.07$ kg/m^3 for SLC), the moisture transfer in water vapor phase is predominant. Therefore, moisture diffusivity increases up to its maximum value. Following this, its value decreases due to capillary condensation. The moisture transport in water phase is more significant compared to vapor phase. Indeed, the results showed that moisture diffusivities of both materials are similar. This should be explain by the similar sorption isotherm slope calculated according to GAB model.

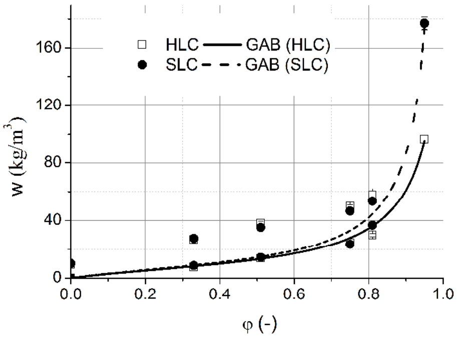

Fig. 5: Sorption isotherms of HLC and SLC.

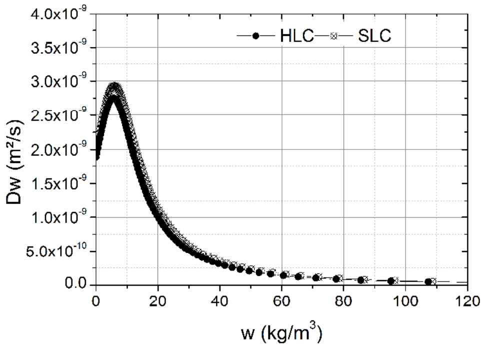

Fig. 6 : Moisture diffusivity as a function of water content for HLC and SLC.

4.3 Moisture buffering capacity of HLC and SLC

Moisture buffer value and classification of materials

The ideal MBV value and penetration depth, calculated from the experimental results, are presented in Table 4. It can be seen that the ideal MBV of SLC is 2.92 g/(m².%RH) and higher than the one of HLC which is equal to 2.66 g/(m².%RH) because SLC has greater moisture effusivity. Since moisture diffuses more rapidly in SLC than in HLC (moisture diffusivity of SLC is 1.69 10^{-9} m^2/s compared to 1.54 10^{-9} m^2/s for HLC), the penetration depth is greater for straw lime concrete case. Penetration depths calculated in Tab. 4 give only a referential thickness of specimen because of the boundary condition is different with the one of Nordtest protocol; This will be discussed in the next section.

Table 4 : MBV$_{ideal}$, d$_{p,1\%}$, D$_w$, b$_m$ of HLC and SLC

	HLC	SLC
Dw [m²/s]	$1.54.10^{-9}$	$1.69.10^{-9}$
b$_m$ [g/(m².Pa.s$^{1/2}$]	$5.67.10^{-7}$	$6.23.10^{-7}$
MBV$_{ideal}$ [g/(m².%RH)]	2.66	2.92
d$_{p,1\%}$ [cm]	3.01	3.14

Fig. 7*Fig.* shows the moisture uptake and release for the SLC sample at steady state, relative humidity and temperature in the climate chamber. The amounts of moisture uptake and moisture release are very close. For the HLC case, the MBV obtained is equal to 2.02 g/(m².%RH), which is very close to the values in the range of 1.75 to 2.15 g/(m².%RH)) given by [6, 8, 22]. These results validate the experimentation done in this work. The MBV value of the SLC is equal to 2.59 g/(m².%RH) and higher than that of HLC. The moisture buffering capacity of straw lime concrete is better.

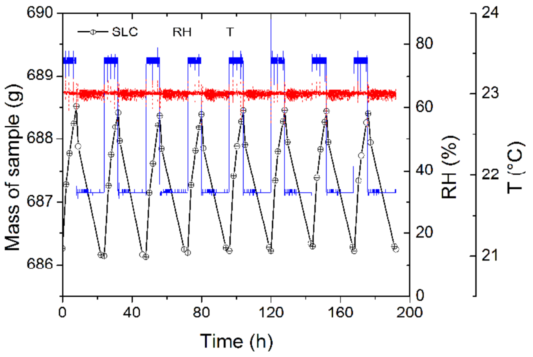

Fig. 7: Moisture uptake and release for the SLC sample at steady state.

To compare with other common building materials, the classification proposed by Rode [12], which defines five ranges for practical moisture buffer values classes varied from negligible to excellent, has been used. Fig. 8 shows the classification of studied materials (obtained with samples thickness of 7 cm) in comparison with other materials tested in Nordtest project. The first noticed point is that the concrete and brick fall into the lowest category. Plaster presents a moderate moisture buffer capacity performance and cellular concrete is the good one. The SLC shows the highest moisture buffering capacity and it is followed by the HLC. Both bio-based materials exhibit an "excellent" moisture buffer performance.

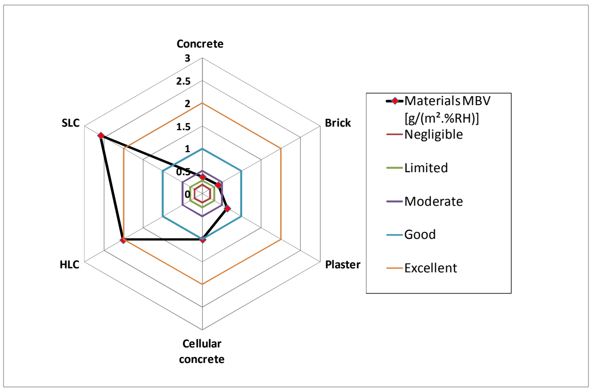

Fig. 8: Moisture buffer value classes of studied materials in comparison with other materials tested in Nordtest project.

Effect of the specimen thickness

According to the Nordtest, the specimen thickness should be as in the intended use or at least the moisture penetration depth (1 % definition) for daily moisture variation. As discussed above, the penetration depth was calculated assuming sinusoidal variation, while the Nordtest protocol applies stepwise change exposure. The moisture penetration depth can be only considered as an approximation. Numerical studies showed that penetration depth like used in Nordtest project effects the MBV value [23].

Therefore, the effects of sample thickness on the MBV values was experimentally investigated. The MBV values as function of specimen thickness are given in Tab. 5. The MBV value increases with the increasing thickness of sample. When the thickness varies from 3cm to 7cm, MBV value increases from 1.84 to 2.02 g/(m².%RH) (a variance of 9.7 %) for HLC case and from 2.29 to 2.59 g/(m².%RH) (a difference of 13.1 %) for SLC concrete case. Indeed, the moisture buffering capacity increases as the thickness has been confirmed in previous studies [23, 24]. This leads to the conclusion that the choice of the sample thickness based on moisture penetration depth for determining MBV may lead to non-representive results.

The theoretical penetration depth is based on steady state data (sorption curve constant and water vapor permeability). However, it is shown that the use of steady state data to characterize dynamic behavior hampers the reliability of calculation. In addition, only one value is taken into account for vapor permeability, or it was shown that the water vapor permeability of hemp concrete increases with humidity [6]. Therefore, the calculated penetration depth is an approximation and the variation of MBV with the thickness of the specimen must be due to the fact that the actual penetration depth is higher than the calculated one. Besides, the MBV value measured is significantly less than the MBV_{ideal} since the ideal experimental condition rarely exist and there is the film resistance on the exchange surface of sample.

Table 5: MBV value of SLC and HLC for different thickness of the samples

Concrete	e [cm]	MBV [g/(m².%RH)]	MBV_{ideal} [g/(m².%RH)]
HLC	3	1.84	2.66
	5	1.86	
	7	2.02	
SLC	3	2.29	2.92
	5	2.45	
	7	2.59	

5 CONCLUSION

This article focuses on the characterization of the moisture properties of two materials: the first one is a new bio-based material called "lime straw concrete" and the second one is lime hemp concrete, which is used to validate the experimental protocol of this work.

The both materials have a high absorption capacity and diffusion of water vapor.

The sorption isotherms were established and the results shows that the sorption curves of the two materials display a similar pattern due to their similar microstructure. For low relative humidity, moisture content is lower and for high relative humidity, the moisture content is higher due for triggering capillary condensation mechanisms. Indeed, compared to SLC, the moisture content of HLC is lower. Moreover, the fitting curves with GAB models give good approximation.

The water vapor permeability of both materials show high vapor diffusion capacity but SLC concrete is more permeable to water vapor than the one of HLC concrete.

Finally, hygric characterization under dynamic conditions has been done in accordance with the Nordtest protocol. It is shown that the MBV values for HLC and SLC concretes are respectively 2.02 and 2.59 g/(m².% RH). Both materials exhibit an "excellent" moisture buffer capacity. In addition, the influence of the thickness of the samples on the MBV value has been examined and the results showed that the choice of the sample thickness based on moisture penetration depth for determining the MBV may lead to nonrepresentive results.

6 ACKNOWLEDGEMENTS

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