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Sorption and moisture buffering capacities of hemp lime concrete embedded with phase change materials (PCM) for buildings.

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Abstract. The use of biobased materials in building construction is increasingly recommended because they have a low environmental impact and allow the reduction of fossil resources and energy consumption. Among biobased materials, hemp lime concrete (HLC) which has high insulation capacity was investigated in many studies highlighting its capacity to regulate interior relative humidity and pollutant. In order to design high-performance biobased concretes, a new hemp lime concrete incorporating micro-capsulated phase change material (HLC-PCM) was developed. The materials studied combine the hygric regulation capacity of HLC with the thermal regulation performance of phase change material (PCM). This article presents hygric properties of three HLC-PCM formulations. The previous studies showed that the thermal conductivity remains low, the heat capacity and thermal inertia increase considerably for hemp concrete with PCM. In this article, the sorption isotherm curves of studied materials were obtained by measuring the moisture content of test samples according to NF EN ISO 12571. Regarding the moisture buffering capacity, it was carried out according to the NORDTEST method. For the three studied composites, the results obtained are consistent with the ones found in the literature. It is shown that these materials are hygroscopic and have good or excellent moisture buffering capacity.

Keywords: Hemp lime concrete (HLC), phase change material (PCM), sorption, moisture buffering capacity

1 Introduction

Due to environmental awareness, the valorization of plant resources as building materials or incorporation in construction process has been carried out in the past few

decades. One of these building materials is hemp lime concrete (HLC). The recent studies show that this material has many advantageous characteristics such as low thermal conductivity (between 0.06 and 0.2 W/(m.K)) and high buffering capacity that can maintain indoor hygrothermal comfort [1], [2]. However, this material has a low mechanic resistance and thermal inertia. Therefore, to increase thermal inertia of hemp lime concrete, the phase change material (PCM) has been added in its formulation because PCM can store and release large amount of latent heat when the material changes phase on a defined temperature range [3], [4]. Therefore, developed material can reduce indoor overheating in summer. The PCM used in our studies is Micronal DS5001X, an organic paraffin phase change material. In the literature, there exists few works on the hygric performances of hemp lime concrete embedded with phase change materials. Regarding the thermal properties of developed materials, it has been presented in the previous publication [5] showing that adding PCM in hemp lime concrete results in higher density, higher thermal conductivity, and higher heat capacity with latent heat storage capacity.

This article presents the experimental hygrothermal characterization of three hemp lime concretes with and without PCM : sorption isotherm and moisture buffer value (MBV).

2 Materials

Three studied materials named: HLC+0%PCM, HLC+20%PCM and HLC+40%PCM were developed. Note that the names are abbreviated according to the percentage of PCM incorporated in each formulation, in which % represents the proportion of PCM used for manufacturing compared to the total dry weight of reference hemp concrete without PCM. Those materials can be used in both renovated and new buildings. The concretes developed are based on the hemp lime concrete formulation widely used in the literature [6], [7].

Table 1. Proportion of hemp shives, lime binder, water and PCM used for studied concretes.

	HLC+0%PCM	HLC+20%PCM	HLC+40%PCM
Hemp shiv	17.9 %	15.1 %	12.2 %
Tradical PF70	33.0 %	27.9 %	22.6 %
Water	49.1 %	46.0 %	42.2 %
PCM	0 %	11 %	23 %
Fresh density [kg/m ³]	692	790	947
Ratio W/B	1.49	1.65	1.86

The concretes are composed of : binder (Tradical PF70: 75% of hydraulic lime, 15% of aerial lime and 10% of pozzolana), hemp shives, water, and phase change material (Micronal DS 5001X). The proportions of PCM used for manufacturing are the first one without MCP noted 0% of PCM (considered as reference concrete) and the two others incorporating 20% and 40% of PCM in mass compared to the total dry weight of reference hemp concrete (binder and hemp shives of HLC+0%PCM). Table 1

represents material proportion (in mass) contained in each sample and its density. Concerning material fabrication method, lime and water were mixed first. Then, hemp shives were added and mixed in the mixer until the mixture was homogenized. Finally, the PCM was added and mixed gradually until the mixture was homogenized. Samples were manually compacted. All specimens produced were conserved in the room with temperature and relative humidity around 20°C and 50%RH, respectively, within 3 months to ensure the total carbonation in the entire concrete specimens.

3 Methods and theory

3.1 Sorption isotherm

The sorption isotherm or the hygroscopic curve relates to the moisture content in material as a function of the ambient relative humidity at a given temperature. The methods to determine the sorption isotherm can be divided in two groups: the continuous and the discontinuous methods [8]. The discontinuous method consists of measuring the variation of the amount of moisture adsorbed or desorbed by the specimen at successive stage of increasing or decreasing pressure under quasi-equilibrium conditions. This method can be performed with desiccators and saturated salt-solutions or with a climate chamber. Regarding the continuous method, it has the principle of slowly changing the quantity of moisture present in the atmosphere in such a way that the sample is permanently in quasi-equilibrium. In this study, the samples used for the test are cubic shape with 4 cm side and the sorption isotherms are measured according to the discontinuous method in the sorption test room. The water content is determined at successive stage of increasing relative humidity according to NF EN ISO 1257. To control the temperature, the desiccators with specimens were placed in a test room where the indoor temperature was maintained at 23°C by an air conditioner.

For each relative humidity level, the water content (w) can be calculated from the specimen mass according to equation (1):

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

With : w : water content [%], m : mass of wet specimens [g] and m_0 : mass of dry specimen [g].

Several mathematical models have been developed to describe the relationship between equilibrium moisture content and relative humidity [9]. Among the existing models which can be applied to biobased building materials, the most used is the GAB (The Guggenheim–Anderson–de Boer) model because it relates water content to specific surface area of the material with multilayer sorption [8], [10]. Also, note that GAB model is physically validated when there is no capillary condensation, and can cover a wide range of relative humidity (from 5 to 90% RH). This model is suitable to fit experimental sorption data all over the relative humidity range for building application.

In this article, the GAB model has been used to fit the experimental sorption data using equation (2). To obtain the equation parameters, a linear regression analysis minimizing the residual sum of squares was applied.

$$w(RH) = \frac{w_m C * k * RH}{(1 - k * RH)(1 + (C-1) * k * RH)} \quad (2)$$

When w_m : is a monomolecular water content [%], C and k : are the fitting parameters of GAB model, RH : relative humidity [%].

The sorption isotherm measurements (from 33 to 97 %RH) were performed at 23 °C in the laboratory and requires 30 months to complete six levels of relative humidity for the adsorption curve.

3.2 Moisture buffer value (MBV)

The MBV, as defined in Nordtest project [11], indicates the amount of water vapor that is transported in or out of the material per open surface area during a certain period when it is subject to relative humidity variations of the surrounding air. To evaluate the moisture buffering capacity of building materials, the Nordtest project proposes a protocol that consists of subjecting sample to cyclic step-changes in relative humidity between 75 %RH for 8 hours and 33 %RH for 16 hours, respectively at 23 °C. In this article, MBV values were measured experimentally according to the Nordtest project protocol using a climate chamber (FITOCLIMAT 500 EC 50 - Aralab). This one can control the temperature in the range of 10 to 90 °C (with an accuracy of ± 0.3 °C) and relative humidity in the range of 10 to 98 % RH (with an accuracy of ± 3 %RH). During the experimental test, the temperature and the relative humidity have been verified using the hygothermal sensor in the climate chamber.

The experimental measurement was carried out with cylindrical samples (a diameter of 10 cm and a thickness of 5 cm). For each concrete, three samples have been tested. According to the protocol, only one circular face of the sample is open to water vapor while the others were sealed with aluminum tape to make them impermeable to water vapor. After conditioning, the samples were placed in the climate chamber and stabilized under 50 %RH and 23°C. The gravimetric determination of the moisture adsorption/desorption was made outside the climate chamber using the Adam Equipment NBL 823e precision balance (820g of capacity and 0,001g of resolution). To minimize the perturbation of temperature and relative humidity due to the manual measurement in the climate chamber, the specimens were weighed five times during the desorption period and four times during the adsorption period.

Nordtest protocol proposes to determine the MBV value at the steady state. This one is reached when the testing satisfies the following conditions between three consecutive cycles: average between the weight gain during moisture uptake and weight loss during drying (Δm) is less than 5%; and the difference between weight gain and weight loss within each cycle should be less than 5% of Δm .

After the experimental measurement carried out, the MBV can be calculated at steady state by the following equation :

$$MBV = \frac{\Delta m}{A (RH_{high} - RH_{low})} \quad (3)$$

Where: MBV : moisture buffer value [$\text{g}/(\text{m}^2 \cdot \%RH)$], Δm : moisture uptake/release during the period [g], $RH_{\text{high/low}}$: high/low relative humidity level [%], and A : exposed surface [m^2].

4 Results and discussion

4.1 Sorption isotherm

Based on the experimental results and equations (1) and (2), the sorption isotherms for both experimental and fitting parameters with GAB model were obtained. Table 2 presents the GAB adsorption fitting coefficients used to predict the adsorption equilibrium moisture content of each material. Low standard deviations and the correlation coefficients (R^2) which are greater than 0.95 indicate a very good fit of the model.

Table 2. Hygic properties and fitting parameters of GAB model of studied materials.

	Dry density [kg/m^3]	GAB			R^2 Coefficients	Standard deviation
		Fitting adsorption coefficients				
		k	C	w_m [%]		
HLC+0%MCP	397	0.99	8	0.800	0.95	0.003
HLC+20%MCP	445	0.98	8	0.742	0.97	0.002
HLC+40%MCP	591	0.95	9	0.749	0.98	0.001

Fig.1 shows the sorption isotherms obtained from experimental adsorption of HLC+0%PCM, HLC+20%PCM and HLC+40%PCM and also fitting curves obtained with GAB model using the coefficients given in Table 2. The curves showed a good fit when the RH is lower than 83% and can be classed as type II according to the IUPAC (international union of pure and applied chemistry) classification of the adsorption isotherms [12].

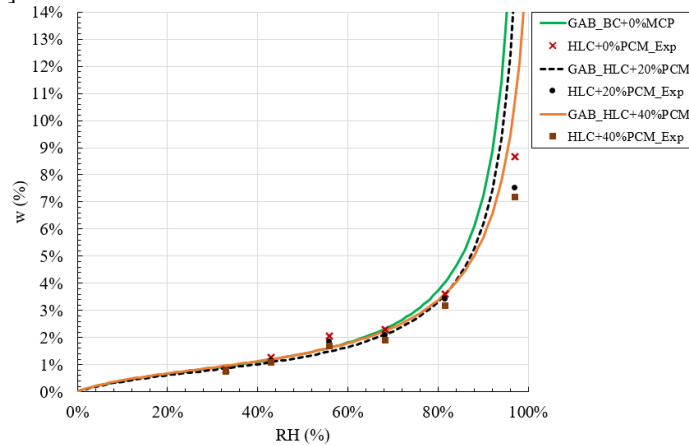


Fig. 1. Sorption isotherms of three different hemp lime concrete studied.

It can be observed that the adsorption isotherms of three materials are close to each other, which is to be expected because they have a similar microstructure. Note that the moisture content of HLC+0%PCM is higher than those of HLC+20%PCM and HLC+40%PCM. At 97 %RH, the water content of HLC+0%PCM is 8.67 % compared to 7.52 % for HLC+20%PCM and 7.17 % for HLC+40%PCM. This should be explained by the infiltrating of PCM microbeads in the pores of hemp lime concrete. The adsorption curve of HLC+0%PCM obtained is quite consistent with the ones found the literature.

4.2 Moisture buffer value (MBV) and classification

Fig.2 shows the relative humidity in the climate chamber and the mass variations of HLC+0%MCP and HLC+40%MCP samples when the equilibrium is reached. It can be seen that the mass increases and decreases according to the variation of relative humidity in the climate chamber. In this figure, we can see that hemp lime concretes with and without PCM have the similar behavior when they are subjected to the surrounding relative humidity variation.

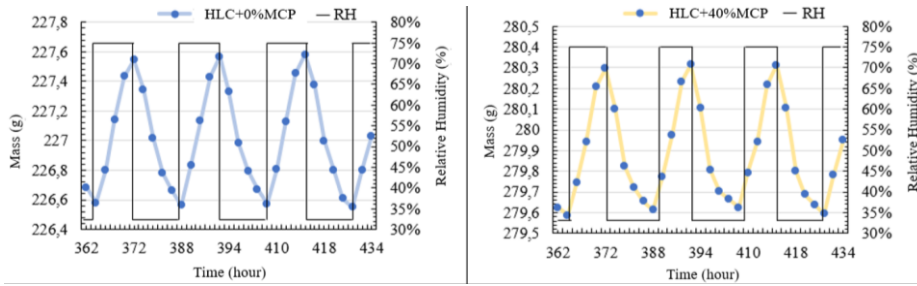


Fig. 2. Mass variation of studied specimens versus RH in climate chamber.

Table 3. MBV obtained of studied concretes.

	Dry density [kg/m ³]	Thickness [m]	Surface Exposed [m ²]	MBV [g/(m ² .%HR)]
HLC+0%MCP	397	0.05	0.01	2.32
HLC+20%MCP	445	0.05	0.01	2.27
HLC+40%MCP	591	0.05	0.01	1.74

Based on the experimental results presented in Fig.2 , MBV values have been calculated using the equation (5) and are presented in Table 3. The MBV value of HLC+20%PCM (2.27 g/(m².%HR)) and HLC+40%PCM (1.74 g/(m².%HR)) are lower than the one of HLC+0%PCM (2.32 g/(m².RH)). It can be noted that the MBV of HLC+20%PCM is very close to the one of HLC+0%PCM which is consistent with the MBV of hemp lime concrete in the literature [8]. The results showed that adding PCM in hemp concrete reduces moisture buffering capacity. It can be explained by the fact that micro capsulated PCM could penetrate and clog the pores of binder and hemp particles.

To compare the moisture buffer value of developed materials with other common building materials, the classification proposed in the Nordtest project has been used. It defines five ranges of practical moisture buffer value classes which vary from negligible to excellent capacity [13]. The comparison with other common building materials is presented in Fig.3 . It can be seen that plaster (MBV=0.69 [g/(m².RH)]) and autoclave concrete (Auto_Clav_Conc, MBV= 1 [g/(m². RH)]) fall into limited category. Our studied hemp lime concretes exhibit an excellent and good moisture buffer capacity: HLC+40%PCM falls into good category while HLC+0%PCM and HLC+20%PCM fall into excellent category.

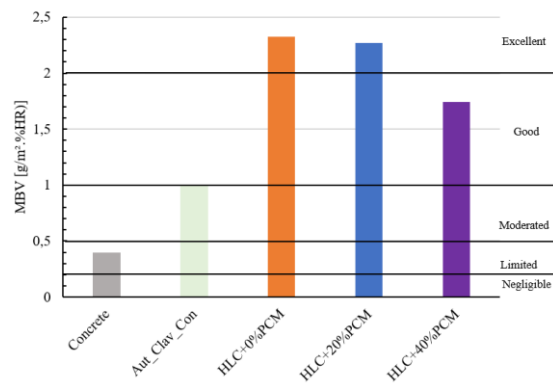


Fig. 3. MBV classification of developed materials according to the Nordtest project.

5 Conclusion

This article focuses on the characterization of moisture properties of hemp lime concrete with and without PCM. The previous study showed that adding PCM in hemp lime concrete can improve significantly its thermal inertia which can avoid the overheating in summer [5]. In this article, the sorption isotherm curves of studied materials were measured according to NF EN ISO 1257 with the continuous method. The GAB fitting parameters were also determined. The results showed that the sorption capacity of HLC+20%PCM and HLC+40%PCM are smaller than the one of HLC+0%PCM. The moisture buffering capacity under dynamic condition was determined according to the Nordtest protocol. It is highlighted that the studied materials are classified as excellent and good hygric regulators and adding PCM in hemp lime concrete is promising for application in buildings because it increases thermal inertia without degrading hygric performance.

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