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Hygrothermal performance of hemp lime concrete embedded with phase change materials for buildings

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Abstract. The use of biobased materials in building construction allows the reduction of fossil resource use and energy consumption. Among biobased materials, hemp lime concrete has been investigated in many studies highlighting its capacity to regulate interior relative humidity and its high insulation capacity. In order to design high-performance biobased concretes, a new hemp lime concrete combining the hygric regulation capacity of hemp lime concrete with the thermal regulation performance of phase change material was developed. This article focuses on the thermal and hygric performance of the new hemp lime concretes incorporating micro-capsulated phase change material (PCM) (named HL-PCM). Three hemp lime concretes that differ from formulation were developed and investigated. The thermal properties, moisture buffer values and its impact on interior relative humidity variation have been presented. Thanks to experimental works and numerical simulations, the results obtained showed that the thermal conductivity remain low, the heat capacity and thermal inertia increase considerably for hemp concrete with PCM, while the moisture buffering capacity remains excellent. Finally, numerical results showed that the used of hemp lime concrete (with and without PCM) reduce indoor relative humidity variation and improve indoor hygrothermal comfort.

1. Introduction

In France, the building consumes about 44% of energy produced and is responsible about 25% of the greenhouse emissions which affect the environment considerably. The use of biobased materials, like hemp lime concrete which is capable to absorb about 35kg of CO_2 equivalent per m² of wall over 100 years [1], allows energy consumption reduction in building and reduces CO_2 emissions.

The thermal conductivity of hemp lime concrete is between 0.06 and 0.15 W/m.K [2], [3], and is lower than the ones of load bearing materials (normal concrete, extruded brick, …). Recent studies showed that hemp lime concrete is very permeable to water vapor and has an excellent capacity of hygric regulation [4]–[6]. However, this material has a low mechanic resistance and thermal inertia. Therefore, this article aims to design a new biobased material by combining hemp lime concrete and phase change material. Phase change materials (PCM) added at hemp lime concrete composition, will allow to increase its thermal inertia thanks to the adsorption of heat during heat peaks and then the release of heat during falling temperature in the building, in order to avoid overheating in summer [7], [8]. This is because the phase change material is able to absorb, store and release large amount of latent heat when the material changes phase which depends on a defined temperature range. The one used for our study is an organic paraffin PCM [9], [10]: Micronal DS 5001X with a melting point at 26°C [11], [12].

In this article, we will present the conception, thermal properties, and moisture buffer capacity of hemp lime concrete incorporating phase change material with different formulations.

2. Experimental study

2.1. Manufacture of test specimens.

The new innovated building materials presented in this article are based on the formulation of hemp lime concrete formulation widely used in the literature. These materials are composed of: binder Tradical PF70 (75% hydraulic lime, 15% aerial lime and 10% pozzolanic), hemp shives, water and phase change material (MCP: Micronal DS 5001X). The dosages used for three different formulations are: the first one with 0% of PCM (without PCM) and the two others incorporating 20% and 40% of PCM compared to the total dry weight (hemp, binder and PCM) of the first formulation. Note that the dosage proposed were based on experience for the application in the building. One of the main difficulties encountered during the hemp concrete mixing with PCM is due to the water absorption of plant aggregate and PCM. Therefore, we keep the same binder/hemp ratio and increase slightly the water/binder ratio until 1.65 for formulation incorporating 20% of PCM and 1.85 for the one integrating 40% of PCM. These concretes will be abbreviated according to the percentage of PCM used in each formulation: HL+0%PCM, HL+20%PCM and HL+40%PCM. Table 1 represents material proportion (in mass) contained in each sample and its density.

Table 1 : Summary of the three hemp lime concretes with and without PCM used in this study.

	HL+0%PCM	HL+20%PCM	HL+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)	686	781	1000
Ratio W/B	1.49	1.65	1.86

Figure 1 : Steps of sample manufacturing: (a) mixing tradical PF70 + water, (b) mixing tradical PF70 + water + hemp = HL+0%MCP, (c) mixing tradical PF70 + water + hemp + PCM = HL+20/40%PCM, (d and e) specimen produced, (f) samples (HL+40%PCM (1), HL+20%PCM (2) and HL+0%PCM (3)).

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. With the water adsorption rate of hemp shives and PCM, water was added during mixing after adding the PCM.

Then, the concrete was poured into the different molds for thermal and hygric characterization and they were compacted using the manual tamping (Figure 1). All specimens produced were conserved in the room with temperature and relative humidity around 20°C and 50%RH, respectively.

2.2. Thermal properties characterization.

The thermal properties characterization of studied concretes has been done and presented in [13]. The method applied to measure thermophysical properties is heat flow meter apparatus. The apparatus has top and bottom plates equipped with heating and cooling systems to control the heat flux through the sample in between [8], [14]. The apparatus creates a steady one-dimensional heat flux through the sample by setting both plates at constant temperature and is calibrated to convert the transducer voltage signal to heat fluxes. The temperature ramps used are from 10 to 20 °C for HL+0%PCM and from 10 to 35 °C for HL+20/40%PCM.

Knowing that the PCM reveals an additional amount of energy due to the solid-liquid phase change, the thermal conductivity (λ), specific heat (C_L=specific heat in the liquid state and C_S= specific heat in the solid state of PCM) and latent heat of studied materials have been determined using the inverse method based on the experimental results of the heat flow meter (controlling the steady-state after each step-change) and GenOpt and Dymola/Modelica softwares [13], [15].

2.3. Moisture buffer value (MBV) characterization.

Knowing that relative humidity is one of the most important factors to evaluate the hygrothermal comfort in the building, the Nordtest project [16] proposed one experimental protocol to evaluate the moisture buffering capacity of building materials. Concerning moisture buffer value (MBV), it can be calculated based on the amount of water vapor that is transported in or out of material per open surface, during a period of times when it is subject to relative humidity variations of surrounding air. The moisture buffer value characterization consists of imposing the sample to cyclic step-changes in relative humidity between 33%RH for 16 hours and 75%RH for 8 hours at a constant temperature (at 23°C) during the measurement, as shown in Figure 2.

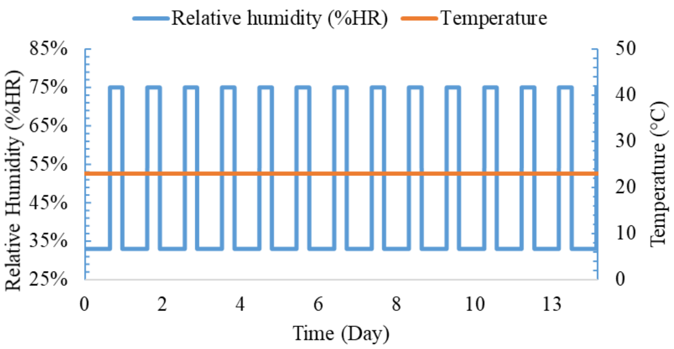

Figure 2 : Cyclic step-changes in relative humidity and temperature recommended by the Nordtest project for MBV measurement.

This test protocol is carried out in three stages. Firstly, we put the sample on the analytical balance to record continuously weight variation. Then, we regulate the indoor relative humidity according to the protocol defined. At last, we collect the weight evolution data for material MBV calculation.

Note that, for the MBV test, five faces of the samples have been scaled with aluminum adhesive tape to make them impermeable to water vapor. After conditioning the samples, we have used the climatic chamber Bioclimatic CL2-25 which is adjustable in temperature and relative humidity (range from -45 to 180°C in the temperature with precision ±0.3°C and relative humidity going from 10 to 98%RH with ±2% of precision). Each protocol is illustrated in the Figure 3.

Figure 3 : Execution of Nordtest project protocol for MBV measurement: the sample and balance (a), the climatic chamber (b) and the climatic chamber control.

According to the measurement protocol, the MBV could be determined at equilibrium state, when between three consecutive cycles, the weight variation (Δm) is lower than 5% between the weight gain in adsorption and the weight loss in desorption, as well as the difference between the loss and the gain in weight of each cycle is less than 5%.

After reaching the equilibrium state, the MBV can be calculated as followings [16]:

$$MBV = \frac{\Delta m}{A\,(HR_{max} - HR_{min})} \tag{1.}$$

With:

Δm: sample weight variation (kg); RH_{min} and RH_{max}: minimal and maximal relative humidity (%RH) respectively; A: exposed surface (m²).

2.4. Effective capacitance model

The effective capacitance model assumes that the envelope MBV is always in equilibrium with interior climatic conditions. This model allows a fast evaluation of the impact of hygroscopic materials, ventilation rate, interior vapor production, moisture production, available surface, moisture buffer value and other parameters on indoor relative humidity variation. This model can be established as following equation [17]:

$$\begin{cases} \left(\dfrac{V}{R_v T_i} + \dfrac{100 HIR^* V}{P_{v,sat}(T_i)} \right) . \dfrac{\partial P_{vi}}{\partial t} = \left(P_{ve} - P_{vi}\right) . \dfrac{nV}{3600 R_v T_i} + G_{vp} \\ HIR^* = \left(\sum_k A_k . MBV_k \right) / V \end{cases} \tag{2.}$$

With:

V: local volume (m^3), R_v: ideal gas constant = 462 J/(kg.K), T_i: exterior temperature (K), HIR^*: moisture buffer value normalized by the volume (kg/ (m^3. %RH)); $P_{v,\,at}$: saturated vapor pressure (Pa), P_{vi}: interior vapor pressure (Pa), P_{ve}: exterior vapor pressure (Pa), n: ventilation rate (l/h), G_{vp}: water vapor source (kg/s), A_k: element area exposed (m²), MBV_k: moisture buffer value of material k (kg/(m². %RH).

The effective capacitance model has been implemented in SPARK (Simulation Problem Analyse and Research Kernel) environment of simulation oriented object and allowing effective resolution of the differential equations system [18]–[20].

3. Results

3.1. Thermal properties

Concerning the thermal properties (the thermal conductivity (λ), specific heat (in liquid and solid state of PCM) and latent heat (around 26°C) of studied materials), Table 2 represents a synthesis of those results [13].

Table 2 : Thermal properties obtained and comparison with the ones of hemp lime concrete in the literature.

	Density [kg/m³]	Thermal conductivity [W/(m.K)]	Specific heat [J/(kg.K)]	Latent heat [J/kg]
HL+0%PCM	370	0.12	1428	-
HL+20%PCM	441	0.14	Cs : 1698 C_L : 1677	28980
HL+40%PCM	596	0.18	Cs : 2048 C_L : 2019	57620
HL [6]	413	0.11	1000	-
HL [21]	440	0,10	1530	-

Table 2 presents the results obtained for the three samples. Those results show that adding PCM in hemp lime concrete results in higher density and the thermal conductivity which increases 11.5% for the HL+20%PCM and 45.9% for the HL+40%PCM [13].

Moreover, it is very important to note that the incorporation of PCM is accompanied by the augmentation of the specific heat (C_L and C_S) : 18.9% and 17.43% for the HL+20%PCM, and 43.41% and 41.38% for the HL+40%PCM, respectively [13]. Therefore, this increasing thermal inertia allows a better regulation of interior temperature to avoid the overheating in summer.

3.2. Moisture buffer value (MBV)

Figure 4 (a, b and c) shows that the sample weight increases and decreases as a function of relative humidity evolution in climatic chamber. Note that before the beginning of the experiment, the specimens were at the equilibrium state at 50%RH.

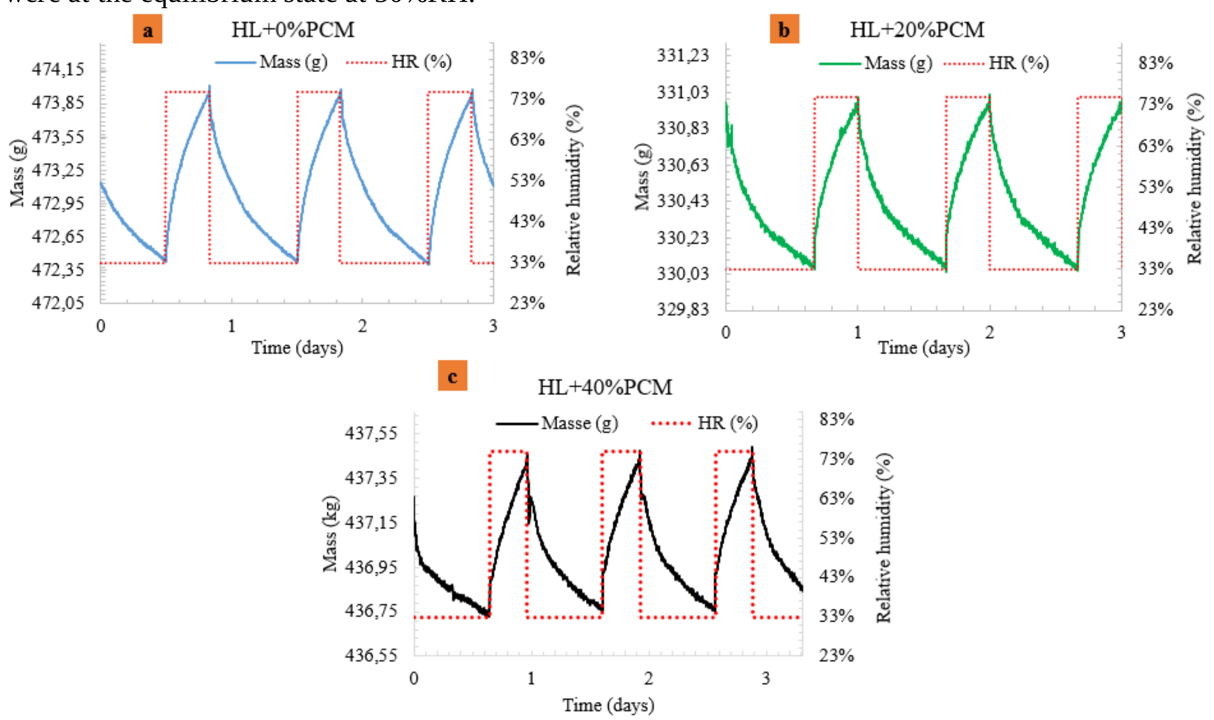

Figure 4 : Moisture uptake and release of HL+0%PCM (a), HL+20%PCM (b) and HL+40%PCM (c) as function of relative humidity variation in climatic chamber.

Based on experimental results and the application of the formula (1), MBV values of samples have been calculated and the results are presented in Table 1. We can see that the MBV value of HL+0%PCM is close to those obtained by other authors ([4], [22],],[23]). The MBV obtained for HL+20%PCM and HL+40%PCM are 2.25 and 1.85 g/(m².%RH), respectively. However, adding PCM will reduce the moisture buffering capacity of hemp concrete due to the incorporation of PCM in the pores of hemp shiv as illustrated in Figure 5.

Table 3: MBV obtained from different materials.

	Density [kg/m^3]	Thickness (m)	Surface exposed (m²)	MBV [g/(m².%RH)]
HL+0%PCM	370	0,07	160*10^{-4}	2.29
HL+20%PCM	441	0,07	99,4*10^{-4}	2.25
HL+40%PCM	596	0,07	93,84*10^{-4}	1.85

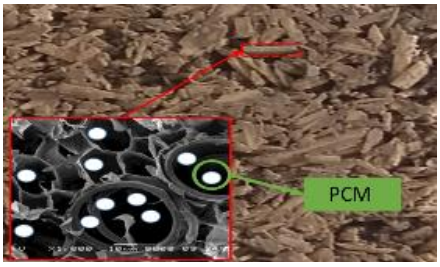

Figure 5 : The incorporation of PCM in the hemp pores (adapted from [5]).

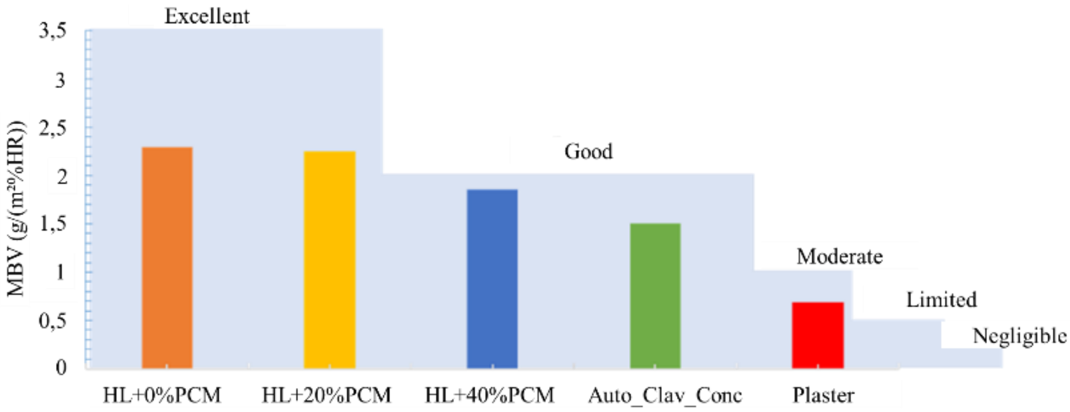

Figure 6 : MBV classification of developed materials according to Nordtest project.

To compare the moisture buffer values obtained with other common building materials, we used the classification proposed in the Nordtest project which defines five range of practical moisture buffer values classes (from negligible to excellent). Figure 6 presents a comparison between the MBV of studied materials and the ones of other construction materials. The results showed that hemp lime concrete developed in our project: HL+0%PCM and HL+20%PCM are classed excellent, and good for the HL+40%PCM. The classification shows that the studied materials are interesting to use in building to reduce interior humidity variation. Therefore, the impact of the MBV on interior relative humidity will be studied in the next part.

3.3. Influence of MBV on indoor relative humidity

Concerning the evaluation of the impact of MBV on the interior relative humidity, the simulations have been carried out with MBV obtained experimentally in this study and the ones of other materials used frequently in buildings like coating plaster (MBV = 0.68g/(m².%RH) and autoclave concrete (Auto_Clav_Conc MBV=1.5 g/(m².%RH) [16].

The room's dimensions are 3x5m² of area and 43m^3 of volume and is occupied by two persons for 10 hours (from 8 to 18h), which correspond to 142g/h of interior vapor production. Moreover, the air change rate considered is 0.5 ACH with outside air. Only the moisture buffer capacity of ceiling and vertical walls are considered in the simulation, while the floor is considered impermeable to water vapor. Lastly, the exterior relative humidity and the temperature are considered constant at 50%RH and 20°C, respectively.

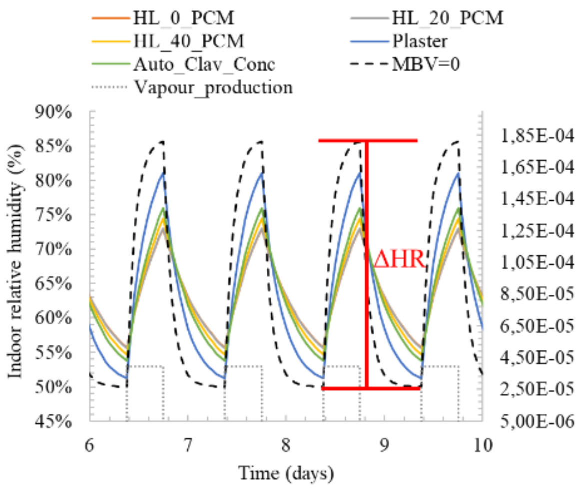

Figure 7 : Influence of MBV on the interior relative humidity.

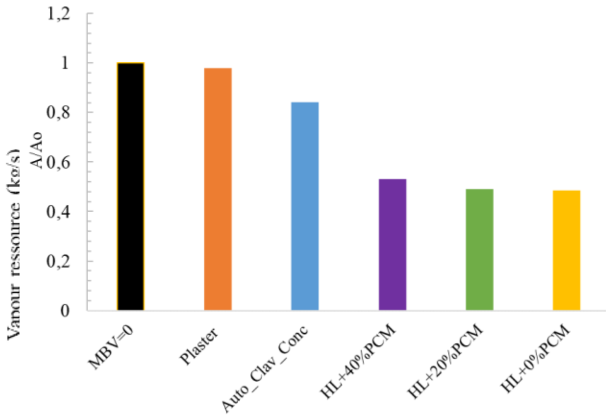

Figure 8 : The comparison of reduction coefficient (A/A_0).

Figure *7* shows that the interior relative humidity evolution depends on occupation scenario. It can be seen that the higher is the MBV, more the interior relative humidity variation is dampened. Indeed, concerning the case when the walls are impermeable to water vapor (MBV=0), the interior relative humidity variation is between the minimum value (52%) and the maximum value (86%) (so an amplitude of 34%RH) compared to the maximum values of 73% for HL+0%PCM and 74% for HL+40%PCM.

To quantify the hygric buffering regulation of building materials compared to the case when MBV is neglected, we define a coefficient called the reduced factor $f=A/A_0$, which is defined as the ratio between interior amplitude of relative humidity variation with and without taking account moisture buffering capacity of building envelope ($A<A_0$). According to Figure 8, the reduced factors are smaller for hemp lime concrete with and without PCM than for other materials frequently used in building. The results showed that hemp lime concrete (with and without PCM) can reduce the amplitude of indoor relative humidity variation with a coefficient f lower than 60% (Figure 8). The results suggest that the use of hemp lime concrete (with and without PCM) allows the attenuation of interior relative humidity variation and so improve interior hygrothermal comfort.

4. Conclusion

This article presents the thermal characterisation and the hygric performance of hemp lime concretes incorporating phase change material. Hemp lime concretes (HL+0%PCM and HL+20%PCM) have an excellent capacity of relative humidity regulation. The experimental results showed that adding PCM in hemp lime concrete results in a significant increase of thermal inertia which is very promising for application in buildings. Finally, it was shown that the use of hemp lime concrete wall (with and without PCM) allows considerable attenuation of interior relative humidity and can ameliorate indoor hygrothermal comfort.

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5. References

[1] INRA, 2016 Chanvre_rapport_final_d235d.pdf.

[2] D. Samri, 2008 Analyse physique et caractérisation hygrothermique des matériaux de construction : approche expérimentale et modélisation numérique, p. 353.

[3] A. D. Tran-Le, S.-T. Nguyen, et T. Langlet, 2018 A novel anisotropic analytical model for effective thermal conductivity tensor of dry lime-hemp concrete with preferred spatial distributions, *Energy Build.*, vol. 182, p. 75-87, doi: 10.1016/j.enbuild. 2018.09.043.

[4] A. D. Tran Le, 2010 Etude des transferts hygrothermiques dans le béton de chanvre et leur application au bâtiment : simulation numérique et approche expérimentale, p. 220.

[5] V. Cerezo, 2005 Propriétés mécaniques, thermiques et acoustiques d'un matériau à base de particules végétales : approche expérimentale et modélisation théorique, Institut Nationale des Sciences Appliquees de Lyon.

[6] F. Collet, J. Chamoin, S. Pretot, et C. Lanos, 2013 Comparison of the hygric behaviour of three hemp concretes, *Energy Build.*, vol. 62, p. 294-303, doi: 10.1016/j.enbuild.2013.03.010.

[7] Y. C. Choi, G. D. Moon, et J. W. Cho, 2010 Moisture Buffering Performance of Materials in Buildings, p. 6.

[8] L. Zalewski, A. Joulin, S. Lassue, et T. Chartier, 2014 Caractérisation thermophysique du comportement de matériaux à changement de phase à échelle macro, p. 6,.

[9] J. Borderon, 2012 Intégration des matériaux à changement de phase comme système de régulation dynamique en rénovation thermique, Theses, ENTPE.

[10] M. Ahmad, 2004 Nouveaux composants actifs pour la gestion énergétique de l'enveloppe légère des bâtiments. Couplage matériaux à changement de phase, super-isolation, apports solaires, Thèse de doctorat, Université Joseph Fourier, Grenoble, France.

[11] S. Guichard, 2013 Contribution à l'étude des parois complexes intégrant des matériaux à changement de phase : modélisation, expérimentation et évaluation de la performance énergétique globale, Theses, Université de La Réunion.

[12] P. Tittelein *et al.* 2014, Simulation of the thermal and energy behaviour of a composite material containing encapsulated-PCM: Influence of the thermodynamical modelling, *Appl. Energy*, vol. 140, p. 269-274, doi: 10.1016/j.apenergy.2014.11.055.

[13] H. Toifane *et al.*, 2019 Caractérisation thermophysique de béton de chanvre intégrant un matériau à changement de phasemicro-encapsulé, Canada, Québec, p. 6.

[14] Abdellatef et Kavgic, 2020 Thermal, microstructural and numerical analysis of.pdf.

[15] M. Wetter, 2009 Modelica-based modelling and simulation to support research and development in building energy and control systems, *J. Build. Perform. Simul.*, vol. 2, nº 2, p. 143-161, doi: 10.1080/19401490902818259.

[16] C. Rode *et al.*, 2005 Moisture buffering of building materials.

[17] H. Janssen et S. Roels, 2008 Qualitative and quantitative assessment of interior moisture buffering by enclosures, *Energy Build.*, vol.41, p.382-394, doi: 10.1016/j.enbuild.2008.11.007.

[18] A. D. Tran Le, C. Maalouf, T. H. Mai, E. Wurtz, et F. Collet, 2010 Transient hygrothermal behaviour of a hemp concrete building envelope, *Energy Build.*, vol. 42, nº 10, p. 1797-1806, doi: 10.1016/j.enbuild.2010.05.016.

[19] E. F. Sowell et P. Haves, 2001 Efficient solution strategies for building energy system simulation, *Energy Build.*, p. 9.

[20] K. Mendonça, C. Inard, E. Wurtz, F. Winkelmann, et F. Allard, 2002 A zonal model for predicting simultaneous heat and moisture transfer in buildings, *Indoor Air*, p. 6.

[21] A. Evrard, 2008 Transient hygrothermal behaviour of Lime-Hemp Materials, p. 142.

[22] F. Collet, 2004 Caracterisation hydrique et thermique de materiaux de genie civil a faibles impacts environnementaux, thèse, Institut Nationale des Sciences Appliquees de Rennes.

[23] M. Rahim, O. Douzane, A.D. Tran Le, G. Promis, B. Laidoudi, A. Crigny, B. Dupre, T. Langlet. Characterization of lime flax and hemp concretes: Hygric properties and moisture buffer capacity, *Energy and Buildings*, 88(1), p.91-99, 2014.