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HYGROTHERMAL BEHAVIOUR OF A HEMP CONCRETE BLOCK, EXPERIMENTAL AND NUMERICAL RESULTS

M. Asli*, F. Brachelet, E. Antczak, D. Defer
Univ. Artois, EA 4515, Laboratoire de Génie Civil et géo-Environnement, Béthune
*Corresponding author; e-mail: mounir.asli.gc@gmail.com

Abstract

Most building materials, and more particularly bio-based materials, are subjected to hygrothermal transfers in the environment in which they are disposed. These transfers depend on the thermophysical characteristics and the ambient humidity and temperature conditions. In this environment and despite these variations, the material must be able to ensure in a sustainable manner, the functions for which it was implemented (thermal, mechanical, acoustic ...). In this paper we treated the coupled heat and mass transfer within bio-based building material problematic. We have chosen the hemp concrete and we proceed as follow: a thermophysical characterizations are done, in order to obtain the thermal, hygroscopic and physical properties of hemp concrete. These values are then used as input parameters for a numerical modelling. Philip and De Vries mathematical model which predicts heat and mass transfer within porous media is implemented. The model takes into account thermal and hygric transfer phenomenon. For the purpose of the model validation, experimental facility is carried out, which consist of monitoring a sample made of hemp concrete. The temperature and relative humidity are recorded with temperature and humidity sensors placed at the interface and inside the material. The sample is positioned into the wall of laboratory, in order to separate the inside and the outside conditions. The sample is submitted to real indoor and outdoor ambient conditions. We aim to investigate the hygrothermal behaviour of hemp concrete and observe its response versus ambient variation on the one hand, and to assess the mathematical model's ability to predict the hygrothermal behaviour on the other hand. The experimental and the modelled results are compared and then discussed.

Keywords:

Hemp concrete, Thermal conductivity, Specific heat, Water vapour sorption, Heat and Mass Transfer, Numerical simulation.

Nomenclatures		
λ Thermal conductivity [$W.m^{-1}.K^{-1}$]	RH Relative humidity [%]	h_t Heat convective coeff [$W.m^{-2}.K^{-1}$]
φ Heat flux [$W.m^{-2}$]	T Temperature [°C]	h_m Mass convective coeff [$m.s^{-1}$]
ρ Density [$kg.m^{-3}$]	w Water content [%]	C, K, Wm GAB model parameters [-]
c Specific heat [$J.kg^{-1}.K^{-1}$]	θ Water content [%]	D Thermal diffusivity [$m^2.s^{-1}$]

1 INTRODUCTION

Building, industrial and transport sectors are the three responsible of the environmental crisis. We are particularly interested in the building sector, which is the biggest cause of pollution, producing waste and consuming large quantities of energy [1] [2] [3]. Furthermore, In France, the building sector is responsible for about 40% of the energy consumed and 25% [4] of greenhouse gas emissions (GHG), mainly Co2. One of the key issues to contain the global warming and climatic derivative is to divide by factor of four by 2050 the GHG, and consequently reduce the associated energy consumption.

The growing interest in sustainable development and the efficient use of energy leads to the adaptation of legal measure, through a strong acceleration of thermal regulations, to meet the need supply of energy, occupant comfort and achieve optimum efficiency power supply facilities.

Moreover, the building material factor is one of the most weighting coefficients in the issues cited before [1] [5]. The bio-based materials represent an ecological solution for the construction sector, in term of thermal performance [6] [7] [8], hygroscopic quality characterized by humidity storage [9] [10], life cycle assessment [11], Comfort [12]...

Among the bio-based materials, the hemp concrete is one of the most interesting insulation material. Hemp concrete is a bio-composite made of the inner woody core of the hemp plant mixed with a lime-based binder. The hemp core or “Shiv” has a high silica content which allows it to bind well with lime. This property is unique to hemp among all natural fibers. The result is a lightweight cementitious insulating material weighing about a seventh or an eighth of the weight of concrete.

Several works have been carried out in order to assess the mechanical properties of hemp concrete. One of them [13] proposed a mixing process to develop a high mechanical performance blocks made from hemp concrete. Other studies conducted an investigation on the effect of binder type on mechanical strength and durability of hemp concrete [14].

The hemp concrete has a high quality with respect to the storage and the moderation of the humidity ambient conditions. In order to study the hygrothermal behaviour of hemp concrete, many authors aim to get the thermal and hygroscopic characteristics of hemp concrete. Elfordy et al [15] assess the impact of the material density on the material thermal and mechanical properties. F. Collet et al [9] determined experimentally the dynamic hygro-characteristics of hemp concrete, represented by the Moisture Buffer Value (MBV). Other authors studied the impact of transient hygrothermal behaviour of hemp concrete on the envelope [16] [17]. Moreover D. Lelievre et al [18] investigated the hygrothermal behaviour of hemp concrete at different scales (sample and wall) under various conditions.

This study deals with hygrothermal behaviour of hemp concrete subjected to dynamic real ambient conditions. Thermal and hygroscopic material properties are experimentally determined, according to the standards. Then, the measured hemp concrete properties are used as input parameters in a mathematical model describing the transient hygrothermal behaviour of hemp concrete.

Moreover, a sample of hemp concrete is equipped by thermocouples and humidity sensors, the whole assembly is placed into the wall of the laboratory. Therefore, the two faces of the sample are both subjected to the laboratory and external conditions. The numerical and the measured data are compared and then discussed.

2 CHARACTERISATION METHODS

2.1 Thermal characterisation

Measurements of thermal conductivity and specific heat is performed by the guarded hot plate and flow meter method according to the standard NF EN 12664 [19]. The experimental setup allows to maintain a temperature difference between two parallel flat plates (ΔT), a sample with known thickness (e) is placed between them. The sample four sides are insulated with material having a low conductivity in order to prevent edge effect. Thermal conductivity λ is calculated in steady state conditions as follow:

$$\lambda = \frac{e.\varphi}{\Delta T} \quad (1)$$

Where φ [W.m^{-2}] is the measured heat flux.

Likewise the specific heat is evaluated with the same device, and between the steady-state at the temperature T_{init} and the temperature T_{fin}, in this case the heat capacity C [J.K^{-1}.m^{-2}] is calculated according to the equation (2):

$$C = \frac{Q}{\Delta T} \quad (2)$$

Where $\Delta T = T_{fin} - T_{init}$, and $Q = \int_{t_{init}}^{t_{fin}} \Delta\varphi.dt$

The specific heat c [J.K^{-1}.kg^{-1}]:

$$c = \frac{C}{\rho.A.e} \quad (3)$$

Where e is the material thickness, concerning the heat flux density measured we assume that A = 1 m².

The measurement of thermal conductivity and specific heat is held for different water contents. The sample is subjected to different relative humidity to evolve its water content in a first time, then covered by waterproof material, and with the same way the thermal conductivity was evaluated. The sample is weighed before and after the test to ensure that the mass variation does not have a significant impact on the result. The test lasted a few hours, until reaching the steady stat. Several studies have shown that the thermal conductivity of a material in the dry state is always lower than when the material is saturated. Fig. 1 represents the evolution of thermal conductivity versus water content. We observe that the dry thermal conductivity λ_0 = 0.073 [W.m^{-1}.K^{-1}], and λ = 0.096 [W.m^{-1}.K^{-1}] at w = 10%, representing an increase in thermal conductivity of 23.95%. Fig.2 shows the volumetric heat evolution versus water content. The measured dry value is ρc_0 = 2,7 10^5[J.m^{-3}.K^{-1}], however ρc growth of 48.90 % for a value of w = 10%.

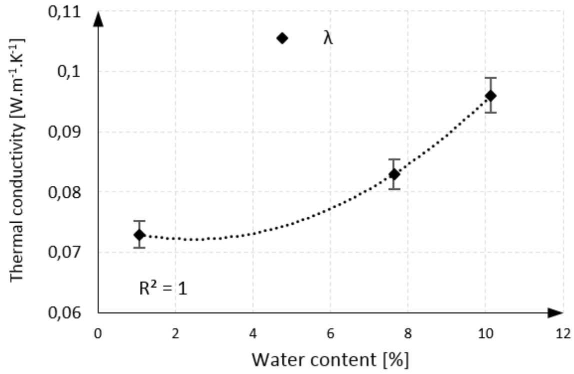

Fig. 1: Thermal conductivity evolution versus water content.

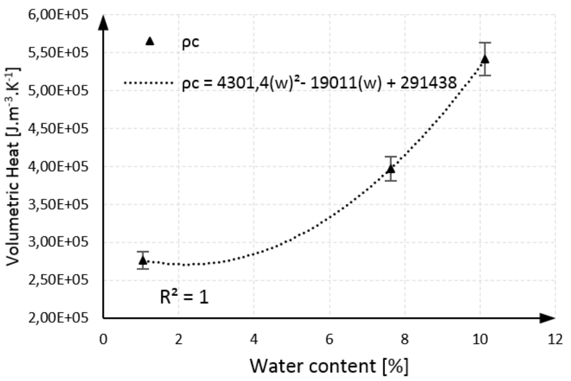

Fig. 2: Volumetric heat evolution versus water content.

In order to ensure that the temperature gradient did not affect moisture migration during the test, the gradient was reversed between the top and bottom of the exchanger plates, the difference between the two tests was estimated less than 3% and was considered negligible.

2.2 Water vapour sorption

Concerning the hygroscopic behaviour, materials showing open porosity adsorb surrounding gas. The water vapor sorption isotherm relates the water content of a material to the ambient relative humidity at constant temperature.

The water vapour sorption is measured according to the to the discontinuous method NF EN ISO 12571 [20]. A sample of hemp concrete was dried and placed inside a climatic chamber. The relative humidity is monitored and the water content is determined for successive steps of relative humidity increasing and then decreasing. The temperature is controlled and set to 23 °C.

Modeled and experimental water contents versus relative humidity are shown in Fig.3. The low value of water content at dry conditions w_0 = 0%, then the evolution continue with the increase of relative humidity, until reaching the maximum of 18 % of w at RH = 97 %. The water vapour sorption curve was modelling by fitting the experimental data according the GAB model [21].The GAB model is described in equation (4).

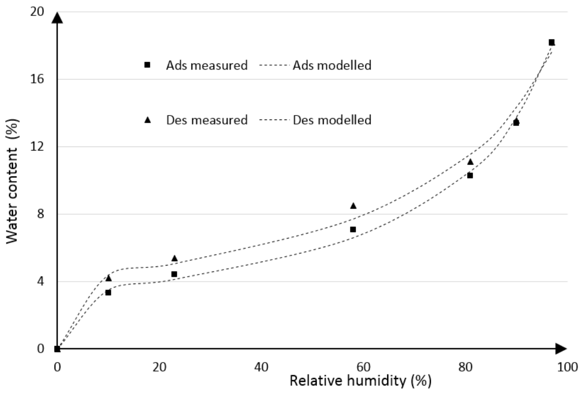

Fig. 3: Sorption isotherm of hemp concrete

Tab.1 represents the fitted parameters by the GAB model and the experimental measured data for the hemp concrete. The values of errors E shows the good agreement of the fittings.

$$w = \frac{C.K.W_m.HR}{(1-K.HR).(1-K.HR+C.K.HR)} \quad (4)$$

Where w is the water content (kg.kg^{-1}), C (-) and K (-) are the model parameters, W_m (kg.kg^{-1}) corresponding to the water content of a monolayer sorption.

Tab. 1: Fitted parameters for the GAB model

Material		C (-)	K (-)	W_m (kg.kg^{-1})	E (%)
Hemp concrete	Ads	165.64	0.834	0.0342	0.55
	Des	257.54	0.784	0.0422	0.50

3 MATHEMATICAL MODELLING

3.1 Philip and De Vries Model

Several model have been carried out in order to predict the heat and mass transfer in porous media. In all modelling cases, the basic principle of heat and mass conservation is respected. The renowned models are Luikov [22] Whitaker [23] Philip and De Vries [24].

The model of Philip and De Vries [24] is taken as the basic model for our work. The aim is to predict the hygrothermal behaviour of hemp concrete. Philip and De Vries model [24] takes into account moisture transport under two phases (liquid and vapour). It assumes that the vapour phase moves under a gradient of partial vapour pressure and the water phase moves under capillarity.

The model of Philip and De Vries is represented by Equations (5) and (6), which describe mass and heat transfer respectively:

$$\frac{\partial \theta}{\partial t} = \left(D_\theta \nabla \theta\right) + \left(D_T \nabla T\right) \quad (5)$$

$$\rho_0 Cp_m \frac{\partial T}{\partial t} = (\lambda \nabla \nabla) + \rho_l L_v \left(D_{T,v} \nabla T\right) + \rho_l L_v \left(D_{\theta,v} \nabla \theta\right) \quad (6)$$

Where θ [kg.kg^{-1}] is the water content, T is the temperature [K], D_T [m².s^{-1}K^{-1}] and D_θ [m².s^{-1}] are respectively, the mass transport coefficients associated to temperature and moisture content gradient. The relationships that relate transport coefficients of mass with transport coefficients of vapour and liquid phase are

$$D_T = D_{T,l} + D_{T,v} \quad [m^2.s^{-1}K^{-1}], \quad (7)$$

$$D_\theta = D_{\theta,l} + D_{\theta,v} \quad [m^2.s^{-1}], \quad (8)$$

The diffusion coefficients are the most important factors used in the mathematical model, while the use of the experimental ways is required, so a great attention is paid to these coefficients. For this purpose the vapour diffusion coefficients are determined according to Zeknoun et al [24], and Maalouf et al [25]. The transport coefficients associated with moisture gradient are related to water vapour permeability δ_0 and the specific hygric capacity ξ, which is the slope of sorption curve:

$$D_\theta = \frac{\delta_0 \; P_{v,s}}{\rho_0} \; \frac{1}{\xi} \quad (9)$$

$$\delta_0 = \frac{\delta_a}{\mu} \quad (10)$$

Where δ_a is the vapour permeability to air and it is equal to 2.10^{-10} kg.m^{-1}.s^{-1}.Pa^{-1}, µ is the water vapour resistance factor.

Vapour transport coefficient under a temperature gradient is given by the relation:

$$D_{T,v} = \frac{\delta_0 \; \varphi}{\rho_l} \; \frac{dP_{v,s}}{dT} \quad (11)$$

$$D_{\theta,l} = \frac{P_{vs}.\delta_p}{\xi_\varphi}\left(\frac{1}{\mu^*(\varphi)} - \frac{1}{\mu_0}\right) \quad (12)$$

µ* (ϕ) is the coefficient of water vapour resistance measured at high relative humidity, μ_0 is the coefficient of water vapour resistance Correspond to the beginning of the capillary condensation.

The associated boundary conditions of mass and heat transfer are represented by the equation (13) and equation (14):

$$\rho_l\left(D_\theta \nabla\theta + D_T \nabla T\right) = h_{m,i,e}\left(\rho_{v,a,i,e} - \rho_{v,s,i,e}\right) \quad (13)$$

$$\lambda \nabla T \quad \rho_l L_v D_{T,v} \nabla T + \rho_l L_v \nabla\theta = h_{T,i,e}\left(T_{a,e} - T_{s,e}\right)$$
$$+ \rho_l L_v\left(\rho_{v,a,e} - \rho_{v,s,e}\right) + \varphi_{rad,i,e} \quad (14)$$

Where $h_{(m,i,e)}$ [$m.s^{-1}$] $h_{(T,i,e)}$ [$W.m^{-2}.K^{-1}$] are respectively the convective mass and heat coefficients from external and internal sides, $\rho_{(v,e,i)}$ [$kg.m^{-3}$] is the air density, while the subscripts e and i correspond, respectively, to the external and internal side, neighboring environment (a) air or solid surface (s), $\varphi_{rad,e,i}$ is a radiation term [$W.m^{-2}$].

4 EXPERIMENTAL VALIDATION

In order to validate the mathematical model, represented by the equation (5) and equation (6) the following experimental setup is performed:

A sample made of hemp concrete, with dimensions 300 x 300 mm and 80 mm of thickness is placed through the laboratory wall in the ventilation opening. However, both large faces are exposed to the surrounding conditions (Fig. 4) and the other faces are insulated by waterproof sealant in order to ensure a unidirectional transfer.

In order to assess the relative humidity and temperature values of the surroundings and inside the hemp concrete, the sample is fitted with sensors placed at three different depths x = 20mm, 40mm and 60 mm. The uncertainty of sensors positions is evaluated to be ± 3 mm. We opted for the thermocouples type T, and commercial humidity sensors type HIH-4000 from Honeywell®. Accuracies are evaluated by the supplier to ± 3.5% for humidity and ± 0.02 °C for temperature. The test has been conducted between 13 July and 08 September, for this reason we observe that a huge relative humidity variation in the external side.

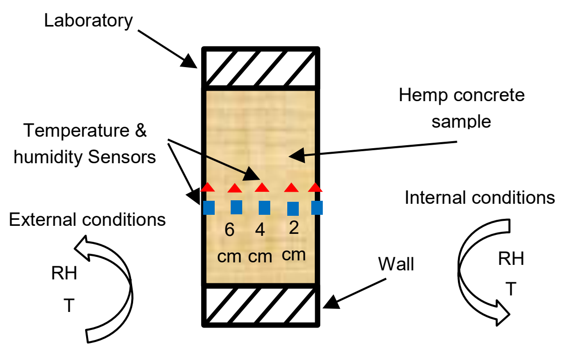

Fig. 4 Schema of the experimental set-up

5 RESULTS & DISCUSSION

The modelling phase is performed using Comsol Multiphysics© [25] software, it is designed to solve the partial differential equations PDE highly coupled with high flexibility by the integrated PDE module. Hemp concrete properties obtained from the hygrothermal characterisation are used as input parameters of the model. The two-dimensional modelling is done with a mesh size of 1 mm and a time step of 300 s. Dirichlet boundary conditions are adopted and the logged data at the interfaces of the samples are implemented in the model.

Fig .5 and Fig. 6 represent the internal and the external ambient conditions, measured on either side of the sample, as illustrated in (Fig.4). We recorded daily cyclical variations with an average value for RH = 73% and T = 20°C outside.

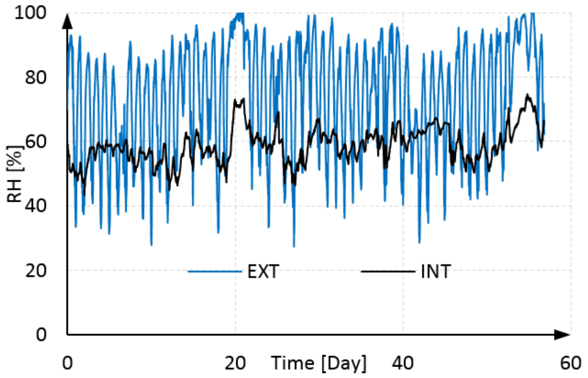

Fig. 5 Internal and external measured relative humidity

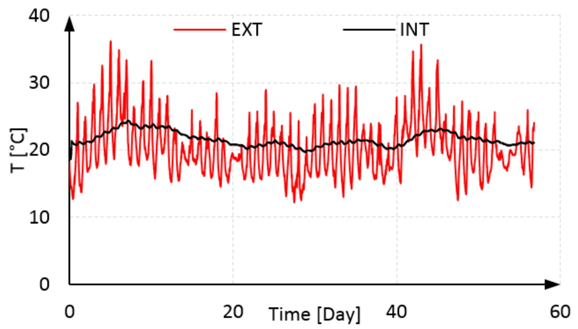

Fig. 6 Internal and external measured temperature

While, inside the laboratory a quasi-steady conditions are logged (Fig.6). The average value recorded for T is 21.5°C ± 2.7°C, and a maximal and minimal values of RH 36% and 12,2% respectively.

The previous measured data are used as boundary conditions for the simulation. Fig.7 (a-b-c) shows the confrontation of the measured and simulated relative humidities versus time, at different positions inside the sample (depth x = 2cm, 4cm and 6cm). We observe a compatibility between the simulated and measured data in terms of kinetics but a difference exists in terms of amplitude. According to the three graphs, the accuracy is related to the position inside the sample. We note that the accuracy decreases close to the inside. This may be justified by the accuracy of the boundary conditions logged for the inner side, and the condensation risk which is very likely especially around the sensors, which generates systematically peaks in the humidity curves. For this reason we note that the minimum value of the humidity at 4 cm is close to that at 6 cm

The decrement factor and time lags are determined from experimental data. The average values of decrement respectively evaluated to be 14%, 20% and 24% at 6cm, 4cm and 2cm. With regards to the phase delay, the following values were found: 2h45, 3h22 and 5h15 at 6cm, 4cm and 2cm. Fig.8 shows a histogram that illustrates hemp concrete decrement and phase delay for the relative humidity. We observe that decrement and phase delay increase with respect to the thickness, which is usually observed for insulation material.

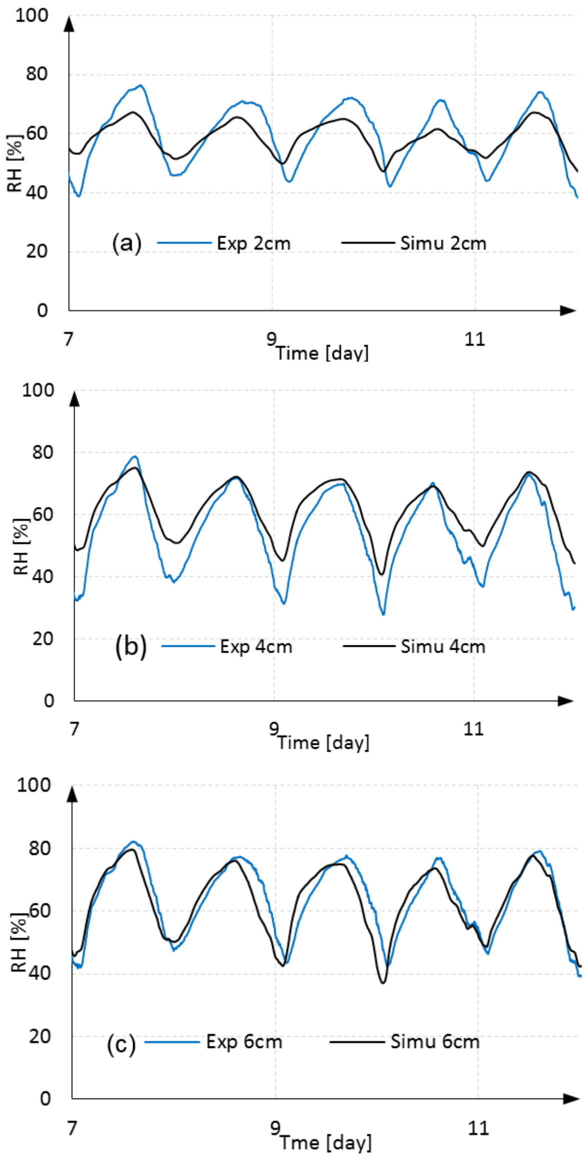

Fig. 7(a-b-c) Measured and simulated relative humidity inside the sample at x = 2cm, 4cm and 6cm

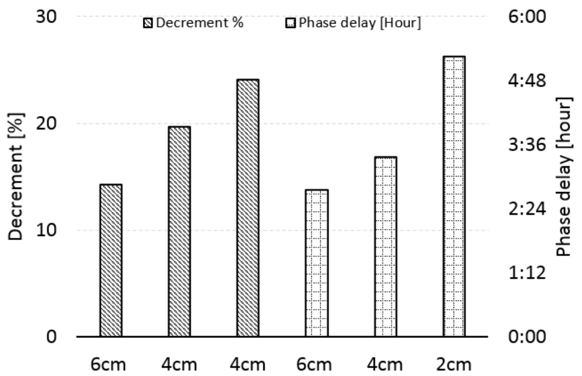

Fig. 8 Decrement and phase delay evaluated at different depths from external to internal side.

Results found for temperature variations at different depths are presented in Fig.9 (a-b-c) and compared with experimental results. In one hand, we note that only minor differences are observed between the simulated and the measured data. The same remark can be done for the temperature at 6 cm a high accuracy. On the other hand, a difference is observed at 2cm. This is due to several causes, the uncertainty of the sensors position, the infiltration of moisture and condensation risk which increases significantly the thermal conductivity and

The thermal decrement and phase delay are very important characteristics from thermal efficiency point of view. Fig.10 illustrates the hemp concrete ability to mitigate the external variations. The mean values of the decrement respectively calculated at 6cm, 4cm and 2cm are 7%, 11.4% and 14.4%. These values coincide with the values calculated from the following formula:

$$\text{Phase\_delay} = \frac{0.023\ e}{\sqrt{D}} \qquad (9)$$

Where D [$m^2.s^{-1}$] is the thermal diffusivity, the thermal diffusivity characterizes the capacity of the material to transmit a signal of temperature from one point to another. It is a function of thermal conductivity and specific heat and is written as follows:

$$D = \frac{\lambda}{\rho.c} \qquad (10)$$

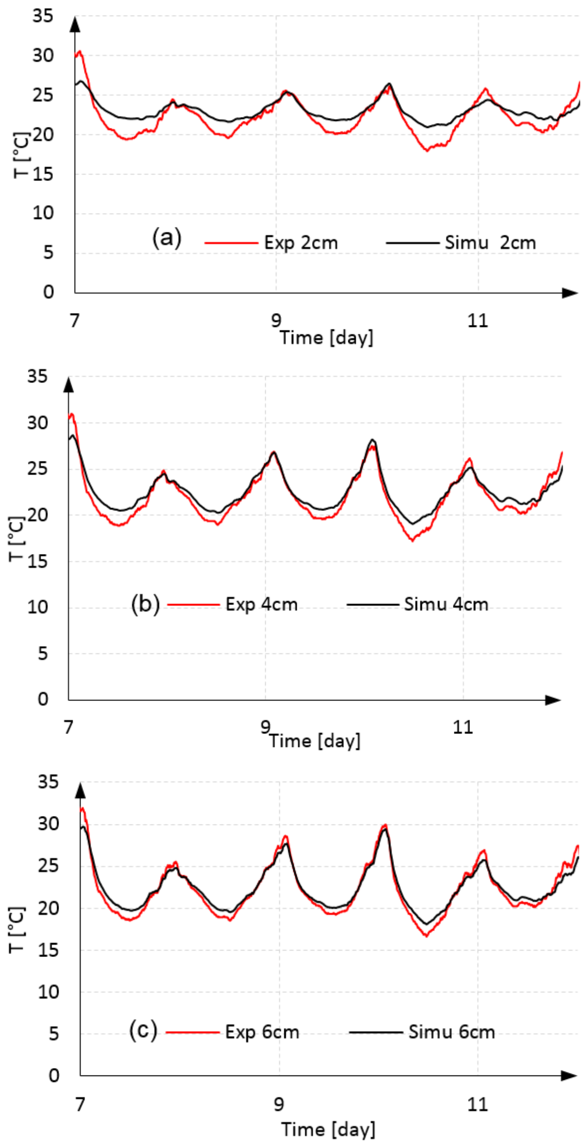

Fig. 9 (a-b-c) Measured and simulated temperature inside the sample at x = 2cm, 4cm and 6cm

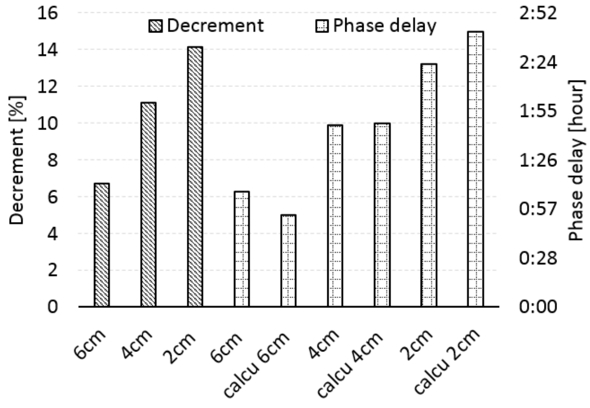

Fig. 10 Decrement and phase delay evaluated at different depths from external to internal sides.

6 CONCLUSION

In the present work, we investigated the hygrothermal behaviour of hemp concrete used as a bio-based building material. The main objective was to compare the numerical and the experimental results at three depths inside hemp concrete block. First, thermal and hygroscopic characterization methods were performed to a sample, in order to determine its thermal conductivity, specific heat and water vapour sorption. These characteristics were used as input parameters in a numerical modelling. Philip and De Vries model describing the coupled heat and mass transfer was presented, based on a system of two partial differential equations, with associated boundary conditions. The model was implemented in Comsol Multiphysics® software. For the purpose of studying the hygrothermal behaviour of hemp concrete, and its response with respect to the ambient variations, an experiment was carried out. A sample of hemp concrete was equipped with humidity and temperature sensors at different positions and then positioned into the ventilation opening in the laboratory wall. The aim of this configuration is to separate the atmosphere on both sides of the sample. The hemp concrete was submitted to ambient conditions, on one side the laboratory conditions and, on the other side the outdoor real conditions. Temperature and relative humidity were recorded at the interfaces of the sample and then were used as boundary conditions for the modeling

The measured and the modelled data at different positions are confronted, compared and discussed. Generally good agreement was found in the analysis of the material behaviour at depths of 4cm and 6cm, indicating that the main material properties were accurately defined. A slight difference was observed at a depth of 2cm but remains into the uncertainty of ±3.5% given for the sensor. Furthermore, the condensation phenomenon was suspected to be the main factor of the observed peaks on the temperature curves.

The heterogeneity of hemp concrete could be one of the factor causing the difference observed between the simulated and the measured results. This point should be investigated in the future. One must keep in mind that hemp concrete is coated with permeable and hygroscopic plaster inside and impermeable coatings outside, thus creating a multi-layered wall. For this reason, this configuration should be further investigated,

7 ACKNOWLEDGMENT

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