Effect of moisture transfer on heat energy storage in simple layer walls: case of a vegetal fibre material

C. Maalouf, A.D. Tran Le, M. Lachi, E. Wurtz, T.H. Mai

Abstract**—**This paper presents the results of a research that looks for to identify the effects of moisture transfer on thermal inertia and for different materials through the case of a simple layer wall under internal periodical conditions. To study moisture transfer in materials, we used a coupled heat and moisture transfer model in which moisture transport is made through liquid and vapour phases. The liquid phase is supposed to move by capillarity whereas the vapour phase diffuses under vapour partial pressure gradient. For the numerical approach, a simulation model was developed and implemented in the program oriented object SPARK. Simulations were used to study the effect of moisture transfer on heat energy storage in simple layer walls and mainly for hemp concrete which is a green material with low environmental impact. Sensitivity analysis identifies the most important parameters.

Keywords**—**Heat and moisture transfer, hemp concrete, simulation, thermal inertia, heat storage, SPARK.

NOMENCLATURE

Symbol	Definition	Unit
C	Specific heat	$J\ kg^{-1}.K^{-1}$
C_0	Specific heat of dry material	$J\ kg^{-1}.K^{-1}$
C_l	Specific heat of water	$J\ kg^{-1}.K^{-1}$
D_T	Mass transport coefficient associated to a temperature gradient	$m^2.s^{-1}.°C^{-1}$
$D_{T,v}$	Vapor transport coefficient associated to a temperature gradient	$m^2.s^{-1}.°C^{-1}$
D_θ	Mass transport coefficient associated to a moisture content gradient	$m^2.s^{-1}$
$D_{\theta v}$	Vapor transport coefficient associated to a moisture content gradient	$m^2.s^{-1}$
L_v	Heat of vaporization	$J.kg^{-1}$
T	Temperature	°C
t	Time	s
θ	Moisture content	$m^3.m^{-3}$
λ	Thermal conductivity	$W.m^{-2}\ K^{-1}$
ρ_0	Mass density of dry material	$kg.m^{-3}$
ρ_l	Mass density of water	$kg.m^{-3}$

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I. Introduction

Environmental design is based on architectural and constructive strategies that avoid waste of energy and improve the environmental comfort of their users. One of these strategies is the use of thermal inertia, important characteristic of constructive systems that depends on the thermal diffusivity and effusivity of the materials used in these systems. Mainly there are two types of thermal inertia [1]:

- Thermal inertia under outdoor varying conditions: It considers envelope behaviour under outdoor periodical time varying meteorological conditions. This inertia causes amplitude reduction of the indoor temperatures and time-lag of the same ones in relation to the outdoor temperatures [2]-[4].
- Thermal inertia under indoor thermal actions: these actions are regarded as permanent (indoor space heating) or random due to solar radiation. In this case, thermal inertia consists of storing heat energy through building envelope and releasing it later by radiation [5]-[7].

In [2], authors studied thermal inertia under outdoor varying conditions and effect of moisture transfer on it (first type of inertia). The purpose of this paper is to study effect of moisture transfer on heat energy storage in simple layer walls which characterizes thermal inertia under indoor thermal actions (second type). We consider three building construction materials: normal concrete, brick and hemp concrete which is an ecomaterial [8]. First we present briefly the equations of the coupled heat and mass transfer model (HAM). These equations were implemented in the simulation environment SPARK which is suited to complex problems [9]–[11]. Then we study the behaviour of a simple layer wall under indoor fluctuating conditions. Results are first shown when neglecting moisture transfer (Th model) and are then compared to the HAM model results for the three studied materials. In the next section we present briefly the model of the simple wall as it is implemented in SPARK, then we will present simulations.

II. Physical Model

In this paper, we use the Umidus model [12]–[16] in which moisture is transported under liquid and vapour phases. Forms of moisture transport depend on the pore structure as well as environmental condition. The liquid phase is transported by capillarity whereas the vapour phase is due to the gradients of partial vapour pressure. With these considerations, the mass conservation equation becomes:

$$.\frac{\partial \theta}{\partial \tau} = \frac{\partial}{\partial x}\left(D_T \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial x}\left(D_\theta \frac{\partial \theta}{\partial x} \right) \quad (1)$$

The governing energy balance equation states that the temporal variation of energy is due to the net amount of heat received/lost by conduction and the phase change within pores:

$$\rho_0 Cp_m \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda_{app} \frac{\partial T}{\partial x}\right) + L_v \rho_l \left(\frac{\partial}{\partial x}\left(D_{T,v} \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial x}\left(D_{\theta,v} \frac{\partial \theta}{\partial x}\right)\right) \quad (2)$$

where Cp_m is specific heat of moist material in J kg^{-1}.K^{-1} and it is given by:

$$Cp_m = Cp_0 + Cp_l \frac{\rho_l}{\rho_0}\theta \quad (5)$$

The boundary conditions for equations (1) and (2) and details of numerical solution using finite difference technique are shown in [15].

III. Study of a Simple Wall Subjected to Fluctuating Indoor Conditions

In order to study interactions between inertia and interior environment, a simple layer wall is considered here. The wall is adiabatic and impermeable from the outside and subjected to a sinusoidal fluctuation of the indoor air temperature between 23 and 25°C over a period of 24h. Indoor humidity ratio is 0.01 kg vapour/kg dry air. Indoor convection coefficient was taken equal to 5 W/m^2 K and indoor mass transfer coefficient 0.004 Kg/m^{2}s according to. The behaviour of three different materials used in construction was studied. These are: normal concrete, brick and hemp concrete. The input data (material properties, sorption isotherms, moisture diffusion coefficients) of these materials are shown in Table 1 [2].

For the sorption isotherm curves they are shown in the Fig. 1.a. Simulations were run for a period of 10 months, initial wall temperature was considered to be 23°C and the moisture content 0.0005 m^3/m^3 along the whole thickness. Wall thickness varies respectively from 2.5 to 5, 10 and 15 cm.

For the three materials two cases were considered: the first one takes into account moisture transfer through the material (HAM case) and the second one, neglects moisture transfer (Th case). For the Th case, dry material properties were used, transport and mass convection coefficients were set to 0. For the HAM case material thermal conductivity is a function of moisture content and it is shown in Fig. 1.b and 1.c.

TABLE I:
MATERIAL PHYSICAL PROPERTIES

Material	Density	Thermal Conductivity	Specific heat	D_Θ	D_T	$D_{\Theta v}$	D_{Tv}
	kg/m3	*W/m.K*	*J/kg.K*	*m²/s*	*m²/(s.K)*	*m²/s*	*m²/(s.K)*
Normal concrete	2300	1.6	850	6.39E-10	7.91E-14	2.29E-11	7.91E-14
Brick	1630	0.6	850	1.1E-09	1E-11	1.1E-09	1E-11
Hemp concrete	413	0.1058	1000	1.16E-09	1.02E-12	1.07E-09	1.02E-12

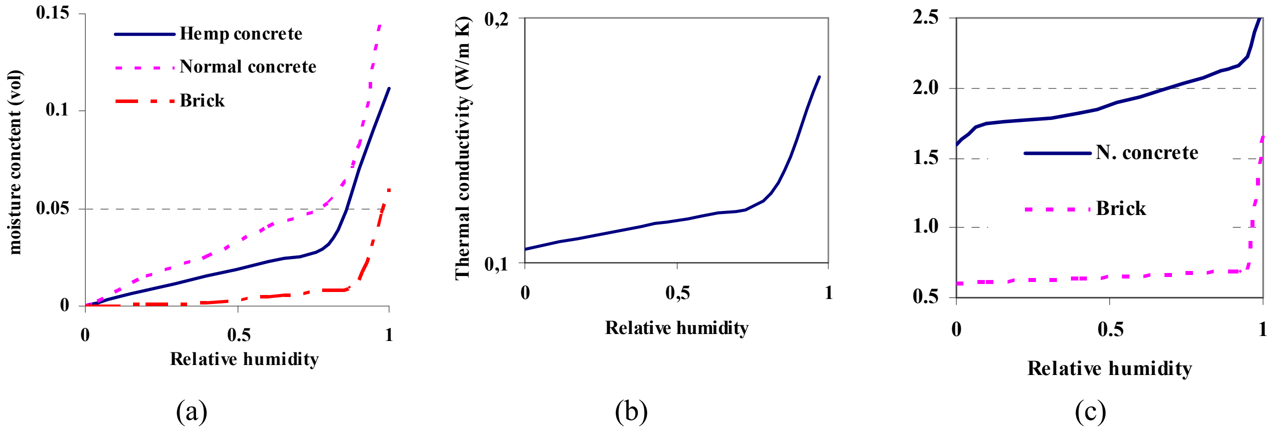

Fig. 1 : Sorption isotherms of the studied materials (a) and variation of their thermal conductivity with relative humidity (b and c)

IV. Results and Discussion

A. For the Th model

Fig. 2 shows time pattern of the wall internal surface temperature, of the temperature at 10 cm depth and of the stored heat flux density within a wall of hemp concrete when its internal surface is subjected to sinusoidal indoor temperature variating from 23 to 25°C over a period of 24 h. This heat flux is stored within the wall when indoor air temperature is higher than wall internal surface temperature (flux density is positive). When both temperatures are equal the flux is null and it becomes negative when indoor air temperature is lower than surface temperature. In this case, thermal inertia is characterised by the thermal heat capacity per surface area THC which is calculated as the product ρ.Cp.L (Wh/m²K) which defines the material capacity to store heat energy when its temperature varies about 1K [4]. In our case, the maximum theoretical variation of material temperature is 2 K which suggests that the maximum heat storage of the material is twice the THC. It is also possible to calculate the really stored energy by the material per surface area (Qcalc in Wh/m²°C). The difference between the THC and Qcalc makes it possible to define a ratio that expresses the percentage of the effectively used thermal capacity. Table 2 shows the values of THC, Qcalc and the utilisation of thermal heat capacity in terms of percentage for the three materials and for wall thicknesses of 2.5 and 10 cm. For hemp concrete wall when wall thickness increases from 2.5 cm to 10 cm, stored energy increases from 5.58 to 12 Wh/m² °C which is almost 115%. For the concrete wall this energy increases from 21.8 to 32.7 Wh/m²K or 50%. In this case the utilisation of the thermal capacity is lower than other materials. In practice it is not of great importance that the utilisation of the thermal capacity is less for normal concrete than other materials, it is the size of the heat accumulation per surface area which is important. We can also use the thermal effusivity ($\sqrt{k\rho C_p}$) which indicates the aptitude of a material to absorb and to restore energy.

Fig. 3 illustrates the influence of the effusivity on the quantity of heat stored in Wh/m ²°C (Qcalc) as well as the influence of wall thickness. Below 1000 J/m²°Cs$^{1/2}$, when the effusivity is doubled, cumulated energy almost will be doubled too. Beyond this value, stored energy increases less quickly but can increase in an important way with wall thickness. This wall thickness will increase heat capacity per surface area and also the quantity of stored energy. When wall thickness passes from 2.5 cm to 10 cm, cumulated energy increases by 150%. However when the thickness increases from 10 cm to 15 cm, energy remains practically constant or even decreases which suggests that beyond 10 cm wall temperature remains constant and there is no heat stored (storage flux is null).

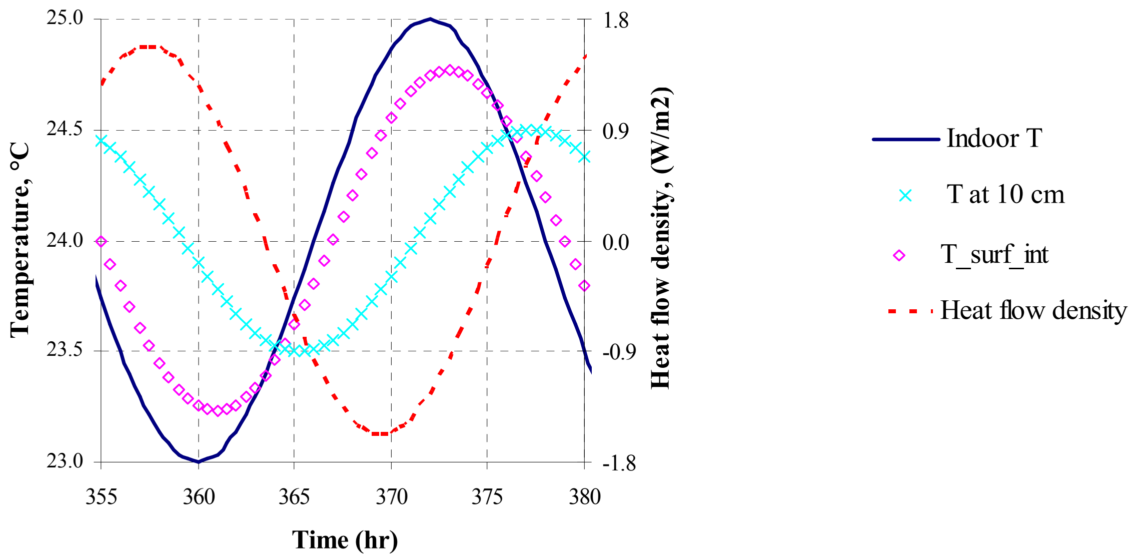

Fig. 2 : Time pattern of the wall internal surface temperature.

TABLE II:: CALCULATION OF THE SURFACE HEAT CAPACITY AND THE FRACTION OF HEAT CAPACITY EFFECTIVELY USED FOR THICKNESSES OF 0.025M AND 0.1 M.

L=0.025	Th. heat capacity per surface area Wh/m² °C	Stored energy (Qcalc) per surface area Wh/m² °C	Effective heat capacity %
N. concrete	13.57	21.81	80
Brick	9.62	16.84	87.52
H. concrete	2.86	5.58	97.55
L=0.1			
N. concrete	54.3	32.7	30.11
Brick	38.95	27.5	35.3
H. concrete	11.47	12	53.47

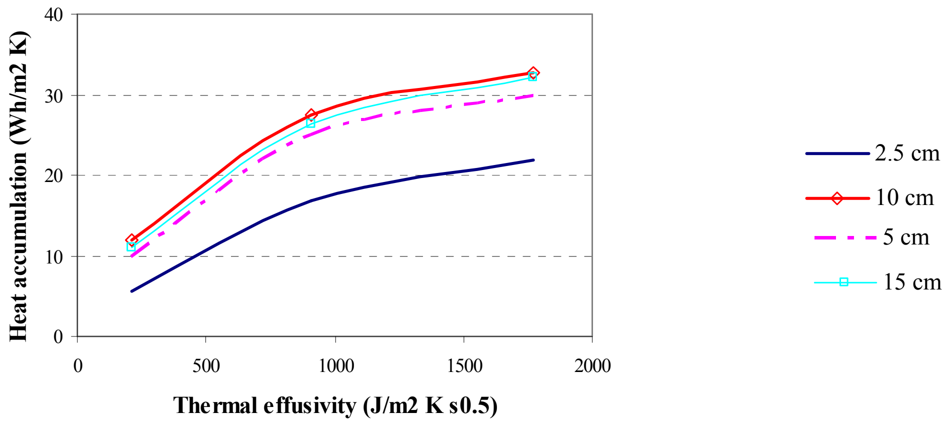

Fig. 3 : Variation of the stored energy within the wall as a function of material effusivity

A. *For the HAM model*

Moisture transfer within the material is a slow phenomenon and it takes several months to reach steady values for both moisture and temperature distributions. Fig. 4 and 5 show internal surface temperature for a 10 cm hemp concrete wall after 15 days and after 3 monthes and for both Th and HAM model. As shown in [2], temperature profile for the HAM model is mainly related to material initial moisture content. The drier it is and the higher temperature will be compared to the Th model because of the phenomenon of moisture adsorption. Concerning brick, taking moisture transfer into account has little impact on temperature distribution within the wall because its moisture content is very low at ambient relative humidities. The same remark applies also to normal concrete but in this case, this is due to concrete low diffusion coefficients.

Fig. 6 shows the influence of the effusivity on the quantity of heat stored in Wh/m ²°C (Qcalc) as well as the influence of wall thickness when moisture transfer is taken into account. It is noticed here that the heat stored refers to the sensible heat term which is calculated the same way as in section 3 when steady conditions in the wall are reached. The same remarks of the section 3 apply here also. However for the low effusivity material (hemp concrete) the values of the stored energy are higher for the HAM model than those of the Th model. For a wall thickness of 2.5 cm HAM model gives a stored energy value of 10.32 Wh/m^2 K which is 40 higher than that of the Th model. For a thickness of 10 cm the value is 30% higher. These differences for the hemp concrete can be explained by the fact that it is a porous material with high moisture diffusion coefficients so heat transfer within this material is coupled to moisture transfer and thus neglecting moisture transfer leads to important errors on wall temperature and its stored energy. Besides for Fig. 5, we note that for wall thicknesses of 2.5 and 5 cm the stored energy varies almost linearly with the effusivity. For higher effusivities which correspond to brick and normal concrete walls the difference in stored energy for both models is negligible (less than 5%) except for the 2.5 cm normal concrete wall where it reaches about 8% because of adsorption phenomenon.

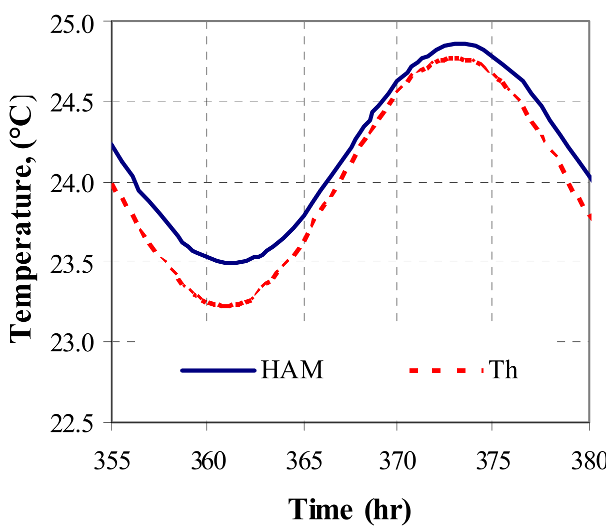

Fig. 4 : Comparison between internal surface temperature patterns for both Th and HAM models for the 10 cm hemp concrete wall after 15 days.

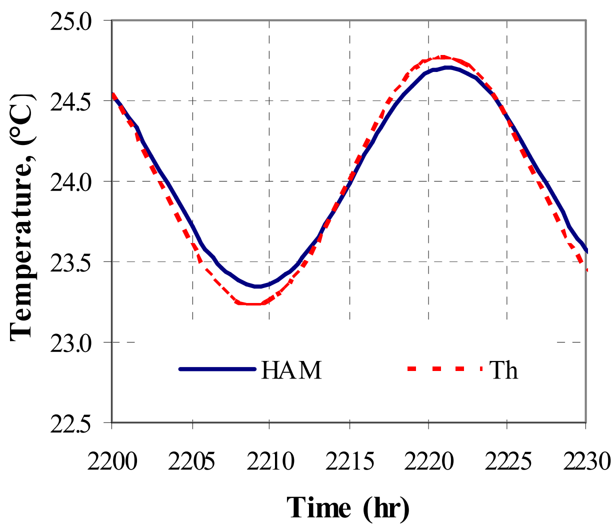

Fig. 5 : Comparison between internal surface temperature patterns for both Th and HAM models for the 10 cm hemp concrete wall after 3 monthes when moisture steady state within the wall is reached

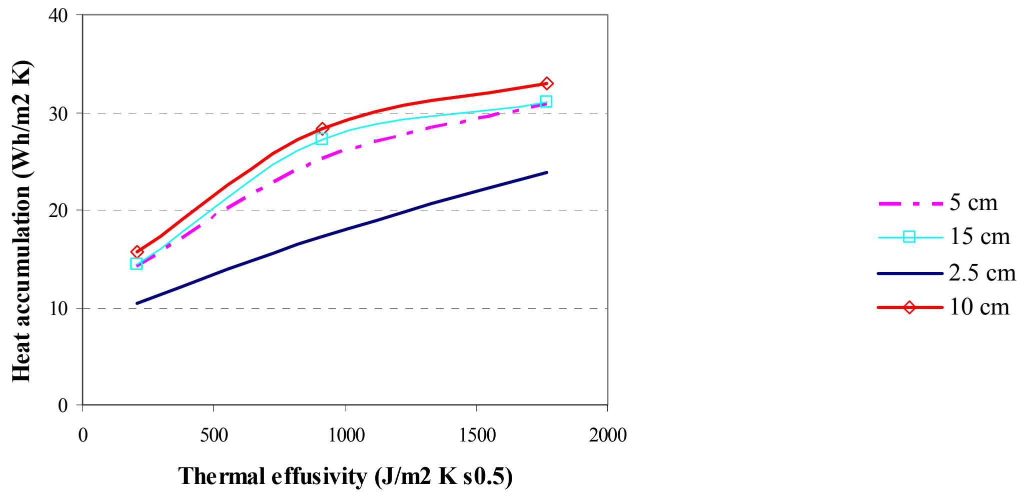

Fig. 6 : Variation of the sensible stored energy within the wall as a function of material effusivity

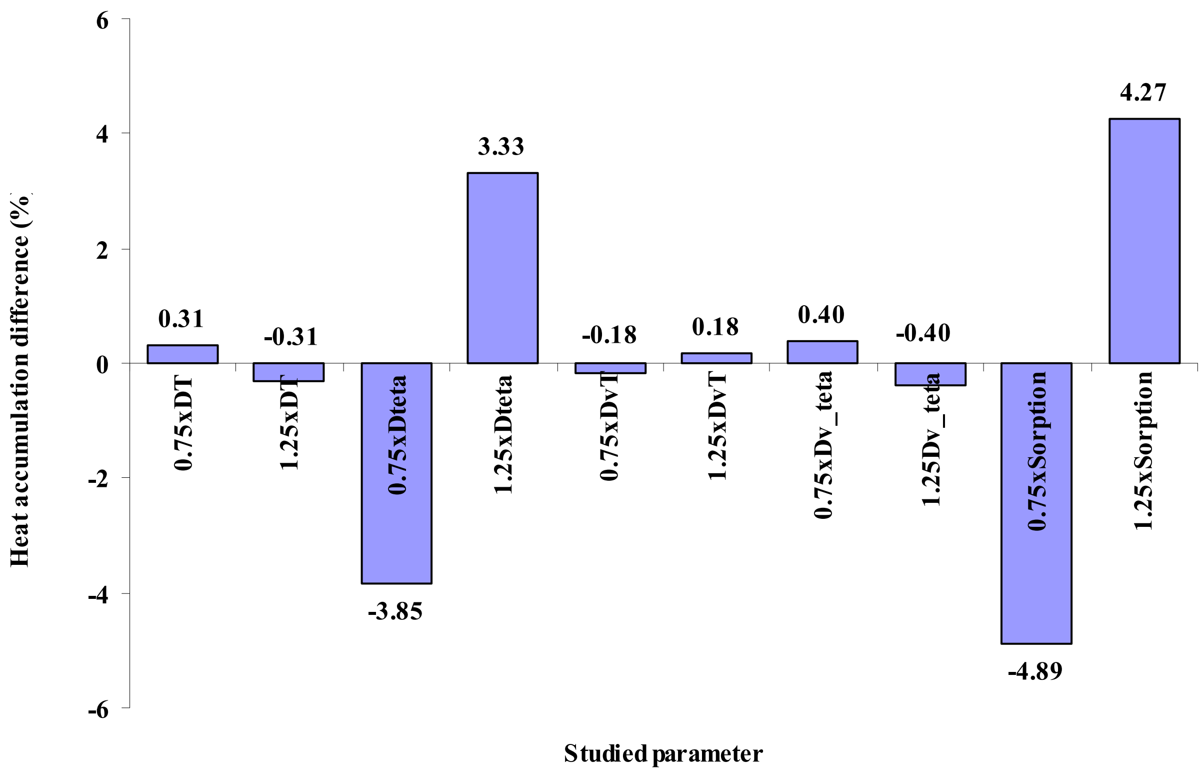

Fig. 7 : Impact of material hygric properties variation on its stored thermal energy.

V. Sensitivity Analysis

To better understand the influence of each parameter of the physical model on the results, a sensitivity analysis is done in this part. We considered a simple layer of hemp concrete of 15 cm and varied its physical properties and parameters.

A. Effect of hygric physical properties

Fig. 7 shows the effect of hygric physical properties on the wall stored energy for a 15 cm thickness wall of hemp concrete. These properties include material sorption isotherm and its transport coefficients (D_T, $D_{T,v}$, D_θ and $D_{\theta v}$). We notice that only the coefficient D_θ and the thermal sorption isotherm have non negligible impact. An increase of 25% of transport coefficient D_θ leads to a growth of 3.33% of the stored energy within the wall because of increasing of the water vapour desorption quantity on the internal surface wall (Fig. 8 shows that when energy is stored (when indoor temperature is higher than wall internal surface temperature), vapour density on wall surface is higher than that of indoor air and desorption phenomenon occurs from the wall to the air). Besides, one can say that as transport coefficient D_θ increases, material moisture content will increase and its thermal effusivity will increase too leading to a growth in material stored energy. For the same reasons, an error in the estimation of the sorption curve of +25%, leads to an error on the stored energy of about +4.27%.

B. *Effect of dry material physical properties*

These properties include material thermal conductivity, its specific heat and mass density. Fig. 9 shows that any growth of any of these properties leads to a growth in the material stored energy because material thermal effusivity will also increase. It is noticed that the impact of mass density is identical to that of the specific heat. Concerning material thermal conductivity, its impact is higher than that of other parameters. An increase of 25% of the thermal conductivity leads to a growth of 7% of the stored energy.

C. *Effect of convection coefficients*

TABLE III:

EFFECT OF INDOOR HEAT AND MASS CONVECTION COEFFICIENTS

	0.75xHint	1.25xHint
Stored energy variation (%)	-11.30	7.87

Table 3 shows the effect of the variation of indoor mass and heat convection coefficients on the material stored energy (they are related by the Lewis relation [2]). This energy depends on the thermal convection coefficient and on the difference between wall internal surface temperature and indoor ambient temperature. When the thermal convection coefficient increases 25%, internal surface temperature tends toward indoor ambient temperature and the difference between both temperatures decreases. However the growth of the convection coefficient is higher and the stored energy within the wall increases about 7.9%.

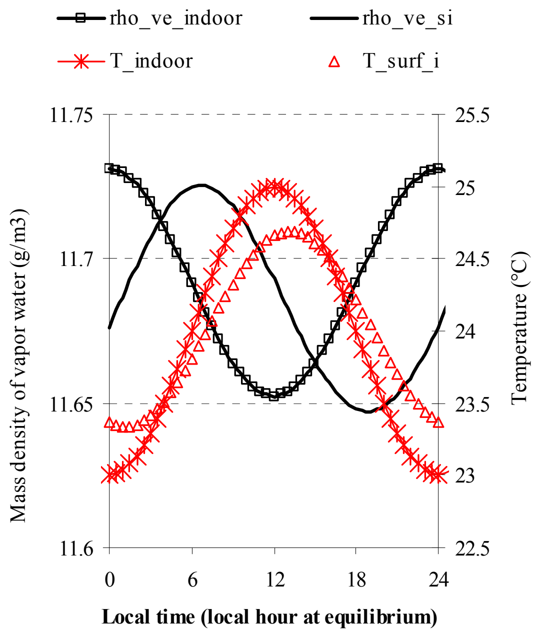

Fig. 8 : Variation of indoor air and internal wall surface temperatures and water vapor densities for the hemp concrete wall when equilibrium conditions are reached after 3 months.

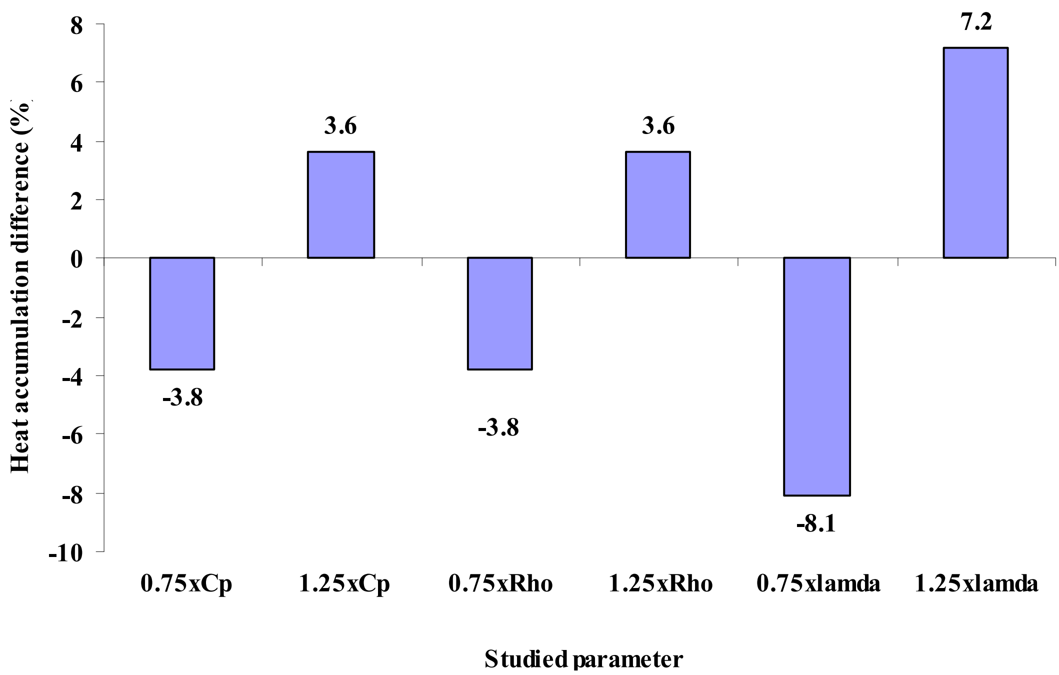

Fig. 9 : effect of material thermal conductivity, specific heat and mass density variation on its stored thermal energy.

D. *Effect of indoor air humidity ratio*

TABLE IV

EFFECT OF INDOOR AIR HUMIDITY RATIO

	X=0.005 kg/kg dry air	X=0.015 kg/kg dry air
Stored energy variation (%)	-10.8	18.5

Previous results were obtained for an indoor humidity ratio of 0.01 kg of water/kg dry air. Table 4 shows effect of variation of indoor humidity ratio on the material stored energy. When humidity ratio varies from 0.01 to 0.015 kg of water/kg of dry air, more moisture will diffuse through the material and thus its moisture content will increase, leading to a growth in its effusivity and its hygric properties. For this case, the stored energy within the material increases about 18.5%. When indoor humidity ratio decreases from 0.01 to 0.005 kg of water/kg of dry air, material stored energy will decrease about 11%.

E. *Effect of initial moisture content*

TABLE V:
EFFECT OF MATERIAL INITIAL MOISTURE CONTENT

	Hri=50%	HRi=80%
Stored energy variation (%)	4.76	7.67

In previous results material initial moisture content was 0.0005 m^3/m^3 along the whole thickness, which corresponds to a dry material (1% initial relative humidity). Table 5 shows the variation of material stored energy for initial relative humidities of 50 and 80%. When initial relative humidity within the material varies from 1% to 80% its stored energy increases 7.7%. This is due to the high desorption rate from the internal surface which leads to a decrease in its temperature and thus stored energy within the wall will increase.

F. *Summary*

Fig. 10 shows a summary of the sensitivity analysis done in this section. It shows the decrease of material stored energy due to an underestimation of physical parameters. Only the most influent parameters are shown. These parameters are (from the most important till the less): Indoor convection coefficients, Thermal conductivity, sorption isotherm, transport coefficient D_θ , dry material density and its specific heat.

VI. CONCLUSION AND PERSPECTIVES

In this paper, we have studied the effect of moisture transfer on heat storage capacity in simple layer walls, for different thicknesses and for three materials: normal concrete, brick and a vegetal fiber material: hemp concrete. Simulations are run for 10 monthes and results are shown when steady conditions are reached. Our results suggest that under normal humidity conditions, neglecting moisture transfer has small impact on the storage capacity of brick walls and normal concrete walls, however for hemp concrete walls; it underestimates stored energy from 30 to 40%. Furthermore, a sensitivity analysis of hemp cocnrete storage capacity to different physical parameters has been done. Our results suggest that the storage capacity is very sensitive to the thermal properties, sorption isotherm; transport coefficient associated to moisture gradient and to the internal heat and mass convection coefficients. A care should be given to initial material moisture content. It is also shown that ambient air humidity ratio has an important effect on material storage capacity. The latter increases about 18.5% when indoor humidity ratio varies from 0.01 to 0.015 kg of water/kg dry air. These results were obtained neglecting hysteresis effect on the sorption curve which could be non negligible especially in hemp concrete walls. Moisture transport coefficients were assumed constant which could also affect moisture distribution. So these cases should be studied carefully.

The impact of moisture transfer should also be computed on the whole building level.

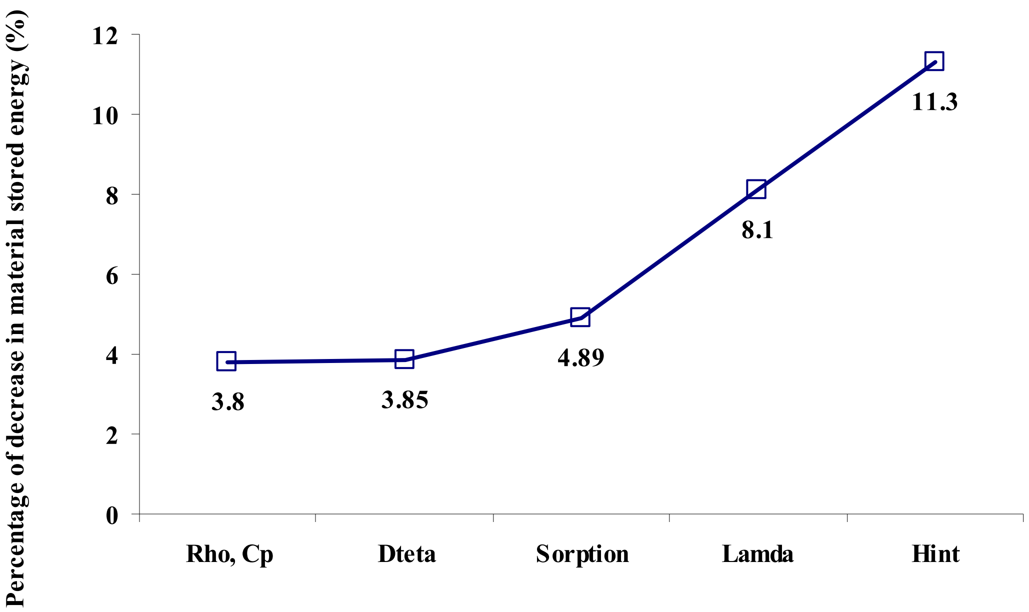

Fig. 10 : Summary of sensitivity analysis showing the stored energy decrease due to a decrease or underestimation of a physical parameter value of 25%.

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