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1     **Behavior of a hemp-based concrete wall under dynamic thermal and hygric solicitations**

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6

7     **Abstract**

8     Here we document the behavior at wall scale of a hemp-based hygroscopic material under  
9     various temperature and moisture dynamic conditions. The wall was made of precast hemp  
10     concrete (HC) blocks with air cavities. It was tested within a bi-climatic chamber and monitored  
11     thanks to hygrothermal sensors in the wall and in the chambers. The results from an in-house heat  
12     and moisture transfer model were compared to the experimental data, using the actual thermal  
13     and hygric characteristics of the hemp-based material determined in a previous study. The  
14     experiments allowed to demonstrate how the heat and moisture transport phenomena within the  
15     wall are coupled, particularly how a temperature difference can be a sufficient driving force for  
16     the release of moisture. The work points out the impact of moisture adsorption on heat release  
17     and on the temperature changes within the wall. Finally the numerical model served also to the  
18     modelling of an equivalent wall made of concrete to help highlighting the moisture dumping  
19     capability of the bio-based material, together with its thermal insulation capacity.

20     **Keywords:** heat and moisture transfer, bi-climatic chamber, wall scale, Hemp Concrete, bio-  
21     based materials.

## 22 Nomenclature

### 23 Latin symbols

24	$A$	Aspect ratio	(-)
25	$A_w$	Sorption coefficient	( $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1/2}$ )
26	$c_p$	specific heat capacity	( $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ )
27	$d$	air layer thickness	(m)
28	$g$	gravitational force	( $\text{m}\cdot\text{s}^{-2}$ )
29	$g_m$	mass flux	( $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ )
30	$h_c$	surface heat transfer	( $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ )
31	$h_m$	surface mass transfer	( $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$ )
32	$H$	height	(m)
33	$k$	thermal conductivity	( $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ )
34	$L$	length	(m)
35	$L_v$	latent heat	( $\text{J}\cdot\text{kg}^{-1}$ )
36	Nu	Nusselt number	
37	$p_c$	capillary pressure	(Pa)
38	$p_v$	vapor pressure	(Pa)
39	$p_{v,sat}$	saturated vapor pressure	(Pa)
40	$q_c$	heat flux	( $\text{W}\cdot\text{m}^{-2}$ )
41	Ra	Rayleigh number	
42	RH	relative humidity	(-)
43	$S_l$	moisture source term	( $\text{kg}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$ )

44  $T$  temperature ( $^{\circ}\text{C}$  or  $\text{K}$ )

45  $t$  time (s)

46  $V$  velocity ( $\text{m}\cdot\text{s}^{-1}$ )

47  $w$  total mass water content ( $\text{kg}\cdot\text{m}^{-3}$ )

48  $W$  width (m)

49

50 Greek symbols

51  $\alpha$  thermal diffusivity ( $\text{m}^2\cdot\text{s}^{-1}$ )

52  $\beta$  thermal expansion coefficient ( $\text{K}^{-1}$ )

53  $\delta$  permeability ( $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$  or s)

54  $\nu$  kinematic viscosity ( $\text{m}^2\cdot\text{s}^{-1}$ )

55  $\rho$  density ( $\text{kg}\cdot\text{m}^{-3}$ )

56

57 Subscripts

58  $f$  free saturation

59  $_{HC}$  Hemp Concrete

60  $i$  liquid or vapor

61  $l$  liquid

62  $s$  solid

63  $_{surf}$  surface

64  $v$  vapor

65

## 66 **1 Introduction**

67 Hemp Concrete (HC) belongs to the class of bio-based construction materials. It is made of the  
68 combination of hemp shiv particles with a binder, generally based on lime in order to maintain  
69 the hygroscopic properties of the resulting material. Hemp shiv is the woody core of the hemp  
70 stalk obtained through defibration by a mechanical breaking process. The terminology HC is  
71 typically used as an analogy to the usual concrete blocks used in construction. Nevertheless, one  
72 has to keep in mind that the basic component of concrete, cement, is not present within the HC  
73 composition.

74 Thanks to photosynthesis, bio-based materials can be called CO<sub>2</sub> storage materials. This  
75 characteristics, together with the hemp hygrothermal properties developed thanks to the hemp  
76 pore structure, make the HC an excellent candidate for meeting sustainable construction  
77 objectives. Such materials are perceived as potential solution for energy efficient buildings with a  
78 reduced carbon footprint. Controlling heat and moisture transfer through the buildings envelope  
79 by using hygroscopic materials may bring a contribution not only on an energy point of view  
80 (Osanyintola and Simonson, 2006, Woloszyn et al., 2009) but also on a health standpoint. The  
81 increase in moisture content comes indeed with a rise in microorganism concentration  
82 (Baughman and Arens, 1996), and the control of mold is directly related to the humidity level in  
83 the buildings envelope.

84 The research field on bio-based construction materials is very active, both on the experimental  
85 side and on the modelling one. As far as the latter is concerned, heat and moisture numerical  
86 models rely on different driving potentials to describe the moisture exchanges: it can be either the  
87 moisture content or the capillary pressure or the vapor pressure. Therefore the final set of

88 equations varies from one author to another one. Examples of models can be found in the works  
89 Hagentoft et al. (2004), Li et al. (2009), Tariku et al. (2010), Steeman et al. (2010), Delgado et al.  
90 (2013), or Van Belleghem et al. (2014). The main modelling challenge lies in the fluid flow  
91 through the porous structure combined to phase change, making the set of equations to solve  
92 highly non-linear. The issue is highlighted in Souza et al. (2008), Mahabaleshwar et al. (2017),  
93 Salimpour et al. (2017), Husman et al. (2016), Pepe et al. (2017).

94 The experimental investigations rang from the sample scale to the building scale in real climatic  
95 conditions. For example, detailed measurements were presented in Lelievre et al. (2014) on a  
96 hemp-based element showing the thermo-hygric response to a change of relative humidity of the  
97 environment. Wall scale laboratory experiments were performed by Aït Oumeziane et al. (2016)  
98 in almost isothermal conditions. In 2018, Moujalled et al. published the results of an  
99 experimental campaign of 4 years on a house which envelope was partially made of a sprayed  
100 hemp and lime concrete, demonstrating the moisture buffering capacity of such material in real  
101 life climatic conditions. This work came after the pioneering works of Shea et al. (2012)  
102 performed on a rather smaller building based on different construction techniques.

103  
104 The work presented in this paper is aimed at investigating the response of a wall made of a hemp-  
105 based material to controlled dynamic solicitations in both temperature and humidity within a bi-  
106 climatic chamber. The temperature and water vapor profiles obtained during the experimental  
107 campaign serve a three-fold purpose: one is to assess the moisture buffering capacity of such  
108 material, the other is to provide a set of HAM (Heat and Moisture) data necessary to the wall-  
109 scale validation of a numerical model based on the finite elements method; the final one is to

110 examine how the hemp-based wall behavior differentiates from a classical concrete wall in terms  
111 of thermo-hygric response.

## 112 **2 Experiments**

### 113 **2.1 Hemp Concrete wall in the test chamber and metrology**

114 Blocks of HC were assembled in order to constitute a wall of 2.3 m in height, 1.6 m in width and  
115 20 cm in thickness. Each HC block had the following dimensions: length =  $50.8 \pm 1.04$  cm,  
116 thickness =  $19.9 \pm 0.09$  cm, height =  $20.3 \pm 0.24$  cm. The assembly was made thanks to thin  
117 horizontal mortar layers (70% metakaolin and 30% hydrated lime, sand/binder = 5 and  
118 water/binder = 0.6), while the vertical sides of the blocks were interlocked to each other (see Fig.  
119 1 for the geometric features). The HC blocks contain air cavities (Fig. 1a). Due to the vibro-  
120 compaction fabrication process, the HC layers were slightly thicker at the bottom of the brick  
121 (HC thickness =  $2.55 \pm 0.07$  cm at the top of the brick against  $2.72 \pm 0.09$  cm at the bottom)  
122 while it was the opposite for the air layer (air thickness =  $0.94 \pm 0.07$  cm at the top against  $0.71 \pm$   
123  $0.06$  cm at the bottom). Mean values of HC layer thickness ( $2.63 \pm 0.08$  cm) and air layer  
124 thickness ( $0.82 \pm 0.07$  cm) were considered in the numerical study.

125 The HC was initially characterized by measuring its physical, thermal and hygric properties:  
126 density, porosity, thermal conductivity, specific heat capacity, air and vapor permeability,  
127 sorption and desorption isotherms, capillary adsorption coefficient. The details of this work can  
128 be found in Seng et al. (2019a, 2019b) and were used here as input data in the numerical model.  
129 The relationship between the relative humidity and the moisture content is an important topic as  
130 in most cases hemp-based materials exhibit a strong hysteretic behavior between adsorption and  
131 desorption, while the temperature at which the sorption-desorption isotherm experiments are

132 conducted may also have impact (Aït Oumeziane et al., 2016). The results corresponding to the  
133 HC tested in this study are provided in Fig. 2, showing that the sorption and desorption  
134 measurements at 23°C and 45°C gather along one single curve, justifying the use of a unique  
135 isotherm in the study.

136

137 

138

139 

140

141 The test environment was made of two climatic rooms; both were controlled in temperature and  
142 relative humidity. Each room has a horizontal surface of  $L \times W = 3.30 \text{ m} \times 1.60 \text{ m}$  and a height of  
143  $H = 2.30 \text{ m}$ . The HC wall was placed into a wooden frame in order to separate the two chambers.  
144 Special attention was dedicated to avoid any humid air leakage through the frame or the wall-  
145 frame interface. Note that deflectors were installed so that the air blown into the chambers to  
146 maintain the chosen boundary conditions was not directly oriented toward the wall.

147

148 The hygrothermal behavior of the HC wall was monitored with 10 hygrothermal sensors  
149 (Honeywell HIH-4602-C). Each hygrothermal sensor was equipped with a 2 wires integral  
150 precision RTD sensor for the temperature (precision: Class B,  $\pm 0.3 + 0.005T \text{ }^\circ\text{C}$ ), and a planar  
151 capacitor for the RH ( $\pm 3.5\% \text{ RH}$ ).



152 The hygrothermal sensors were distributed along the thickness of the wall, at the wall mid-height,  
153 in the air cavities inside the wall and against the wall (Fig. 3). One sensor was deported  
154 horizontally (sensor 7) so that the one-dimensional aspect of the transfer could be checked. All  
155 the sensors were connected to a data acquisition processor which returned the measurements to a  
156 computer outside the bi-climatic chamber.

157

158 Insert Figure 3

159

## 160 **2.2 Tests summary**

161 A first series of test consisted in measuring the hygrothermal response of the wall to a  
162 temperature step solicitation without any moisture exchange between the wall and its surrounding  
163 environment. To this sake, the 2 faces of the wall were coated with a vapor barrier. After an  
164 initial stabilization phase at 25°C in the 2 rooms, the temperature was steeply increased to 45°C  
165 on one side, and maintained to this value for about 4 days.

166 In a next series, one chamber represented outdoor conditions, while the opposite one (hot side)  
167 was meant to reproduce indoor conditions. The hot side was always maintained at a constant  
168 temperature. In one case, vapor was produced for 1 hour in order to model room occupancy; the  
169 cold side was kept at 6°C and RH = 80%. The test lasted about 4 days. In the other case, the cold  
170 chamber was submitted to a sinusoidal temperature signal with an average temperature of 14°C, a  
171 total temperature amplitude of 16°C and a period of 24 hours. The RH slightly fluctuated around

172 80%. The hot chamber RH was not controlled. The test lasted 6 days. Figure 4 summarizes the 3  
 173 configurations.

174 Insert Figure 4

### 175 **3 Numerical study**

#### 176 **3.1 Heat and moisture transfer through the HC**

177 The problem is described by the conservation laws written for the HC layers and for the air  
 178 layers. Equations (1) to (3) present the moisture transfer, the energy transfer and the moisture  
 179 phase change rate in time. A first version of the model considering only HC was published in  
 180 Seng et al. (2017). In this paper the work was compared to experimental data obtained on a small  
 181 sample of HC from Lelievre et al. (2014). Working with realistic boundary conditions at a much  
 182 bigger scale with actual wall elements is the aim of the present study.

183 The set of equations was solved for three variables: the capillary pressure  $p_c$ , the temperature  $T$   
 184 and the moisture source term  $S_l$  which corresponds to the amount of moisture stored or released  
 185 in time by the solid phase.

$$\frac{\partial w}{\partial p_c} \frac{\partial p_c}{\partial t} = -\nabla \left[ \left( \delta_l + \delta_v \frac{\rho_v}{\rho_l} \right) \nabla p_c - \delta_v \left( \text{RH} \frac{\partial p_{v,sat}}{\partial T} - p_v \frac{\ln \text{RH}}{T} \right) \nabla T \right] \quad (1)$$

$$\left( \rho_s c_{p,s} + \sum_i w_i c_{p,i} \right) \frac{\partial T}{\partial t} = k_{HC} \nabla^2 T - [(c_{p,l} - c_{p,v})T - L_v] S_l - \sum_i w_i \mathbf{V}_i c_{p,i} \nabla T \quad (2)$$

$$\left( \frac{1}{1 - \rho_v / \rho_l} \right) \frac{\partial w}{\partial t} = -\nabla (\delta_l \nabla p_c) + S_l \quad (3)$$

186 where  $w$  is the total moisture content,  $\delta_l$  is the liquid permeability,  $\delta_v$  is the vapor permeability,  
 187  $\rho_v$  is the water vapor density,  $\rho_l$  is the liquid water density,  $p_v$  is the vapor pressure,  $p_{vsat}$  is the  
 188 saturated vapor pressure,  $\rho_s$  is the material apparent density,  $w_i$  ( $i = v$  for water vapor or  $i = l$  for  
 189 liquid water) is the moisture content,  $c_{p,i}$  is the specific heat capacity of water vapor or liquid  
 190 water,  $k_{mat}$  is the material thermal conductivity,  $\mathbf{V}_i$  is the velocity of water vapor or liquid water  
 191 and  $L_v$  is the latent heat of vaporisation.

192 The HC thermal and hygric properties were measured in Seng et al. (2019a) and Seng et al.  
 193 (2019b). The curved fitting parameters obtained by means of the GAB model (Anderson, 1946)  
 194 are provided in Table 1 together with a summary of the other material properties. Note that the  
 195 amount of transported water vapor or liquid water  $w_i \mathbf{V}_i$  can be defined by  $w_v \mathbf{V}_v = -\delta_v \nabla p_v$  and  
 196  $w_l \mathbf{V}_l = \delta_l \nabla p_c$ , and that the  $\sum_i w_i c_{p,i} \approx w c_{p,l}$  due to the small value of  $w_v$  compared to  $w_l$ .

197

### 198 **3.2 Heat and moisture transfer through the air layers**

199 The Rayleigh number of an air cavity is given by

$$Ra_d = \frac{g\beta\Delta T d^3}{\alpha\nu} \quad (4)$$

200 where  $g$  is the gravitational force,  $\beta$  is the thermal expansion coefficient written  $\beta = 1/T$  as air  
 201 was considered as an ideal gas,  $\Delta T$  is the temperature difference between the two faces of the  
 202 cavity,  $d$  is the air layer thickness,  $\alpha$  is the air thermal diffusivity and  $\nu$  is the air kinematic  
 203 viscosity.

204 It was assumed that the temperature difference  $\Delta T$  within an air layer varies from 1°C to 5°C.  
 205 The Rayleigh number based on d,  $Ra_d$  estimated with Eq. (4) was therefore lower than 300. With  
 206 an air layer thickness  $d = 0.82$  cm, the air cavity aspect ratio is  $A = H/d = 24.8$ , with  $H = 20.3$   
 207 cm. As  $Ra_d < 10^4$  and  $5 \leq A \leq 80$ , the Nusselt was evaluated with the expression provided by  
 208 Zhao et al. (1997):

$$Nu = \left( 1 - 0.00813277 \left( \frac{Ra_d}{A} \right) + 0.00723291 \left( \frac{Ra_d}{A} \right)^{1.08597} \right)^{0.279072} \quad (5)$$

209 Because  $Nu \leq 1$ , only conductive transfer was considered through the air cavity. With no  
 210 convective transfer effect and no liquid phase transfer in the air cavity, the resulting HAM  
 211 equations are:

$$\frac{\partial w_{air}}{\partial p_c} \frac{\partial p_c}{\partial t} = -\nabla \left[ \left( \delta_v \frac{\rho_v}{\rho_l} \right) \nabla p_c - \delta_v \left( RH \frac{\partial p_{vsat}}{\partial T} - p_v \frac{\ln RH}{T} \right) \nabla T \right] \quad (6)$$

$$(\rho_{air} c_{p,air} + w_v c_{p,v}) \frac{\partial T}{\partial t} = k_{air} \nabla^2 T \quad (7)$$

$$S_l = 0 \quad (8)$$

212 where  $w_{air}$  is the water vapor content in air defined from the ideal gas law (Table 1).  
 213

214 Table 1 : HC and air properties used in the numerical study

Parameter	Hemp Concrete (from Seng et al., 2019a, Seng et al. 2019b)	Air
-----------	--	-----

Density	$\rho_{HC} = 466.2 \text{ kg.m}^{-3}$	$\rho_{air} = 1.2 \text{ kg.m}^{-3}$
Thermal conductivity	$k_{HC} = 0.112 \text{ W.m}^{-1}.\text{K}^{-1}$	$k_{air} = 0.026 \text{ W.m}^{-1}.\text{K}^{-1}$
Specific heat capacity	$c_{p,HC} = 905 \text{ J.kg}^{-1}.\text{K}^{-1}$	$c_{p,air} = 1004 \text{ J.kg}^{-1}.\text{K}^{-1}$
Isotherm	<p>GAB model</p> $w_{HC} = \frac{\rho_{HC} \cdot u_m \cdot C \cdot K \cdot RH}{(1 - K \cdot RH)(1 + K(C - 1)RH)}$ <p> <math>u_m = 0.0182</math>  <math>C = 18.048</math>  <math>K = 0.8219</math> </p> <p>(NB: the curve-fitting parameters correspond to a temperature of 23°C in adsorption)</p>	<p>Water vapor considered as an ideal gas</p> $w_{air} = \frac{RH \cdot p_{v,sat}(T)}{R_v T}$ <p>where <math>R_v</math> is the water vapor specific gas constant (<math>R_v = R/M_v</math>)</p> <p><math>R = 8.314 \text{ J.mol}^{-1}.\text{K}^{-1}</math>  <math>M_v = 18 \cdot 10^{-3} \text{ kg.mol}^{-1}</math></p>
Water vapor permeability	$\delta_{v,HC} = 9.67 \cdot 10^{-11} \text{ kg.m}^{-1}.\text{s}^{-1}.\text{Pa}^{-1}$	$\delta_{v,air} = 1.95 \cdot 10^{-10} \text{ kg.m}^{-1}.\text{s}^{-1}.\text{Pa}^{-1}$
Liquid permeability	$\delta_{l,HC} = D_w \frac{\partial w}{\partial RH} \frac{RH}{\rho_l R_v T}$ <p>where <math>D_w = 3.8 \left(\frac{A_w}{w_f}\right)^2 1000 \frac{w}{w_f}^{-1}</math></p> <p><math>A_w = 0.139 \text{ kg.m}^{-2}.\text{s}^{-1/2}</math>  <math>w_f = 541 \text{ kg.m}^{-3}</math></p>	$\delta_{l,air} = 0 \text{ kg.m}^{-1}.\text{s}^{-1}.\text{Pa}^{-1}$

215

### 216 3.3 Boundary conditions

217 The thermal boundary conditions between the wall and the air in the climatic chambers were

218 described with a convective heat flux  $q_c$  ( $\text{W.m}^{-2}$ ) in which the chamber temperature,  $T_{air}$ , may

219 vary in time.

$$q_c = h_c(T_{surf} - T_{air}) \quad (9)$$

220 where  $h_c$  is the convective heat transfer coefficient.

221 The hygric boundary conditions were given by a convective mass transfer flux  $g_m$ , in which  $h_m$   
222 is the convective mass transfer coefficient.

$$g_m = h_m(p_{v,surf} - p_{v,air}) \quad (10)$$

223 The convective heat transfer coefficient was determined based on the air velocity  $v_{air}$  ( $\text{m}\cdot\text{s}^{-1}$ )  
224 using a correlation of NF EN 15026 (AFNOR, 2008). The convective mass transfer coefficient  
225 was established with the heat and mass transfer analogy used by the same reference.

226 The air velocity was measured in the bi-climatic chamber; the corresponding convective heat and  
227 mass transfer coefficients are given in Table 2.

228 Table 2: Convective heat and mass transfer coefficients

Cold chamber	Hot chamber
$v_{air} = 5.3 \text{ m}\cdot\text{s}^{-1}$	$v_{air} = 5.1 \text{ m}\cdot\text{s}^{-1}$
$h_c = 23.5 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$	$h_c = 22.85 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$
$h_m = 1.21 \cdot 10^{-7} \text{ (kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1})$ .	$h_m = 1.18 \cdot 10^{-7} \text{ (kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1})$ .

229

### 230 3.4 Numerical procedure

231 The model based on Eqs. (1)-(3) and Eqs. (6)-(8) was implemented in a FEM software, using the  
232 Partial Differential Equations module (COMSOL, 2017). The boundary conditions were set  
233 according to Eqs. (9) and (10): the air temperature and vapor pressure came from the  
234 measurement in the middle of the chamber (sensor 1 and 10, see Fig.3). A mesh sensitivity was  
235 performed this way: the maximum element size was set initially to 4 mm (corresponding to 114

236 elements) and divided by two one run after the other. We observed the temperature and the  
237 capillary pressure in the positions corresponding to the sensors shown in Fig.3. The error from  
238 one mesh to the other one was lower than 2.5% when the maximum element size was 0.25 mm  
239 which corresponded to 808 elements. We selected the case with the next step mesh refinement,  
240 i.e. with elements of maximum 0.125 mm leading to a mesh of 1600 elements.

241 At the interface between HC and air cavity, we considered temperature and capillary pressure  
242 continuity (Eqs. (11) and (12)).

$$T_{air} = T_{HC} \quad (11)$$

$$p_{c,air} = p_{c,HC} \quad (12)$$

243

## 244 **4 Results and Discussions**

### 245 **4.1 Moisture exchange potential**

246 The experimental results obtained in the presence of the vapor barriers are presented in Fig. 5  
247 together with the simulations results after 1, 12 hours and 90 hours. The temperature and vapor  
248 pressure measured at the start of the test were used as initial conditions in the numerical model.  
249 One hour after the right-hand side (hot) chamber temperature was increased to 45°C, a  
250 temperature profile typical to heat diffusion was measured within the wall. The conductive heat  
251 wave propagated towards the opposite side until a linear temperature profile was reached after  
252 about 90 hours.

253 The temperature gradient occurring on the right hand side of the wall comes with a vapor  
254 pressure gradient of the same sign. Because the two vapor barriers ensure that no moisture uptake  
255 happens from the climatic chambers, the vapor pressure increase in the material was due only to a  
256 moisture release from the bio-based material. The desorption of water molecules happened from  
257 right to left, and stopped after 90 hours as depicted by the horizontal vapor pressure profile.

258 The release of vapor was activated by the temperature gradient. The temperature profile was  
259 almost linear after 12 hours, while it took about 90 hours for the moisture to be released and the  
260 water vapor pressure profile to become horizontal. Once the temperature change stopped, the  
261 moisture gradient was a strong enough driving force to generate an additional release of vapor by  
262 the solid phase towards the left-hand side of the wall.

263 The numerical results reproduce the thermo-hygric behavior with a good accuracy. It is worth  
264 pointing out that the numerical temperature profile is the result of heat transfer by conduction  
265 through the wall combined to the latent heat contribution that accompanies the release of water  
266 molecules by the hemp-based matrix (see Eq. (2)). The scale analysis of heat and moisture  
267 transfer conducted in Seng et al. (2017) demonstrated that, for the range of temperature and  
268 humidity tested here, the third term in the right-hand side of the energy conservation was  
269 negligible.

270

271

Insert Figure 5

272



## 273 **4.2 Occupancy in winter conditions**

274 This situation corresponds to the presence of an occupant within the right-hand side (hot)  
275 chamber for 1 hour leading to a peak in RH while the ambient temperature remained constant.  
276 The cold chamber was maintained at 6 °C. Figure 6 shows the temperature and moisture  
277 measurements in time on the wall surface (hot chamber side) and within the wall. The ambient  
278 conditions (hot chamber) are shown in Fig. 6a, while Fig. 6b and c show the response at  
279 respectively about 3 cm (sensor 8) and about 6.5 cm (sensor 6) from the hot surface.

280 The vapor production happened a little bit before the start of the 3<sup>rd</sup> day of test. Because the  
281 ambient temperatures had been maintained constant on both sides of the wall, the latter was in  
282 thermal equilibrium when vapor started to be produced. Yet, Fig. 6b exhibits a temperature bump  
283 of about 1°C at 3 cm from the hot surface which cannot be attributed to the thermal conditions.  
284 Indeed, the adsorption of molecules of water vapor onto a hydrophilic surface comes with a heat  
285 released. The enthalpy of adsorption, which depends on the type of solid surface, generates a  
286 temperature increase detected by the sensors. Figure 6 indicates that this exothermic property of  
287 water molecules adsorption was well predicted by the numerical model. Moving deeper into the  
288 wall, the vapor pressure peak continued to appear but with a time lag: the increase in vapor  
289 pressure and temperature was detected by the sensor at 3cm in the wall as soon as vapor was  
290 produced in the hot chamber. A few centimeters deeper into the wall (sensor 6) a bump in vapor  
291 pressure and in temperature remains noticeable but more centered towards Day 3, while its  
292 amplitude decreased as the bio-based material kept adsorbing moisture. Consequently, as less  
293 vapor was adsorbed onto the surface of the hemp fibers, the resulting peak temperature also  
294 decreased. The numerical model describes coherently the thermos-hygric behavior even though  
295 the temperature evolution in time are 1 °C below the measured values.

296

297

Insert Figure 6

298

### 299 **4.3 Sinusoidal solicitations**

300 Sinusoidal temperature and moisture solicitations tests are yet another way to assess the dynamic  
301 behavior of the HC. The results presented in this section correspond to a moment when a steady  
302 periodic regime is established. As shown in Fig. 4c, the sinusoidal temperature in the left-hand  
303 side (cold) chamber had a period of 24 hours. The RH was set to slightly fluctuate around 80%.  
304 There was a small overall increase of RH along the 6 days of test, around 1% per cycle. The  
305 temperature in the hot chamber was maintained at 24°C, and maintained constant throughout the  
306 test which lasted one week. The RH was left free to vary in this chamber.

307 The measurements in the 2 chambers are plotted in Fig. 7 in terms of vapor pressure and  
308 temperature. Note that in the cold chamber the temperature peaks correspond as expected to the  
309 vapor pressure peaks (Fig. 7a). As shown in Fig. 7b, the vapor pressure change in the hot  
310 chamber also followed a sine wave in time, but with a much smaller amplitude than the one of the  
311 vapor pressure in the cold chamber. This amplitude remained unchanged over the course of the  
312 test, the vapor pressure ranging between 1000 and 1445 Pa. The RH corresponding to that  
313 evolution was between 34% and 48%. The period was also 24 hours. Moisture was absorbed by  
314 the wall, and its peak was detected in the opposite chamber about 4.3 hours after the moisture  
315 peak solicitation.

316 Figure 8 provides the temperature and vapor pressure changes in time at 3 different locations  
317 within the wall: in the vicinity of the left-hand side (cold) chamber where the ambient was  
318 controlled, at mid-distance within the wall, and in the vicinity of the hot chamber. In this figure,  
319 all the plain lines correspond to experimental results, while the dotted lines are for the numerical  
320 results.

321 The 3 sensors measured a steady periodic response of the temperature within the wall. The  
322 amplitude of the sine wave is higher in the vicinity of the cold side, and almost linear next to the  
323 opposite side where the ambient temperature was maintained constant.

324 Figure 8 shows how the sinusoidal variation in vapor pressure is transmitted from the cold side to  
325 the warm chamber. The vapor pressure flow goes from the cold side to the hot one, as a sine  
326 wave which amplitude decreases while approaching the hot chamber, as indicated by the  
327 experimental values. Because only the cold chamber was controlled in relative humidity, a wall  
328 made of a material with less hygroscopic properties would let the relative humidity in the hot  
329 chamber increase in time. In the case of a wall made of HC, part of the water vapor is trapped  
330 within the material and this moisture damping property explains the lower vapor pressure  
331 amplitude on the hot side.

332 Plotted in Fig. 8 are also the numerical results obtained for the simulation of the HC wall. Note  
333 the good agreement between the numerical results and the experimental ones. This final  
334 validation of the model allowed to consider with confidence the case of a classical wall made of a  
335 material with non-hygroscopic properties with the purpose of differentiating thermal and hygric  
336 behaviors.

337 To this sake, we chose to model a wall made of a classic plain concrete. Concrete has a thermal  
338 conductivity more than 10 times higher than the HC one, with a similar specific heat capacity. In  
339 addition to being more thermally conductive, a typical concrete is also much less hygroscopic.  
340 The concrete properties are provided in the EN 15026 norm (AFNOR, 2008). The initial and  
341 boundary conditions were identical to the ones used in the modelling of the experiment. The  
342 results corresponding to the simulation of the concrete wall were added to Fig. 8. The vapor  
343 pressure wave decreases in amplitude when moving from the cold chamber to the hot one. Yet  
344 the amplitude is larger than in the case of HC. The concrete wall clearly does not have the same  
345 damping property as the hemp-based wall. Figure 8 also highlights the lower moisture buffering  
346 capacity of concrete: its peak of vapor pressure is less delayed than for the HC, meaning that the  
347 moisture wave travels faster than for the hemp-based wall. As expected, the same result is  
348 obtained for heat transfer. Figure 8c shows that the thermal wave is still present in the case of the  
349 plain concrete wall in the vicinity of the hot chamber. These results highlight the potential of  
350 HC as a material suitable for thermal comfort: relatively to a classical concrete-based wall, the  
351 hemp-based wall is able to dampen moisture changes while demonstrating a good thermal  
352 insulation.

## 353 **5 Concluding remarks**

354 In this paper, the hygrothermal behavior of a wall made of precast HC blocks in a bi-climatic  
355 chamber was measured in different boundary conditions corresponding to realistic situations. The  
356 experimental data were compared to the numerical results obtained from a model based on FEM.  
357 The hygrothermal properties of the HC came from the works of Seng et al. (2019a, 2019b). The  
358 numerical model, once validated, was used as a comparison tool with a typical wall made of plain

359 concrete, in the case of a dynamic solicitation in temperature and vapor pressure on one side of  
360 the wall. The study highlighted:

- 361 - The potential for the hemp-based wall to release moisture under an applied temperature  
362 difference while water exchange with the ambient is prevented.
- 363 - The ability to adsorb a sudden peak of humidity from the ambient environment within a  
364 few hours,
- 365 - The capacity, unlike a concrete-based wall, to dampen a thermal and hygric sinusoidal  
366 solicitation, decreasing the moisture wave amplitude from one chamber to the other one,  
367 while delaying its travel through the wall.

368

369

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372

373 **Figures caption**

374 Figure 1 (a) HC block, (b) HC wall (built by Vu et al., 2015), and (c) wall instrumented  
375 with hygrothermal sensors.

376 Figure 2 Sorption and desorption isotherm of the HC at 23°C and 45°C, adapted from Seng  
377 et al. (2019b).

378 Figure 3 Hygrothermal sensors in the bi-climatic chamber: (a) side view of the bi-climatic  
379 chamber, (b) top view of the sensors installation.

380 Figure 4 The different experimental configurations: (a) the wall is coated with a vapor  
381 barrier on each side and submitted to a temperature difference between the 2  
382 ambiences, (b) 1 hour of vapor production in one chamber simulates the presence  
383 of an occupant indoor, the outside is meant to represent winter conditions, and (c)  
384 a sinusoidal temperature solicitation with constant RH in the cold chamber while  
385 the other chamber is maintained at constant temperature.

386 Figure 5 Temperature and vapor pressure distribution within the wall when the wall is  
387 coated by a vapor barrier on its both sides. (a) initial conditions, after (a) 1 hour,  
388 (b) 12h (b) and (c) 90 hours.

389 Figure 6 Temperature and vapor pressure evolution in time (a) in the hot chamber, (b) at 3  
390 cm and (c) at 6.5 cm from the hot side. The solicitation is meant to resemble the  
391 moisture production that an individual would produce during 1 hour of room  
392 occupancy. The plain lines are for the experimental results, while the dotted lines  
393 correspond to the experimental ones.

394 Figure 7 Temperature and vapor pressure changes in time in (a) the hot chamber and (b) the  
395 cold chamber when the cold side is submitted to sinusoidal temperature with ~  
396 constant RH and the hot side is simply maintained at constant temperature. The  
397 plain lines are for the experimental results, while the dotted lines correspond to the  
398 experimental ones.

399 Figure 8 Temperature and vapor pressure changes in time within the material at (a) 3 cm  
400 from the cold side, (b) mid wall thickness and (c) 6.5 cm from the hot side, when  
401 the boundary conditions are those of Fig. 7. The experimental curves are

402 completed by the numerical ones in the case of the HC wall and for a similar wall  
403 made of concrete. The plain lines are for the experimental results, while the dotted  
404 lines correspond to the experimental ones.

405

406

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Figure 1

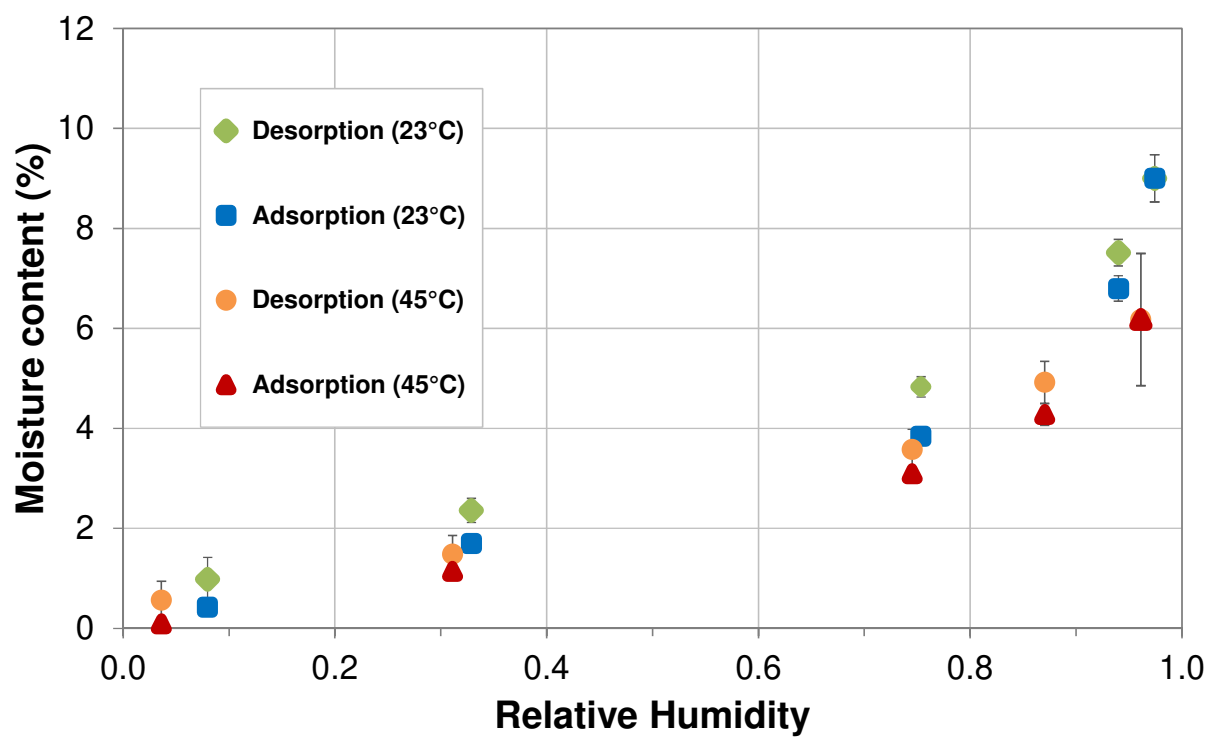


Figure 2

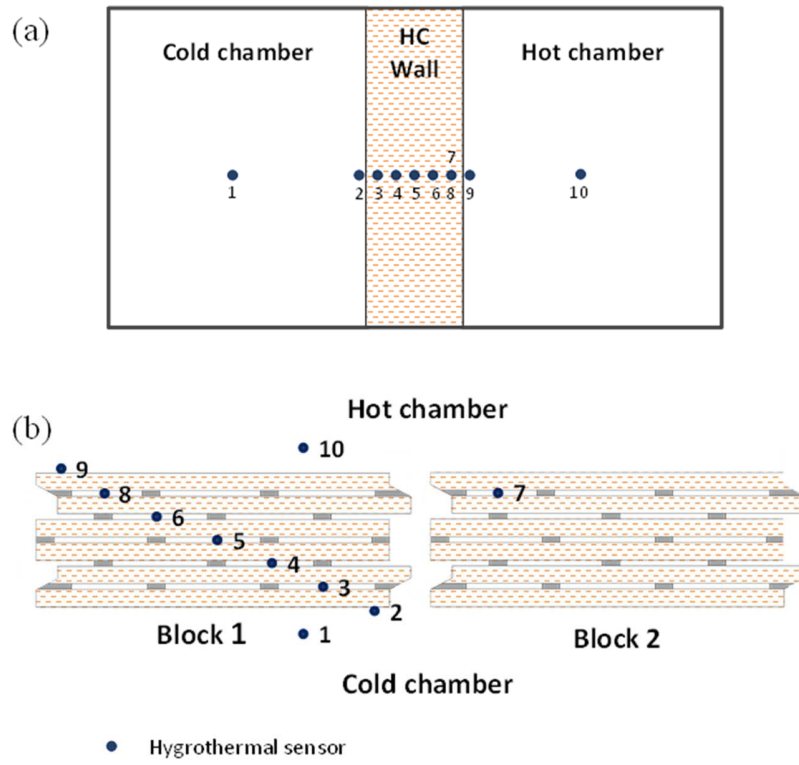
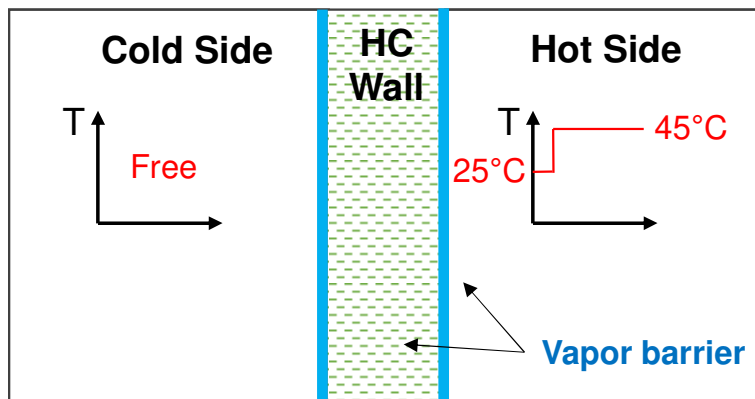
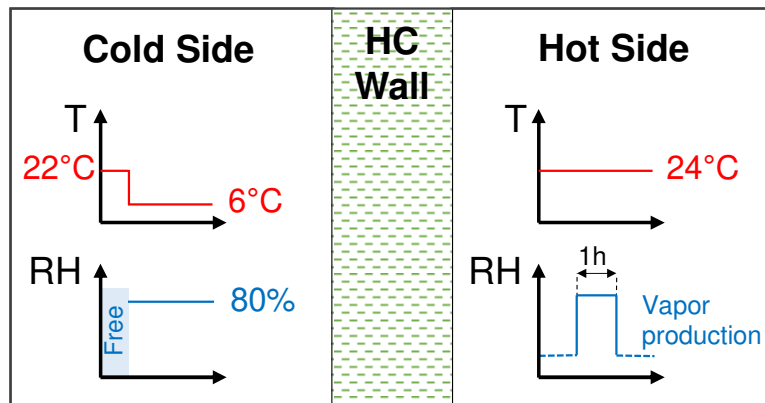


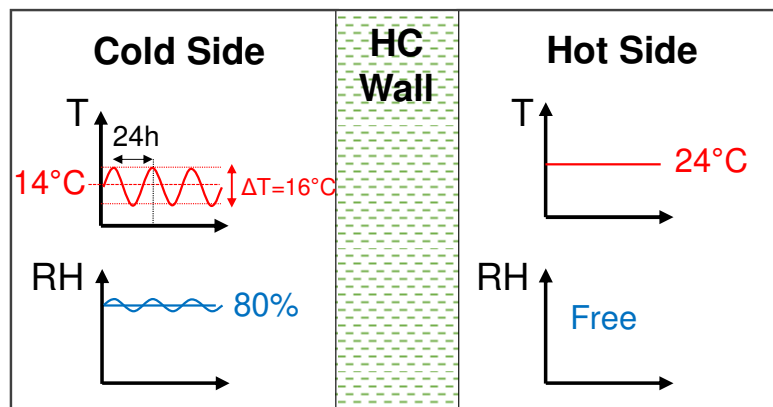
Figure 3



(a)



(b)



(c)

Figure 4

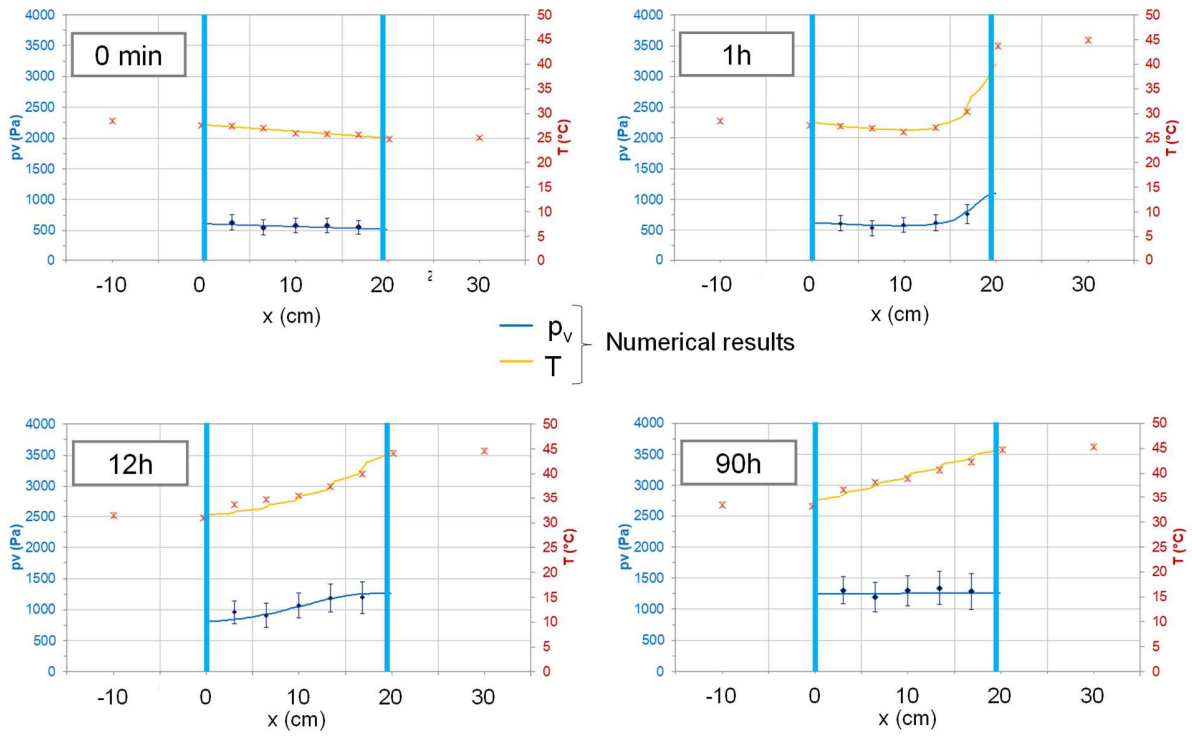


Figure 5

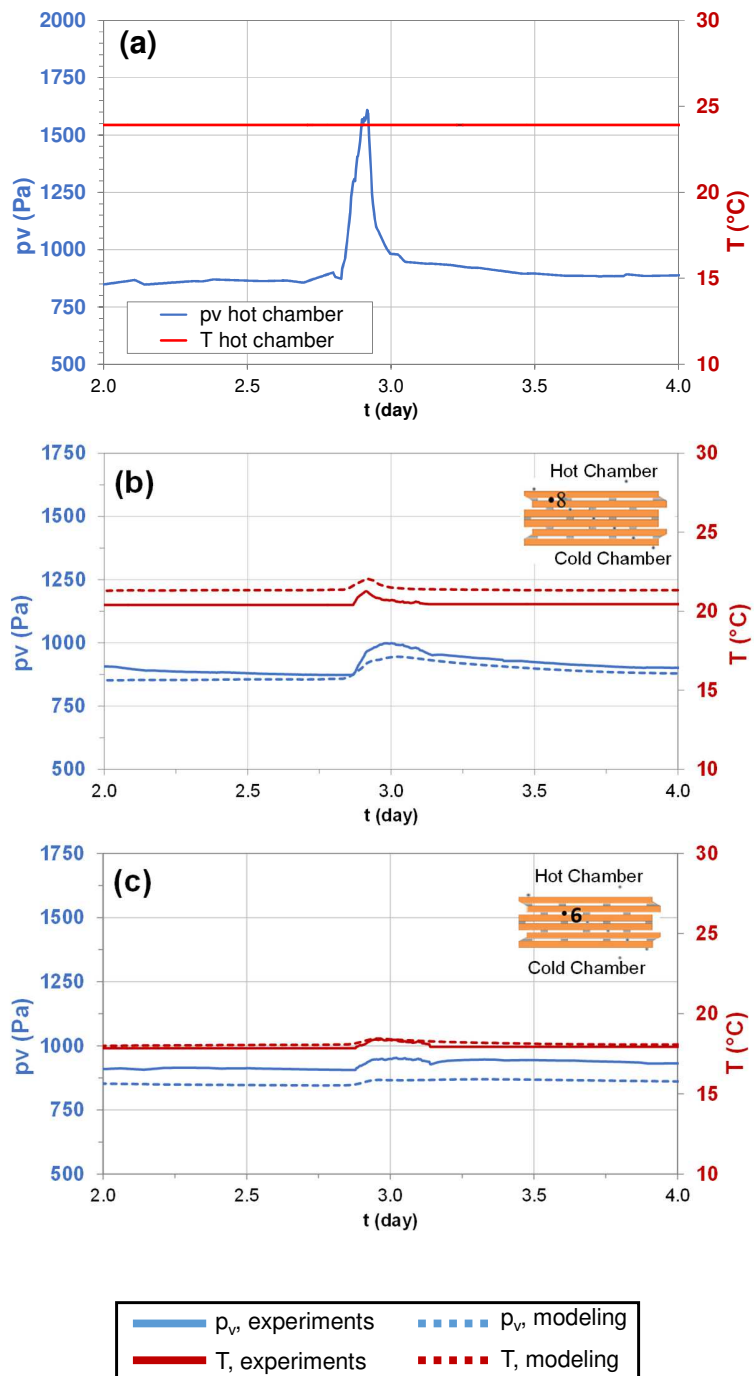


Figure 6

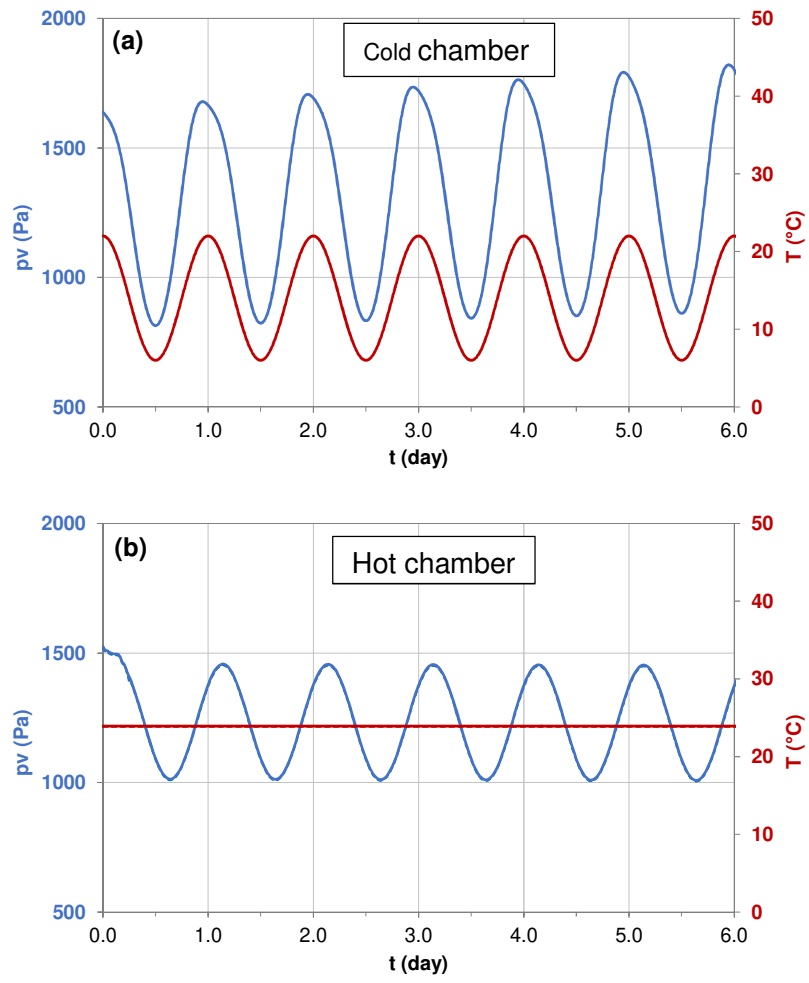


Figure 7



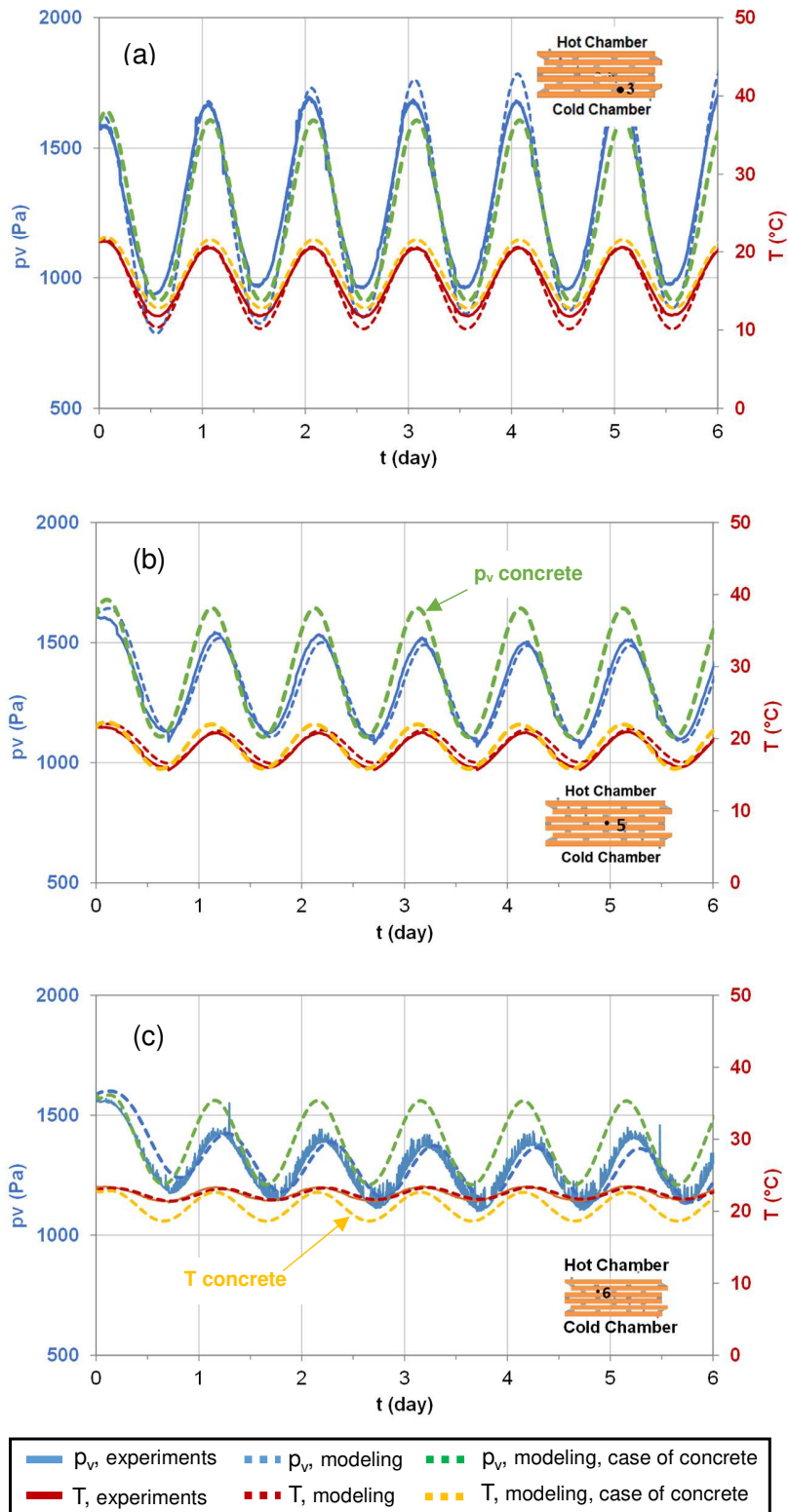


Figure 8