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# 1            **Dynamic hygrothermal behavior and energy performance** 2   **analysis of a novel multilayer building envelope based on PCM** 3            **and hemp concrete**

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## 13   **Abstract**

14            Phase change materials (PCMs) have high thermal inertia while hygroscopic materials have high  
15   hygric inertia. However, few studies have integrated the two materials and considered both  
16   hygrothermal behavior and energy performance. This study proposed a novel multilayer building  
17   envelope integrated by PCM and bio-based hygroscopic material (hemp concrete) to utilize the  
18   advantages of both materials. Four envelope configurations were experimental studied based on the  
19   presence and location of the PCM to study the effect of PCM and its location on the hygrothermal  
20   behavior and the energy performance of the integrated envelope. The results demonstrated the benefits

21 of PCM in reducing the temperature/relative humidity (T/RH) amplitude and energy consumption as  
22 well as delaying the peak T of the envelope. Placement of the PCM in the middle of the envelope was  
23 recommended, with the PCM kept in a partially melted state. Compared to the configuration without  
24 PCM, the T/RH amplitude and energy consumption were reduced by 50%/60% and 15.3%,  
25 respectively, and the peak T was delayed by 70.4%. The PCM placed on the outdoor side had the  
26 highest efficiency and energy participation, but it absorbed the most heat and was prone to overmelting.  
27 The envelope with PCM placed on the indoor side lost the benefit of regulating RH. This study  
28 provides a reference for multilayer envelopes composed of PCMs and hygroscopic materials and  
29 dedicated to T/RH regulation.

30

## 31 **Keywords**

32 Building envelope; Phase change material (PCM); Bio-based hygroscopic material; Hygrothermal  
33 behavior; Energy saving

34

## 35 **1. Introduction**

36 It is reported that building envelopes account for almost 50% of building energy consumption [1].  
37 Therefore, research on building envelopes helps save energy and reduce CO<sub>2</sub> emissions in the context  
38 of the global energy crisis and global warming [2]. Meanwhile, designers strive to achieve indoor  
39 hygrothermal comfort, which is mainly assessed by temperature (T) and relative humidity (RH) [3].  
40 Improper combinations of T and RH may adversely affect the occupants' health [4, 5] and increase the

41 risk of indoor mold growth [6, 7]. Therefore, the related characteristics of the building envelope are  
42 important for energy saving, environmental protection, and indoor comfort.

43 Bio-based materials are generally made from biologically renewable materials such as wood,  
44 hemp, straw, etc. [8, 9]. These materials have received a lot of attention in recent years thanks to their  
45 advantages. The renewable nature and low carbon emissions characteristic of bio-based materials are  
46 significant. They have a low carbon emission during manufacturing, installation, utilization,  
47 maintenance, and demolition [10, 11]. Some bio-based materials also have high porosity and low  
48 thermal conductivity, making them useful insulation materials for building envelopes. Liu et al. [12]  
49 reviewed the development history of bio-based materials as building insulation, and listed the four  
50 most popular bio-based materials: hemp, straw, flax, and wood. Moreover, the hygroscopic properties  
51 of bio-based materials can regulate the amount of water vapor in the air to maintain the RH balance [13,  
52 14], which is attributed to their porous structure. The hygroscopic properties have been proven to  
53 affect energy consumption and HVAC (heating, ventilation, and air conditioning) system design. For  
54 buildings with hygroscopic envelopes, the HVAC structure can be reduced by 13% [15], while cooling  
55 energy consumption can be reduced by 5–30% [16].

56 The hygrothermal properties of bio-based materials have been studied by many researchers  
57 hoping to integrate them into the building envelope. In a typical laboratory study of a given envelope,  
58 the materials were usually placed between a controlled climate chamber and the laboratory  
59 environment, or directly between two controlled climate chambers. Colinart et al. [17] compared the  
60 hygrothermal behavior of uncoated and coated hemp concrete walls by placing them between two  
61 climatic chambers. The results showed that the vapor pressure gradient was the main driving potential,

62 and that coatings could dampen heat and moisture transfer through the hemp concrete. Chennouf et al.  
63 [18] imitated indoor and outdoor environments using a passive shell and a climate chamber to study  
64 the hygrothermal behavior of date palm fiber concrete. The hygrothermal response showed the  
65 potential of utilizing the hygric inertia. Furthermore, the T dependence of hygric behavior has been  
66 noted and investigated [19, 20]. Rahim et al. [21] investigated the hygrothermal behavior of hemp and  
67 straw rape concrete, and found that the impact of T on RH within the material was more significant  
68 than the water vapor pressure gradient. They emphasized the importance of the T effect on sorption  
69 curves. Poyet et al. [22] proposed the theoretical background of the Clausius-Clapeyron equation and  
70 the isosteric heat of sorption to describe the impact of T on the sorption properties. This theory was  
71 confirmed by Colinart et al. [23, 24], who studied the RH variations in three bio-based materials. To  
72 sum up, the bio-based materials have hygric inertia to dampen the RH variation; it is significantly  
73 affected by T.

74 Integrating phase change materials (PCMs) into the building envelope is another promising  
75 technique. PCMs can store and release large amounts of latent heat during the phase change process,  
76 which makes them have high thermal inertia [25, 26]. As a building envelope, they can be used in  
77 different seasons, countries, and climates [27] to manage the thermal environment, improve the  
78 occupants' comfort, and save energy [28-30].

79 Consequently, bio-based hygroscopic materials have the advantage of hygroscopic properties, but  
80 their low density and low heat capacity make them low thermal inertia. On the other hand, PCMs have  
81 a large capacity for thermal energy storage and release, but they can only regulate thermal behavior but  
82 not hygric behavior. In previous research, the advantages of these two materials have always been

83 studied separately. Therefore, it would be meaningful and innovative to integrate the two types of  
84 materials and utilize their respective advantages. In this study, a common approach of envelope  
85 assembly, i.e., multilayer assembly, was used to integrate the two types of materials.

86 Multilayer integrating PCMs with porous materials such as gypsum [31], plaster [32], wood[33],  
87 and concrete [34] are the most widespread approach for latent heat energy storage in building elements.  
88 The location of PCM in the multilayer envelope has been proven to affect the thermal behavior of the  
89 envelope. Lee et al. [35] assessed a south and west wall by integrating a PCM at different locations,  
90 and found that the optimum location depended on the wall's orientation. Fateh et al. [36, 37] used a  
91 simulation method to study the thermal performance of a light wall with PCMs placed at different  
92 locations, and the optimum location in their test conditions was the middle. Likewise, Kishore et al.  
93 [38, 39] studied the optimum location in five U.S. cities, and the optimum location of PCMs was the  
94 middle of the envelope. Murathan et al. [40] evaluated the energy consumption when placing a PCM in  
95 different locations, and found that the envelope with the PCM placed between the middle and the  
96 outside consumes less energy. Li et al. [41] investigated the optimum PCM location by evaluating the  
97 heat flux, and the highest heat flux reduction was 47.6% when the PCM was placed close to the  
98 exterior. However, these studies mainly focused on thermal behavior and energy performance while  
99 ignoring hygric behavior, even though the porous materials (gypsum, plaster, wood, and concrete) that  
100 are part of the PCM multilayer envelope have been shown to have hygroscopic properties [42-45].  
101 Moreover, considering the T-dependent hygric behavior of hygroscopic material and the  
102 location-dependent thermal behavior of PCM, it can be inferred that the PCM location affects the  
103 hygric behavior of the envelope. However, this inference has not been studied or proven in the

104 previous literature. Therefore, it is necessary to explore the effect of PCM and its location on the  
105 thermal and hygric behavior as well as the energy performance of the integrated envelope.  
106 Furthermore, since buildings are constantly exposed to climatic variations, continuous dynamic  
107 boundary conditions should be considered for several days to access the hygrothermal dynamic of the  
108 envelope, not just transient from initial conditions to a partially state.

109 In this study, a novel multilayer building envelope integrated by bio-based hygroscopic material  
110 and PCM was proposed to simultaneously regulate T and RH and save energy of buildings. The  
111 bio-based hygroscopic material used in this paper was hemp concrete, whose hygroscopic properties  
112 have been shown to be superior to conventional materials such as gypsum, plaster, and common  
113 concrete [46]. The thermal and hygric behavior as well as energy performance of the integrated  
114 envelope were experimentally investigated under imitated dynamic outdoor conditions. Three  
115 envelope configurations with PCM placed in different locations were proposed and compared with the  
116 configuration without PCM to study the effect of PCM and its location on hygrothermal behavior and  
117 energy performance. Special attention was paid to the T/RH amplitude and time delay, especially in  
118 the case where the location within the envelope was close to the interior. The energy performance of  
119 the whole envelope and of the PCM layer was studied, the activation and energy storage/release  
120 efficiency of the PCM in different locations were analyzed.

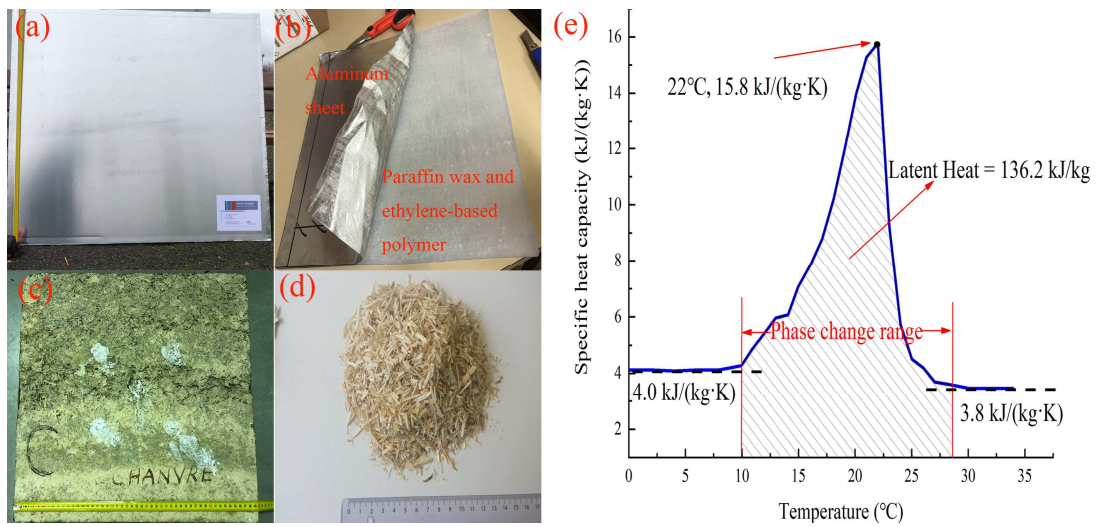
121

122 **2. Materials and methods**

123 **2.1. Materials and their properties**

124 The PCM panel [47] shown in Fig. 1(a, b) is a shape-stabilized PCM wrapped on both sides in an  
125 aluminum sheet with a thickness of 0.1 mm, preventing deformation and leakage during use. The main  
126 element producing the phase change is a mixture of 60% paraffin wax and 40% ethylene-based  
127 polymer. Fig. 1(e) shows the specific heat capacity of the PCM. It remains in the liquid-solid  
128 coexistence state during the phase change range from 10 to 28 °C, making its latent heat deduced as  
129 136.2 kJ/kg. The maximum specific heat capacity corresponds to a T of 22°C.

130



131

132 Fig. 1. (a) PCM panel; (b) Aluminum sheet and the mixture of paraffin wax and ethylene-based polymer; (c)

133

Hemp concrete; (d) Hemp shives; (e) Specific heat capacity of the PCM [47]

134

135 The bio-based material used in this study is hemp concrete (Fig. 1(c)). It was composed of water  
136 (24%), a lime-based binder (12%), and hemp shives (64%, (Fig. 1(d))). Table 1 lists the dimensions



137 and basic hygrothermal properties of the PCM and the hemp concrete.

138

	PCM [47]	Hemp concrete [48]
Dimensions (L × W) (cm)	50 × 50	50 × 50
Thickness (cm)	2.12	7
Density (kg/m <sup>3</sup> )	810	478
Thermal conductivity (W/(m·K))	Solid: 0.18; Liquid: 0.14	0.12
Specific heat capacity (kJ/(kg·K))	Solid: 4.0; Liquid: 3.8	1.08
Porosity (%)		76.44
Water vapor permeability (kg/(m·s·Pa))		$2.23 \times 10^{-11}$

139 Table 1. Dimensions and hygrothermal properties of the PCM and the hemp concrete

140

## 141 2.2. Experimental facilities

142 To set the boundary conditions, a climate chamber (LabEvent L C/64/40/3) was used. It runs with  
143 an accuracy of  $\pm 0.3$ – $1$  °C in a T range of  $-40$  to  $180$  °C and  $\pm 1$ – $3\%$  in an RH range of 10 to 95%. After  
144 the parameters are set, continuous humidification/dehumidification and heating/cooling take place  
145 automatically.

146 The sensors for measuring T and RH were thermocouples (K type) and HMP-110 sensors. The  
147 diameter of the thermocouples was 0.25 mm; they could measure a T range from  $-70$  to  $200$  °C with an  
148 accuracy of  $\pm 0.1$  °C. The HMP-110 sensors had an elongated cylindrical shape with a length of 71 mm

149 and a diameter of 12 mm. They were inserted into the hemp concrete layer from the lateral side to  
150 measure the T and RH simultaneously, and the measurement ranges of T and RH were from  $-40$  to  $80$  °C  
151 and from 0 to 100% with an accuracy of  $\pm 0.2$  °C ( $0-40$  °C) and  $\pm 1.5\%$  ( $0-90\%$ ), respectively. The heat  
152 flux was monitored with HFS sensors with dimensions of  $50\text{ mm} \times 50\text{ mm} \times 0.5\text{ mm}$ ; the measurement  
153 range was  $-2.0$  to  $2.0\text{ kW/m}^2$  with an accuracy of  $\pm 2\%$ .

154 The data acquisition system (Keithley 2700, with a resolution of 6.5 digits) was connected to a  
155 computer. All the data were collected and recorded automatically with time intervals of 120 seconds.

156

### 157 **2.3. Methodology**

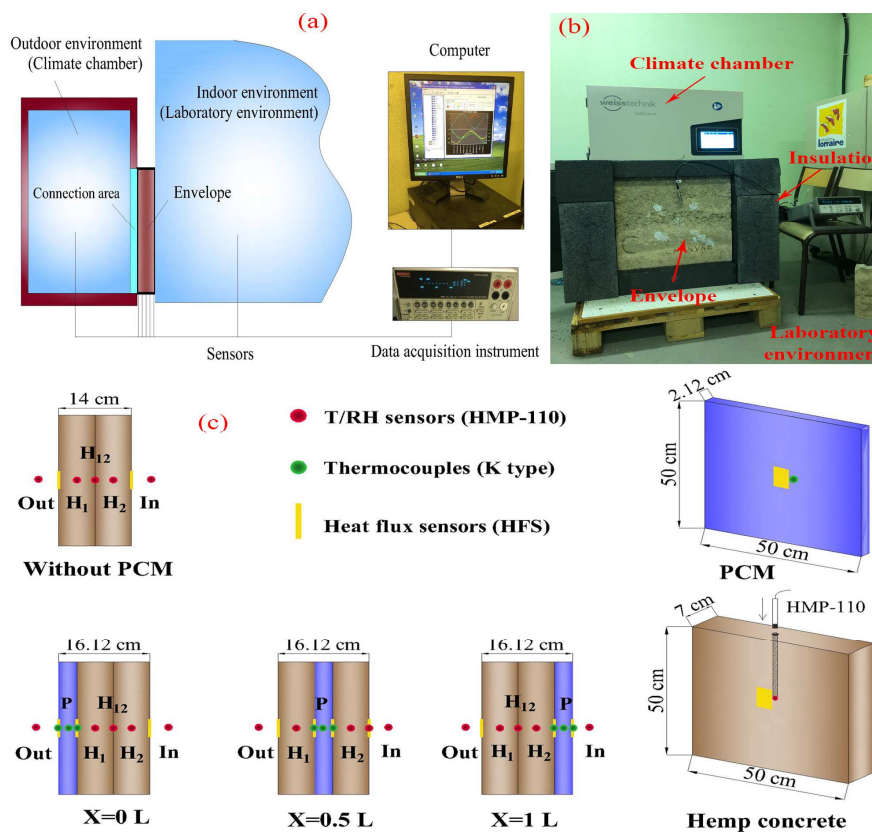
158 The overview schematic of the experiment is shown in Fig. 2(a). One side of the envelope was  
159 connected to a climate chamber to imitate the outdoor environment. The other side of the envelope was  
160 exposed to the laboratory environment with a relatively stable hygrothermal environment to imitate the  
161 indoor environment of a real building. Fig. 2(b) shows the actual experimental setup. To ensure  
162 thermal and moisture insulation in the transversal plan (perpendicular to the thickness), polystyrene  
163 foam and polyethylene film were wrapped around the lateral envelope sides.

164 The envelope elements consisted of one PCM layer and two hemp concrete layers. To explore the  
165 effect of PCM and its location on the hygrothermal behavior and the energy performance of the  
166 envelope, three integrated envelope configurations ( $X = 0\text{ L}$ ,  $X = 0.5\text{ L}$ , and  $X = 1\text{ L}$ ) with PCM placed  
167 in different locations were proposed to compare with a configuration without PCM. They were given  
168 the following names and descriptions (Fig. 2(c)):

- 169 1. Configuration without PCM: Two hemp concrete layers without PCM;  
 170 2. Configuration  $X = 0 L$ : PCM was placed on the outdoor side (climate chamber), and  $L$   
 171 denotes the total thickness of the two hemp concrete layers;  
 172 3. Configuration  $X = 0.5 L$ : PCM was placed between the two hemp concrete layers;  
 173 4. Configuration  $X = 1 L$ : PCM was placed on the indoor side (laboratory environment).

174 It should be noted that the transferability of heat/moisture or the accuracy of results were not  
 175 affected when two hemp concrete layers are in direct contact (configuration without PCM,  $X = 0 L$ ,  
 176 and  $X = 1 L$ ), because the  $T$  and  $RH$  were constant on the interface of the two hemp concretes [49-51].

177



178

179

180

Fig. 2. (a) Diagram of the experimental setup; (b) Actual experimental setup; (c) Four envelope configurations

181

182 The main measurement points are also shown in Fig. 2(c), their names are given below :

- 183 • Out: outdoor environment (climate chamber)
- 184 • In: indoor environment (laboratory environment)
- 185 • H<sub>1</sub>: middle of the first hemp concrete layer
- 186 • H<sub>12</sub>: between the two hemp concrete layers
- 187 • H<sub>2</sub>: middle of the second hemp concrete layer
- 188 • P: middle of the PCM layer

189 Furthermore, some heat flux sensors were affixed on each side of the PCM and the whole  
190 envelope.

191 Fig. 3 shows the fluctuations of T and RH provided by the climate chamber (outdoor). Due to the  
192 large phase change range of the PCM as shown in Fig. 1(e), a large diurnal T range of 15 to 40 °C (e.g.,  
193 summer climate of Ruoqiang, China) was chosen to better observe the T and RH fluctuations at  
194 different locations within the hemp concrete. The overall T range contains five smaller T ranges to  
195 represent various weather conditions: cool (15–20 °C), temperate (20–25 °C), warm (25–30 °C), hot  
196 (30–35 °C), and very hot (35–40 °C) [52]. On the one hand, the large T range helps to observe the  
197 feedback of the envelope to cold T, very hot T, and the T between them. On the other hand, if the  
198 integrated envelope is shown to be applicable over a large T range, it is also applicable over a small T  
199 range. The RH was set to a range of 25% to 95%, which represented the variation centered on a  
200 comfortable level (60%) and fluctuating between extremely dry (25%) and humid (95%) conditions.  
201 The combination of T and RH represented dynamic boundary conditions in the outdoor environment

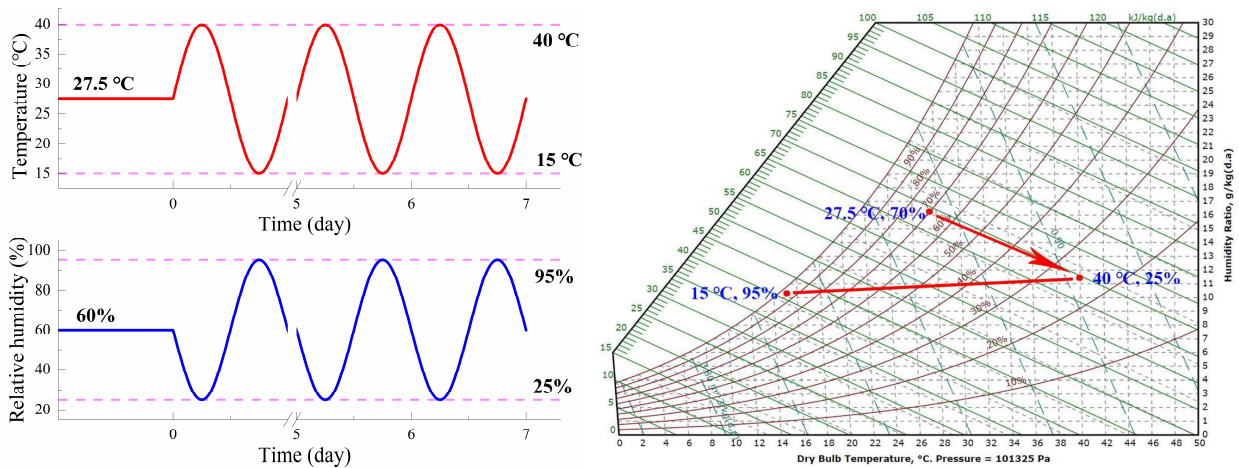
202 with a wide T/RH range but little vapor pressure fluctuations. In the beginning, the T and RH were held  
 203 at 27.5 °C and 70% for two days until stabilization. Then the T and RH evolved periodically for seven  
 204 days according to the sinusoidal function with time (day) as the variable:

205 
$$T = 27.5 + 12.5\sin\left(\frac{\pi}{12}t\right)$$

206 
$$RH = 60 - 35\sin\left(\frac{\pi}{12}t\right)$$

207 As for the hygrothermal conditions in the laboratory environment (indoor), they were relatively  
 208 stable during the experiment, with a T of  $21.4 \pm 0.7$  °C and RH of  $45.2 \pm 5.1\%$ . Thus, one side of the  
 209 envelope was exposed to a dynamic condition, while the other side faced a relatively stable condition.

210



211

212

Fig. 3. Imposed oscillating outdoor boundary conditions

213

### 214 3. Results and discussion

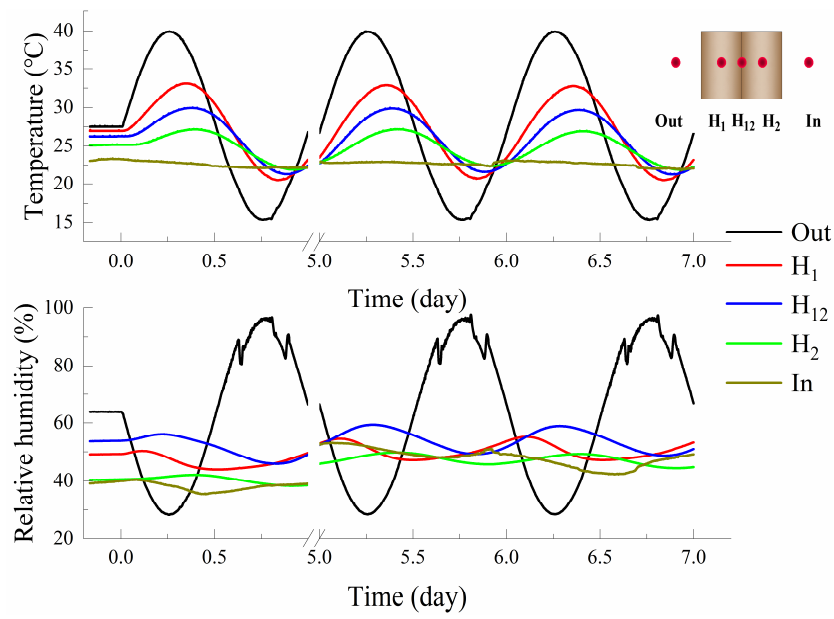
#### 215 3.1. Hygrothermal behavior of the configuration without PCM

216 Fig. 4 represents the hygrothermal behavior of the configuration without PCM, which had  
 217 unrestricted transfer of heat and moisture on each side of the envelope. For the boundary conditions,

218 the  $T_{out}$  and  $RH_{out}$  (T and RH in the outdoor environment, i.e., in the climate chamber) evolved well  
 219 and matched the set values. In the laboratory environment, the T and RH remained relatively stable.  
 220 The  $T_{hemp}$  and  $RH_{hemp}$  (T and RH within the hemp concrete, i.e., at  $H_1$ ,  $H_{12}$ , and  $H_2$ ) kept a steady state  
 221 4 h (0.17 days) before the start of the dynamic change, and their respective standard deviations were  
 222 below 0.03 °C and 0.05%, respectively.

223  $T_{hemp}$  was mainly affected by the  $T_{out}$ . The T amplitudes at points  $H_1$ ,  $H_{12}$ , and  $H_2$  decreased  
 224 sequentially, with values of 6.1, 4.2, and 2.4 °C, respectively. There was a response time delay between  
 225 the outdoor environment and the envelope, with average time delays of 2.1, 3.0, and 3.7 h at points  $H_1$ ,  
 226  $H_{12}$ , and  $H_2$ , respectively.

227



228

229 Fig. 4. Hygrothermal behavior of the configuration without PCM

230

231 Compared to the  $T_{hemp}$ , the  $RH_{hemp}$  variation was more complex, which can be inferred from the  
 232  $RH_{hemp}$  at  $H_1$  and  $H_{12}$ . Both the overall value (45.5–52.7%) and the amplitude (3.6%) of  $RH_{hemp}$  at  $H_1$

233 were lower than those at  $H_{12}$  (48–58.1% and 5.1%). These phenomena were caused by the  
234 superposition effect within the hemp concrete.

235 Before explanation, the two effects caused by boundary conditions T and RH were introduced. In  
236 previous similar studies, the boundary T/RH of the envelope was set almost as static or from one static  
237 to another [17-20]. Few studies [21] have covered the dynamic boundary T/RH. Generally, the effect  
238 of one parameter (T or RH) on the RH variation within the materials can be analyzed under  
239 static-to-static boundary conditions while keeping the other parameter constant. Using this method,  
240 Chennouf et al. [18] and Colinart et al. [17] investigated the effect of boundary RH and T on the RH  
241 variation within the material, respectively.

242 Specifically, in this study, the increase of  $T_{out}$  led to the instantaneous moisture evaporation within  
243 the hemp concrete, which led to the increase of the  $RH_{hemp}$ . Conversely, the decrease in  $T_{out}$  led to  
244 moisture condensation and a decrease in the  $RH_{hemp}$ . On the other hand, the increase in  $RH_{out}$  led to  
245 moisture diffusion from the outdoors to the envelope, and therefore increased the  $RH_{hemp}$ . Conversely,  
246 the decrease in  $RH_{out}$  caused the evacuation of the vapor out of the hemp concrete and decreased the  
247  $RH_{hemp}$ . Thus, the dynamically opposite variations of boundary  $T_{out}$  and  $RH_{out}$  had opposite transient  
248 effects on  $RH_{hemp}$  variation. As for different points, the effect of  $RH_{out}$  was strong at points close to the  
249 outdoors ( $H_1$ ) but weak at points far away from the outdoors ( $H_{12}$  and  $H_2$ ), which can be inferred from  
250 two aspects. First, the overall values and amplitudes of  $RH_{hemp}$  at  $H_1$  were smaller than that of  $H_{12}$ .  
251 Because the decreased/increased  $RH_{out}$  inhibited the increase/decrease of  $RH_{hemp}$  caused by the  
252 increased/decreased  $T_{out}$ . Second, the time difference between peak/valley  $RH_{hemp}$  and peak/valley  
253  $T_{hemp}$  was longer at point  $H_1$  than that of point  $H_{12}$  and  $H_2$ , and the longer time difference implied

254 stronger competition between the effects of  $RH_{out}$  and  $T_{out}$ . At point  $H_1$ , the peak  $RH_{hemp}$  appeared 6.3  
255 h earlier than the peak  $T_{hemp}$ . In contrast, at points  $H_{12}$  and  $H_2$ , the corresponding values were 1.9 and  
256 0.03 h, respectively. Therefore,  $RH_{hemp}$  variations at point  $H_1$  were affected by the superposition effect  
257 of T and RH, while at point  $H_{12}$  and especially  $H_2$ ,  $RH_{hemp}$  variations were mainly affected by T.

258 Rahim et al. [21] have reported similar  $T_{hemp}/RH_{hemp}$  variation in the middle of the envelope and  
259 close to the outdoors (corresponding to  $H_{12}$  and  $H_1$  in this paper, respectively). However, the points  
260 close to the indoor side ( $H_{12}$  and especially  $H_2$ ) are the main interest to us, because their T/RH behavior  
261 influences indoor hygrothermal comfort. Therefore, the T/RH behavior of  $H_{12}$  and  $H_2$  will be the focus  
262 of the following sections.

263

## 264 **3.2. Hygrothermal behavior of the configurations with PCM**

### 265 **3.2.1. PCM placed on the outdoor side ( $X = 0$ L)**

266 Fig. 5 shows the hygrothermal behavior of the configuration  $X = 0$  L. The standard deviations of T  
267 and RH in hemp concrete and PCM were below  $0.06$  °C and  $0.09\%$  during 4 h preceding the start of the  
268 dynamic change, indicating that the dynamic change started from a steady state. Importantly, the PCM  
269 was impermeable to moisture, meaning that there was no moisture transfer from the outdoor side to the  
270 envelope, but the moisture transfer between the envelope and the indoor environment was not affected.  
271 As for heat transfer, it can occur through any material.

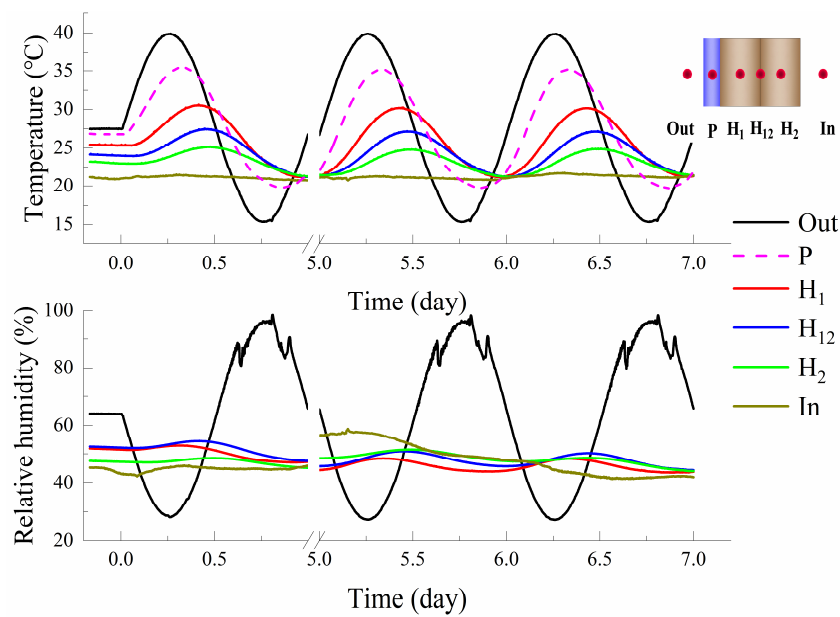
272 Regarding the T variation, the T amplitude was smaller and the time delay was longer than in the  
273 configuration without PCM. At  $H_1$ ,  $H_{12}$ , and  $H_2$ , the T amplitudes were reduced by 1.6, 1.2, and 0.4 °C,



274 and the time delays were extended by 2.4, 2.4, and 2.1 h, respectively, because PCM damped the heat  
275 transfer between the hemp concrete and the outdoor side.

276 For the RH, the amplitudes at  $H_{12}$  and  $H_2$  were 2.9 and 1.9%, which was 2.2 and 0.1% less than in  
277 the configuration without PCM. As mentioned above, the RH at  $H_{12}$  and  $H_2$  was mainly influenced by  
278 T variation, so their RH amplitudes decreased with the reduction of the T amplitude.

279



280

281

Fig. 5. Hygrothermal behavior of the configuration  $X = 0$  L

282

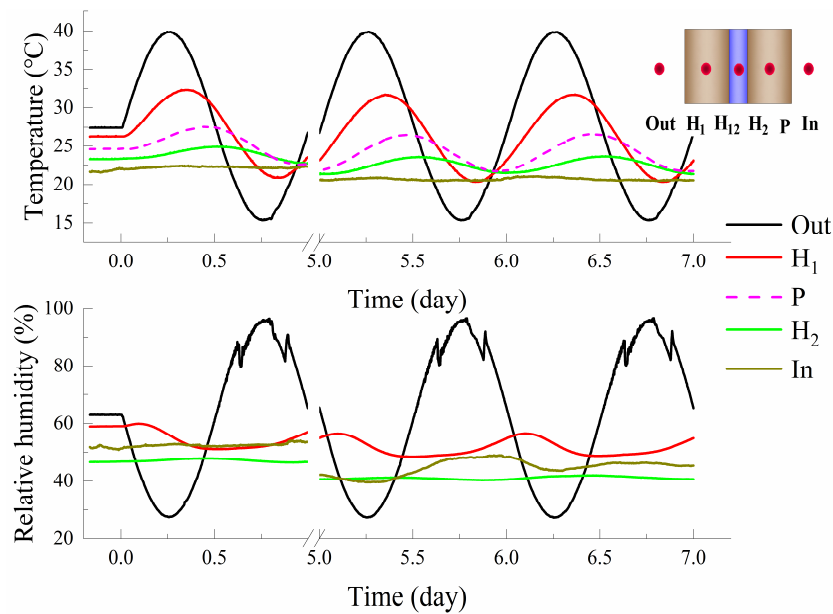
### 283 3.2.2. PCM placed between two hemp concrete layers ( $X = 0.5$ L)

284 The PCM was placed between the two hemp concrete layers in this configuration, and the  
285 heat/moisture transfer could occur on both sides of the envelope. In Fig. 6, the T amplitudes at  $H_1$  and  
286  $H_2$  were 5.7 and 2.1 °C, respectively, both smaller than in the configuration without PCM. However,  
287 the amplitude at  $H_1$  was reduced by only 6.5%, while at  $H_2$  it was as high as 50%, because the PCM's

288 thermal inertia had a greater effect on H<sub>2</sub>. Likewise, the time delay at H<sub>2</sub> was more noticeable, which is  
 289 extended by 2.3 h compared to the configuration without PCM.

290 Due to the effect of T amplitude, the RH at H<sub>2</sub> was significantly reduced, from 2.0 to 0.8%  
 291 compared to the configuration without PCM.

292



293

294 Fig. 6. Hygrothermal behavior of the configuration X = 0.5 L

295

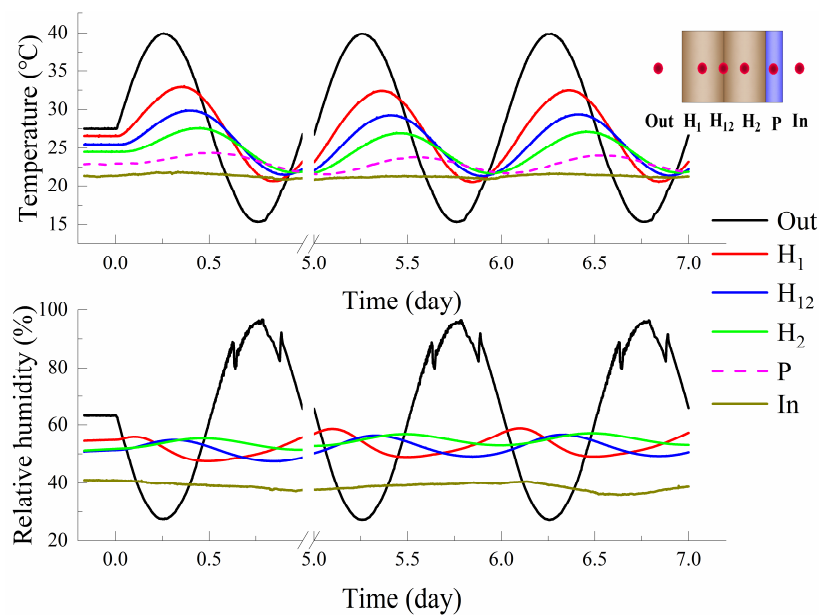
### 296 3.2.3. PCM placed on the indoor side (X = 1 L)

297 The T/RH behavior of configuration X = 1 L is shown in Fig. 7, with only heat transfer and no  
 298 moisture transfer occurred on the indoor side. The T amplitudes at H<sub>1</sub> and H<sub>12</sub> were slightly smaller  
 299 (0.1–0.2 °C) than in the configuration without PCM. Since there was little heat transfer between the  
 300 indoor environment and the PCM, the PCM thermal inertia had little effect on the T distribution at H<sub>1</sub>  
 301 and H<sub>12</sub>. Inversely, the amplitude at H<sub>2</sub> was 0.1 °C higher than in the configuration without PCM,

302 which was caused by the thermal accumulation at H<sub>2</sub>. Although there was little change in T amplitude  
 303 compared to the configuration without PCM, time delays were still extended by 0.3, 0.7, and 1.2 h at  
 304 points H<sub>1</sub>, H<sub>12</sub>, and H<sub>2</sub>.

305 Compared with configuration without PCM, the RH amplitude was lower at H<sub>12</sub> (3.7%), and  
 306 slightly higher at H<sub>2</sub> (2.1%) because the PCM's impermeability caused moisture to accumulate around  
 307 H<sub>2</sub>. Therefore, the configuration X = 1 L should be avoided in practice because the moisture transfer  
 308 between the envelope and the indoor environment was completely blocked by the PCM. However, in  
 309 this study, this configuration was considered for comparison and as a reference for T/RH and energy  
 310 analysis.

311



312

313

Fig. 7. Hygrothermal behavior of the configuration X = 1 L

314

315 **3.3. Summary of T/RH amplitudes and time delay**

316 Fig. 8(a) shows the mean daily T and RH amplitudes at H<sub>1</sub>, H<sub>12</sub>, and H<sub>2</sub> in the different  
317 configurations. Due to the superposition effect at H<sub>1</sub>, the magnitude order of RH and T amplitude at  
318 different configurations was not consistent. However, for points H<sub>12</sub> and H<sub>2</sub>, higher T amplitudes  
319 meant higher RH amplitudes.

320 To reduce indoor T/RH fluctuations, the T/RH amplitudes should ideally be low in the layer  
321 closest to the indoor environment. Therefore, configuration X = 0.5 L was optimal, with the smallest T  
322 and RH amplitudes (1.2 °C and 0.8%, respectively) at H<sub>2</sub>, which were 50% and 60% less than in the  
323 configuration without PCM (2.4 °C and 2.0%). Furthermore, compared with the outdoor T and RH  
324 amplitudes, the reduction was as high as 90.4% and 97.7%, respectively, ensuring indoor hygrothermal  
325 comfort under a wide range of outdoor T/RH fluctuations.

326

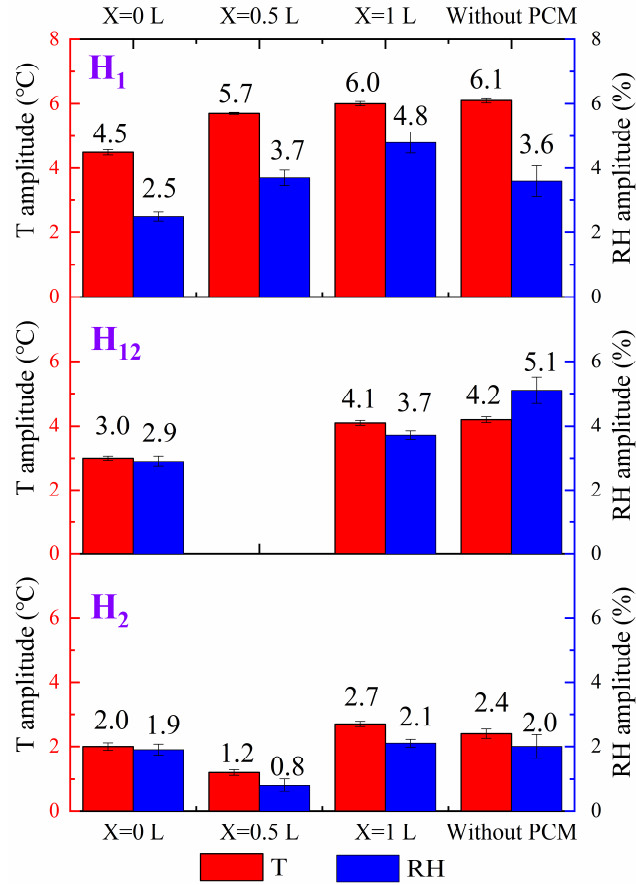


Fig. 8. T and RH amplitudes of hemp concrete in different configurations

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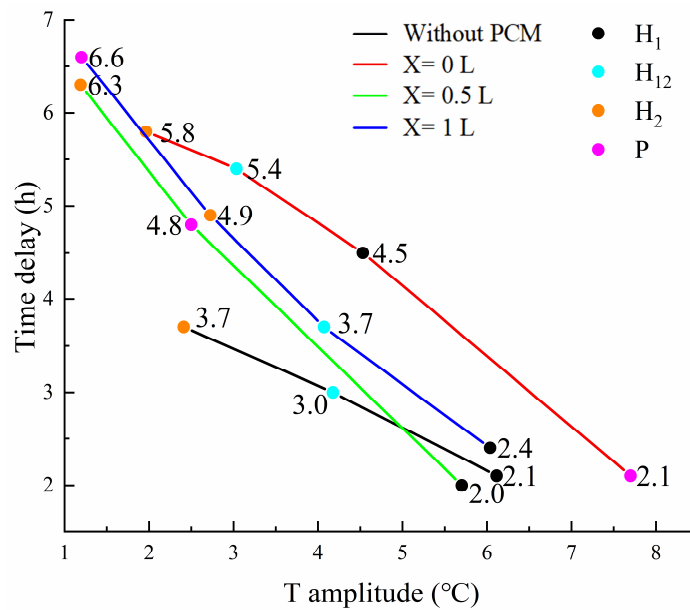
336

337

Fig. 9 presents the relationship between the T amplitude and time delay. The time delay decreased almost linearly as the T amplitude increased from the outdoor side to the indoor side, reflecting the decay in T fluctuation over time. Both parameters were affected by the PCM, but the effect was different on the two sides of the PCM. Compared to the configuration without PCM, the T amplitude was reduced significantly at points between the PCM and the indoor side (H<sub>1</sub>, H<sub>12</sub>, and H<sub>2</sub> of configuration X = 0 L— reduced by 26.2%, 28.6%, and 16.7%; H<sub>2</sub> of configuration X = 0.5 L— reduced by as much as 50%). In contrast, for points between the PCM and the outdoor side (H<sub>1</sub> of configuration X = 0.5 L; H<sub>1</sub> and H<sub>12</sub> of configuration X = 1 L), the reduction was less than 6.5%.

338 Similarly, the time delays at points between the PCM and the indoor side were extended by 56.8% to  
 339 114.3% compared to the configuration without PCM. But on the other side, the time delay was  
 340 extended by less than 35%. Thus, the PCM had a significant effect on the T amplitude and time delay at  
 341 points between the PCM and the indoor side, which explains the small T/RH amplitude at H<sub>2</sub> for the  
 342 configuration X = 0.5 L.

343



344

345

Fig. 9. T amplitude and time delay at different configurations and measurement points

346

347 It is worth noting that the closest layers to the indoor environment for configuration X = 1 L and X  
 348 = 0.5 L (PCM layer and second concrete layer, respectively) had the smallest T amplitudes (1.2 °C for  
 349 both) and almost the longest time delays (6.6 and 6.3 h, which were 78.4% and 70.3% longer than the  
 350 configuration without PCM, respectively). In real buildings, these behaviors would have provided  
 351 thermal comfort and shifted peak electricity demand. However, due to the moisture impermeability of  
 352 the PCM positioned between the envelope and the indoor environment, the configuration X = 1 L

353 should be avoided. Therefore, configuration  $X = 0.5 L$  was considerable in terms of T/RH amplitude  
354 and time delay.

355

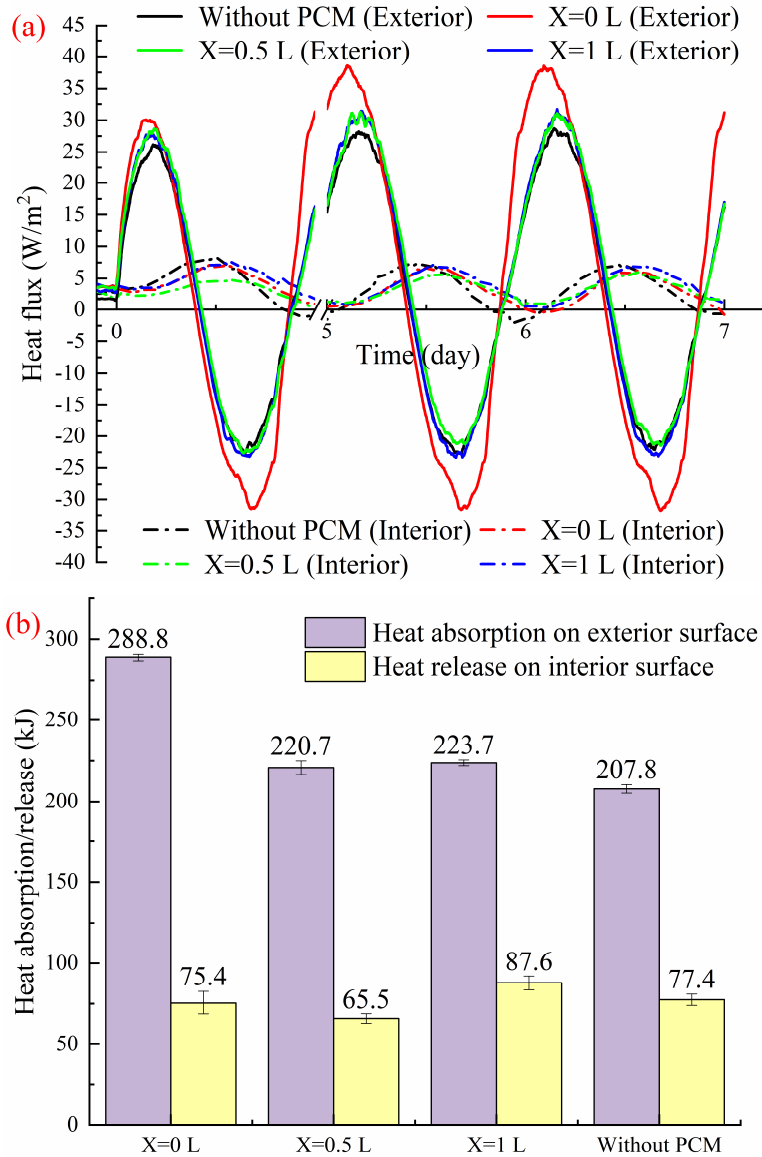
### 356 **3.4. Heat flux and released/absorbed heat on the interior/exterior surface**

357 Fig. 10(a) shows the heat flux on the interior and exterior surface of the envelope. On the interior  
358 surface, the configuration without PCM showed negative values for 6 h per day, indicating that the  
359 envelope released heat into the indoor environment for 18 h of the day. In comparison, the remaining  
360 configurations released heat for almost 24 h. For the heat flux amplitudes, the configuration without  
361 PCM was high because of the low thermal inertia. With the presence of PCM, the thermal inertia of the  
362 envelope was significantly improved, and the heat flux fluctuation was reduced. Configuration  $X = 0.5$   
363 L had the smallest amplitude at  $4.4 \text{ W/m}^2$ , which was 53.7%, 36.2%, and 36.2% less than configuration  
364 without PCM,  $X = 0 L$ , and  $X = 1 L$ .

365 As for the exterior surface, the heat flux fluctuation of configuration  $X = 0 L$  was the highest,  
366 indicating a great potential to absorb/release energy. Configurations  $X = 0.5 L$  and  $X = 1 L$  had similar  
367 fluctuations and were slightly higher than the configuration without PCM.

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Fig. 10. (a) Heat flux on the exterior/interior surface; (b) Heat absorption/release on the exterior/interior surface

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374

In order to calculate the released heat on the interior surface and the absorbed heat on the exterior,

375

the calculation was implemented using the following formula:

376

$$Q = \int_{t_1}^{t_2} q A dt$$

377

where Q is the absorbed/released heat (J); t is time (s); t<sub>1</sub>, t<sub>2</sub> are the start and the end time for the



378 calculation (s);  $q$  is the heat flux on both surfaces ( $\text{W}/\text{m}^2$ ); and  $A$  is the transversal envelope area ( $\text{m}^2$ ).  
379 It is noted that this formula can be applied to any material, whether the interior/exterior material is  
380 PCM or hemp concrete.

381 Fig. 10(b) summarizes the daily released heat on the interior surface and the absorbed heat on the  
382 exterior surface. The heat released on the interior surface represents a part of the building cooling load  
383 and affects the building's energy consumption. The released heat of the configuration without PCM  
384 was 77.4 kJ, which was higher than that of the configurations  $X = 0$  L and  $X = 0.5$  L. That is to say, the  
385 configuration without PCM released more heat in 18 h than the configurations  $X = 0$  L and  $X = 0.5$  L  
386 did in 24 h, which indirectly demonstrated the energy-saving potential of the PCM. For the  
387 configurations with PCM, their released heat changed in a non-linear manner as the PCM's location  
388 changed from the outdoor to the indoor side. Configuration  $X = 0.5$  L released the least heat at 65.5 kJ,  
389 which was 13.1, 25.2, and 15.3% less than the configurations  $X = 0$  L,  $X = 1$  L, and without PCM,  
390 respectively. Therefore, the placement of the PCM in the middle of the envelope is promising based on  
391 its energy-saving potential.

392 As for the absorbed heat on the exterior surface, the heat of configuration  $X = 0$  L (288.8 kJ) was  
393 significantly higher than those of the other configurations. The heat absorption of configurations  $X =$   
394  $0.5$  L and  $X = 1$  L (220.7 and 223.7 kJ) was almost the same and slightly higher than the configuration  
395 without PCM (207.8 kJ). Therefore, the configuration with the PCM directly exposed to the outdoor  
396 environment adsorbed the most heat due to its higher thermal inertia, while the remaining three  
397 configurations with hemp concrete facing the outdoor environment adsorbed almost identical amounts  
398 of heat.

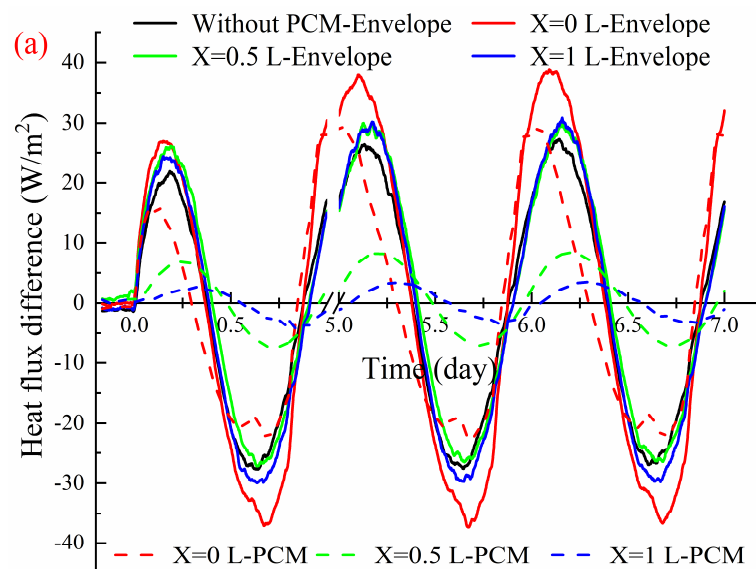
399

### 400 3.5 Energy storage/release by the whole envelope and the PCM

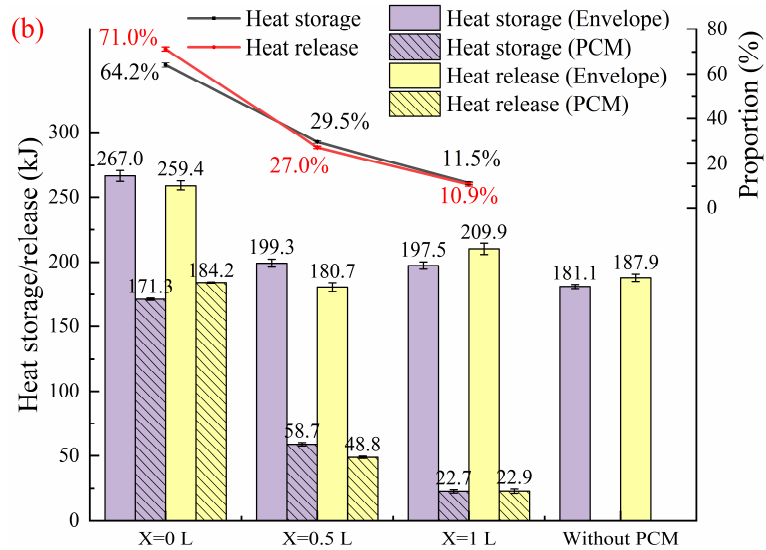
401 The heat flux difference on both sides of the envelope/PCM is plotted in Fig. 11(a). The  
402 configuration  $X = 0$  L has the highest fluctuations for both the envelope and the PCM, indicating a high  
403 energy storage/release potential. The daily energy storage/release by the envelope/PCM is plotted in  
404 Fig. 11(b). For the envelope, the energy storage/release was very similar for the configurations  $X = 0.5$   
405 L,  $X = 1$  L, and without PCM, while the configuration  $X = 0$  L had the highest value. For the PCM, the  
406 energy storage/release capacity decreased significantly as the PCM moved away from the outdoor side.  
407 This trend is consistent with the proportion of energy storage/release by the PCM (on the right axis),  
408 which showed a linear downward trend from configuration  $X = 0$  L to  $X = 0.5$  L to  $X = 1$  L. Therefore,  
409 when PCM was placed closer to the outdoor side, it had a greater role in participating the thermal  
410 energy management in the envelope.

411

412



413



414

415

Fig. 11. (a) Heat flux difference of the envelope and the PCM; (b) Energy storage/release and the

416

proportion of the PCM

417

418

As mentioned earlier, the absorbed heat on the exterior surface of the configuration  $X = 0 L$  was

419

the highest, while the other three configurations were similar to each other (see Fig. 10(c)). The

420

released heat on the exterior surface also followed this pattern (204.8, 140.4, 136.6, and 147.3 kJ for

421

configurations  $X = 0 L$ , without PCM,  $X = 0.5 L$ , and  $X = 1 L$ , respectively). Therefore, when the PCM

422

was placed on the outdoor side and interacted with the outdoor environment directly, the envelope and

423

PCM tended to store/release more energy, and the energy participation of the PCM in the envelope was

424

high. In contrast, when the PCM was far away from the outdoor side, the thermal interaction between

425

the PCM and the outdoor environment was damped by one or two hemp concrete layers, which

426

reduced the stored/released energy and the PCM's energy participation.

427

### 428 3.6 PCM activation and storage/release efficiency

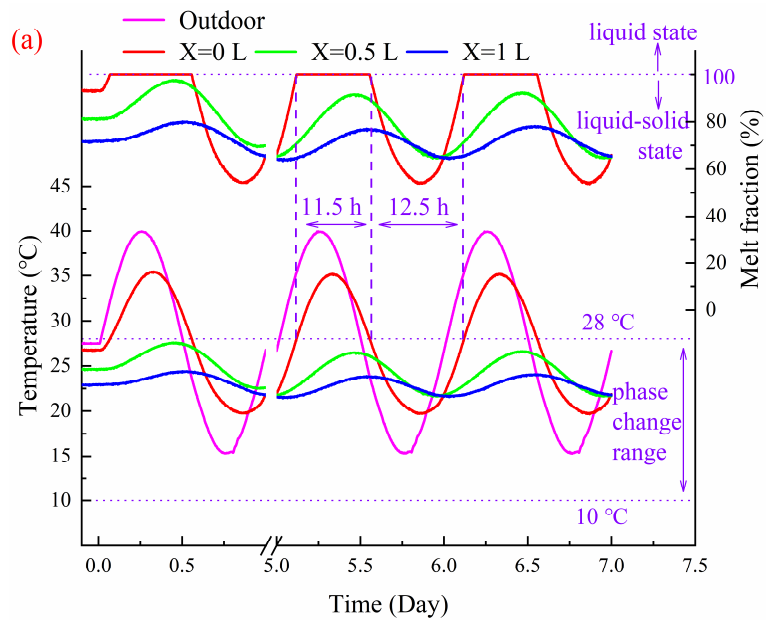
429 This section discussed the PCM utilization, including its activation and energy efficiency. The  
430 melt fraction ( $f$ ) represents the percentage of the activated (melted) PCM that has undergone the phase  
431 change. The PCM's storage/release efficiency ( $\eta$ ) allows an assessment of how much latent heat has  
432 been utilized. The two equations for calculating the melt fraction and energy efficiency of PCM were  
433 expressed as:

$$434 \quad f = \frac{T - T_s}{T_f - T_s}$$
$$435 \quad \eta = \frac{E_{st}}{L} = \frac{\int_{t_s}^{t_f} \Delta q A dt}{\int_{T_s}^{T_f} m C_p dT}$$

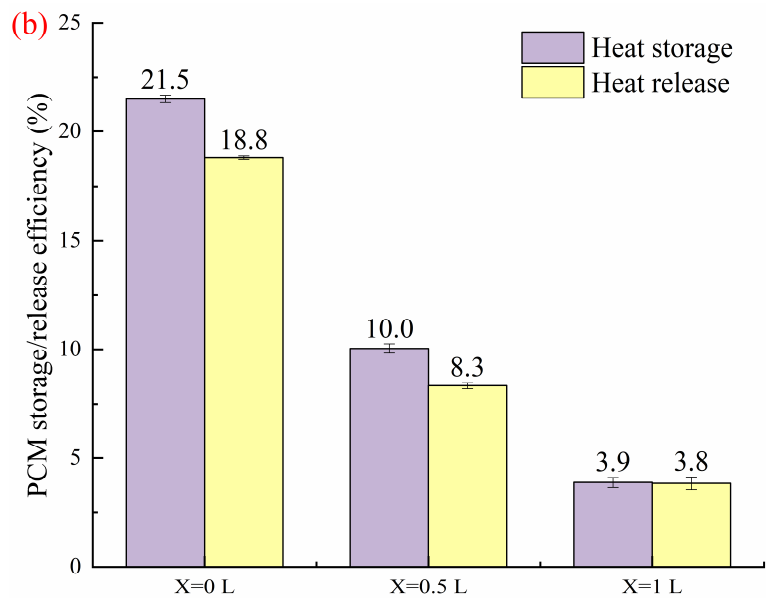
436 where  $T$  is the mean T of the PCM ( $^{\circ}\text{C}$ );  $T_s, T_f$  are the initial and final T of melting ( $^{\circ}\text{C}$ );  $E_{st}$  is the  
437 actual latent thermal energy stored/released by the PCM (J/kg);  $L$  the PCM's total latent thermal  
438 energy (J/kg);  $t_f, t_s$  are the start and end time for the calculation (s);  $\Delta q$  is the heat flux difference  
439 between the inflow and outflow of the PCM ( $\text{W}/\text{m}^2$ );  $A$  the transversal envelope area ( $\text{m}^2$ );  $m$  is the  
440 mass of the PCM (kg); and  $C_p$  is the specific heat capacity of the PCM ( $\text{J}/(\text{kg}\cdot\text{K})$ ).

441 The middle T of the PCM (point P) is considered the mean T of the PCM and is shown on the  
442 left axis of Fig. 12(a). On the right axis, the corresponding melt fraction is plotted. Since the phase  
443 change T ranges from 10 to 28  $^{\circ}\text{C}$ , the mean T of the configurations  $X = 0.5$  and  $X = 1$  L both lie  
444 within the phase change range. Their corresponding melt fractions were below 100% (80.1–97.7%  
445 and 64.8–69.2%, respectively), indicating that the PCM was partially melted and the configurations  $X$   
446 = 0.5 L was more activated. Under the circumstances, phase change continued throughout the  
447 experiment period and energy was stored/released only in the latent heat mode. For the configuration

448 X = 0 L, the PCM's melt fraction was equal to 100% for almost half the day (11.5 h), implying that it  
 449 remained in the liquid state and the energy storage/release was mainly taking place by the sensible heat  
 450 mode during this period. For the remaining 12.5 h, with the melt fraction below 100%, the PCM was  
 451 in a liquid-solid coexistence state and the energy storage/release was in latent heat mode.  
 452



453



454

455

Fig. 12. (a) PCM's mean T and melt fraction; (b) PCM's storage/release efficiency

456

457 The PCM's daily storage/release efficiency is plotted in Fig. 12(b). It is notable that these values  
458 were significantly lower than the melt fraction due to the non-uniformity between the specific heat  
459 capacity and T. Furthermore, the PCM storage/release efficiency in this study was not high: the highest  
460 value was only 21.5%. This is because its value is affected by several factors, such as the convective  
461 heat transfer coefficient, boundary T, and peak melt T [53-56]. Since the experiment was done with the  
462 given boundary conditions, PCM, etc., the efficiency could not reach its optimal value. Nevertheless,  
463 this study concerns the relationship between the PCM's efficiency and its location in the envelope. For  
464 the values, the highest PCM storage/release efficiency was 21.5%/18.8%, which was 2.2/2.3 and  
465 5.7/4.9 times higher than the configurations X = 0.5 L and 1 L, respectively. It should be remembered  
466 that the efficiency of configuration X=0 L was only generated for about half of the day (latent heat  
467 mode for 12.5 h, see Fig. 12(a)). Hence, when located close to the outdoor side, the PCM was more  
468 likely to be activated and had a higher efficiency.

469 However, although the PCM had a high efficiency when it was exposed to the outdoor  
470 environment directly (configuration X=0 L), it was liable to overactivation (overmelting, 11.5 h a day),  
471 which may increase the risk of leakage [57, 58]. The configuration X = 0.5 L is preferable because the  
472 PCM was kept in a partially melted state throughout the experimental period. Besides, the PCM's  
473 efficiency was more than twice as high as that of configuration X = 1 L for the same heat absorption on  
474 the exterior surface.

475

### 476 3.7 Discussion

477 Most of the prior studies related to PCM multilayer envelopes in the literature [35-41] focused on  
478 thermal behavior and energy performance. However, the hygric behavior of the envelope was ignored  
479 in these studies, even though porous materials (e.g., gypsum, plaster, wood, and concrete) that are part  
480 of the PCM multilayer envelope have been proven to have hygroscopic properties [42-45]. In Sections  
481 3.2 and 3.3, the RH amplitude was given special attention in addition to T amplitude and time delay.  
482 The RH amplitudes at H<sub>2</sub> for configurations X=0 L and X=0.5 L were 1.9% and 0.8%, respectively,  
483 both lower than the configuration without PCM of 2.0%. The configuration X=0.5 L absorbed/released  
484 less heat from the outdoors (see Fig. 10) and the heat transfer to H<sub>2</sub> was damped by the PCM (high  
485 melted but not overmelted, see Fig. 12), which was the reason for the smaller T/RH amplitude at H<sub>2</sub>  
486 than the configuration X=0 L. Therefore, both configurations, especially the configuration X=0.5 L,  
487 were indicated to ensure not only low indoor T amplitude, low energy consumption, and long peak T  
488 delay, as mentioned in [35-41], but also the low indoor RH amplitude as proved in this study.

489 In addition, in previous experimental studies related to the hygrothermal behavior of the  
490 hygroscopic materials, static or static-to-static boundary conditions [17-20] were often implemented,  
491 and dynamic boundary conditions [21] were rarely used. In the study [21] using sinusoidal boundary  
492 conditions, the T and RH amplitudes in the middle of hemp concrete were reduced by 63% and 80%,  
493 respectively, compared to the outdoors. In this paper, the reductions were further increased with the  
494 addition of PCM. The T and RH amplitude reductions at the corresponding location (point H<sub>12</sub>) for the  
495 configuration X = 0 L were 76% and 92%, respectively, compared to the outdoors (see Fig. 5 and Fig.  
496 8). The results were satisfactory as expected because of the damping effect of the PCM on outdoor heat

497 and the leading role of T on RH.

498 Furthermore, when evaluating the optimal PCM location for the PCM multilayer envelope,  
499 thermal behavior [35, 41] and energy performance [36, 38-40] were often used as evaluation metrics in  
500 prior studies. However, the findings of this paper recommended that the hygric properties of the  
501 envelope also need to be considered. Also, the T behavior should be the main focus because of the  
502 variation/amplitude consistency of T and RH at H<sub>2</sub> (see Fig. 8). On the other hand, determining the  
503 optimal PCM location is complex because it also depends on the thermal properties of the PCM  
504 (thickness, latent heat, phase transition interval, etc.) and the boundary environmental conditions [58],  
505 in addition to the evaluation metrics. This is the reason that the optimal PCM location varies in  
506 different literature [35-41]. However, this study focused more on the interaction between PCM and  
507 hygroscopic material and the effect of PCM and its location on the hygric behavior of the hygroscopic  
508 material. Therefore, a further recommendation can be applied to any type of PCM multilayer envelope  
509 integrated by a PCM and a hygroscopic material. The reduction of T and RH amplitudes can be  
510 achieved simultaneously by optimizing the location or thermal properties of the PCM.

511

#### 512 **4. Conclusion**

513 In this study, PCM and hemp concrete were integrated into a novel multilayer building envelope  
514 that enables simultaneous T/RH regulation and energy savings. Three configurations with PCM placed  
515 in different locations were experimentally compared with a configuration without PCM to study the  
516 effect of PCM and its location on the hygrothermal behavior and energy performance of the envelope.



517 The primary conclusions and recommendations can be drawn as follows:

518 T plays a dominant role in affecting the RH variation at locations close to the indoor side. Since  
519 the moisture-buffering capacity of hemp concrete increases as T decreases, the presence of the PCM  
520 damped the T fluctuation, which increased the moisture retention capacity and reduced the RH  
521 fluctuation of the hemp concrete. Besides, the PCM's location affected the hygrothermal behavior and  
522 energy performance of the integrated envelope.

523 When the PCM was placed on the outdoor side, it had the highest energy participation  
524 (64.2%/71.0%) and storage/release efficiency (21.5%/18.8%) during the energy storage/release  
525 process. However, the PCM absorbed more heat from the outdoors than in other configurations,  
526 causing the overmelting of the PCM (11.5 h) and the high T/RH amplitude of the envelope.

527 PCM placed on the indoor side improved the thermal behavior of the envelope as it resulted in the  
528 smallest T fluctuation and the longest peak T delay at locations close to the indoor side. However, the  
529 PCM hindered the hemp concrete's ability to regulate the indoor RH.

530 The placement of the PCM in the middle of the envelope was recommended. The PCM was kept  
531 in a partially melted state with a high melt fraction of 80.1–97.7%, which resulted in the smallest  
532 indoor T/RH amplitude and the greatest energy savings. Compared to the configuration without PCM,  
533 the T/RH amplitude was reduced by 50%/60% and the peak T was delayed by 70.3% at locations close  
534 to the indoor side. Also, the energy consumption was reduced by 15.3%.

535 The current work is a start, and future study aims to explore the performance of the integrated  
536 envelope with PCM placed at more locations under different climates by numerical approach.

537

538 **CRedit authorship contribution statement**

539 **Dongxia Wu:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis,  
540 Writing - original draft. **Mourad Rahim:** Conceptualization, Methodology, Investigation, Formal  
541 analysis, Writing - review & editing. **Mohammed El Ganaoui:** Supervision, Project administration,  
542 Conceptualization, Methodology, Formal analysis, Writing - review & editing. **Rachid Bennacer:**  
543 Conceptualization, Methodology, Formal analysis, Writing - review & editing. **Rabah Djedjig:**  
544 Methodology, Review & editing. **Bin Liu:** Methodology, Review & editing

545

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550

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554

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