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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**

4
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12
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 CO₂ 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.

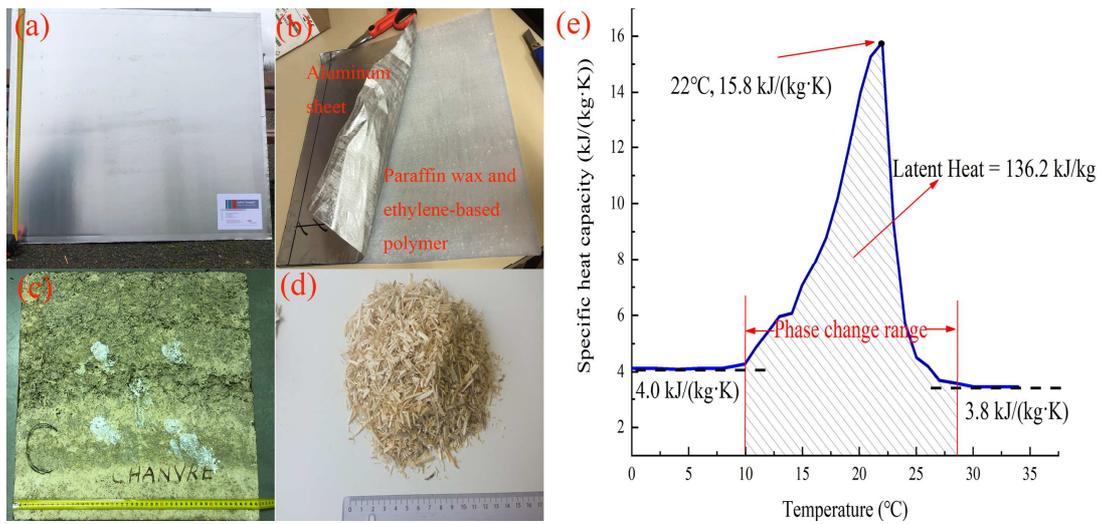
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122 **2. Materials and methods**

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 ³)	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))		2.23×10^{-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 ± 0.3 – 1 °C in a T range of -40 to 180 °C and ± 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 ± 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 ± 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 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**

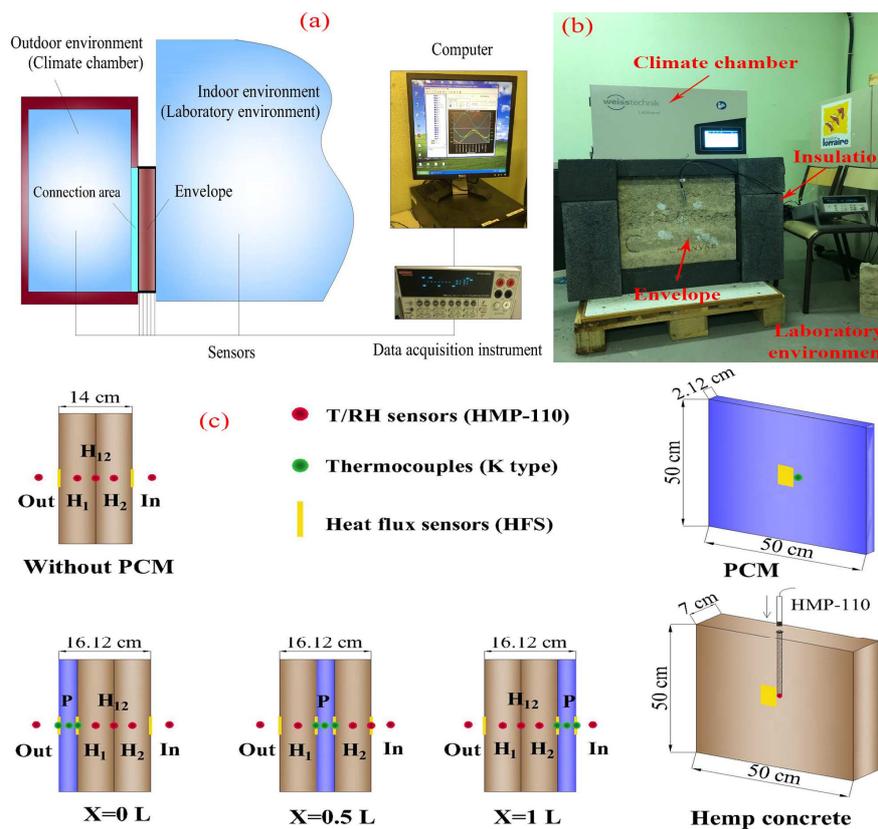
158 The overview schematic of the experiment is shown in Fig. 2(a). One side of the envelope was
159 connected to a climate chamber to imitate the outdoor environment. The other side of the envelope was
160 exposed to the laboratory environment with a relatively stable hygrothermal environment to imitate 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 • H₁: middle of the first hemp concrete layer
- 186 • H₁₂: between the two hemp concrete layers
- 187 • H₂: 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

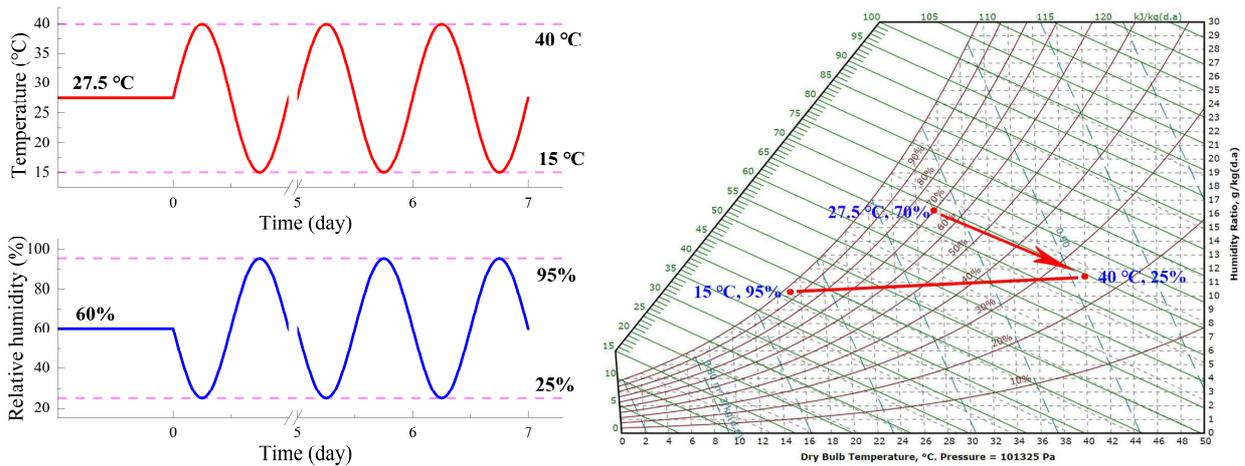
202 with a wide T/RH range but little vapor pressure fluctuations. In the beginning, the T and RH were held
 203 at 27.5 °C and 70% for two days until stabilization. Then the T and RH evolved periodically for seven
 204 days according to the sinusoidal function with time (day) as the variable:

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 ± 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

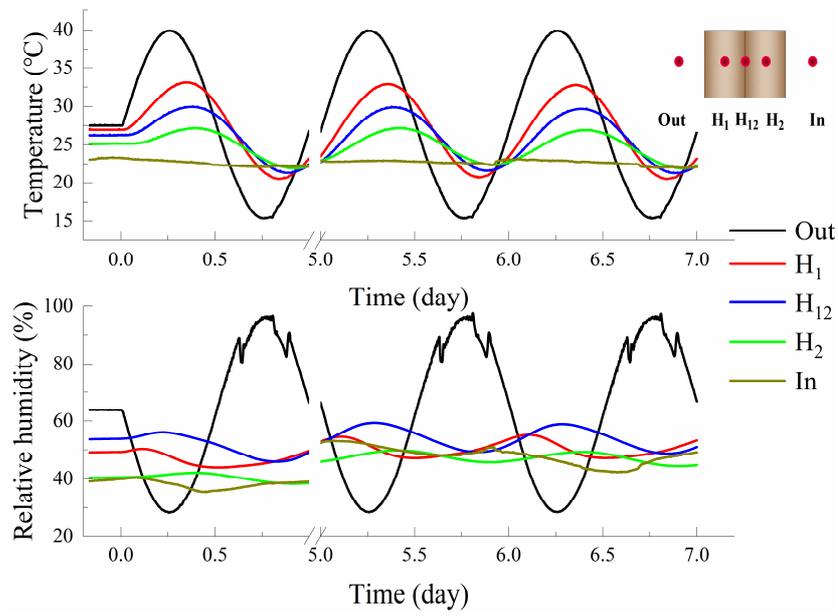
215 3.1. Hygrothermal behavior of the configuration without PCM

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)**

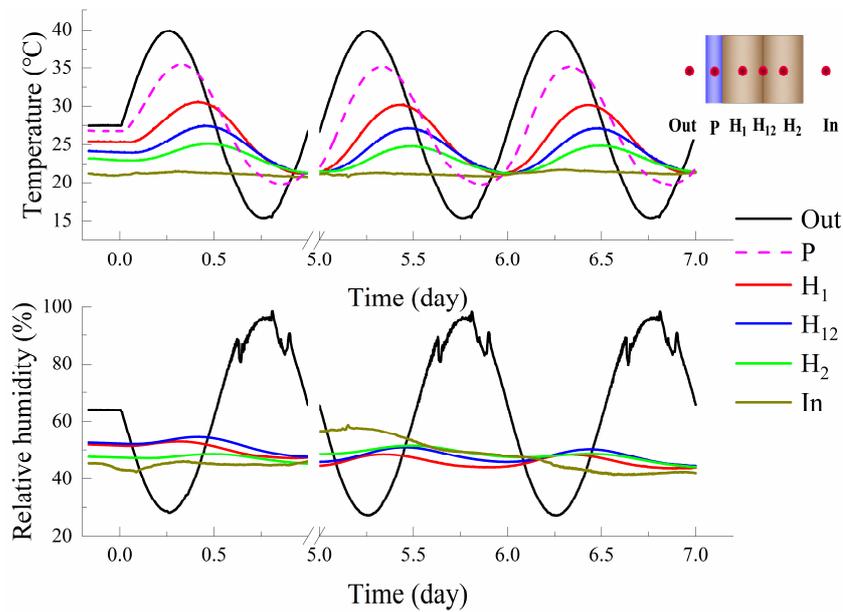
266 Fig. 5 shows the hygrothermal behavior of the configuration $X = 0$ L. The standard deviations of T
267 and RH in hemp concrete and PCM were below 0.06 °C and 0.09% during 4 h preceding the start of the
268 dynamic change, indicating that the dynamic change started from a steady state. Importantly, 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

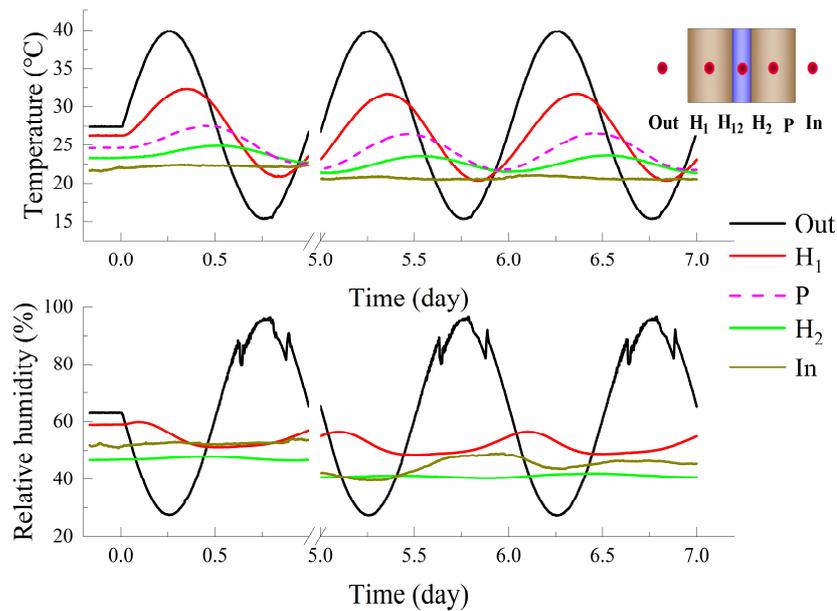
283 3.2.2. PCM placed between two hemp concrete layers ($X = 0.5$ L)

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_2 . Likewise, the time delay at H_2 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_2 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

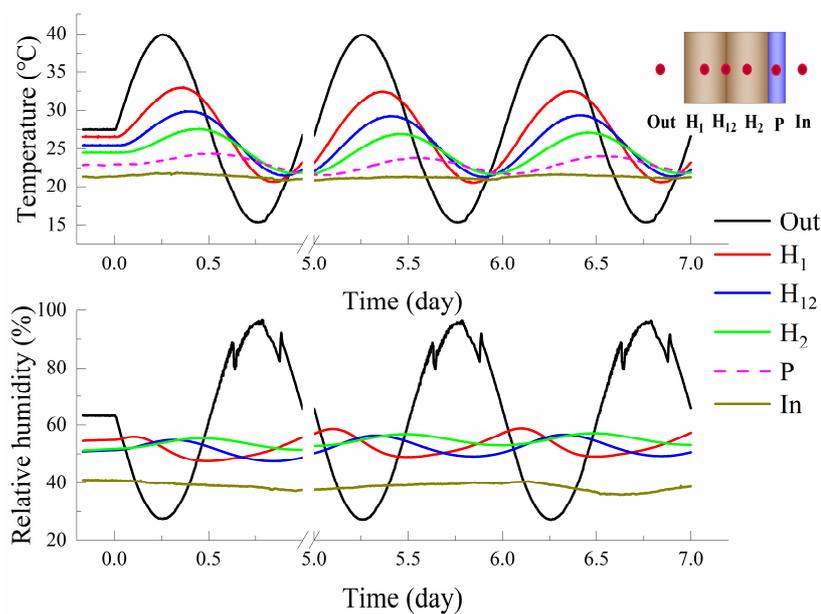
296 3.2.3. PCM placed on the indoor side ($X = 1 L$)

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_1 and H_{12} 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_1
301 and H_{12} . Inversely, the amplitude at H_2 was 0.1 °C higher than in the configuration without PCM,

302 which was caused by the thermal accumulation at H₂. 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 H₁, H₁₂, and H₂.

305 Compared with configuration without PCM, the RH amplitude was lower at H₁₂ (3.7%), and
 306 slightly higher at H₂ (2.1%) because the PCM's impermeability caused moisture to accumulate around
 307 H₂. 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 H₁, H₁₂, and H₂ in the different
317 configurations. Due to the superposition effect at H₁, the magnitude order of RH and T amplitude at
318 different configurations was not consistent. However, for points H₁₂ and H₂, 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 H₂, 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

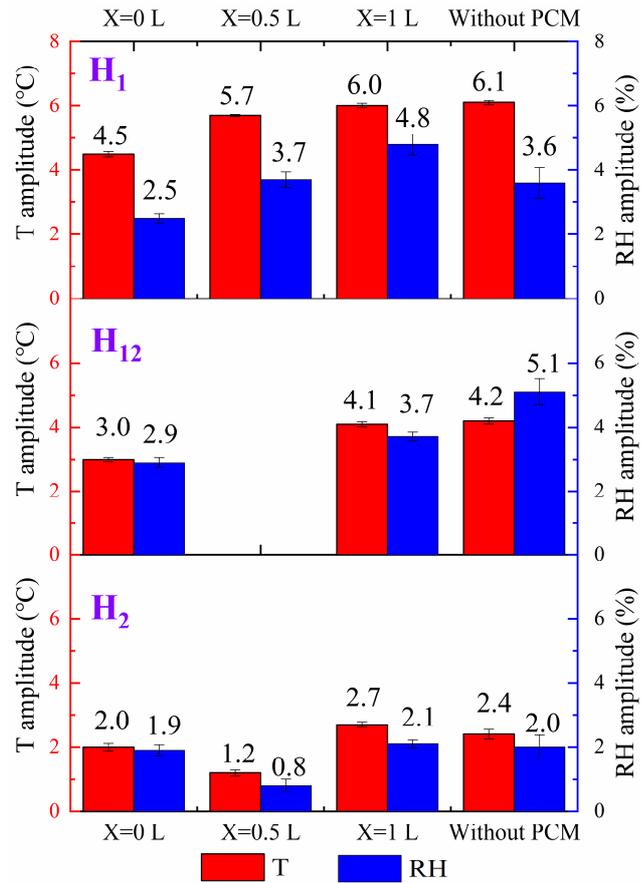


Fig. 8. T and RH amplitudes of hemp concrete in different configurations

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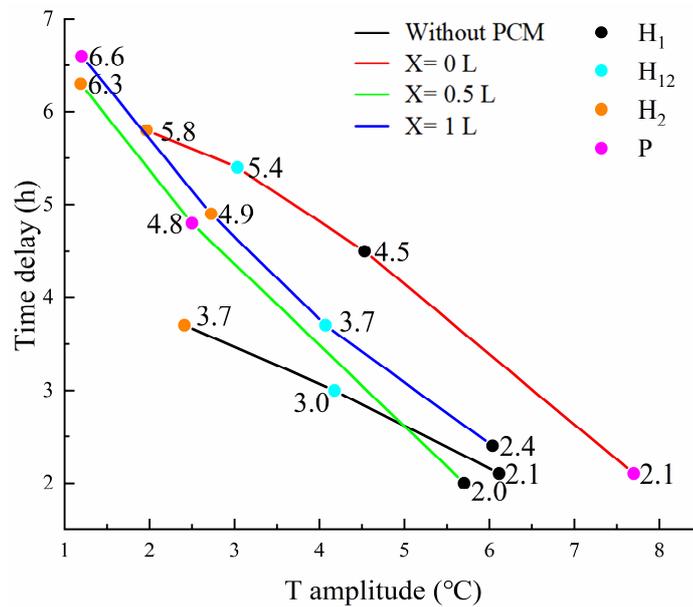
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Fig. 9 presents the relationship between the T amplitude and time delay. The time delay decreased almost linearly as the T amplitude increased from the outdoor side to the indoor side, reflecting the decay in T fluctuation over time. Both parameters 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 (H₁, H₁₂, and H₂ of configuration X = 0 L— reduced by 26.2%, 28.6%, and 16.7%; H₂ of configuration X = 0.5 L— reduced by as much as 50%). In contrast, for points between the PCM and the outdoor side (H₁ of configuration X = 0.5 L; H₁ and H₁₂ 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 H₂ for the
 342 configuration X = 0.5 L.

343



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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

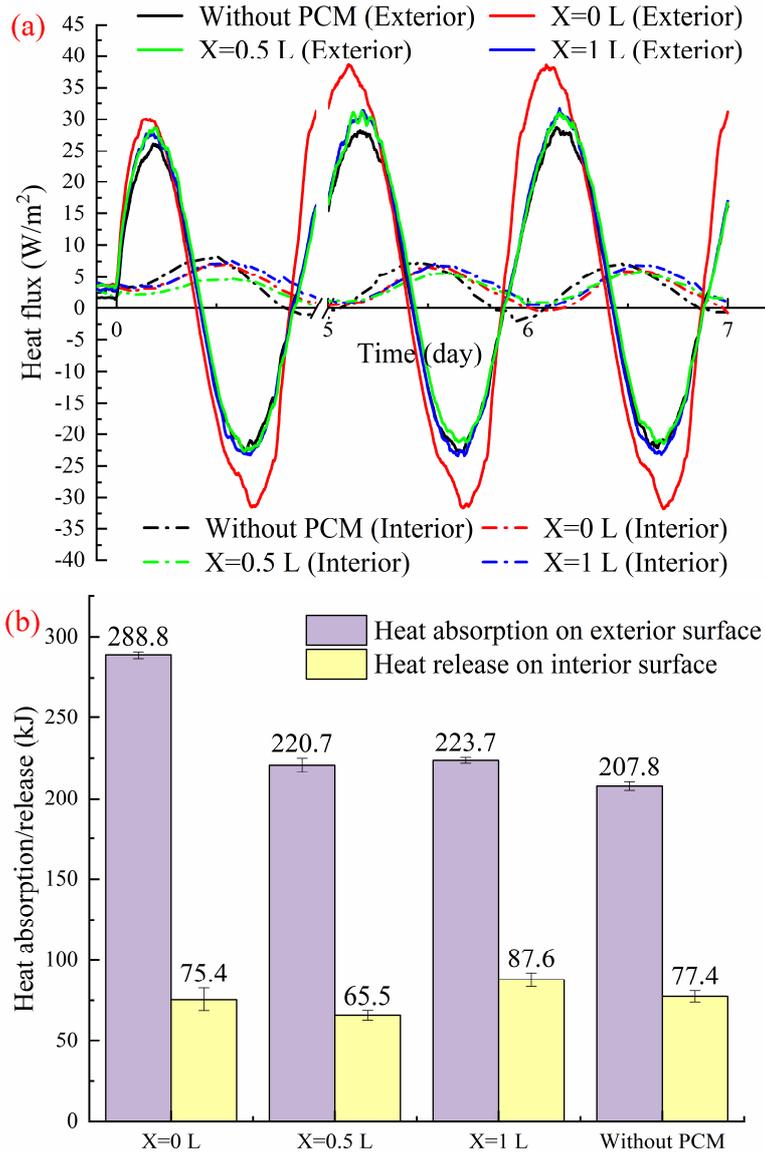
356 **3.4. Heat flux and released/absorbed heat on the interior/exterior surface**

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 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.

368

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

372

surface

373

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_1, t_2 are the start and the end time for the

378 calculation (s); q is the heat flux on both surfaces (W/m^2); and A is the transversal envelope area (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.

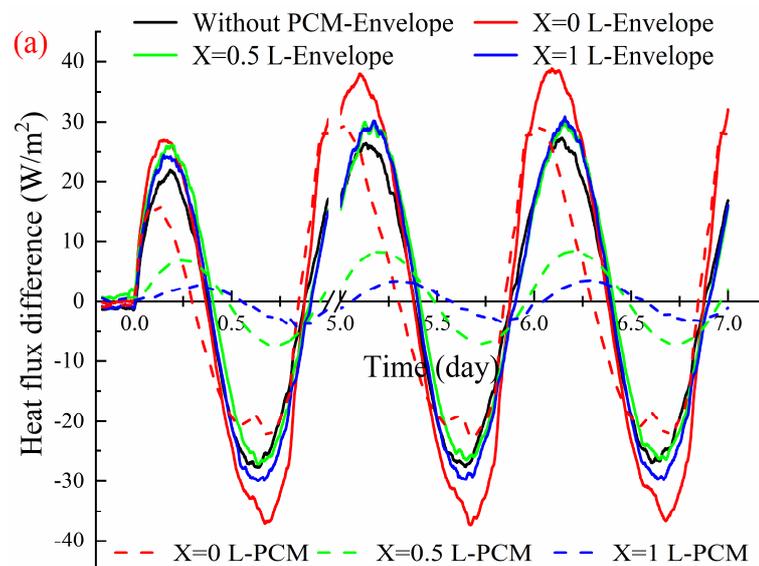
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400 3.5 Energy storage/release by the whole envelope and the PCM

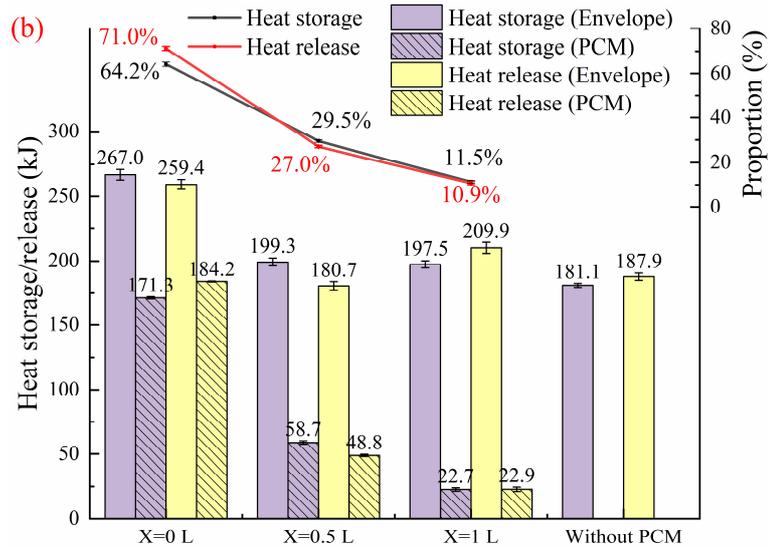
401 The heat flux difference on both sides of the envelope/PCM is plotted in Fig. 11(a). The
402 configuration $X = 0$ L has the highest fluctuations for both the envelope and the PCM, indicating a high
403 energy storage/release potential. The daily energy storage/release by the envelope/PCM is plotted 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



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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

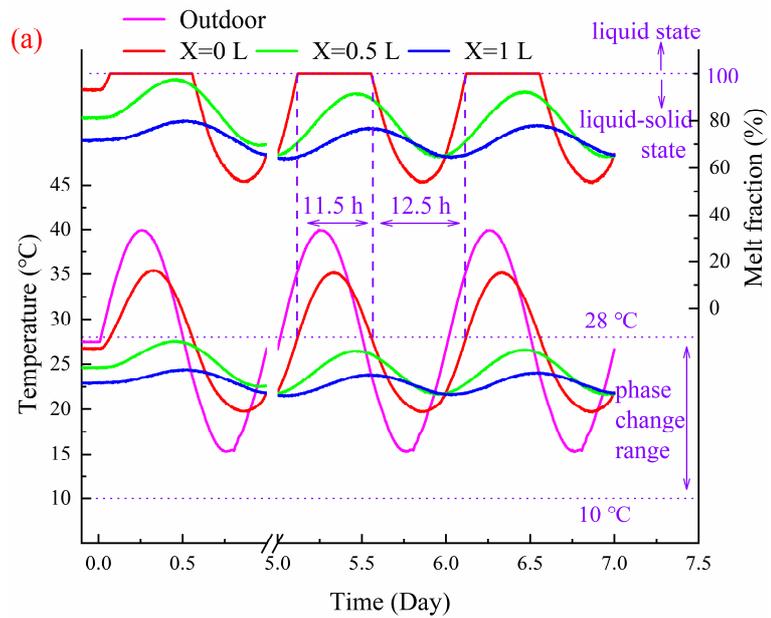
429 This section discussed the PCM utilization, including its activation and energy efficiency. The
430 melt fraction (f) represents the percentage of the activated (melted) PCM that has undergone the phase
431 change. The PCM's storage/release efficiency (η) allows an assessment of how much latent heat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

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

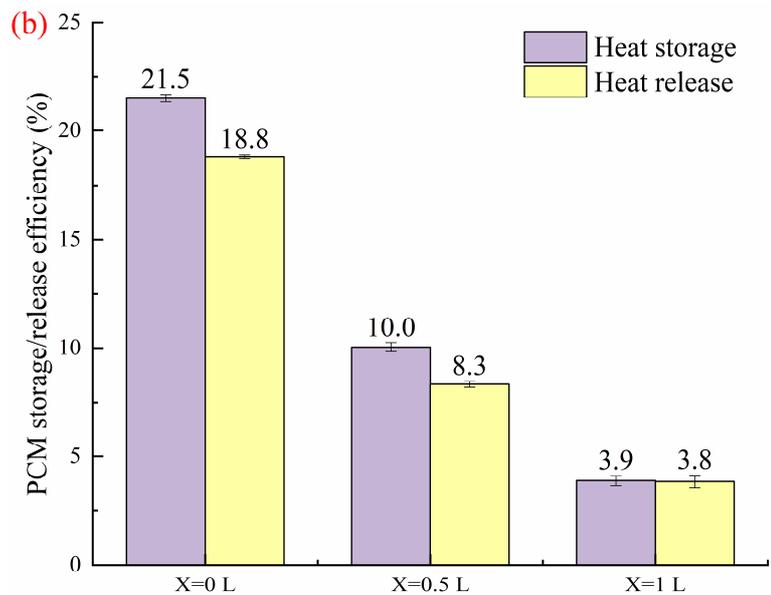
436 where T is the mean T of the PCM ($^{\circ}\text{C}$); T_s, T_f are the initial and final T of melting ($^{\circ}\text{C}$); E_{st} is the
437 actual latent thermal energy stored/released by the PCM (J/kg); L the PCM's total latent thermal
438 energy (J/kg); t_f, t_s are the start and end time for the calculation (s); Δq is the heat flux difference
439 between the inflow and outflow of the PCM (W/m^2); A the transversal envelope area (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 H₂ 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 H₂ 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 H₂
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 H₁₂) 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 H₂ (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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554

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