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# Exploring the integration of bio-based insulations for compressed earth blocks walls

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The growing concern about the environmental impact of contemporary construction has posed emphasis on the need of adopting new sustainable building technologies with lower embodied energy, higher energy efficiency and minimized waste production. In this context, bio-based construction and in particular raw earth construction are promising fields that can ensure inexpensive technologies, characterized by wide availability, non-toxicity and high adaptation to several climatic and geographic conditions. The front challenge for the establishment of earth-based technologies in contemporary building markets is the guarantee of high structural and energy performances, which could enable a real competition with conventional building materials which nonetheless have higher environmental impact (clay bricks, concrete masonry units, reinforced concrete).

For this reason, this work focuses on the performance analysis of compressed earth blocks (from now on CEBs) which are currently commercialized for the construction of massive vertical envelopes, with high thermal inertia. However, this is not always sufficient to obtain an acceptable comfort. In fact, it is also necessary to have a construction material with high thermal resistance to optimize thermal behavior.

This issue can be overcome by the design of insulated CEB stratigraphies using bio-based insulations presenting hygrothermal properties compatible with raw earth-based materials. In this way, the thermal performance of CEB walls can be increased so to respond to the high demanding energy standards (recently adopted in several countries), while preserving the hygroscopic behavior of earth-based materials.

In this spirit, this work reports the results of the experimental characterization of the analyzed CEBs combined with two innovative bio-based insulation panels (lime hemp and sugarcane bagasse), comprising their composition, their main physical (dry density, porosity, capillary water absorption), thermal (specific heat capacity, thermal conductivity) and hygrometric (sorption isotherm, water vapor permeability) properties.

Finally, these experimental data are used for the implementation of several numerical simulations at a wall scale in a reference climate to estimate the hygrothermal performances of both uninsulated and bio-insulated CEB walls. The simulations allow for a better comprehension of CEBs' behavior in view of their combination with the chosen bio-based thermal insulations.

**Keywords:** earth-based construction technologies; compressed earth blocks; bio-based insulation; material characterization; performance analysis.

## 1. Introduction

The need to adopt new sustainable building technologies with lower embodied energy, higher energy efficiency, and reduced waste production has been highlighted by the growing concern about the environmental impact of the modern construction industry. In this context, bio-based construction and in particular raw earth construction are promising fields which promote the use of low-cost materials, characterized by wide availability, non-toxicity, low tech production processes and recyclability [1]. As highlighted by several works developed during last decades [2], the wide range of earth-based construction technologies show good adaptation to several climatic (hot and temperate climate, but also continental ones) and geographic conditions (seismic-prone areas or not). Promising applications of raw earth technologies explore the possibilities of industrialization, prefabrication, mechanization and digitization [3,4] in response to the need of increasing the reliability, the performances and the streamlining of production and construction processes, without neglecting the cost-effectiveness of the finished product.

Several companies of the construction sector have turned their efforts to the production of contemporary raw earth materials: among these, the pioneering experience of *Cycle Terre* (France) stands out. Indeed, it has set its production of compressed earth blocks and panels, of mortars and earth-based plasters, on the material deriving from the excavations of the *Grand Paris* infrastructure network [5].

Numerous studies focused on the assessment of the performances of compressed earth blocks (CEBs). In the literature, CEBs are often stabilized (for instance with lime and cement) to increase compressive strength, but unstabilized CEBs have proved to reach higher moisture buffer potential and water vapor permeability [6-11]. In [6], unstabilized CEBs store 2.2% of moisture inside them, reach a moisture buffer value of 3 g/(m<sup>2</sup> %RH), and a water vapor resistance factor of 5.65 on average. In [7], hypercompacted and unstabilized CEB samples have a moisture buffer value of 4.2 g/(m<sup>2</sup> %RH).

On the other hand, use of stabilizers decreases the capillary water absorption coefficient compared to unstabilized samples [8, 9]. Fiber stabilized CEB materials have in general higher capillary absorption coefficient as shown in

54 [10]. More in general it has been observed that it should exist a threshold value from which an inverse trend (from  
55 decrease to increase of capillary water absorption coefficient is recorded [11].  
56 In the same work [11], the authors propose a review of the thermal properties of bio-stabilized compressed earth  
57 blocks. Because the CEBs analyzed in the present work are unstabilized, we will just recall that the thermal  
58 conductivity of unstabilized CEBs' can range from less 0.64 W/mK to 1.46 W/mK, which for this type of raw  
59 earth technique, seems to be strictly correlated with the increase of dry density [11].  
60 For the reviewed works, dry density ranges between 1600 kg/m<sup>3</sup> and 2760 kg/m<sup>3</sup>. In [12], dry density of CEB is  
61 changed to find an optimum between compressive strength and thermal conductivity, by varying the compaction  
62 pressure and consequently the porosity. With a minimal compaction pressure of 0.39 MPa, a bulk density of 1610  
63 kg/m<sup>3</sup> is found, corresponding to a thermal conductivity of 0.618 W/mK; at the same time, for the highest bulk  
64 density of 2194 kg/m<sup>3</sup>, a thermal conductivity of 1.483 W/mK is assessed.  
65 Specific heat capacity is a property which is seldom assessed in the literature. In [13], the specific heat capacity of  
66 earth brick is assessed to be 869 J/kg K, while in [14] is found a value of 1000 J/kg K. CEB's specific heat capacity  
67 was also assessed by [15] where it is found to be equal to 808 J/kg K. Similar values are found for rammed earth  
68 materials [17], where specific heat capacity of the unstabilized material is assessed to be equal to 962 J/kg K and  
69 in [18] where are reported specific heat capacity above 1000 J/kg K for unstabilized and fiber reinforced rammed  
70 earth.  
71 Water vapor permeability  $\pi$  and so, water vapor resistance factor  $\mu$ , of earth materials has been studied in the past.  
72 In [19],  $\mu$ -values varies between 7 and 14 (with the dry cup method) and from 3 to 7 (with the wet cup method).  
73 Higher  $\mu$ -values, up to 14, have been found when stabilizers are used [20], while use of natural fibers in the mix  
74 can decrease the water vapor resistance factor [21].  
75 In light of these results, it is possible to infer that the high dry density of CEB materials, in combination with the  
76 good values of specific heat capacity, entail good inertial properties, beneficial in summer conditions [22].  
77 Nonetheless, this is not always sufficient to obtain an acceptable comfort, especially during winter and in more  
78 severe climates. In fact, it is also necessary to have a construction material with satisfactory thermal resistance to  
79 obtain a satisfactory thermal behavior.  
80 This issue can be overcome by the design of insulated CEB stratigraphies which make use of bio-based insulations  
81 and are characterized by compatible hygrothermal properties and permeability capacities compared to raw earth-  
82 based materials.  
83 Only few works have focus on the combination of raw earth walls and thermal insulations. Among them,  
84 SIREWALL system, a patented technology used in Canada, proposes a two walls cement stabilized rammed earth  
85 with an interior layer of synthetic thermal insulation (as PU or XPS). In [23] the author lists the positive outcomes  
86 of using rigid panel insulation interposed between two rammed earth walls; in cold climates, the use of such  
87 technology results in mean indoor winter temperatures of 16 °C compared to the 7 °C outside, while humidity is  
88 maintained between 40% and 65%, consistent with comfort values. In cold climates, the combined use of thermal  
89 insulation (natural or synthetic) and rammed earth walls leads to the amortization of heating consumption by up  
90 to 70%, as reported by [24] with reference to four residential buildings in Canada.  
91 The same design strategy is adopted in the UK [25]. At first, the authors aimed at designing several retrofit  
92 solutions for existing earth based construction systems which could satisfy current UK building standards (with U  
93 values below 0.35 W/m<sup>2</sup>K). They proposed the use of indoor thermal insulations in order not to alter the appearance  
94 of the façades and made use of bio-based materials as straw, pads, wool or paper [25]. After that, they developed  
95 a new optimized cob construction technology, whose thermal transmittance properties meets current building  
96 standards. This wall is done by combining a 30 cm thick loadbearing cob wall (a mix of soil and 2.5% flax straw,  
97 with  $\lambda = 0.45$  W/mK) with an exterior layer of lightweight thermal insulation (a clay slip with 50% hemp shives  
98 and a thermal conductivity of 0.12 W/mK).  
99 In [26], the effects of several retrofitting solutions for 14-cm thick CEB walls are studied by means of dynamic  
100 thermal simulation in free running conditions on *EnergyPlus* software. The building model is validated by means  
101 of measurements made on a real test-box located in a hot and dry tropical country. The work focuses on the impact  
102 of type of insulation (synthetic as glass wool, or bio-based as straw and lime) and wall thickness in the enhancement  
103 of indoor air temperature profiles. It is found that, in hot and dry climates, uninsulated CEB walls of thickness  
104 below 0.35 m are able to perform well without need of thermal insulation; at the same time, a thinner CEB wall  
105 (14 cm thick) needs a straw and lime thermal insulation in order to reduce heat conduction through walls until  
106 acceptable levels.  
107 In general, when used in warm temperate or dry climates, there is a tendency to avoid use of thermal insulation in  
108 order to prevent overheating of indoors, even if several authors have pointed out the importance of shading  
109 elements and night cross ventilation to prevent from this risk [22, 27]. In continental and cold climates, the need  
110 to face low temperatures in winter season has imposed, *de facto*, the use of thick insulation layers on the vertical  
111 envelopes. Nonetheless, in Central European Countries as France is, use of hyper insulated envelopes poses serious

112 risks of overheating of indoors in warmer season, especially against a worsening context of rising global average  
113 temperatures [28].

114 This work intends to show how using bio-based thermal insulation materials can help in enhancing thermal  
115 resistance of CEB walls while preserving the benefices of their thermal mass. Moreover, it is advanced the  
116 hypothesis that the combination of hygroscopic materials as raw earth, hemp shives and sugarcane bagasse fibers,  
117 determine walls with high permeability toward water vapor, able to store it inside their pores, and favor the  
118 humidity buffering effect. Finally, adopting bio-based and local materials as raw earth and hemp, respond to a  
119 programmatic sustainable building approach, able to deem with current building regulations as the RE2020, where  
120 high energy performances must be accompanied by adequately low environmental embodied carbon values of  
121 materials composing future building stock.

122 In order to adapt the performance of raw earth building components to the high energy requirements determined  
123 by current regulations, there is an increased need for research works that focus not only on bio-based material  
124 performances assessment, but also on their behavior at the masonry scale and at a building scale (even by means  
125 of numerical simulations). In this sense, the study of the thermal and hygrometric performances of raw earth walls  
126 for exterior walling systems seems fundamental.

127 This work contains the physical, thermal and hygrometric characterization of the compressed earth blocks  
128 (currently commercialized by the industrial partner *Cycle Terre*) combined with bio-based insulation materials as  
129 lime hemp and sugarcane bagasse. On the base of the material characterization, this paper focuses on the  
130 assessment of the hygrothermal behavior of uninsulated and insulated CEB walls by means of numerical  
131 simulations. These ones are assessed with *Delphin* software, which allows investigating the building components  
132 behavior under combined heat, moisture, air, and salt transport. In a second phase of the research, the uninsulated  
133 and bio-based insulated CEB walls constructions are further studied by means of wall scale measurements in a Hot  
134 Guarded Box Equipment.

## 135 **2. Materials**

### 136 **2.1 Compressed earth block (CEB)**

137 The compressed earth blocks provided by *Cycle Terre* are designed for several applications, including load-bearing  
138 walls (for single-story or double-story buildings), being their compressive strength at least 2.00 MPa, but also  
139 massive walls applications in combination with load-bearing framing and curtain walls. The CEBs are realized in  
140 different sizes depending on the application, but all of them use a mix design made up of at least 65% of raw earth  
141 (composed by clays, silts, sands and small gravels) and 35% sand (with a particle size distribution comprised  
142 between 0 and 2 mm or from 0 to 4 mm) from Paris region [29]. CEBs are sold in various sizes, but the more  
143 common is the block with dimensions 9.5 x 15 x 31.5 cm, that weighs 8.7 kg. The environmental performance of  
144 30 cm thick CEB walls has been calculated by the company and it has been found a global warming potential of  
145 27.8 kg eq. CO<sub>2</sub> for the production phase of 1 m<sup>2</sup> functional unit.

### 146 **2.2 Lime hemp (LH)**

147 Lime-hemp or hempcrete is a biomass-based product, which is currently used for non-load-bearing purposes in  
148 new construction to produce blocks for walling systems, but also for roof insulation. Moreover, it is increasingly  
149 used for the energy retrofit of existing building stock. The use of hemp shives and lime or cement leads to insulating  
150 mixes with really low dry density (ranging from 200 kg/m<sup>3</sup> to 800 kg/m<sup>3</sup>) and thermal conductivity (ranging from  
151 0.06 W/m K to 0.18 W/m K) [30]. These types of walls present thermal resistance from 0.22 K m<sup>2</sup>/W to 0.40 K  
152 m<sup>2</sup>/W from low to medium density (200 – 400 kg/m<sup>3</sup>). Lime hemp or hempcrete materials have also high specific  
153 heat capacity, being it around 1500 J/kg K in the dry state and up to 2900 J/kg K at 99% RH [31]. As raw earth,  
154 lime hemp and hempcrete mixes are known to be able to regulate relative humidity. It has been found to have a  
155 water vapor permeability of 2.3 10<sup>-11</sup> kg/Pa m s, and a moisture buffer value (the ability of a material to uptake or  
156 release moisture when it is exposed to repeatedly varying levels of relative humidity) of 2 g/m<sup>2</sup> %RH [32, 33].  
157 Water vapor resistance coefficient of hemp concrete was assessed in [34] and it was found to be ranging between  
158 1.49 and 2.30 depending on the calculation method, while in [35] it was found a μ-value ranging from 5.42 to 5.71  
159 depending on the concrete type.



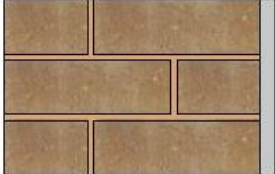
### 160 **2.3 Sugarcane bagasse (SB)**

161 Sugarcane, scientifically known as *Saccharum officinarum*, is a tall grass plant with strong stems, largely grown  
 162 in Southeast Asia, South American and South Africa [36]. Sugarcane bagasse is an agro waste, a byproduct  
 163 obtained after extraction of the juice from sugarcane stalks.  
 164 Various studies [36, 37] reported that its chemical composition is composed by cellulose, hemicellulose, lignin.  
 165 The cellulose content of sugarcane bagasse helps to reduce the use of synthetic binders. Considering the abundance  
 166 of sugarcane bagasse, it is currently investigated as an ideal raw material to produce low-cost green thermal  
 167 insulation which could also satisfies environmental regulations, given its biodegradability and reusability.  
 168 Previous studies found that sugarcane bagasse insulation materials exhibited low thermal conductivity 0.034–  
 169 0.0496 W/m K for densities ranging from 100 kg/m<sup>3</sup> to 200 kg/m<sup>3</sup> and porosity from 83.33% to 92.18% [36]. The  
 170 company *Emerwall* provided the sugarcane bagasse panels characterized in this study.  
 171

172 **2.4 Design of insulated and bio-based insulated CEB constructions**




173 Several raw earth standards indicate the minimum thicknesses of CEB walls for structural stability to be within  
 174 0.3 and 0.4 m [38, 39]. The new CEB French standard does not indicate minimal thickness, but the ATEX provided  
 175 by the company *Cycle Terre*, indicates possible combinations of not loadbearing CEB envelopes with several  
 176 loadbearing frames in wood or concrete. The BTC masonry is framed by stiffeners (integrated into the main  
 177 structure of the building or not) whose maximum spacing depends on the thickness, on the height of the masonry  
 178 and on its exposure to the wind. In particular, the ATEX presents the possibility of realizing 0.15 m thick CEB  
 179 walls coupled with an eventual thermal insulation and a wood ventilated façade, or thinner CEB walls, 0.095 m  
 180 thick, coupled with a mandatory thermal insulation. It also specifies that the thermal resistance of CEB walls must  
 181 be adequate to the local climate and energy performances standard requirements.  
 182 In this work CEB wall thicknesses of 0.15 m, 0.30 m and 0.45 m have been studied in order to estimate the change  
 183 in hygrothermal behavior of uninsulated and bio-insulated CEB walls depending on raw earth wall thickness.  
 184 Moreover, several bio-based insulations have been considered, namely lime hemp and sugarcane bagasse  
 185 insulations, with several thicknesses which enable the achievement of a range of thermal transmittances and  
 186 allowing for the adoption of CEB walls in a wide assortment of climatic conditions. The insulation layers are  
 187 always applied to the outmost layer of CEB walls in order to take advantage of the thermal inertia of the raw earth  
 188 wall, according to what has been found in previous research [22, 26, 40]. In table 1, 2, 3 are reported the main wall  
 189 scenarios considered in the simulation study explained section 3.

Table 1. Scenarios of CEB wall thicknesses

	CEB 15 0,15 0,025	CEB 30 0,3 0,025	CEB 45 0,45 0,025
			
INNER SIDE	0.15 m thick CEB wall	0.30 m thick CEB wall	0.45 m thick CEB wall
OUTER SIDE	0.025 m Lime Plaster	0.025 m Lime Plaster	0.025 m Lime Plaster

190




Table 2. Scenarios of CEB walls insulated with an outside lime hemp (LH) insulation

	LH 5 0,3 0,05 0,025	LH 10 0,3 0,1 0,025	LH 15 0,3 0,15 0,025
			
INNER SIDE	0.30 m thick CEB wall	0.30 m thick CEB wall	0.30 m thick CEB wall

	0.05 m Lime Hemp	0.10 m Lime Hemp	0.15 m Lime Hemp
OUTER SIDE	0.025 m Lime Plaster	0.025 m Lime Plaster	0.025 m Lime Plaster

191

Table 3. Scenarios of CEB walls insulated with an outside sugarcane bagasse (SB) insulation

	SB 5	SB 10	SB 15
	0,3 0,05 0,025	0,3 0,1 0,025	0,3 0,15 0,025
			
INNER SIDE	0.30 m thick CEB wall	0.30 m thick CEB wall	0.30 m thick CEB wall
	0.05 m Sugarcane Bagasse	0.10 m Sugarcane Bagasse	0.15 m Sugarcane Bagasse
OUTER SIDE	0.025 m Lime Plaster	0.025 m Lime Plaster	0.025 m Lime Plaster

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### 3. Methods

#### 3.1 Material characterization

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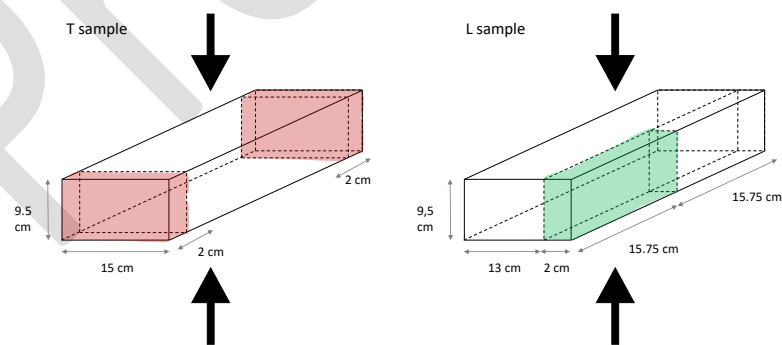
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208

A material characterization campaign was carried out on the three main innovative materials at the center of this study: compressed earth blocks (CEB), lime hemp (LH) and sugarcane bagasse (SB) thermal insulations. The characterization comprises the assessment of the main physical (dry density, porosity, capillary water absorption), thermal (specific heat capacity, thermal conductivity) and hygrometric (sorption isotherm, water vapor permeability) properties. Please note that the porosity of CEB samples is assessed for two portions of material: one taken from the surface and the other from the core of the CEB block. Besides, the thermal conductivity of CEB blocks is measured in two main directions, corresponding to samples cut in the longitudinal and transversal direction of the entire compressed earth block. This choice was motivated by the fact that in a double layer CEB wall (as for instance are the CEB 30 and CEB 45 wall configurations of the present study), CEBs are arranged in both directions, and an eventual inhomogeneity of thermal conductivity performance in the two directions would have caused an effect on the final wall behavior. Figure 1 shows the two cuts of CEB samples and the direction of compaction they are produced with.



209

210

Figure 1. Cut directions for T and L CEB samples

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#### 3.1.1 Dry density

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Dry density was assessed after oven-drying three samples of each materials at 70 °C (about 7% RH) to constant weight until steady state was reached (namely, two measures 24 hours apart differ of less than 0.1%  $m_{(t,t+24)} < 0.1\%$ ). After oven-drying, samples were weighted and their mass divided for the volume (sizes of samples were assed via a caliper).

216

#### 3.1.2 Porosity

217 Mercury intrusion porosimetry (MIP) is a method used to determine the dimensions of the pores in a material and  
 218 their distribution. A non-wetting liquid (mercury) is forced into the material's pores by external pressure, until it  
 219 reaches the smallest pores. Being the volume of intruded liquid known, it is possible to assess the pore size  
 220 distribution at each pressure increment. This method is used to measure the range of pores between 0.0025  $\mu\text{m}$   
 221 and 430  $\mu\text{m}$ . For the analysis, an AutoPore IV 9500 V1.10 porosimeter from Micromeritics Instrument Corporation  
 222 was used, capable of applying pressures up to 207 MPa. The contact angle between the solid and the mercury was  
 223 assumed to be 140°, with a surface tension of 0.485 N/m. The quantity investigated for a typical experiment was  
 224 around 1.2 g per sample for compressed earth block samples and 0.13 g for the bagasse insulation.  
 225 The total volume porosity in water method was instead used to estimate porosity inside the lime-hemp insulation  
 226 [41, 42]. The total volume porosity can be calculated in the water by measuring the block weight after water  
 227 saturation from the initial dry weight, because of the absorbed water by the block which penetrates into accessible  
 228 pores in the block. The volume of water absorbed to saturation is equal to the total volume of the block pores.  
 229 Thus, the total water absorption is converted to porosity using the following:

$$230 \quad n(\%) = \frac{TWA * \rho}{100 * \rho_w}$$

231  $n(\%)$  = total volume porosity.

232  $\rho$  = block dry density ( $\text{kg}/\text{m}^3$ )

233  $\rho_w$  = water density 1000 ( $\text{kg}/\text{m}^3$ ).

234 TWA= total water absorption (%).

### 235 *3.1.3 Capillary water absorption and free water saturation*

236 The water absorption coefficient  $A_w$  due to capillary action is determined for three samples of each material by  
 237 partial immersion according to the standard NF EN ISO 15148:2003. Oven-dried samples (at 70 °C until mass  
 238 stabilization  $m(t, t + 24) < 0.1\%$ ) are thus brought into contact with the 5 mm water level and left to soak for an  
 239 appropriate time. The samples are removed from the water and weighed at preset time intervals. The results are  
 240 expressed as the ratio of mass change to base area and then plotted against the square root of time to calculate the  
 241 water absorption coefficient. The test was easily run for the two insulation materials (LH and SB), taking care of  
 242 letting the material drain all the free water contained in their open pores, by gravity action. On the other hand,  
 243 considering the extreme affinity of the unstabilized CEBs with water, in this study the contact with water was  
 244 mediated by means of a perforated basket equipped with absorbent paper, so that the water could pass through  
 245 without causing any loss of material in the water. Mass increase of absorbent paper was deducted from separate  
 246 measurements. Similar approaches have been used previously in the literature, where the contact of the unstabilized  
 247 block with water was mediated, for example, by a wet sponge or sand [43, 44]. Once the test was completed, the  
 248 free water saturation of the materials was assessed by immersing the samples inside water. The samples were then  
 249 kept in water until the weight was stabilized with a mass variation of 0.1%. In particular, CEB samples were closed  
 250 in absorbent paper to allow water saturation thus avoiding any loss of material during the test.

### 251 *3.1.4 Moisture dependent thermal conductivity and specific heat capacity*

252 Moisture dependent thermal conductivity was assessed on 2 cm-thick CEB and 4 cm-thick LH and SB samples.  
 253 Samples were left in a climatic chamber at a constant temperature of  $T = 20^\circ\text{C}$ , while relative humidity was  
 254 successively increased following the methodology already adopted in [18, 45]. Thermal conductivity was assessed  
 255 on several points of sample's surface and when its mass was stabilized: more in detail, a condition of mass  
 256 stabilization  $m(t, t + 24) < 0.1\%$  was adopted because of the need of adopting bigger sizes of samples due to  
 257 minimal thermal conductivity measurement area. The relative humidity steps were 25% RH, 40% RH, 60% RH,  
 258 80% RH.

259 The samples were kept in the climatic chamber during the thermal conductivity measurements with a Hot Disk  
 260 device (NF EN ISO 22007-2), a transient method using a flat probe that serves as both a heating device and a  
 261 temperature sensor. The probe is placed between two identical, smooth, flat samples to avoid contact with air. This  
 262 measurement method allows the determination of thermal conductivity and heat capacity for any water content,  
 263 with a fast and reliable procedure. A Kapton 5501 probe with a radius of 6.403 mm, a power of 90 mW and a  
 264 measurement time of 80 s was used for the measurement of CEB thermal conductivity. A Kapton 8563 probe with  
 265 a radius of 9.868 mm was used both for LH and SB samples, with a measurement time of 80s and a power of  
 266 33mW for LH and 30mW for SB.

267 The same Hot Disk measurements and parameters were used for specific heat capacity assessment. In this case  
 268 only dry state specific heat capacity was determined, by previously oven drying samples at 25°C until mass  
 269 stabilization ( $m(t, t + 24) < 0.1\%$ ).

### 270 3.1.5 Sorption isotherms

271 The sorption isotherm is assessed in accordance with NF EN ISO 12751:2021; in particular, the sorption step  
 272 consists of successively placing a previously dried sample (at 70°C until stabilization of the mass  $m(t, t + 24) <$   
 273  $0.1\%$ ), in several environments with increasing relative humidity and constant temperature. In this work, three  
 274 samples of each material (CEB, LH and SB) were put in a climatic chamber with a temperature of 23°C and a  
 275 ventilation rate of 100%, and increasing relative humidity of 25% RH, 40% RH, 60% RH, 80% RH. Moreover, a  
 276 further sorption condition, equal to 95%RH, was reached inside a desiccator and using a saturated salt solution of  
 277  $\text{Na}_2\text{PHO}_4$ . The sample is weighed periodically, and it remains in a given environment until a constant mass ( $m(t,$   
 278  $t + 24) < 0.01\%$ ) is obtained. Then, the percentage of mass increase due to moisture penetration is calculated.

### 279 3.1.6 Water vapor permeability

280 Water vapor permeability is commonly assessed according to the "wet cup" or "dry cup" methods using the  
 281 standard EN ISO 12572. The experimental protocol used for these two tests consists in sealing the samples on a  
 282 "wet" or "dry" cup whose relative humidity is controlled by a saturated salt solution. These cups are then placed  
 283 in a climatic chamber (with controlled T and RH), so that the tested material is located between two environments  
 284 with different vapor partial pressures, namely and outside  $p_{v1}$  and an inside (cup)  $p_{v2}$ . It is important to remark  
 285 that a layer of air is present inside the cup. The partial vapor pressure gradient between the inner part of the cup  
 286 and the outside (the climatic chamber), enables a flow of water vapor through the sample: in particular, during the  
 287 dry cup test the assembly of the cup and the sample experiences a mass uptake, while during the wet cup test the  
 288 assembly experiences a mass loss.

289 For the wet cup, a di-sodium hydrogen phosphate solution is used, leading to a relative humidity level of 95% at  
 290 23°C. For the dry cup, potassium hydroxide solution (RH level, 8% at 23°C) was used. To seal the samples to the  
 291 cup, silicon and vapor-tight aluminum tape are used, because they do not adsorb a significant quantity of moisture  
 292 themselves. Tested samples (CEB, LH, SB) have all a minimum surface of 10 cm<sup>2</sup>. Two samples were tested for  
 293 each condition, being previously dried in an oven at 70°C until mass was constant ( $m(t, t + 24) < 0.1\%$ ). The cup  
 294 systems are then put in a chamber at 50%RH and 23°C, and their mass evolution is assessed every 24 hours until  
 295 steady-state is reached.

296 In particular, the mass change rate  $\Delta m_{12}$  is calculated as the ratio between the difference of masses (measured in  
 297 kg) of the test assembly at time  $t_2$  and  $t_1$ , and the times of weighing themselves (measured in seconds).  $G$  is the  
 298 mean of five successive determinations of  $\Delta m_{12}$ . Equilibrium is attained when each of the last five successive  
 299 determinations of  $\Delta m_{12}$  is within a variation of 5% of  $G$  value.

300 After that, it is calculated the density of water vapor flow rate  $g$ , as the ratio between  $G$  and the exposed area  $A$  of  
 301 the specimen (in m<sup>2</sup>). The  $G$  value is used to calculate the water vapor permeance  $W$ , by this formula:

$$302 \quad W = \frac{G}{A \Delta p_v}$$

303 where  $\Delta p$  is the difference in partial pressure of vapor between the two faces of the samples, which can be  
 304 calculated as [46]:  
 305

$$306 \quad p_v = RH * \exp\left(23.5771 - \frac{4042.9}{T - 37.58}\right)$$

307  
 308 The water vapor resistance  $Z$  is the reciprocal of the water vapor permeance  $W$ . From  $W$  value it is possible to  
 309 calculate the water vapor permeability by multiplying it for the sample thickness:

$$310 \quad \delta = Wd$$

311 Assuming that inside the cup there is an ideal mixing of humid air, the water vapor resistance factor  $\mu$  is:

$$312 \quad \mu = \frac{Sd_{tot} - d_{air}}{d}$$



313 where  $d_{air}$  is the thickness of air layer between the sample and the saturated salt solution in the cup and  $Sd_{tot}$  is the  
314 total vapor diffusion thickness:

$$315 \quad Sd_{tot} = \frac{\delta_{air} A \Delta p_v}{G}$$

316 Where  $\delta_{air}$  is the water vapor permeability of air, that is calculated as:

$$317 \quad \delta_{air} = 2.306 \cdot 10^{-5} \frac{M_w}{RT} \left( \frac{T}{273.15} \right)^{1.81}$$

318 With  $R = 8.314$  [J mol<sup>-1</sup> K<sup>-1</sup>] is the ideal gas constant,  $M_w = 18$  [g mol<sup>-1</sup>] the molar weight of water.

### 319 **3.2 Walls behavior : Hygrothermal performance simulation**

320 In this study, material properties assessed for both CEBs and bio-based thermal insulations (SB, LH) are used to  
321 run several numerical simulations in order to assess the hygrothermal behavior of both uninsulated and bio-based  
322 insulated CEB walls. Several design solutions (introduced in paragraph 2.4), are simulated by means of the  
323 software tool *Delphin 6.1.2*. This software allows for the numerical solving of balance equations in a finite control  
324 volume to describe the combined heat and mass transfer inside the wall construction. For each investigated  
325 material, the software requires several hygrothermal properties to describe the following functions:

- 326 • heat transfer and heat storage (for which are implemented bulk density  $\rho$ , specific heat capacity  $c_p$  and  
327 dry thermal conductivity  $\lambda$ );
- 328 • moisture storage (for which sorption isotherm are required, not taking in consideration the desorption  
329 phase and the eventual hysteresis);
- 330 • vapor transport (quantified by water vapor resistance factor  $\mu$ );
- 331 • liquid water transport (described by the capillary water absorption coefficient  $A_w$ ).

332 In this study, hygrothermal simulations are run in the reference climate of Paris (France) classified as a Cfb (marine  
333 west coast climate), and performed over three consecutive years, with initial conditions  $T=25^\circ\text{C}$  and  $RH=60\%$  for  
334 all the materials.

335 The target objectives of this study are the estimation of average (1) temperature distribution and (2) moisture  
336 contained in the walls, with particular reference to the change in moisture contained in CEB wall when a bio-based  
337 thermal insulation is added. The study also envisages the assessment of (3) moisture dependent thermal  
338 transmittance, whose fluctuation could cause an increase of heat losses through the envelope, by calculating it on  
339 the base of the moisture dependent thermal conductivity values assessed by simulation for each material used [47].  
340 The simulation study investigates the influence of CEB walls and thermal insulation thicknesses in the (4) dynamic  
341 wall behavior with attention to summer conditions for the estimation of dynamic parameters as decrement factor  
342 and time lag. Time lag is the time delay required for the heat wave to be transferred from one side to the other of  
343 a wall. It is calculated by the following equation:

$$344 \quad TL = t_{T_{si, \max}} - t_{T_{so, \max}}$$

345 Decrement factor is the ratio of the heat wave amplitude on the inner and outer surface of the wall and it is  
346 calculated with the following equation:

$$347 \quad DF = \frac{T_{si, \max} - T_{si, \min}}{T_{so, \max} - T_{so, \min}}$$

## 348 **4. Results and discussion**

### 349 **4.1 Materials' properties**

#### 350 **4.1.1 Physical properties**

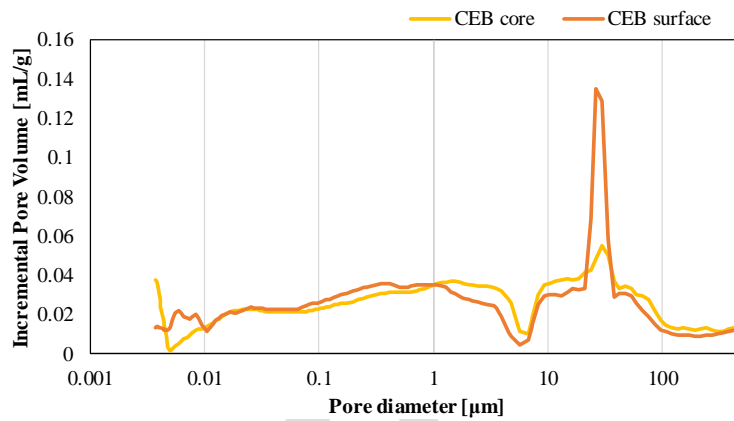
351 In table 3 are reported the main physical properties assessed for the three investigated materials. Dry density  
352 average value for CEB is around  $1800 \text{ kg/m}^3$ , according to the values reported in the manufacturer data sheet.  
353 Concerning SB and LH thermal insulations, the assessed values are respectively  $54.6 \text{ kg/m}^3$  and  $394.8 \text{ kg/m}^3$ .  
354 The porosity values are 24.3% for the CEB core sample, 24.9 for the CEB surface sample, 74% for the SB  
355 (calculated by means of MIP), and 55% for LH (calculated with TWA method). Figure 2 show the pore diameter

356 against the incremental pore volume for compressed earth blocks samples, which allow for a deeper  
 357 comprehension of the pore distributions inside the material, and reveals the difference in pore distribution between  
 358 CEB core and surface samples.  
 359 The dry density values for *Cycle Terre* CEB is in the average compared to what is found in the literature. Indeed,  
 360 the relatively low dry density is accompanied by a low porosity, even when compared with other CEBs tested [12,  
 361 45], for which the porosity values are around 30%. The porosity of SB sample found in this study is lower  
 362 compared to values reported in [34].

363 *Table 4. Physical properties of materials analyzed in this study*

	<b>CEB</b>	<b>LH</b>	<b>SB</b>
Dry density [kg/m <sup>3</sup> ]	1800	394.8	54.6
Porosity [%]	24.3 (core) – 24.9 (surface)	55	74
Capillary water absorption coeff. [kg/m <sup>2</sup> s <sup>1/2</sup> ]	0.137	0.112	0.113

364



365

366 *Figure 2. Mercury Intrusion Porosimetry for CEB core and surface samples*

367 Figure 3 shows the setup adopted for the capillary water absorption test of CEB samples. The capillary water  
 368 absorption coefficient  $A_w$  of CEB sample is found to be equal to 0.137 kg/m<sup>2</sup>s<sup>1/2</sup>, while the  $A_w$  0.113 and 0.112 for  
 369 SB and LH respectively. The capillary water absorption of the CEB at 24 hours is lower compared to values found  
 370 in [8, 9], fact which is easily explained by the reduced percentage of porosity compared to other CEBs analyzed  
 371 in the literature.

372 Once the test is completed, samples were totally immersed inside water to assess water content at saturation. In  
 373 particular, CEB samples were transferred inside absorbent paper bags and brought at saturation.



Figure 3. Capillary water absorption test for CEB samples

#### 4.1.2 Thermal Properties

Table 5 show the thermal properties assessed for the CEB sample cut in the longitudinal direction (CEB L) and for the one cut in the transversal direction (CEB T) of the blocks. The thermal conductivity values for the CEB L samples range from 0.833 W/m K at 25%RH to 0.903 W/m K at 80%RH. For the CEB T samples the values are higher and range from 0.980 W/m K at 25%RH to 1.021 W/m K at 80%RH.

It is important to point out that the slight difference between thermal conductivity values for the two samples cut in the longitudinal and transversal direction may be due to the specific manufacturing procedure adopted, using a double compression on the upper and lower surface of the CEB. This process could likely make the extremities of the CEBs more compacted compared to the lateral samples.

The porosity of CEB samples enables the storage of moisture within the material when ambient relative humidity increases. In this condition, the thermal conductivity of samples increase because moisture contained in the sample leads to heat transfer by conduction.

Noticeably, the obtained thermal conductivity values are lower compared to other CEBs' thermal conductivity values with similar density [12, 45], even if the porosity of *Cycle Terre* CEBs is lower. This apparent contradiction can be explained by the fact that the analyzed CEBs have an optimized particle size distribution (leaving less pore) and use solid phase components with a considerable lower conductivity.

Table 5. Thermal conductivity of CEB blocks in two different directions

	CEB L	CEB T
$\lambda_{25\%RH}$ [W/m K]	0.833 ± 0.0002	0.980 ± 0.0003
$\lambda_{40\%RH}$ [W/m K]	0.868 ± 0.0009	0.985 ± 0.0007
$\lambda_{60\%RH}$ [W/m K]	0.875 ± 0.0024	0.996 ± 0.0015
$\lambda_{80\%RH}$ [W/m K]	0.903 ± 0.0020	1.021 ± 0.0021

The good thermal insulating properties of the SB and the LH are confirmed by the thermal conductivity values reported in table 6. In particular, LH insulation values range from 0.115 to 0.13 W/m K, while SB insulation have thermal conductivity values which vary from 0.049 to 0.059 W/m K, for relative humidity values ranging from 25%RH and 80% RH.

The dry thermal conductivity of lime-hemp insulation assessed in this study is an average value compared to those reported in [30]. The few studies conducted on sugarcane bagasse insulation confirm the data found in this study. Indeed, for a low-density sugarcane bagasse panel, it is found a thermal conductivity of 0.049 at the dry state and of 0.095 at the moist state [34].

403

Table 6. Thermal conductivity of analyzed thermal insulating materials

	LH	SB
$\lambda_{25\%RH}$ [W/m K]	$0.115 \pm 0.0017$	$0.049 \pm 0.0001$
$\lambda_{40\%RH}$ [W/m K]	$0.116 \pm 0.0018$	$0.051 \pm 0.0003$
$\lambda_{60\%RH}$ [W/m K]	$0.120 \pm 0.0013$	$0.054 \pm 0.0001$
$\lambda_{80\%RH}$ [W/m K]	$0.131 \pm 0.0008$	$0.059 \pm 0.0002$

404

405 The specific heat capacity of samples (reported in table 7) was assessed in dry conditions, at 20°C and 25%RH for  
 406 all the tested samples. CEB samples have specific heat capacity about 816.11 J/ kg K, while SB samples have a  $c_p$   
 407 value of 1438 J/ kg K and LH samples of 495.46 J/ kg K.

408 The specific heat capacity of the studied CEBs is slightly lower compared to other studies [13, 14, 16, 17],  
 409 nevertheless it is worth to remind that this value is obtained without use of binders or fibers integrated in the mix,  
 410 as it is often done in the literature. Specific heat capacity value for the LH sample is slightly lower compared to  
 411 [31], probably because of the absence of sand in the lime hemp mixture used in present study.

412

Table 7. Dry weight Specific Heat Capacity

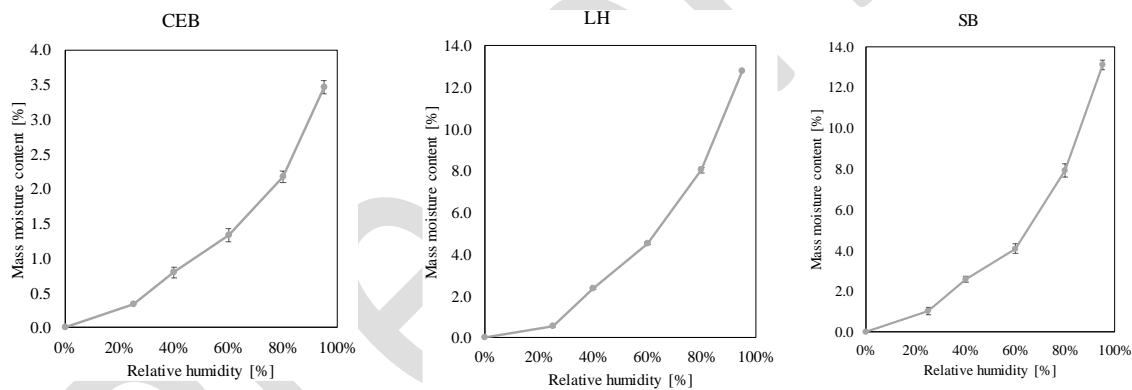
	CEB	LH	SB
$c_{p\ DRY}$ [J/ kg K]	$816.11 \pm 30.508$	$495.46 \pm 6.918$	$1438 \pm 24.464$

413

414

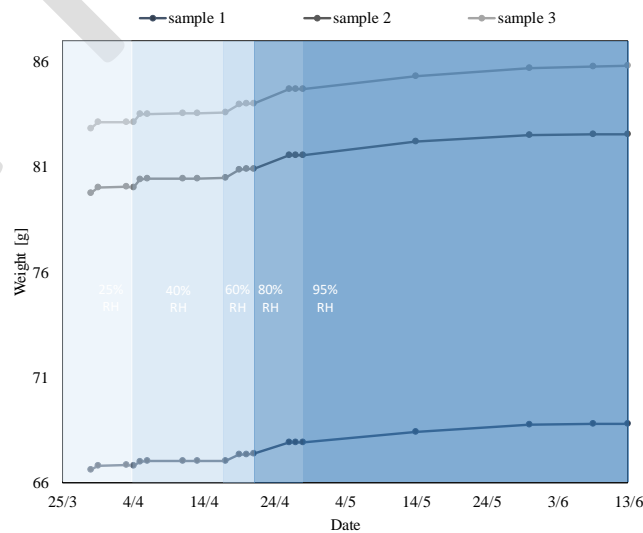
4.1.3 Hygric properties

415 Sorption isotherms for all the investigated materials were assessed and are shown in figure 4. Moreover, an  
 416 example of the kinetic of sorption of CEBs is shown in figure 5.



417

Figure 4. Sorption curves of the analyzed material



418

419

Figure 5. Evolution of mass moisture content in increasing relative humidity for CEB samples

420 It is important to point out that the first part of the sorption curve (until a relative humidity of 80%) was performed  
 421 inside a climatic chamber with a ventilation system activated. Instead, the 95% relative humidity condition was  
 422 performed inside a desiccator, without any ventilation, which made the sorption process in the last step much  
 423 slower.

424 For Delphin simulation it is important to know quantify the water content at 80%RH (the well-known W80 value),  
 425 which is found to be equal to 39.705 kg/m<sup>3</sup> for the CEB, 9E-06 kg/m<sup>3</sup> for the SB sample and 33.603 kg/m<sup>3</sup> for the  
 426 LH sample. The W80 of CEB entails good moisture storage properties.

427 Concerning the water vapor permeability test, the following values (table 8) were assessed.

428 *Table 8. Water vapor permeability and water vapor diffusion resistance factor of the material*

Test	Sample	CEB	LH	SB
Dry cup	$\delta$ [kg/m s Pa] $10^{-11}$	2.18	5.39	1.37
	$\mu$ [-]	8.87	3.65	1.41
Wet cup	$\delta$ [kg/m s Pa] $10^{-11}$	3.93	6.74	1.61
	$\mu$ [-]	4.92	2.91	1.20

429 When comparing these results with values from the literature, the water vapor permeability of CEB measured in  
 430 this study is higher compared to other raw earth products [19]; besides, the water vapor resistance factor obtained  
 431 for the lime hemp insulation is comparable with other works as [34, 35].

432 Material properties of CEB, LH and SB assessed in this study are resume and reported in table 9.

433

434 *Table 9. Resume of material properties obtained in this study*

	Dry density	Porosity	Capillary water absorption	Thermal conductivity (RH)	Specific heat capacity	W80	Water vapour res. factor
	[kg/m <sup>3</sup> ]	[%]	[kg/m <sup>2</sup> s <sup>1/2</sup> ]	[W/mK]	[J/kgK]	[kg/m <sup>3</sup> ]	[-]
CEB	1800	24.3 (core)	0.137	0.833 - 0.903	816.11	39.705	8.87
		24.9 (surface)		0.980 - 1.021			(dry cup)
LH	394.8	55	0.112	0.115 – 0.131	495.46	36.002	4.92
							(wet cup)
SB	54.6	74	0.113	0.049 - 0.059	1438	9.00E-06	3.65
							(dry cup)
							2.91
							(wet cup)
							1.41
							(dry cup)
							1.20
							(wet cup)

435

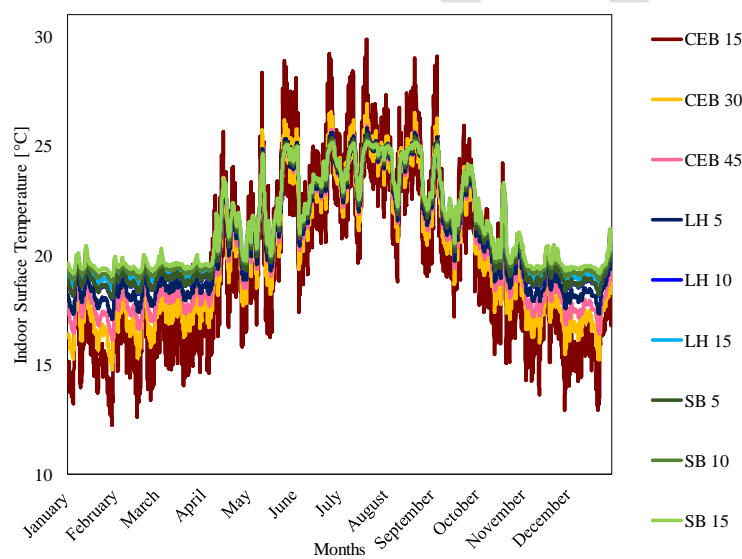
## 436 **4.2 Hygrothermal walls behavior**

437

### 438 *4.2.1 Temperature distribution and dynamic walls behavior*

439 Ensuring comfort conditions to inhabitants is one of the most essential construction requirements. Being  
 440 contemporary raw earth construction a relative new domain, there is still need to design compatible wall assemblies  
 441 which could maintain indoors at comfortable levels. In general, thermal comfort is determined by the room's  
 442 temperature, humidity and air speed, but there are many additional factors such as activity level, clothing, age,  
 443 gender and health status that affect it. Radiant heat (hot surfaces) or radiant heat loss (cold surfaces) are also  
 444 important factors for thermal comfort. Optimal microclimatic conditions are deemed to be reached for temperature  
 445 range between 19°C and 26°C, and for relative humidity between 40% and 60% [48, 49]. Moreover, relative  
 446 humidity of the wall itself is a variable which can have huge impact in the overall thermal behavior of the envelope  
 447 and in the durability of the assembly during time. Indeed too high relative humidity inside the CEB wall can result

448 in the development of pathologies or in the decrease of mechanic performances [50]. In the following lines, the  
 449 results of numerical simulation run in the reference climate of Paris (France) are presented.  
 450 In the following figure 6 it is shown the yearly profile of temperatures variation in the inmost layer of all the  
 451 investigated wall assemblies, while on figure 7 the statistical distribution corresponding to the maximum,  
 452 minimum and average values for all the tested solutions. It is possible to observe that the largest indoor surface  
 453 temperature fluctuation corresponds to the CEB 15 wall assembly which, because of its contained thickness (and  
 454 so to its poor thermal capacity) and total absence of thermal insulation layer, is the more prone to outdoor thermal  
 455 variations. Indeed, this solution has the largest value dispersion, as it reaches temperature values below 13°C and  
 456 above 29°C, indicating poor thermal performance. The increase of the wall thickness to 30 cm and to 45 cm  
 457 manage to attain average value which are comprised between 17°C and 24°C for the CEB 30, and 18°C and 23°C  
 458 for the CEB 45 solution. It is evident the benefic effects on outdoor temperature mitigation performed by the  
 459 increase of CEB wall thickness.  
 460 If we focus instead on the insulated solution LH5, LH10 and LH15 and SB5, SB10, SB 15, it is possible to point  
 461 out that the variation of average indoor surface temperatures is more contained when compared to the uninsulated  
 462 solution. Nevertheless, in LH5 and SB5 scenarios, using only 5 cm thick thermal insulations, the effect of the  
 463 thermal insulation is less marked.  
 464 In particular, all the simulated maximum indoor surface temperatures are near and all below 26°C during warmer  
 465 season, while some differences can be observed in lower temperatures, which are, for the 5 cm-thick insulated  
 466 solutions, above 17°C, and for the 10 cm and 15 cm thick insulated solution, above 19°C.  
 467 Please note that given the lower thermal conductivity of the SB insulation, the SB insulated solution have a slight  
 468 higher thermal performance compared to the LH insulated solutions. Indeed, the performance of the SB 5 and SB  
 469 10 solution is almost the same as the LH 10 and LH 15, respectively, with a gain in thermal performance for the  
 470 half of the thickness of the insulating layer.



471  
 472 *Figure 6. Yearly evolution of indoor surface temperature: temperature profiles*  
 473

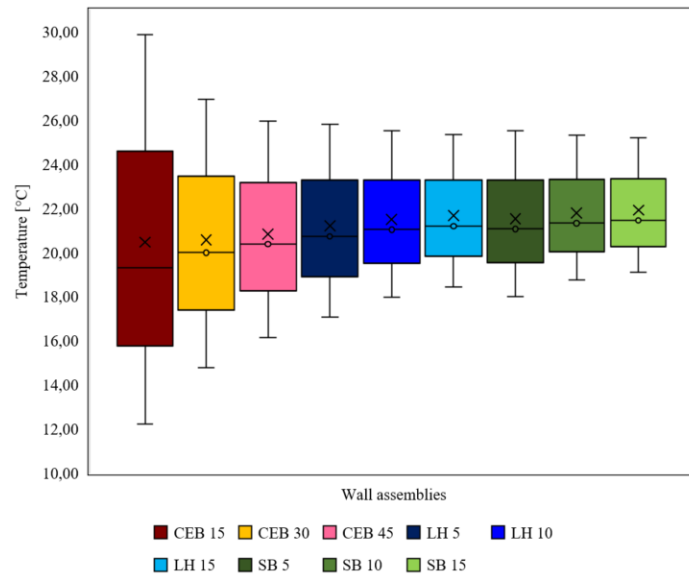


Figure 7. Yearly evolution of indoor surface temperature: statistical distribution

474

475

476 The same effect can be further observed when focusing on envelope's behavior during warmest season. In figure  
 477 8 (a, b c) are reported three graph representing the envelope behavior of the three solutions for a warm summer  
 478 week (15-21/07/2022). This week is characterized by high outdoor air temperatures which cause high outdoor  
 479 surface temperatures ( $T_{so}$ , represented by the grey profile in the graphs).

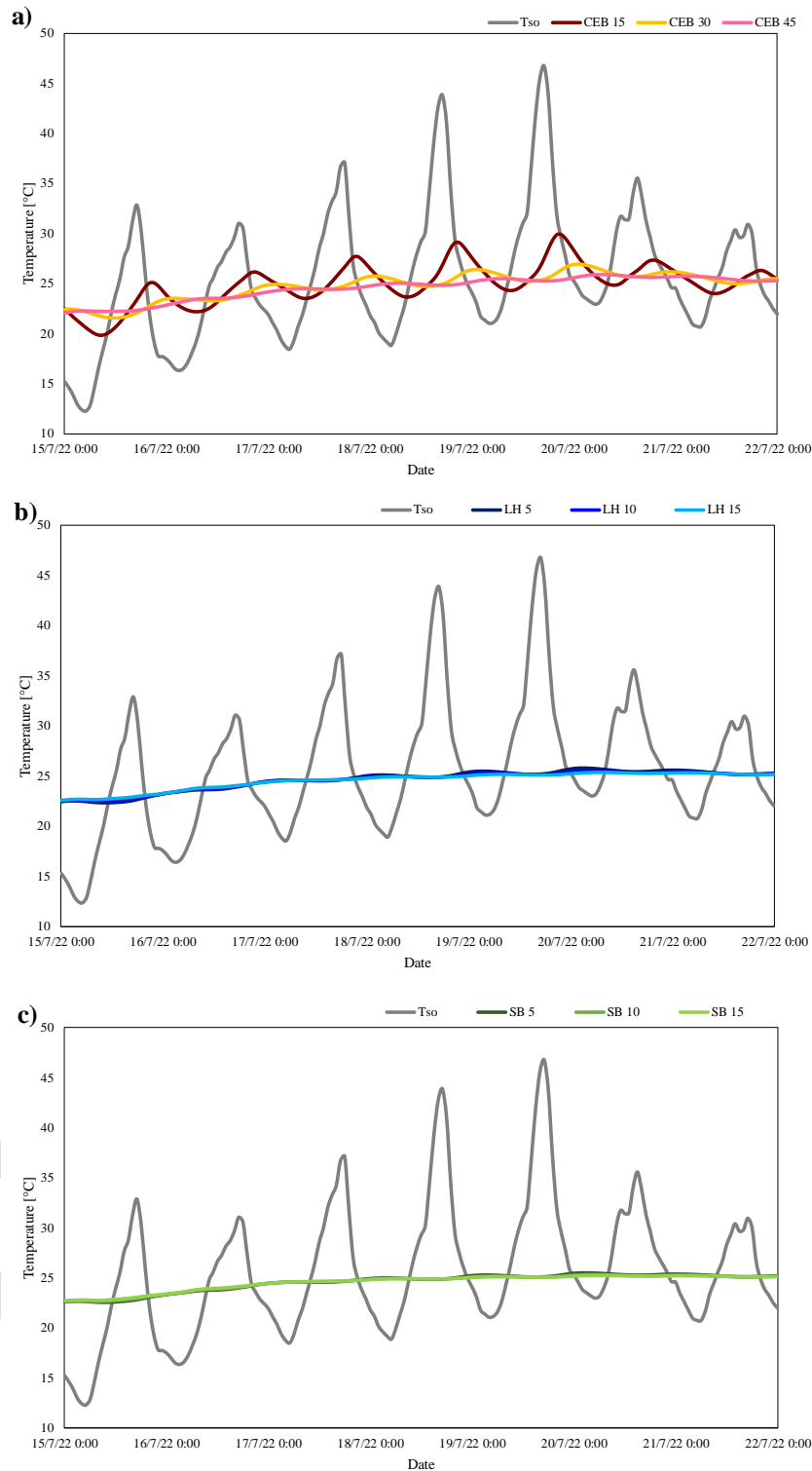
480 If we focus on the warmest week shown in the graph 8a, the influence of the CEB wall thickness on the dynamic  
 481 thermal parameters, gives a measure of the dampening and attenuation effect of massive raw earth walls on the  
 482 thermal heat wave. Concerning thermal lag, it is equal to 4.1 hours for CEB 15, 8.4 hours for CEB 30 and 14.3  
 483 hours for CEB 45 solution. At the same time decrement factor is 0.23 for CEB 15, 0.073 for CEB 30 and 0.033  
 484 for CEB 45 solution. Indeed, it is evident that a low thickness is detrimental for the thermal behavior of CEB walls,  
 485 walls thicknesses above 30 cm, which correspond to current load-bearing building technologies, reconstitute satisfying  
 486 TL and DF.

487 The addition of a 5 cm-thick insulation layer allows an increase of time lag values to 9.5 hours for lime hemp and  
 488 to 10.7 hours for sugarcane bagasse, while decrement factor values decrease to 0.02 for LH 5 and to 0.012 for SB  
 489 5 solution. Finally, for higher insulations thickness the TL and DF values are near: for 10 cm-thick lime hemp  
 490 insulation is 11.7 hours whereas for sugarcane bagasse is 11.2 hours, while DF is 0.011 for the first and 0.006 for  
 491 the latter. For 15 cm-thick insulations, TL is 13.5 hours for lime hemp and 12.8 hours for sugarcane bagasse, while  
 492 DF is 0.006 for the first and 0.004 for the latter. Calculated values for TL and DF are reported in table 10.

493

Table 10. Time lag and decrement factor of different CEB wall constructions

	<b>CEB 15</b>	<b>CEB 30</b>	<b>CEB 45</b>	<b>LH 5</b>	<b>LH 10</b>	<b>LH 15</b>	<b>SB 5</b>	<b>SB 10</b>	<b>SB 15</b>
TL [h]	4.1	8.4	14.3	9.5	11.7	13.5	10.7	11.2	12.8
DF [-]	0.230	0.073	0.033	0.020	0.011	0.006	0.012	0.006	0.004



494

495 *Figure 8. Outdoor and indoor surface temperature for uninsulated (a), lime hemp insulated (b) and sugarcane bagasse*  
 496 *insulated (c) CEB walls of different thickness*

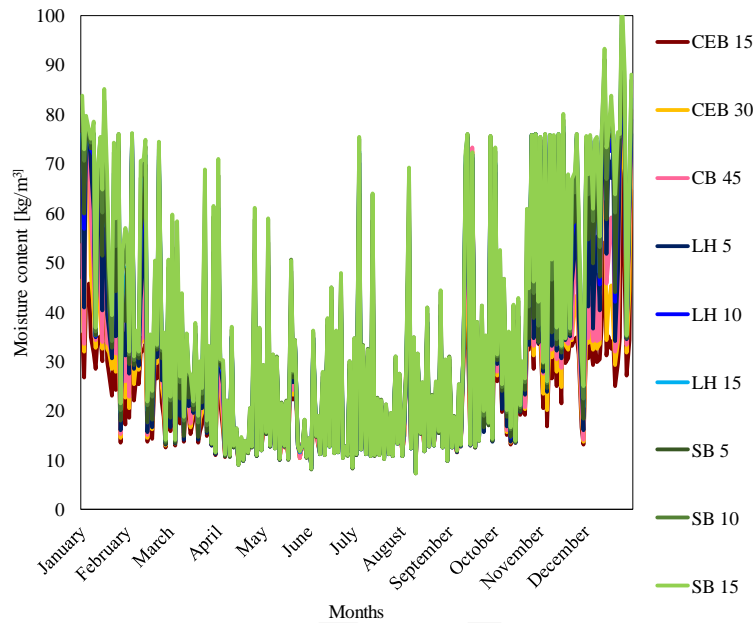
497

#### 4.2.2 Moisture dependent thermal transmittance of the walls

498 The following figures 9 and 10 show the profiles and the statistical distribution of kilograms of moisture contained  
 499 for cube meter of wall for the different wall configurations. It is evident that for uninsulated CEB walls of different  
 500 thickness the amount of water stored is really low, ranging from 16 to 30 kg/m<sup>3</sup> for the CEB 15, from 17 to 36  
 501 kg/m<sup>3</sup> for CEB 30 and from 18 to 40 kg/m<sup>3</sup> for CEB 45. The increase of wall thickness cause an increase of



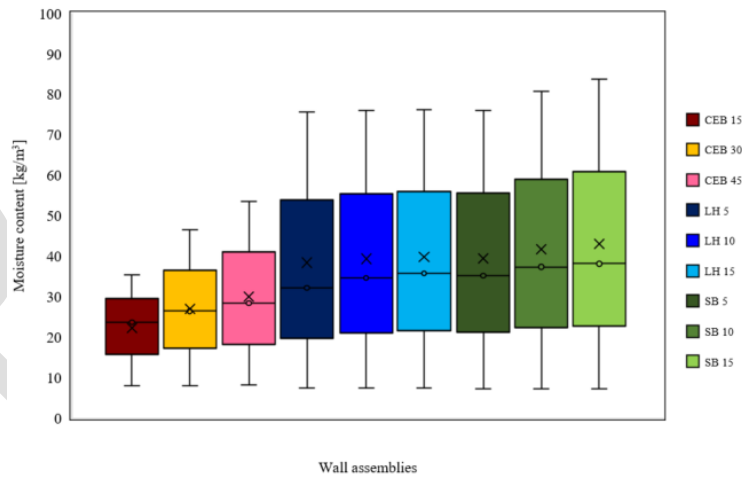
502 moisture stored inside the wall which, as we will see in the second part of this paragraph, worsens the thermal  
 503 performance of uninsulated CEB walls.  
 504 Different considerations have to be made about moisture contained inside bio-based insulated CEB walls which  
 505 store a far higher content of moisture due to the high hygroscopicity of lime hemp and sugarcane bagasse  
 506 insulations. Indeed, both LH and SB insulated wall constructions, and in particular for LH 5, LH 10, LH 15 and  
 507 SB 5 insulated CEB constructions, the moisture contained inside the wall varies, all over the year, between a  
 508 minimum value (during warmest months) of 20 kg/m<sup>3</sup> to a maximum value of 58 kg/m<sup>3</sup> (during coldest months).  
 509 Indeed, SB 10 and SB 15 have even higher moisture content, being the highest value around 62 kg/m<sup>3</sup>.



510

511

Figure 9. Yearly evolution of moisture contained in the wall: moisture content profiles



512

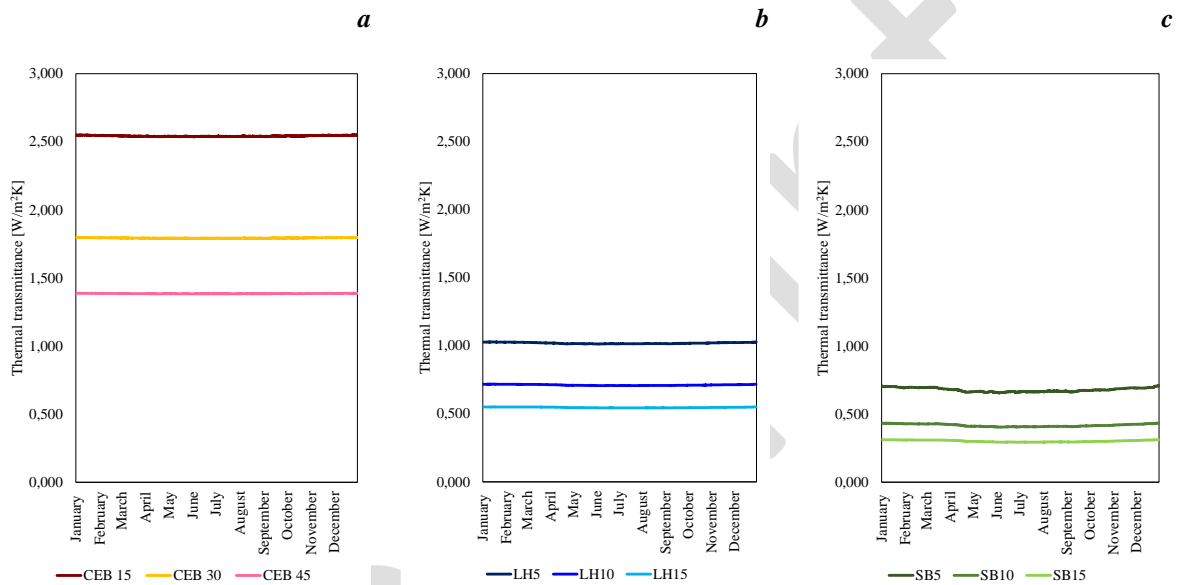
513

Figure 10. Yearly evolution of moisture contained in the wall: statistical distribution

514 Based on results of moisture contained inside the walls and values provided by Delphin software about moisture  
 515 dependent thermal conductivity for each layer, it is possible to estimate the moisture dependent U-value for the  
 516 nine investigated constructive solutions.

517 From figure 11 is it possible to observe that all along the year, thermal transmittance of uninsulated CEB walls are  
 518 quite stable; this result is confirmed in table 11 where the variations between U-value calculated in dry conditions  
 519 is compared to moisture dependent U value. Indeed, for CEB 15 solution,  $U_{dry}$  is 2.52 W/m<sup>2</sup>K and average  $U_{moist}$   
 520 is 2.54 W/m<sup>2</sup>K and the increase of U-value in moist condition is 0.69%. Similar values have been found for CEB

521 30 solution for which  $U_{dry}$  is 1.78 W/m<sup>2</sup>K, average  $U_{moist}$  is 1.79 W/m<sup>2</sup>K, with an increase of 0.69% and for CEB  
522 45, for which  $U_{dry}$  is 1.38 W/m<sup>2</sup>K and average  $U_{moist}$  is 1.39 W/m<sup>2</sup>K, with an increase of 0.70%.  
523 A different behavior is visible for bio-based insulated CEB walls, where the evolution of U-value is worsened by  
524 the presence of moisture. In particular, lime hemp insulated solution have a slight worsening of thermal  
525 performances compared to uninsulated CEB walls. For instance, LH 5 solution have an increase of U value of  
526 4.88% in moist conditions ( $U_{dry} = 0.97$  W/m<sup>2</sup>K, average  $U_{moist} = 1.02$  W/m<sup>2</sup>K). LH 10 solution presents an increase  
527 of U value of 6.49% in moist conditions ( $U_{dry} = 0.67$  W/m<sup>2</sup>K, average  $U_{moist} = 0.71$  W/m<sup>2</sup>K). Finally, LH 15  
528 solution has and increase of 7.35% of U-value ( $U_{dry} = 0.51$  W/m<sup>2</sup>K, average  $U_{moist} = 0.55$  W/m<sup>2</sup>K).  
529 Sugarcane bagasse insulated solution have the highest differences in U-value between dry and moist conditions:  
530 SB 5 solution has an increase of U-value of 10.28%, being the  $U_{dry} = 0.62$  W/m<sup>2</sup>K and the average  $U_{moist} = 0.68$   
531 W/m<sup>2</sup>K. Higher increases are visible for SB 10 solution, which have a U-value increase of 12.31% ( $U_{dry} = 0.37$   
532 W/m<sup>2</sup>K, average  $U_{moist} = 0.42$  W/m<sup>2</sup>K), and for SB 15 solution, for which U-value is increased by the 13.23% ( $U_{dry}$   
533  $= 0.27$  W/m<sup>2</sup>K, average  $U_{moist} = 0.30$  W/m<sup>2</sup>K).



534 Figure 11. Evolution of moisture dependent thermal transmittance all over the year for the investigated CEB walls:  
535 uninsulated (a), LH insulated (b) and SB insulated solutions (c)

536 Table 11. Increase of average U-values between moist and dry conditions

	CEB 15	CEB 30	CEB 45	LH 5	LH 10	LH 15	SB 5	SB 10	SB 15
$U_{dry}$ [W/m <sup>2</sup> K]	2.52	1.78	1.38	0.97	0.67	0.51	0.62	0.37	0.27
$U_{moist}$ [W/m <sup>2</sup> K]	2.54	1.79	1.39	1.02	0.71	0.55	0.68	0.42	0.30
% Increase	0.70	0.70	0.70	4.88	6.49	7.35	10.28	12.31	13.23

537

## 538 5. Conclusions

539 This work has dealt with the design of bio-based insulated compressed earth blocks walls and with the assessment  
540 of their hygrothermal behavior for use in the building vertical envelope. The base wall constructions are composed  
541 by compressed earth blocks produced by the French company *Cycle Terre* from the raw earth masses excavated  
542 for the *Grand Paris* transport network construction sites.

543 As it is well known, raw earth materials have good thermal inertia but poor thermal insulation properties. For this  
544 reason, in this work, several bio-based thermal insulations for compressed earth block walls are proposed. The

545 choice of bio-based thermal insulation is motivated by the comparable moisture storage and transport properties  
546 of compressed earth blocks and bio-based insulations as lime hemp and sugarcane bagasse. The comparability of  
547 material properties of bio-based and geo-based materials have been confirmed by an in-depth material  
548 characterization campaign which has focused on the assessment of dry density, porosity, capillary water  
549 absorption, thermal conductivity, specific heat capacity, absorption isotherms and water vapor permeability.  
550 On the base of material properties, the impact of bio-based thermal insulations on CEB walls has been studied by  
551 means of hygrothermal simulations on Delphin software, which simulates coupled heat and moisture transfers in  
552 walls, in the reference climate of Paris (France), classified as a Cfb (marine west coast climate). The simulation  
553 study has allowed to compare the impact of CEB wall thickness and bio-based insulation thickness and type on  
554 surface wall temperatures, moisture content inside the walls and to assess their impact on dynamic wall behavior  
555 and moisture dependent U-value.  
556 Concerning the influence of CEB wall thickness on the overall hygrothermal behavior, is possible to infer that thin  
557 CEB walls (15 cm) have poor thermal performances, as they lack of both thermal inertia and insulation; moreover,  
558 this type of wall does not store a high moisture content. The increase of CEB wall thickness to 30 cm and to 45  
559 cm (thicknesses which are in use for loadbearing CEB wall constructions) have a much higher inertial behavior:  
560 the time lag is 8.4 hours for the CEB 30 solution and 14.3 for CEB 45 solution, while decrement factor is below  
561 0.1. Moisture dependent U-value of these solutions is higher compared to the dry condition U-value but the  
562 increase is never above 0.70%. Considering the most common thicknesses used in raw earth construction and the  
563 comparable wall behavior between the CEB 30 and CEB 45 solution, the study on the influence of bio-based  
564 thermal insulations has been done using 30 cm-thick CEB walls.  
565 The influence of bio-based thermal insulation thickness and type on 30 cm-thick CEB walls reveal that the addition  
566 of smaller layers of thermal insulations are effective to reduce thermal transfer through walls. As known, dynamic  
567 parameters are useful to understand the wall behavior during warmer seasons. Indeed, for lime hemp (LH)  
568 insulation, the addition of 5 cm-thick thermal insulation to the CEB 30 construction, give an increase of 13% of  
569 time lag (TL) and a reduction of 72.7% of decrement factor (DF). For the same thickness, sugarcane bagasse (SB)  
570 manage to attain an increase of TL by the 27% and a reduction of 83.7% of DF. For a 10 cm-thick external  
571 insulation, the LH 10 wall has an increase of time lag of 38%, while for the SB 10 wall this increase is limited to  
572 33%; at the same time the attained DF reductions are 85.5% and 91.5% for LH 10 and SB 10 solutions. Finally,  
573 for the 15 cm-thick wall insulations, the LH 15 solution has an increase of TL of 60% and a decrease of DF by  
574 91.2%; furthermore, the SB 15 solution has an increase of TL of 52% and a decrease of DF by 94.7%. Moreover,  
575 indoor surface temperatures for all insulated solutions are really near and seasonal minimum and maximum are  
576 always comprised between 19°C (during winter) and 23°C (during summer), inside comfort values.  
577 It is then possible to infer that in warmer seasons of the analyzed climate, the use of larger insulation thicknesses  
578 is not convenient because, the relatively small increase of thermal performance (in comparison with 10-cm thick  
579 insulations) could not motivate the extra cost of a thicker insulation. From the simulation study performed in this  
580 work, it is found that a 10 cm-thick insulation (both in LH or in SB), is sufficient to ensure a satisfactory wall  
581 behavior. Moreover, it appears that in dynamic conditions, more massive thermal insulations as LH performs better  
582 compared to lightweight insulation as sugarcane bagasse.  
583 The influence of moisture in the evolution of U-value all over the year is more marked for SB insulated solutions  
584 than in LH insulated solutions. LH insulation has a poorer thermal performance compared to SB insulation, but  
585 when combined with CEB walls, it seems to provide a more stable hygrothermal behavior and a lower quantity of  
586 moisture stored inside the wall. For this reason, in the analyzed climate, LH insulated solutions seems to be more  
587 safe towards moisture related pathologies inside the walls. Future studies should focus on the lifetime behavior of  
588 bio-based insulated raw earth wall constructions, focusing on the risk of moisture related pathologies as  
589 development of mold, by comparing experimental data to previsions obtained by means of hygrothermal  
590 simulations.

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## 592 **CRedit authorship contribution statement**

593 **Giada Giuffrida:** Writing- Original draft preparation, Visualization, Investigation, Software, Data curation,  
594 Conceptualization, Methodology. **Hamza Allam:** Writing- Reviewing and Editing, Validation, Supervision,  
595 Project administration, Conceptualization, Methodology. **Laurent Ibos:** Writing- Reviewing and Editing,  
596 Supervision, Resources, Validation, Conceptualization, Methodology. **Abderrahim Boudenne:** Writing-  
597 Reviewing and Editing, Resources, Validation, Conceptualization, Methodology.

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