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Giada Giuffrida, Laurent Ibos, Abderrahim Boudenne, Hamza Allam. Analysis of the thermal performances of uninsulated and bio-based insulated compressed earth blocks walls: from the material to the wall scale. *Journal of Building Engineering*, 2024, 90, pp.109370. 10.1016/j.jobee.2024.109370 . hal-04715719

HAL Id: hal-04715719

<https://hal.u-pec.fr/hal-04715719v1>

Submitted on 13 Nov 2024

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1 Analysis of the thermal performances of uninsulated and bio-based insulated 2 compressed earth blocks walls: from the material to the wall scale

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7 The lively international debate on the future of the built environment has placed the emphasis on the
8 possibilities offered by bio and geo-based building materials. Among these, raw earth-based materials
9 offer several advantages associated to their reusability and low embodied energy.

10 Nowadays, several emerging companies are basing their corporate assets on prefabricated raw earth
11 products, as is the case of compressed earth blocks (from now on CEB). CEBs are commercialized for
12 the construction of massive vertical envelopes, characterized by a high thermal inertia. Nevertheless, in
13 order to compete with conventional building materials, it is also necessary to guarantee a high thermal
14 resistance.

15 In this work, this issue is overcome by the design and testing of full-scale uninsulated and bio-based
16 thermal insulated CEB walls. In this way, the thermal performance of CEB walls can be increased so to
17 respond to the high energy requirements which are currently adopted in European Countries.

18 More in detail, this work reports the results of the experimental thermal and physical material
19 characterization of the analyzed CEBs and of two innovative bio-based insulations (lime hemp and
20 sugarcane bagasse panels), and compared them with measurements made on full-scale uninsulated
21 and insulated CEB walls. For this purpose, walls are tested inside a double-room climatic chamber
22 where they are subjected to variable temperatures on the two faces reproducing typical indoor and
23 outdoor conditions during summer and winter conditions in a continental climate.

24 Results show the enhancement of thermal performances of compressed earth block walls when thin
25 layers of bio-based thermal insulations are added. The thermal resistance of weakly bio-based insulated
26 CEB walls is found to be nine times (for the sugarcane bagasse insulated CEB wall) and four times (for
27 the lime hemp insulated CEB wall) higher than that of uninsulated CEB walls. Moreover, the addition of
28 the insulation layers enhance the time lag and the decrement factor of compressed earth block walls.

29 *Keywords: compressed earth blocks; lime hemp; sugarcane bagasse; material characterization; thermal*
30 *performance; hot guarded box.*

31 1. Introduction

32 The built environment is the hub around which human activities are concentrated; suffice it to say that
33 in Europe people spend around 90% of their time inside buildings [1]. It is well known that Architecture,
34 Engineering and construction (AEC) sector account for the 40% of Europe's energy consumptions, while
35 generating the 36% of GHG emissions in the EU. Moreover, construction and demolition waste (CDW)
36 accounts for 25%-30% of the total European waste generation.

37 It is thus obvious the efforts made by central authorities, AEC actors and international policies in
38 providing a framework for rethinking the way we design, build and maintain the built environment over
39 time. Nowadays the reduction of energy consumptions and emission of greenhouse gases is being
40 included in various energy and environmental standards, accompanied by the need of assessing the
41 circularity of constructions and infrastructures [2].

42 The challenges herein briefly reported are at the core of the intertwined green and energy transition
43 policies promoted by the EU, and they are reflected in the three major goals identified by the *European*
44 *Construction, built environment and energy efficient building Technology Platform* (ECTP). In particular,
45 the three addressed goals are: (1) reaching clean built environment and cities, (2) built for and with the
46 people and (3) generate prosperous construction ecosystem.

47 In this context, new production lines using more sustainable components and materials are being
48 developed. Bio-based materials, waste materials and urban mining [3], with their reduced environmental
49 impacts in the production phase, are at the core of several industries assets as it happens for *Cycle*
50 *terre* company (France), whose production of earth-based products derives from the excavations of the
51 *Grand Paris* infrastructure network.

52 Compressed earth blocks are building products made from a damp mix of raw earth, sand and eventually
53 a stabilizer (cement or lime). This earth mix is then poured into steel presses and compressed either
54 with a mechanic or a pneumatic process. The compaction of the earth mixes allows for the increase of
55 the block density and consequently the improvement of the block's mechanical performances. As a
56 consequence of their increased density and reorganization of their macrostructure by the compaction
57 process, CEBs' thermal conductivity can change, as we will see in the following paragraphs. Due to their
58 density, CEBs are endowed with high thermal inertia but poor thermal insulating properties [4, 5].
59 There is therefore a need to enhance the thermal performance of CEB envelopes in order to reduce
60 heat losses in winter and heat gains in summer. To achieve these results, building envelopes with
61 adequate inertial mass but also appropriate thermal resistance are needed. In this sense, it seems to
62 be promising the design of CEB walls in simple, double or more complex wall configurations, as for
63 instance cavity wall or insulated wall, in combination with insulations layers endowed with compatible
64 vapor permeability values to CEB ones.

65 Several works have focused on the assessment of the thermal behavior of raw earth historical walls built
66 in different techniques (rammed earth, adobe [4]), while few studies focused on contemporary raw earth
67 building techniques [5], and even less on the combination of raw earth walls coupled with thermal
68 insulations [6, 7, 8].

69 In absence of insulation panels [5], five different types of earth products, including proctor compacted
70 full blocks, hypercompacted full blocks, hypercompacted full blocks with hemp fibres, hypercompacted
71 hollow blocks and conventional fired bricks are tested at the material and at the wall scale. The bulk and
72 dry density, the porosity and the water content of these samples are assessed. Moreover, the earth
73 blocks and the fired bricks are equalized at three different levels of relative humidity (RH%=25%,
74 RH%=62% and RH%=95) at a constant temperature of 23°C. Under these conditions, thermal
75 conductivity is measured using a hot disk apparatus. For the fired bricks, thermal conductivity is around
76 0.75 W/mK for every RH% condition. For the hypercompacted and hemp bricks, thermal conductivity
77 slightly varies between 1.45 W/mK and 1.55 W/mK for the firsts, and from 1.30 W/mK to 1.35 W/mK for
78 the seconds; this change in performance is due to their low porosity. For the proctor bricks, the lower
79 porosity allows a higher moisture storage inside the blocks, causing an increase of thermal conductivity:
80 indeed, it ranges from 0.85 W/mK to 1.35 W/mK. At the wall scale, wall samples constituted by the same
81 earth products are tested inside a hot guarded box (HGB) equipment, in static and dynamic conditions.
82 Results of this study show that the fired bricks wall, despite having a lower thermal conductivity at a
83 material scale, performs worse than the unfired earth blocks wall due to its incapacity of storing and
84 exchanging pore water with the environment. Proctor unfired earth blocks wall performs better than
85 hypercompacted unfired earth block wall because of its lower density and consequently, lower thermal
86 conductivity (0.94 W/mK compared to 1.33 W/mK). The addition of hemp fibers in the hypercompacted
87 unfired earth blocks, produces an improvement of the thermal performance at a wall scale by the 4.5%
88 (1.27 W/mK compared to 1.33 W/mK).

89 In presence of insulation panels [6] two wall types were compared in two test boxes, the first one realized
90 with a 0.29-m thick rammed earth wall and the other using the same construction system with a 0.06 m
91 exterior layer of wood fiber insulation panel and a straw-clay render. Walls are monitored in a Csa
92 climate. For the uninsulated rammed earth south wall is found a thermal lag between 6.5 h and 9 h
93 (respectively for sunny and cloudy days), while for the insulated rammed earth south wall is found a
94 thermal lag between 8.2h and 9.8h (respectively for sunny and cloudy days). Moreover, the thermal
95 stability coefficient TSC (i.e. the ratio between outside thermal amplitude and south wall thermal
96 amplitude) is comprised between 0.191 and 0.256 for the uninsulated rammed earth box and between
97 0.030 and 0.059 for the insulated rammed earth box. The authors conclude that in the case of thin
98 rammed earth walls, the use of an external layer of thermal insulation achieve better dynamic
99 parameters compared to uninsulated rammed earth and other conventional construction technologies
100 [6].

101 Another study investigates the opportunities of combining cob earth walls with bio-based thermal
102 insulation [7]. In particular, this work focuses on the design of two types of cob mixes: the best dense
103 mix has a thermal conductivity of 0.45 W/mK, and the best light mix (called thermal cob and obtained
104 by incorporating hemp shiv in the earth matrix) has a thermal conductivity of 0.12 W/mK. On the base
105 of these material properties, the authors design a dual layer monolithic cob wall, and calculate a total
106 thermal resistance of 3.35 m² K/W, i.e., U-value of 0.30 W/ m² K.

107 A similar study has been developed in [9], which tested rammed earth walls and lightweight earth panels
108 in a heat flow meter with guarded ring. A combined wall using an interior layer of 0.03-m thick lightweight
109 earth panels and an exterior layer of 0.12 m-thick rammed earth has an attenuation value comprised
110 between 0.53 and 0.83 and a thermal lag comprised between 3.87 h and 4.07 h.
111 Another study on possible thermal insulation for raw earth walls has been proposed by [8]. In this case,
112 adobe walls were insulated from the inside with 0.05 m-thick reed mattress realized with a cane growing
113 spontaneously in the Andean lakes. The addition of this thin thermal insulation layer, together with other
114 bioclimatic design strategies at the building scale, allowed keeping the indoor air temperatures always
115 above 5°C with positive peaks at 15°C, even when outdoor temperature lies below 0°C.
116 This work aims at advancing the state of knowledge on the convenience of combining massive walls
117 made of unfired earth (and in particular of compressed earth blocks) with bio-based thermal insulations.
118 The choice fell on bio-based insulations for their renowned low embodied carbon [10, 11] and for their
119 compatibility in terms of water vapor permeability values with earth-based materials [7, 9, 8].
120 The effectiveness of these types of insulations on CEB walls was evaluated in a Hot Guarded Box
121 equipment, as done before by Bruno et al [5]. Compared to this work, the present study focuses on the
122 difference in thermal behavior between uninsulated CEB walls, and CEB walls insulated with lime hemp
123 panels or sugarcane bagasse panels. The walls are tested in a double climate chamber that allows to
124 apply different temperatures on the two faces of the wall, in order to reproduce typical indoor and outdoor
125 conditions. In this study, two types of tests were carried out on the walls: a set of static tests to determine
126 the heat flow exchanged between indoors and outdoors under stationary conditions, resulting in the
127 assessment of the thermal resistance of the wall in question; and a dynamic test to evaluate the inertial
128 characteristics of the insulated and uninsulated CEB wall. Results show the interest of using natural
129 materials for CEB façade insulation.

130

131 **2. Materials and methods**

132 **2.1 Materials**

133 *Compressed earth block (CEB)*

134 Compressed earth blocks are made by compacting damp admixtures of raw earth and aggregates in mechanical
135 or pneumatic presses. The CEBs used in this study are realized with a mix made of 65% of raw earth (composed
136 by clays, silts, sands and small gravels) and 35% sand (with a particle size distribution comprised between 0 and 2
137 mm or from 0 to 4 mm) from Paris region [12]. The environmental performance of 0.30 m thick CEB walls has been
138 calculated by the manufacturing company *Cycle Terre* and it has been found a footprint of 27.8 kg eq CO₂ [12] for
139 the production phase of 1 m² functional unit. In the literature, dry density ranging from 1600 kg/m³ to 2760 kg/m³
140 have been found [13]. In [14], the specific heat capacity of earth brick is assessed to be 869 J/kg K, whereas in [15]
141 is found a value of 1000 J/kg K; moreover in [16], it is assessed to be equal to 808 J/kg K. Finally, thermal
142 conductivity of CEBs seems to be strictly correlated with dry density values. Indeed, in [13, 17] thermal conductivity
143 of CEBs range from 0.62 W/mK to 1.48 W/mK, the large dispersion of values being due to the change in dry density.

144 *Lime hemp (LH)*

145 Lime-hemp or hempcrete is a biomass-based product, which is currently used for non-load-bearing purposes in
146 new construction to produce blocks for walling systems, but also for roof insulation. The use of hemp shivs and lime
147 or cement leads to insulating mixes with low dry density (ranging from 200 kg/m³ to 800 kg/m³) and thermal
148 conductivity values (ranging from 0.06 W/m K to 0.18 W/m K) [18]. Lime hemp or hempcrete materials have also
149 high specific heat capacity, being it around 1500 J/kg K in the dry state and up to 2900 J/kg K at 99% RH [19].

150 *Sugarcane bagasse (SB)*

151 Sugarcane bagasse is an agricultural waste, a byproduct obtained after extraction of the juice from sugarcane stalks
152 [20]. Various studies [20, 21] reported that its chemical composition is composed by cellulose, hemicellulose, lignin.
153 The cellulose content of sugarcane bagasse helps to reduce the use of synthetic binders. Considering the
154 abundance of sugarcane bagasse, it is currently investigated as an ideal raw material to produce low-cost green
155 thermal insulation which could also satisfies environmental regulations, given its biodegradability and reusability.
156 Previous studies found that sugarcane bagasse insulation materials exhibited thermal conductivity ranging from
157 0.03 to 0.05 W/m K for densities between 100 kg/m³ and 200 kg/m³ [20]. Sugarcane bagasse panels used in this
158 study were provide by *Emerwall* company.

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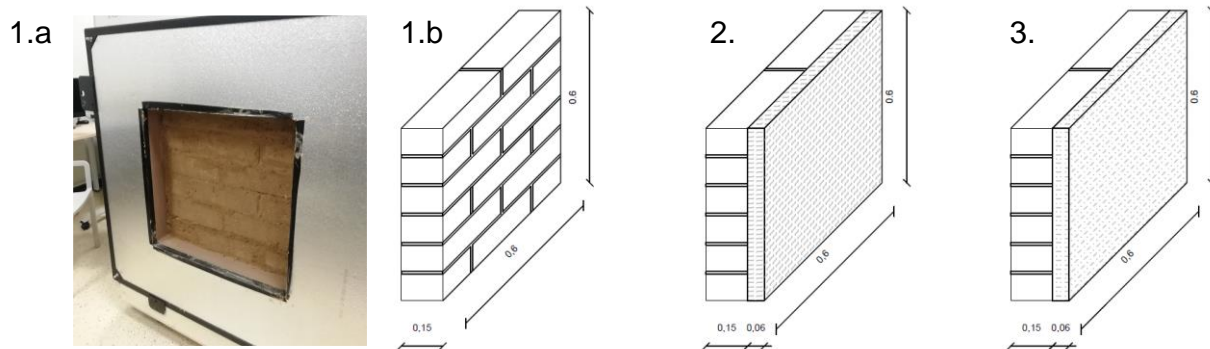
Table 1. Material properties found in the literature

Material / Supplier	Material composition	Dry density [kg/m ³]	Specific heat capacity [J/kg K]	Thermal conductivity [W/m K]
CEB (Cycle Terre)	raw earth, sand [12]	1600 – 2760 [13]	869 [14] 1000 [15] 808 [16]	0.62 – 1.48 [13, 17]
Lime Hemp	Hemp shives, lime [18, 19] cellulose,	200 - 800 [18]	1500 – 2900 [19]	0.06 – 0.18 [18]
Sugarcane Bagasse (Emerwall)	hemicellulose, lignin [20, 21]	100 – 200 [20]	-	0.03 – 0.05 [20]

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Combined walls

In this work three 0.60 x 0.60 m CEB walls have been tested. The first one is an uninsulated compressed earth wall (CEB wall) with a thicknesses of 0.15 m. The second wall, is composed by a 0.15 m thick compressed earth block wall combined with a 0.06 m-thick sugarcane bagasse panel (CEB+SB wall). The third wall is realized by juxtaposing a 0.15 m thick compressed earth block wall to a 0.06 m-thick lime hemp insulation (CEB+LH wall). The insulation layers are always applied to the outmost layer of CEB walls in order to take advantage of the thermal inertia of the CEB wall, according to what has been found in previous research [7, 22, 23]. A scheme of the tested walls is given in figure 1.



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Figure 1. CEB wall (1a and 1b), sugarcane bagasse insulated CEB wall (2) and lime hemp insulated CEB wall (3)

2.2 Methods

2.2.1 Material characterization

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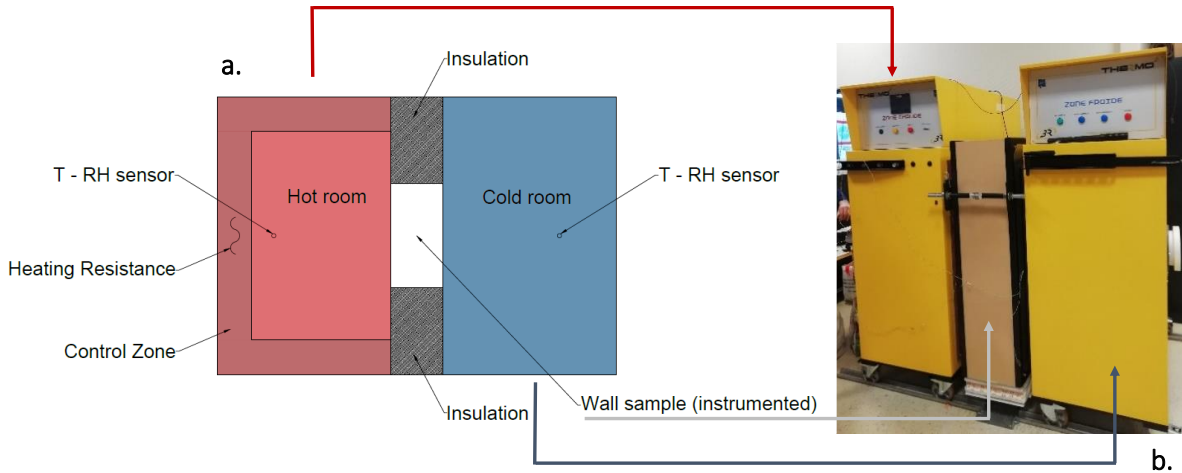
A material characterization campaign was carried out on the three materials studied: compressed earth blocks (CEB), lime hemp (LH) and sugarcane bagasse (SB) thermal insulations. The characterization comprises the assessment of dry density, specific heat capacity and temperature dependent thermal conductivity.

Dry density of samples was assessed after oven-drying of samples 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 assessed via a caliper).

Temperature dependent thermal conductivity was assessed after conditioning 0.02 m-thick CEB and 0.06 m-thick LH and SB samples in an oven, at increasing temperatures of $T = 25^{\circ}\text{C}$, $T = 30^{\circ}\text{C}$, $T = 35^{\circ}\text{C}$ and $T = 40^{\circ}\text{C}$. Thermal conductivity and specific heat capacity were assessed when samples' mass was stabilized: more in detail, a condition of mass stabilization $m_{(t, t+24)} < 0.1\%$ was adopted because of the need of adopting bigger sizes of samples due to minimal thermal conductivity measurement area. The samples were kept in the oven during the thermal conductivity measurements with a Hot Disk device (NF EN ISO 22007-2), a transient method using a flat probe that serves both as a heating device and a temperature sensor. The probe is placed between two identical, smooth, flat samples to avoid contact with air. This measurement method allows the determination of thermal conductivity and heat capacity for any temperature, with a fast and reliable procedure. Please note that specific heat capacity values were calculated by dividing the pc_p obtained from the Hot Disk by the density of samples assessed at each tested temperature. The Kapton 5501 probe with a radius of 6.403 mm, a power of 90 mW and a measurement time of 80 s was used for the measurement of CEB thermal conductivity. The Kapton 8563 probe with a radius of 9.868 mm was used both for LH and SB samples, with a measurement time of 80s and a power of 33mW for LH and 30mW for SB.

196 **2.2.2 Procedure for assessing walls thermal performance**

197 The wall samples described in paragraph 2.1 were tested inside a Thermo3 equipment, a double-room climatic
 198 chamber by 3R company. This equipment is a hot guarded box used to test full-scale walls. It is composed by two
 199 separates room, a cold and a hot room, which are thermally insulated from external effects by two guarded control
 200 zones. During a test, the difference in temperature between the two rooms create a unidirectional heat flow which
 201 cross the walls to be tested. Figure 2 shows a schema of the machine.

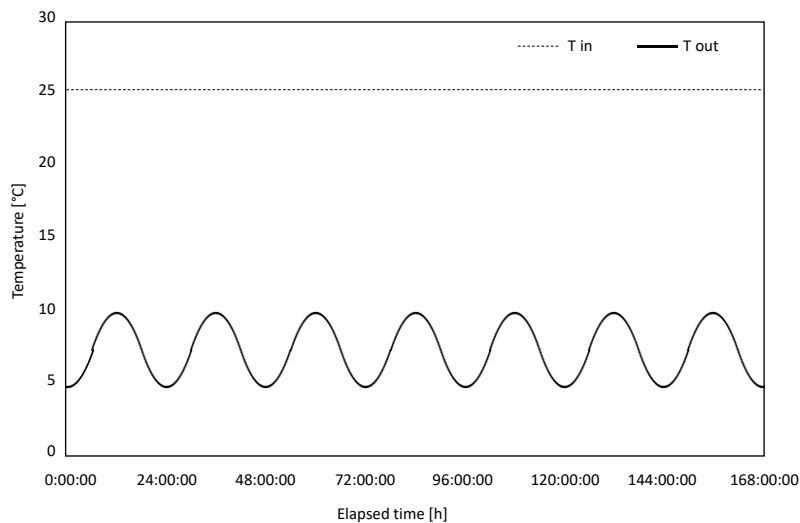


202 *Figure 2. Schematic plan of the double room climatic chamber (a) and double room climatic chamber with testing frame (b)*
 203

204 In the hot room, the temperature is regulated by two heating resistances (200 W for zone) supplied at low voltage
 205 (48 VDC), located in the outer hot guarded zone. The resistances are activated each time that heat is lost from the
 206 hot to the cold room, and the amount of energy released is registered and then averaged in order to assess the
 207 heat flow through the wall. It is important to remark that the hot room is not equipped with a refrigerator system, fact
 208 which means that the temperature can never decreased, but only be increased. The range of admissible
 209 temperatures of the hot room goes from 20°C to 50°C.

210 The cold room is equipped with a refrigeration unit 450 W, with a cold exchanger connected to the cold zone and a
 211 hot exchanger connected to the outside. The cold room is able to increase and decrease its temperature setpoints,
 212 allowing the setting of temperature cycles. The range of admissible temperatures of the cold room goes from -20°C
 213 to 30°C.

214 The three wall samples are subjected to two types of tests, simulating both summer and winter seasons. In terms
 215 of winter behavior, the walls are tested under dynamic condition by using the Thermo3 option "Daily cycle". This
 216 option allows the setting of a constant temperature in the hot room and of a sinusoidal cycle (entirely described by
 217 a maximum and a minimum temperature value and a period) on the cold room. In this test, a constant temperature
 218 of 25°C is maintained in the hot room, while the cold room's temperatures vary between 5°C and 10°C with a 24
 219 hours' period. A scheme of the winter dynamic testing conditions is shown in figure 3.



220 *Figure 3. Winter dynamic testing conditions*
 221

222 The propagation of temperature profiles on the wall exposed to a variable outdoor air temperature is assumed to
 223 be sinusoidal. In the passage from outdoor to indoor surface of the wall, the amplitude of the sinusoidal temperature
 224 wave is reduced [22]. In order to quantify the thermal mass of the wall assemblies, Time lag (TL) and Decrement
 225 Factor (DF) dynamic parameters are assessed. Time lag is defined as the time interval required for the thermal
 226 wave to pass from the outer surface to the inner surface of the wall. It can be expressed by the formula:

227
$$TL = t_{T_{so,max}} - t_{T_{si,max}}$$

228 Where t is the time at which the peaks of indoor ($T_{si,max}$) and outdoor ($T_{so,max}$) surface temperatures occur. Time lag
 229 is expressed in hours.

230 The decrement factor is the ratio between the amplitude of inner surface temperatures and the amplitude of outer
 231 surface temperatures, and can be calculated as follows:

232
$$DF = \frac{T_{si,max} - T_{si,min}}{T_{so,max} - T_{so,min}}$$

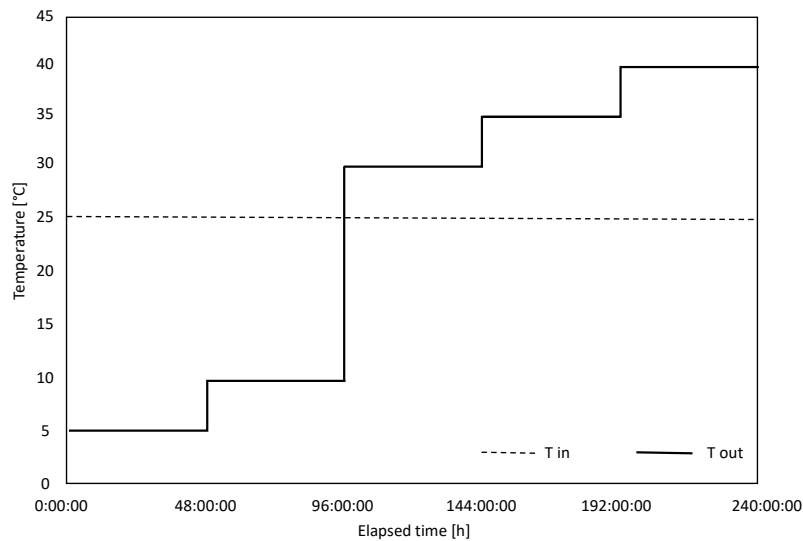
233 Moreover, in the same weather and wall configuration (winter behavior, CEB wall with an exterior layer of thermal
 234 insulation), the wall is tested under static condition in order to assess its thermal resistance when the hot room
 235 temperature is 25°C, and the cold room temperatures are $T=5^{\circ}\text{C}$ and $T=10^{\circ}\text{C}$.

236 Due to the limitations of the cold room in admissible temperatures range and to the absence of a refrigeration unit
 237 on the hot room which could enable the decrease of the temperature, the summer behavior cannot be assessed in
 238 dynamic conditions, so it has been estimated in static conditions. In particular, three thermal resistance measures
 239 have been performed, by maintaining the indoor temperature constant at 25°C, and by increasing the outdoor
 240 temperature at $T=30^{\circ}\text{C}$, $T=35^{\circ}\text{C}$ and $T=40^{\circ}\text{C}$. Due to the limitation in admissible temperatures in the cold room, the
 241 position of wall is inverted compared to the winter behavior, so in the summer tests the indoor is simulated by the
 242 cold room and the outdoor is simulated by the hot room of the equipment.

243 The assessment of thermal resistance is done by the formula:

244
$$R = \frac{T_{s,hot} - T_{s,cold}}{\varphi}$$

245 Where $T_{s,hot}$ is the surface temperature on the hot side of the wall, $T_{s,cold}$ is the surface temperature on the cold side
 246 of the wall, φ is the heat flow measured in W/m^2 . A scheme of both winter and summer static testing conditions is
 247 shown in figure 4.



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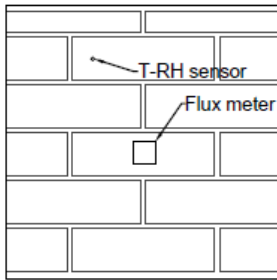
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Figure 4. Static testing conditions

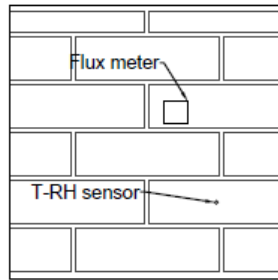
250 The positions and the types of instrumentations are reported in the following figure 5 and 6. The sensibilities of the
 251 sensors are shown in table 1.

CEB wall

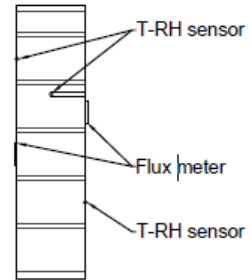
Indoor side



Outdoor side

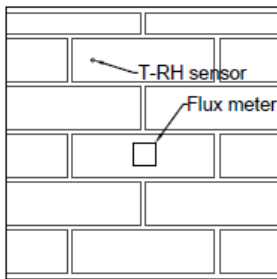


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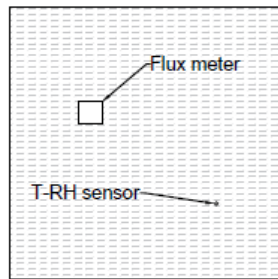


CEB + SB wall

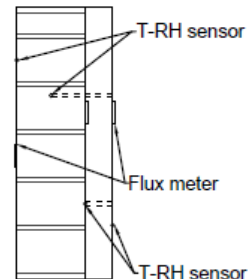
Indoor side



Outdoor side

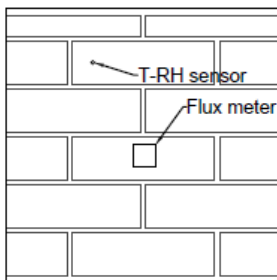


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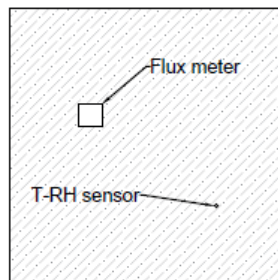


CEB + LH wall

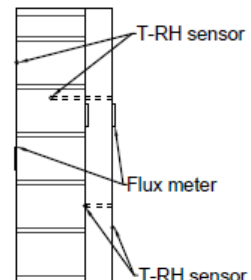
Indoor side



Outdoor side



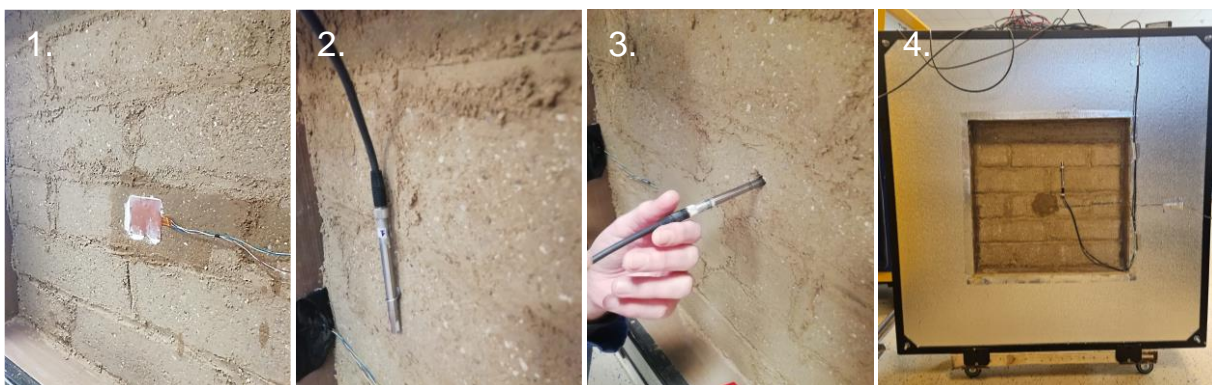
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Figure 5. Wall instrumentation scheme



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Figure 6. Instrumentation of CEB walls: installation of heat flow meter (1), T-RH sensors (2, 3), final refinements (4)

256

Table 1. Type and position of sensors used

Wall	Type of Sensor	Position
BTC	Heat Flow meter Captec 22.9 $\mu\text{V}/\text{W}^{-1}\text{m}^{-2}$	Indoor surface
	Heat Flow meter Captec 22.9 $\mu\text{V}/\text{W}^{-1}\text{m}^{-2}$	Outdoor surface
	3 T-RH sensors DKRF400	Indoor surface
		0.075 m deep inside the wall
BTC + SB	Heat Flow meter Captec 22.9 $\mu\text{V}/\text{W}^{-1}\text{m}^{-2}$	Indoor surface
	Heat Flow meter Captec 22.9 $\mu\text{V}/\text{W}^{-1}\text{m}^{-2}$	Interface between CEB wall and insulation
	Heat Flow meter Captec 66.3 $\mu\text{V}/\text{W}^{-1}\text{m}^{-2}$	Outdoor surface
	4 T-RH sensors DKRF400	Indoor surface
		0.075 m deep inside the wall
		Interface between CEB wall and insulation
BTC + LH	Heat Flow meter Captec 15.2 $\mu\text{V}/\text{W}^{-1}\text{m}^{-2}$	Indoor surface
	Heat Flow meter Captec 22.6 $\mu\text{V}/\text{W}^{-1}\text{m}^{-2}$	Interface between CEB wall and insulation
	Heat Flow meter Captec 60.0 $\mu\text{V}/\text{W}^{-1}\text{m}^{-2}$	Outdoor surface
	4 T-RH sensors DKRF400	Indoor surface
		0.075 m deep inside the wall
		Interface between CEB wall and insulation
	Outdoor surface	

258 A resume of the wall configurations, and of static and dynamic test conditions is reported in table 2.

259

Table 2. Tested conditions in the Hot Guarded Box

WALL CONFIGURATION	STATIC CONDITIONS		DYNAMIC CONDITIONS
CEB	Winter conditions $T_{in} = 25^{\circ}\text{C}$ $T_{out} = 5^{\circ}\text{C}, 10^{\circ}\text{C}$	Summer conditions $T_{in} = 25^{\circ}\text{C}$ $T_{out} = 30^{\circ}\text{C}, 35^{\circ}\text{C}, 40^{\circ}\text{C}$	Winter conditions $T_{in} = 25^{\circ}\text{C}$ T_{out} cyclic [5;10] T=24h
	Winter conditions $T_{in} = 25^{\circ}\text{C}$ $T_{out} = 5^{\circ}\text{C}, 10^{\circ}\text{C}$	Summer conditions $T_{in} = 25^{\circ}\text{C}$ $T_{out} = 30^{\circ}\text{C}, 35^{\circ}\text{C}, 40^{\circ}\text{C}$	Winter conditions $T_{in} = 25^{\circ}\text{C}$ T_{out} cyclic [5;10] T=24h
CEB + SB	Winter conditions $T_{in} = 25^{\circ}\text{C}$ $T_{out} = 5^{\circ}\text{C}, 10^{\circ}\text{C}$	Summer conditions $T_{in} = 25^{\circ}\text{C}$ $T_{out} = 30^{\circ}\text{C}, 35^{\circ}\text{C}, 40^{\circ}\text{C}$	Winter conditions $T_{in} = 25^{\circ}\text{C}$ T_{out} cyclic [5;10] T=24h
	Winter conditions $T_{in} = 25^{\circ}\text{C}$ $T_{out} = 5^{\circ}\text{C}, 10^{\circ}\text{C}$	Summer conditions $T_{in} = 25^{\circ}\text{C}$ $T_{out} = 30^{\circ}\text{C}, 35^{\circ}\text{C}, 40^{\circ}\text{C}$	Winter conditions $T_{in} = 25^{\circ}\text{C}$ T_{out} cyclic [5;10] T=24h
CEB + LH	Winter conditions $T_{in} = 25^{\circ}\text{C}$ $T_{out} = 5^{\circ}\text{C}, 10^{\circ}\text{C}$	Summer conditions $T_{in} = 25^{\circ}\text{C}$ $T_{out} = 30^{\circ}\text{C}, 35^{\circ}\text{C}, 40^{\circ}\text{C}$	Winter conditions $T_{in} = 25^{\circ}\text{C}$ T_{out} cyclic [5;10] T=24h
	Winter conditions $T_{in} = 25^{\circ}\text{C}$ $T_{out} = 5^{\circ}\text{C}, 10^{\circ}\text{C}$	Summer conditions $T_{in} = 25^{\circ}\text{C}$ $T_{out} = 30^{\circ}\text{C}, 35^{\circ}\text{C}, 40^{\circ}\text{C}$	Winter conditions $T_{in} = 25^{\circ}\text{C}$ T_{out} cyclic [5;10] T=24h

260

261 3. Results and discussion

262 3.1 Material properties

263 The material properties assessed in this study have been reported in the following tables. In particular,
264 the dry density of compressed earth blocks, sugarcane bagasse and lime hemp are reported in table 3.

265

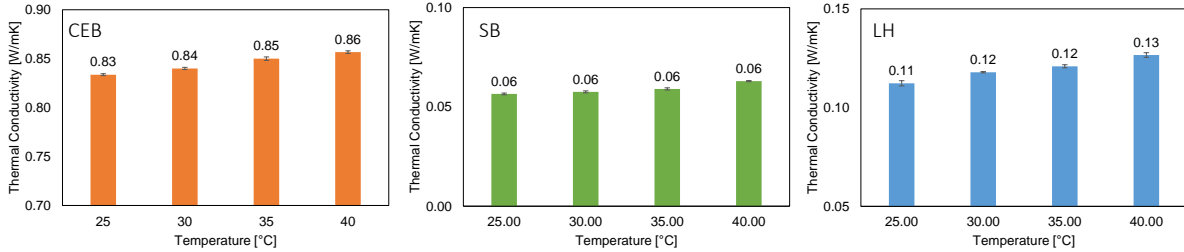
Table 3. Dry density of the analyzed materials

	CEB	SB	LH
Dry density [kg/m^3]	1800 \pm 3	55 \pm 2	395 \pm 8

266

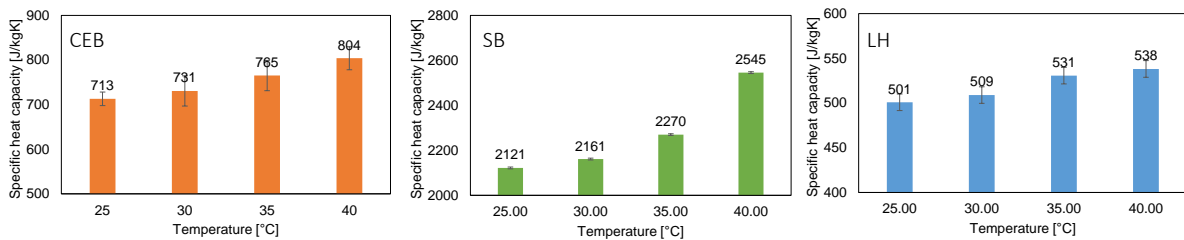
267 Figure 7 reports the values of thermal conductivity measures made on the analyzed samples as
268 temperature varies between 25°C and 40°C. Observing the results, it is evident that all the insulating

269 materials as SB and LH show little variation of thermal conductivity as the temperature increase. Indeed,
 270 SB thermal conductivity is constant to 0.06 W/mK when temperature increase from 25°C to 40°C, while
 271 LH thermal conductivity ranges from 0.11 W/mK when T=25°C to 0.13 W/mK when T=40°C. Conversely,
 272 massive materials as CEB have a slightly higher thermal conductivity variation: their thermal conductivity
 273 passes from 0.83 W/mK when T=25°C to 0.86 W/mK when T=40°C. We can therefore conclude that no
 274 significant variation in thermal conductivity is observed with varying temperatures.



275
 276 *Figure 7. Temperature dependent thermal conductivity of the analyzed materials*

277 We will now focus on figure 8. Specific heat capacity values were calculated by dividing the ρc_p obtained
 278 from the Hot Disk by the density of samples at each temperature. It was observed a reduction of dry
 279 density of samples for increasing testing temperature, fact which could be explained by the loss of some
 280 residual moisture contained inside the samples. The c_p of CEB samples varies from 713±15 J/kg K to
 281 804±26 J/kg K for temperatures raising from 25°C to 40°C. For SB samples, they range from 2121±4
 282 J/kg K to 2545±4 J/kg K and for LH samples from 501±9 J/kg K to 538±10 J/kg K, when temperature is
 283 increased from 25°C to 40°C.



284
 285 *Figure 8. Temperature dependent specific heat capacity of the analyzed materials*

286 3.2 Walls thermal performances

287 3.2.1 Static conditions

288 As anticipated in section 2.2.2, the three investigated walls were tested under several stationary
 289 conditions. In particular, indoor temperature was set to 25°C, while the outdoor one simulated both
 290 winter ($T_{out} = 5^\circ\text{C}$, $T_{out} = 10^\circ\text{C}$) and summer conditions ($T_{out} = 30^\circ\text{C}$, $T_{out} = 35^\circ\text{C}$, $T_{out} = 40^\circ\text{C}$). In particular,
 291 the abovementioned outdoor air temperatures for summer conditions were chosen to allow a
 292 comparison between the R-values assessed by the Hot Guarded Box equipment and the R-values
 293 calculated from the hot disk measurements at a material scale.

294 Throughout the tests, heat flow entering ϕ_{in} and leaving ϕ_{out} the walls were monitored by means of the
 295 heat flow meters installed on the inmost and outmost faces of the wall, and steady-state condition was
 296 deemed to be attained when the two flows were constant across the wall for at least 24 hours. During
 297 the test, it was observed that a time interval of at least 48 hours for the walls was enough to achieve the
 298 steady-state condition.

299 Figure 9 shows the heat flow values calculated in the last 24 hours of the test for all the investigated
 300 wall configurations. Please note that in the calculation of the R-value, only the heat flow entering in the
 301 wall (ϕ_{in}) was considered, to avoid the phenomenon of thermal diffusion [24].

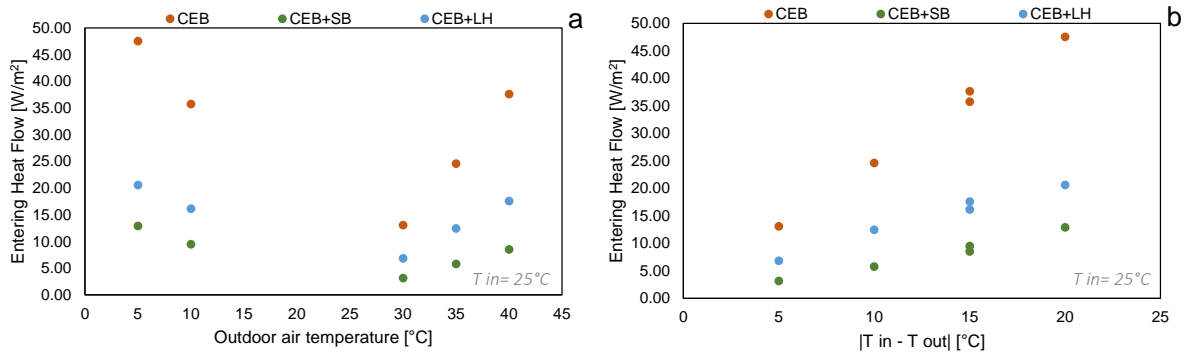
302 By observing the plotted values in figure 9, it is possible to remark that heat flow values for CEB wall
 303 are more scattered compared to those of CEB+SB wall and CEB+LH wall. Furthermore, heat flow in the
 304 insulated solutions is much lower and near for all the tested temperature conditions. In particular, for the
 305 CEB wall, in the $T_{out}=5^\circ\text{C}$ condition the ϕ_{in} is 47.55 W/m², in the $T_{out}=10^\circ\text{C}$ condition the ϕ_{in} is 35.74

306 W/m^2 , in the $T_{out}=30^\circ C$ condition the ϕ_{in} is $13.08 W/m^2$, in the $T_{out}=35^\circ C$ condition the ϕ_{in} is $24.59 W/m^2$
 307 and in the $T_{out}=40^\circ C$ condition the ϕ_{in} is $37.63 W/m^2$. Indeed, the lower the temperature difference
 308 between indoor and outdoor, the lower the heat flow across the wall; besides, it is possible to affirm that
 309 the measured heat flows are quite high, due to the relatively high thermal conductivity of compressed
 310 earth blocks.

311 For the CEB+SB wall, in the $T_{out}=5^\circ C$ condition the ϕ_{in} is $12.92 W/m^2$, in the $T_{out}=10^\circ C$ condition the ϕ_{in}
 312 is $9.51 W/m^2$, in the $T_{out}=30^\circ C$ condition the ϕ_{in} is $3.17 W/m^2$, in the $T_{out}=35^\circ C$ condition the ϕ_{in} is 5.78
 313 W/m^2 and in the $T_{out}=40^\circ C$ condition the ϕ_{in} is $8.53 W/m^2$. By comparing these heat flow values to the
 314 ones of the uninsulated CEB wall it is easy to remark the benefic effect of thermal insulation in
 315 decreasing the heat exchange between the indoor and the outdoor.

316 For the CEB+LH wall in winter static conditions, for the $T_{out}=5^\circ C$ condition the ϕ_{in} is $20.59 W/m^2$, while
 317 for the $T_{out}=10^\circ C$ condition the ϕ_{in} is $16.15 W/m^2$. Instead, in summer static conditions, for the $T_{out}=30^\circ C$
 318 condition the ϕ_{in} is $6.83 W/m^2$, for the $T_{out}=35^\circ C$ condition the ϕ_{in} is $12.44 W/m^2$ and for the $T_{out}=40^\circ C$
 319 condition the ϕ_{in} is $17.58 W/m^2$. These heat flow values are less than half the heat flows for the
 320 corresponding conditions in the uninsulated CEB wall configuration, but they are in general more than
 321 double the heat flows in the CEB+SB wall configuration.

322 It is also possible to observe that between all the tested conditions there is a global decrease in the heat
 323 flow, with a minimum around $T=25^\circ C$ followed by an increase (see figure 9a). In figure 9b the measured
 324 heat flow values are plot against the absolute value of the differences between T_{in} and T_{out} .

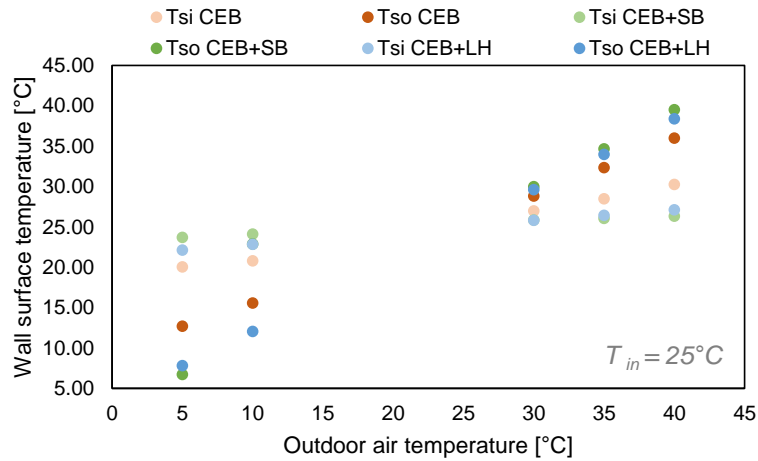


325
 326 *Figure 9. Heat flow entering into the wall for CEB, CEB+SB and CEB+LH wall configurations plotted against outdoor air*
 327 *temperature (a) and against the absolute value of the difference between indoor and outdoor air temperature (b)*

328 Figure 10 shows the wall surface temperatures evolution for each wall and tested temperature condition.
 329 In the graph are reported both indoor (T_{si}) and outdoor (T_{so}) surface temperatures. Differently from [5],
 330 who, analyzing the behavior of several uninsulated unfired earth walls, observed the strong dependency
 331 of wall temperatures to the imposed environmental conditions, in our study the indoor surface
 332 temperature values between different wall configurations are quite scattered (as it is shown in figure 11a
 333 and 11b).

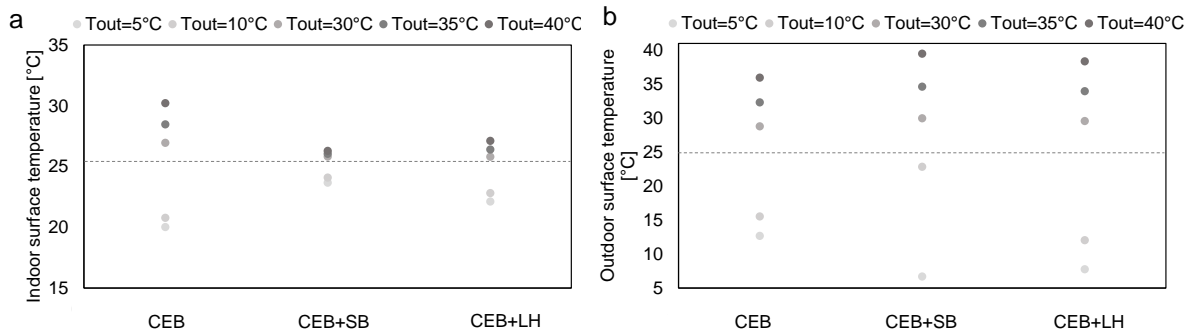
334 Indeed, for the CEB wall, the $T_{si} = 20^\circ C$ when $T_{out}=5^\circ C$, $T_{si} = 20.8^\circ C$ when $T_{out}=10^\circ C$ and T_{si} ranges from
 335 $27.0^\circ C$ to $30.2^\circ C$ when T_{out} goes from $30^\circ C$ to $40^\circ C$.

336 Instead, for the CEB+SB wall, the indoor surface temperatures between all the tested conditions are
 337 more similar between them, as they are mitigated by the insulation layer. In particular, they range from
 338 $T_{si} = 23.7^\circ C$ when $T_{out}=5^\circ C$ to $T_{si} = 26.3^\circ C$ when $T_{out}=40^\circ C$. Finally, for the CEB+LH wall, the indoor
 339 surface temperatures range from $T_{si} = 22.1^\circ C$ when $T_{out}=5^\circ C$ to $T_{si} = 27.1^\circ C$ when $T_{out}=40^\circ C$.



340
341
342

Figure 10. Wall surface temperatures in static conditions for CEB, CEB+SB and CEB+LH wall configurations (indoor air temperature $T = 25^\circ\text{C}$)



343
344

Figure 11. Effect of thermal insulation on indoor surface temperature (a) and outdoor surface temperature (b)

345 As explained in section 2.2.2, the heat flow and the surface temperatures measured inside the Hot
346 Guarded Box equipment allowed, in steady-state conditions, for the assessment of the thermal
347 resistance for all the examined walls. Thermal resistance values are reported in figure 12. For the CEB
348 wall, the assessed thermal resistance varies between $0.14 \text{ m}^2\text{K/W}$ and $0.16 \text{ m}^2\text{K/W}$ for the different
349 imposed temperature conditions. For the CEB+SB wall the thermal resistance ranges from $1.31 \text{ m}^2\text{K/W}$
350 to $1.55 \text{ m}^2\text{K/W}$. Finally, for the CEB+LH wall the thermal resistance fluctuates between $0.55 \text{ m}^2\text{K/W}$
351 and $0.70 \text{ m}^2\text{K/W}$. We notice that the maximum of thermal resistance in the CEB wall configuration is found
352 in the $T_{out}=35^\circ\text{C}$ condition; for the CEB+SB wall configuration in the $T_{out}=40^\circ\text{C}$ condition, and for the
353 CEB+LH wall configuration in the $T_{out}=5^\circ\text{C}$ condition.

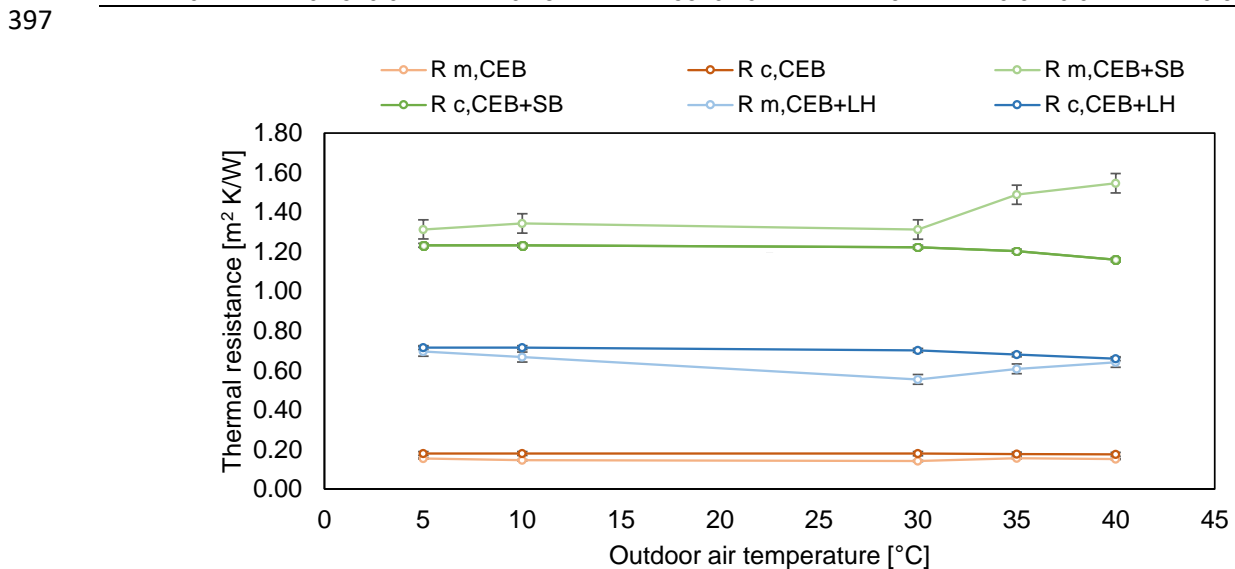
354 In this study, it seemed to be interesting to compare the measured thermal resistance values to those
355 which can be calculated from the thermal conductivity values reported in section 2.2.1. It is important to
356 remember that in this work thermal conductivity measurements were made by means of a Hot Disk
357 Equipment at different temperatures (ranging from 25°C to 40°C with differences of 5°C), but thermal
358 conductivity was not assessed in correspondence of $T=5^\circ\text{C}$, $T=10^\circ\text{C}$ due to setup limitations. For these
359 conditions the calculated thermal resistance relies on thermal conductivity values measured at 25°C .
360 For all the other conditions (respectively those using $T_{out}=30^\circ\text{C}$, 35°C , 40°C), the calculated thermal
361 resistance value is evaluated by considering an average thermal conductivity between the indoor side
362 and the outdoor side of each material used in each wall configuration. So, for instance for the static
363 condition $T_{in}=25^\circ\text{C}$ and $T_{out}=35^\circ\text{C}$ of CEB wall, the calculated thermal resistance is an average between
364 the R calculated with $\lambda_{25^\circ\text{C}}$ (temperature condition on the inmost side of the wall) and the one calculated
365 with $\lambda_{35^\circ\text{C}}$ (temperature condition on the outmost side of the wall). It is possible to make this assumption
366 because the surface temperatures are near to the nominative air temperatures of the two chambers.
367 The same principle is adopted for the two CEB insulated wall solutions.

368 Measured (R_m) and calculated (R_c) values of thermal resistance for all the wall configurations are
369 reported in table 4 and plotted in figure 12. Comparing the two set of values, we can observe that the

370 calculated values (R_c) are higher than the measured values (R_m) for the CEB wall configuration and for
 371 the CEB+LH wall configuration, while for the CEB+SB wall configuration the opposite condition occurs.
 372 If we calculate the difference between measured and calculated thermal resistances in the three test
 373 conditions, it is possible to observe that for the CEB wall, it is around $0.03 \text{ m}^2\text{K/W}$, for the CEB+SB wall
 374 it is on average $0.19 \text{ m}^2\text{K/W}$, and for the CEB+LH wall is on average $0.06 \text{ m}^2\text{K/W}$. This fact reveals that
 375 the CEB wall configuration is the one having the best fitting between the measured and the calculated
 376 thermal resistance values, followed by the CEB+LH wall configuration. The CEB+SB wall configuration
 377 has the highest gap between calculated and measured values of thermal resistance.
 378 The difference between calculated and measured thermal resistance values can have several
 379 explanations. First of all, calculated values are based on the Hot disk measurements, which rely on a
 380 small depth of the material (below 1 cm), while the thermal resistance measured in the HGB involve the
 381 full thickness of CEBs and insulations. In this sense, eventual inhomogeneities of the CEBs and
 382 insulation materials might not be reflected in the λ -values calculated via the Hot disk, but would influence
 383 the R-value assessment at the wall scale.
 384 Furthermore, in this work the influence of the laying earth mortar has not been considered as its
 385 percentage on the surface of the tested wall is fairly lower than the surface occupied by the CEBs (in
 386 particular, the surface occupied by the mortar is the 7.4% of the total surface). Nevertheless, the
 387 quantification of the contribution of the mortar layers is an aspect that should be addressed in future
 388 works.
 389 Moreover, the gap between calculated and measured values could be due to the particular humidity
 390 conditions during the test (which were not controlled due to setup limitations).
 391 Finally, an explanation for the higher gap between R_c and R_m values found for CEB+SB wall
 392 configuration (in particular for higher outdoor air temperature conditions) may be found in the possible
 393 presence of air leaks in the test setup, influencing the assessment of R_m . In particular some residual air
 394 resistance could be located at the interface between the sugarcane bagasse panel and the compressed
 395 earth block wall.

396 *Table 4. Measured and calculated thermal resistance values for different outdoor air temperature*

T_{out} [°C]	CEB		CEB+SB		CEB+LH	
	$R_{measured}$ [m ² K/W]	$R_{calculated}$ [m ² K/W]	$R_{measured}$ [m ² K/W]	$R_{calculated}$ [m ² K/W]	$R_{measured}$ [m ² K/W]	$R_{calculated}$ [m ² K/W]
5	0.15±0.01	0.18	1.31±0.07	1.23	0.70±0.04	0.72
10	0.15±0.01	0.18	1.34±0.03	1.23	0.67±0.05	0.72
30	0.14±0.02	0.18	1.31±0.15	1.22	0.55±0.07	0.70
35	0.16±0.02	0.18	1.49±0.12	1.20	0.61±0.05	0.68
40	0.15±0.01	0.18	1.55±0.10	1.16	0.64±0.04	0.66

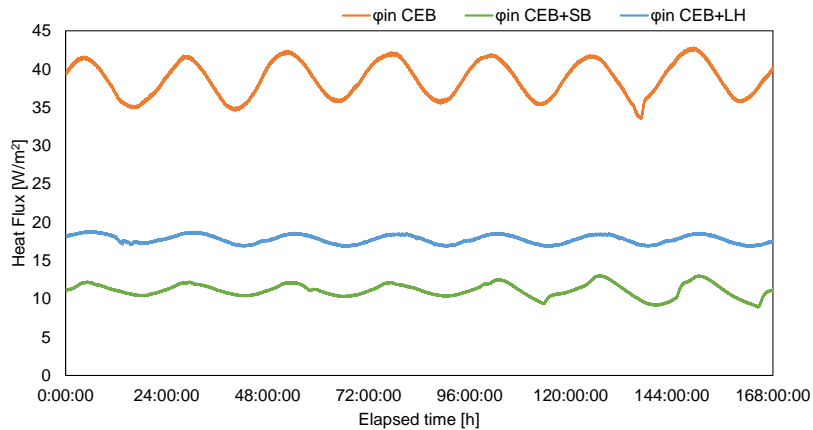


398 *Figure 12. Measured and calculated thermal resistance of CEB, CEB+SB and CEB+LH wall configurations*
 399

400

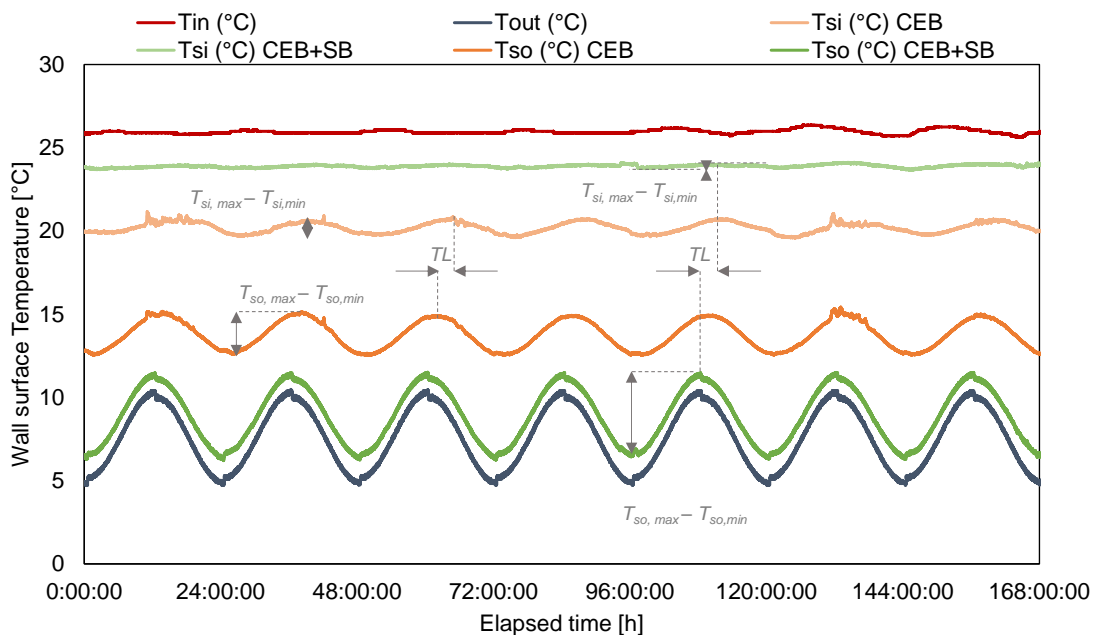
401 **3.2.2 Dynamic conditions**

402 Under winter conditions, a dynamic test, reproducing a daily cyclic oscillation between 5°C and 10°C, is
 403 performed on the three tested wall configurations. Figure 13 reports the heat flow across the three walls
 404 under 7-days of test. In this work, the presence of wall insulation radically changes wall's behavior. The
 405 phases of the heat flow for the CEB+SB and CEB+LH walls are delayed with respect to the one of the
 406 CEB wall. The intensity of heat flow for the CEB wall is quite high, and oscillating between 41.5 W/m²
 407 and 35.06 W/m². If we now compare the behavior of the two insulated solution, the lowest heat flow is
 408 the one guaranteed by the CEB+SB wall solution, with heat flow values oscillating between 12.95 W/m²
 409 and 9.03 W/m². The CEB+LH wall has heat flow values which varies 18.75 W/m² and 16.86 W/m².

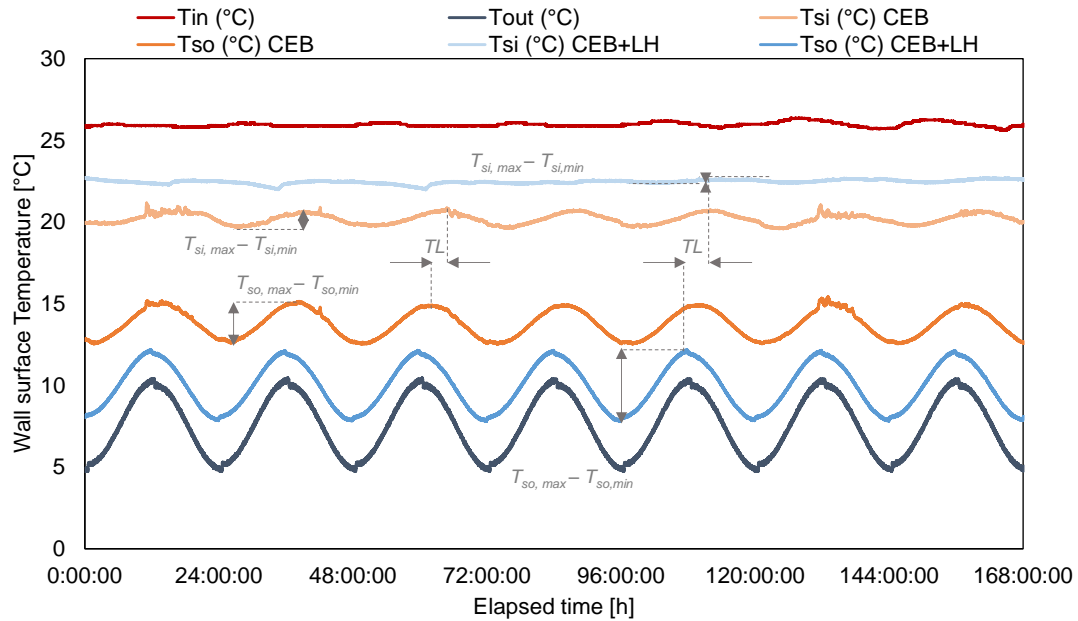


410
 411 *Figure 13. Heat flow across the tested walls under winter dynamic test conditions*

412 We will now focus on the inertial behavior of the walls, and we will analyze the data which are reported
 413 in figure 14 and 15. First, when observing the indoor surface temperature values in CEB, CEB+SB and
 414 CEB+LH wall solutions, only the CEB+SB and CEB+LH solutions manage to attain values near to the
 415 indoor air temperature of 25°C. Indeed, the absence of thermal insulation in the CEB solution cause a
 416 decrease in T_{si} values, which range from 19.7 °C to 20.9 °C values which, in a living space, could have
 417 effect on the comfort of the inhabitants. This issue is exasperated by the contained thickness of the CEB
 418 wall. Conversely, CEB+SB wall have T_{si} values which range from 23.7 °C to 24.0 °C, and CEB+LH wall
 419 has temperatures which range between 22.0 °C and 22.6 °C, both nearer to comfort conditions.



420
 421 *Figure 14. Daily cycle for CEB and CEB+SB wall configurations*



422

423

Figure 15. Daily cycle for CEB and CEB+LH wall configurations

424 On the base of the indoor (T_{si}) and outdoor (T_{so}) surface temperatures of the three wall configurations,
 425 and considering the time delay between the outdoor and indoor peak, it is possible to assess the time
 426 lag and decrement factor values. These parameters, which were defined in section 2.2.2, are the
 427 expression of the inertial behavior of the wall. Average results for TL and DF over 7-days of test are
 428 reported in table 5 together with other data found in the literature. It is interesting to remark the benefic
 429 effect of the thermal insulations in increasing the time lag and decreasing the decrement factor.

430

Table 5. Time lag and decrement factor for all the tested wall configurations and comparison with literature values

Type of wall	Reference	Average TL [h]	Average DF [-]
Hypercompacted brick (0.10 m)	[5]	1.43	0.40
Fired brick (0.11 m)	[5]	1.50	0.28
Hemp brick (0.10 m)	[5]	2.00	0.45
Uninsulated RE (0.29 m)	[6]	6.50 – 9.00	0.191 – 0.256
Wood fiber (0.06 m) insulated RE (0.29 m)	[6]	8.20 – 9.80	0.030 – 0.059
Light earth (0.03 m) insulated RE (0.12 m)	[9]	3.87 – 4.07	0.530 – 0.830
CEB (0.15 m)	<i>This study</i>	3.78	0.369
CEB+SB (0.15 m + 0.06 m)	<i>This study</i>	4.80	0.049
CEB+LH (0.15 m + 0.06 m)	<i>This study</i>	6.90	0.049

Note: RE (rammed earth), CEB (compressed earth block)

431 In table 5 we compare the results obtained in this study to those found in the literature. In particular,
 432 note that TL and DF of [5] were calculated by the Authors from figure 10 of [5]. For a 0.11-m thick fired
 433 brick wall [5], the time lag is around 1.5 hours, while the decrement factor is about 0.28. At the same
 434 way, it is possible to calculate that for a 0.10-m thick hypercompacted brick wall [5], the time lag is
 435 around 1.43 hours and the decrement factor is around 0.4. In [6], the uninsulated rammed earth wall,
 436 0.29 m thick, has a time lag ranging between 6.50 and 9.00 hours and a decrement factor comprised
 437 between 0.191 – 0.256. The use of 0.06 m thick wood fiber thermal insulation increase time lag values
 438 to 9.80 hours and decrease decrement factor values to 0.03 [6]. Finally, 0.03 m thick light earth insulated
 439 rammed earth (0.12 m thick), has a time lag ranging from 3.87 to 4.07 hours and a decrement factor
 440 comprised between 0.53 and 0.83.

441 Values for uninsulated raw earth walls [5, 6] are in line with results found in this study for the 0.15 m-
 442 thick CEB wall: in particular it is easy to observe that the differences on dynamic wall's parameters
 443 compared to values of [5, 6] are likely to be due to the increased wall's thickness used in present study.
 444 The results found for the bio-based insulated wall configurations [6, 9 and this study] confirm that the
 445 use of thin layers of thermal insulation can be preferable to the lightening of earth mixtures in order to

446 enhance the dynamic thermal parameters of the walls. Indeed, the time lag values found in this study
447 are 4.8 hours for the CEB+SB wall and 6.9 hours for the CEB+LH wall. These values are higher than
448 those of a wall realized by lightening the compressed earth wall with hemp fibers (the hemp brick wall
449 in [5]) for which it is calculated a time lag of 2 hours. This is confirmed by the decrement factor value
450 found in this study for the uninsulated solution (0.049), which is below the 0.45 value calculated from
451 [5]. Moreover, our CEB+SEB and CEB+LH wall configurations seem to perform better than [9], both in
452 terms of TL and DF, and have comparable values to [6] even if the thicknesses of materials used are
453 lower.

454 **4. Conclusion**

455 This work focused on compressed earth blocks (CEB) walls characterization at a material and at wall
456 scale. The analyzed CEB wall configurations included an uninsulated 0.15 m thick CEB wall, and two
457 bio-based insulated walls, one using 0.06 m-thick sugarcane bagasse insulation (CEB+SB wall) and the
458 other using 0.06 m-thick lime hemp wall insulation (CEB+LH wall).

459 Materials used in this study were characterized concerning their dry density, and temperature dependent
460 thermal conductivity and specific heat capacity were assessed by means of a Hot Disk equipment. In
461 particular, thermal properties were assessed at 25°C, 30°C, 35°C and 40°C.

462 Full-scale wall's thermal behavior was studied in a Hot Guarded Box equipment, which allowed for the
463 testing of both static and dynamic thermal conditions. The three wall configurations were tested under
464 winter dynamic conditions (by setting an indoor air temperature of 25°C, and a varying sinusoidal
465 outdoor air temperature between 5°C and 10°C), from which were calculated two dynamic thermal
466 parameters, time lag and decrement factor. Moreover, five sets of static tests were performed on the
467 three walls, by maintaining an indoor air temperature of 25°C and increasing outdoor air temperature
468 from 5°C, to 10°C, 30°C, 35°C and 40°C. The measures of surface temperatures and heat flows from
469 the static tests were used to measure the thermal resistance on site. Finally, the thermal resistance
470 values measured on site for each outdoor temperature condition were compared to the thermal
471 resistances calculated from thermal conductivity values assessed at the material scale.

472 Results on walls' thermal resistance show that there is a slight difference between R-value calculated
473 from the thermal conductivity assessments done at a material scale and R-value calculated on full-scale
474 walls. In particular, this study finds out that for CEB and CEB+LH wall configurations, calculated R-
475 values are higher than measured R-values, while for CEB+SB wall the opposite condition occurs, and
476 measured R-values are higher than calculated R-values for all the tested temperatures. This can be
477 explained by the presence of some residual air layer between the sugarcane bagasse panel and the
478 compressed earth blocks walls in the tested setup, or by a competing effect of relative humidity.

479 In general, thermal resistance of weakly bio-based insulated CEB walls are found to be nine times (for
480 the CEB+SB wall) and four times (for the CEB+LH wall) higher than that of uninsulated CEB wall.

481 The dynamic test conditions allowed for the estimation of indoor surface temperatures (T_{si}) for a wide
482 series of outdoor air temperatures. For the CEB wall, T_{si} range from 19.7 °C to 20.9 °C. For the CEB+SB
483 wall, T_{si} range from 23.7 °C to 24.0 °C, and for CEB+LH wall temperatures range between 22.0°C and
484 23.0 °C.

485 Dynamic thermal parameters found in this study confirm the optimal potentialities of CEB walls to
486 guarantee comfortable indoor conditions. For a 0.15 m-thick CEB wall the time lag is 3.78 hours, while
487 for the CEB+SB wall is 4.8 hours and for the CEB+LH wall is 6.9 hours. Besides, the decrement factor
488 of CEB wall is 0.369, while for both the bio-based insulated CEB walls is 0.049.

489 Future studies will have to focus on the influence that different relative humidity conditions (determined
490 for example by different vapor concentration classes depending on the intended use of the building) can
491 have on the static and dynamic behavior of CEB walls. In this sense, the choice of combining bio-based
492 thermal insulations with CEBs will be additionally scrutinized through the lens of material compatibility
493 from a hygrometric point of view. In addition, the behavior of uninsulated and bio-based insulated CEB
494 walls should be tested in cyclic hygrothermal conditions, in order to estimate the effect of the
495 hygrothermal fatigue on these materials. Finally, the execution of cyclic tests in climate-controlled
496 chambers, which could reproduce the real operating conditions of full-scale earthen walls, including the
497 effect of rain and solar radiation, would allow predicting the seasonal behavior of the walls and the
498 durability of these technological solutions over time.

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500 **CRedit authorship contribution statement**

501 **Giada Giuffrida:** Writing- Original draft preparation, Visualization, Investigation, Software, Data
502 curation, Conceptualization, Methodology. **Laurent Ibos:** Writing- Reviewing and Editing, Investigation,
503 Software, Data curation, Supervision, Resources, Validation, Conceptualization, Methodology.
504 **Abderrahim Boudenne:** Writing- Reviewing and Editing, Resources, Validation, Conceptualization,
505 Methodology. **Hamza Allam:** Writing- Reviewing and Editing, Validation, Supervision, Project
506 administration, Conceptualization, Methodology.

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508 **Acknowledgements**

509 The authors want to acknowledge *Cycle Terre* and *Emerwall* Companies for the interest in the research
510 and the continuous technical exchange.

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