Rammed earth walls in Mediterranean climate: material characterization and thermal behaviour

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Abstract

Rammed earth is considered a very sustainable construction system due to its low embodied energy, long service life and high recyclability. However, authors found that there is a lack of experimental results at real scale regarding rammed earth thermal behaviour. For this reason, this paper is first focused on the characterization of two different types of earth in order to check the suitability of being used in rammed earth walls. After the characterization, two experimental cubicle-shape buildings were built in Barcelona and Puigverd de Lleida (Spain) in order to test the thermal behaviour of their walls in two different climatic conditions. Temperature profiles inside walls have been monitored using thermocouples and temperature profile of southern walls was analysed in free floating conditions during summer and winter periods of 2013. Results show that thermal amplitude from outside to inside temperatures are decreased by rammed earth walls, achieving constant temperatures in inner surface of southern walls.

Keywords: sustainable; earth building; experimental set-up; low embodied energy materials

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1 INTRODUCTION

Nowadays, a large amount of high embodied energy materials are used in conventional construction, which involves high energy costs during their life cycle (extraction, manufacture, transportation, construction and disposal). As Cabeza *et al.* [1] states, operation embodied energy is taken into account in many studies. However, evaluating the embodied energy in materials is more complex and time consuming, for this reason it is not done although it accounts for a high proportion of the total embodied energy of a building. The reduction of building sector carbon emissions is mandatory in the European Union [2, 3]; therefore, new policies have been promoted all over the world to construct sustainable buildings and hence to reduce CO_2 emissions.

Rammed earth is considered a very sustainable solution due to its low embodied energy, small materials treatment process, long service life and high recyclability [4]. Moreover, transportation CO_2 emissions can be reduced if on-site excavation earth is used as a rammed earth material. Thus, rammed earth follows the European requirements [3], a fact that increases the scientific interest of its use.

Historically, earth building has been an answer to the housing demand of populations from all over the world. However, in recent history the use of rammed earth declined with the use of other modern construction techniques during the Industrial Revolution. After the 1st World War, rammed earth was undertaken in UK and, after the 2nd World War, in East Germany. In the last centuries, rammed earth was used in extreme conditions (after a war, for example) in Europe because the material required was available in many parts of the world and it had no cost. Likewise, the use of Portland cement since 1824, iron and steel have pushed rammed earth away from conventional construction [5]. Unfortunately, Spanish building regulations [6] do not include rammed earth as a building material and this fact hinders its use [7].

From an energy point of view, earth walls have a good thermal behaviour due to their high mass and can contribute, with proper natural ventilation strategies, to the indoor building comfort providing high thermal inertia to deal with the

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day–night temperature changes [8, 9]. Constructions with high thermal mass, such as rammed earth wall buildings, slow heat transfer into and out of the building [10]. However, rammed earth has important structural limitations, especially, in multi-storey buildings. These limitations are aggravated in modern construction systems, where smaller wall thicknesses are needed to optimize the useful floor area. However, these structural limitations can be avoided if rammed earth is used as an enclosure.

The aim of this investigation is to physically and mechanically characterize two different earthen materials (from two different building sites in the north-eastern of Spain—Barcelona and Puigverd de Lleida) in order to check the possibility of being used as construction materials. This characterization is done by testing the particle size distribution and thus, classifying the earth used. Furthermore, compressive strength of rammed earth samples that have different stabilizers, such as cement, expanded clay and straw is tested at laboratory scale. Authors found that there is a lack of thermal analysis and, therefore, experimental results at real scale with rammed earth buildings in the literature. For this reason, after the characterization at laboratory scale, two rammed earth house-like cubicles were built in Barcelona and Puigverd de Lleida (Spain) and were properly monitored in order to test the thermal behaviour of their walls in summer and winter conditions in two different climates.

2 MATERIALS

Rammed earth can be classified as stabilized and non-stabilized. Non-stabilized rammed earth consists entirely of clay, silt, sand, gravel and water. Stabilized rammed earth includes other materials in order to improve its properties. In the present study, straw is added to increase its durability against water erosion, expanded clay to improve thermal properties and Portland cement to increase compressive strength [11].

Portland cement acts as a physicochemical stabilizer. Its manufacture is extremely energy consuming and originates residual dust in quarries that causes a significant environmental impact. Its use should be restricted to structural elements with optimized design section and its durability should be extended to the maximum. One of the disadvantages of using Portland cement as a stabilizer is that it makes rammed earth not recyclable, although it would still be reusable [11]. Furthermore, it adversely increases the embodied energy of rammed earth [12]. Favourably, cement stabilized rammed earth embodied energy is notably lower than conventional construction systems as concrete, reinforced concrete or clay brick [12, 13]; moreover, it acts as a stabilizer against water erosion. Straw acts as a physical stabilizer [14, 15] that is used to minimize shrinkage during the curing process and to reduce rammed earth density. It also decreases swelling and contraction caused by water during moulding as well as fragility and, on the other hand, it improves elastic deformation. This physical stabilizer is biodegradable and, therefore, it can be fully returned to the environment. Expanded clay is added in order to improve thermal properties of rammed earth (high porosity) and to reduce its density (very low density).

Three different types of rammed earth (Figures 1 and 2) were used to construct the prototype located in Barcelona, and one type was used in Puigverd de Lleida. Information about walls orientation, thickness and stabilizer material used in each prototype are presented in Table 1.

Barcelona walls include: 40% (in vol.) of expanded clay (3–10 mm diameter) in the northern wall (Figure 2b) and 3% (in vol.) of cement (CEM II/B-L 32.5 R) in the southern wall (Figure 2c). North-western and south-western walls have no additives. The earth used to construct the cubicle was obtained from the site excavation and has a composition of (in vol.): 71% of clay and 29% of sand (Figure 2a). On the other hand,

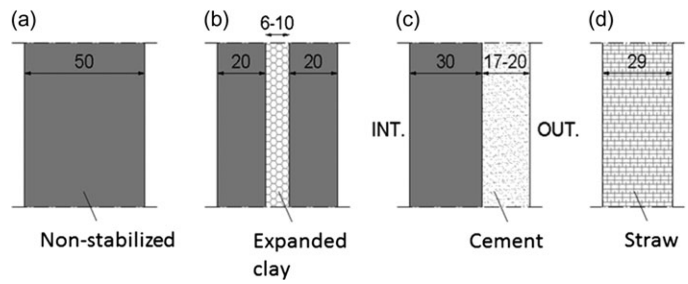

Figure 1. *Wall section of the rammed earth walls (in cm). (**a**) Non-stabilized, (**b**) stabilized with expanded clay, (**c**) stabilized with cement and (**d**) stabilized with straw.*

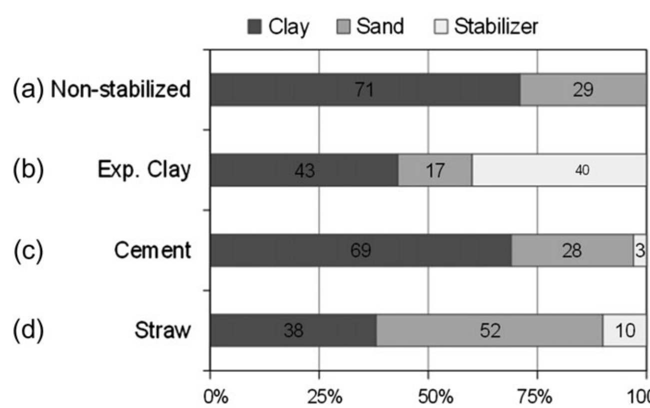

Figure 2. *Mixture composition (in vol.) of rammed earth walls.*

Table 1. *Characteristics of rammed earth walls.*

Prototype	Location	Wall name	Wall orientation	Wall thickness (cm)	Stabilizer material
#1	Barcelona	a) Non-stabilized	N, S	50	-
		b) Expanded Clay	N	50	Expanded clay
		c) Cement	S	50	Cement
#2	Puigverd de Lleida	d) Straw	N, S, E, W	29	Straw

Puigverd de Lleida walls include 10% (in vol.) of straw. Earth is composed by: 38% of clay, 45% of sand and 7% of gravel [16] (see Figure 2d).

3 METHODOLOGY

3.1 Laboratory scale

In this section, the methodology followed to characterize earth materials used in the construction of both prototypes is explained.

The particle size distribution was determined by Unified System of Soil Classification (USSC) developed by A. Casagrande [17], following the standard UNE 103101:1995 [18]. This experiment is focused on determining different particle sizes (up to 0.08 mm) of a soil and obtaining the percentage of each size in the sample under study. Particle size distribution is obtained by sieving the soil using different sieves sizes and weighing the amount of earth retained in each sieve. The earth material (Figures 1 and 2) is analysed using this test methodology in order to evaluate particle size variation of earth compounds and, therefore, to classify the earth used in Barcelona and Puigverd de Lleida rammed earth prototypes. Particle size distribution of the earth used in Barcelona prototype has been studied without stabilizer, with 40% of expanded clay, and with 3% of cement [19]. The addition of expanded clay into rammed earth is completely new; therefore, there are no previous scientific studies to justify the percentage of expanded clay used. However, due to its good insulation properties, Casa S-Low Company decided to add this material into rammed earth following the recommendations of CETARemporda Association, which is an expert in earth constructions. The earth used in Lleida prototype has been studied without stabilizers and 10% straw.

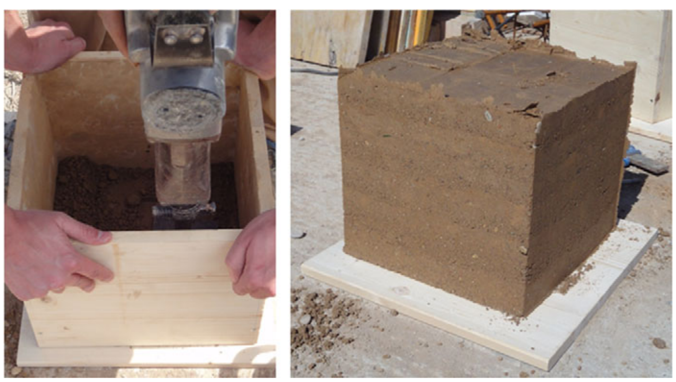

Figure 3. *Rammed earth sample during manufacturing by layers (left) and finished (right).*

Rammed earth construction technique involves the compaction of the soil mixture (clay, sand, gravel, stabilizer and water) in layers about 7 cm thick on a wooden form work. It simulates geological processes that form a sedimentary rock, so that rammed earth has a hardness and durability comparable to low diagenetic grade (Figure 3) [20]. Barcelona compositions were manually rammed because of Casa S-Low Company requirements but, in order to check the variability of results depending on the compaction method used, Puigverd de Lleida samples were both manually and mechanically rammed.

In previous research, a wide range of sizes were used to determine compressive strength: 10 cm cubes [21] or 15 cm [22], 10 × 10 × 20 cm, 30 × 30 × 60 cm [23], 40 × 40 × 65 cm [11] and even bigger 100 × 100 × 30 cm [24]. In the present study, four samples (25 × 30 × 30 cm) of Barcelona type and two samples of each compaction method (30 × 30 × 30 cm) of Puigverd de Lleida type were used in order to test compressive strength of rammed earth without additives (Figure 4).

To determine compressive strength of walls, UNE EN 772-1:2011 [25] standard has been followed. This test consists of applying a uniformly distributed load in the sample and increasing it until the sample is broken. The maximum load resisted by the sample is divided by the surface where the load has been applied in order to obtain the compressive strength value. Compressive strength of each composition is obtained as the average of all results. Finally, the results obtained are compared with literature values presented in Barbeta [15] and Bauluz and Bárcena [26] that present a range of theoretical values of compressive strength of rammed earth.

3.2 Experimental set-up

In order to experimentally determine the thermal behaviour of rammed earth walls, they were tested in two experimental

Figure 4. *Rammed earth samples during compressive strength tests.*

set-ups located in Barcelona and Puigverd de Lleida (Spain) (Figure 5). They consist of two house-like cubicle buildings that are analysed in summer and winter conditions by measuring free floating temperature profile of the south wall of both prototypes. The experiments took place along winter and summer of 2013.

The geographical and climatic characteristics of both experimental set-ups are listed in Table 2, as well as the prototype and rammed earth walls features. The experimental set-up located in Barcelona has a Mediterranean central coast climate, characterized by long, warm to hot, dry summers and mild, wet winters. The experimental set-up located in Puigverd de Lleida has a Mediterranean continental climate, characterized by cold winters and hot and relatively dry summers.

3.2.1 *Barcelona set-up*

Experimental set-up in Barcelona consists of a prototype with North −74° orientation and 2.48 × 2.15 × 2.50 m inner dimensions. The construction system is based on wooden load structure and wooden green roof (Figure 6a). The foundation consists of a reinforced concrete base. South and north facades have no window but there are two openings in the east and west facades. Rammed earth walls of 50 cm are manually rammed with different mixtures in each facade (Figure 6b), without neither inner nor outer coating. This prototype was constructed according to Casa S-low Company requirements.

Temperatures of Barcelona cubicles are measured using thermocouples type K with accuracy 0.75%. Six thermocouples are located in the inner surface (north, south), inside the wall (north, south at 25 cm depth) and the exterior surface (north, south).

3.2.2 *Puigverd de Lleida set-up*

The experimental set-up in Puigverd de Lleida consists of a prototype with orientation N-S 0° and size of 2.40 m of interior width and height. The construction system is based on load-bearing rammed earth walls and wooden green roof (Figure 7a). The foundation consists of a reinforced concrete base of 3.60 × 3.60 m. It only has one opening, which is the insulated door located in the north façade (Figure 7b). In order to protect rammed earth walls from ground humidity, they were built on a base of one row of alveolar brick (19 cm high) with a waterproof sheet of polypropylene.

The Puigverd de Lleida experimental set-up allows measuring the thermal performance of rammed earth cubicle by registering the inner surface wall temperature (east, west,

Table 2. *Experimental set-up of Barcelona and Puigverd de Lleida characteristics.*

Characteristics		Barcelona #1	Puigverd de Lleida #2
Prototype	Inner dimensions	2.48 × 2.15 × 2.50 m	2.4 × 2.4 × 2.4 m
	Structure	Wooden load structure	Load-bearing rammed earth walls
	Roof	Two different wooden green roofs	Wooden green roof
	Coating	No inner neither outer coating	No inner neither outer coating
Rammed earth walls	Function	Enclosure, no load-bearing	Load-bearing and enclosure
	Thickness	50 cm	29 cm
	Compaction method	Manual	Mechanical
Geographical	Orientation	North −74°	North 0°
	Location	N 41°23′, E 2°6′	N 41° 32′, E 0° 44′
	Elevation above sea level	9 m	219 m
Climatic	Climate	Mediterranean central coast	Mediterranean continental
	Climate classification [27]	Csa	Csa/Cfa
	Annual number of heating degree days [28]	573	1,230
	Annual number of cooling degree days [9]	354	423
	Average summer temperatures [29]	21.1°C	22.6°C
	Average winter temperatures [29]	12.2 °C	8°C
	Annual precipitation [29]	568 mm	456 mm

Figure 5. *Experimental set-up in Barcelona, prototype #1 (left) and Puigverd de Lleida, prototype #2 (right).*

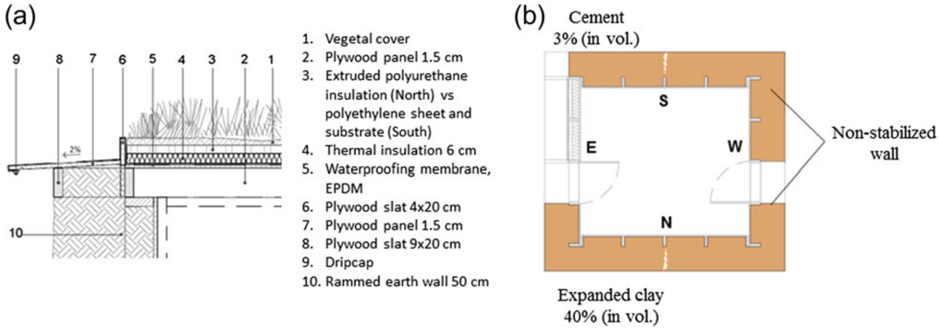

Figure 6. *Barcelona prototype #1: (**a**) Detail of facade-roof section, (**b**) Plan.*

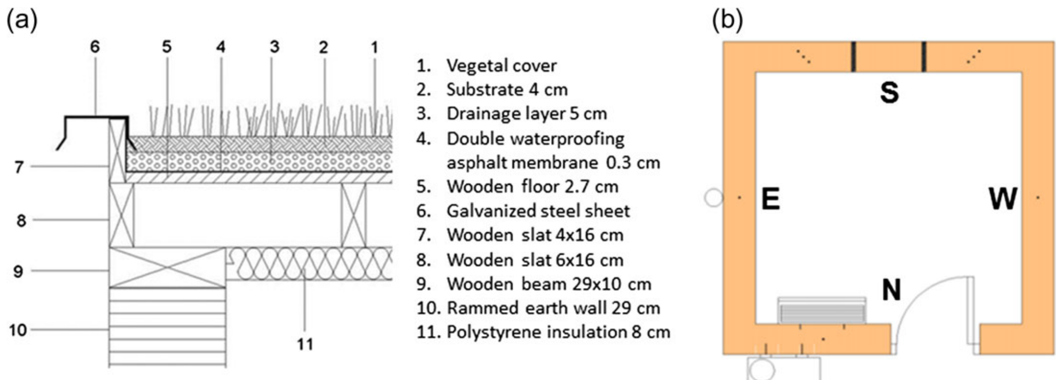

Figure 7. *Puigverd de Lleida prototype #2: (**a**) Detail of facade-roof section, (**b**) Plan.*

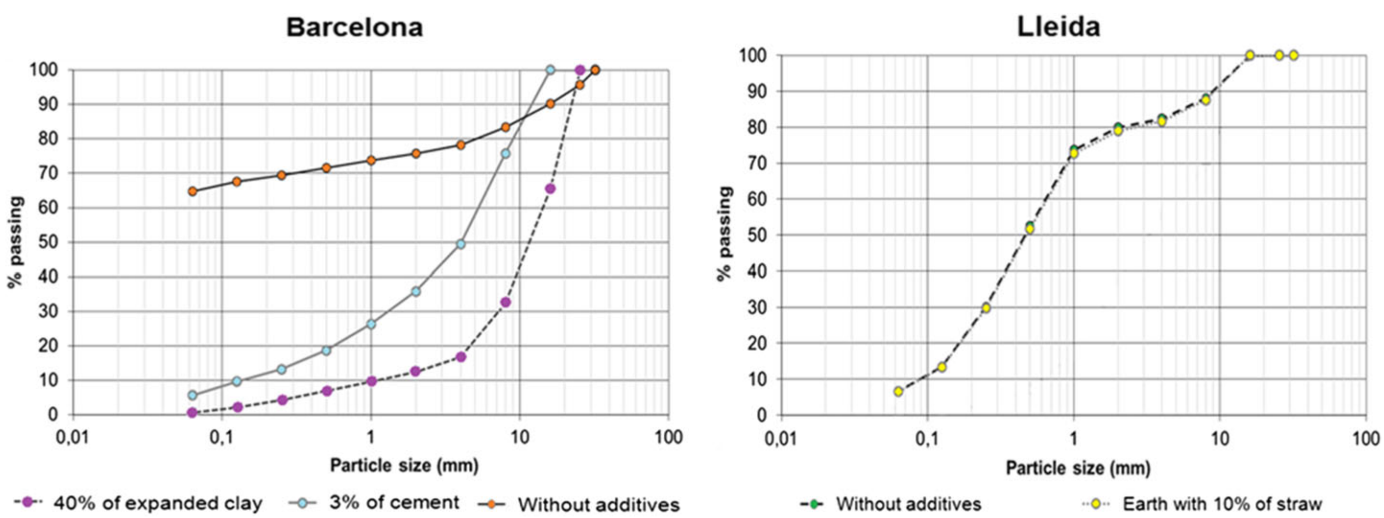

Figure 8. *Barcelona earth: 40% of expanded clay, 3% of cement and without additives (left). Puigverd Lleida earth: without additives and 10% of straw (right).*

north, south, ceiling and floor), temperatures inside walls (north, south, east and west), the exterior surface wall temperature (south), the indoor ambient temperature and air humidity, the solar radiation and the outdoors temperature, and the wind speed. All temperatures were measured using Pt-100 DIN B sensors, calibrated with a maximum error of ±0.3°C.

4 RESULTS

Firstly, particle size distribution of both earth materials without stabilizers, in Barcelona and Puigverd de Lleida, is shown in Figure 8. According to Unified System of Soil Classification Casagrande [17], the earth of Barcelona cubicle corresponds to a cohesive soil of clay with medium plasticity. The earth of Puigverd de Lleida cubicle is a granular soil of sand properly mixed with 6% of clay. There are significant differences between both earth granulometry because they have different origins: Barcelona earth came from the construction site whereas Puigverd de Lleida earth was bought and mixed properly according to the literature [16]. These dissimilarities, because of the different origin of the earth used in each prototype, depend on the availability of clay, sand and gravel of the site excavation and the accuracy of the earth quality in its use. Rammed earth needs higher or lower amounts of water during its construction depending on the earth composition and, for this reason, a proper material characterization of the earth used in rammed earth buildings would be needed in every new construction.

Secondly, mixtures responses (Figure 8) are different due to the methodology of the test, which takes into account material densities in particle size distribution calculation. The addition of 3% of cement and 40% of expanded clay modifies the particle size distribution of Barcelona earth increasing the percentage of big particles. However, Puigverd de Lleida earth particle size distribution remains almost constant when 10% of straw is added (which has a very low density).

Finally, compressive strength results obtained for each rammed earth type are shown in Table 3. Puigverd de Lleida samples results show that compaction method used modifies

Table 3. *Compressive strength results of rammed earth without additives.*

	Manual compaction (N/mm^2)	Mechanical compaction (N/mm^2)	Barbeta [15] (N/mm^2)	Bauluz and Bárcena [26] (N/mm^2)
Barcelona #1	1.08	–	0.5–2	0.6–1.8
Puigverd de Lleida #2	0.85	0.94		

Results of compressive strength are the arithmetic average of maximum values in compressive strength.

the results of compressive strength, being 10% higher if samples are compacted mechanically. Furthermore, the type of earth and particle size also affects compressive strength of rammed earth, being 21% higher Barcelona type. Results are in the range of literature values [15, 26], and therefore both earths are suitable to being used in rammed earth construction.

Once compressive strength was tested and authors found out that the higher compressive strength was obtained with mechanical compaction in Puigverd de Lleida, authors decided to build the cubicle using mechanical compaction. However, in Barcelona cubicle manual compaction had to be used because of requirements of Casa S-Low project.

Figures 9 and 10 present temperature profiles in free floating conditions in two representative days (one for summer and one for winter) in Barcelona and Lleida locations. As outer surface wall temperatures denote, Lleida have wider range temperatures along the day (thermal amplitude of 15°C in summer and 17°C in winter) whereas in Barcelona temperature range is smaller (thermal amplitude of 5°C in summer and <2°C in winter). These are common thermal profiles in both cities: Lleida has a more arid and continental climate and Barcelona has a milder climate because it is near the Mediterranean Sea.

Figure 9 shows temperature profiles through the Barcelona south wall. Inner surface temperature is very constant along the day in both summer (2°C of thermal amplitude) and winter periods (0.5°C of thermal amplitude). However, the external surface temperature denotes a differential of 5°C in summer and 1°C in winter during the day under study.

On the other hand, the inner surface wall of Puigverd de Lleida (Figure 10) cubicle denotes a higher thermal amplitude in summer (3.5°C) and winter (5°C) periods but also thermal amplitude in outer surface walls is higher (15°C in summer and 17°C in winter).

In both cases, the thermal amplitude (from outside to inside) is reduced along rammed earth wall, achieving nearly constant temperatures in the inner surface of south walls. In the case of the 50 cm wall, thermal amplitude of inner surface temperature wall was reduced 80% in summer and 75% in winter in these

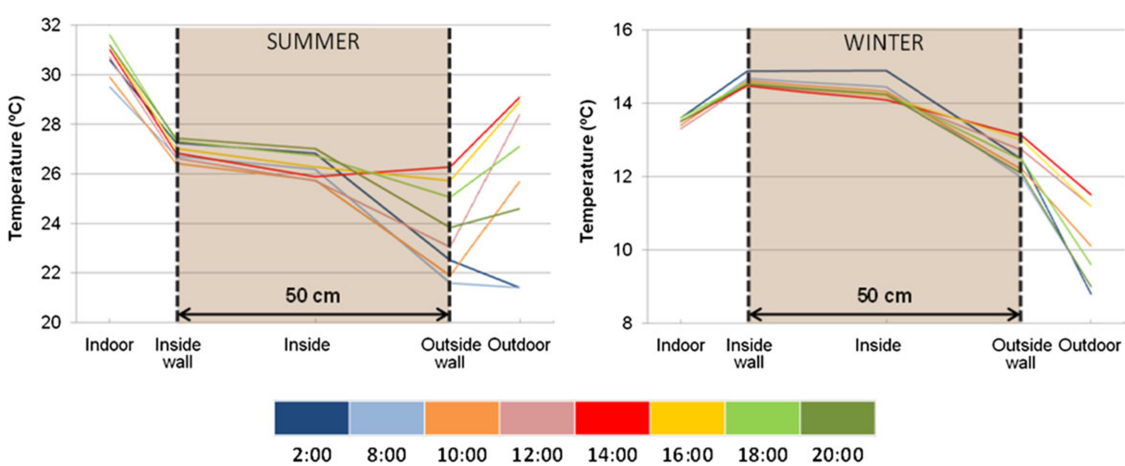

Figure 9. *Barcelona prototype #1. Temperatures of the south wall in summer conditions—10 July 2013 (left) and winter conditions—10 January 2014 (right).*

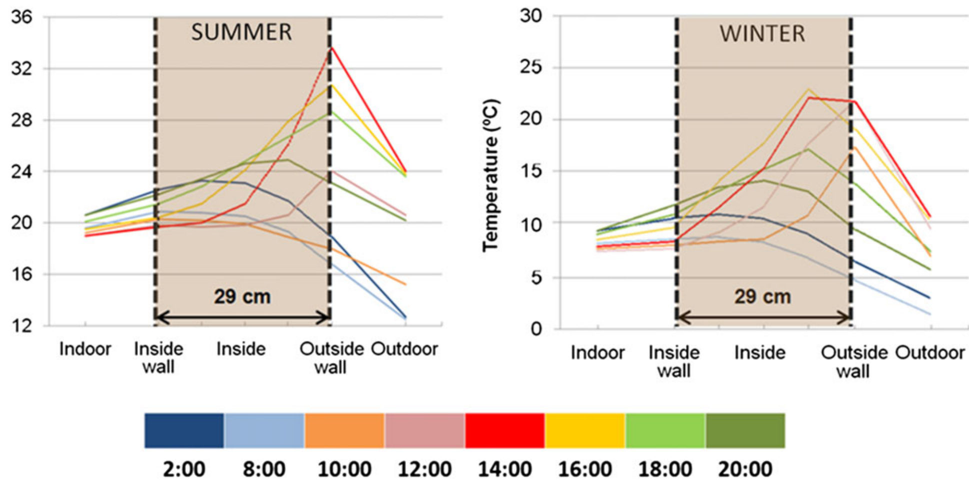

Figure 10. *Puigverd de Lleida prototype #2. Temperatures of the south wall in summer conditions—15 October 2013 and winter conditions—7 February 2013.*

specific conditions. As expected, using thinner rammed earth walls (29 cm), inner surface wall temperatures showed higher thermal amplitude. However, although the thickness of rammed earth is a determining factor, it is important to remark that the more extreme ambient temperature differences between day and night (in the Puigverd de Lleida climate) have a stronger negative effect on the rammed earth wall, having wider thermal amplitudes in the outer surface of 15°C in summer and 17°C in winter. When the reduction of the thermal amplitude is quantified, it can be noticed that thermal amplitude was strongly reduced achieving reduction of 77% in summer and 70% in winter periods.

5 CONCLUSIONS

The characterization at laboratory scale of different earth mixtures used has revealed that Barcelona earth consists in a cohesive soil of clay with medium plasticity and Puigverd de Lleida earth consists of a granular soil of sand properly mixed with 6% of clay. These dissimilarities are due to the different origin of the earth used in each prototype.

Results of the compressive strength test reveal that the compression strength of earth materials analysed are in range with literature values. Furthermore, results of the compressive strength demonstrate that earth type and particle size did not strongly affect compressive strength in the cases under study. Regarding the compaction method, mechanical compaction achieved slightly higher strength results in Puigverd de Lleida earth.

Finally, the thermal experimentation under free floating conditions in summer and winter periods showed that in spite of the thermal amplitude of the outer surface temperature along the day, the temperature of the inner southern surface wall tends to be constant in both cubicles.

Despite the reduction of wall thickness worsening the thermal behaviour of rammed earth, a reduction of the thickness will be needed in most of cases if rammed earth is used in modern buildings due to the current high prices of the housing floor area. Modern building constructions tend to reduce thicknesses of walls using smaller thicknesses (30–35 cm) while traditional buildings (including rammed earth buildings) have thicknesses from 60 to 100 cm. Moreover, thermal behaviour disadvantages can be reduced, for example, by the implementation of insulation materials attached to the external side of the wall; by a passive design (orientation, openings, shadows, etc.) of the building and by using rammed earth wall as an enclosure element (not as structural element), especially in multi-storey buildings.

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