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Adaptation of rammed earth to modern construction systems: Comparative study of thermal behavior under summer conditions

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HIGHLIGHTS

- Rammed earth is adapted to modern requirements by reducing its thickness.
- Wooden insulation panels are placed in the outer face of rammed earth walls.
- Sustainable and conventional morphologies are thermally tested at real scale.
- Similar thermal response than in high embodied construction systems is achieved.

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ABSTRACT

Buildings should be understood as a process that consumes energy in all their phases (design, construction, use and end-of-life) and, more specifically, the building envelope is clearly involved in all of them. For this reason, the International Energy Agency defines in its latest publication the improvement of building envelopes as one of the key points to reduce the energy consumption in buildings. In the present study, two sustainable construction systems based on rammed earth walls are adapted to modern requirements to be thermally tested and compared against three Mediterranean conventional systems under summer conditions. The experimentation was done by performing several experiments in free floating and controlled temperature conditions at real scale in five cubicle-shape buildings with inner dimensions 2.4 × 2.4 × 2.4 m. The purpose of this study is to demonstrate that more sustainable construction systems can be used instead of conventional ones, with higher embodied energy, and achieve similar thermal response. Results show that the reduction of rammed earth wall thickness strongly penalizes its thermal behavior. However, similar thermal response than conventional systems is reached when 6 cm of wooden insulation panels are added in the outer face of the cubicle-shape building.

1. Introduction

The improvement of building envelopes has been identified by the IEA (International Energy Agency) as one of the key points to reduce the energy consumption in buildings [1]. The building sector was responsible for 19% of total greenhouse gases (GHG) emissions in 2010 [2] and one of the most energy consumer sub-sectors accounting around 32% of global final energy use [1]. Space heating and cooling represents 34% and 40% of energy consumption in residential and commercial buildings, respectively, and this consumption is directly related with the building envelope [3–7].

However, buildings must be considered as a process which consumes energy and affects the environment in all their phases (design, construction, use and end-of-life) and the building envelope is involved in all of them [8,9]. Materials choice is a key element involved in design and construction phases, and the end-of-life of a building [10]. Reddy [11] demonstrated that embodied energy of buildings strongly depends on materials and building techniques choice by comparing embodied energy between basic building materials and floor and roofing systems commonly used in India as well as the energy expenditure during transportation. Authors concluded that embodied energy of materials can be reduced up to 62% when a proper selection of materials and systems is done. Similar results were obtained in Reddy [12], where the author demonstrated that 50% of embodied energy can be achieved by using alternative low-energy building technologies in walls, floor and roofing systems.

Within this context of sustainable materials for building design, earth is an ancient material that has been used in buildings until

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nowadays and its recovery as building material becomes more attractive when other parameters are taken into account as its low embodied energy, low price, availability and recyclability. As an example, Melià [13] compared the environmental impact of earthen plasters based on clay with conventional plasters based on cement or hydraulic lime using LCA methodology evaluated from a cradle-to-gate perspective. They demonstrated that total embodied energy in plasters can be halved by choosing earthen plasters instead of hydraulic lime and cement based ones.

Earth buildings and, in particular, rammed earth buildings provides suitable thermal resistance properties into walls using large thicknesses [14] and high thermal inertia due to its high mass [15]. Li et al. [16] experimentally demonstrated that thick rammed earth buildings (between 0.7 and 1.7 m) consumes less energy than normal rural buildings in different Chinese rural zones. However, construction systems used today tend to reduce thickness and mass of walls and rammed earth cannot provide a proper thermal behavior when thin walls are used [17].

For this reason, the main aim of the present study is to experimentally demonstrate that similar thermal behavior than in other conventional construction systems with high embodied energy can be achieved by using only low embodied energy construction materials and systems. To reach this goal, five house-like cubicles are thermally tested at real scale under summer conditions. Two of them were identically built with thin rammed earth walls and wooden green roof, the only difference between them is that one cubicle has non-insulated walls and, the other one has wooden insulation panels placed in the outer surface of walls and a finishing coating composed by clay and straw fibers. The other three were built using Mediterranean conventional construction systems, one of them without insulation. Furthermore, the experimental measurements presented in the paper provide unique available information to the scientific community to test technologies and provide data for validation of numerical models.

2. Experimental set-up

Five cubicles with different construction systems were studied in the experimental set-up of Puigverd de Lleida, Spain (Fig. 1), with Csa climate according to Geiger climate classification [18]. Two cubicles were built with rammed earth technique, an ancient and traditional construction system, and the other three were built with Mediterranean conventional construction systems. These three conventional construction systems used (among others) were previously tested and evaluated in Cabeza et al. [19]. All of them have the same inner dimensions (2.4 × 2.4 × 2.4 m) and orientation (N–S, 0°), with an insulated metal door in the north wall and no windows.

As is well known, rammed earth was traditionally used with large thicknesses (from 50 cm to 1 m approximately) that provides good thermal and acoustic properties to buildings [15]. However, as mentioned before modern construction systems tend to use thinner walls than traditional ones with similar or better thermal responses [20,21]. For this reason, rammed earth should be insulated if thin walls are used in order to achieve a good thermal response [22].

In the present study, rammed earth is adapted to modern construction systems by using thicknesses of 29 cm and by adding insulation. As a novelty, rammed earth was insulated in the outer face and a sustainable and low embodied energy insulation material was selected. This natural insulation material based on wooden fibers by-product does not adversely affect the embodied energy of the whole system. Furthermore, and following the same sustainable guidelines, a wooden green roof was selected as roofing system.

Each construction system is listed below and Fig. 2 illustrates their constructive details:

1. *Non-insulated rammed earth (RE):* Load-bearing rammed earth walls of 29 cm (with ground humidity protection of 19 cm composed by one row of alveolar brick and a polypropylene waterproof sheet).
2. *Insulated rammed earth (IRE):* Same construction system than RE but walls are insulated with natural wood fibers panels of 6 cm (SYLVACTIS 140 SD ITE) and 1 cm of natural coating based on clay and straw (thickness <2 cm).
3. *Reference cubicle (REF):* Gypsum, perforated bricks, air chamber, hollow bricks, and cement mortar coating. Structure made of 4 reinforced concrete pillars
4. *Polyurethane cubicle (PU):* Same layer distribution than REF but with 3 cm of polyurethane sprayed foam between the perforated bricks and the air chamber.
5. *Polystyrene cubicle (XPS):* Same layer distribution than REF but with 3 cm of extruded polystyrene.

All foundations consist of a 3.60 × 3.60 m reinforced concrete base with gravel drainage layer and all roofs are insulated with 5 cm of polyurethane. Values of thermal conductivity of insulation materials used in walls are provided by each manufacturer as Table 1 specifies.

Thermal transmittance in steady state, also known as *U*-value, was calculated as the inverse of the envelope thermal resistance [23]. Moreover thermal lag of walls were calculated according to the methodology presented in ISO 13786:2001 [24]. Table 2 presents the results of these calculations showing that thermal transmittance of the envelopes are significantly reduced when adding an insulating layer, being this reduction around 77% in case of rammed earth, and around 70% in case of typical brick constructive system. Moreover, the results also demonstrate that the addition of insulation also increases the thermal lag in all cases, and that the constructive system based on rammed earth presents higher thermal lag than the system based on bricks.

Cubicles are fully monitored to register inner temperature and humidity (using ELEKTRONIK EE21 at a height of 1.5 m with an accuracy of ±2%) and surface wall temperatures (using calibrated Pt-100 DIN B sensors with error ±0.3 °C which measure east, west,

Fig. 1. Puigverd de Lleida experimental set-up.