Thermal monitoring on an earthbag building in Mediterranean continental climate

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Abstract

Earthbag and superadobe are low-cost and environmentally friendly building techniques that use the raw earth to build structural walls, usually in dome shape. This research analyzes the thermal performance and comfort of an earthbag building located in Mediterranean continental climate by experimentation in real conditions. The monitoring consisted in data collection of air temperature and humidity, horizontal solar radiation, and surface wall temperatures in summer and winter periods, using free floating and controlled temperature experiments. Passive design strategies for winter were tested, such as high thermal inertia of walls and direct solar gain. Natural ventilation was also tested in summer period. Results showed a very stable interior temperature in the earthbag building and the increase of day temperatures due to the direct solar radiation collection through the glassed openings located in the east and south façade. However, the high U-value of the earthbag walls and the lack of internal loads caused the interior temperature to be out from the comfort range, and a heating system was required with an energy consumption of 1-1.7 kWh/m^2 per day, in winter. The direct contact of the building with the ground caused a high relative humidity in the dome in both summer and winter periods that could be reduced by using natural ventilation. Night ventilation was a suitable passive strategy in summer period to reduce the average temperature level in the dome.

Keywords: Earth building, Thermal comfort, Passive design, monitoring and simulation.

Introduction

Earthen architecture historically has been widely used for wall construction around the world. According to Minke (Minke, 2012) earth construction has been used for more than 10,000 years. Among the earthen building techniques, adobe is widely spread because is economic, and it is an environmentally friendly and abundantly available building material (Minke, 2000). Adobe construction is associated with low embodied energy, low pollution impacts and low carbon dioxide emissions. This type of construction is also responsible for an indoor air relative humidity beneficial to human health (Ouedraogo, 2012). It is also important to highlight that this type of construction is efficient from a thermal point of view because of the thermal inertia of the earth. Moreover, there is a study (Zhao et al., 2015) which highlights the interest of earthen construction technique as a passive design principle to improve thermal comfort. Earthbag and superadobe count with the advantages of adobe technique but overcome some of the disadvantages. Superadobe is a form of earthbag construction patented and developed by the Iranian architect Nader Khalili who proposed fundamentals rules for the design and building recommendations (Khalili, 1999). Earthbag and superadobe are building techniques that consist in the use of earth-filled sandbags in order to build structural walls, usually in dome shape (Canadell et al., 2016). Among their possible uses, they can be a good solution to temporally emergency housing. Earthbag offers more structural integrity and durability than adobe (Sargentis et al., 2009) and it is four times cheaper compared with conventional techniques (Adegun and Adedeji, 2017). Previous researchs have thermally simulated and monitored raw earthen buildings (Martín et al., 2010, Desogus et al., 2014, Palme et al., 2014 and Serrano et al., 2017), but not earthbag buildings yet. This research analyzes the thermal performance and comfort of an earthbag building located in Mediterranean continental climate by experimentation of a real construction. Passive design strategies are tested, such as the use of high thermal inertia in the enclosure, the capturing of direct solar radiation through the glassed openings and the use of natural ventilation.

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Materials and method

2.1. The monitored earthbag building

The building is constructed with the superadobe technique and dome shape. It has a net floor area of 7.07 m^2, a circular plant of 3 m of diameter and a height of 3.6 m (Fig. 1). The walls are 32 cm thick, but the buttress is formed by a double, 64 cm thick earthbag. The main glass opening is the entrance door, which is facing exactly south (0.8 x 2.05 m). Two confronted windows in the east (0.5 x 0.7 m) and west (0.8 x 0.8 m) facades allow crossed ventilation. The continuous polypropylene bag contains an earthen mixture of on-site earth and construction sand in a 1:1 proportion. Slaked lime in water was used as stabilizer, in approximately 10% of the total earthen volume. The sieve analysis showed that the earth mixture contained in weight: 0.80 % fine gravel, 92.21% sand, 3.42% slime and 3.57% clay. The earth mixture was manually rammed. The building was exteriorly coated with 4 cm thick lime mortar.

Fig. 1: Earthbag building, University of Lleida Campus, Spain.

2.2. Experimentation equipment

The experimental setup consisted of 4 temperature sensors, 1 solar meter, 2 relative humidity sensors and the control and data acquisition systems. Monitoring consisted in data collection of interior and exterior air temperatures as well as interior surface temperatures in both south and north walls. Interior temperature sensor was located in the geometrical center of the dome at 1.50 m high. North surface wall temperature sensor was located at 1.50 m high and south surface wall temperature sensor was located at 2.10 m. Temperatures were registered every 5 minutes thanks to a data acquisition system connected to a computer. Air temperature and humidity were measured by Elektronik device model EE210. The experimentation equipment consisted of a data logger (model DIN DL-01-CPU), connected to the adapter data logger-computer (model AC-250). The temperature sensors used were PT100 (TR-M416) for the surface temperature, and for the air temperature are PT-100 class B. The computer software to compile the data was TCS-01. When controlled temperature experiments were carried out in winter, a 1500 W electric radiator was used and its energy consumption was also measured with a Finder E7energy meter. Horizontal solar radiation was measured in all experiments with a KIPP & ZONEN CMP 6 (±2.50% error).

2.3. Validation of energy simulation

Simulated and experimental interior air temperatures in the dome were compared during three weeks of July 2017 for validation purposes (Fig. 2). The energy simulation has been done with Energyplus software and Open Studio. The default heat balance algorithm based on the conduction transfer function (CTC) transformation and 6 time steps per hour for the simulation were applied. The validation showed a good agreement, with an average error along the period of 2%.

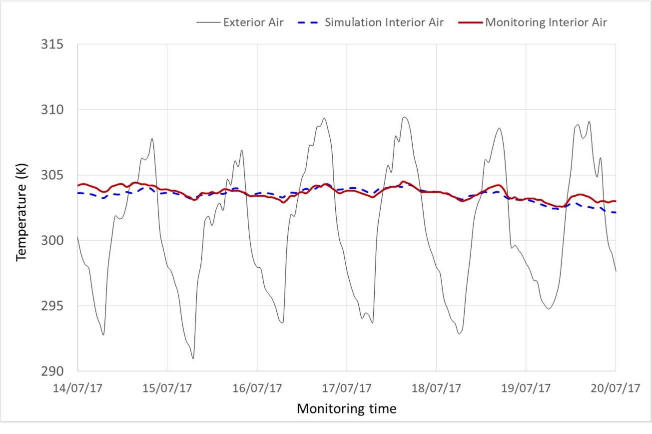

Fig. 2: Simulated and monitored interior air temperatures, free floating in summer period.

Results

3.1. Passive design by using direct capturing of solar radiation

Experimental free floating temperatures during winter conditions are presented. The daily thermal amplitude is very stable inside the dome of 1.5-3.1 K, while in the exterior the thermal amplitude is much higher ranging from 8.3 to 14.6 K (Fig. 3). The solar radiation overheats the interior air temperature in the morning, through the east window, and in the midday, through the south glassed door. There is no visible effect in the west window due to the smaller size of that window. The incidence of solar radiation through the glassed openings produces an increase of the maximum temperature even before achieving the maximum temperature in the exterior. That was caused by the greenhouse effect, which increased the thermal amplitude in about 2 K.

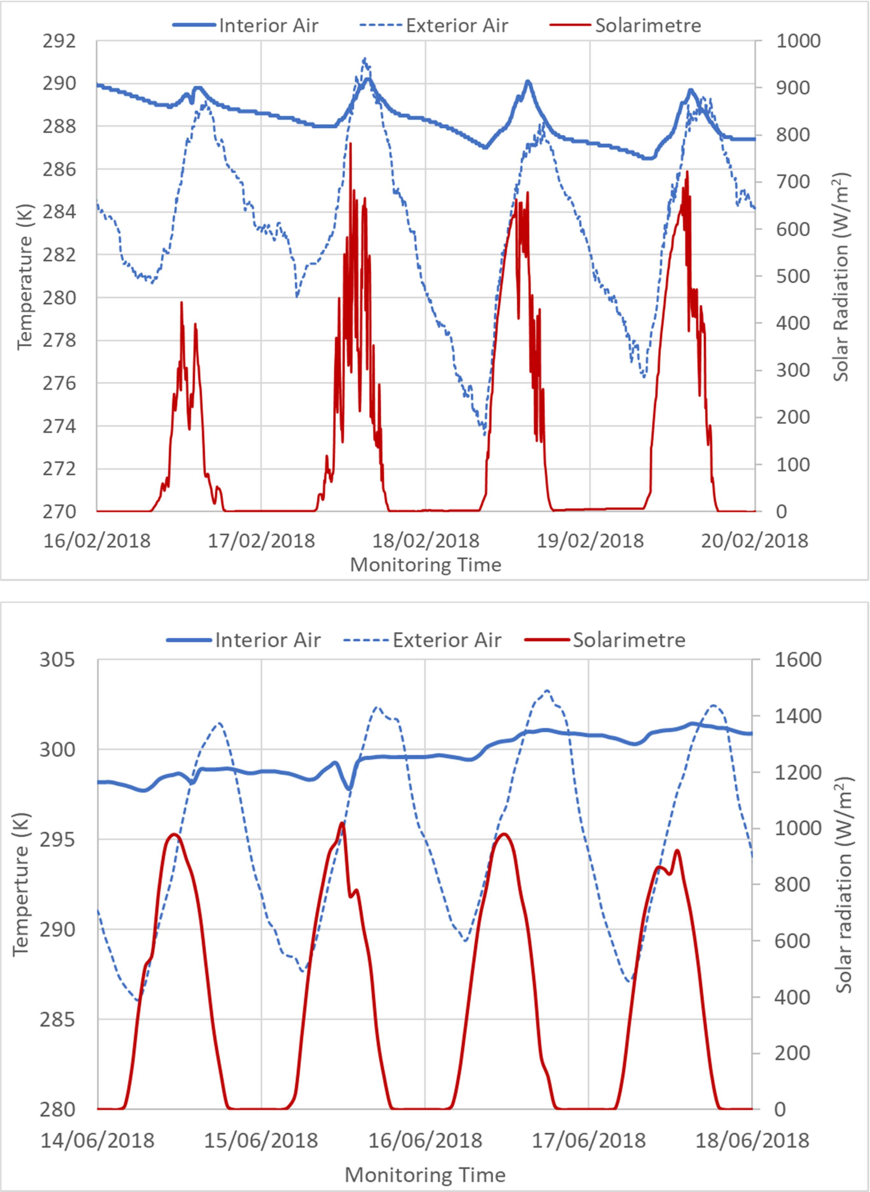

Fig. 3: Interior and exterior air temperature and solar radiation in winter period (above) summer period (bottom).

3.2. Humidity level in summer and winter conditions

The humidity level was all year above the comfort range. In summer time, it reached around 76 % of relative humidity and in winter time around 67% (Fig. 4). It was caused by the direct contact of the building with the ground, which transferred the subsoil humidity to the interior of the dome. In summer period, the humidity level reached a value within the comfort range when natural ventilation was applied.

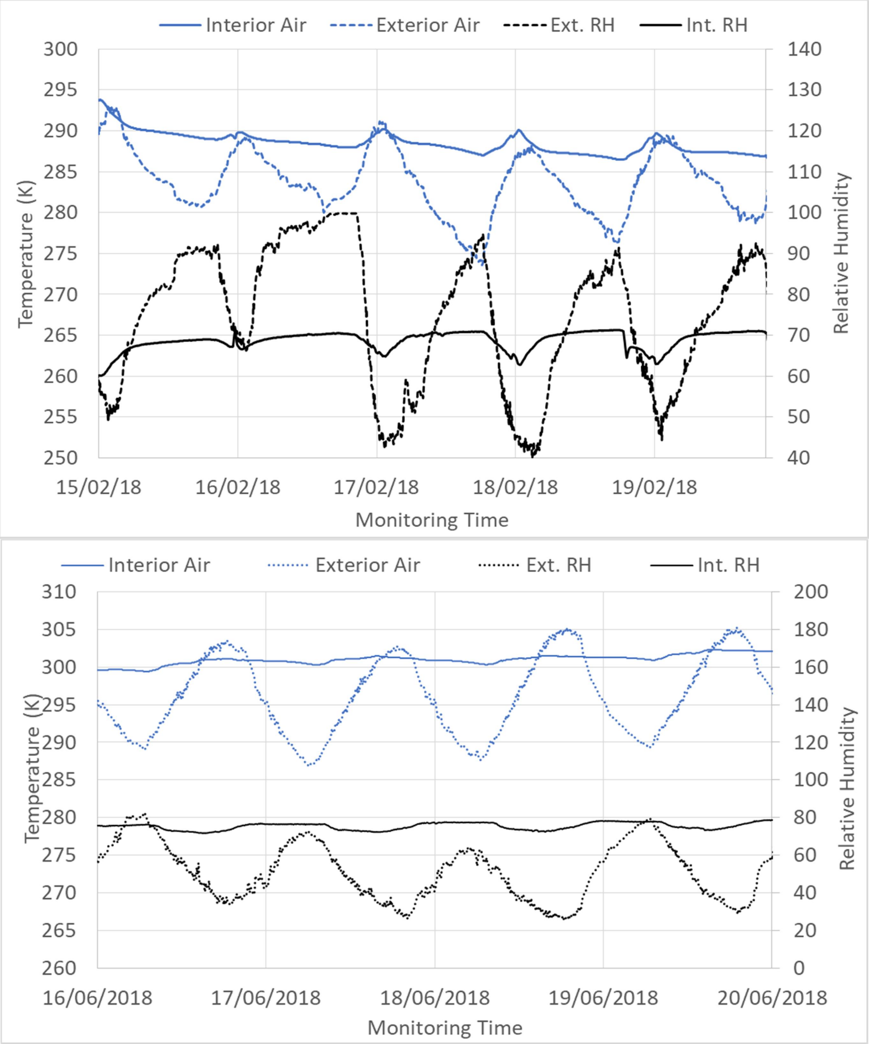

Fig. 4: Humidity and interior air temperature in winter (above) period and summer period (bottom).

3.3. Effect of natural crossed ventilation

Two experiments were set up in summer period; one with all day ventilation (Fig. 5) and another with just night ventilation, from 8 PM to 7:30 AM (Fig. 6). Night ventilation decreased the night temperatures over the expected minimum peak night temperature with no ventilation. When the dome is ventilated during all day in summer period, interior temperatures are closer to the exterior temperatures than when it is not ventilated, what produces a higher daily thermal amplitude in the dome, and more hours of discomfort along the day.

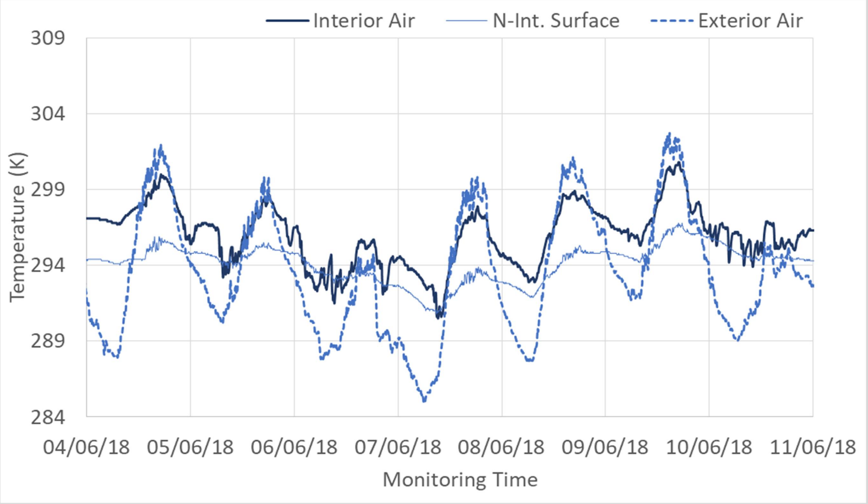

Fig. 5: Interior air temperature during all day ventilation experiment in summer period.

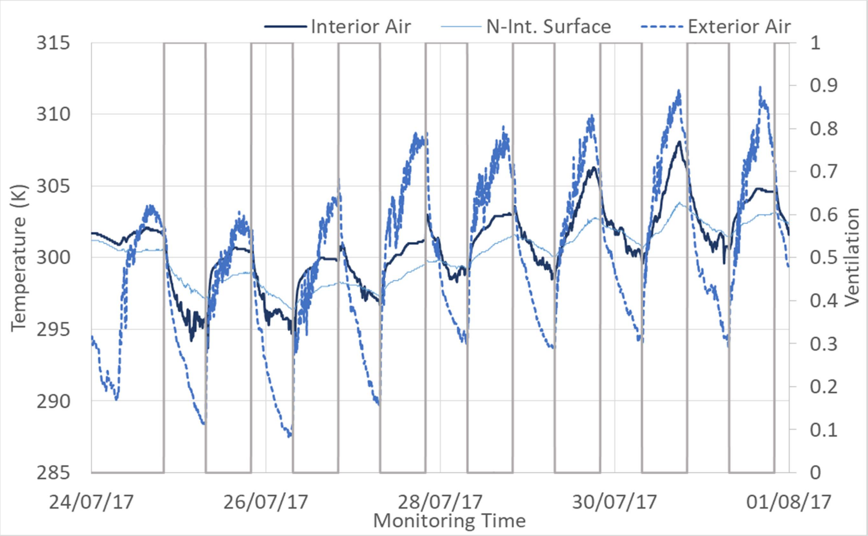

Fig. 6: Interior air temperature during night ventilation experiment in summer period.

3.4. Heating consumption

A controlled temperature experiment with a set point of 294 K was performed during one week in winter conditions. The daily energy consumption for heating ranged between 1-1.7 kWh m^{-2}. It increased proportionally the days with lower temperature and lower solar radiation (Fig. 7).

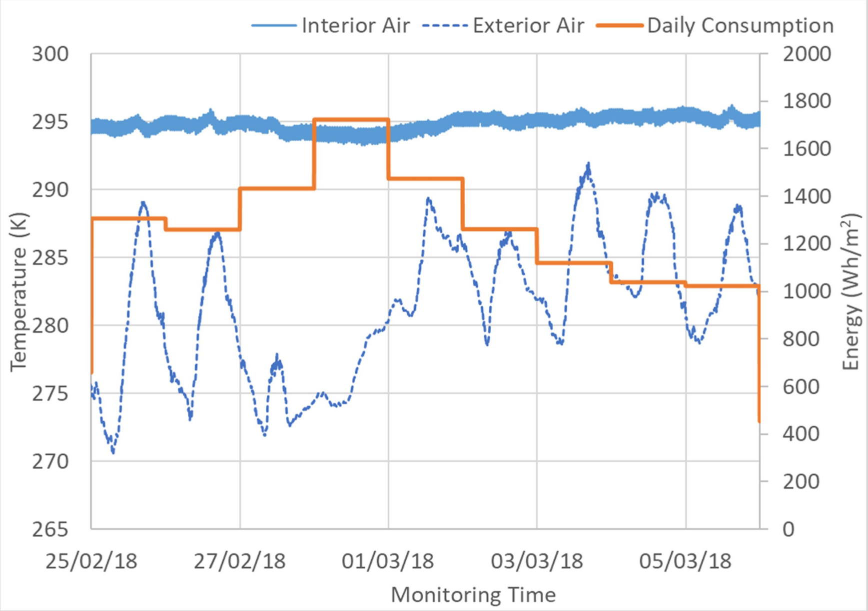

Fig. 7: Controlled temperature in winter period.

3.5. U-value calculation

During winter period, 3 foggy days in December 2017 with exterior air constant temperature and controlled temperature with a set point of 294 K allowed to calculate the overall heat transfer coefficient of the earthbag walls (TESTO 2017) (Fig. 8). According to eq. 1 and considering an interior surface thermal resistance of 0.13 $m^2 K W^{-1}$ (CTE 2013), it resulted in a U-value of 2.7 W m^{-2} K^{-1}. This result is within the conventional U-value range of a rammed earth wall.

$$U = \frac{(T_i - T_{si})}{(T_i - T_e)} * \frac{1}{R_{si}} \qquad \text{(eq. 1)}$$

T_i: Interior temperature
T_{si}: Interior surface temperature
T_e: Exterior temperature
R_{si}: Surface thermal resistance

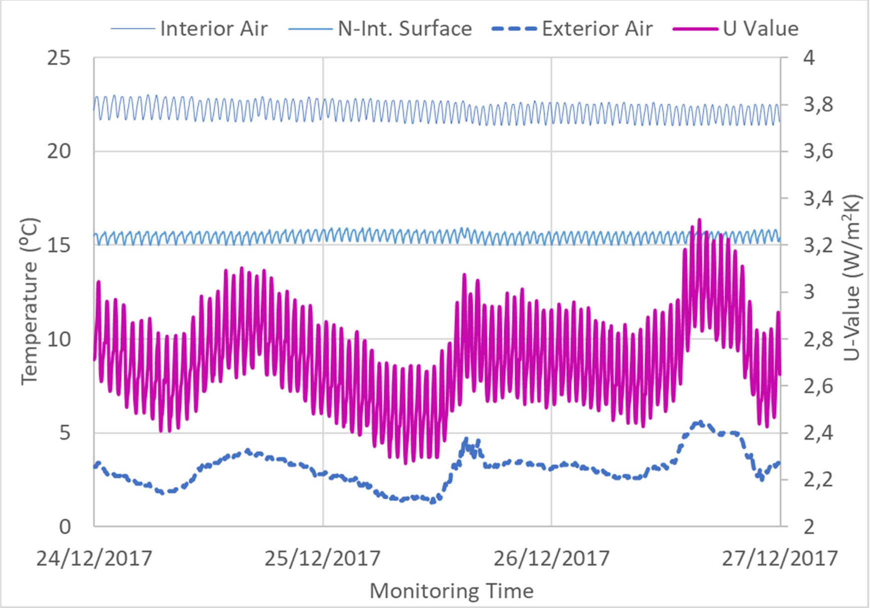

Fig. 8: Monitored temperatures and U-value calculation during winter period.

Conclusions

Passive design strategies in the earthbag building contributed to achieve the thermal comfort in the dome, despite the high U-value of the earthbag walls. Those strategies were, for winter period, the use of high thermal mass to store thermal energy and the capturing of direct solar radiation, and, in summer period, the use of night natural ventilation.

The use of high thermal mass in the building envelope caused a stable interior air temperature along the year, reducing the exterior thermal oscillation from 14.6 K to 3.1 K in winter period. Low shape factor and the thermal inertia of the dome floor in contact with the ground would also cause this result.

Direct solar radiation through the east and south glazed openings produced an increase in the interior air temperature, especially during the midday in winter period, what made increase the maximum interior temperature in about 2 K in winter.

The humidity level in the dome was in winter and summer period over the comfort range and it was caused by the direct contact with the ground, which should be avoided by placing a waterproofing layer.

Night ventilation in summer period was a suitable passive strategy to achieve a lower average temperature inside the dome and reduce the humidity level to a comfort range. However, all day ventilation cannot be recommended because the high exterior day temperatures increase the average temperatures inside the dome.

Despite the passive design strategies, the earthbag building requires in winter period a heating system to achieve thermal comfort levels because the U-value (2.7 W m^{-2} K^{-1}) of the 32 cm earth wall is well above the Spanish building code threshold (0.66 W m^{-2} K^{-1}). In the case of the analyzed building, to achieve a comfort temperature of 294 K, energy consumption in the range 1-1.7 kWh m^{-2} per day was required.

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