Analysis of the Thermal Performance and Comfort Conditions of Vernacular Rammed Earth Architecture From Southern Portugal

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Introduction

From the beginning, humans had to look for shelters to protect themselves from other animals and the climatic elements. But it was in the Neolithic, when humans moved from a nomadic to a sedentary life, that they decided to build permanent shelters. These shelters evolved over thousands of years and generations, across the world, and diverse vernacular techniques and forms have been developed and improved to better respond to climate constraints and to provide the best comfort conditions possible.

To attain thermal comfort conditions vernacular buildings were built using low-tech passive strategies that take advantage of available endogenous resources and other criteria such as sun exposure, geometry, form, and materials, among others (Coch, 1998; Singh *et al.*, 2011; Fernandes *et al.*, 2015a,b). With the industrialization of the building sector, the vernacular knowledge was often forgotten in building design and its use declined. Moreover, nowadays, buildings too often rely on heating, ventilation, and air conditioning (HVAC) systems to ensure indoor thermal comfort conditions (Fernandes *et al.*, 2015a,b). Thus, the relevance of vernacular features is still valid today in the scope of sustainability, being the basis of what is now defined as sustainable building design (Cardinale *et al.*, 2013).

Environmental awareness is increasing and underlining the problems related to energy efficiency and environmental impacts in buildings. The building sector is one of the largest energy and natural resources consuming sectors, being responsible for a third of global total CO_2 emissions and primary energy use (Ürge-Vorsatz *et al.*, 2015). Therefore, new high-performance building concepts have been defined, such as the "nearly zero-energy buildings" (nZEB). An nZEB is a building with a very high energy performance (due to an improved envelope and use of very efficient HVAC systems) and where the very low energy demand must be covered by energy from renewable energy sources.

The awareness of vernacular architecture regarding passive and low energy architecture is increasing, since it is intrinsically related to the local climate, uses passive, low-tech techniques, and is not dependent on nonrenewable energy sources (Kimura, 1994; Singh *et al.*, 2011; Fernandes *et al.*, 2013), which makes these strategies suitable and valuable to achieve the nZEB level in different climate contexts.

Several studies have shown that vernacular buildings have a good thermal performance, allowing achieving acceptable thermal comfort levels during most of the year by passive means only, reducing the energy demand for heating and cooling (Martín *et al.*, 2010; Singh *et al.*, 2010; Priya *et al.*, 2012; Cardinale *et al.*, 2013; Fernandes *et al.*, 2015a,b).

In Portugal, there are some studies focusing on the passive strategies used in the vernacular building, but there is a lack of results showing the influence of these strategies on the thermal performance of vernacular buildings, namely of rammed earth buildings.

Portugal is a relatively small country, but it is a territory full of contrasts. Even though the variation in climatic factors is rather small, they are sufficient to justify significant variations in air temperature and rainfall, as can be seen in **Fig. 1**, which shows the differences in mean air temperature for mainland Portugal during winter and summer.

As **Fig. 1** shows, the northern part of the country has cold winter and dry and mild summers, while in the southern part, the winters are mild, and summers are warm and dry. As a response to these differences, Portuguese vernacular architecture developed specific and different strategies in both regions. In the north, these strategies are more oriented to increase heat gains and reduce heat losses during winter, while in the south they are more focused on passive cooling during summer. A more detailed explanation about the characteristics of these vernacular strategies can be seen in the following sections.

As vernacular architecture has shown, a building solution/strategy does not fit all contexts. The diversity of vernacular construction systems that exist in Portugal leads to the necessity of understanding the actual performance of these buildings. In this study, the main goal was to measure the hygrothermal parameters that characterize the indoor thermal environment and that affect the heat exchanges in vernacular rammed earth buildings from Southern Portugal.

Vernacular Architecture in Inland Southern Portugal

Vernacular architecture from the southern part of Portugal has developed specific mitigation strategies to suit the local climatic conditions mentioned above. As seen in **Fig. 1**, summer is the most demanding season in the region due to the intense heat. Therefore, in general, the strategies present in this type of building are more oriented for passive cooling (Fernandes *et al.*, 2015a,b). From these, the more common and frequent are (**Fig. 2(a–h)**) as follows:

(1) To minimize the size and number of windows exposed to the outdoor environment to reduce solar gains. Also frequent is taking advantage of the wall's thickness to recess the window in the facade, allowing depth to act as a shading system (**Fig. 2(a)**).
(2) The use of heavy weight building elements, with a high thermal inertia, as rammed earth walls and domes, to dampen the flow of the thermal wave and to increase the height and thermal stratification, respectively (**Fig. 2(b)**).

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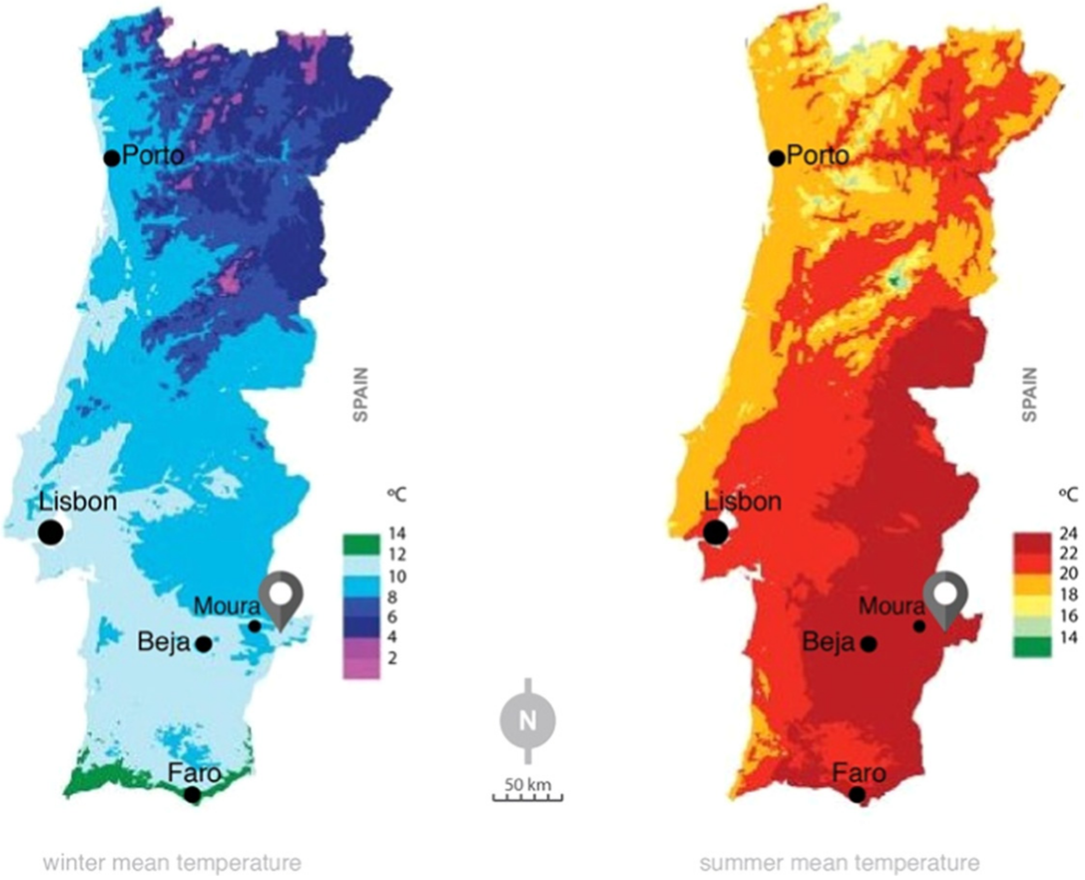

Fig. 1 (left) Winter and (right) summer mean air temperature maps for mainland Portugal. Adapted from Fernandes, J., Pimenta, C., Mateus, R., Silva, S.M., Bragança, L., 2015b. Contribution of Portuguese vernacular building strategies to indoor thermal comfort and occupants' perception. Buildings 5, 1242–1264.

(3) The use of white-washed surfaces, to reflect the incident solar radiation (Fig. 2(a)).
(4) Ventilation openings integrated into windows and/or walls, to foster air circulation and night cooling to remove diurnal thermal loads (Fig. 2(c–d)). In some cases, these ventilation openings have gridded shutters, like the *mashrabiya*. These techniques allow simultaneously ventilation and shading from intense light and radiation without compromising privacy and security.
(5) The use of patios (courtyards), usually containing vegetation and/or water, useful to generate a cool microclimate through evapotranspiration and water evaporation, respectively (Fig. 2(e)).
(6) Vegetation is also frequently used as a shading system (Fig. 2(f)).
(7) In an urban context, the use of a compact and irregular layout with narrow streets is also frequent, allowing for reducing the surface area exposed to the sun's rays and enabling buildings to provide shade for one another, thereby reducing solar gains by the building envelope (Fig. 2(g–h)).

These strategies are often combined to maximize their effectiveness to achieve a comfortable thermal environment, as shown in other studies (Fernandes *et al.*, 2015a,b). From these strategies, there is one that stands out for being the building element that characterizes Portuguese southern vernacular architecture. The heavy walls made of rammed earth are the most widespread vernacular construction technique in the southern, and mainly in the Alentejo region (the major area of all the southern part of Portugal). The heavy mass and the good heat storage capacity of rammed earth walls allow them to react appropriately to the hot summer of Alentejo, dampening the outdoor thermal wave and keeping indoor temperature and relative humidity stable (Martín *et al.*, 2010; Fernandes *et al.*, 2015a,b). The use of rammed earth in the region is ancient and there are several possible factors to explain it, such as the flat terrain, dry climate, the abundance of clayey material, and cultural influences from Romans and Moors.

The continued use for centuries of theses strategies indicates the effectiveness in mitigating the effects of the climate and, therefore, the quantitative study is useful to discuss their potential nowadays in scope of energy efficiency and sustainability.

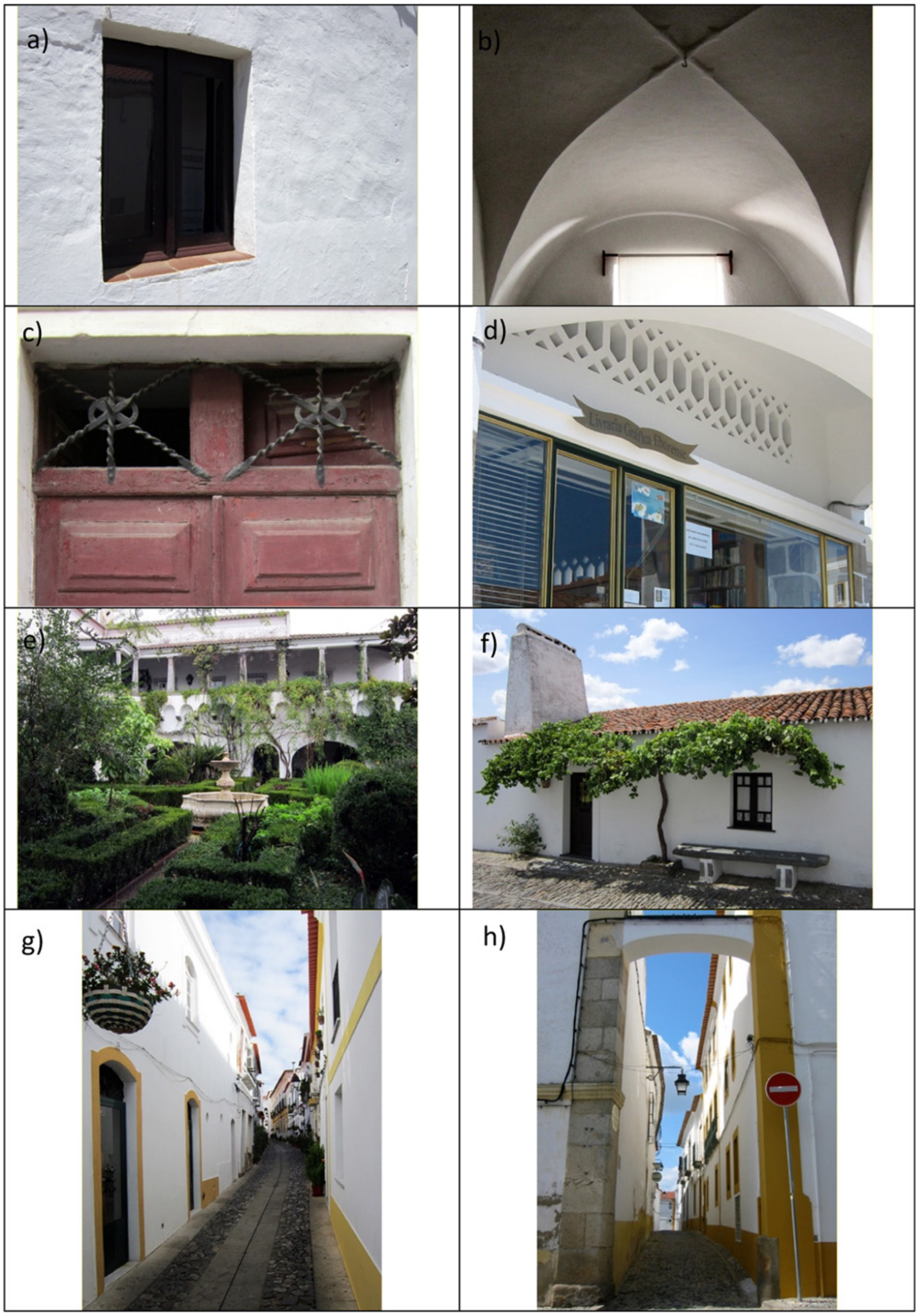

Fig. 2 (a) Small window recessed in a white-washed façade; (b) vaulted ceiling; (c) ventilation shutter integrated into window frame; (d) ventilation openings integrated into wall; (e) a patio containing vegetation and fountain; (f) vegetation shading the façade; (g–h) compact layout with shaded narrow streets.

Case Study Description

The case study is a rammed earth building located in the center of an old village, in the municipality of Moura, southern Portugal (Fig. 1). The Safara territory has an ancient occupation, with some archeological remains dating back to the 2nd Iron Age. The Romans (3rd century BCE to 5th century CE) and the Arabs (8th to 13th century CE) had a long dominion on this territory, having been integrated into the kingdom of Portugal in the 13th century. The origin of the village name has been attributed to the Arabs and means extensive plain without trees, but also adjectives such as *desert*, *arid*, and *harsh*.

This region is characterized by having a Mediterranean climate (subtype Csa), with a hot and dry summer (AEMET and IM, 2011). Summer is the most demanding season in this area, with an average maximum air temperature between 32 and 35°C, but sometimes the maximum temperatures can reach 40–45°C. July and August are the hottest months (AEMET and IM, 2011). The number of days in the year with a maximum temperature above or equal to 25°C is greater than 110 days in a large part of the southern area (AEMET and IM, 2011). In summer, the inland has more than 80 days with a maximum temperature above or equal to 25°C (AEMET and IM, 2011). In terms of precipitation is one of the Portuguese regions with less rainfall (the average value is less than 500 mm), July being the driest month (less than 5 mm) (AEMET and IM, 2011).

To cope with this climate, vernacular buildings from this region have several strategies to minimize heat gains and to promote passive cooling, such as small and few windows and doors, the use of high thermal inertia construction solutions, the use of patios (courtyards), the use of light colors on the envelope to reflect solar radiation, and ventilation openings. Regarding the latter, these are usually integrated into the upper part of windows and doors to promote air circulation, and are particularly useful for night-time cooling without compromising the safety of the building (Fernandes *et al.*, 2015a,b).

The village is strategically implanted next to the confluence between a river and two streams. It is located in a plain area of fertile agricultural land (abundant in cereals and olive trees). However, it is implanted in the transition area to the rugged terrain of streams' valleys and on the less fertile soil (lithosols), in border limit of the fertile land (**Fig. 3(a)**). Additionally, the characteristics of the surrounding soils show that they are rich in clay (luvisols and vertisols) (**Fig. 3(b)**), and at a lithological level there is presence of limestone and calcareous formations (**Fig. 3(c)**). These features were favorable factors in this site for using earth as a building material – The clayey soils for rammed earth, tiles, and bricks; and the limestone to produce lime for plasters, whitewash, etc. For example, the former military walls of Safara were built in rammed earth.

The village's urban layout is compact with a mix of narrow and wide streets, composed mostly of single-story buildings. Most of the buildings have a private courtyard, with vegetation that acts as thermal regulator, as explained in previous sections. The irregular and compact urban layout of narrow streets, with almost no streets and facades facing south, allows for reducing heat gains by the building envelope.

The case study building has an approximate gross floor area of 200 m^2 divided into two floors; however, the upper floor is just a small attic (originally a granary), usually not occupied. The living areas and the bedrooms are located in the southeast part of the ground floor, and the kitchen and the bathroom are located in the northern part (**Fig. 4**).

The envelope of the case study building consists of white-washed heavy weight external walls made of rammed earth with an average thickness of 60 cm (as the heavy thermal inertia delays the effect of outdoor temperature variation and stabilizes indoor temperature), pitched roof with ceramic tiles and reeds on timber structure (a small insulation layer of sprayed polyurethane foam was added a few years ago), wooden doors and wooden framed single glazed windows (**Fig. 5**). Indoor partition walls are in rammed earth and several of the indoor spaces are vaulted and the floor is paved with *baldosa* – a sun-dried clay tile. The building does not have an air-conditioning system and the only heating "system" is a wood-burning stove (in the living room) and the sporadic use of electric fan heaters (in the other rooms).

Materials and Methods for the Evaluation of Thermal Comfort Conditions

The purpose of the study was to assess indoor thermal performance and comfort conditions of a rammed earth building, measuring hygrothermal parameters that characterize indoor thermal environment and affect the body/environment heat exchange (air temperature, relative humidity, mean radiant temperature, and air velocity). In this study, to assess indoor thermal performance, the in situ measurements were divided into short- and long-term monitoring.

The first were carried out at least one time (usually one day) per season and were performed with the purpose of quantitatively assessing the thermal conditions within a specific room using a thermal micro-climate station (model Delta OHM 32.1) equipped with the probes required, namely, globe temperature probe Ø150 mm (range from −10°C to 100°C); two-sensor probes for measuring natural wet bulb temperature and dry bulb temperature (range from 4°C to 80°C); combined temperature and relative humidity probe (range from −10°C to 80°C and 5–98%RH); and omnidirectional hot-wire probe for wind speed measurement (range from 0 to 5 m/s). This data is used in the analysis of the thermal comfort conditions to determine the operative temperature, namely in the adaptive model of comfort, as explained below. Simultaneously, occupants were surveyed to evaluate their satisfaction with the indoor thermal environment, according to ASHRAE survey and thermal sensation scale (ASHRAE, 2004). The results of both procedures were then compared to conclude if converged or diverged.

Long-term monitoring had the aim of understanding fluctuations of air temperature and relative humidity, indoors and outdoors, throughout the various seasons. Therefore, combined temperature and humidity sensors were installed outdoors and indoors (in the most relevant rooms) for the assessment of thermal performance. The equipment used was composed by a thermohygrometer with datalogger (model Klimalogg Pro, TFA 30.3039.IT) (temperature range between 0 and 50°C with accuracy of ±1°C; humidity range from 1% to 99% and accuracy of ±3%), and a set of wireless thermohygrometer transmitters (model 30.3180.IT) connected to the datalogger (the transmitters have the same accuracy values; temperature range from −39.6°C and +59.9°C and relative humidity range from 1% to 99%).

The air temperature and relative humidity measurements were carried out for periods of at least 25 days in each season and with the different thermohygrometer sensors recording data at 30-min intervals. Results on indoor environmental climate parameters were correlated with the outdoor parameters. During these measurements, occupants filled an occupancy schedule where

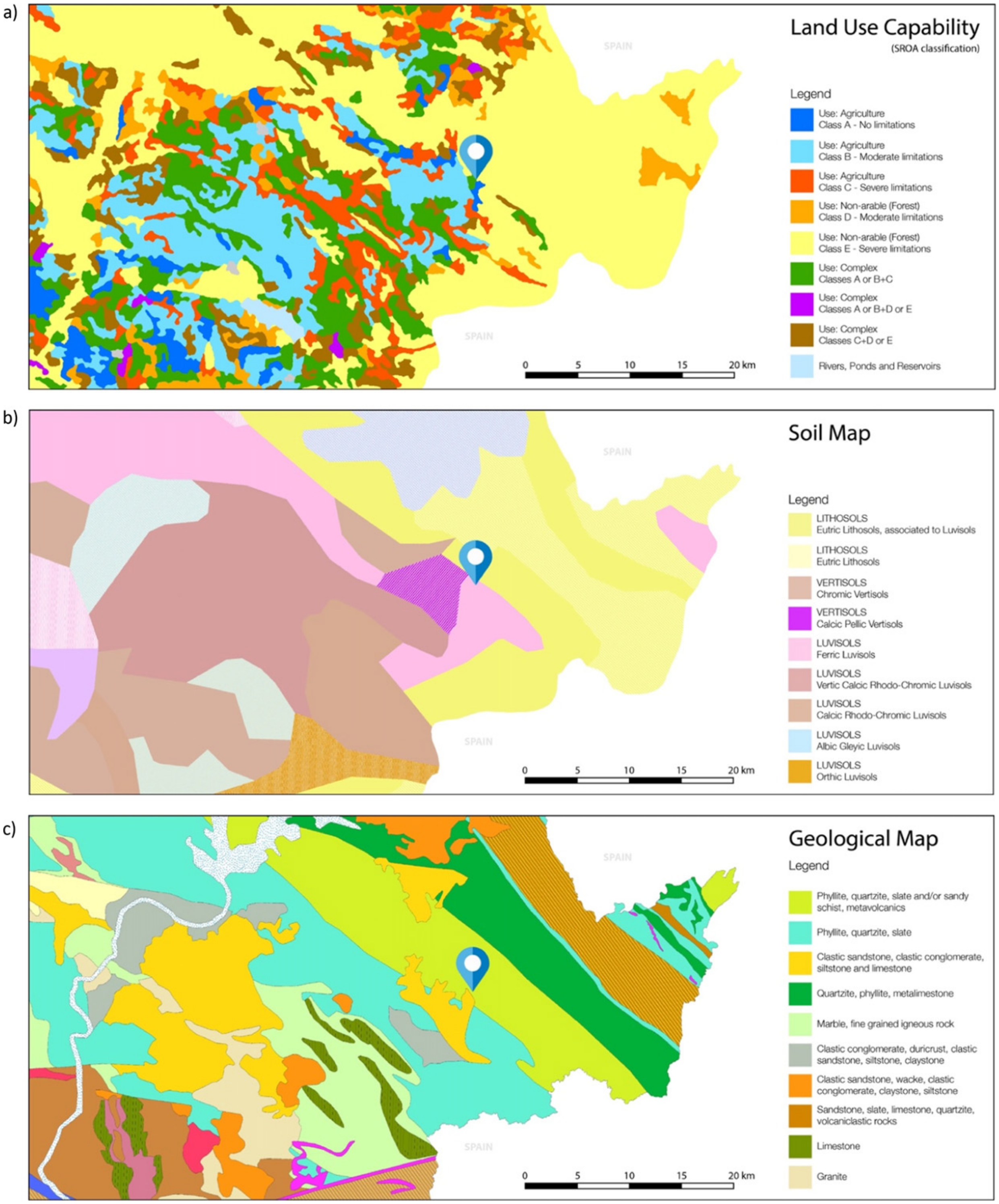

Fig. 3 (a) land use capability map of Safara area. (b) Soil Map of Safara area. (c) Geological map of Safara area. Adapted from APA-SNIAmb, 2018. Environment Atlas – SNIAmb – Agência Portuguesa do Ambiente (online). Available from: https://sniamb.apambiente.pt/content/geo-visualizador?language=pt-pt (accessed 14.06.18).

they documented how they used the building (occupation periods, opening windows pattern, for example). These occupancy records were useful to understand, for example, sudden changes in air temperature and relative humidity profiles. The weather data used in the study was collected from the nearest weather station (approximately 5 km). All the measurements were carried out according to standards ISO7726 (2002), ISO7730 (2005), and ASHRAE 55 (2004).

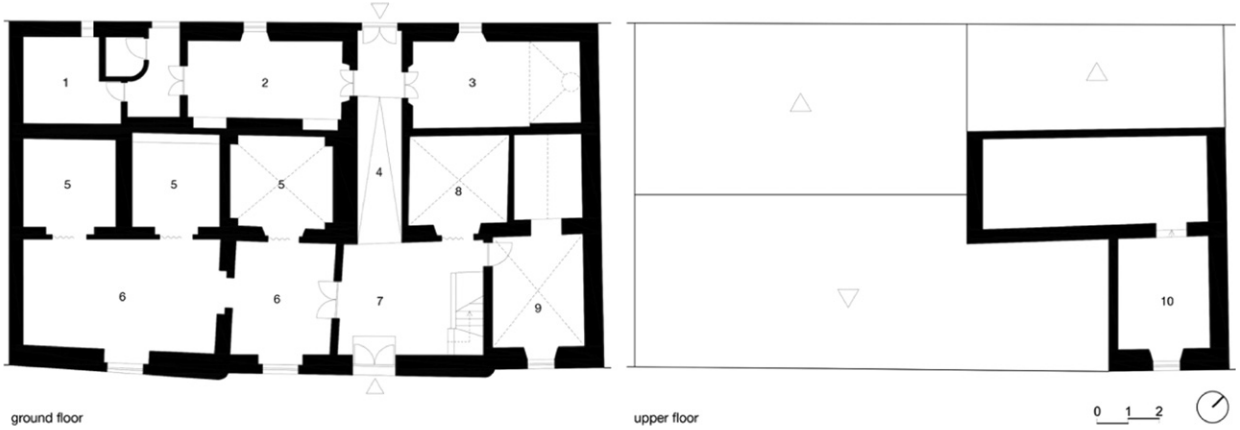

Fig. 4 Floor plans (1 – bathroom; 2 – kitchen; 3 – living room (the kitchen was previously located here); 4 – corridor; 5 – alcove; 6 –living room; 7 – hall; 8 – library; 9 – bedroom; 10 – attic). Adapted from Fernandes, J., Pimenta, C., Mateus, R., Silva, S.M., Bragança, L., 2015b. Contribution of Portuguese vernacular building strategies to indoor thermal comfort and occupants' perception. Buildings 5, 1242–1264.

Fig. 5 External view (left), living room (right), with the micro-climate station measuring.

In the analysis of thermal comfort conditions, the relation between indoor comfort temperature and outdoor temperature was evaluated using an adaptive model of comfort, since this is the most adequate model for naturally conditioned areas. To be more representative of the Portuguese reality, the chosen model was the Portuguese adaptive model of thermal comfort (Matias, 2010) developed in the Portuguese National Laboratory of Civil Engineering (LNEC), which is an adaptation to the Portuguese context of the adaptive comfort model of ASHRAE 55 (2004) and EN15251 (2007). The Portuguese model takes into consideration the Portuguese climate (temperate climate Type C according to Köppen-Geiger Climate Classification), typical ways of living and operating buildings. It also considers that occupants may tolerate broader temperature ranges than those usually mentioned in standards and that outdoor temperature highly influences occupants' thermal sensation. A more detailed explanation of the model can be seen in Matias (2010) and Fernandes *et al.* (2015a,b).

The operative temperature was calculated based on the results obtained in the measurements from the Thermal Micro-Climate Station. With the operative temperature (Θo) and the outdoor running mean temperature (Θrm) it is possible to represent in the adaptive chart the point that characterizes the thermal environment condition in the moment of measurement.

Results and Discussion

The analysis of the thermal performance focused on the two most demanding seasons in terms of thermal comfort in the Portuguese context, namely winter and summer.

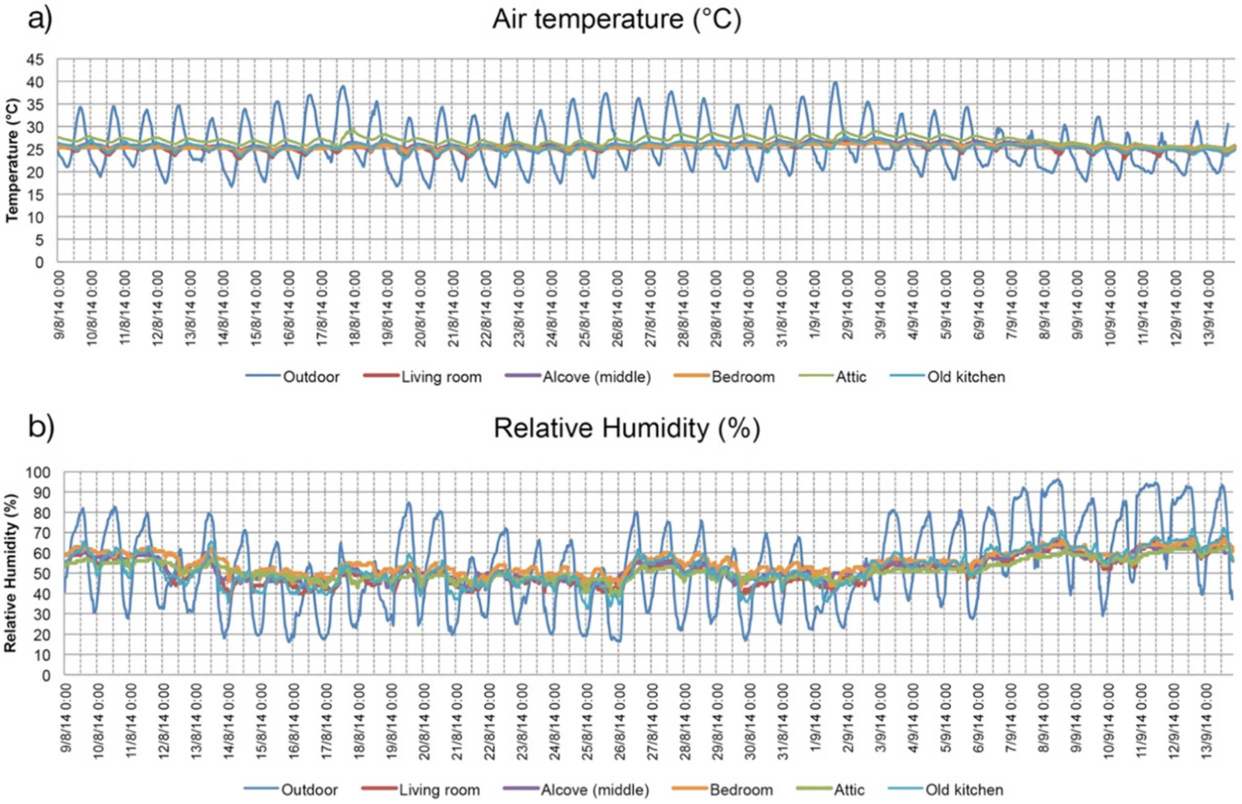

Fig. 6 Thermal performance during summer. (a) Indoor and outdoor air temperature profiles; (b) indoor and outdoor relative humidity profiles. Adapted from Fernandes, J., Pimenta, C., Mateus, R., Silva, S.M., Bragança, L., 2015b. Contribution of Portuguese vernacular building strategies to indoor thermal comfort and occupants' perception. Buildings 5, 1242–1264.

Summer Monitoring

The summer monitoring was carried out from August 9 to September 13, 2014, and the results are presented in **Fig. 6**. It is possible to verify that during this period the outdoor mean air temperature was of about 26°C. During the day, the maximum air temperature was often higher than 35°C, reaching, in some days, nearly 40°C. The minimum air temperature was usually around 20°C. Although the daily outdoor temperature variation is high, the indoor temperature remained very stable during the monitoring period, with temperature values around 25°C (**Fig. 6(a)**). Due to its location near the roof, the attic was the room that recorded the highest temperature (27°C), while outdoor peak temperature was around 40°C. The indoor temperature profile shows that the high thermal inertia of the building envelope (e.g., thick rammed earth walls and vaulted ceilings) provides a high capacity to delay the effect of outdoor temperature variation and to stabilize indoor temperature.

The relative humidity profile also presented high outdoor day/night variation, presenting minimum values lower than 20% and maximum values of approximately 95% (**Fig. 6(b)**). On the other hand, indoor spaces had more stable relative humidity profiles varying between 40% and 60%. These differences were due to the hygroscopic inertia of the building systems, such as the rammed earth walls and the lime plaster, which have a moisture regulation capacity (Fernandes *et al.*, 2015a,b), by absorbing when it is excessive and releasing it when the air is dryer.

Fig. 7 shows the results of the thermal comfort conditions assessment in the living room. This room was chosen because it is where the occupants remain for longer periods during the day. The results showed that the thermal comfort conditions in the building are in the center of the limits defined for the Portuguese adaptive thermal comfort model, i.e., in a condition of thermal comfort. In the survey, one occupant answered as being "slightly cool" and two occupants answered as being "neutral" (comfortable), confirming the measurements.

Winter Monitoring

The winter monitoring was carried out from December 22, 2014 to February 7, 2015. From the results obtained it can be seen that outdoor air temperature presented several fluctuations, with maximum temperature rarely reaching 15°C during the day and minimum values frequently lower than 5°C during the night (**Fig. 8**). As observed for summer, the indoor temperature remained very stable with a temperature of approximately 15°C (**Fig. 8(a)**). The indoor rooms with higher temperature variation were the

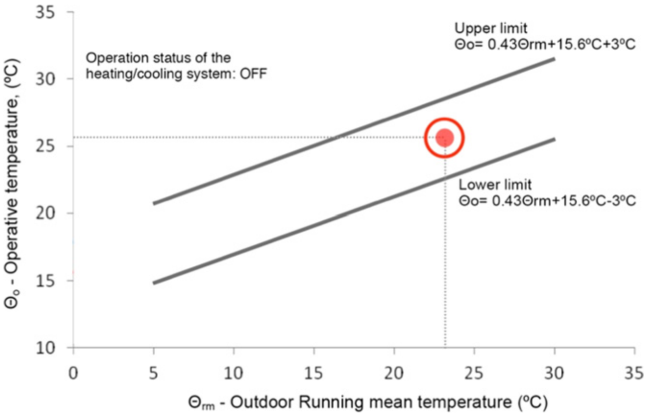

Fig. 7 Thermal comfort temperature (operative temperature) in the living room during summer monitoring, based on the relation between the limits of the indoor operative temperature (Θo) for buildings without mechanical air-conditioning systems as a function of the exponentially weighted running mean of the outdoor temperature (Θrm). Adapted from Fernandes, J., Pimenta, C., Mateus, R., Silva, S.M., Bragança, L., 2015b. Contribution of Portuguese vernacular building strategies to indoor thermal comfort and occupants' perception. Buildings 5, 1242–1264.

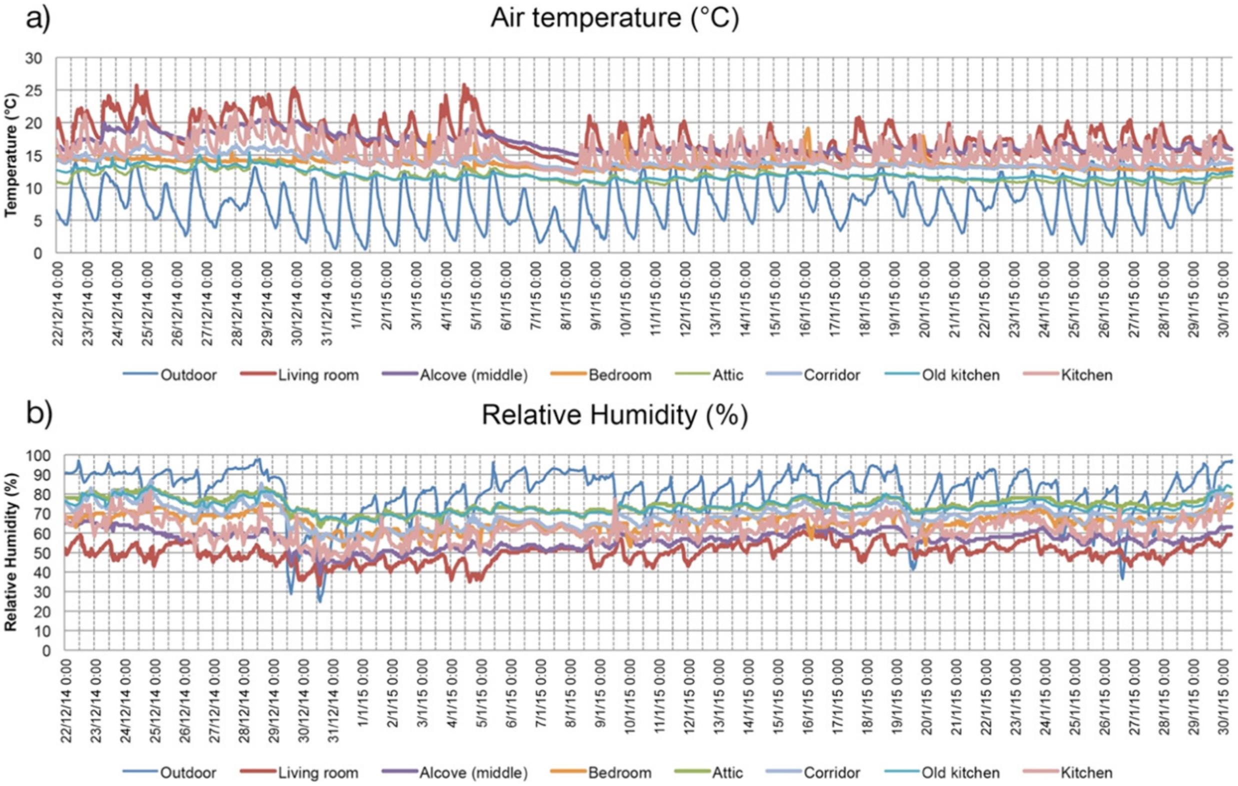

Fig. 8 Performance during the winter. (a) Indoor and outdoor air temperature profile; (b) indoor and outdoor relative humidity profile.

ones where the occupants frequently use heating equipment (stove and electric heating fan), namely in the living room and kitchen. These were also the rooms with better comfort conditions, since the other rooms were not heated and although they had stable temperatures, they were below 18°C. Nevertheless, in Fig. 8(a) it is possible to see that when rooms are heated it is relatively easy to increase, and maintain, the indoor temperature above 18°C, and in some situations up to 25°C.

In winter, the relative humidity indoors was very stable, though with values above 60%, with the exception of the living room and alcove (around 50%) (Fig. 8(b)). The decrease observed in the living room could be associated with the use of heating (a wood-burning stove).

The evaluation of thermal comfort was carried out with the stove in operation. In the living room the comfort conditions are in the center of the comfort range (Fig. 9). However, the thermal sensation in the rooms without heating was considerably below the

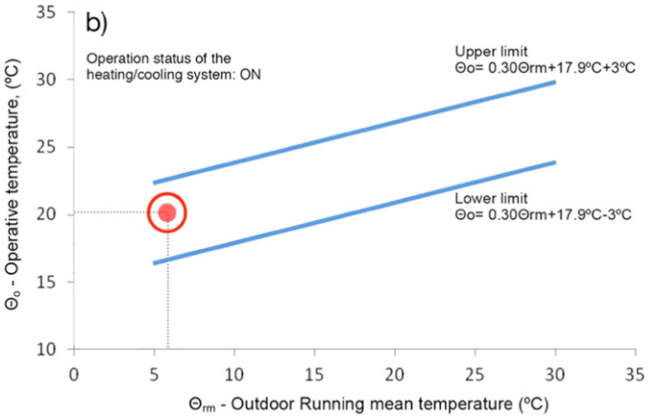

Fig. 9 Thermal comfort temperature (operative temperature) in the living room during winter monitoring when the heating system was on, based in the relation between the limits of the indoor operative temperature (Θo) as a function of the exponentially weighted running mean of the outdoor temperature (Θrm). Adapted from Fernandes, J., Pimenta, C., Mateus, R., Silva, S.M., Bragança, L., 2015b. Contribution of Portuguese vernacular building strategies to indoor thermal comfort and occupants' perception. Buildings 5, 1242–1264.

thermal comfort range. Although the indoor temperature was considerably higher and more stable than outdoors, it was not possible to achieve thermal comfort conditions without heating. Nevertheless, it was verified that a simple heating system is sufficient to achieve thermal comfort conditions. The results from survey to the occupants supported the measurements, with three occupants answered as being "neutral" (comfortable) and one as being "slightly cool."

Conclusions

The results of the thermal performance and comfort conditions assessment of the rammed earth building showed that is possible to achieve indoor thermal comfort just with passive means, confirming a strong relation of cause and consequence between vernacular architecture and the climatic context. The building had a high thermohygrometic performance during summer, the harshest season in this climatic zone, confirming the effectiveness of the passive cooling strategies. In winter, it was not possible to maintain thermal comfort conditions only with passive strategies. However, the thermal discomfort situations were overcome using a simple heating "system" (wood-burning stove).

It was noticed that the thermal inertia of the building, the solar exposure, the shading and natural ventilation devices, the adequate organization of the rooms taking into consideration solar orientation, and the action of occupants are significant aspects that have a positive influence in the indoor temperature and humidity profiles (e.g., promoting passive cooling by natural ventilation during the night and early morning, shutting doors and windows during the periods with incident radiation, etc.).

The results observed in this study allow concluding that with the use of a combined set of passive strategies, such as the passive cooling strategies during summer, it is possible to ensure thermal comfort conditions without using HVAC systems. The adoption of such strategies in buildings in this region can greatly contribute to reducing energy needs for cooling and therefore to reducing energy use and potential environmental impacts during the operation phase.

Considering the results and taking into consideration that the case study is an old building with building elements that are not optimized, it can be stated that the passive strategies used in vernacular architecture have high potential to be improved and adapted to new buildings, allowing thermal comfort while reducing energy demand.

Acknowledgments

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