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Assessment of the Thermal Behaviour of Rammed Earth Walls in the Summer Period

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Abstract: The constructive solutions characteristic of vernacular architecture are the result of the convergence of geographical, cultural and climatic factors that bring about constructions characterised by adaptation to their surroundings. However, at present, Spanish regulations do not contemplate the properties of traditional materials, such as those found in earthen constructions, whose great thermal inertia is ignored despite their thermal gains and compensations. Given these limitations, the purpose of this study is to assess the thermal behaviour of traditional earthen architecture adjusting to its real performance and original surroundings. This work thus examines a methodology to assess the thermal behaviour of rammed earth walls based on on-site data specifically collected in the summer in a case study located in La Serranía, a region in the northwest of the province of Valencia (Spain). The results show the evolution of exterior and interior surface temperatures of the earthen wall, quantifying its variation frequency and thermal energy transmission. Based on these data, the thermal transmittance of the wall is calculated and compared to highlight the difference from the normalised value, showing that a review of the Spanish regulations applied to earthen architecture is needed.

Keywords: thermal behaviour; rammed earth; vernacular heritage; earthen architecture; thermal transmittance

1. Introduction

Regarding the Building Technical Code (CTE) currently in place in Spain, it is important to note the existence since 2006 of the Basic Document in Energy Saving (DB HE) [1], which aims to improve the quality of buildings and to ensure a rational use of the energy needed in buildings based on design, construction, use and maintenance. In addition to calling for a reduction in energy consumption, these regulations aimed to maintain energy services, guaranteeing proper supply and the protection of the environment without hindering comfort or quality of life.

It is also worth reflecting on the interest in the sustainability of traditional architecture that has appeared over the last few years [2–4], heralded by earlier research on the bioclimatic behaviour of traditional architecture [5–7]. The main aim of the most recent studies is the quantification and assessment of specific parameters of traditional constructions and the identification of their response to the surrounding geographic and climatic factors. This research generally focuses on points relating to the hygrothermal behaviour of traditional constructive materials and systems, using different methodologies in specific case studies within a given territory [8–11].

However, the DB HE does not consider the properties of traditional materials, such as those found in earthen constructions, whose great thermal inertia is largely ignored despite its thermal gains and compensations [11]. As a result of its application and in view of the threshold values of the theoretical thermal transmittances established, in order to comply with regulation, traditional earthen constructive systems must increase thermal insulation.

Given the unreliability of these regulations in the evaluation of traditional earthen buildings [11,12], the use of other methods is advised when assessing the thermal behaviour of these constructions. Those found in the Iberian Peninsula show a wide range of solutions characteristically adapted to their surroundings [13]. In order to adjust to the real behaviour of earthen buildings, these methods necessarily require prior measurement of hygrothermal variables [14] to be used to calculate thermal parameters.

Thus, this article describes the experimental methodology used to assess the thermal behaviour in summer for a traditional residential building located in the region of La Serranía in Valencia, as well as the results obtained from its application. This small region of great natural wealth is the site of a wide variety of vernacular rammed earth buildings [15] whose construction follows the guidelines imposed by their location and materials. It should also be noted that this study is part of broader research on the study of traditional earthen architecture in the Iberian Peninsula, which analyses this heritage from different perspectives such as bioclimatic behaviour [16] and energy efficiency in interventions.

The aim of this article is the quantification and comparison of the gradient of thermal oscillations outside and inside the rammed earth wall that makes up the envelope of a representative case study in the traditional earthen architecture in the region, as well as the effects of thermal inertia in the delay in the transmission of thermal waves in the successive day cycles and day–night cycles based on on-site data collected in summer. This study also aims to contrast the thermal transmittance values obtained using different calculation methods, which will be contrasted with the parameter thresholds required in current regulations.

2. Materials and Methods

The research methodology is based on the analysis of a representative case study of traditional earthen architecture in the region of La Serranía, and the prior on-site collection of data and documentary information. Thus, three research phases are proposed:

2.1. Case Study Analysis

This study required detailed prior (direct and indirect) documentary research and inventory of buildings in the region studied. This analysis included the general building characteristics and location, current use, architectural type and state of conservation of immediate surroundings, in addition to examining aspects relating to the constructive earthen technique, family, building variant and size of modules used. The lesions on the buildings were recorded, along with the interventions and transformations of individual elements (foundations, walls, floors, roof, openings). This information was compiled in a database and analysed to establish the main variable for each of the characteristics recorded. This provided a representative image of traditional earthen architecture in the region from which a case study was selected for the assessment of thermal behaviour.

Research began with a bibliographical study of the territory through local and regional publications. This madeit possible to collect information on the geography and climate, as well as to examine the adaptation mechanisms of the architecture to its location, based on architectural typologies of reference in other regions with similar climate features. As the research focused on the assessment of the thermal behaviour of rammed earth walls, special attention was paid to the study of the thermal parameters defining the bioclimatic strategies of adaptation to the environment [16].

While several authors have provided an in-depth inventory and analysis of traditional earthen buildings in the Iberian Peninsula [17], the region of La Serranía has been part of a broader study resulting in a detailed definition of the constructive and typological characteristics of this regional architecture [15]. The dimensions and material composition of the earthen modules were analysed and different constructive variants were identified, as were the individual architectural typologies to which they were associated, their state of conservation, geographical distribution and relationship with immediate surroundings [18].

After establishing the general characteristics of traditional earthen architecture in the region and its mechanisms for adapting to surroundings, a case study was selected for the accurate assessment of thermal behaviour. The building was selected from a previous database [15] that classifies constructions by constructive technique, surroundings, visible lesions and transformations undergone. These case parameters correspond to the majority results obtained for the study of the earthen architecture in the region. However, in order to carry out detailed environmental, architectural and constructive analyses, the building must remain accessible throughout the study, fit a specific architectural typology and conserve its original architectural and constructive characteristics intact.

After an analysis of the building's immediate surroundings, the rooms characteristic of its architectural typology were identified using a metric survey. The constructive characteristics of the building were studied visually, combined with measurements of constructive elements in order to classify and date them [19].

A thermographic camera was also used to ensure a complete understanding of the dwelling and the transformations undergone. A thermographic study was thus carried out of the constructive elements of the dwelling (walls, roof, openings, etc.), paying special attention to the joints between these. Thermal images were captured when there was a high thermal contrast between the interior and exterior, which happened naturally before sunrise. A FLIR E60bx 1.3 thermographic camera with 18 mm FOL lens was used in the study to produce thermal images with a 320×240 pixel resolution, in a temperature range of -20 to 120 °C and with a thermal sensitivity below 45 mK NETD (Noise Equivalent Temperature Difference). The thermal images were processed with FLIR Tools software (Version 5.9.16284.1001), which makes it possible to vary the thermal field, colour palette for emissivity, distance, ambient temperature and reflected temperature, as well as to calculate the maximum, minimum and mean values for the area under study in the image captured.

2.2. Hygrothermal Data Collection

Assessment of the thermal behaviour of rammed earth walls requires the prior collection of data, with real readings of temperature for both surface and ambient conditions of the rammed earth wall and the room within. Three dataloggers were used to monitor these measurements.

The dataloggers were placed on the building's main southeast-facing façade, on the middle storey. They were placed on both sides of the wall, as well as inside the room. Dataloggers were placed on both surfaces of the wall at equal distances from the floor and the jamb of the opening of reference. Each datalogger recorded data on temperature in relation to their positions at hourly intervals, thus establishing a distinction between the values of the interior surface, interior ambient and exterior surface. The data was collected cover two months in the summer period of 2017 (from 24 June to 23 August).

Before placing the dataloggers in the buildings, an inspection was carried out using a thermographic camera to ensure that there were no material anomalies or discontinuities in the wall with the devices (Figures 1 and 2). In addition, the datalogger on the outer surface was protected from the direct solar radiation to prevent error due to overheating [20].

According to the specifications of the datalogger manufacturer, the temperature may be subject to an error of around ±1 °C of the value recorded, leading to potential alterations in results in the following research phase.

Figure 1. View of the datalogger on the outer surface of the rammed earth wall. Source: L. Balaguer.

Figure 2. Verification with a thermographic camera of the wall surface with a datalogger. Source: L. Balaguer.

2.3. Data Analysis and Calculation of Thermal Parameters

Based on the data obtained from the dataloggers on the wall, a comparative dynamic analysis of three variables was carried out: exterior surface temperature of the wall (T_{se}), interior surface temperature of the wall (T_{si}) and room ambient temperature (T_{amb}). This allowed the frequency of the variations between the interior and exterior surface temperature of the wall and their relation to interior ambient temperature to be determined.

In addition, the thermal behaviour of the rammed earth walls was assessed based on thermal transmittance (U) through the comparative analysis of the results obtained using theoretical calculation processes and processes based on data collected. The theoretical calculation of transmittance is based on normalised standard UNE-EN ISO 6946 [21] and Spanish regulations [1]. This allowed this parameter and the total thermal resistance (R_T) of the rammed earth wall to be calculated based on the layers that make it up (R_n):

$$R_T = R_{si} + R_1 + R_2 + \ldots + R_n + R_{se}\ [m^2K/W]$$

$$U = 1/R_T\ [W/m^2K]$$

The values required for these equations were obtained from the review of the bibliography and the calculation of the wall components following visual and metric inspection.

In addition, thermal transmittance (U) was calculated based on the on-site data using a dynamic analysis method, which uses thermal resistance (R) as a starting point following Fourier's linear equation [11,20] and the temperature values recorded:

$$R = \frac{\frac{1}{8(T_{si} - T_{amb})}}{T_{se} - T_{si}}\ [m^2K/W]$$

Based on this equation, thermal transmittance is defined as follows:

$$U = \frac{\frac{1}{6\ (T_{si} - T_{amb})}}{(T_{se} - T_{si})} \times d.\ [W/m^2K]$$

where: T_{se} is the exterior surface temperature of the wall [K], T_{si} is the interior surface temperature of the wall [K], T_{amb} is the ambient temperature of the room [K] andd is the wall thickness [m].

Finally, the theoretical and actual thermal transmittance values obtained in both procedures were contrasted.

3. Results

Traditional earthen architecture was born in response to the needs of the inhabitants of specific regions and used locally available materials in the construction, taking into consideration the geography, climate, culture and socioeconomic context of the location. The anonymous builders in the region were experts in the thermal behaviour of earthen walls thanks to their experience and they took full advantage of the qualities of earth to construct buildings of great architectural value, which offered comfortable spaces to their occupants [16]. However, at present, Spanish regulations do not consider the benefits of traditional constructive systems and only establish a threshold value for thermal transmittance that walls must not exceed, regardless of their material, such that it is necessary to analyse their thermal behaviour based on real data collected on site.

3.1. Case Study: Traditional Earthen Dwelling in Villar Del Arzobispo (La Serranía)

The region of La Serranía, in the northwest of the province of Valencia, is geographically unique as it is the point of convergence of two characteristically Valencian landscapes: the mountain and the *huerta* [13]. Although the Valencian territory enjoys a Mediterranean climate with mild semi-arid winters and summers, the geographical location of La Serranía far inland and its relief give rise to certain features that define its climate. The region can thus be divided into three sectors with individual climate characteristics [22] that become more extreme towards the north and south: climate in the transition zone, mountain climate in the northwest and climate in the western central sector. The case study is located in Villar del Arzobispo, in the transition zone, with greater thermal oscillation and variable rainfall.

It should be stressed that the mean temperature values in this climate sector are milder than in other parts of the region. The annual mean temperature of the municipality is around 13 °C according to the most recent measurements [23]. The highest temperatures are recorded in the month of July, with a mean maximum temperature of 32 °C, whereas the lowest thermal values are recorded in the month of January with a mean minimum temperature of 2 °C.

This area, with warm summers and mild winters, has a mean thermal oscillation of 10–12 °C. The daily thermal amplitude is greater in the summer months (12–14 °C) than in the winter ones (7–12 °C) due to the continental climate of the territory.

Radiation or advection frosts linked to minimum temperatures are a common phenomenon in the area, especially in the months of December, January and February. Frosts occur around 20–30 days a year.

In addition, there is an average limited rainfall of 450–550 mm [23]. The volume of annual rainfall days, around 40–50 days, is within the usual margins for the Valencian territory, and varies by season. A higher concentration is generally observed in autumn (mean of 160.1 mm) and spring (meanof 125.8 mm).The rainfall mean in summer is 77.6 mm. Rainfalls are common, whereas snowfalls are an unusual phenomenon in this municipality (mean of 0.8 days a year). Hailstones are a frequent occurrence, associated with the storms that occur on a mean of 0.9 days a year.

The direct influence of solar radiation in the temperatures recorded in the region should also be noted, with mean values between 4.2 and 4.4 kWh/m^2. In addition, in the region, there are a great number of hours of sunlight a year, between 2400 and 2600.

In the historic centre of Villar del Arzobispo, this dwelling is one of the few examples of residential traditional architecture that appears unchanged by modernity. This typical agricultural house of a relatively well-off labourer has undergone different interventions as a result of the changes in the functional needs of its inhabitants, who modified both the interior distribution and constructive solutions. Among these changes, it is worth highlighting the work carried out at the start of the twentieth century, remodelling the entrance space, modifying access points and including new sleeping quarters [19].

The dwelling is located on a corner with a southeast-facing main façade and a northwest-facing one. There is also a façade that corresponds to a southwest-facing secondary access, although it is not relevant to the study proposed as it does not outline an inhabitable space. The variable incidence of solar radiation on the façades of the building studied is due to the sun's movements during the day and the changes in its trajectory at different times of the year, as well as its position among narrow streets and buildings of different heights.

The 345.5 m^2 dwelling preserves spaces characteristic of traditional architecture, distributed over three floors above ground level, as well as a semi-basement which covers part of the surface of the plot [19] (Figure 3). As is common in traditional earthen dwellings, there is a low proportion of openings on the façades, 24.5% of the main façade (SE) and 6.7% of the side façade (NE).

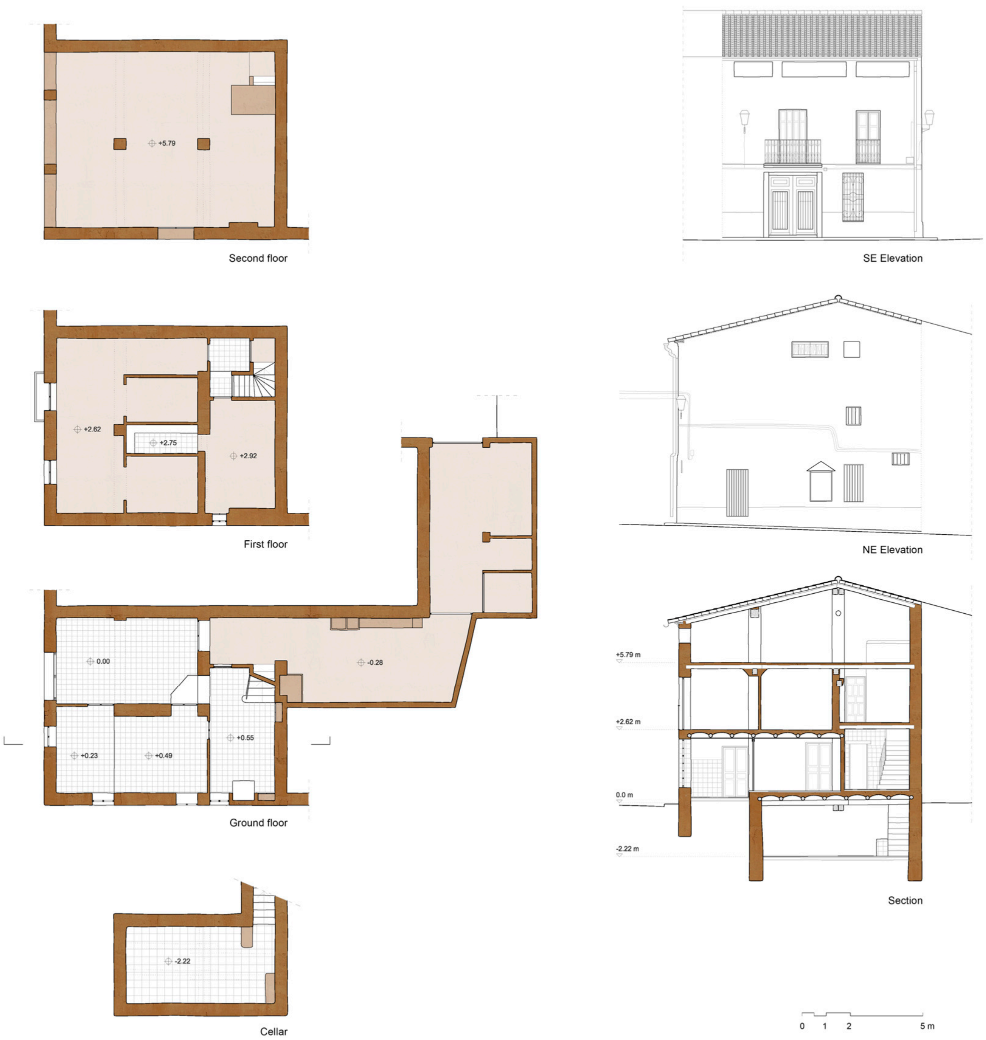

Figure 3. Metric survey of the case study. Source: L. Balaguer.

The walls of the building envelope hada mean thickness of 50 cm and were built in a variant of supplemented rammed earth, with masonry on the exterior surface and including gypsum *brencas and rafas* (wave-like and pillar-like coffered supplements, respectively), as well as rammed earthlayers (5–10 cm thick) in every coffered course (Figure 4). Although the walls were rendered, the thermographic study carried out revealed the constructive solution of these rammed earth walls (Figure 5).

In addition, the constructive systems of the residential building were those traditionally associated with local earthen architecture, taking advantage of natural resources available at the time of construction. Thus, floors were made of square beams and joists or wood logs, with gypsum-poured jack arch vaults between joists (ground and first floor) and reed frameworks (roof). The walls and horizontal surfaces varied from traditional continuous renderings in lime and gypsum to renderings based on ceramic and hydraulic tiles. It should be noted that little original joinery remained as it has been replaced due to damage or changes in the use of rooms. Nevertheless, these elements preserved the traditional character of the dwelling and its material characteristics.

Figure 4. Detail of the interior surface of the earthen wall on the upper level of the dwelling. Source: L. Balaguer.

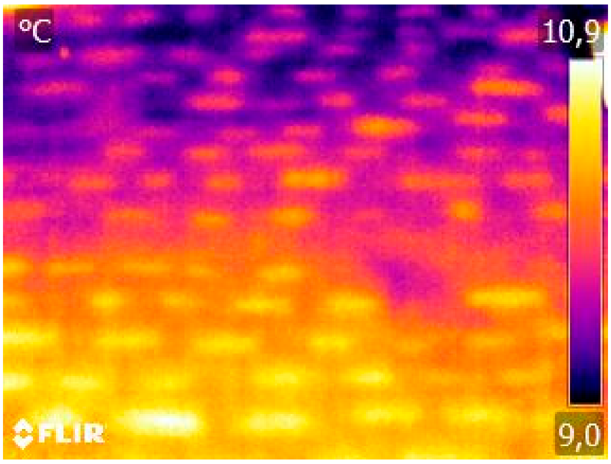

Figure 5. Thermal image of the NE façade showing the different masonry courses in the rammed earth wall. Source: L. Balaguer.

3.2. Thermal Behaviour of Rammed Earth Walls Based on Data Collected In Situ

In order to verify the information from existing literature on traditional earthen architecture heritage in La Serranía, the thermal oscillation of the rammed earth wall was analysed using the on-site hygrothermal data collected in the summer period (from 24 June to 23 August 2017). The rammed earth wall monitored was that of the main façade (SE) and outlined the anteroom of the bedroom (first floor).The thermal oscillation for this period, as well as the damping and delay in the successive day and day-night cycles, were analysed and quantified.

The thermal behaviour of the walls was analysed graphically through the oscillations of exterior and interior surface temperature, as well as ambient temperature. The graphs therefore show the evolution of the three variables mentioned in the period studied. The x-axis represents the number of measurements carried out in this period at hourly intervals, while the y-axis shows the temperature reached measured in degrees Celsius (°C). The variables represented in the graphs are:

1. T_{se} (exterior surface temperature), in blue.
2. T_{si} (interior surface temperature), in red.
3. T_{amb} (ambient temperature), in green.

The oscillations between maximum and minimum represented in the variables in the graphs correspond to daily cycles. The maximum exterior surface temperature was reached at solar noon while the minimum was reached in the early hours of the day, with a 6-h difference.

Analysis of the graph shows that for these two months, the exterior surface temperature reached a maximum of 46.4 °C and a minimum of 15.4 °C, while the interior surface temperature remained between 22.2 °C and 28.4 °C and ambient temperature between 21.9 °C and 29.1 °C. A high variation frequency (Figure 6 and Table S1) with a daily thermal gradient between 8.2 °C and 23.5 °C was observed in the exterior surface temperature, contrasting with the regular interior surface temperature and room ambient temperature. Both interior variables recorded daily oscillations in an interval below 2 °C.

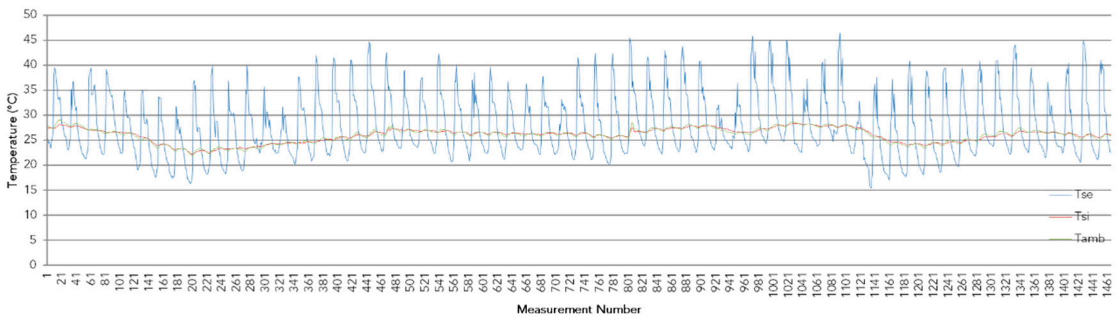

Figure 6. Thermal oscillation of the wall for the period 24/06/2017–23/08/2017. Source: L. Balaguer.

Therefore, the maximum oscillation of the interior surface temperature was at least a twelfth of the oscillation of the exterior temperature, while the minimum is barely a quarter. This proportion of thermal oscillation of the interior compared to the exterior was due to the thermal damping of the material, which reduced fluctuations in temperature and improved the comfort sensation for room occupants. In addition, the oscillation of the interior surface temperature and ambient temperature developed in parallel, although the latter tended to be higher. Nevertheless, the graph lines peak and intersect, indicating some level of activity in the rooms or the building.

Some parts of the graph clearly show the effects of the cycle of successive days on the rammed earth walls, as the tendency of the exterior surface temperature to increase or decrease was reflected in the interior temperatures, although with a delay of 2 to 6 days rather than an immediate one. As this phenomenon can be observed in detail when analysing shorter periods this study focused on the example of the period from 7 to 23 August (Figure 7).

An initial decrease was observed in exterior surface temperature, with minimums between 24.4 °C and 15.9 °C over a 3-day period. However, this decrease was not reflected in interior temperatures (T_{si} and T_{amb}) until two days later when their values started to decrease proportionally. After this decrease, the exterior surface temperature increased over a 7-day period from 10 August, although this was only reflected indoors two days later. Although the decrease in T_{se} occurred over 3 days and the increase over 7 days, T_{si} and T_{amb} varied proportionally after 4 and 6 days, respectively. This simultaneously shows the thermal lag from outdoors to indoors and the damping of the material of the oscillation of temperatures in cycles of successive days. In addition, the less pronounced decrease in exterior surface temperature from 17 August was also reflected in interior temperatures, with proportionally decreasing values and a 2-day delay.

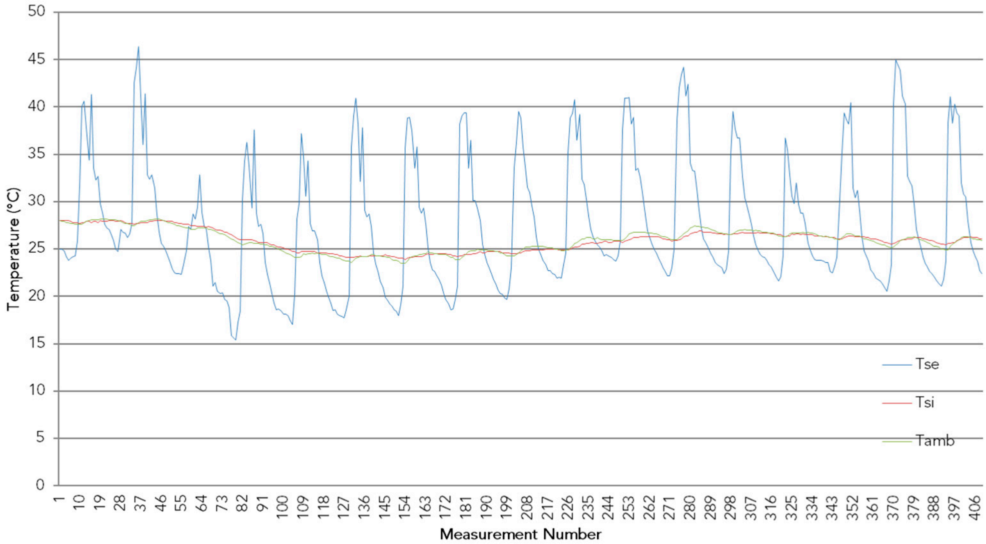

Figure 7. Thermal oscillation of the wall for the period 07/08/2017–23/08/2017. Source: L. Balaguer.

Furthermore, a delay was observed in the transmission of thermal energy from the exterior to the interior in the day–night cycle, depending on whether exterior surface temperature rose or fell. In the first case, a 5–8 h delay was calculated, whereas in the second, this decreased to 1 or 2 h.

3.3. Thermal Behaviour of Rammed Earth Walls Basedon Thermal Transmittance

Thermal transmittance (U) is defined as the heat flow in steady state for an area and difference of unit temperatures of the mediums situated on either side of the element under study [1]. Based on the normalised procedure for calculating thermal transmittance [1], the theoretical value of this parameter was 1.5836 W/m^{2}K (Table 1).

Table 1. Theoretical calculation of thermal resistance and transmittance in the rammed earth wall. Source: L. Balaguer.

Rammed Earth Wall	d [1] (m)	λ [2] (W/mK)	R (m^{2}K/W)	U (W/m^{2}K)
Interior surface	-	-	0.13	
Gypsum mortar rendering	0.015	0.8	0.01875	
Rammed earth wall	0.465	1.1	0.42273	
Cement mortar rendering (1600 < d < 1800)	0.02	1	0.02	
Exterior surface	-	-	0.04	
TOTAL	0.5		0.63148	1.58359

[1] d = thickness of the layer, [2] λ = thermal conductivity.

According to the calculation methodology described above, the mean value of the actual thermal transmittance of the rammed earth wall (based on hygrothermal data recorded) was 0.352 W/m^{2}K.

There was a difference between the thermal transmittance values obtained for both procedures, as the value obtained based on on-site data was 26.6% of the resulting theoretical value of the normalised method.

4. Discussion

In the current context in which the study of energy behaviour of traditional architecture has been subject to major international debate, the research developed by different groups contributes to the creation of a growing body of knowledge worldwide, allowing the execution of conservation and intervention actions suited to specific characteristics. However, these studies have a primarily local or regional focus concentrating on specific cases with particular architectural and climatic characteristics, given the complexity of the proposed analysis. Therefore, although the methodology used can be extrapolated to buildings in other regions, the results cannot. It is also worth highlighting that the methods used in the analysis of energy behaviour in traditional architecture vary depending on the means available for research, potentially affecting the results. Equally, traditional constructive systems are characterised by their spontaneous execution and heterogeneous material composition, which differ worldwide despite sharing common features.

Therefore, the results of this research ought to be interpreted taking into account certain limitations in the energy study of traditional architecture, as the rammed earth wall analysed was located in a currently uninhabited building that conserved its original construction but has undergone some transformations, such that hygrothermal values recorded may have been affected.

It is interesting to contrast the theoretical and actual thermal transmittance values obtained with the threshold thermal transmittance (U_{lim}) as established in the Technical Building Code [1], which depends on the climate area in which the building is located and the position of the wall in relation to the entire building. This shows that the values obtained following the theoretical procedure do not comply with the limitations of current regulations, while the results of thermal transmittance based on on-site data do not exceed 0.73 W/m^2K in any of the periods studied.

The major differences between the theoretical values and those calculated based on real data may be due to factors such as inaccurate conductivity values assumed for wall components, calculated thickness, alterations in the measurements of hygrothermal data, etc.

Furthermore, it would be interesting to contrast the values obtained in the summer period with those for other seasons, as well as the whole year. Equally, global results for this territory could be obtained through a comparative study of the assessment of the thermal behaviour of the rammed earth walls in other buildings in the climate sector of the transition zone, as well as in other parts of the region.

In this regard, it is worth highlighting the results obtained in the recent study of a similar case by the authors. The dwelling analysed, located in the same climate sector, shares the same architectural typology as the building in this case study and uses a similar constructive variant. However, it has undergone major interventions on different constructive elements, including the partial replacement of rammed earth walls by brick and the replacement of the traditional roof by current systems. These changes have therefore affected the overall thermal behaviour of the building, based on the initial analysis of the data obtained. The damping of the exterior surface thermal oscillation was between 1.5 and 3.5 times higher than that of interior oscillation. Therefore, daily thermal variations may be more noticeable in the interior of this second building, unlike the case study in this article.

In contrast, although humidity data for wall surfaces and interior ambient were not analysed in the current case study, some authors point to possible alterations in the results [11]. Therefore, data could be rectified based on variations in humidity considering that the enthalpy (H) of the rammed earth wall should remain constant.

5. Conclusions

The study of the thermal behaviour of rammed earth walls is a complex matter. In addition to requiring knowledge of the physical characteristics of the material, the architectural characteristics of the building should be taken into consideration, as well as the climate and urban conditions of the location. Although multiple factors influence the temperature values recorded for the rammed earth walls (both on the exterior and interior surfaces), a notable thermal damping of the fluctuations of exterior temperatures was observed in relation to the interior ones, guaranteeing a stable thermal sensation for occupants. This phenomenon of damped transmission of thermal energy was due to the high thermal inertia of the rammed earth walls. Equally, the analysis of thermal oscillations made it possible to quantify the delay in thermal transmission from the outside in, which led to variations in temperature being perceived in the room hours (day–night cycle) or days (cycle of successive days) later. For the cycle of successive days, depending on the climate conditions from earlier days, the delay could range from 2 to 6 days; while the day–night cycle oscillated between 1 and 8 h.

The thermal transmittance of the constructive elements was one of the parameters for the assessment of energy efficiency of building envelopes and their consequent thermal behaviour. Therefore, in the case study the value of thermal transmittances was calculated based on two different procedures, which provided a theoretical value and a real value (based on on-site data measurement) that differed greatly. While the theoretical value of thermal transmittance of the wall was double that permitted in current Spanish regulations, the result provided by the real value was below this threshold. The evident contradictions between both systems, therefore, highlight a clear need to further review the demands of the regulations applied to traditional earthen architecture based on a prior study of thermal behaviour in a wide number of representative case studies in Spain.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/7/1924/s1, Table S1: Temperatures collected of the exterior and interior surfaces of the wall and the interior space for the period 24/06/2017–23/08/2017. Source: L. Balaguer.

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