Comparative analysis of thermal characterization methodologies of a historical double leaf masonry wall

Cristian Carmona*, Gabriel Horrach,
Francisco Masdeu, Joan Muñoz

Physics Department,
University of the Balearic Islands,
Cra. Valldemossa, km 7.5,
Palma, Balearic Islands, Spain
Email: cristian.carmona@uib.es
Email: gabriel.horrach@uib.es
Email: francesc.masdeu@uib.es
Email: joan.munoz@uib.es
*Corresponding author

Abstract: Energy consumption for heating and air conditioning is one of the main factors to consider in the energy efficiency of buildings. Correctly assessing thermal losses in the envelope is essential for decision making when it comes to minimizing the cost of using thermal installations and improving the thermal comfort of a building.

This paper presents a comparative analysis between different thermal transmittance characterization methodologies. The comparison is carried out between different quantitative methodologies, including that which is described in the Spanish Technical Building Code CTE DB-HE, direct measurement methodologies through an analysis of materials, and in-situ measurements based on the recording of heat flux and temperature differentials as described in ISO 9869. The results of the application of these methodologies on a traditional Mediterranean wall reveal significant differences between each of them. Further, the discrepancies between the default transmittance values and the values obtained through direct measurement of the envelope are determined.

Keywords: thermal characterization, double leaf masonry wall, heat flux analysis, thermal analysis methodologies.

1 Introduction

Domestic energy consumption is influenced by the heating and air conditioning needs of buildings, with households devoting up to 66.6% of the thermal and electric energy consumed to said purpose (Institute for Energy Diversification and Saving - IDAE, 2016). In order to apply energy saving measures that will enable us to achieve buildings with high levels of energy efficiency and to reach the goals set by the Europe’s “Nearly zero-energy buildings” plan (Berardi, 2013), it is necessary to have a precise thermal characterization of the building envelope and to understand the application of local standards and regulations (Schroeder, 2016).

Spanish regulations (CTE HE, 2013) try to establish realistic and precise thermal properties by means of different energy characterization methodologies of the envelope components. Methodologies normally used in the construction of new buildings, where the composition and distribution of materials used in the envelope are known, allow for thermal properties directly obtained from manufacturers or technical handbooks to be used (Safranez and Safranez, 1981; ISO 6946, 2007). The use of predefined or established values by these methodologies introduce an estimation error when applied to existing buildings, as there is no precise knowledge of the distribution of components or the thermal characteristics of the materials that were used (Martín-Consuegra *et al.*, 2014; Walker and Pavía, 2015). Even with the application of destructive thermal characterization methodologies, the heterogeneity of the materials used (organic substrates, mixed aggregates, etc.) as well as the nonexistence of precise construction details, pose high levels of uncertainty. A clear example of this problem is observed in the analysis of traditional buildings where neither the materials nor their arrangement are known, leading to discontinuous thermal characteristics throughout the envelope (Cuitiño *et al.*, 2015).

Additionally, even in buildings with a high level of knowledge about the composition and distribution of elements, the variation between different characterization methodologies can be up to 43% (Asdrubali *et al.*, 2014).

This article presents a comparative analysis between thermal characterization methodologies in order to establish the most appropriate characterization technique for a traditional Mediterranean wall, which will make it possible to determine the most appropriate corrective actions to favor energy savings. The methodologies analyzed are based on both destructive and non-destructive tests, and they include those laid out in the Spanish Technical Building Code (CTE, 2006) - analysis of walls with homogeneous layers and analysis of walls with heterogeneous layers (analysis of materials using ISO standard 8302 (ISO 8302, 1991)) - and in-situ thermal analysis methodologies based on the application of ISO 9869 (ISO 9869, 2014) for diagnosing the thermal characterization of surfaces.

2 Thermal characterization

The application of energy saving measures in construction is closely related to the improvement of the thermal properties of the envelope (Fargallo, Alés and Rodríguez, 2015). There are numerous applicable methodologies for acquiring a value that defines the thermal characteristics of a wall, including the ones used to find their thermal transmittance or U-value ($W/(m^2*K)$). The thermal transmittance of a wall is defined as the amount of heat flux that is able to go through a surface of one square meter per unit of time when the surface is exposed to a heat gradient of 1 K. In addition to this value, the thermal resistance of a wall - the R-value - is defined as the inverse of the U-value.

Thermal transmittance is not the only factor known to affect energy consumption analyses (Aste, Angelotti and Buzzetti, 2009). Although thermal inertia and phase change phenomena have a substantial impact, the need to comply with legal requirements (CTE,

2006) where only the value of transmittance is considered as a characterization variable implies the need for a comprehensive analysis and determination of the U-value of a wall.

Characterization methodologies for walls are classified both according to the level of simplification of the calculation methodology, and to the test process to be performed differentiating between destructive and non-destructive tests. For instance, the thermal characterization used by default by different energy certification software - thermal resistance calculation methodology via thermally homogeneous layers (Safranez and Safranez, 1981) - considers that the layers of material making up a wall are infinite, disregarding the thermal dispersion effects of the solid, and that the materials of said layers are completely homogeneous.

The methodology of thermal characterization through the application of thermal resistance via thermally heterogeneous layers considers the thermal variations that are produced within the layers of material. For this methodology to be performed, the behavior of a sample of the material that forms each of the layers is analyzed in-depth, and the total thermal resistance value of the envelope is determined as the sum of these interactions.

Although this methodology takes into consideration the real behavior of the materials, it does not allow for the consideration of either the thermal behavior derived from the interaction between the different materials, or the surface response of the materials, as it utilizes predefined values that are the same for surfaces with different resistances and roughnesses.

Finally, use of the in-situ thermal resistance measurement methodology is suggested (Asdrubali *et al.*, 2014). It allows for a more realistic thermal characterization of envelopes, as the analysis is carried out on the real constructed element and is assessed while considering its use in a real environment.

2.1. Traditional mediterranean wall

The methodologies compared in the present article were analyzed on a south-east-facing, exterior wall, in a traditional Mediterranean dwelling (Bucci and Mollo, 2010). The house was located in the municipality of Lloret de Vistalegre, in the center of Mallorca (Balearic Islands, Spain - Coordinates 497,700 U.T.M. Huso 31 ETRS89). The houses’ exterior walls were composed of two layers of limestone, one on the inside and another on the outside, each between 0.20 and 0.25 m thick, with an internal core of between 0.10 and 0.20 m, based on clay, argillaceous materials, and small calcareous stones, which act as a binder for the wall as a whole (Julià, 2013).

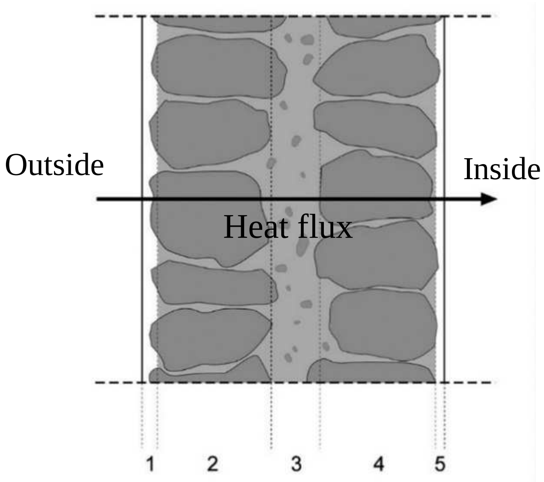

Fig. 1 – Traditional Mediterranean wall: double leaf masonry wall.

As seen in Fig. 1, the wall was made up of five layers (described from 1 to 5 and from exterior to interior, respectively) of materials.

- Layer 1, rendering made from clay mortar/argillaceous material and lime, thickness of 0.02 m.
- Layer 2, limestone of medium hardness, thickness of 0.25 m.
- Layer 3, central core based on clay or argillaceous material and gravel, thickness of 0.10 m.
- Layer 4, limestone of medium hardness, thickness of 0.25 m.
- Layer 5, lime plaster, thickness of 0.01 m.

3 Application of thermal characterization methodologies

3.1. Thermal resistance via thermally homogeneous layers, non-destructive test

The Spanish Technical Building Code (CTE, 2006), in its core document DB-HE section 1, describes a simplified method for calculating thermal transmittance through non-destructive tests of the different elements that make up the thermal envelope of the building. This thermal characterization methodology is based on the establishment of the total transmittance of the wall by adding up the transmittance values of the elements included therein. These thermal transmittance values are given in ISO 6946 (ISO 6946, 2007). It is a widely established and well-used methodology where the thermal resistance data come from handbooks or databases produced by authorized laboratories. The U-value is expressed through equation 1.

$$\text{U-value}=\frac{1}{R_t}\ \left(W/(m^2*K)\right) \tag{1}$$

Where, R_t is the total thermal resistance of the wall. The R_t of a component made up of thermally homogeneous layers is calculated through equation 2.

$$R_t=R_{si}+R_{se}+\sum_{x=1}^{n} R_x\ \left(m^2*K/W\right) \tag{2}$$

Where R_x is the thermal resistance of each layer making up the wall, R_{si} is the internal surface thermal resistance, and R_{se} is the external surface thermal resistance. The thermal resistance of a thermally homogeneous layer is defined by equation 3.

$$R_x = \frac{e}{\lambda} \left({}^{m^2 * K}\!/_{W} \right) \tag{3}$$

Where λ (W/(m*K)) is the theoretical thermal conductivity of the material and e (m) is its thickness. The ease of obtaining λ values from handbooks considerably simplifies the application of this system for calculating the thermal characteristics of walls in which there is a high level of component homogeneity and the materials are well known.

The application of this thermal characterization methodology in a traditional Mediterranean wall presents three fundamental drawbacks:

1. Without carrying out destructive tests, the real composition of the wall it’s not know.
2. Since natural construction materials are used, the exact nature and physical characteristics (isolating properties) of these materials cannot be established from handbooks.
3. Traditional Mediterranean building methods do not create homogeneous sections, thus the calculation of thermal resistance using homogeneous layers can only be considered an approximation.

The difficulty in ascertaining the composition of the layers that make up the wall mean that approximate theoretical values are used as data to calculate the thermal transmittance, which is different from the real value. Approximations based on the historical bibliography of materials and methods used for the type of building being analyzed (Institute for Energy Diversification and Saving - IDAE, 2016), even if acceptable ranges of thermal transmittance are established for comparison with the applicable regulations, may not provide an accurate idea with which to make decisions that will enable the energy consumption of the building to be improved.

Table 1 – Thickness and conductivity values of the layers.

	Layer 1	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**
Thickness e(m)	0.02±0.002	0.25±0.002	0.10±0.002	0.25±0.002	0.01±0.002
Conductivity λ(W/(m*K))	1.00	1.40	0.52	1.40	1.00

The composition of the wall being analyzed is made up of exterior layers composed of lime mortar with a high/medium density and thicknesses varying between the interior and exterior layers as observed in Table 1. The core layer was made up of clay or manually compacted argillaceous material with a mean density of 1500-1900 kg/m^3.

Both the conductivity values and the thicknesses of the different layers are summarized in Table 1. With these data, the application of the thermal resistance methodology via homogeneous layers was possible, leading to the result observed in equation 4.

$$\sum_{x=1}^{n} R_x = \frac{e_1}{\lambda_1}+\frac{e_2}{\lambda_2}+\frac{e_3}{\lambda_3}+\frac{e_4}{\lambda_4}+\frac{e_5}{\lambda_5} = 0.749\pm0.0100 \left(\mathrm{m^2{*}K}/\mathrm{W}\right) \quad (4)$$

The values of R_{si} and R_{se} were obtained from the DB-HE 1 document (CTE HE, 2013), which states that the surface thermal resistances in contact with external air depend directly on the position of the wall and the direction of heat flux. In this case it was a vertical wall with a horizontal flux, therefore an R_{se} value of 0.040 (m^2*K/W) and an R_{si} value of 0.130 (m^2*K/W) is obtained. The resistance value, considering the R_{si} and R_{se} values obtained, is observed in equation 5.

$$R_t=R_{si}+R_{se}+\sum_{x=1}^{n} R_x = 0.919\pm0.0100 \left(\mathrm{m^2{*}K}/\mathrm{W}\right) \quad (5)$$

Therefore, using the characterization methodology via homogeneous layers, the total transmittance value (U-value) of the wall, which is inversely proportional to the thermal resistance, is observed in equation 6.

$$\text{U-value}=\frac{1}{R_t}=1.08\pm0.010 \left(\mathrm{W}/(\mathrm{m^2{*}K})\right) \quad (6)$$

3.2. Thermal resistance via thermally heterogeneous layers, destructive test

In order to more reliably know the composition and thickness of the elements making up a wall, it is possible to carry out tests of a destructive nature. With the direct analysis of a section of a wall, the drawbacks of carrying out approximations as in the simplified homogeneous layers method are minimized.

This kind of analysis is carried out in two stages: an initial descriptive stage of the materials that make up the wall during the process of obtaining samples, and a second stage which entails a thermal characterization of the samples through tests in laboratories using ISO standard 8302 (ISO 8302, 1991).

The thermal characterization of the different materials comprising the wall is done through a modified application of the hot box characterization methodology. The foundation for the application of said methodology is described in EN ISO 8990 (ISO 8990, 1996) and ASTM C1363-05 (ASTM-C1363, 2014), and it is based on exposure to a thermal gradient in steady-state conditions. The thermal resistance of the material is determined by the amount of energy required to maintain said steady state.

Given the nature of the wall that was studied and the traditional Mediterranean building methods used, it was impossible to obtain a sample that had the same geometric and physical material allocation characteristics as the whole wall being analyzed (Heathcote and Heathcote, 2011). In this instance, the hot box methodology (ISO 8990, 1996) needs to be modified in such a way that a full wall analysis is not performed, but rather a separate analysis is performed on each one of the different elements that make up the wall. Using this methodology, R_x values are still obtained for each of the elements making up the wall, but with the advantage that they are calculated from real samples of the wall being studied.

Once the thermal resistance and arrangement of the elements making up the wall it's known, like in the diagram of their arrangement, the simplified method via heterogeneous layers described in DB-HE 1 section 3 (CTE, 2006) can be implemented. In this section, and as explained in equation 7, the total thermal resistance R_t of a wall made up of heterogeneous layers parallel to the surface is established as the arithmetic mean of the upper and lower limit values of the resistance.

$$R_t = \frac{R_{st}+R_{it}}{2} \quad \left(\mathrm{m}^2{*}\mathrm{K}/W\right) \tag{7}$$

Where R_{st} is the upper limit and R_{it} is the lower limit of the total thermal resistance. In order to calculate the upper limit, R_{st}, in equation 8, it is necessary to have the resistance values of each of the elements (R_x) and the fractional areas of each of the horizontal sections (f_x).

$$\frac{1}{R_{st}} = \sum_{x=1}^{n} \frac{f_x}{R_x} \quad \left(\mathrm{W}/(\mathrm{m}^2{*}\mathrm{K})\right) \tag{8}$$

To calculate the lower limit, the surfaces of all the planes parallel to the section analyzed are assumed to be isothermal. Equation 9 shows how the equivalent thermal resistance of each of the sections analyzed (R_{xj}) is obtained.

$$\frac{1}{R_{xj}} = \sum_{y=1}^{n} \frac{f_y}{R_{yj}} \quad \left(\mathrm{W}/(\mathrm{m}^2{*}\mathrm{K})\right) \tag{9}$$

Where R_{yj} is the thermal resistance of each of the elements analyzed as per ISO 8302:1991 (ISO 8302, 1991) and f_y is the fractional area occupied by each material that makes up the wall being analyzed. Finally, the lower limit value is obtained in equation 10, using R_{xj} and both the interior and exterior surface thermal resistance values (R_{si} and R_{se}).

$$R_{it} = R_{si}+R_{se}+\sum_{x=1}^{n} R_{xj} \quad \left(\mathrm{m}^2{*}\mathrm{K}/W\right) \tag{10}$$

The thermal resistance values of each of the layers making up the wall analyzed is observed in Table 2. This table also presents a comparison between the characterization methods via homogeneous and heterogeneous layers; and as seen, the central layers were the ones that showed the greatest difference from the thermal resistance values provided by the Spanish Technical Building Code (CTE, 2006) tables.

Table 2 – Thermal resistance values for heterogeneous (R_{yj}) and homogeneous (R_{yj}’) layers.

	R_{yj} (m^2*K / W)	**R_{yj}’ (m^2*K / W)**	**Variation**
Layer 1	0.021±0.0005	0.020±0.0020	4.76%
Layer 2	0.141±0.0005	0.178±0.0020	26.24%
Layer 3	0.103±0.0005	0.190±0.0020	84.46%
Layer 4	0.141±0.0005	0.178±0.0020	26.24%
Layer 5	0.011±0.0005	0.010±0.0020	9.09%

This effect is due mainly to discretization of the transmittance value in the CTE tables, where it is not possible to consider the real characteristics of the material in a given area and they must be approximated from established values.

$$R_{it} = R_{si}+R_{se}+\sum_{x=1}^{n} R_{xj} =0.587\pm0.0025 \left(\mathrm{m^2{*}K}/\mathrm{W}\right) \tag{11}$$

The total thermal resistance value of the wall using the characterization methodology via homogeneous layers is observed in equation 11, and its U-value is calculated in equation 12.

$$\text{U-value} = \frac{1}{R_t} = 1.70\pm0.004 \left(\mathrm{W}/(\mathrm{m^2{*}K})\right) \tag{12}$$

3.3. In-situ thermal resistance measurement

The in-situ methodology, which was used to determine the thermal transmittance of the wall as a whole without having to carry out destructive tests, is based on ISO 9869 (ISO 9869, 2014). In this procedure, through the use of heat flux transducers (HFTs) and temperature transducers (TT), the density of heat flux going through the wall was measured along with the thermal increase between the surfaces being analyzed.

For this methodology to be employed properly, the wall to be characterized must be measured using thermography. This analysis involves placing sensors on representative areas of the wall, avoiding irregularities or thermal bridges therein and preventing the obtaining of non-representative values (Asdrubali, Baldinelli and Bianchi, 2012). Solar protection of the sensors while measurements are being taken is necessary and is achieved by avoiding, as much as possible, exposure to direct solar radiation.

The methodology described was implemented in real conditions, and due to the outside environment during the characterization, a variable thermal cycle was presented. In order to minimize the impact of the transitory state on these variations, measurements were made over a long period of time. This contrasts with other methodologies based on steady-state measurements of the wall (Peng and Wu, 2008). The thermistors used for this implementation were different for the interior and exterior surfaces; outside, digital heat sensors were used (resolution ± 0.05 ºC), and inside, NTC 100k analogue thermistors were used. The sampling of both the temperature (inside and outside) and thermal flow was done every 5 minutes, value set by limitations of the data logger used.

Thus, the total thermal resistance value (R_t) of a wall, calculated using the methodology described in ISO 9869, is determined by the thermal increase between the internal (T_{ix}) and external (T_{ex}) faces of the wall and the heat flux measured by the HFT (q_x) for each of the n finite measurements carried out, as observed in equation 13.

$$R_t=\frac{\sum_{x=1}^{n}(T_{ix}-T_{ex})}{\sum_{x=1}^{n} q_x} \left(\mathrm{m^2{*}K}/\mathrm{W}\right) \tag{13}$$

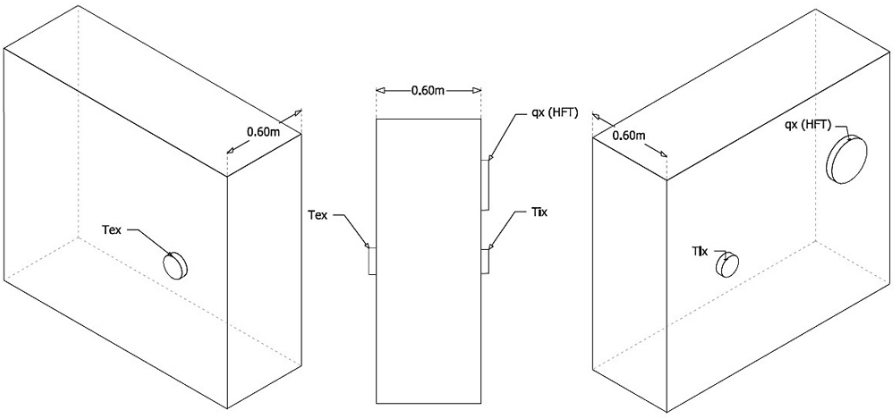

Fig. 2 – Sensor placement detail.

The installation of thermal transducers (TTs) was carried out on both the internal and external faces of the wall, with Tix representing the internal transducer and T_{ex} the external transducer in Fig. 2. Five TTs were installed on each side of the wall, at a minimum height of 1.20 m and with a distance of 0.20 m between sensors. The measurements they made determined the thermal gradient the wall was subjected to throughout the test.

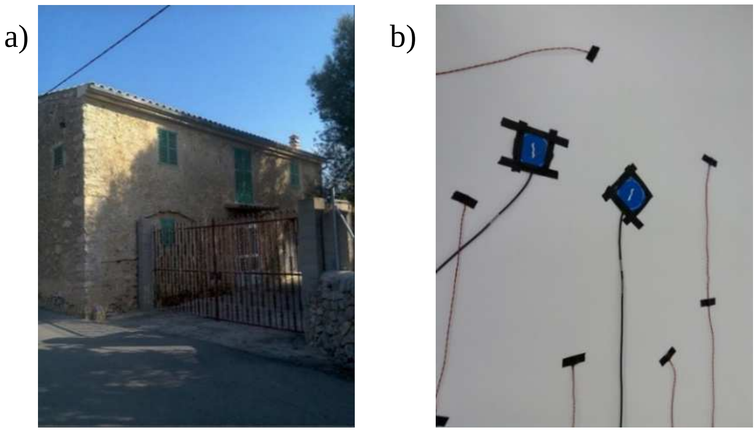

Fig. 3 – (a) Location general view; (b) final interior sensor placement.

The HFT was installed in the interior of the house, thereby avoiding possible interference or error due to solar radiation. Two HFP01 heat flux transducers were installed at a height of 1.5 m, in the center of the TTs. Fig. 3a shows the location and Fig. 3b positioning of the sensors used to carry out the test of the in-situ thermal characterization methodology.

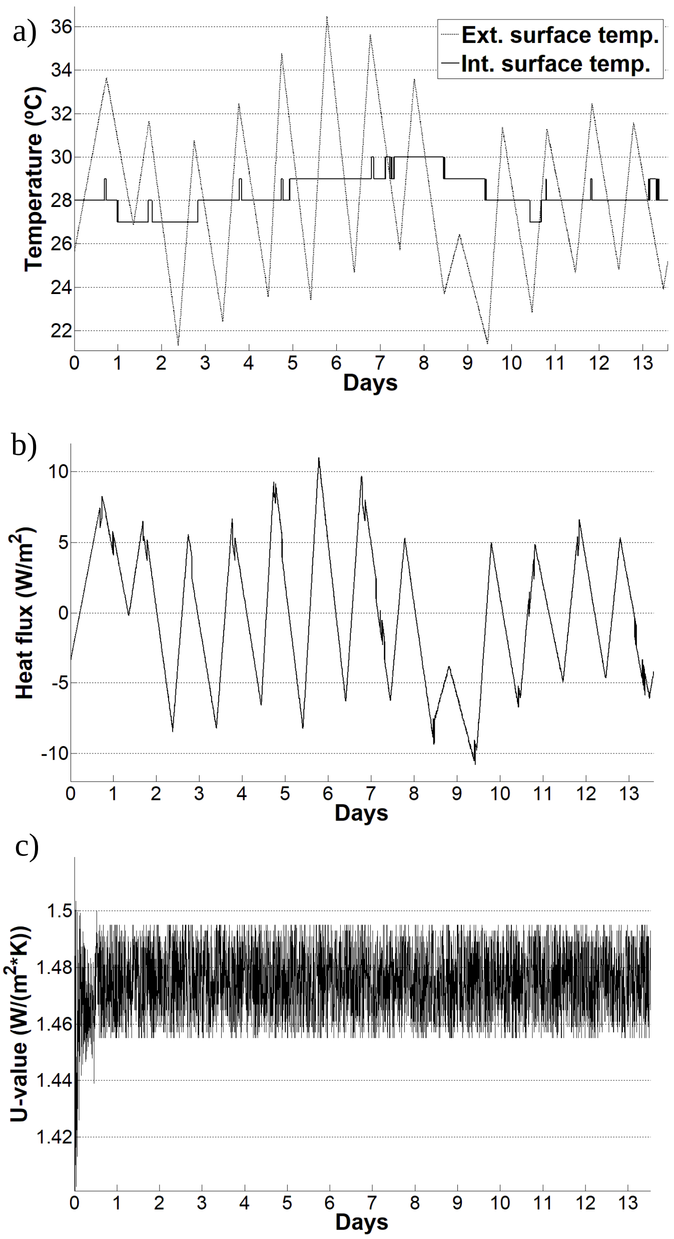

Fig. 4 – In-situ measurements results: (a) external and internal temperature; (b) heat flux transmitted by the wall; (c) U-value measurements.

The test was carried out over a period of 14 days, which enabled better discretization of values and minimized environmental thermal impact on the experiment. Both internal and external surface temperatures (Fig. 4a) followed a daily cyclical pattern where they oscillated between daily maximum and minimum values.

The heat flux measurement (Fig. 4b) was strongly related to the thermal differential to which the wall was subjected, obtaining a maximum value at the same time as the maximum surface thermal value was observed. The wall that was analyzed was facing south-east, and while the test was being carried out, measures were taken to prevent the external temperature sensors from receiving direct solar radiation.

The U-value obtained, unlike in other methodologies analyzed, was not completely stable (Fig. 4c). The oscillation of the thermal transmittance value was directly related to the variability of the thermal gradient to which the wall was exposed, but this variability was not so in the case of the thermal transmittance values prepared by the CTE DB in which the material is subjected to a stable thermal gradient between 15 ºC and 24 ºC (ISO 6946, 2007).

Table 3 shows the variability of the measurements taken, both with regard to temperature and U-value. As mentioned, the internal temperature values in the house showed an increase in maximum temperature of only 3 ºC over the 14 days. On the other hand, the external temperature showed the effect of the day/night cycle, with differences of up to 15 ºC between the maximum and minimum values. Lastly, it is worth noting the low variance of the U-value obtained, which enables us to accurately establish the thermal transmittance of the wall.

Table 3 – In-situ measurement analysis.

	Max.	**Min.**	**Mean**	**Variation**
Ti (ºC)	30.00±0.025	27.00±0.025	28.28±0.025	0.690
Tix (ºC)	30.00±0.025	27.00±0.025	28.30±0.025	0.696
Tex (ºC)	36.47±0.050	21.31±0.050	28.13±0.050	9.472
Te (ºC)	36.50±0.025	19.00±0.025	27.00±0.025	11.009
U-value (W/m^2*K)	1.35±0.120	1.53±0.120	1.47±0.120	1.96e-04

4 Discussion

The three thermal characterization methodologies applied present certain advantages and drawbacks when analyzing the thermal transmittance of the chosen wall, which was characterized by high thermal mass and heterogeneous materials. As observed in the table of results (Table 4), the transmittance values obtained vary substantially between methodologies.

Table 4 – U-values obtained for the different methodologies.

	Homogeneous	**Heterogeneous**	**In-situ**
U-value (W/m^2*K)	1.08 ± 0.010	1.70 ± 0.002	1.47 ± 0.120

As has been described, both the structure and the composition of the wall must be taken into consideration in the case of the homogeneous methodology, although by using the values given in the handbook and not performing an in-depth analysis of the materials, the values obtained in this case were too lenient compared to the real properties. Therefore, this methodology lead to insufficient energy saving decisions for the wall analyzed.

On the other hand, the heterogeneous methodology requires an in-depth analysis of the materials that make up the wall, its structure, and its composition. By individually analyzing the materials that make up the wall, the interaction between them is assumed ideal, and as observed in the in-situ characterization this layer-to-layer interaction has a direct impact on the transmittance of the wall. This simplification means that the characterization methodology via heterogeneous layers gives excessively large thermal transmittance values.

Due to these effects, and in order to obtain as exhaustive a transmittance value for the wall as possible, the in-situ thermal characterization methodology was postulated as the ideal solution for the case that was studied as it considers the real behavior of the wall, obtaining its thermal transmittance value and allowing us to observe how it behaves when exposed to different thermal gradients.

5 Conclusions

The thermal transmittance of an exterior wall was analyzed using three different methodologies. The wall was part of a house that was located in the center of the island of Mallorca, Spain, and represents an example of traditional building methods: exterior layers of limestone and an inner core made of a clay material as a binder.

Thermal transmittance is the fundamental parameter used for the thermal characterization of walls. The methodologies used to obtain this value are based on different approaches, ranging from estimation based on numerical simulations to an analysis of the materials that make up the wall.

Although the most used characterization methodologies - i.e., those required by regulations and current laws - obtain approximate values of the transmittance of the wall, none of them analyze the real behavior of the wall. The lack real behavior assessment entails substantial thermal variations, especially in traditionally built walls where the thermal mass is significant and the materials vary in their form and composition.

Thus, the application of a third thermal characterization methodology known as "in-situ" was proposed. In general, this methodology aims to obtain a transmittance value that reflects the thermal response of the wall with a high rate of reliability. This methodology employs tests on real walls, where values of surface temperatures and the heat flux circulating therein are obtained in-situ.

The results obtained show that the lowest value of thermal transmittance is observed when the characterization methodology that utilizes homogeneous layers is applied, and the greatest transmittance value is obtained from the application of the characterization methodology via heterogeneous layers. The application of the in-situ methodology provided transmittance values in between the other two.

Different factors influence the variation between the transmittance values obtained with methodologies via homogeneous and heterogeneous layers, including that the thermal performance values given in handbooks and by manufacturers are obtained in a laboratory, under very controlled conditions; the construction of multilayer walls is not perfect and therefore the interaction between the materials making them up is not ideal, thereby impacting the final behavior of the wall; and environmental conditions (direct solar radiation, rain, wind, etc.) influence the thermal behavior of the wall.

For all of these reasons, the use of in-situ thermal characterization methodologies for the analysis of walls is recommended, especially when they have heterogeneous building characteristics that are not precisely known, or when it is impossible to perform destructive tests. When it is impossible to apply the in-situ methodology, using characterization methodologies based on thermal resistance through thermally heterogeneous layers is recommended. The values obtained using this methodology are highly restrictive, providing complementary thermal insulation solutions that will improve the minimum benefits established by regulations.

5 Bibliography

Asdrubali, F. *et al.* (2014) 'Evaluating in-situ thermal transmittance of green buildings masonries–A case study', *Case Studies in Construction Materials*. doi: 10.1016/j.cscm.2014.04.004.

Asdrubali, F., Baldinelli, G. and Bianchi, F. (2012) 'A quantitative methodology to evaluate thermal bridges in buildings', *Applied Energy*, 97, pp. 365–373. doi: 10.1016/j.apenergy.2011.12.054.

Aste, N., Angelotti, A. and Buzzetti, M. (2009) 'The influence of the external walls thermal inertia on the energy performance of well insulated buildings', *Energy and Buildings*, 41(11), pp. 1181–1187. doi: 10.1016/j.enbuild.2009.06.005.

ASTM-C1363 (2014) 'Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus 1', *American Society for Testing Materials*, 90(Reapproved), pp. 1–44. doi: 10.1520/C1363-11.2.

Berardi, U. (2013) 'Clarifying the new interpretations of the concept of sustainable building', *Sustainable Cities and Society*, 8, pp. 72–78. doi: 10.1016/j.scs.2013.01.008.

Bucci, A. and Mollo, L. (2010) *Regional Architecture in the Mediterranean Area*. Available at: https://books.google.es/books?hl=en&lr=&id=YuQZcdbG0HQC&oi=fnd&pg=PA15&dq=Alessandro+Bucci,+LM.+(2010)+Regional+Architecture+In+The+Mediterranean+Area&ots=U8fhFAjeHO&sig=h0911QVHs395ORJe9X-CQtYy5Go (Accessed: 16 May 2017).

CTE (2006) 'Spanish Building Technical Code', *Real Decreto 314/2006 de 17 de marzo*, pp. 11816–11831. doi: CTE-DB-SE.

CTE HE (2013) *Basic document HE energy saving, Documento básico HE ahorro de energía*. Available at: http://www.codigotecnico.org/web/recursos/documentos/ (Accessed: 1 June 2017).

Cuitiño, G. *et al.* (2015) 'Análisis de la transmitancia térmica y resistencia al impacto de los muros de quincha', *Informes de la Construcción*, 67(537), p. e063. doi: 10.3989/ic.12.082.

Fargallo, A. P., Alés, V. F. and Rodríguez, J. M. C. (2015) *Comparison of energy-saving restoration costs based on Spain's initial constraints [single-family zone B4], Revista de* *la Construccion*. Pontificia Universidad Católica de Chile, Escuela de Construcción Civil. doi: 10.4067/S0718-915X2015000200006.

Heathcote, K. and Heathcote, K. (2011) 'El comportamiento térmico de los edificios de tierra', *Informes de la Construcción*, 63(523), pp. 117–126. doi: 10.3989/ic.10.024.

Institute for Energy Diversification and Saving - IDAE (2016) *Project Sech-Spahousec, Analysis of the Energetic Consumption of the Residential Sector in Spain (Proyecto Sech-Spahousec, Análisis del consumo energético del sector residencial en España), Idae*. Available at: www.idae.es.

ISO 6946 (2007) *Building components and building elements. Thermal resistance and thermal transmittance. Calculation method, British Standards Institution*. doi: 10.3403/30127651.

ISO 8302 (1991) *Thermal insulation - determination of steady-state thermal resistance and related properties. Guarded hot plate apparatus.* Available at: https://www.iso.org/standard/15422.html (Accessed: 9 October 2017).

ISO 8990 (1996) *Thermal insulation — Determination of steady-state thermal transmission properties — Calibrated and guarded hot box, BSI*. Available at: https://www.iso.org/standard/16519.html (Accessed: 16 May 2017).

ISO 9869 (2014) *Thermal insulation - Building elements - In-situ measurement of thermal resistance and thermal transmittance - part 1: Heat flow meter method, British Standards Institution*. Available at: https://www.iso.org/standard/59697.html (Accessed: 16 May 2017).

Julià, M. i (2013) 'Habitatges tradicionals: característiques arquitectòniques, tipològiques i constructives dels habitatges en sòl rústic a Mallorca'. Available at: https://scholar.google.es/scholar?q=Ballester%2C+M.+%282013%29.+Habitatges+tradicionals+-+Característiques+arquitectòniques%2C+tipològiques+i+constructives+del+habitatges+en+sòl+rústic+a+Mallorca.+Edicions+Universitat+de+les+Illes+Balears.+&btnG=&hl=en&as (Accessed: 16 May 2017).

Martín-Consuegra, F. *et al.* (2014) 'Análisis y propuesta de mejoras para la eficiencia energética del edificio principal del Instituto c.c. Eduardo Torroja-CSIC', *Informes de la Construcción*, 66(536), p. e043. doi: 10.3989/ic.14.125.

Peng, C. and Wu, Z. (2008) 'In situ measuring and evaluating the thermal resistance of building construction', *Energy and Buildings*, 40(11), pp. 2076–2082. doi: 10.1016/j.enbuild.2008.05.012.

Safranez, C. and Safranez, C. (1981) 'Conceptos esenciales de la transmisión de calor en una edificación', *Informes de la Construcción*, 33(330), pp. 51–68. doi: 10.3989/ic.1981.v33.i330.2242.

Schroeder, H. (2016) 'Standards and regulations in earth block masonry - the current situation in Germany', *International Journal of Masonry Research and Innovation*, 1(3), p. 241. doi: 10.1504/IJMRI.2016.080432.

Walker, R. and Pavía, S. (2015) 'Thermal performance of a selection of insulation materials suitable for historic buildings', *Building and Environment*, 94, pp. 155–165.

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doi: 10.1016/j.buildenv.2015.07.033.