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Original article

The thermal conductivity of the masonry of handmade brick Cultural Heritage with respect to density and humidity

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ABSTRACT

It is very common that the energy refurbishment of buildings of Cultural Heritage is undertaken without considering that their materials and the methods of construction are different from those of modern buildings. Therefore, when seeking the most efficient and effective solutions from an energy point of view, the first step is to understand the thermal characteristics of the materials with which these buildings were constructed. Likewise, as part of this heritage, the fact that many such buildings were constructed using uncoated bricks and with rich voluminous ornamentation or murals must be taken into consideration. This prevents the use of normal construction solutions which consist of attaching a layer of insulating material to the interior or exterior. In addition, the rich surface ornamentation of the walls is not conducive to carrying out tests *in situ*, so other procedures are needed to determine the thermal behaviour of the facade and thus be able to determine the most appropriate processes for their conservation. To this end, various heat flow tests have been carried out on brick masonry specimens that have characteristics similar to those of the walls of such buildings. This allows an abacus of the approximate thermal conductivity of such brick masonry to be produced with respect to the density of the brick and the moisture content of the wall. The values of this abacus will serve as a reference to guide the energy refurbishment work to be performed on these buildings.

1. Introduction

Cultural heritage is very important culturally, environmentally, socially and economically. Its sustainable management is therefore a strategic opportunity for the 21st century, as considered by the European Union [1], which establishes the need for it to be managed in a way that allows its conservation for future generations, including its energy efficiency. Various committees and research teams have drawn up guides and standards to achieve this, and have developed projects to analyse cultural heritage intervention, including proposals to improve energy efficiency [2–7].

There is a dilemma when it comes to addressing interventions. On the one hand there are studies that focus on the importance of maintaining heritage values [8] and, in stark contrast, studies that address environmental sustainability, focusing mainly on energy efficiency measures [9]. Obviously, the ideal solution is to be able to address both challenges [10], although, in order to tackle the second of them and to reduce energy consumption, it is necessary to know the thermal functioning of the envelope and specifically that of the facades, since these constitute the largest surface area of that envelope.

One of the most common methods for investigating the thermal behaviour of facades is the *in situ* non-destructive heat flow tests of standard ISO 9869-1 [11] for the calculation of their conductance and transmittance [12]. There are, also, other procedures for calculating or ascertaining these values [13], and even proposals to use multiple tests in order to achieve more reliable results [14–16]. However, these tests cannot be carried out on buildings in which the material that makes up the pilasters, cornices and ornamental mouldings remains visible, either externally or internally, or when the interior walls contain murals, such as is the case for the churches of Mudejar Architecture of Castilla y León (Spain) (Figs. 1 and 2) [17,18]. In these situations, it is not advis-

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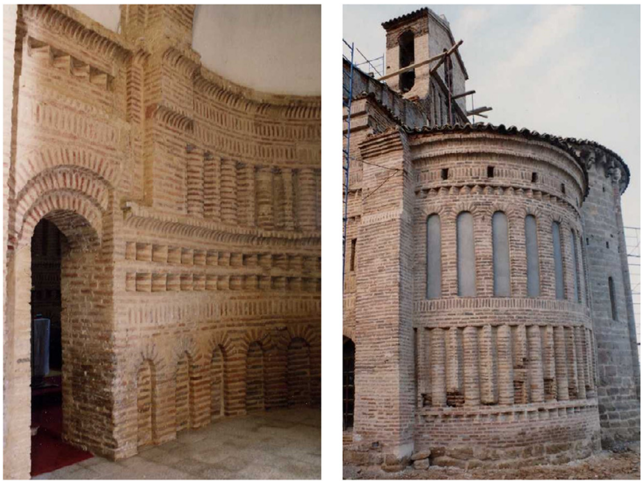

Fig. 1. Epistle Apse of the Church of San Gervasio and San Protasio in Santervás de Campos (interior and exterior) in the province of Valladolid, Spain.

Fig. 2. Church of Santa María la Mayor in Arévalo, Ávila, Spain.

able to carry out tests *in situ*, or to install an insulating material cladding, either externally or internally, meaning there is no way to improve the thermal insulation of the walls.

When it is not possible to conduct tests *in situ*, it is necessary to define another type of procedure that allows the thermal behaviour of the facades to be evaluated. The procedure proposed in this article is one such possibility, and consists of performing laboratory tests with materials and construction systems that simulate those of such heritage. While in general it is more effective to carry out tests *in situ*, when this is not possible or is inadvisable, the procedure explained in this text is a useful and valid method. With the results of the tests from these simulations, it is possible to evaluate the energy efficiency of old buildings. The data from the laboratory tests can be complemented with other tests, such as infrared thermography [19–21], especially in the analysis of thermal bridges [22] and peculiarities, which are very abundant in such brick facades.

In the case of old buildings constructed with handmade brick, it is necessary to take special care since this type of brick is known to absorb a significant amount of water [23,24]. However, the standards and documents used to evaluate energy efficiency only provide thermal conductivity values for bricks of modern manufacture [25], with little information on the values of handmade bricks. However, research can be found that provides some information in this regard [26].

Bearing the above in mind, a procedure based on laboratory testing of a series of masonry specimens, fabricated with bricks similar to those used in construction in past centuries, has been examined in order to ascertain the thermal performance of such buildings. Considering that transmittance varies with the water content of the piece, it is considered important to understand the behaviour of these walls from when they are in a dry state until they have reached saturation, so that the variation in the thermal behaviour of the specimens with different moisture content can be evaluated. This will allow the thermal improvement of an intervention to be assessed, and wetting of the facades avoided [27,28].

2. Objective

It is increasingly important to thermally characterise buildings of Cultural Heritage to find solutions that allow their efficient thermal refurbishment and therefore contribute to their conservation, since the use of the values and characteristics of modern materials can result in significant errors being made as these values are different from those of the original materials [12,29].

This text aims to contribute to the understanding of the thermal conductivity values of the type of the masonry of handmade brick and mortar very commonly found in the area where the research was carried out. This is done by means of heat flow tests carried out in the laboratory to establish the relationship between the values of thermal conductivity with respect to the apparent density of the specimen bricks and to their water content, also related to the absorption of the brick [30].

The final objective of the tests is to define an abacus that relates the conductivity of the type of masonry used in the construction of these buildings to the density of the brick and the water that they may hold due to rain, condensation or from the ground. This abacus would offer information to professionals involved in the conservation of heritage based on which they can make proposals to improve the energy efficiency of historic buildings.

3. Materials and methods

The tests were carried out in the Architectural Construction Laboratory of the Escuela Técnica Superior de Arquitectura de Valladolid. To carry them out, four brick masonry specimens were built with thick mortar joints, emulating the facades of old buildings. Each specimen was constructed with handmade bricks of different density, although all with joints of the same type of mortar so that its influence on the fabrication was similar in all the specimens and to avoid deviations attributable to this.

The process to perform the tests occurred in several phases:

In the first phase and by way of a preliminary task, a selection was performed of the bricks from which the specimens to be studied would be manufactured. The chosen bricks were measured and characterised, their density and water absorption values being obtained by immersion. These same tests were carried out on the lime and sand mortar that was to be used for the joints of the specimens. Subsequently, the specimens were constructed using the two materials, which were also measured and tested to obtain their density and their water absorption by immersion.

The main part of the investigation was carried out in a second phase, which tested the heat flow of the masonry specimens.

Table 1
Material properties: dimensions, apparent density and water absorption.

Brick/mortar	B1	B2	B3	B4	Mortar
Type of brick	handmade	handmade	handmade	semi-traditional	lime and sand
Dimensions (mm^3) Length/width/thickness	302 × 148 × 40	275 × 140 × 47	246 × 117 × 53	474 × 100 × 43	160 × 40 × 40
Apparent density (Kg/m^3)	1,676	1,789	1,846	2,028	1,729
Water absorption (m^3/m^3)	0.247	0.258	0.200	0.125	0.231

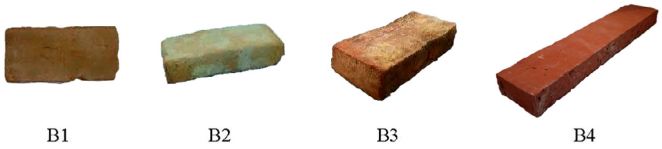

Fig. 3. Bricks

3.1. Selection of materials: bricks, lime and sand

Four types of handmade brick, (Fig. 3), were selected following the sole criterion that their density and absorption values were different, in order to be able to relate these characteristics to the transmittance of the wall to be manufactured using them, and in the knowledge that the volume and dimensions could also be different (Table 1). These bricks were denominated B1, B2, B3 and B4, ordered from lowest density to the highest. The first three correspond to old handmade bricks from demolitions or items collected from a building of adequate age, while the fourth type was a modern day brick with semi-traditional procedures. It was decided to include the latter type because its density and water absorption values are very different from those of old bricks and, in refurbishments or restorations, on many occasions it is necessary to replace original pieces with others that emulate old ones.

With respect to the mortar, it was manufactured using CL90 aerial lime and washed river sand of controlled granulometry which could pass through a sieve with an opening of less than 5 mm, and in a ratio of 1/3 of lime/sand, as indicated in the old masonry processes [31].

3.2. Tests. Bricks and mortar

Non-destructive tests were carried out on whole pieces of the located bricks and once the density and absorption values were obtained, those with similar characteristics were grouped and selected for use in the manufacture of each handmade brick and mortar specimen.

The tests carried out on the bricks were as follows:

- measurement of the dimensions EN 772-16 [32],
- dry apparent density in accordance with the process of standard EN 772-13 [33],
- absorption of cold water in accordance with the standard EN 772-21 [34].

To analyse the mortar, samples of aerial lime and sand were manufactured in the proportion 1/3, with dimensions, length/width/thickness (160 × 40 × 40 mm^3), which were tested following the same standards as those specified for the bricks, except for the density test which was carried out in accordance with the process of standard EN 1015-10 [35].

The tests were carried out on 24 bricks of each type and on 12 mortar samples, which were manufactured expressly. Table 1 contains the mean values of the four types of brick analysed that were used to make the specimens and also those obtained from the mortar test: dimensions, apparent density and water absorption by immersion.

3.3. Building of the masonry specimens

Four specimens were built using the selected bricks and the prepared mortar, which were named following the same order as the bricks, thus P1, P2, P3 and P4. Their measurements were different since they depended on the dimensions of the brick pieces and the thickness of the mortar joints, placing between four and five rows to be able to attain a similar height for each of them and a volume ratio of bricks to mortar of 70/30% (Table 2). The joints were adapted to the size of the bricks to ensure that this ratio was similar in all the specimens. With respect to P4, the bricks used were cut because their length was excessive to work well with the specimen.

The first process consisted of drying and curing of the specimens in the laboratory environment for 28 days, then drying in an oven until a constant weight was reached to attain the dry weight. At this point, all the specimens were immersed in cold water until they reached saturation and the saturated weight attained, needed to calculate the water absorption of the specimens according to the procedures of standard EN 772-21 [34] for testing the cold water absorption of bricks.

As can be seen, the mortar plays a significant role in the density values of the specimens and, therefore, on the amount of water they can absorb, causing the value to decrease in some specimens, (B1 and B2) and increase in others (B3 and B4), with respect to the values of the bricks [24,36].

3.4. Heat flow tests

For the heat flow test, a highly insulated refrigerated chamber with 10 cm thick extruded polystyrene sheets was used, located in the same laboratory where the specimens were developed. To emulate the cold environment outside the buildings, a compact Zanotti MGM10328F chiller with internal evaporator was placed inside the chamber to maintain the environment at a controlled temperature of between 0 and 5°C.

In order to save time and to be able to test two specimens at the same time, two of the four vertical facing walls, which we will call doors, were made up of removable elements. These doors were used to put in place the manufactured brick masonry specimens, achieving the effect of the thermal exposure of a façade wall, with one of its faces in contact with the cold environment of the chamber and the other with the temperate environment of the laboratory. To avoid perimeter heat transmissions from the specimens, these two walls were built thicker than the specimens, using four insulation panels, while the other two, the ceiling and the floor, were built with two (Fig. 4).

Once the specimens were saturated with water, they were placed in the gaps of the chamber doors. A heat flow plate and a

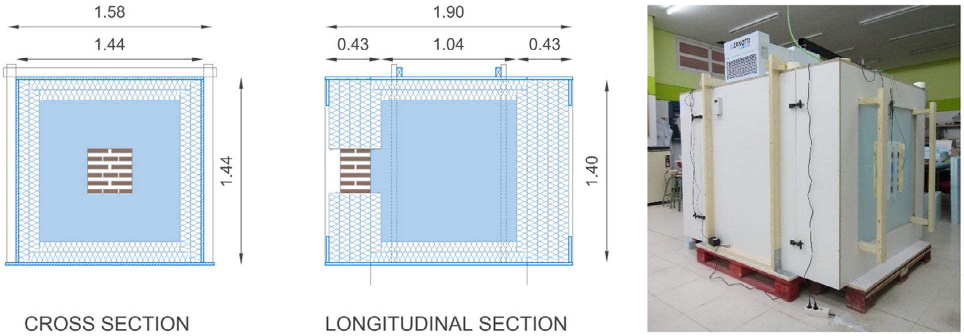

Fig. 4. On the left, sections of the cold room. On the right, the chamber with one of the test specimens.

Table 2
Manufactured specimens: photographs, dimensions, dry and saturated weights, and water absorption.

Specimens	P1	P2	P3	P4
Photographs				
Dimensions (mm^3) Length/width/thickness	300 × 305 × 255	270 × 270 × 260	245 × 245 × 260	320 × 215 × 215
Proportion by brick/mortar volume	69/31%	68/32%	72/28%	69/31%
Apparent density of specimen (kg/m^3)	1,692	1,770	1,813	1,935
Water absorption (m^3/m^3)	0.242	0.249	0.209	0.158

Table 3
Characteristics of the Heat Flow Meter (HFM) apparatus used.

Instruments		
Heat flux plate	Name Shape Dimensions Thickness Type of substrate Accuracy of the measurement Sensitivity of the instruments	Ahlborn AMR model FQAD18TSI Square 120 × 120 mm 3 mm Silicone ±0,02 % Not specified
Surface temperature probes	Number of probes Typology Position Range of the measurement Accuracy of the measurement	2 surface temperatures, interior y exterior Thermocouple Inside and outside the chamber 00 to +95 °C ± 0.05%

Source: Taken by the authors from the Almemo manufacturers' manuals.

surface temperature probe were placed on the outer face (laboratory environment), and a surface temperature probe was placed on the inside face (refrigerated environment of the chamber). The heat flow test was carried out following the procedure of standard ISO 9869-1 [11,37,38], weighing the specimens at intervals of weeks, depending on the desorption of the water, so that the value of heat flow and surface temperatures could be related to their water content. The test lasted from two to four months depending on the time taken for each specimen to go through the water desorption process. The instruments employed to carry out this heat flow test are listed in Table 3.

Using the data obtained in the heat flow test, namely the surface temperatures and the value of the heat flow passing through each specimen, we can calculate the thermal conductance by means of the formula for the simplified average method from the standard ISO 9869-1 [11]:

$$\Lambda = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} \left(T_{sij} - T_{sej}\right)} \tag{1}$$

Where:

Λ thermal conductance, in W/ (m^2·K) q density of heat flow rate = Φ/A, in W/m^2

T_{si} surface interior temperature, in °C

T_{se} surface exterior temperature, in °C

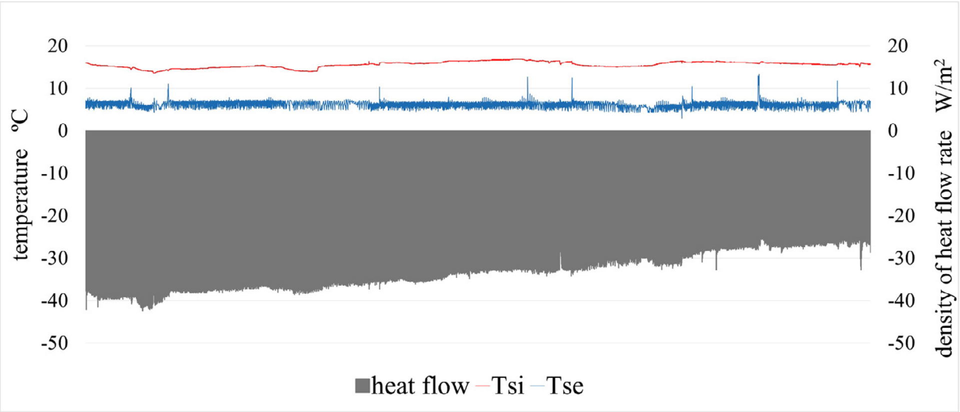

Fig. 5. Graph with the result of the heat flow test of P1.

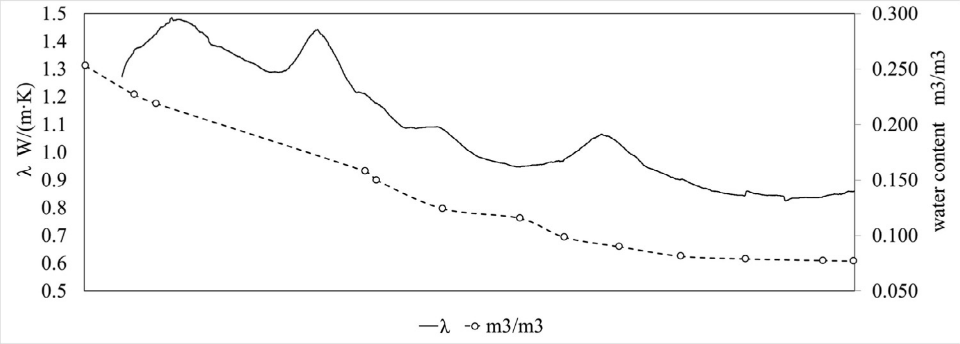

Fig. 6. Graph showing the values of thermal conductivity and the water content of specimen P1.

Table 4
Conductivity coefficient as a function of water content.

Brick Specimens	Apparent density (kg/m^3)	Water absorption (m^3/m^3)	λ dry W/(m·K)	λ saturated W/(m·K)	λ/ water content exponential formulaW/(m·K)
P1	1,692	0.242	0.64	1.43	$0.64e^{3.31x}$
B1	1,676	0.247			
P2	1,770	0.249	0.87	1.74	$0.87e^{2.78x}$
B2	1,789	0.258			
P3	1,813	0.209	1.02	1.75	$1.02e^{2.57x}$
B3	1,846	0.200			
P4	1,935	0.158	1.13	1.72	$1.13e^{2.65x}$
B4	2,028	0.125			
P mortar	1,729	0.238	0.80	2.02	$0.80e^{3.91x}$

Once the thermal conductance value is known, the thermal conductivity can be estimated using the formula:

$$\lambda = \Lambda \times d \tag{2}$$

Where:

λ the thermal conductivity (W/m·K)

d the thickness of the specimen (m)

With the value of the thermal conductivity for each specimen in each test phase, and the water content in m^3/m^3 that was obtained by weighing the specimens, a relationship between the two values can be established for each specimen tested.

4. Results of the heat flow tests

Fig. 5 reflects the test process of specimen P1 and the heat flow results, as well as the values of the temperatures recorded throughout the entire period, both internally and externally, where T_i sup corresponds to the surface temperature of the laboratory and T_e sup to the surface temperature inside the refrigerated chamber. These values are required to calculate the thermal conductivity using formulas (1) and (2).

The test of P1 was carried out during a summer, over a period of 69 days, which was the time it took for the specimen to go from its saturated state to its dry state at room temperature in the laboratory. As can be seen, there are oscillations in the T_i sup data, reflecting the variations in temperature of the room, due to the lack of air conditioning during the summer. For its part, the graph of T_e sup presents the variations in temperatures typical of the air cooling system in the cold chamber. Throughout the process, it is observed that the heat flow value decreases as the specimen dries. The slight variations observed are due to the change in surface temperatures.

The specimens were weighed at regular intervals throughout the test period to measure the water content, as shown in the graph in Fig. 6, along with the thermal conductivity trend line, in order to evaluate the relationship between the two values. As can be seen, as the water content of the specimen decreases, the thermal conductivity also decreases.

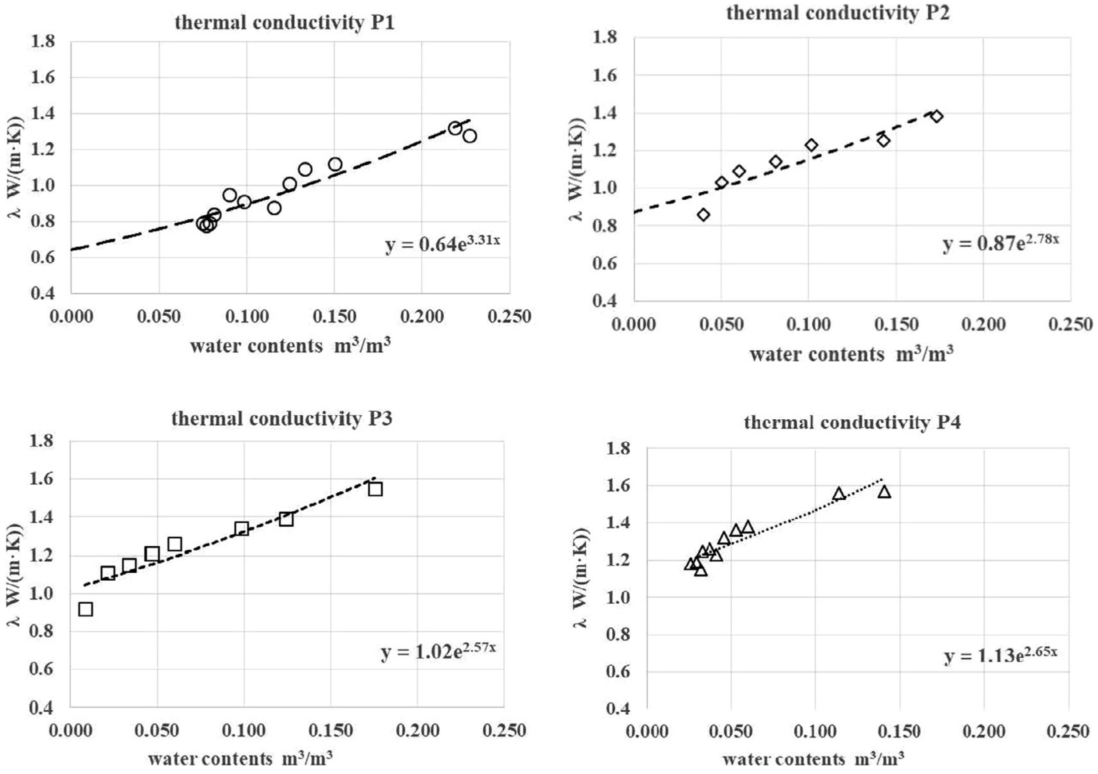

Fig. 7. Graph showing the result of the heat flow test: the thermal conductivity of the specimens in relation to the water content in m3/m3.

Once the tests had been carried out on the four masonry specimens, and using the data obtained for each specimen with the procedure indicated above for P1, independent graphs were generated for each specimen, where the calculated thermal conductivity values are listed with the water content (Fig. 7). These graphs show the thermal conductivity trend line and the exponential formula, permitting analysis of the individual performance.

The results were used to generate Table 4, which shows the conductivity values in the dry state, the conductivity in the saturated state, and the formula for the trend line of the four specimens, in order to compare performance between them. The data obtained on densities and water absorption coefficients have also been included, from the specimens as well as from the brick pieces and the mortar, in order to allow analysis of the changes that occur due to the action of this material.

5. Discussion

In the study of the specimens tested, it is observed that with the bricks and mortar used, the thermal conductivity of the bricks is inversely proportional to their density when in the dry state, corroborating the introductory statement. Furthermore, it is also shown that, in the dry state, there is a clear positive relationship between the thermal conductivity and the density, showing, for example, a jump of 0.26 points between the λ_{dry} value of P4 and the λ_{dry} value of P2, while in the saturated state, the difference of the $\lambda_{saturated}$ value actually falls 0.02 points, i.e., the $\lambda_{saturated}$ value of P2 is higher than that of the $\lambda_{saturated}$ value of P4. Here this relationship breaks down and reaches an important crossroads with the thermal conductivity values practically attaining the same level. In fact, in the saturated state, the thermal conductivity values of specimens P2, P3 and P4 are very similar (Table 4).

This fact is due to the ability of the bricks to absorb water, which, as has been proven, does not necessarily bear a direct relationship to their density. For this reason, beyond density, the fundamental factor influencing the good or bad thermal conductivity of masonry in its saturated state is its water absorption coefficient.

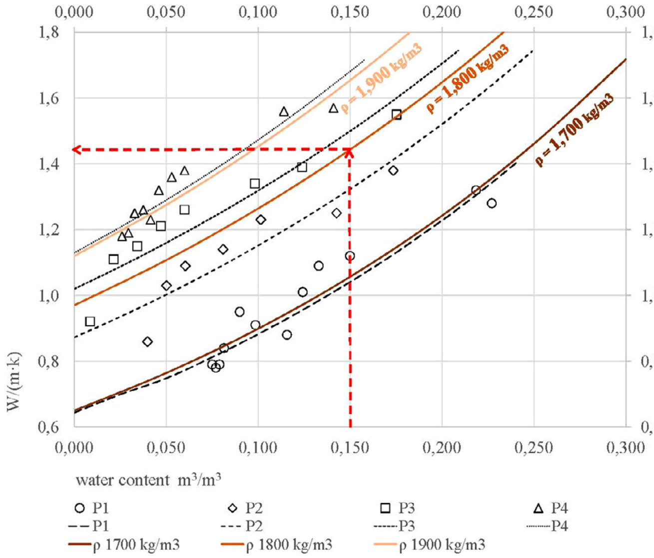

Fig. 8. Abacus with the result of the heat flow test, the thermal conductivity of the specimens in relation to the water content in m3/m3.

It is shown that the mortar has a significant influence on the thermal conductivity values of the masonry, sometimes positively, lowering the water absorption coefficient, as in the P3 and P4 specimens and in others, raising it, as shown by the tests of specimens P1 and P2.

From the results of the tests, an abacus (Fig. 8) has been produced that can be used to estimate the thermal conductivity of handmade brick masonry with densities of between 1,700 kg/m^3 and 1,900 kg/m^3 and at different levels of humidity. This abacus has been generated from the thermal conductivity trend lines of the four specimens tested. To use it, it is sufficient to know the density and moisture content of the brick masonry under study, as shown in the example marked in the graph, in which it is estimated that, for masonry with a density 1,800 kg/m^3 and a moisture content of 0.150 m^3/m^3, the thermal conductivity is 1.43 W/(m·K).

6. Conclusions

- In general, it is established that the thermal conductivity coefficient is related to density and humidity, so that the higher the density of the brick, the higher the thermal conductivity of the brick masonry. Likewise in relation to the water content, the higher the water content of a brick masonry, the higher the thermal conductivity in all cases.
- It should be noted that for the dry state, the values of conductivity obtained coincided extensively with some other studies on traditional heritage buildings, which in turn reinforces its results [30].
- The results of the tests show that for masonrys with similar proportions and types of mortar, it is possible to define a abacus that estimates the thermal conductivity of a masonry created with handmade bricks and lime and sand mortar, with an approximate brick/mortar volume ratio of 70/30%, as a function of the density of the masonry and its water content.
- The experimental work carried out to determine the thermal conductivity of the masonry studied allows a more accurate prediction of the effective response to the thermal behaviour of this type of masonry when subjected to different states of humidity. Its development makes it possible to determine the behaviour of the envelope of existing buildings in order to recommend suitable technological solutions that can improve human hygrothermal comfort and reduce energy consumption, in addition to avoiding unexpected pathologies.

The suitability, compatibility and complete understanding of the behaviour of traditional materials allows them to be used, prolonging their useful life and life cycle and thus avoiding the need and processing of new materials, thereby helping to reduce CO_2 emissions which are very high in the construction sector.

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