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Brick Walls of Buildings of the Historical Heritage. Comparative Analysis of the Thermal Conductivity in Dry and Saturated State.

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Abstract. In the energy efficiency restoration, one of the most important aspects to consider is the loss of heat through the enclosing walls, for which constructive solutions are sought to improve their thermal performance, being usual to place a sheet of insulating material on the inner side of the facade, avoiding intervening on the outside, so as not to alter the appearance of the buildings. This fact is aggravated in the buildings built with brick factory, especially in those belonging to the Historical Heritage whose walls are raised with handmade bricks joined by mortar joints. This type of wall has a high porosity, whose immediate consequence is the absorption of a large amount of water, which is a good conductor of heat, which means that a wall saturated with water has a higher thermal conductance than being dry, increasing the consumption of energy needed to thermally condition the interior. Applying the current regulations, in order to determine the thermal conductivity of the mentioned walls, laboratory tests have been carried out on dry and saturated specimens and also on similar materials. The analytical study of the values obtained from the thermal conductance of the brick factory wall in wet state and in dry state offers data with important variations. The most immediate conclusions are two, firstly that it is necessary to know the state of humidity of the facades to determine the insulating behavior of the same and that to save energy and achieve an effective intervention, it is necessary to act on the outside of the walls, keeping it dry by applying treatments on the facades.

1. Introduction

From the point of view of its thermal characteristics, materials present significant changes depending on its water content. The heat flow going through a wall is greater when the wall is wet than when it is dry; only dry air fills the capillaries of a dry wall whereas water in liquid or vapour form can be found in a wet wall, being water a good heat conductor. Additionally, in the heat flow, this difference will be enhanced by the evaporation process which, in order to happen, absorbs heat from the surroundings and cools both the air and the material on which it is produced because, as we know, it is an endothermic reaction.

Hand-made brick in old buildings and lime mortar are materials with high apparent porosity, and they may contain a high water volume in pores and capillaries [1]. For this reason, the heat flow going through a wall built with these materials will be significantly different when the wall is dry from when it is wet. This difference in the heat flow can also be useful to estimate the moisture content in the walls,

in spite of the fact that there are other tests [2] more recommended and that this may not be its main purpose. However, being a non-destructive test, it is very appropriate to analyze historical buildings and offers valuable information, which can be very useful to determine the actions to be taken in an energy rehabilitation project. In many of the ongoing energy rehabilitations carried out in buildings, an envelope with greater thermal insulation is achieved by covering the outer façade with a layer of insulating material, which is protected with rendering or other weather-resistant materials. In old buildings this solution is not feasible, as it would alter the aspect of those materials. Also, this type of project is appropriate for flat façades, and old buildings usually abound with moldings, window moldings, pilasters and many other ornamental elements projecting from the façade plane.

One solution bound to improve energy efficiency in these walls would be to try to avoid dampness caused by rain applying a water-repellent material on the outer face; thus, achieving energy savings which could be significant depending on the characteristics of the wall, climate and weathering. In old building walls, built with brick and stone, the problem with damp is more urgent, as rainwater seeps into them more easily. Consequently, if we consider how important the conditioning of these buildings is nowadays in order to maintain them in good use, while aiming for a significant reduction in energy consumption, it is essential to evaluate solutions whose implementation will allow us to save energy. In this respect, this article will present data referring to the theoretical analysis and the tests carried out to verify the energy savings derived from maintaining the walls dry instead of damp –trying to protect them from rainwater damp– as a plausible method to improve thermal behavior in old walls.

The type of test was selected for several reasons: it is non-destructive and it could be carried out in situ in building walls in order to obtain information before deciding the type of action needed for the preservation and energy conditioning of Cultural Heritage buildings.

2. Materials and experimental process

In order to assess if the prevention of damp in a wall is important in the energy rehabilitation process of old buildings, we have proceeded to estimate the thermal conductance in a brickwork test specimen in two different ways: one analysis following the procedure set in Standard EN 1745 [3] and a second one consisting in a laboratory test aimed to measure the thermal flow going through a brick and mortar specimen. This test started with the specimen saturated with water, which continued during the desorption process; the values of the thermal flow were measured with a heat flow meter (HFM), complying with the procedure described in standard ISO 9869 [4] and standard EN1934 [5].

2.1 Materials

In order to estimate energy savings, we have taken as a baseline a solid brick test specimen built by extrusion with air lime and washed river sand (dose rate 1/3), laid header bond, with an equal proportion between the volume of the brick and the mortar– a type of building system used in historical buildings. Water absorption in this type of brick proves to be as high as the one in hand-made bricks. The specimen thickness has been fixed in a brickwork stretcher so as to make it easy to handle. We understand this thickness is enough –even a lesser one if we take into account other studies- [6] to obtain reliable data that allow us to evaluate the proposal from a thermal point of view. Also, due to another question derived from the way in which rainwater seeps through the walls. Previous tests have confirmed that water can penetrate through a stretcher bond one-brick-thick wall [7], which means that rainwater could saturate the whole thickness of a wall built in such a way.

Tests on density and water absorption complying with the corresponding EN standards have been carried out to estimate the quantity of water that the test specimen and the materials with which it was built can absorb. Whole blocks have been used for brickwork while 160x40x40mm specimens have been used in mortar tests.

2.2 Masonry brickwork specimen

A brick and mortar header bond test specimen was built. Mortar was left to harden before carrying out the tests, so the characteristic values of the materials could be compared with those in the specimen.

Then the specimen was saturated with water and the test started with the measuring of the heat flow meter 'figure 1'.
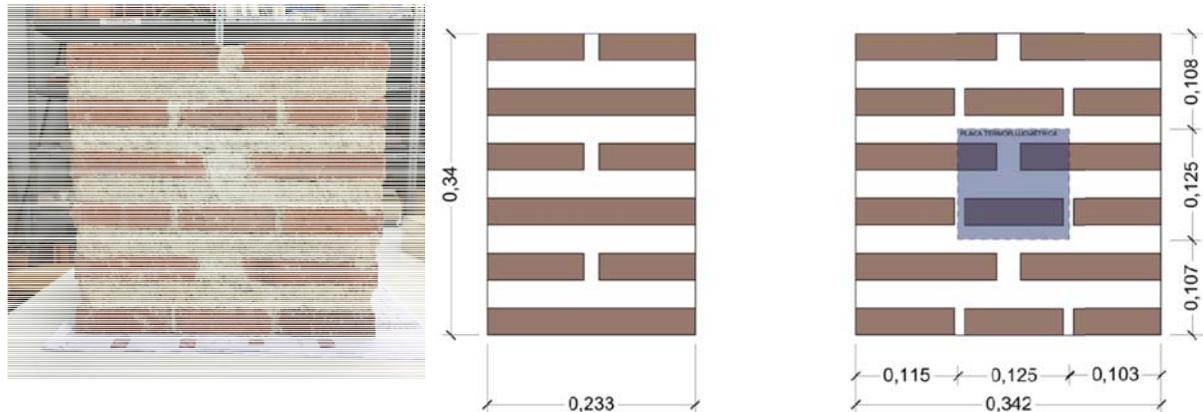
Figure 1. Test specimen used in the test, which measured the heat flow, and dimensional state of the specimen with the location of the flow meter (blue square).

2.3 Calculation method according to standard EN 1745

Se According to the procedure described in standard EN 1745 [3] the value of thermal conductivity in masonry brickwork $\lambda_{design,mas}$ can be determined depending on the values of its components; in this case, brick $\lambda_{design,unit}$ and mortar $\lambda_{design,mor}$, taking into account the percentage of the area in the elevation in compliance with the following:

$$\lambda_{desing,mas} = a_{unit} \, x \, \lambda_{design,unit} + a_{mor} \, x \, \lambda_{design,mor} \tag{1}$$

Starting at the value of thermal conductivity of the material at an average temperature of 10°C and in a dry state $\lambda_{10,dry}$, the design value for thermal conductivity is estimated using the moisture conversion factor F_m.

$$\lambda_{design} = \lambda_{10,dry} \times F_m \tag{2}$$

The factor F_m is estimated with the moisture conversion factor per volume f_ψ given in anex A of the aforementioned standard, for each material and the design moisture content ψ_{design}.

$$F_m = e^{\, f_\psi \, x \, \psi_{desing}} \tag{3}$$

where:

$\lambda_{10, dry}$	thermal conductivity of the material at 10 ºC, W(m.K);
λ_{design}	design thermal conductivity, in W(m.K);
α_{mor}	percentage of area of mortar joints;
α_{unit}	percentage of area of brickwork;
F_m	moisture conversion factor;
f_ψ	design moisture coefficient in volume per volume.

From the data tables in annex A of the aforementioned standard, we have taken values $\lambda_{10,dry}$ y $f_{\psi \, of}$ the two materials. With these formulas, thermal conductivity of the specimen from dry to water saturated has been estimated, considering the proportion of surface of both materials in the flow meter and the relation between the water absorption of the materials with regard to the absorption of water in the specimen. In this case, the measurement of the water absorption value has folllowed the procedure in EN 772-21 [8].

2.4 Test to estimate thermal conductance

The test method was designed according to the aforementioned standards [9]. For the completion of the test, a sealed cold chamber was built, with a side door where the masonry brickwork specimen was located. Heat flow going through it was measured, due to the heat difference between the inside on the chamber –between -5 and -3°C– and the laboratory room temperature –between 20 and 22°C 'figure 2a'– by means of a heat flow meter. Additionally, the interior surface temperature and the exterior surface temperature were measured with probes. The indoor air in the box was cooled with a refrigerating unit and room temperature was the same as the one in the laboratory, which fluctuates depending on whether the heating system is on or off. To carry out the test, the specimen was saturated with water through immersion and then placed on the side door of the chamber 'figure 2b'. The equipment used to collect data and cool the inside of the chamber is the following:

- Heat flow meter AMR model FQAD18TSI by Ahlborn, dimensions 120x120x3 mm in silicone (precision 0.02% of measured value).
- Four thermocouples to measure surface temperature, two in the inside and two in the outside of the box (precision ± 0.05°C ± 0.05% of measured value).
- For the storage of data regarding heat flows and surface temperatures in the specimen, the equipment used was a baseline measurement or data logger; model Almemo 2590 by Ahlborn (precision 0.03%).
- Refrigerating equipment by Zanotti, model MGM10328F, with compact evaporator in the inside of the chamber.

Figure 2. Left, 2a, cold chamber. Right, 2b, measuring equipment.

Using the surface temperature and the value of the flow going through the specimen, we can estimate the value of the thermal conductance in compliance with the procedure described in standard ISO 9869-1 [4], with the formula:

$$\Lambda = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n}(T_{sij}-T_{sej})} \qquad (4)$$

where:

Λ thermal conductance, en W/(m2.K)
q density of heat flow rate $=\Phi/A$, en W/m^2;
T_{si} interior surface temperature, en ºC;
T_{se} exterior surface temperature, en ºC.

Once the value of the thermal conductance is known, we can estimate the value of the thermal conductivity coefficient with the formula:

$$\lambda = \Lambda \times d \tag{5}$$

where:
λ is the thermal conductivity, in W/(m.K);
d is the thickness of the test specimen, in m.

Throughout the test the values of the flow and temperatures were obtained at 30-minute intervals while the process of desorption of the specimen –weighed every seven days to measure the evaporated water– was taking place. The test was finished when the difference between two consecutive weight measurements was lower than 0.5% of the initial weight. Thus, we have succeeded in relating the value of the thermal flow with the water content in the specimen and, consequently, the value of the thermal conductance with that of the water content. The water content was estimated comparing the weights of the specimen during the desorption process with the weight of the specimen dried in an oven to constant weight.

3. Results and discussions

Once the tests were finished we proceeded to analyze and compare the results. First of all, the results concerning the materials characterization tests and the estimated values according to standard EN 1745 [3]. These values are shown in 'table 1'.

Table 1. Brick and lime mortar.

	Brick dimensions mm	Test specimen dimensions mm	Absorption in cold water m^3/m^3	Density ρ kg/m³	Dry conductivity coefficient EN 1745 λ W/(m.K)	moisture conversion coefficient EN 1745 $f\psi$ m³/m³	Surface percentage heat flow meter %
Brick	230x107x30		0.185	2,067	0.61	10	40
Lime mortar		160x40x40	0.210	1,847	0.81	4	60

As can be seen, the characteristics of both materials are different; consequently, the estimations for the values of the thermal conductivity coefficient have been carried out with the values of each material according to the percentage of surface in the flow meter 'figure 1'.

With regard to the masonry brickwork specimen, several tests have been carried out, following the same procedure as for the materials, with the aim of assessing the absorption of cold water and the density. The values of the thermal conductivity coefficient were estimated as described in standard EN 1745 [3]. The values relating the specimen are shown in 'table 2'.
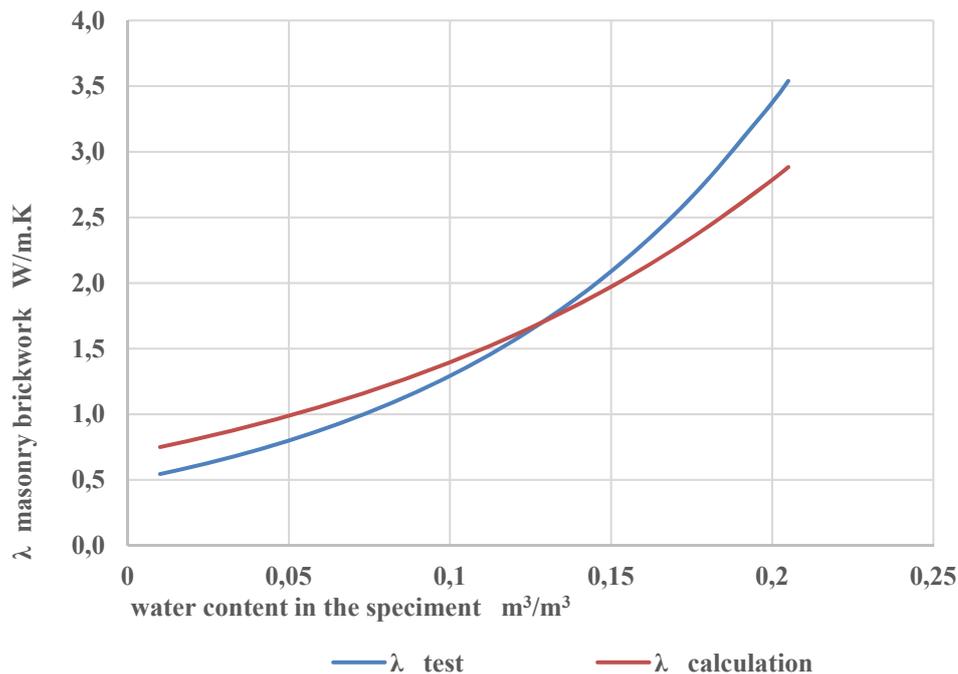
Table 2. Masonry brickwork specimen

	Dimensions mm	Absorption in cold water m^3/m^3	Density ρ kg/m³	Dry conductivity coefficient $\lambda_{10,dry}$ W/(m.K)	Satured conductivity coefficient λ W/(m.K)
specimen	342x340x233	0.205	1,962	0.77	2.68

This implies that the value of the specimen thermal conductivity when saturated is nearly four times that of the dry specimen, according to the system based on standard EN 1745 [3]. The values regarding the specimen water content are shown in the graphic in 'figure 3'.

The other system was the estimation of the value of the thermal conductivity coefficient on the basis of the values of the flow meter and the surface temperatures, starting with a saturated specimen and finishing with a dry one, while weighing it at regular intervals. These values are shown in 'figure 3'.

'Figure 3' shows the trend lines with λ values when the test specimen presents a water content between 0.01m3/m3 and 0.205 m3/m3. The lowest value was chosen because the specimen, when at laboratory room temperature, presents a minimum water content around this value, as it has absorbed part of the water in the air and, consequently, its weight is higher than that of the specimen after being dried in the oven. Similarly, the highest value was fixed because that is the value of the quantity of water that the specimen may absorb when immersed in cold water.

Figure 3. Values of thermal conductivity coefficient λ of the masonry brickwork specimen obtained through estimations and experimentally.

As can be seen, the two trend lines intersect at a water content point of 0.115 m^3/m^3 and for a thermal conductivity coefficient value of λ=1.50 K/m.K, although at the beginning of the curves and at the end the results of the two methods differ notably. However, in both calculation methods the value of thermal conductivity is higher with a saturated specimen than when the specimen has absorbed air moisture.

We can estimate the thickness of an insulating leaf to be attached to the brickwork leaf so that it maintains the same thermal conductance value while it gets soaked, taking for granted that the choice is an insulating material with waterproof skin such as extruded polystyrene with λ = 0.04 W/m.K. For this calculation, the value of the thermal conductivity coefficient of the specimen has been estimated as the average value in the systems used. When representing the values of the thermal conductivity coefficient, according to the two methods used and to the thickness of the insulating material in the graphic in 'Figure 4', we can confirm graphically how important it would be, from the point of view of energy savings that rainwater would not penetrate in the brickwork wall.
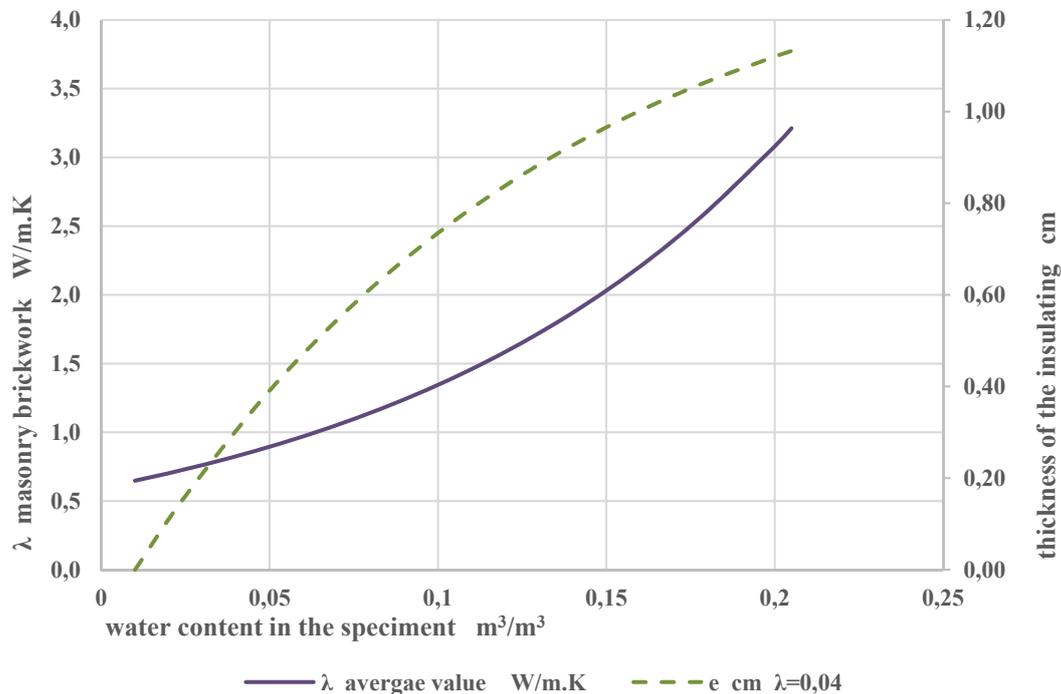
Figure 4. λ values for the thermal conductivity coefficient of the specimen –according to the results obtained in the test and in the calculation method– and thickness of the insulating leaf needed to complete the thermal insulation of the specimen in order to maintain the value in the dry specimen as it gets soaked, depending on the water content.

The results obtained in the tests that were carried out allow us to set the needs for the insulating material that would be necessary to use for the wall studied to present the same conductance in a dry state as in a saturated one. In particular, the thickness of the tested specimen would require a 1.1 cm thick leaf in order to obtain the same results regarding thermal conductivity. Consequently, the results would be different when we find different thicknesses in the brickwork walls used in this type of historical buildings. Thus, if the thickness in the brickwork affected were to double, the thickness of the needed insulating material would also have to double.

Finally, we should note that the values obtained would be very different in bricks with a lower density [10] and a greater absorption than those bricks with which the test was carried out and with different types of mortar in the joint [11].

4. Conclusions

The conclusions reached after carrying out the tests allow a major breakthrough in different aspects.

From the point of view of experimental and theoretical design, the study has succeeded in determining the values for thermal conductivity in the test specimen both in a dry state and in a saturated state through the theoretical calculation and the use of non-destructive tests.

Focusing on the methodology used, we have confirmed that the two methods chosen to estimate the variation in thermal conductance show differences. Therefore, it is essential to continue carrying out studies with different types of brickwork in order to analyze the underlying reasons.

However, when analyzed separately, they offer relevant data, particularly the flow meter system is recommended when carrying out tests in situ. It can be complemented with thermal images, which allow us to determine the drier or damper areas in a wall based on the difference in surface temperature. This way we can obtain really valuable information in order to plan an energy rehabilitation project in this type of buildings, thus complying with the main objective of the ongoing research.

From the results obtained in this study we can conclude that thermal conductivity in the brickwork specimen in a damp state and in a dry one shows a significant difference. This fact allows us to go deeper in the field of energy savings, making it possible to confirm that preventing dampness in masonry brickwork may contribute to improving energy savings in buildings constructed with this type of envelope.

Moreover, also notable is the collection of specific data for the thickness of the insulating material in the tested specimen as well as the assessment of the proportionality of thickness needed in the aforementioned material depending on the brickwork thickness.

Furthermore, the study confirms that the results obtained are exclusive to the type of brickwork tested both from the perspective of the material and from a dimensional point of view. However, it will be necessary to carry out specific studies in other cases.

On a different note, it should be stressed that guaranteeing the behavior of the material when this is affected by the outdoor environmental conditions also guarantees the reduction in the expenses derived from the reduction of heat consumption.

Finally, it must be stated that in the absence of confirmation and a larger number of specimens, it is so far possible to estimate the λ value obtained in the laboratory. The next step in our research will be to contrast the data obtained with other devices that will help us to validate the reliability of the resulting values, starting from the value of the flow that goes through the specimen and that of the surface temperatures.

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