Brick of the Historical Heritage: Comparative Analysis of The Thermal Conductivity, Density and Moisture

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Brick of the Historical Heritage: Comparative Analysis of The Thermal Conductivity, Density and Moisture

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Abstract. In the renovation of historic buildings, the facades deserve special attention because, in general, it is where the property's value and heritage lies. Additionally, they have a fundamental impact in the energetic efficiency of buildings. When you want to achieve an efficient building, the facades must comply with certain construction standards, generally difficult to achieve in renovations, especially in facades built with exposed brick, not altering their external appearance is a sine qua non condition. Against this background, in order to carry out optimal interventions in the thermal behavior of a brick wall, it is essential to have an exhaustive knowledge of the characteristics and values that influence thermal conductivity. To do so, calculations and simulations are carried out using the density and porosity parameters that are published in the different documents and regulations. However, these values are not reliable because they refer to the materials currently manufactured, and therefore, they are not valid when working with centenary materials that have been produced without quality control or precise technical specifications. On the other hand, the values provided by the regulations refer to the material in the dry state. It has not been considered that bricks, and especially those manufactured manually, due to their intrinsic conditions, are capable of absorbing large amounts of water, and therefore, of significantly varying its thermal conductivity. This feature is extrapolated to brickwork facades, where water can rise from the ground and penetrate from the rain. Thus, it is necessary that in the thermal conductivity study its hygrothermal behavior is taken into consideration. Against this background, this article presents the results of the tests carried out on specimens of various bricks from different traditional bricks factories and manufacturing processes and with an approximate age of about 100 years, to show that the old bricks have very different density, porosity and thermal conductivity values from the current ones. In addition, these values vary greatly depending on the moisture they contain, and also, the manufacturing system they had. Likewise, it is clear that the bricks of the facades of historic buildings, even if they are contemporaries, have different characteristics among them, showing different thermal behavior.

1. Introduction

Many old European cities have an "architectural ouvre" of great wealth, made up of buildings that were built between the late 18th and early 20th centuries, the preservation of which has become a priority action for public administrations. For this, it is necessary to carry out important restoration, rehabilitation and conservation works, which return the buildings to a new use, adapted to new habitability conditions, which have obviously changed in the last hundred years. Added to the complexity of these interventions is the obligation to comply with the multiple demands on sustainability and energy efficiency, to comply with the Kyoto Protocol to reduce carbon dioxide emissions. Should not be forgotten that residential buildings use represents about 63% of total energy consumption in the building sector [1]. For this reason, scientists who work on issues related to Cultural Heritage have the challenge of finding the best solutions, seeking methodological approaches for the evaluation of sustainability and intelligent solutions, based on the characteristics of the constructive elements. Additionally, they also analyze the factors that they influence energy behavior and include actions that, although not considered strictly necessary by the regulations, but allowed, it is observed that they affect energy efficiency. [2]

Lowering the necessary energy consumption in a building by means of a good thermal conditioning of the building envelope is a priority aim, in order to achieve good energy efficiency, mainly of the façade, since it is an element where there is a great loss of heat. This challenge has become a great concern for architects, which is aggravated in restoration projects, since they work with walls built with old materials of which their characteristics and therefore their thermal behavior is unknown. In Europe, this concern has been growing in recent years, reason why multiple investigations have been carried out on the thermal behavior of old buildings, focused on the experimental or computational thermal analysis of the walls and on the influence of thermal flux. There are also studies that evaluate the energy efficiency of building facades, using very advanced techniques, such as obtaining thermographic 3D models and orthoimages [3] and others that analyze energy consumption and CO2 emissions related to the conditions of the thermal gradient required for tests [4]. However, with a few exceptions [5] [6] [7], the effect of moisture has not been taken into account, therefore, in construction elements that are capable of absorbing large amounts of water, such as masonry brickwall exposed, moisture can play an important role, and not having contemplated this fact, can lead to a deviation from physical reality in the results of the studies [8].

Therefore, knowing the thermal conductivity values of the materials that make up the facades to be restored is the first step in evaluating the thermal quality of the complex. For this, the usual thing is to use the data shown by the different regulations, such as the UNE-EN 1745 [9] standard, which contains tables that relate density to thermal values. However, there is a legal loophole when it is necessary to know the values of ancient materials, such as the centenary bricks of the facades that must be preserved, since they only appear values relative to current materials. It should be borne in mind that, in the restorations and rehabilitations, the bricks were made more than a century ago, without quality controls. In addition, it must be taken into account that the bricks have undergone modifications in their characteristics, produced by the passage of time and by the incidence of climatic factors.

To this must be added that, in the energy efficiency regulations, factors such as the water content of the facades are not taken into account, which obviously is a factor that must be assessed. This problem has also been noted by other researchers, who believe that traditional buildings require different assessment and practice with regard to the control of moisture in buildings [10]

In general, the solutions adopted in restoration work are focused on placing insulating material inside the wall, without having prior knowledge of what its thermal behavior really is. For this reason, and knowing that bricks are recurring materials in old facades that must be preserved, they must be analyzed from the thermal point of view in a specific way.

This article will present the results of the tests carried out on a series of centenary bricks, from stockpiles and demolition of old buildings, in order to know their thermal conductivity, considering them at various levels of humidity, from dry to saturated. Different parameters will be analyzed, such as density, water absorption and mineral composition, and the relationship between them and the value of thermal conductivity will be verified. In addition, these results will be compared with those shown in the current standards to be able to analyze the possibility of being able to use them in studies and simulations in energy rehabilitation projects of old buildings. By contrast, they are not valid and specific tests must be carried out to determine the thermal behavior of the brick facades of a Cultural Heritage building.

2. Materials and experimental process.

This article analyzes the results of the tests carried out on bricks from different origins and different manufacturing systems, selected in such a way that they present densities with different and staggered values. Specifically, two types of hand-made bricks have been found, two types of mechanical bricks, manufactured by extrusion and a type of pressed brick, in which the density values present important differences, which allows a better analysis of the relationship between density and conductivity. As can be seen when analyzing the results, it has not been possible to find bricks with water absorption values that present as many differences as has happened with density. A different specimen has been extracted from each brick, which is the one that has been subjected to the different tests.

Five different types of bricks have been located ‘figure 1’: two types made by hand (B1 and B2), another two that were manufactured by extrusion (B3 and B4) and a pressed type (B5). Of the types B1, B2, B3 and B5, there were six samples and of the type B4 with four samples. All of them were cut and ground to form the specimens, which must meet two minimum requirements to be able to perform the thermal conductivity test: have parallel faces and minimum dimensions of 100x80x30mm. In addition, bad edges with chips, cracks and other disturbances have been removed. As can be seen in 'figure 1', the boards of the bricks are not flat and the edges of the bricks present alterations since they have been forming part of the walls of buildings.

Figure 1. Bricks, left to right: B1 handmade brick 1, B2 handmade brick 2, B3 common brick 1, B4 common brick 2 y B5 pressed brick.

Figure 2. Brick specimens. Left to right: 6 B1 brick specimens, 6 B2 brick specimens, 6 B3 brick specimens, 4 B4 brick specimens and 6 B5 brick specimens.

Once the specimens were cut, they were subjected to various tests to measure the dimensions of the specimens, and calculate the density and absorption of cold water, in the Construction laboratory of the E.T.S. of Architecture of the University of Valladolid and the mineralogical composition, in the Center of Scientific Instrumentation of the University of Granada. The tests carried out on the specimens were made according to the following standards:
- measurement of the UNE-EN 772-16 (11) dimensions,
- dry bulk density according to the process of standard UNE-EN 772-13 (12),
- absorption of cold water according to standard UNE-EN 772-21 (13),
- chemical composition by X-ray fluorescence test (XFR).

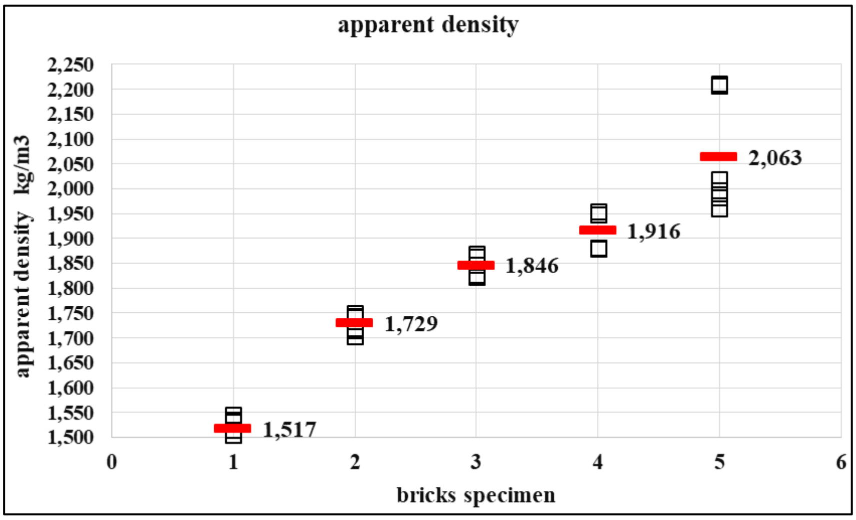
Once these tests were carried out, some of the specimens were dried and others were saturated to subject them to the thermal conductivity test with different water contents and thus be able to evaluate the difference in conductivity between dry and wet. This test was carried out with the QTM-710/700 Quick Thermal Conductivity Meter with the following environmental conditions: 22 ± 2ºC of temperature and 50±5 % of relative moisture.

3. Results and discussions.

In the first place, in 'table 1' the results of the values of the tests carried out on the specimens are indicated, where their dimensions, apparent density and water absorption are shown. In the graphs of 'figure 3' all the results of the density and water absorption tests of all the specimens have been represented so that the dispersion can be observed and evaluated:

Table 1. Brick specimens, dimensions, apparent density and water absorption.

		Long (mm)	Wide (mm)	Thickness (mm)	density (kg/m^3)	water absorption (m^3/m^3)
Handmade brick 1	**B1**	147	94	33	1,517	0.278
Handmade brick 2	**B2**	125	82	36	1,729	0.271
Common brick 1	**B3**	116	84	30	1,830	0.278
Common brick 2	**B4**	117	88	49	1,916	0.254
Pressed brick 1	**B5**	108	85	30	2,063	0.148



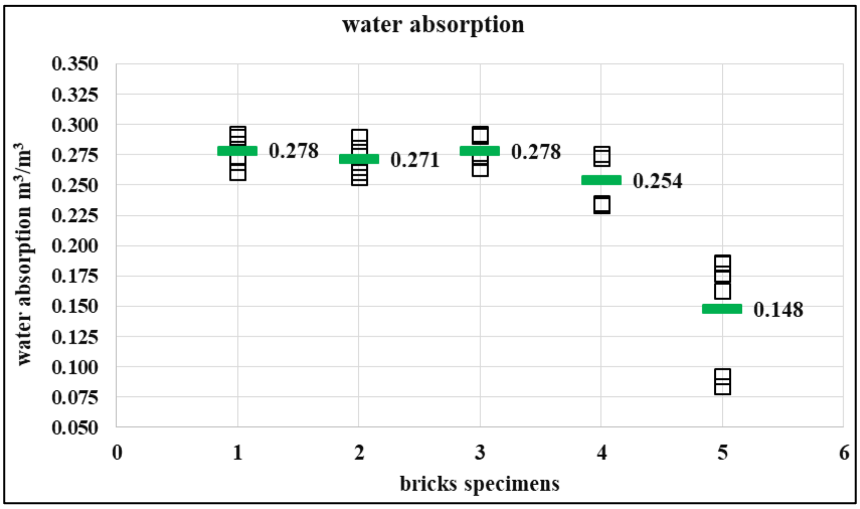


Figure 3. Values of density and water absorption from specimens.

In the graphs of 'figure 3', for the specimens of the same type of brick, from 1 to 5, the density values have been represented in columns, in the graph on the left, and the water absorption values in the graph of the right. As can be seen, the average values of apparent density of the specimens range from 1,571 kg/m3 to 2,063 kg/m3, which represents a great difference, however, several of the specimens, those of brick type B1, B2 and B3 present a similar water absorption, within the range of 0.271 to 0.278 m3/m3, which seems to indicate that the pores not accessible to water present a greater volume in bricks B1 and B2 than in brick B3, a characteristic that can influence the conductivity value, which should be lower in B1 than in B2 and lower than in B3. In 'figure 3' it can be seen that the studied specimens have similar values in terms of density and water absorption, except for the specimens of brick B5 in which the dispersion of results is important.

The chemical and mineralogical properties of the materials used in the samples were studied using X-Ray Fluorescence (XRF) and XRay Diffraction (XRD). The results are shown in 'table 2'. The samples were analysed using a PANalytical Zetium X-ray fluorescence spectrometer (XRF) with a ceramic x-ray tube, a 4 KW rhodium anode x-ray generator and a non-coupled goniometer of h/2. The XRF samples were mechanically ground in an agate mortar and then sieved to a grain-size fraction of < 0.354 mm (mesh size 45).

Table 2. Bricks specimens, mineralogical composition.

	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	MnO %	MgO %	CaO %	Na_2O %	K_2O %	TiO_2 %	P_2O_5 %	Zr (ppm)	LOI %
B1	68.04	16.01	3.34	0.06	1.52	2.15	2.39	4.39	0.60	0.22	430.1	1.16
B2	72.35	14.14	3.85	0.04	1.59	1.11	1.45	3.76	0.63	0.10	214.8	0.94
B3	72.77	14.44	5.57	0.04	1.33	0.55	0.50	2.90	0.84	0.12	310.2	0.71
B4	67.95	16.89	6.32	0.04	1.68	1.34	0.49	3.38	0.83	0.15	261.2	0.62
B5	67.55	17.52	6.08	0.04	1.68	1.10	0.42	3.82	0.86	0.14	255.5	0.69

The mineralogical composition is also similar, although specimens B2 and B3 present a higher percentage of SiO_2 than the other specimens and less in Al_2O_3.

And finally, the results of the conductivity tests of all the test pieces are indicated as a function of the water content, calculating this by means of the difference between the weight of the test piece during the test and the weight of the test piece oven-dried to constant weight, as It has already been indicated in 'figure 4'.

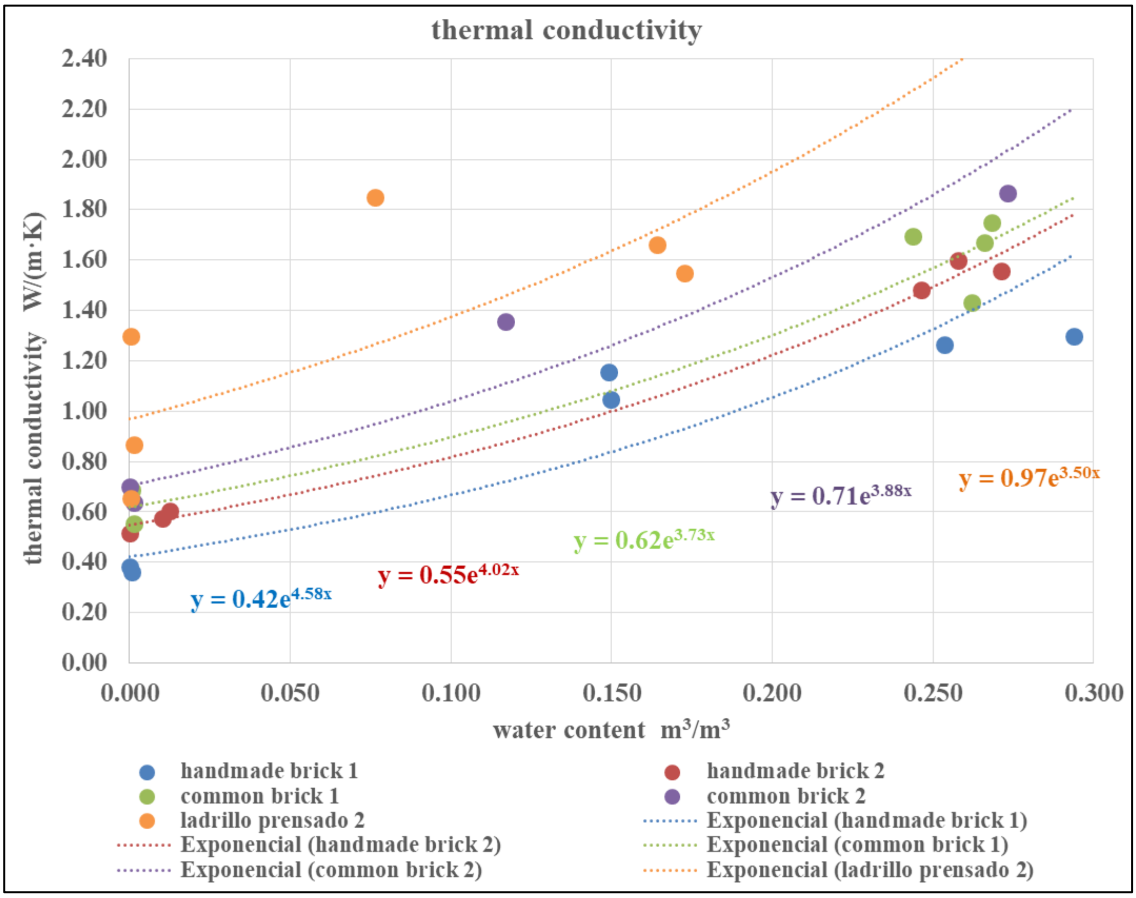


Figure 4. Thermal conductivity bricks specimens W/(m·K).

The graph in 'figure 4' shows the results of each conductivity test performed on the dry, semi-saturated and saturated specimens, and the exponential trend line obtained with these results. In the graph, the formulas of the ordered exponential trend lines for the brick specimens from lower to higher density, B1 to B5, have been indicated. As can be seen, the lower the density of the brick, the conductivity is lower and the conductivity values increase in a similar way in all types of brick with the water content. In 'table 3' are included the conductivity values in dry and saturated state, for each specimen, calculated with the formulas of the exponential lines in 'figure 4'

Table 3. Conductivity of brick specimens in dry and saturated state.

		Density (kg/m^3)	λ dry W/(m·K)	Water absorption (m^3/m^3)	λ saturated W/(m·K))
Handmade brick 1	**B1**	1,517	0.42	0.278	1.50
Handmade brick 2	**B2**	1,729	0.55	0.271	1.63
Common brick 1	**B3**	1,830	0.62	0.278	1.75
Common brick 2	**B4**	1,916	0.71	0.254	1.90
Pressed brick 1	**B5**	2,063	0.97	0.148	1.63

As can be seen, in the dry state the conductivity of the specimens is greater the higher the density. For the saturated state, the conductivity is also higher the higher the density, except in the case of the B5 brick specimens that due to its low water absorption, the conductivity in the saturated state is much lower.

The UNE-EN ISO 10456 (14) standard establishes the procedure to convert the thermal conductivity values obtained under a set of determined conditions, into valid values for another set of different conditions: temperature and moisture, admitted for ambient temperatures between -30ºC and + 60º C. The conversion of thermal values from some initial conditions (i) to another set of final conditions (f) would be carried out according to the expression:

$$\lambda_f = \lambda_i \, F_T \, F_m \, F_a \tag{1}$$

Where: λ is the coefficient of thermal conductivity in W/(m K), FT is the temperature conversion factor, F_m is the moisture correction factor and F_a is the aging correction factor.

In these tests, the temperature has been kept constant, so the temperature conversion factor can be considered equal to 1, the aging correction factor has also been considered 1, since the conductivity of the bricks is not compared when manufactured and when the tests have been carried out and the moisture conversion factor is calculated by the formula:

$$F_m = e^{f_\psi \, (\psi_f - \psi_i)} \tag{2}$$

Where: f_ψ is the conversion coefficient of moisture content per unit volume, which for fired clay according to table 4 of the cited standard, the value of $f_\psi = 10$. ψ_i, ψ_f are the values of the initial moisture content and final per unit volume in m^3/m^3.

In the exponential formulas calculated based on the results of the tests, the conversion coefficient for moisture per unit of volume, f_ψ, presents values between 3.50 and 4.58, which indicates that this value is very different for bricks in old buildings, of the current bricks.

4. Conclusions

From the tests carried out it can be concluded that the conductivity of the bricks is clearly related to the density; the higher the density, the higher the conductivity value.

The conductivity presents higher values when the materials are wet than when they are dry and in the case of materials with high water absorption such as old bricks, the difference is important. This aspect should be taken into account when estimating energy efficiency in buildings, since it depends to a great extent on the water absorption of the materials.

It does not seem appropriate to use on the facades of old buildings the values and calculations indicated in the standards and technical documents for the bricks that are currently manufactured, for which it is advisable to carry out tests that provide their real conductivity values.

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