



Evaluation of the behavior of brick tile masonry and mortar due to capillary rise of moisture

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ABSTRACT: For a better understanding of the behaviour of old brick masonry in facing the rising damp problem, multiple tests were made in the laboratory: water absorption, moisture content, apparent porosity, temperature and thermal camera imaging on brick masonry and its components: brick and mortar. This has allowed us to determine which of the previous tests is the best in predicting the behaviour of a real wall. In addition, the tests have also helped in defining a process to evaluate the moisture content of walls in a buildings, which is important for heritage restoration projects.

KEYWORDS: Brick; Brickwork; Rising damp; Absorption; Thermography

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RESUMEN: *Evaluación del comportamiento de las fábricas de ladrillos de tejar y argamasa debido a la humedad que asciende por capilaridad.* Para un mejor conocimiento del comportamiento de las fábricas antiguas de ladrillo frente a la ascensión capilar de agua, se han realizado en laboratorio ensayos de absorción de agua, de contenido de humedad, de porosidad aparente, de temperatura e imágenes con cámara termográfica sobre muros de fábrica y sus materiales componentes: ladrillo y argamasa. Ello ha permitido inferir cuál es el ensayo realizado a los ladrillos que mejor predice el comportamiento del muro real. También ha permitido definir un procedimiento para evaluar el contenido de humedad de fábricas existentes, importante para los proyectos de restauración del patrimonio construido.

PALABRAS CLAVE: Ladrillo; Fábrica de ladrillo; Ascensión capilar; Absorción; Termografía

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1. INTRODUCTION

The research on the behavior of old brick masonry against capillary rise of moisture, brings about the need to know the exact behavior of each components that make up these walls: ceramic bricks and air-entrained hydrated lime mortar.

The theoretical analysis that study the capillary rise of water can be of use to us to know this process when it comes to homogeneous constructive

elements, but this is not the case with brick masonry which are made up of two materials: bricks and mortar, with each having different characteristics, causing this capillary rise not to be linear or uniform.

The classic expression of capillary rise is by Jurin, by which the height reached within a capillary tube depends on the surface tension, of the wettability or the angle created by the surface of the liquid with the wall of the tube, capillary radius, density of the liquid and gravity.

However, when considering a real wall this requires an approach that allows to take into consideration other factors that can determine more clearly the scope of this phenomenon. In this sense, Mason (1) developed a model by which capillary rise is conditioned by the nature of the capillary pores, the wall thickness and its evaporation rate. In addition from a series of tests, he related the influence of age to greater absorption/ permeability of masonry mortar.

In 2002, Hall and Hoff (2) proposed a new model which states that the height of capillary rise (H) in a wall is proportional to the absorption of water by the mortar (S), and to the square root of the ratio of the wall thickness (b) and twice the product of the evaporation rate per unit of wet area (e) and the volume of water per unit of volume of the material (θ_w). The formula $H = S(b/2e\theta_w)^{1/2}$ is complicated to apply in the case of brick masonry walls with thick mortar joints because except b , the thickness of the wall, in our case it's a foot, the rest of variables are difficult to evaluate because they are affecting two different materials in imprecise environmental conditions.

Subsequently, Risch (3), in an estimable attempt to approach the real situation, revealed the difficulty to obtain actual data by direct measurements of the walls in order to check the validity of the theoretical formulations. The model Hall and Hoff did is based on the theory of unsaturated flow, like what happens in the complex porous structure of a brick wall, it predicts theoretical situations consistent with field observations. However, the same work shows the difficulty to carry out measurements that allows us to verify the approximation to these theoretical predictions. He also notes the uncertainty resulting from the parameter of sorptivity (absorption coefficient), given the difference in permeability of the brick and mortar, their age and the possible presence of sulfates. In his tests, he used different types of mortar and the masonry is joint with thin mortar and the bricks are quiet thick, because he wanted to verify the importance of mortar in the processes of absorption. And one of the conclusions reached is that there is a big difference between the results of the formulas used to calculate the level to which moisture can reach and the real tests on masonry.

More recently Peixoto (4) notes that due to the complexity of the problem it is extremely difficult to present scientific explanations for various forms of capillary rise and together with theoretical studies that he carried out with various tests mainly on stone walls with different concrete facing reached a conclusion on the absorption process and drying process of the masonry. He establishes the factors that influence rising damp: environmental weather conditions, sunlight, presence of sulfates, porosity and porometry of the material, wall thickness and facing material, and he defines a technique for when

intervening in the rehabilitation of historic buildings which is already used in various restoration work. It is based mainly in preventing the damp rising in the building by using barriers, and in the providing a network of cavities with controlled ventilation depending on the moisture, to regulate the drying process (5) at the base of the walls, since he concludes that the density of the flux g [$\text{kg}/(\text{m}^2 \cdot \text{s})$] is calculated according to the surface transfer coefficient of moisture β in m/s and the amount of water vapor on the surface C'_s and air C'_a in kg/m^3 using the formula $g = \beta(C'_s - C'_a)$ [$\text{kg}/(\text{m}^2 \cdot \text{s})$]. Another conclusion he reaches is that the process may have limitations when the walls are not homogeneous (6), as is the case with a brick wall.

The main objective of this research, based on the results of the studies aforementioned, is to evaluate which of the tests done with bricks and mortar provides the most reliable and accurate for the study of the behavior of masonry walls. Another objective is to find a procedure that allows to assess the moisture content and the process of capillary rise of water in old brick walls by conducting tests of the individual materials of the walls and measurements "on site" of the temperature and humidity, with probes and thermal imaging camera; all as previous steps to the decision-making in a restoration project.

2. MATERIALS AND WORK METHODOLOGY

Since the research is to know the state of old masonry, we opted on using brick tile from demolition and sufficient number for tests were found in Serrada (Valladolid). Some have the brand of the roof builder "La Operaria" and are more than 100 years old. Old masonry was made of lime mortar and sand and because it was not possible get specimens of mortar from the old demolished buildings because it's not possible to retain the mortar joints, specimens have been made with lime and sand in the proportion three to one (7) with air-entrained hydrated lime mortar type CL 90S (calcium hydroxide) and washed sand river, silica. In order to compare results of the old bricks with other solid bricks, tests have also been made with solid bricks that are currently being manufactured with the appearance that imitates the old masonry, and these came from the brick factory Santoveña, Santander.

Once the materials were selected: bricks, lime and sand two types of tests were made: to know the dimensions, apparent density and porosity, and others related to water absorption.

The dimensions of the bricks, length \times width \times height, in mm were measured in accordance with the UNE-EN 772-16 (8), the apparent dry density according to the UNE-EN 772-13 (9), and the percentage of channels/spaces or porosity UNE 772-3 (10). The mortar specimens were made of $40 \times 40 \times 160$ mm and the apparent density and the

percentage of visible pores was obtained by tests according to the UNE-EN 1015-10 Test Methods for mortar for masonry. Part 10: Determination of apparent dry density of dry mortar.

Determination of water absorption was made according to various standards in order to compare the results of the tests carried out on the bricks to the walls made of these bricks allowing us to determine which of the test results obtained were nearest the real situation. Different UNE tests regarding water absorption were used are:

UNE EN 15801 Conservation of cultural heritage. Determination of the capillary water absorption. The test procedure was as follows: at the bottom of a container was placed a dry permeable base of about 6 mm thick. Water was added until the bed was saturated, and the liquid level was kept constant throughout the test, adding water when necessary. The specimens of dried brick and mortar, were placed on the base and were weighed at intervals to determine amount of absorbed water. The test was carried out with samples of the two types of bricks and mortar:

- Specimen of old solid brick tile, dimensions 258 × 128 × 47 mm for the test the brick was laid on the smaller side of 0.006016 m².
- Specimen of modern semi-handmade bricks of dimensions 233 × 108 × 38 mm for the test the brick was laid on the smaller side of 0.003564 m².
- Specimen of mortar, dimensions 40 × 40 × 160 mm, hydrated lime and river sand 1:3, to carry out the test the mortar was laid on the smaller side, 0.0016 m².

The test provides the coefficient of capillary water absorption AC which is represented by a curve obtained by plotting the change in mass per unit area Q_i in relation to the square root of time t_i^{1/2}, and is calculated by linear regression using at least five points aligned with

$$Q_i = (m_i - m_0) / A \text{ en kg/m}^2 \quad [1]$$

where m₀ = mass of the dry specimen (Kg); m_i = mass of the specimen in time t (kg); A = surface area in contact with water (m²).

UNE-EN 772-11: Methods of test for masonry units. Determination of water absorption by capillarity for masonry elements, concrete, natural and artificial stone, and the initial rate of water absorption of clay bricks for masonry. The test was performed on samples of the same types of bricks. Allowed to dry in an oven at a temperature of 105 °C to a constant weight. Then left to cool at room temperature and then measure the dimensions of each of the faces which would then be submerged in the test to calculate gross area of absorption. They were then placed on small supports so that the lower part did

not touch the bottom and remained submerged at a depth of 5 mm. After the specified time, 1 minute, the specimens were removed, the surface water was dried and then they were weighed. The initial rate of absorption of each brick is calculated using the following formula:

$$C_{wi,s} = 10^3 \times (m_{so,s} - m_{seco,s}) / A_s t \text{ en kg/} (m^2 \times \text{min}) \text{ where } t = 1 \text{ min} \quad [2]$$

Where: C_{wi,s} is the initial rate of water absorption, m_{so,s} the mass after the immersion, m_{seco,s} the mass after drying, A_s the surface area and t time which is equal to 60 seconds.

Although the test is for masonry elements it has also been conducted on mortar specimens of 40 × 40 × 160 mm.

UNE-EN 1015-18: Methods of test for mortar for masonry. Part 18: Determination of water absorption coefficient by capillarity of dried mortar. Procedure: the absorption coefficient of water by capillarity was determined by immersing the cut face of the mortar specimen balanced on four supports at 5 to 10 mm height so as not to touch the bottom for a specified time with the vertical faces of the test pieces coated in paraffin. The water absorption coefficient of the 6 tested specimens was calculated, depending on the masses of the specimens after 10 minutes and ninety minutes of being deposited in the tray with water, from the following formula:

$$C = 0.1 (M2 - M1) = 1.22 \text{ kg/(m}^2 \cdot \text{min}^{0.5}) \quad [3]$$

where, C is the absorption coefficient kg/(m²·min^{0.5}), M1 mass after 10 minutes immersion M2 mass after 90 minutes immersion.

Note that while the first of the standard used (UNE-EN 15801, published recently, has been drafted by the European Committee for Conservation of Cultural Heritage CEN_TC_346, and in principle, it seems indicated to determine the characteristics of the materials when it comes to a restoration projects), the other two standards are intended to evaluate the characteristics of the materials for use in new buildings.

To find out how much water vapor from the atmosphere can penetrate materials by sorption, tests were conducted in a climatic chamber (model WEISS-WK 3) where bricks and samples of mortar joints were introduced after being dried at 105 °C, to a temperature of 20 °C and constant relative humidity of 50% at a constant weight. The oven used in the laboratory is the model IBERTEST with forced convection and a temperature range of 0 °C to 200 °C.

After the tests were carried out on the bricks, and to find out what happens with capillary rise on a brick masonry with mortar joints, tests were done

on two brick masonry walls built in the laboratory: the first one $78 \times 28 \times 100$ cm, made with solid brick tiles, and the other one $65 \times 24 \times 100$ cm, made of solid modern brick (the different width of the two is due to the two being done with the same number of bricks per course 5 in a heading bond). The walls have the same number of courses, thirteen, the same height, and the thickness of the brick is different, so it was decided to have the courses of brick at the same height and the mortar joints of different thicknesses between 5 and 10 mm, thicker for the modern brick masonry. These walls built on a sand bed of 5 cm thick, on a solid base with a waterproof sheet (Figure 1). The ambient temperature during the test was between 19°C and 21°C and relative humidity between 45% and 55%, measured with a probe type “Saveris H4D”.

In the first tests performed on the walls sand in the raft was saturated with water which rose up the wall, allowing us to take measurements of the moisture content in the walls as a result of the capillary rise. The data collection procedure consisted in drilling holes of 8 mm diameter in the brick every two rows, penetrating up to the center of the walls, and to place type “Saveris H4D” probes to measure the temperature and humidity within the holes (11).

To determine the state of saturation of the bricks and mortar, the walls were demolished in an orderly manner once the moisture absorption was stabilized. During the demolition, the bricks and bits of mortar joints were weighed, after that



FIGURE 1. One foot brick tiles wall with moisture probes, standing on a bed of sand.

they were dried in an oven which allowed to really know how much water the specimens had absorbed (bricks and mortar). While the bricks could be recovered wholly and were cleaned of the mortar, it was more laborious to obtain specimens of mortar, especially from the sides of the walls, so there is only data of the mortar of the central area walls.

Before demolition various images were captured with a FLIR ThermoCAM B29 thermal imaging camera with a thermal sensitivity of 0.1°C , measuring range temperature -20°C to $+100^\circ\text{C}$, spectral range 7.5 to $13\mu\text{m}$ and emissivity value of 0.9, for brick.

3. RESULTS AND DISCUSSION

3.1. Dimensions, apparent density and porosity of the materials

Table 1 shows the results obtained after carrying out the tests on materials and testing standards:

The porosity of the two bricks is fairly close. These values are close to those found in other studies, in which the old bricks have water accessible porosity of 30.5% and modern bricks of 26.3%, Fort (12) and within the range of porosity assessed by MOP (polarized light microscopy) of 15 to 30%, Setti (13).

As seen by the results, the two types of bricks have different apparent densities the modern brick is similar to that of the mortar. The bricks presents values below the results of other researches, though the brick tiles density is lower (1760 kg/m^3) than the modern brick (1915 kg/m^3). With the microscope MOTIC SM2-168 $500\times$ magnification and 2300 MOTICAM camera photographs have been made of the two blocks in which it can be seen that in the brick tiles the pores are larger than the modern brick (Figure 2).

3.2. Water absorption of the materials

In Table 2 are the results of absorption tests carried out on different materials according to the nomenclature and units used in each test standard.

The study of the data obtained in the above-referenced tests shows that brick tiles have the lowest coefficient of capillary absorption when in contact with a wet base (closer to the real situation). In the UNE EN 772-11 test, traditional suction (partially submerged), the initial absorption rate turns out to be the higher in the two bricks.

Regarding the test according to the standard EN 15801 it is interesting to study the graph (Figure 3) of the process shown on the graph are the values of Q_i in relation to $t_i^{1/2}$ during the six-day test. The first part in which the values are aligned make it possible to calculate AC.

TABLE 1. Dimensions, density and porosity of the materials

Standar	Dimensions (mm)			Density apparent kg/m ³	Porosity apparent %
	Length (stretcher)	Width (header)	Height (cull)		
	UNE EN 772-16			UNE EN 772-13	UNE EN 772-3
Brick tile	279	140	48	1680	28.8
Modern brick	233	108	38	1830	27.2

Standar	Dimensions (mm)			Density apparent kg/m ³	Porosity apparent %
	Length	Width	Height		
	UNE EN 1015-10			UNE EN 1015-10	UNE EN 1015-10
Lime mortar	40	40	160	1810	20.5

The first consideration, from the test is that, in the two types of bricks in the first stage the water absorbed is very similar in proportion, but from a certain point and for a short period the brick tiles specimen absorbs less water and in a third phase the amount of both tends to a horizontal asymptote. In the first stage the brick tiles absorbs more water which also happens in the suction test according to UNE-EN 772-11. As for the mortar it is apparent that water absorption is slower, the first part of the graph is less steep and less water is absorbed.

3.3. Capillary water absorption in walls

The results of tests are to be compared with the results of water absorption of the materials in the brick walls. First, the data of humidity probes taken during the months that have lasted the test have been transferred to Figure 4 (brick tile wall) and Figure 5 (modern brick wall). In them you can see how the process of capillary absorption develops very rapidly up to the third probe and slows down at the probes 4, 5 and 6. It's interesting the behavior of row 3 in both walls, though it ends up reaching the same moisture content, it takes longer in the modern brick - five times - to achieve it. This would

be because of its lower initial absorption rate compared to the brick tiles.

Moisture variations of the probes located in the upper rows are influenced by the conditions inside the test room in which it is performed, because of hygroscopic variations absorption / desorption of water vapor in the surrounding atmosphere. Observing the data of the probes in Table 4, before demolition, it's clear that the temperature is higher the lower the relative humidity and this process is very similar in the two walls. This happens due to desorption: the higher the moisture content of the wall, the higher the humidity difference between the external environment and the wall, so the desorption is greater, which causes the temperature to drop.

This information is important because the same thing happens on the surface, and images taken with a thermal camera can clearly show that the temperature at the base of the walls is lower than the area above where it is similar to that of the environment, 1 to 2 tenths of a degree lesser. In Figure 6 are the elevations of the walls before demolition. The thermal image is attached to the elevation of the two walls: brick tiles on left and on the right modern brick. The lower the temperature the higher content of water in the wall and this corresponds with the data from the probe in Table 3. If the image is

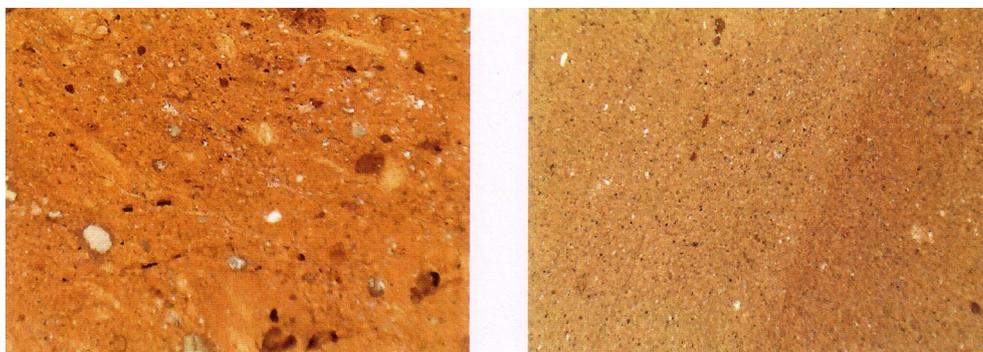


FIGURE 2. On the left a section of a brick tiles and right section of a modern brick made with microscope with 100x magnification.

TABLE 2. Results of water absorption tests of the materials according to UNE

Time	UNE EN 15801		UNE EN 772-11	UNE EN 1015-18
	6 days		1 min	10 to 90 min
	Q_i	AC	$C_{wi,s}$	C
	kg/m^2		$kg (m^2 \cdot min)$	$kg (m^2 \cdot min^{0.5})$
Brick tile	59.01	0.22	1.6	–
Modern brick	63.26	0.18	0.9	–
Lime mortar	20.47	0.12	0.64	1.22

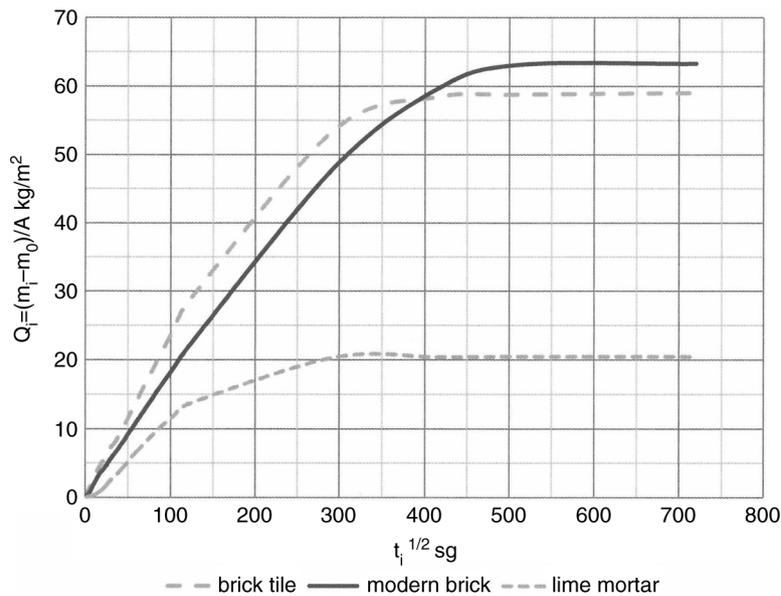


FIGURE 3. Graph of the values obtained from the test UNE EN 15801 of the materials.

captured from a shorter distance, you can see the difference in water content between the bricks and the mortar.

As noted above the measurement of the moisture with the probes provides information about the process of capillary water rise but provides no information on the amount of water absorbed, as the probes indicated 99% relative humidity when the brick had absorbed less than 10% of the total water that it may contain, as shown by the tests. However, this measurement allows us to know the timing of the capillary rise process as well as the oscillations due to changes in temperature and the humidity in the environment.

To understand the process capillary moisture rise, the walls were demolished and brick and mortar specimens were tested, procedure already described, and thus know the amount of water absorbed. The data obtained is reflected in the following diagrams by colors and figures that represent the elevations of the two types of walls, it's in l/m^3 to be able to compare the data from the two walls (Figure 7). These

units have been chosen since Peixoto (13) studied the capillary absorption in walls as W_{sat} saturation moisture content in kg/m^3 , and these units can better compare to the results obtained of the densities of the three different materials. Because we are using water I has been adopted as a unit instead of kg.

As can be seen by comparing Figures 6 and 7, the image of the thermal camera is indicating quickly and fairly precise the areas of the wall where the moisture content is higher, thus demonstrating that the imager is an adequate tool for diagnosis of moisture problems in buildings. In both cases, on brick and mortar, it can be seen that in the upper area the material is not completely dry but has a small amount of water, due to ambient humidity. To better compare the results of studies of the materials and the walls we have moved data from all tests to Table 4 in which the moisture content is expressed in l/m^3 . In one column test values according to UNE EN 15801, located on the right UNE EN 772-11 tests which have also been made with mortar specimens, even

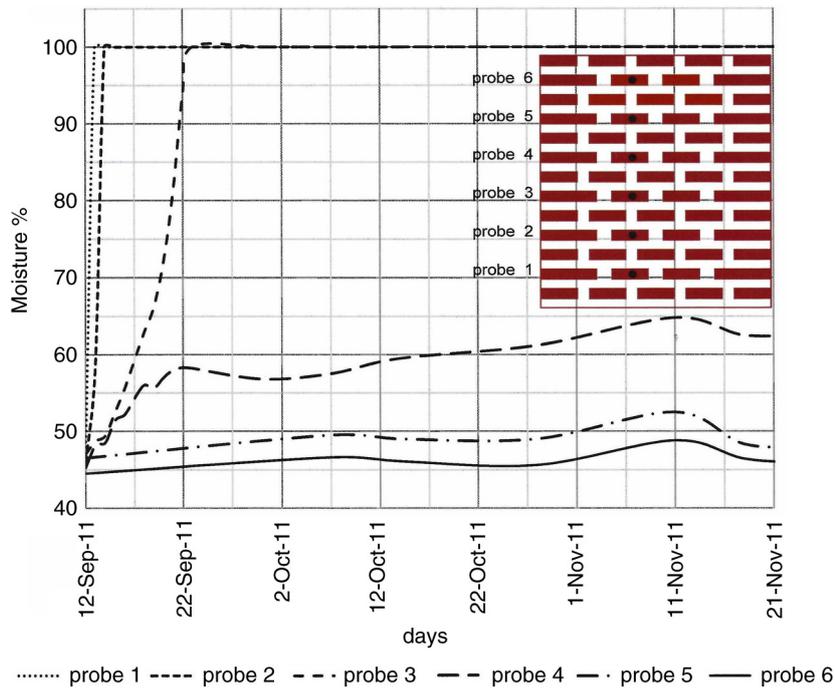


FIGURE 4. Brick tile Wall. RH values (%) of probes placed in the holes of the brick courses.

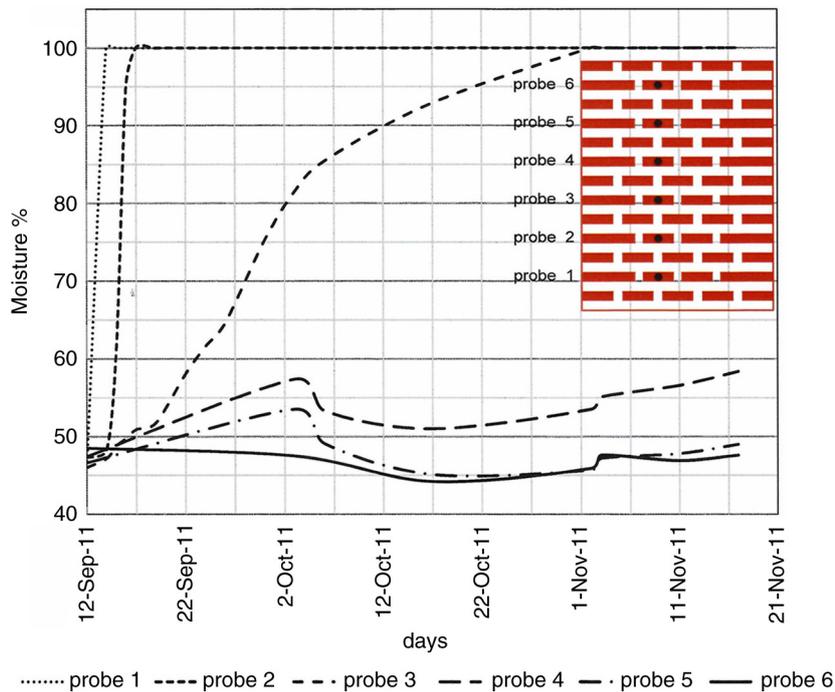


FIGURE 5. Modern brick wall. RH values (%) of probes placed in the holes of the brick courses.

though it is a test meant for bricks. In the following columns, with mean values, are the moisture content of the lower courses of bricks and mortar joints of the two walls, being the ones closest to

the wet base. The last column shows the values of the climate chamber test indicating the water content of the material because of the ambient water vapor.

TABLE 3. Temperature and relative humidity from the probes from the walls

		brick tile		modern brick	
		T °C	Hr %	T °C	Hr %
course 12	probe 6	22.1	40.1	22.2	40.1
course 10	probe 5	21.9	44.8	22.0	41.5
course 8	probe 4	21.4	67.3	21.3	61.9
course 6	probe 3	21.0	99.9	21.0	99.9
course 4	probe 2	19.9	99.9	19.9	99.9
course 2	probe 1	19.9	99.9	19.9	99.9

The tests whose results are closer to that of the walls are the ones made according to the UNE EN 15801 standard and the absorption value

indicating the process in brick masonry is of the brick because as can be seen the values of water capillary absorption by mortar specimens is different in the two walls even when they were executed at the same time and with the same type of mortar. Values of water absorption in the lower courses are superior in the tests on walls than in the tests performed under the UNE standards which is somewhat predictable as the brick and mortar specimens of the wall are confined, and the specimens materials present only one side in contact with the moisture source and the rest in contact with air, however, the results of tests of the standard UNE 15801 have a very similar proportion: in the case of brick tiles they absorb 11% more water in the wall and the modern brick absorbs 12% more water.

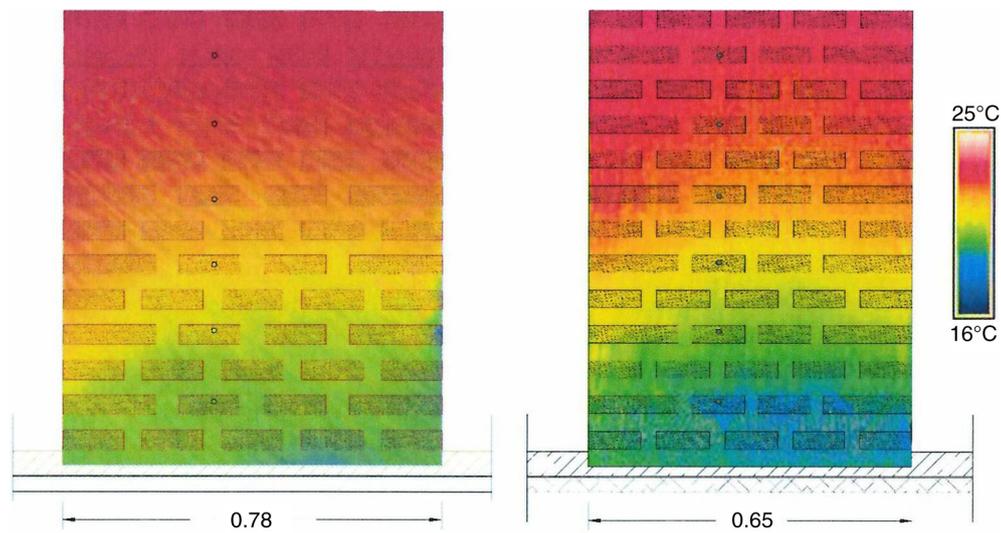


FIGURE 6. Images from the thermal camera: brick tiles on left and on the right modern brick.

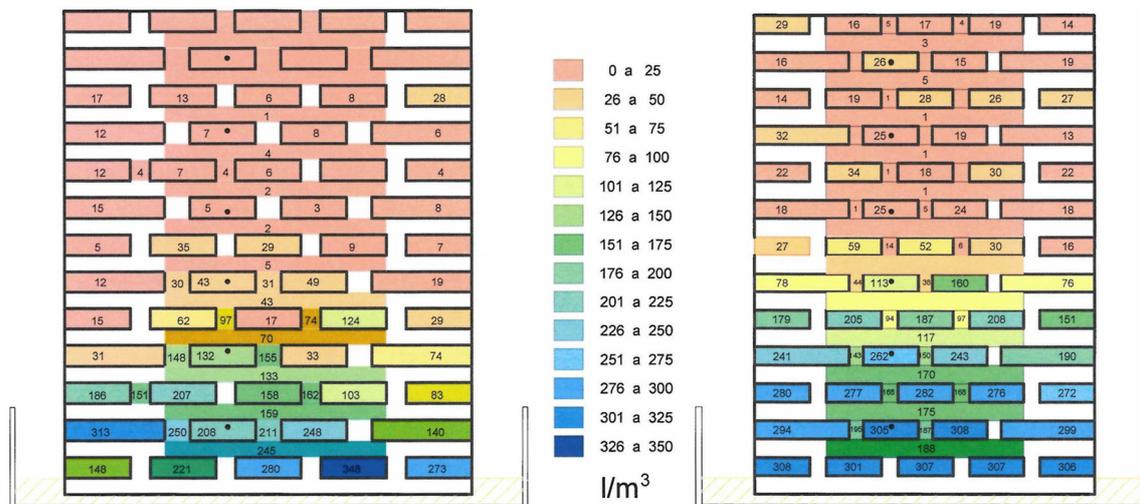


FIGURE 7. Moisture content in the bricks and mortar specimens after demolition (l/m^3): left brick tiling wall and right wall modern brick.

TABLE 4. Results of the various tests done on the materials

	UNE EN 15801		UNE EN 772-11		test brick wall		test climatic chamber T = 20 °C Hr = 50%
	6 days		1 min		brick tile	modern brick	
	W_{sat}		W_{sat}		course 1, bed joint 2		
	l/m^3		l/m^3		W		
					l/m^3		l/m^3
brick tile	228		33		254		2.5
modern brick	271		24		306		9.0
lime mortar	146		16		188		1.3

If the values in the right hand column of the table are compared with the values of the stretcher course and bed joints it can be seen that the moisture present is not due to the water rising through capillary absorption and reaching this point but due to the water vapor in the ambient that entered and condensed in the materials.

4. CONCLUSION

When comparing the results of tests conducted on the material: bricks and mortar and brick walls:

- It has been shown that tests on bricks made according to the standard “UNE-EN 15801 Conservation of cultural property - Test methods - Determination of water absorption by capillarity” can obtain information representing the behavior of the brick walls against the rise of capillary water.
- The tests on materials according to UNE EN 15801, UNE EN 772-11 and tests done using moisture probes for the process of capillary rise of water in walls indicate that the modern brick absorbs more water than the brick tile and mortar at the end of the process, but water absorption in brick tiles is faster at the beginning.
- The mortar has different absorption values in the two walls suggesting that absorption value of the brick, which is the highest, is more relevant.

With the various tests which were carried out it would be possible to assess the level reached by ascending capillary water from the base of a brick wall of a building using the data that can be obtained with:

- Moisture probes that permit the determination of how far the capillary water has risen, and is approximately where the probe inserted into the wall presents the same data as the one on the outside of the wall.
- Thermal images, since the surface temperatures are related to the moisture content of the wall.
- The tests according to the EN 15801 with which information about absorption of the material is

obtained. One could make the extraction of large brick specimens thick x thickness x at three different levels, test them, and calculate the water content of the wall.

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