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To cite this article: María Soledad Camino-Olea *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **603** 032040

IOP Conf. Series: Materials Science and Engineering **603** (2019) 032040 doi:10.1088/1757-899X/603/3/032040

Test evaluating the effectiveness of hydrofugation in the protection of handmade brick walls against rainwater

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Abstract. The soaking of rainwater into brick walls of cultural heritage can be the source of various injuries due to the processes of migration and crystallization of salts, the formation of ice inside them in rainy and cold areas, as well as the growth of organisms in humid areas. The ancient handmade bricks and the mortar used in the construction of these walls are porous materials in which water penetrates easily and is therefore very exposed to these deterioration processes. One of the most usual solution to avoid it is to apply a surface treatment by water-repellent products to prevent the entry of rainwater. The handmade bricks are orthohedrons with more or less flat faces, which do not present grooves, recesses or perforations like mechanical bricks, meaning that at the interface between brick and mortar there may be discontinuities that facilitate the entry of rainwater. The values of water absorption and brick and mortar are high, which also favours the entry of direct rainwater through the materials. The hydrophobic facade treatments are usually applied by projection on the surface of the facade and the discontinuities that the surface of the facade presents could have the result that the application of the water repellent would not be effective. For this reason, a test procedure was designed and executed on four walls built in a garden. Above them, water was projected imitating rain. The data was captured by infrared thermography and humidity probes, in order to analyse the efficiency and hydrophobicity and to study if the test method was valid.

1. Introduction

The entrance of rainwater into brick walls is the source of many of the injuries that occur in them, especially those built with bricks and mortar made by hand, which absorb large amounts of water. The entrance of rainwater can be avoided me by a surface treatment [1]. Research on masonry walls, have come to the conclusion that in the process of entry of rainwater, is determining the sortivity of bricks [2], even have set up the time in which a brick works can absorb water in function from: the sortivity, the intensity of the rain and the wind speed [3]. Therefore, it can be deduced that this characteristic is also determinant in the effectiveness of the water-repellent products.

In the current regulations for the facades of brick, as the Technical Building Code [4, 5], is estimated to be the feature of the brick that allows to evaluate the capacity of a factory to prevent the entry of rainwater, the initial rate of water absorption also taking into consideration the rainfall areas and exposure to wind. Therefore, it is necessary to analyze the influence of the absorption rate on hydrophobic processes.

Other research examines both the sortivity and porosity on the penetration and filtration of water in walls with boards fine both experimentally as with numerical analysis [6]. All these studies explores the behavior of the wall according to the characteristics of the brick. Factories oldest ranging to analyze are formed by bricks and together thick mortar so it is important to analyze the brick as the mortar, as well as the interface between the two materials. These issues have been studied by researchers as Delgado [7] who stresses the importance of the brick-mortar interfaces in the movement of water into the wall, mainly which rises through capillary action. Other authors understand that implementation of the brick work has a clear impact on the movements of water in the wall [8], and come to the conclusion that when the brick is not sufficiently moistened, before the construction of the wall, can absorb water, which is required for the setting of the mortar of the board and as a result a smaller union with brick there is what allows the water to enter through the interface.

The bricks and the mortar present different characteristics, and their properties can vary across the same wall because of their handmade production. The bricks were formed manually [9] and fired in simple ("Arab") kilns, and the mortar was kneaded on site with lime and sand, where the lime was processed on site [10]. Moreover, variations in humidity and temperature during construction can affect the setting of the mortar and brick-mortar adhesion. The consequence of these variations is that these walls can have very different characteristics, particularly with regard to water intrusion, so the level of deterioration can vary over a façade (figure 1).

Figure 1. Photograph of a Mudejar-style church facade, where the differences in the states of the brick and mortar joints can be observed

In the theoretical analysis carried out on the entry process of rain water it's complex to take into account the heterogeneity of this type of wall, by what results may differ significantly from the actual situation. For this reason, we estimate that to analyze this process, as well as the effectiveness and duration of the treatments by means of surface-applied water repellents, a good option is to carry out tests on brick walls, executed in a similar way to those of the old buildings, and to project water over

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them imitating the rain while monitoring the process, to know the processes of water penetration and the relationship with the characteristics of the aforementioned materials. The process that has been designed would also serve to carry out "in situ" tests of buildings of the cultural patrimony in which hydrofugers are used as protection.

2. Experimental procedure

Four separate walls were constructed in the garden of the Escuela Técnica Superior de Arquitectura (Higher Technical School of Architecture) of at the Universidad de Valladolid (UVa), Spain. To prevent the walls from absorbing moisture from rain and the ground below them prior to the tests, the walls were protected with a structure consisting of polycarbonate sheets supported by two steel IPE beams (figure 2). The walls were built in an area where direct exposure to the sun was very low so that evaporation due to solar radiation was negligible.

To analyse the importance of the characteristics of the brick in the entry of water, two types of brick were used. The first type was handmade (hmB), or tiled, brick reclaimed from demolitions of structures with an age of approximately 100 years and average dimensions of 279 x140 x 48 mm^3. The second type was modern, solid bricks (sB) manufactured by extrusion with dimensions of 230 x107 x 30 mm^3 [11]. The bricks were obtained from a ceramics works located near where the handmade bricks had been originally located to achieve a similar chemical composition (Figure 3). Of the four walls that were constructed, walls 1 and 3 were erected with solid brick (sB) and walls 2 and 4 were erected with handmade brick (hmB) (figure 3).

The four walls were constructed with the same type of mortar, which consisted of washed river sand and lime hydroxide in a ratio of three to one [10]. The thickness of the mortar joints resulted in a ratio of mortar to brick of 48% in the walls containing hmB and 53% in the walls containing sB. To evaluate the effectiveness of waterproofing, it was applied to walls 2 and 3.

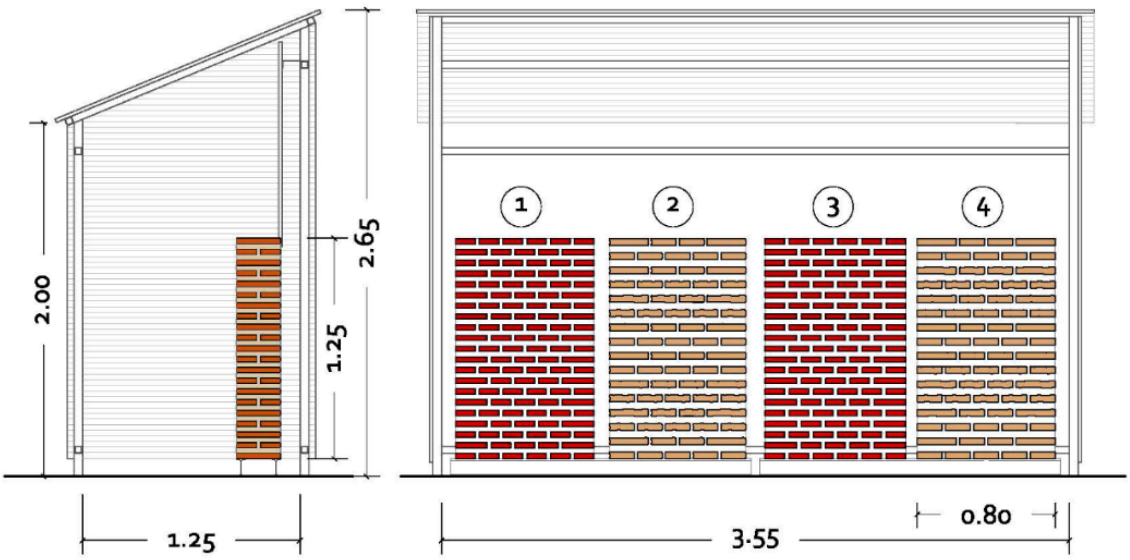

Figure 2. Section and elevation views of the test walls and the protective structure

Figure 3. Photographs of actual bricks used in the tests: (from left to right) handmade brick (hmB), modern brick (sB) and mortar test sample (20 cm rulers included for scale)

2.1 Physical characterization of materials
They were conducted several tests on the basis of its relationship with the absorption of water to six bricks of each type and six test specimens of mortar of dimensions 160 x 40 x 40 mm3 [12]:

- The dry bulk density was measured according to the procedures specified in EN 772-13 [13] for bricks and standard EN 1015-10 [14] for mortar.
- The porosity was tested according to standard EN 772-3 [15] for brick and standard EN1015-10 for mortar.
- The absorption was measured by immersion in cold water according to standard EN 771-1 [16] for brick and mortar. The absorption values were obtained as a percentage of weight, as dictated by the test standard, and by volume, in litres of water absorbed per cubic metre because this metric allows a more relevant comparison of the results.
- The initial rates of absorption of water by the bricks and mortar were measured according to standard EN 772-11 [17].

The sorptivity was measured by following the procedures described by Gummerson [18] and by Hall [19]. The six specimens of each type of brick and mortar were cubes 40 mm in length. The samples were first dried in an oven until the weight reached a steady value, and then four faces were coated with paraffin, leaving two parallel faces with no coating. The specimens were placed in a container of water with one untreated face facing down and supported on cylindrical glass rods so that the face was exposed to the water. The water level in the container was maintained throughout the test. The eighteen samples were tested simultaneously so that the environmental conditions were identical.

2.2 Tests on sample walls
Four separate walls 0.80 m wide by 1.25 metres high were constructed, it was built on header bond. This form of brickwork was chosen because it was the most common type used in the historical buildings in the where the handmade bricks were located (figure 4).

To allow the mortar to set and the water used in construction to evaporate, the walls were allowed to dry for a period of two months prior to the start of the tests. Then, a water-repellent substance containing a combination of silanes/siloxanes in organic solvents that allows the diffusion of water vapour in both directions was applied. The surfaces of the walls were cleaned, and two coats of the water-repellent substance were applied by spraying 0.5 l/m^2 per coat at an ambient temperature between 20º and 21º C. The second coat was applied while the first coat was still wet.

The water-repellent coating was allowed to dry before the water intrusion tests were conducted. The walls were separated with polycarbonate sheets to prevent the simulated rainfall on one wall from dampening the adjacent walls. A water spraying system was designed based on the procedures of standard EN 13051 [20]. A polycarbonate sheet 1.10 metres high was placed above the wall so that water running off of the sheet would drain onto the upper part of the. A perforated vertical tube was used to spray water at a rate of 1 l/m^2 per minute “figure 4”. To analyse the water absorption process in the walls se two different systems were used:

- Moisture in the walls was measured using Testo Saveris H4D (accuracy ± 0.2 ºC) humidity probes, which were monitored using a Testo Saveris 868 base. The probes were inserted in holes 8 mm Ø by 10 cm deep drilled at various points in the mortar and the brick at the rear surfaces of the walls [21].
- Images of the rear surfaces of the walls were taken with a FLIR Therma CAM B29 thermal imaging camera with a thermal sensitivity of 0.1° C, a measurement range of -20º C to +100º C, a spectrum range from 7.5 to 13 µm, and an emissivity of 0.9, corresponding to the brick [22].
- Visual inspections were conducted to determine that water had permeated to the rear surfaces of the walls (wet brick and mortar have a darker colour, so wet and dry areas are clearly distinguishable).

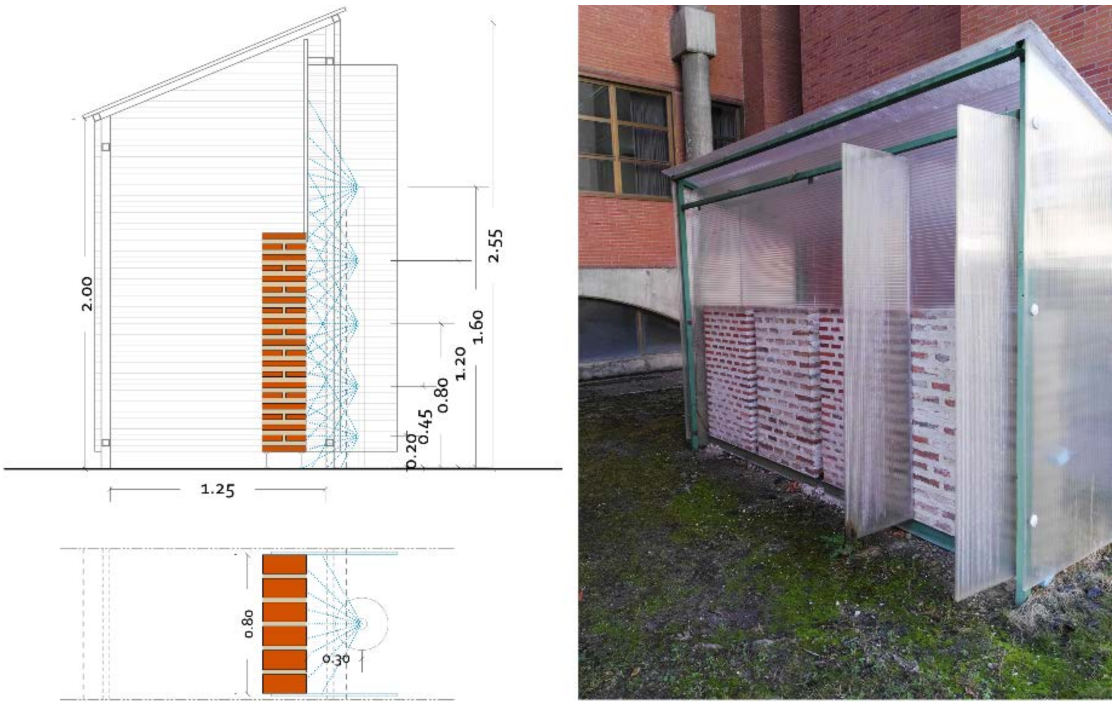

Figure 4. Diagram and photograph of the rainfall simulation system

The simulated rainfall was activated for several hours. The tests were performed on different days, and thus, the humidity and the ambient temperature were also monitored. In the tests conducted on the walls not treated with the water-repellent coating, the tests were concluded when water permeated to the rear surfaces. For the treated walls, the simulated rainfall was sustained for five hours on three consecutive mornings. No penetration of water to the rear surfaces was observed at the end of the third day.

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3. Results

The tests, of physical type, were carried out in an environment with a temperature of 21 and 23ºC and a humidity between 40% and 45%. The values of the results of all the tests carried out have been transferred to table 2. Since the dispersion in the results of some tests is important, and confirms what was previously indicated about the heterogeneity of the materials, in the table, below the average value, the minimum and maximum values appear, because this figure has seemed more significant than that of dispersion.

Table 1. The results of the tests

			Material		
physical properties	units		hm B	s B	mortar
Dimensions	mm		279 x 140 x 48	230 x107 x 30	40 x 40 x 160
Dry bulk density	kg/m^3	mean	1.783	2.067	1.859
		min-max	1734 – 1.836	2016 - 2117	1.858 - 1860
Porosity	% (en peso)	mean	26,6	17,1	20,0
		min-max	25,3 – 28,2	14,6 – 20,7	19,3 – 19,7
Absorption W_(s)	% en peso	media	14,9	8,2	11,29
		min-max	14,0 – 16,3	6,3 – 10,2	10,87 – 11,87
Absorption	l/m^3	mean	266	163	210
		min-max	253 -282	122 - 198	197 - 215
initial rates of absorption of water (1 min)	$kg/(m^2xmin)$	mean	1,6	0,58	0,6
		min-max	1,1 – 2,3	0,46 – 0,75	0,5 – 1,0
absorption of water capilariy	$kg/(m^2.min^{0,5})$		--	--	1,22
Sortivity	$mm.min^{1/2}$	mean	1,088	0,684	1,335
		min-max	0,317-1,467	0,404-1,029	1,280-1,397

3.1 Test of four walls

3.1.1. Results of monitoring by means of probes. The moisture values measured by the probes are shown (figures 5 and 6). The results for the walls constructed with the same type of brick are shown in the same figures. The illustrations to the right of the graphs show the locations of the probes in the walls. The horizontal axis shows the time in minutes, and the vertical axis shows the percent humidity. The dashed lines represent the values measured by the probes located in the mortar beds, and the solid lines represent the values measured by the probes located in the bricks. The thick, dark green, dashed line shows the ambient humidity. These graphs show the differences in moisture between the walls with and without waterproofing: the moisture levels in the treated walls remained approximately constant, and the moisture levels in the untreated walls increased. It can also be observed that the maximum moisture levels occurred later than in the walls constructed with modern bricks than in the walls constructed with handmade bricks.

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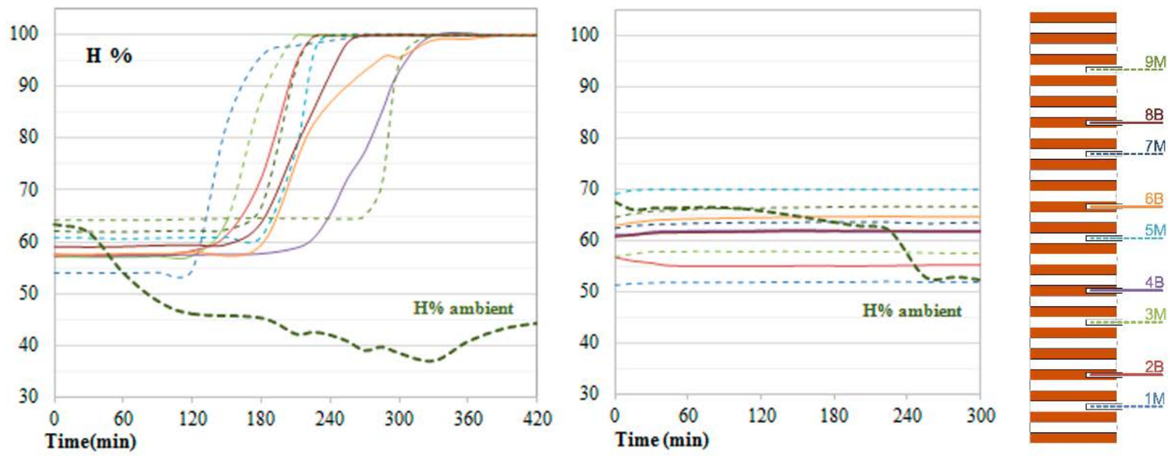

Figure 5. Measured moisture levels for sB walls: wall 1 (left) and wall 3 (right)

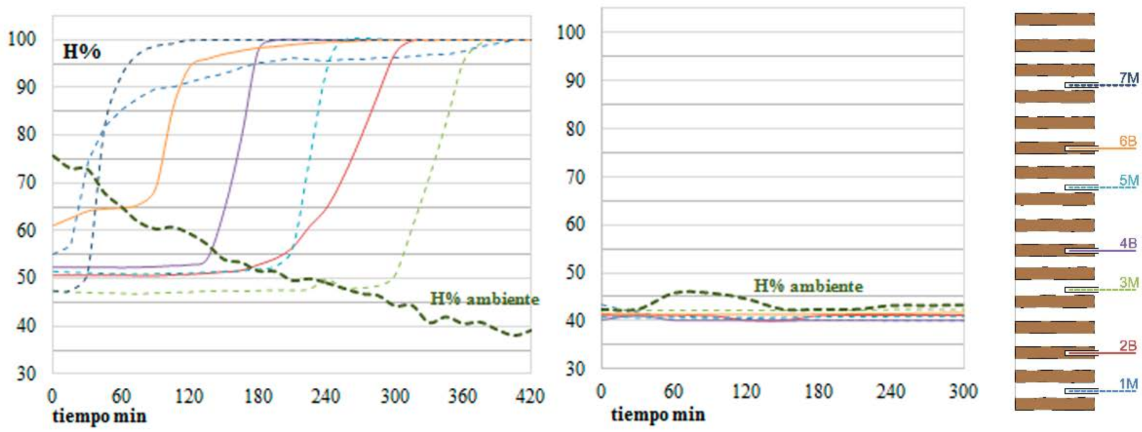

Figure 6. Measured moisture levels for hmB walls: wall 2 (left) and wall 4 (right)

3.1.2 *Thermal images.* Thermographic images. On the walls where the repellent is designed are not appreciated temperature changes with the thermal imaging camera by the batter, so it only presents a succession of two walls thermographic images not water-repellent. Throughout the trial, since it has been in an outside, the temperature of the atmosphere has changed and therefore the surface temperatures, by which each image has a different scale so you can see better progression of moisture toward the batter's l wall. At the bottom it has indicated the time that has passed since the beginning of the essay (figures 7 and 8).

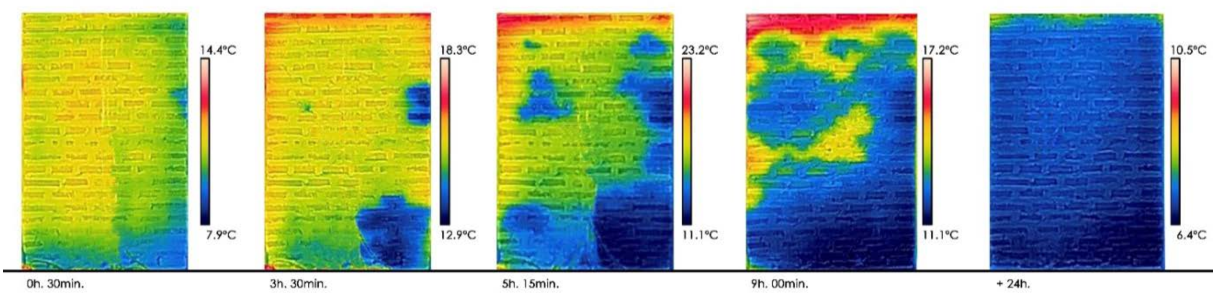

Figure 7. Successive thermographic images of the rear surface of wall 1 (sB)

As can be observed by the difference in the surface temperature of the rear surfaces of the walls, the water reached the rear surfaces and then underwent desorption by evaporation, which reduced the surface temperatures in the areas with greater moisture after the moisture values reached 100%. The thermographic images do not reflect the same process of penetration of the moisture, as was indicated by the probe measurements. The water continued to permeate to the rear surface after the simulated rainfall was stopped. It can also be observed that, similar to the trend observed with the moisture probes, the water penetrated to the rear surface of the hmB wall faster than in the sB wall.

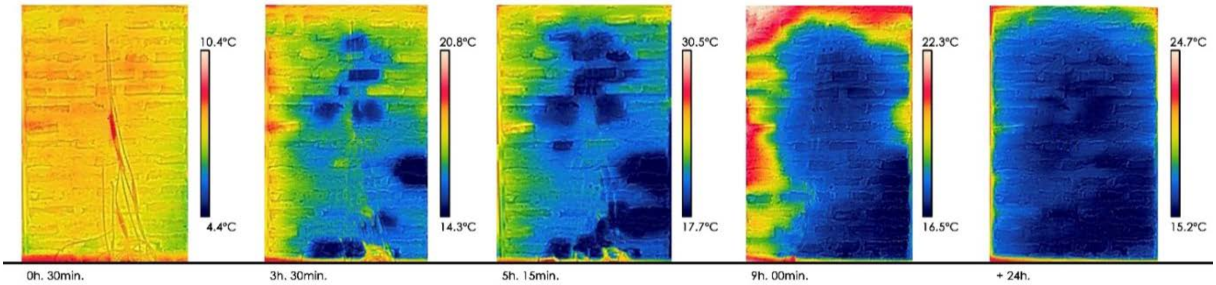

Figure 8. Successive thermographic images of the rear surface of wall 4 (hmB)

4. Discussion

Handmade bricks have a high porosity, as well as absorption, initial rate of also high water absorption values, while the value of the sortivity can be considered as a means of comparing the values of the studies of Hall. The manufactured solid bricks have values porosity, water absorption, rate initial absorption of water and sortivity, below the of hand-made bricks. The dispersion of values is smaller. The most significant difference is in the test of the initial rate of water absorption that is 36% of the value of the brick made by hand.

The characteristics of mortar: the values of apparent porosity and water absorption by immersion presented values between the two types of brick, initial absorption rate presents a value substantially equal to the brick extruded and the value of the sortivity is the highest of the three materials, twice the value of the sortivity of the extruded brick, which confirms the idea that in this type of wall entry of rainwater studies cannot be made without considering the characteristics of mortar.

Comparing the humidity values on the walls non treated with the water-repellent coating, we can check up on that the wall wetting is produced in a more uniform and slower way in an extruded bricks wall, which is consistent with the values of the absorption tests that present less dispersion is this type of brick than in the handmade brick, as well as lower values in the different tests. The first probe that measures a 100% of humidity is situated in a handmade bricks wall, when 120 minutes have passed from the beginning of the test in a mortar joint. But the first probe that measures a 100% of humidity in an extruded bricks wall is situated when 225 minutes have passed from the beginning of the test. The projected water goes though the mortar more easily. The mortar is the material with the highest value of sortivity.

Graphs that represent the humidity measured by the probes located in the wall of brick made by hand are more separated from one another in the extruded brick wall, indicating that the process of penetration of water has a greater dispersion in this wall, dispersion, reflecting the results of the tests carried out to randomly selected bricks.

On the walls in which it has been projected the repellent is not observed variation in humidity probes measures which can be interpreted as it has not crossed the water repellent barrier.

As to the images of the thermographic cameras, it can be seen that the water doesn't follow a path sharp by the joints or bricks. As a consequence of this, the back part doesn't get wet uniformly. The humidity is higher in the lower part because of the gravity effect and because the wall is sustained on steel profiles that don't let the water go through.

Related to the apparition of the water in a liquid shape on the back of the walls without waterproof treatment, it also occurs not uniformly. On the perforations of the probes is where the water entrance, seen as drops that run down the wall, first can be seen. This is obviously caused because the water has to overpass a lower wall thickness.

The dispersion in the results of the tests of the material are reflected in the graphs of the humidity probes and in the thermographic images, which can show that the theoretical analyzes provide valid results when the material is very homogeneous, that is to say mechanical bricks with quality control and thin mortar joints. In old brick factories with handmade bricks and thick mortar joints of lime and sand, the results of theoretical analysis may not be as reliable.

5. Conclusions

One of the most obvious conclusions is that the water repellent applied on the front surfaces of two of the walls prevented the water from penetrating. This type of treatment can protect brick walls from damage caused by water intrusion, regardless of the characteristics of the bricks or the mortar.

The degree of water penetration depended on the characteristics of the materials: penetration was slower in the modern brick walls, which had lower values of water absorption, initial rate of absorption, and sorptivity. The sorptivity was higher in the mortar than in the bricks; the probes located in the mortar measured 100% humidity before the other probes did.

The dispersion in the results of the tests of the construction materials was reflected in the measurements from the moisture probes and in the thermographic images, where there was also dispersion in the results. Theoretical analyses provide valid results when the materials are very homogeneous, that is, bricks that are manufactured with quality controls and laid with thin mortar joints. In older brick walls with handmade bricks and thick, lime-and-sand mortar joints, theoretical analyses may not be applicable.

The mortar sorptivity was very high, and the proportion of mortar in the wall surfaces was high, so it is clear that the characteristics of not only the bricks but also the mortar must be considered.

The system that has been used to perform the test using probes and thermal imaging camera can be applied to walls of buildings where you could leave a few test probes to check if the effectiveness of the water repellent decreases since with the passage of time it is usually necessary to perform another application.

Acknowledgement(s)

The tests were carried out with the aid granted by the Ministry of Economy and Competitiveness of Spain to Research Project entitled "Protection against moisture in old brick masonry walls. Study of the use of repellents in their restoration" BIA2010-19245 in the construction laboratory of the Escuela Técnica Superior de Arquitectura de la Universidad de Valladolid.

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