Evaluation of the Behaviour of a Macroporous Mortar Coating with Respect to Rising Damp

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Abstract

Brick masonry walls in Cultural Heritage buildings often have problems caused by rising damp. One solution is to coat the walls with repair mortars, including macroporous mortars. Their function is to ensure that the wall has a lower moisture content than without the coating to reduce deterioration, prevent efflorescence and prevent damp stains. This article presents the conclusions reached on the behaviour of macroporous mortars with regard to water absorption by capillary action and the drying process, by means of laboratory tests carried out on brick and mortar specimens of a similar composition to the old walls, coated with macroporous mortars. From the study it can be concluded that these coatings can help to maintain a lower level of humidity in the masonry before reaching saturation.

Keywords: *historic buildings, brickwork, restoration, dampness, macroporous mortars*

1. Introduction

In historic buildings constructed with handmade brick walls, one of the most frequent injuries is the deterioration of the masonry and the coatings at the wall starts as a result of the actions caused by water rising by capillary action. The rise of water in the walls depends on the water table, the type of soil, the capillarity and/or porosity of the masonry, and the evaporation that occurs on the outer surface of the façade, which varies according to temperature, relative humidity and air movement [1] and it is important for the conservation of Cultural Heritage to be able to determine the water content [2] and to study the processes that allow the water to be eliminated and prevent deterioration.

Water rising by capillary action causes material degradation phenomena due to freeze-thaw cycles and crystallisation of soluble salts, either on the exterior surface, efflorescence, or inside the wall, crypto-efflorescence, which, over the years, deteriorates the start of the masonry [3, 4], as well as causing damp stains [5].

The presence of water in the pores of the components of these walls: handmade bricks and mortar, not only causes the degradation of the walls but also negatively affects the thermal conductivity, since the materials with which the old walls are constructed have a high capacity to absorb water [6, 7] and there is research in which it has been estimated that 1% water content can increase thermal conductivity by up to 5%, depending on the characteristics of the materials [8]. It also affects the mechanical resistance of walls designed as part of the resistant structure of buildings, since, at the start of the walls, where the loads are highest, capillary rising damp causes a reduction in the load-bearing capacity [4]. In addition to these damages, there are also aesthetic damage, which often significantly deteriorate the image of buildings [4].

This is a recurrent problem with a great impact on the world's architectural heritage [9], so research in this field is extensive and diverse and has focused on the analysis of different systems that allow the wall to remain dry or, at least, reduce the water content. Among the systems being used [4] are those that try to minimise the presence of water in the ground, lowering the water table by draining the soil, or accelerating the drying of the walls with ventilation [10, 11] below the level of the surrounding ground [12] and methods that act directly on the masonry, creating physical and/or chemical barriers, or using electrical systems [13, 14]. These systems are preferably used on walls with exposed material; stone or brick, where it would not be possible to modify the image of the facades with coating. There is also research that focuses on analysing the durability of old bricks [15] in order to find systems that facilitate their conservation.

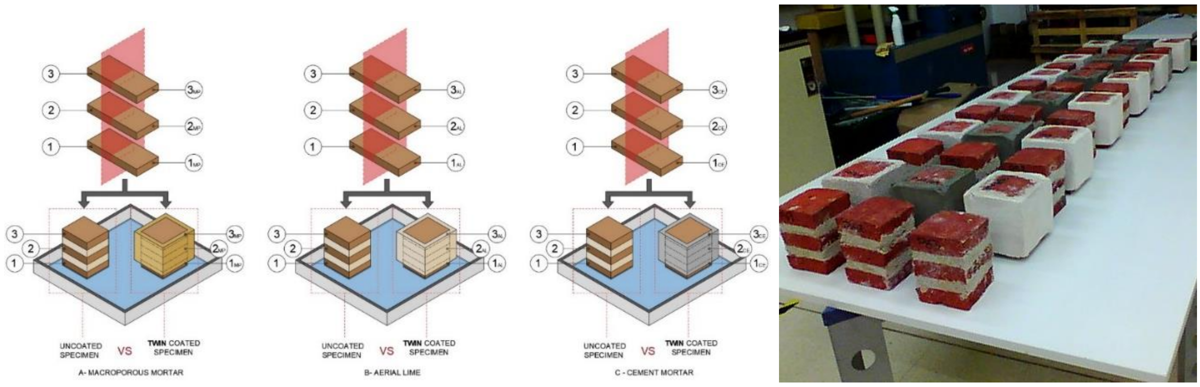
When walls are coated with mortar, research is directed towards the type of mortar used and its composition, seeking to prevent water rising by capillary action in the case of joint mortars [16, 17], or to facilitate the drying of the wall in the case of coating mortars. Studies have shown that the characteristics of the facing mortar are key factors in controlling the height of rising damp and the amount of subsequent evaporation [18-21] and that mortar substrate compatibility is an important factor [22]. For this reason, hydraulic lime mortars with different types of additives, such as lapilli or volcanic ash [23] or even gypsum [24], are currently used. More recently, the addition of natural and artificial fibres [25], and other additives such as sodium silicate are being used. Recycled aggregate material [26] or metallic waste is also being used to obtain mortars that generally have a much higher porosity than other mortars [27]. The use of these mortars in wall coatings can accelerate the drying process and, consequently, help to keep the walls looking better, preventing or reducing the precipitation of salts, traces of moisture and stains, limiting the loss of load-bearing capacity and thermal insulation.

The aim of this study is to assess the behaviour of handmade brick and aerial lime mortar masonry coated with a hydraulic lime repair mortar with high porosity against capillary rising water, by means of laboratory testing of samples of handmoulded bricks and thick joints of aerial lime mortar, imitating the construction of the old masonry. In order to better evaluate the performance of this mortar, the same type of test will be carried out on samples coated with the two most commonly used types of lime and cement mortar, so that the performance of the repair mortar can be compared with that of the other two types of mortar.

2. Methodology and Materials

In order to analyse the moisture behaviour of brick masonry coated with a macroporous repair mortar, capillary absorption and drying tests were carried out on samples similar to samples of a wall of a historic building, for which the samples were made with handmoulded bricks with aerial lime mortar joints [28], with a thickness of 21 to 22 millimetres. The joint thickness was determined based on previous research [29].

This analysis was carried out indirectly, comparing the behaviour of coated and uncoated samples, which we will call "twins", since each coated sample and its twin are made with the same three bricks cut in half: one sample is made with three half bricks and the other three half bricks are used to make the "twin" sample ‘Figure 1(a)’. Once the samples had been made, half of them were coated with the three types of mortar indicated, one third with each type of facing, and the testing campaign began.



(a) (b)

Fig. 1. (a) execution of the "twin" specimens. Uncoated on the left and coated on the right (b) specimens.

2.1 Bricks

The first step was the selection of the bricks with which the test pieces were to be made, for which 80 bricks were acquired from a ceramics company that moulds bricks manually. Subsequently, tests were carried out to determine the dimensions and water characteristics of the bricks, as these were the most significant for the study to be carried out. The tests carried out and the testing procedures were as follows: dimensions according to the procedure of standard EN 771-16 [30], density according to EN 772-13 [31], water absorption according to EN 772-21 [32] and initial capillary water absorption rate according to EN 772-11 [33].

The following equipment was used to dry, weigh and measure the bricks and specimens:

- drying oven model ES-6 from Ibertest with a power of 900W,
- Cobos industrial scale, model D-17 CDKi, up to 17 kg and an accuracy of 1.0 g. Automatic internal calibration,
- digital caliper Mitutoyo model CD-12 "AX, measuring range 0-300 mm, minimum value 0.01 mm.

The test results of the selected bricks have been transferred to (table 1).

Tab. 1. Results of the tests carried out on the bricks from which the specimens were produced.

	Dimensions EN 772-16			**Density**	**Water absorption**	**Initial rate of absorption**
	length	**width**	**thickness**	**EN 772-13**	**EN 772-21**	**EN 772-11**
	mm	mm	mm	Kg/m^3	%	$Kg/(m^2 \cdot min)$
Mean value	232	112	36	1,855	10.9%	1.73
Standard deviation	1	1	0	13	0.2%	0.11

The greatest variation in values is found in the initial rate of water absorption, a decisive characteristic in determining the capacity of the bricks to allow water to rise by capillary action. This fact led to the establishment of three groups of bricks, according to this absorption rate, and the criterion was set, in the execution of the brick samples, to place at the base the bricks with the highest initial absorption rate, with an average value of 1.85 Kg/(m2·min), in the middle course the bricks with an initial absorption rate, with an average value of 1.73 Kg/(m2·min), and in the upper course the bricks with the lowest initial absorption rate, with an average value of 1.62 Kg/(m2·min). Thus, the samples would show similar behaviour in the water absorption tests.

2.2 Execution of the brickwork samples

With the selected bricks, after the characterisation tests, and 1/3/2 air lime mortar, one part of lime of the Calcium Hydroxide CL-90 S type, for 3 parts of siliceous sand and 2 parts of water [28], 36 samples were made up of three courses of half bricks and mortar with a thickness of 21 to 22 millimetres, as indicated above. The preparation of the samples was carried out manually by experienced personnel, in order to avoid unevenness in the execution. Once the samples were made, they were left to dry in the laboratory at a temperature of 22±1 ºC and a humidity of 45±5 %. During the first week, the samples were moistened as was done when a brick masonry was made [28].

2.3 Coating of the samples

Three types of coating were used to coat the samples, the main one:

Macroporous repair mortar, industrial type: composed of natural hydraulic lime, pozzolanic fillers, selected aggregates and special additives to modify pore size and volume up to an occluded air ratio > 30% according to EN 1015-7 [34], classified as R, render mortar for renovation according to EN 998-1 [35], with capillary water absorption >0.3 kg/m2 according to EN 1015-18 [36], according to the manufacturer's information.

And two other mortars made of aerial lime and cement, to compare the behaviour of the macroporous mortar:

- Aerial lime mortar of the type Calcium Hydroxide CL-90 S, washed river sand, siliceous, grain size 0 to 4 mm, according to EN 933-1 [37] of 1/3/2 dosage (1 part lime to 3 parts sand and 2 parts water), with a capillary water absorption of 1.5 kg/ (m2·min) according to tests carried out in accordance with EN 1015-18 [36]. Lab-made mortar
- Portland cement mortar, washed river sand, siliceous, grain size 0 to 4 mm, according to EN 933-1 [37], dosage 1/5/3 (1 part cement to 5 parts sand and 3 parts water), with a capillary water absorption of 1.1 kg/(m2·min) according to tests carried out in accordance with EN 1015-18 [36]. Industrial-type mortar.

Two months after the samples had been made and once the mortar in the joints had set, they were measured and weighed to obtain the dry weight of the samples, which was done according to the rules for testing bricks. Afterwards, 18 samples were coated, leaving the other 18 "twin" samples uncoated. Six with each type of mortar. The coating was carried out on the four lateral faces with an average thickness of 15 mm because only one layer was required [38]. This coating was done at a height of 1 cm above the base of the brick so that the water was absorbed only from this base and, in this way, the comparison between the behaviour of the coated and uncoated samples would be more accurate.

2.4 Tests carried out on the samples

After two months from the execution of the coating, during which time the samples were left in the laboratory ambient, under the conditions, tests were carried out on them. In order to monitor the results, the samples were named as follows:

- First group of 12 specimens: 6 uncoated specimens (named S1brick-mp to S6 brick-mp) and 6 specimens coated with the macroporous mortar, (S1 mp to S6 mp). The Si brick-mp and Si mp samples are made with the same half-bricks.
- Second group of 12 samples: 6 uncoated samples (called S1 brick-al to S6 brick-al) and 6 samples coated with the air lime mortar and sand (S1 al to S6 al) made with the same half-bricks, in a similar way to the previous samples.
- Third group of 12 samples: 6 uncoated samples (named S1 brick-ce to S6 brick-ce) and 6 samples coated with cement mortar and sand (S1 ce to S6 ce) made with the same half-bricks, in a similar way to the previous samples.

The first tests consisted of measuring and determining the volume and mass of the coated, dry samples, which were tested according to brick testing standards. The results of the mean values per group of six samples have been transferred to (table 2) together with the values of the standard deviation, determined according to the usual procedure of the square root of the mean of the difference between each value and the mean squared value.

Tab. 2. Dimensions, volume and mass of the samples.

	S1 a S6 brick-mp	**S1 a S6 mp**	**S1 a S6 brick-al**	**S1 a S6 al**	**S1 a S6 brick-ce**	**S1 a S5 ce**
Base (cm^2)	128.8	125.6	128.6	127.9	128.6	125.3
standard deviation	3.4	1.3	1.5	0.9	1.1	4.4
Height (cm)	15.0	14.9	15.2	15.0	15.2	15.2
standard deviation	0.3	0.3	0.3	0.2	0.3	0.3
Volume (cm^3)	1950.7	3057.4	1948.3	3158.7	1927.9	3057.4
standard deviation	45.8	157.7	43.1	54.9	74.9	157.7
Dry mass (gr)	3400.4	5038.3	3452.6	5380.9	3409.5	5535.4
standard deviation	79.1	170.7	94.2	98.7	92.4	122.9

Subsequently, the absorption test was carried out on the 36 samples, at the same time, so that the tests were performed under the same laboratory conditions, with the temperature being between 20-22 ºC and the humidity being 35-42%, following the procedure of the EN 15801 standard [39]. The samples were dried and weighed and then placed on a moistened base and they were weighed at intervals to determine the water absorbed by comparison with the dry weights. The first 3 hours at intervals of 20 minutes, then every hour until 12 hours after the start of the test, then every 12 hours for the next two days and finally every 24 hours until approximately 7 days after the start of the test, until a constant weight was reached in all the samples. In this way, the water absorption coefficient was obtained with respect to the absorption base and time in ½ sg.

Once the absorption test was completed, the samples were removed from the wetted base and the drying test was carried out following a test procedure based on EN 16322 [40]. Similar to the previous test, the samples were left on a dry base, 20 cm apart, and were weighed at intervals: the first 3 hours at 20-minute intervals, then every hour until 12 hours into the test, then two days every 12 hours, two days every 24 hours and then every 7 days until the end of the test 62 days after the start of the test, when all the samples had dried to constant weight. Desorption is given in gr/hour.

Finally, in order to determine the water content absorbed by the two components of the clad samples (coating and core of three half-bricks with mortar joints), the clad samples were again saturated by capillary action from a wet base, following the same procedure. Once the samples had reached the same saturated weight as in the first test, the lining was carefully separated from the brickwork and the two saturated components were immediately weighed separately. They were then allowed to dry to a constant weight and the sum of the weights of the two dry components was checked to ensure that it was equal to the dry weight of the coated sample. Subsequently, the weight of the masonry core of the samples was compared with the weight of the samples before coating to check whether the separation of the coating from the brick sample had been carried out correctly. The largest variation in weight was 8 grams, 0.2% of the weight of the sample.

3. Results

3.1 Results of the absorption tests of the samples

The results of the water capillary absorbed water (absorbed water in Kg / surface of the base of each test piece in m2), test on the 6 groups of specimens are shown in ‘Figure 2’, where they have been represented in three graphs (according to the type of coating mortar), comparing the results of the two types of specimens, with coating (white markers) and without coating, "Twin" specimens (black markers). On the left, the results of the macroporous mortar specimens and their uncoated twins, in the centre, those of the air lime mortar coated specimens and their uncoated twins and on the right, those of the cement mortar coated specimens and their uncoated twins.

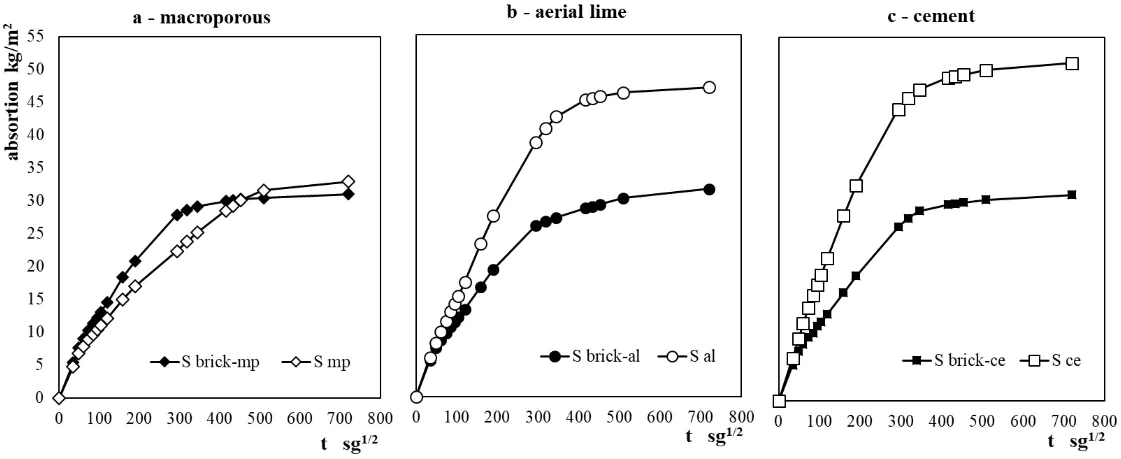


Fig. 2. Graphs of the absorption test results.

In all three groups, the uncoated samples absorb 11.8% water of the dry mass of the specimen, with a mean weight of 404.4 g and a standard deviation of 1%. In the case of the macroporous mortar coated samples, the percentage is the lowest of the six groups, with a value of 8.3%, with an average weight of 417.0 g, followed by the aerial lime mortar coated samples, which reached 11.2%, and an average weight of 606.7 g, reaching 11.6% in the cement mortar coated samples, with an average weight of 642.9 g, which are the ones that absorb more water.

In the water absorption, it can be observed that there are two periods: the first one with a faster absorption and a final one in which the process slows down, but with different values depending on whether the samples are uncoated or coated with the three types of coating. The values of the capillary water absorption coefficients of the first phase have been transferred to table 3 to better analyse the differences.

Tab. 3. Water absorption coefficient by capillary action in kg/ (m2·s ½)

	Coated samples	**Uncoated samples (twins)**
Coating mortar	**$Kg/m^2 \cdot sg^{1/2}$**	**$Kg/m^2 \cdot sg^{1/2}$**
Macroporous hydraulic lime	0.0712	0.0885
Aerial lime	0.1272	0.0771
cement	0.1551	0.0825

The difference in the absorption process between the coated and uncoated "twin" specimens seen in ‘Figure 2’ has been transferred to the graph in ‘Figure 3’, where it is observed that while the specimens coated with air lime and cement mortar absorb more water than the uncoated "twin" specimens, in the case of the macroporous coated specimens the process is different, so that, in a first stage the coated specimens absorb less water than the uncoated ones, the situation being reversed at the end of the process. In the case of macroporous coated specimens this process is different, in a first stage the coated specimens absorb less water than the uncoated ones and at the end of the test the situation is reversed.

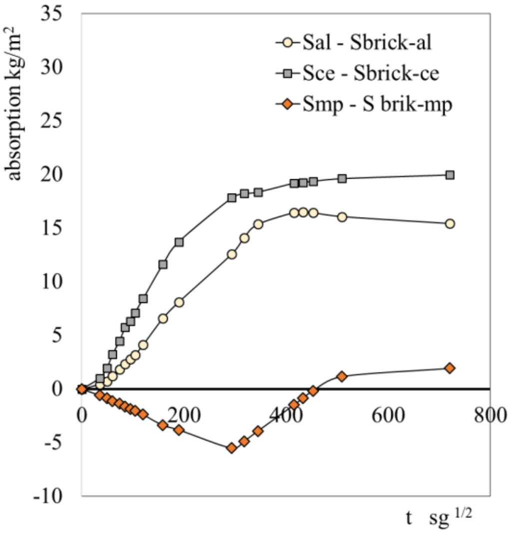


Fig. 3. Graph comparing the different drying processes between coated specimens and uncoated "twins".

3.2 Test results of the drying process of the samples

The comparative graphs of the drying process are represented in 'Figure 4' with three graphs (according to the type of coating mortar) comparing the results of the two types of samples, coated (white markers) and uncoated, "twin" samples (black markers): on the left the results of the macroporous mortar samples and their uncoated twins, in the centre those of the air lime mortar coated samples and their uncoated twins and on the right those of the cement mortar coated samples and their uncoated twins.

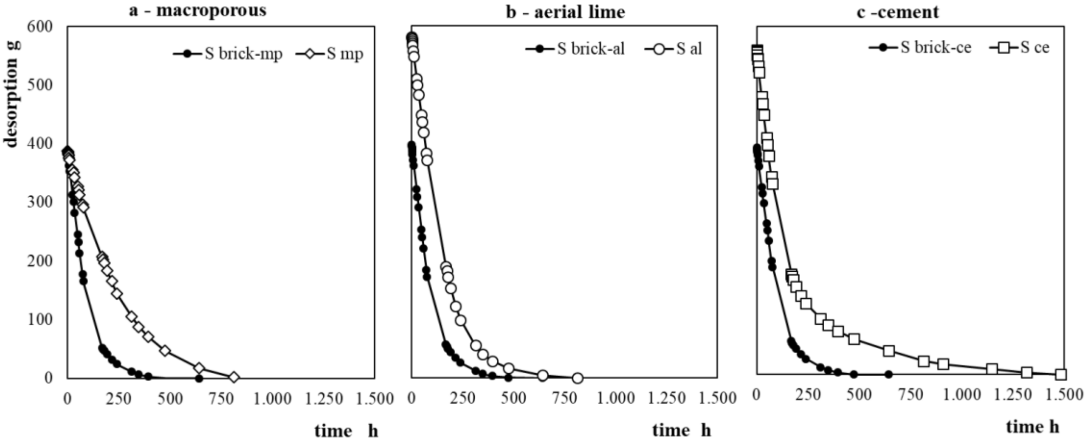


Fig. 4. Graphs of the drying test results of the samples.

Regarding the drying process, the specimens clearly present two phases in the process, the first one with a high drying speed since the water in the coating is evaporating rapidly and another slower one, at the end, due to the fact that the water must migrate from the inside of the specimen to the outside surface; however, the specimens coated with macroporous mortar present a slower process and the slope is lower than in the other specimens [40].

If the slopes of the first stage are compared, corresponding to the first 76 hours from the beginning of the test, it is verified that the slope, in the first phase, is higher in the cement mortar samples, 3.04 g/h, followed by the slope of the uncoated samples, 2.86 g/h, being a little lower for the air lime mortar samples, 2.74 g/h and finally the lowest slope is for the samples coated with macroporous mortar, 1.25 g/h. However, at the end of the drying process, the uncoated samples lose water earlier, reaching constant weight, i.e. a difference in weight of less than 0.1%, after 27 days, and among the coated samples, the macroporous mortar and lime mortar samples take approximately the same time, 34 days, to dry, while the cement mortar samples take 61 days.

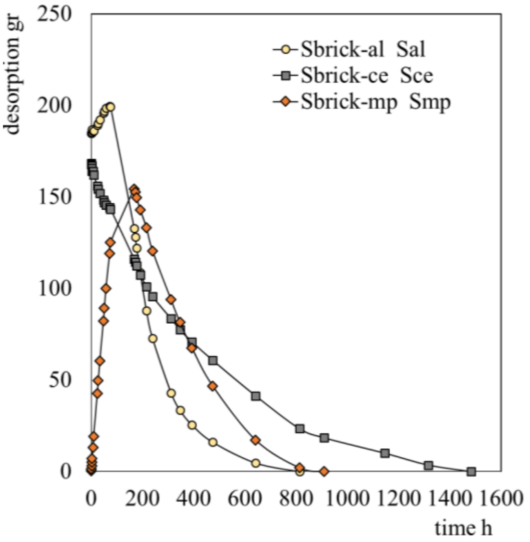


Fig. 5. Graph comparing the different drying processes of coated and uncoated "twin" samples by type of coating.

Similar to the absorption process, the difference in the drying process for the coated and uncoated "twin" specimens will be analysed. 'Figure 5' shows that when calculating the difference in weight of the drying of the coated specimens and their uncoated "twins", differences between the three types of coating can also be observed. The macroporous mortar and lime mortar coated specimens reach the end of the drying process practically at the same time, although the lime coated specimens lose water more quickly in the first phase, and there is a previous process in which the uncoated specimens dry more quickly, the difference being significant in the macroporous mortar coated specimens. The difference in the drying process of the cement mortar coated specimens is longer in time, lasting almost twice as long as the specimens with the other types of coating and the process is more constant.

3.3 Results of the drying tests that have been carried out independently on the two components of the samples: brickwork core and cladding

The results of the last test, in which the water content of the samples and the coatings are determined separately, are shown in (table 4), where the values in percentage of absorbed water content are shown.

Regarding the total water content absorbed by the coated specimens, the macroporous mortar coating only contains 1.7% of the total water absorbed by the sample, while the specimens with the other two coatings contain approximately one third of the total water. This shows the different behaviour of the macroporous mortar coating compared to the other two.

Tab. 4. Water absorption of samples and coatings, relative to the water absorption of the coated sample.

	Brickwork core	coating
Coating mortar	**Water content %**	
Macroporous mortar	98.3	1.7
Lime aerial mortar	66.7	33.3
Cement mortar	66.2	33.8

4. Discussion

When analysing the results of the absorption tests, important differences can be found in the absorption process of the macroporous mortar-coated specimens and the other two types of mortar.

A comparison of the absorption coefficients in the first phase of the test shows that in the macroporous mortar coated specimens this coefficient is lower than that of the uncoated specimens, while in the case of the specimens coated with lime mortar and cement mortar, the water absorption coefficient is higher in both cases than in the uncoated specimens ‘Figure 2’.

In the first phase of the water absorption process, the absorption coefficient of the specimens coated with lime and cement mortar is higher than that of the uncoated specimens. However, in the case of the specimens coated with macroporous mortar the process is different, the absorption coefficient is lower than that of the uncoated specimens (table 3).

At the point on the abscissa axis of 294 sg ½ which corresponds to 24 hours after the start of the absorption process, the sample coated with macroporous mortar has absorbed less water than the uncoated "twin" samples, the difference being - 5.5 kg/m2. From this point onwards, the process is reversed until reaching the point on the abscissa axis at 453 ½ sg, which corresponds to 57 hours after the start of the test, where the volume of water absorbed by the macroporous mortar-coated specimens and their uncoated "twin" samples is equal ‘Figure 3’.

‘Figure 3’ shows the differences in water absorbed with respect to the base between the coated samples and the uncoated "twin" sample, it can be determined that the difference between the macroporous mortar coated samples and their coated twins is 1.9 kg/m2, in the case of the area lime coated samples it is 15.4 kg/m2 and in the case of the cement samples it is 20.0 kg/m2. This indicates that the macroporous coated samples have absorbed less water than the samples coated with the other two types of mortar, compared to the uncoated "twin" samples ‘Figure 3’. This coincides with the results obtained with the mortar samples in (table 2), where it can be seen that the capillary water absorption of the macroporous mortar coated samples is much lower than the water absorption of the samples with the other two types of mortar.

From the graphs of the drying test, relevant information is extracted on the drying times and their speed, finding large differences between the coated and uncoated samples, which in all cases dry earlier. The drying curves of the air lime and cement mortar coated samples present the maximum slope at the beginning, marking the fastest process of the entire test, after which there is an inflection point that gives way to a second phase, where drying is slower, because the water inside the sample must migrate to the outer surface [40]. However, in the macroporous mortar specimens, a first phase is observed in which they lose water much more slowly than the uncoated "twin" specimens, possibly due to the fact that macroporous mortar retains a much smaller amount of water at the end of the absorption process than the other two types of mortar, which may mean that in this first phase, as the water has to migrate from the core to the outside, drying is slower in the coated specimens than in the uncoated specimens.

From the results of the third test, it can be determined that the macroporous mortar coating contains, in the most extreme conditions of higher saturation of the specimens, a much lower water content than the air and cement mortar linings, which contain approximately one third of the total water content of the specimens. The very low water content in the macroporous coating is also denoted in the graph in ‘Figure 4’, since in the first phase of drying the coated samples are slower because the water is in the masonry core and must migrate to the surface. When observing the graph of the difference in water content in the drying process, it can be seen that in the macroporous mortar coated samples there is a first stage in which the coated samples dry at a faster rate than the uncoated ones, during the first 76 hours of the test, then the trend changes and the uncoated samples lose water at a faster rate, possibly because the water content in the macroporous mortar is very low and water migrates rapidly from the core of the masonry to the outside, which can be interpreted as the macroporous rendering mortar actively collaborating in the drying of the masonry it coats. A similar phenomenon occurs in the lime mortar coated samples in the first 72 hours, but the difference in the process is smaller.

5. Conclusions

The conclusions obtained during the present investigation are:

- During the first 24 hours of the absorption process, the macroporous mortar coated specimens absorb a lower amount of water than the uncoated "twin" specimens, for the same environmental and absorption conditions from a wetted base. This is not the case for the specimens lined with air lime and cement mortar, which in all cases and during the whole process absorb more water than the uncoated "twin" specimens. From a brick wall conservation point of view, this would mean that the one lined with the macroporous mortar would have a lower water content than the one lined with the other two types of mortar, and consequently less damage due to moisture and less loss of insulation and load-bearing capacity of the wall.
- During the absorption of water from a wet base, the macroporous mortar samples absorb the least amount of water at the end of the saturation process, 8.3%, while those coated with lime mortar and cement mortar absorb 11.2% and 11.6% respectively.
- The macroporous mortar used as a coating for the masonry samples in the capillary water absorption processes contains a very small amount of water, 1.7% compared to the 33.3% and 33.8% (table 4) absorbed by the other two types of coating, of the total water absorbed by the coated samples, while the brick core of the samples with the three coatings absorbed the same amount of water with an average value of 404.3 g, with a variation of 1%.
- Regarding the drying process, it can be said that the samples coated with lime and cement mortar have a first phase in which they dry more quickly than those coated with macroporous mortar. However, at the end of the drying process, the time taken for the lime and macroporous mortar coated samples to dry was the same, 34 days, while the cement mortar coated samples took longer, 61 days. The uncoated "twin" specimens in all cases dried earlier.

Based on the results of the tests, it can be confirmed that macroporous mortar behaves differently from lime and cement mortars, absorbing less water, which means that in the samples coated with this mortar, the water that rises through capillary action is less in most of this process.

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