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The role of the pointing mortar in the damage due to salt crystallisation

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Abstract

An accurate choice of a re-pointing mortar is fundamental for successful restoration work. Nevertheless many cases of failure show that the choice is not always sensible and that there is still a lack of knowledge on the compatibility of repair mortar for historic masonry. The new re-pointing mortar should be as durable as possible and possess physical, chemical and mechanical characteristics which are compatible with the ones of the existing masonry components. The use of an incompatible mortar can affect the moisture transport inside the masonry and consequently lead to a different drying behaviour of the various material: this can cause damage or speed up the decay process already present in the wall.

The object of this paper is an experimental study carried out on two types of re-pointing mortar (cement and putty lime) applied to wallettes built with different combinations of bricks and bedding mortars. The specimens were subjected to a crystallisation test and the damage was surveyed. The drying behaviour was studied by NMR on little brick/mortar specimens to understand the moisture transport mechanism between the three components: brick/bedding mortar/pointing mortar. The aim was to find a relation between the drying behaviour and the damage due to salt crystallisation.

From this research it results that damage is generally located where the evaporation is stronger. The influence of pointing mortar in the damage process due to salt crystallisation is verified: a coarse lime pointing allows evaporation so the damage consists in a superficial loss of cohesion of the material; a dense pointing slows down the evaporation and creates a discontinuity at the interface bedding mortar/pointing mortar resulting in the end in a loss of bond between the components of the wall.

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1. Introduction

The accurate choice of re-pointing mortar is very important in restoration work. Realising a mortar identical to the old one is often impossible, because the once used materials are difficult to be found and the old fabrication techniques can hardly be brought to live again. The new re-pointing mortar should be as durable as possible and, at the same time, possess chemical, physical and mechanical properties compatible to those of the bedding mortar and those of the brick /stone that constitute the masonry. A repair mortar can affect the drying behaviour of masonry and, consequently, an incompatible mortar can cause damage or worsen the decay process already present in the wall. Therefore the compatibility of the re-pointing mortar has to be checked by taking into account the damage and the decay mechanism surveyed on the building. The diagnosis of the cause of degradation phenomena present is often neglected and this may lead to severe incompatibility problems after restoration.

Salt crystallisation is one of the most common causes of damage in monuments. The soluble salts can come from the ground, from the materials and from the external environment. The soluble salts, dissolving in the presence of moisture, migrate into the structure and, when the moisture evaporates and salt solution becomes over-saturated, crystallise. The crystallisation can take place either on the surface (efflorescence) of the materials or just behind it (crypto-florescence), this behaviour being influenced by environmental conditions, physical characteristics of the materials and rate of solution supply. For these reasons the compatibility of a re-pointing mortar has to be verified also in the case of salt crystallisation, if reliable results on its durability are to be achieved.

2. Crystallisation test

2.1 Materials and methods

A salt crystallisation test was carried out on wallettes consisting of two bricks. Experience has shown that tests performed on single materials are not reliable for understanding the behaviour of the masonry as a whole and that the mechanism of water transport between the masonry components is important for the understanding of the damaging process(es) [1].The materials chosen for the tests are the following:

Brick:	Italian hand moulded brick produced for restoration Belgian extruded brick sampled from an old building
Bedding mortar:	hydraulic lime and Belgian river sand (0-2mm); binder/sand ratio 1:3 (v/v), 1:4.4 (w/w); putty lime and Italian calcareous sand; binder/sand ratio 1:3 (v/v);
Pointing mortar:	Cement CEM I 32.5 and siliceous sand (65μm-2mm); binder/sand ratio: 1:2.5 (v/v), 1:3.3 (w/w); Putty lime and siliceous sand (65μm-2mm);binder/sand ratio: 1:2.1 (v/v), 1:4.5 (w/w);

In order to study the physical properties, the materials were sampled from the wallettes and characterised. In this way the mortar characteristics are more realistic and represent the situation in practice. The results obtained from water absorption and porosity tests are reported in table 1.

The Italian (I) and the Belgian (B) bricks are very different in porosity, water absorption and, consequently, in mechanical strength [2]. The bedding mortar used with the Italian brick is a putty lime-calcareous sand mortar; the bedding mortar used for the Belgian brick is a hydraulic lime. On purpose two very different pointing mortars were selected: a cement mortar (C), with a low porosity and absorption, and a coarse putty lime mortar (K). In the first case a very strong pointing is obtained: the high mechanical strength should guarantee the durability, but, at the same time, the very different physical properties of bedding and pointing mortar could create incompatibility problems due to the alteration of the drying behaviour of the masonry. In the second case the putty lime pointing mortar is considered as a sacrificial material that should preserve the original materials from further damage.

Two salt types were selected for the crystallisation test:

- NaCl: this is commonly found in buildings located near the sea;
- Na_2SO_4: this is the most destructive salt because it can crystallise with a different number of water molecules related to temperature and relative humidity conditions.

Using different combination of materials 16 wallettes were built; half of them were contaminated with NaCl and half with Na_2SO_4. The test was performed according to the RILEM Recommendation MS-A1 [3]. The wallettes were put into glass boxes and sealed so that evaporation could occur only from the surface opposite to the side from which salt solution was introduced.

2.2 Results and discussion

The damage occurring on the specimens was surveyed by visual and photographical inspection. A qualitative evaluation and a description of the damage after 6 months from the starting of the test is given in table 2. The description of the damage is performed according to the MDDS definitions [4]. From these results the following conclusions can be drawn:

Table 1. Physical characteristics of materials

Material		Porosity	Density	Water absorption by capillary rise (2h)	Water absorption by complete immersion (2h)	Water absorption coeff.
		(v)	(Kg/m3)	(w%)	(w%)	$Kg/m^2s^{0.5}$
Bedding mortar	hydraulic	32.1	1800	8.34		0.06
	putty lime	33.3	1770	12.72		0.45
Pointing mortar	cement	27.5	1920	9.53		
	putty lime	33.1	1770	12.9		
Italian brick		41.6	1530	22.09	21.58	0.32
Belgian brick		29.1	1880	9.30	10.78	0.11

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Comparing Italian and Belgian bricks: in all cases the Italian bricks show more serious damage than the Belgian. Only a little scaling can be sometimes observed on Belgian bricks whereas Italian bricks contaminated with Na_2SO_4 show very serious exfoliation, scaling and crumbling. Damage on Italian bricks often occurs as a detachment of many subsequent very thin layers (exfoliation). The differences in damage between Italian and Belgian bricks are probably due to the higher porosity and water absorption of the Italian bricks and consequently to their different drying behaviour. This process will be explained in the following paragraphs.

Comparing Na_2SO_4 and NaCl contaminated specimens: the specimens contaminated with the sodium sulphate solution show, in all cases, more serious damage. These results confirm those obtained in previous experimental research [2] and can be due to the capacity of sodium sulphate of crystallising anhydrous or with 2, 7 (not stable) or 10 molecules of water with a high increase of volume. A difference in the shape of the crystals can be noticed: sodium sulphate forms fluffy efflorescences; sodium chloride creates a thin layer on the surface of the specimen.

Comparing putty lime pointing and cement pointing: the damage on bricks is similar notwithstanding the different type of pointing mortar. The putty lime pointing in Na_2SO_4 contaminated specimens shows a clear superficial scaling and

Table 2. Evaluation and description of damage

Wallette	Brick	Bedding mortar	Pointing mortar	Salt	Seriousness of damage		Type of damage	
					Brick	Pointing	Brick	Pointing
23SO4K	Italian	putty lime	putty lime	Na_2SO_4	***	**	efflorescence and crypto-florescence, exfoliation, scaling	scaling
24SO4K	Italian	putty lime	putty lime	Na_2SO_4	***	**	efflorescence and crypto-florescence, exfoliation, scaling, powdering	efflor., scaling
7SO4C	Italian	putty lime	cement	Na_2SO_4	***	**	efflorescence and crypto-florescence, exfoliation, scaling.	loss of bond brick/bedding mortar, crack at bedding/pointing
8SO4C	Italian	putty lime	cement	Na_2SO_4	***	*	efflorescence and crypto-florescence, exfoliation, scaling, powdering	loss of bond at brick/bedding mortar interface
21CLK	Italian	putty lime	putty lime	NaCl	*	*	efflorescence	efflorescence, little sanding
22CLK	Italian	putty lime	putty lime	NaCl	*	*	efflorescence	efflor., little sanding
5CLC	Italian	putty lime	cement	NaCl	*	-	efflorescence	-
6CLC	Italian	putty lime	cement	NaCl	*	-	efflorescence	-
23BSO4K	Belgian	hydr.	putty lime	Na_2SO_4	-	***	-	efflor., sanding
24BSO4K	Belgian	hydr.	putty lime	Na_2SO_4	*	***	little scaling	efflor., sanding
7BSO4C	Belgian	hydr.	cement	Na_2SO_4	-	-	-	-
8BSO$_4$C	Belgian	hydr.	cement	Na_2SO_4	-	-	-	-
21BCLK	Belgian	hydr.	putty lime	NaCl	*	*	little efflorescence	little efflor.
22BCLK	Belgian	hydr.	putty lime	NaCl	*	-	efflorescence	-
5BCLC	Belgian	hydr.	cement	NaCl	*	-	efflorescence	-
5BCLC	Belgian	hydr.	cement	NaCl	*	-	efflorescence	-

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sanding whereas the cement pointing has no surface-damage, however in Italian brick-cement pointed specimens a loss of bond between the bedding mortar and the brick and in one case also a crack at the bedding-pointing interface can be observed.

After the visual and photographical survey of damage, the specimens were brushed and the loss of material (in weight) measured. The damage due to salt crystallisation only affects the exterior part of the material and, under the damaged zone, the material is sound. In the brick the damage occurs in the form of powdering, scaling, exfoliation or crumbling of the surface. So the difference in weight before and after brushing the specimens can be considered as an indication of damage, since it gives the amount of material loss. The values obtained are approximate because it is not possible to weigh separately salt efflorescence and material. In graph 1 the loss of material (grams) is reported.
It can be seen that specimens made with Italian bricks and contaminated with sodium sulphate show the most serious damage. The highest value is measured on putty lime repointed wallettes because in this case a serious material loss occurred also on the mortar joints.

The absorption and drying behaviour of the specimens was studied in order to understand the influence of the type of pointing mortar on the moisture transport. At the beginning the water absorption by capillary rise was studied, on the four different brick/bedding mortar/pointing mortar combinations, by visual observation drawing the moisture profile visible on the side faces of the specimens at different times. In the Italian brick wallettes the water absorption occurs mainly through the mortar joints, due to the difference in water absorption coefficient between Italian brick (0.32 $Kg/m^2\ s^{0.5}$) and putty lime bedding mortar (0.45 $Kg/m^2\ s^{0.5}$). No important differences are visible between the level of capillary rise in Belgian brick and hydraulic bedding mortar: in this case the water absorption coefficient of brick (0.11 $Kg/m^2\ s^{0.5}$) and mortar (0.06 $Kg/m^2\ s^{0.5}$) is not so different. The specimens were weighed every month to study their drying behaviour. The results, expressed as water loss per cm^2 of evaporating surface are shown in graphs 2a-b.From these graphs the following conclusion can be drawn:

- the type of brick influences the drying behaviour more than the type of mortar. This is due to the fact that bricks constitute about 80% of the evaporating surface.
- there is a change in the slope of the drying curve after one month from the start of the test: probably in the first period the drying occurs by liquid water and is quicker; later, when the surface is not wet anymore, the drying occurs by water vapour diffusion and, consequently, is slower. In both cases (NaCl and Na_2SO_4 contaminated specimens), the Italian wallettes show a higher evaporation rate than the Belgian. This behaviour is due to the higher porosity and water absorption of the Italian brick (see table 1). The difference is more clear with sodium chloride than with sodium sulphate.
- in NaCl contaminated specimens the effect of pointing mortar is negligible. In Na_2SO_4 contaminated wallettes some influence can be noticed. However, the effect of pointing on the Italian wallette is opposite to the Belgian ones. This very limited and non unanimous influence of the pointing on the drying behaviour can be due to the low percentage of mortar compared to the whole evaporating surface of the specimens used in this test.

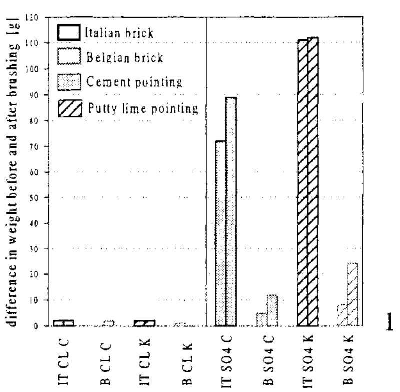
- sodium chloride is more hygroscopic than sodium sulphate. The effects of this hygroscopic behaviour on the drying rate is more evident on the slower drying Belgian bricks (graph 2).

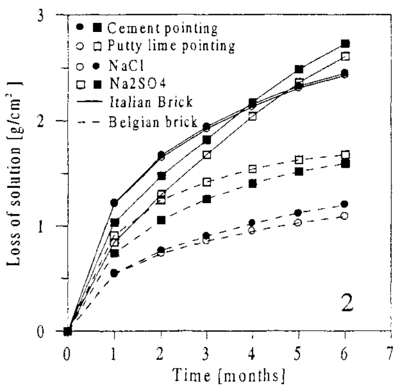
3 NMR tests

The study of the weight loss of specimens in the course of time may give an idea of the overall drying but does not explain how the drying occurs. To understand this process, Nuclear Magnetic Resonance (NMR) measurements were performed at the Faculty of Applied Physics, at Eindhoven University of Technology.

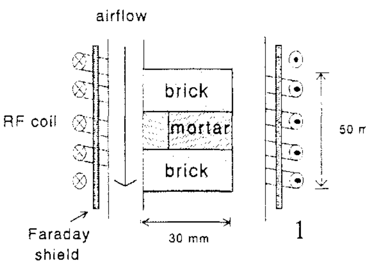
3.1 Principles of the method and description of the test

An extensive description of this method is given by Dixon and Ekstrand [5], Kopinga and Pel [6] and Pel [7]. The method offers the possibility to determine moisture content quantitatively and non-destructively and with a high spatial resolution. For NMR measurements the magnetic moments of hydrogen nuclei are manipulated by suitable chosen alternating radio frequency fields, resulting in a so-called spin-echo signal. The amplitude of this spin-echo signal is proportional to the amount of nuclei exited by the radio frequency field. Because of the resonance condition this method can be made sensitive to hydrogen only and therefore to water [8].
To enable quantitative measurements in porous materials, a special apparatus was designed by Kopinga and Pel. In this NMR apparatus, a RF coil is placed around the sample for creating and receiving the radio frequency fields during NMR measurements. A Faraday shield is placed between the RF coil and the sample to reduce the effects of variations of the dielectric permittivity resulting from changing moisture contents in the sample [8]. The principle of the method and the used apparatus is explained in fig. 1. NMR measurements were carried out on small (dimension 28mm x 43mm x 28mm) brick/mortar specimens: (fig.2). They were wetted by complete submersion for two hours; unidirectional drying took place under environmental circumstances of 20°C, 50% R.H. The measurements took 24 hours.





Graph 1 - Loss of material after brushing
Graph 2 - Drying behaviour



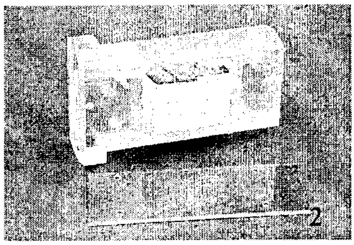


Fig.1 Principle of the method and apparatus
Fig.2 One of the sample in a container

3.2 Results of the NMR measurements

The results of the NMR measurements are given in figures 3–6.

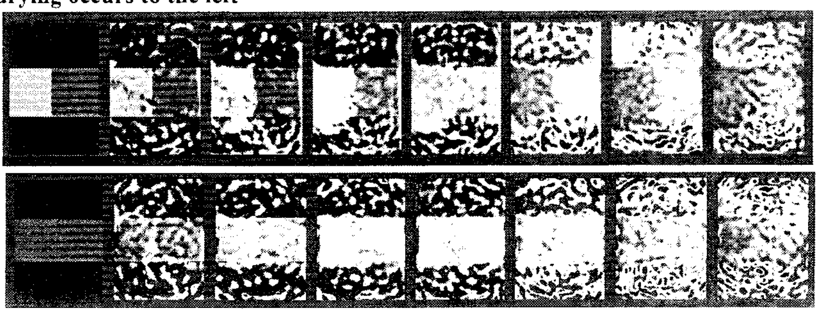
- Italian brick – putty lime bedding mortar – cement pointing mortar (fig.3):

at the beginning the different materials show a moisture content related to their porosity and in accordance with the results of the water absorption test (see table 1): the higher moisture content is measured in the brick (porosity: 41.56% V/V), the lower in the cement pointing mortar (porosity: 27.77% V/V). The cement pointing mortar is quite dry after 4 hours, and consequently the drying process of the bedding mortar seems to occur through the bricks, and from these towards outside. The bedding mortar is quite dry after 16 hours. The evaporation occurs mostly through the bricks probably because of their high porosity and their bigger pores (lower water retention): after 24 hours the brick is not completely dry yet.

- Italian brick – putty lime bedding mortar – putty lime pointing mortar (fig.4):

at the beginning there is no considerable difference between the moisture content of bedding and pointing mortar (the porosity is quite similar: bedding mortar: 33.45% V/V: pointing mortar: 32.74% V/V). The highest moisture content is in the bricks (porosity: 41.56% V/V). At the interface bedding/pointing mortar there is a zone that dries quickly: this is probably due to the not perfect adherence between the two mortars.

drying occurs to the left



0 1h 2h 3h 4h 8h 16h 24h

Figures 3-4: Drying behaviour of two different systems: Italian brick – putty lime bedding mortar – cement pointing mortar (6) and Italian brick – putty lime bedding mortar – putty lime pointing mortar (7)

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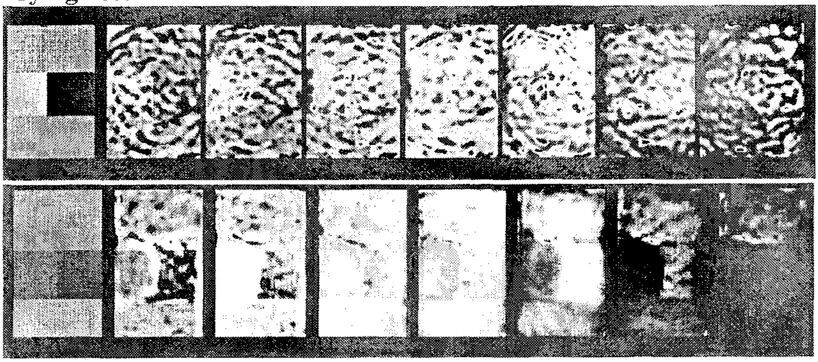
drying occurs to the left



0 1h 2h 3h 4h 8h 16h 24h

Figures 5-6: Drying behaviour of two different systems: Belgian brick – hydraulic bedding mortar – cement pointing mortar (8) and Belgian brick – hydraulic bedding mortar – putty lime pointing mortar (9)

The drying of the bedding mortar seems to occur mainly through the brick and less through the pointing mortar. In fact the rate of evaporation of the two mortars is similar and the pointing mortar appears not to slow down the evaporation in a considerable way. The pointing mortar is quite dry after 16 hours; the bedding mortar a little later. After 24 hours the brick is not completely dry yet.

- Belgian brick – hydraulic bedding mortar – cement pointing mortar (fig. 5): there is a relation between porosity (P) and moisture content (MC) at the beginning of the test.

$$P_{\text{(cement pointing mortar)}} < P_{\text{(Belgian bricks)}} < P_{\text{(bedding hydraulic mortar)}}$$

$$27.29\%\ V/V < 29.1\%\ V/V < 32.54\%\ V/V$$

$$MC_{\text{(cement pointing mortar)}} << MC_{\text{(Belgian bricks)}} < MC_{\text{(bedding hydraulic mortar)}}$$

The drying process of the cement pointing is quick at the beginning but takes a long time to be completed. After 24 hours there are some wet areas inside. The bedding mortar dries slowly. Pointing mortar and bricks from 8h to 24h show a similar moisture content: this can mean that the drying of the bedding mortar occur through both materials.

- Belgian brick – hydraulic bedding mortar – putty lime pointing mortar (fig.6): at the beginning (1 hour) of the test the bedding mortar is very wet, more than the pointing mortar. The putty lime pointing dries very quickly: it is quite dry in 3 hours. The drying of the bedding mortar occurs through the bricks. The pointing mortar appears not to take part to this process.

4. Discussion of salt crystallisation test and NMR results

Salt crystallisation can occur if evaporation of water and consequently super-saturation of the salt solution takes place. It should be possible to find a relation between the decay surveyed on the wallettes subjected to crystallisation test and the results of NMR that suggest a risk of cryptoflorescences in the case of the cement repointing. This is visible in the case of Italian brick specimens contaminated with sodium sulphate: in the cement pointed wallette damage is more serious on the bricks where the evaporation process mainly takes place through the brick and takes more time to be completed; no damage occurs on the surface of pointing mortar, that is completely dry in only 8 hours. Notwithstanding the sound surface of cement pointed joints, a loss of bond at the brick-mortar interface and a crack at bedding-pointing mortar are visible: it is very probable that further crystallisation will lead to the complete push out of the pointing. The study of the drying process can explain this behaviour. The cement pointing, due to its low porosity, slows down the drying of the bedding mortar and water evaporates mostly through the bricks. So it is possible that water accumulates at the brick/bedding mortar/cement pointing interface. In the presence of frost or salts, mechanical stresses will be generated at the interface, leading to the push out of the pointing (fig. 7a). In the putty lime pointed wallettes the pointing causes no slowing down of the drying process, so the evaporation can take place both through the pointing and the bricks. Consequently the decay is serious and is present also on the pointing mortar where the drying process takes 16 hours (fig. 7b).

It is more difficult to find a clear relationship between the damage that occurred on Belgian brick specimens and their drying behaviour:

- in the cement pointed wallettes damage occurred neither on the bricks nor on the mortar;
- in the putty lime pointed specimens contaminated with sodium sulphate, damage is located on the joints even if the drying of the pointing is very quick and the drying takes place mostly through the bricks. To explain this behaviour the physical characteristics, the mechanical strength and the pore size distribution should be taken into account. The lower water content and the relatively quick drying (compared with the Italian brick) means less salt content in the specimens and a lower concentration of salts near the surface: this, as well as the higher mechanical strength of Belgian brick, can explain the good behaviour of Belgian brick compared with the Italian.

5. Conclusions

The compatibility of a foreseen repair mortar has to be checked by taking into account the decay process(es) surveyed on the masonry. In fact the new mortar can modify the moisture transport causing or increasing damage. Salt crystallisation is one of the most common causes of damage in monuments. Damage due to salt crystallisation takes place where evaporation, and, consequently, super-saturation of salt solution, occurs. The drying process in porous materials depends on the physical characteristics (above all porosity and pore size distribution) that influence water absorption and water retention. If porous building materials (brick, stone, mortar) are combined in a wall the drying behaviour of the masonry can only be understood studying the moisture transport between brick and mortar. In this work the drying process was investigated by means of NMR. The NMR measurements allowed to clarify how the type of pointing (in this case putty lime and cement pointing) influences the drying behaviour of the masonry components.

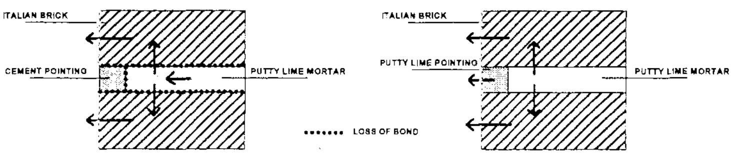


Fig. 7a-b: Drying behaviour and mechanism of damage in cement (a) and putty lime (b) pointed Italian wallettes

In cement pointed wallettes the drying of the bedding mortar occurred mainly through the brick, whereas where a putty lime pointing was used the evaporation took place both through the pointing and the bricks. So two different damage mechanisms can occur: in the first case the loss of bond at the brick/mortar interface (already visible in Italian wallettes contaminated by sodium sulphate) followed by the complete push out of the cement pointing (this can be expected in the next crystallisation cycle); in the second case the powdering and the crumbling of the bricks and the pointing mortar. In the Italian wallettes contaminated with sodium sulphate a relation was found between the localisation of evaporation and the damage due to salt crystallisation. The relation between evaporation and damage was not so clear in the Belgian specimens: in this case a more accurate study of pore size distribution and mechanical strength, and further crystallisation cycles will be necessary to understand the behaviour. The influence of pointing mortar in fastening or slowing down the drying velocity was also studied by measuring the evaporated water for the evaporating surface of the wallettes subjected to the salt crystallisation test. In this case the low percentage of mortar compared to the brick did not allow to verify the influence of the pointing on the drying behaviour of the specimens. So it is clear that the direction of moisture transport is clearly influenced but total drying velocity only slightly.

6. Acknowledgement

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