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Salt Weathering on Buildings and Stone Sculptures

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Salt durability tests of repair mortars used in the restoration of porous limestones

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ABSTRACT

Repair mortars mainly used in the restoration of porous limestone and sandstone were studied under laboratory conditions for salt durability. Cubic specimens of various types of repair mortars were exposed to sodium-sulphate solution by applying standard salt crystallization test methods. Loss of weight and changes of mechanical properties were detected. The response of repair mortar and porous limestone to typical wetting–drying experiments and salt exposure experiments were compared. Uniaxial compressive strength was measured after 14, 28 days of casting, while durability was assessed by comparing strength test results of samples kept dry conditions, in water or after salt exposition. The results show that damaging of limestones and repair mortars are closely related to material properties and especially to the pore-size distribution of samples.

Keywords: repair mortar, sodium-sulphate, immersion, uniaxial compressive strength, freeze-thaw

1 INTRODUCTION

Repair mortars are very commonly used for loss compensation of stone objects (Griswold & Uricheck 1998). From the various types of stones, porous limestones (Beck & Al-Mukhtar 2008) and sandstones (Přikryl & Šťastná 2010) require special mortars. In Hungary, a very common application of repair mortars is for the restoration of porous limestone (Figure 1). This stone type is a widely used building and ornamental stone across the country and even in other countries (Austria, Slovakia, Czech Republic, etc.) in Central Europe (Török et al. 2004, Laho et al 2010). This type of stone could suffer extensive deterioration in a relatively short time span (Török 2002), which explains why the use of repair mortars is so common in these countries. Mechanical disintegration of porous building materials are often caused by crystal growth (Scherer 1999, Steiger 2005). The process of crystal growth is highly dependent on the relative humidity (RH) and temperature (Rodriguez-Navarro & Doehne 1999). For accelerated weathering tests of natural rocks and building materials sodium sulfate is one of the most commonly used substance. These laboratory methods are also standardized (EN 12370). Sodium sulfate has different crystalline forms. The two most common forms are Na_2SO_4 (thenardit) to Na_2SO_4*$10H_2O$ (mirabilite). Previous studies have reported that both forms of sodium sulfate cause damage in materials (Goudie and Viles 1997). The present paper attempts to show the changes of mechanical properties of repair mortars caused by salt weathering. In order to understand the salt durability of repair mortars the mechanical properties and the porosity of materials were analyzed. The main objective of this research thus; is to understand the relationship between porosity and the durability of mortars against salt weathering. Furthermore it assesses the applicability of strength tests in salt weathering durability studies.

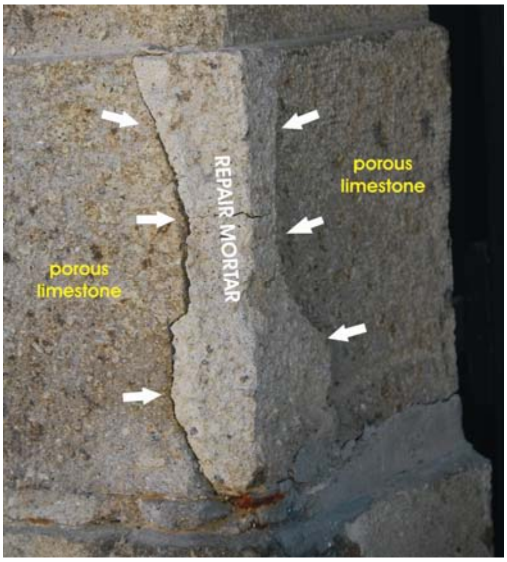

Figure 1. The use of repair mortar in the loss compensation of porous limestone.

2 MATERIALS AND TESTS

In the present paper commercially available three types of ready-to-use mortar and a non-industrial mixture were tested. The material properties of the mortars are listed in Table 1. Altogether 72 pieces of cubes with dimensions of 30mm x 30mm x 30mm were prepared for the experiments. The test procedure is given in EN 12370:2000 standard. The repair mortar cubes were immersed in a sodium sulfate solution and dried gradually (Fig 2.). The drying temperature was increased from 20°C to 105 °C in 10 hours. After this cycle the specimens were cooled to room temperature (20°C), and a new cycle began with the salt immersion into Na_2SO_4 solution. 15 cycles were used and after each cycle the weight of the specimens were measured.

Table 1. Tested mortars and their characteristics

Code of mortar	Product type	Major application (country)	Open porosity (%)	Apparent density (g/cm^3)	Real density (g/cm^3)
1 series	Industrial product	Loss compensation repair mortar for limestones and sandstone (Hungary)	25.55	1.93	2.19
2 series	Non-industrial (mixed in laboratory)	Experimental stage for porous limestone	38.57	1.64	2.03
3 series	Industrial product	Loss compensation repair mortar for limestones and sandstone (Hungary)	32.72	1.79	2.13
4 series	Industrial product	Loss compensation repair mortar for brick and stone (Germany)	34.89	1.77	2.08

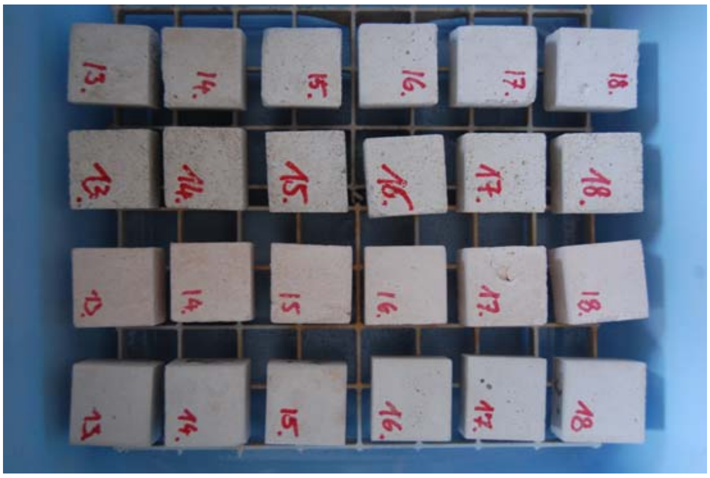

Figure 2. Repair mortar test cubes.

The capillary water absorption test of cubes was also measured (EN 1936:2007). The cubes were hanging and immersed in distilled water (immersion was 2 mm). The weight change was continuously monitored (readings were in every 5 seconds) by using special scale and computerized logging system with an accuracy of 0.1g. Before the experiments the specimens were placed in a closed system with standard humidity and temperature. By using these data the water absorption coefficient was calculated. For comparing the durability against salt weathering with freeze-thaw durability of repair mortars additional tests were made. Set of cubic specimens were subjected to 50 standardized freeze-thaw cycles. The procedure followed the ones given in EN 12371:2002. Another set of repair mortars were fully water saturated. To assess the durability the compressive strength of air-dry, water saturated, freeze-thaw subjected and salt immersed repair mortars were compared. The uniaxial compressive strength tests were performed according to EN 1926:2000.

3 RESULTS

Water absorption tests showed that there is a significant difference in capillary water absorption of the studied repair mortars. Water absorption of the 2 and 3 series samples were higher than that of the two other mortars (1 and 4. series) (Figure 3).

The durability of repair mortars was assessed at first by using visual inspection after each test procedure. The accelerated salt weathering tests lead to the damage of all but one repair mortars after 15 cycles (Figure 4). Three of four mortar series were completely disintegrated after the 15 salt crystallization cycles, and the one that survived (1 series) show intense rounding of edges (see Figure 4). The freeze-thaw cycles caused less dramatic change in repair mortars (Figure 5), however mortar type 4 that damaged significantly during the salt crystallization tests seemed to be fairly frost resistant even after 50 freeze-thaw cycles.

The weight changes of the samples were also recorded (Figure 6). The trends in weight changes can be divided into three sections. In the first few cycles samples often gained weight. It is typical for the first 3-5 saturation and crystallization cycles (Figure 7).

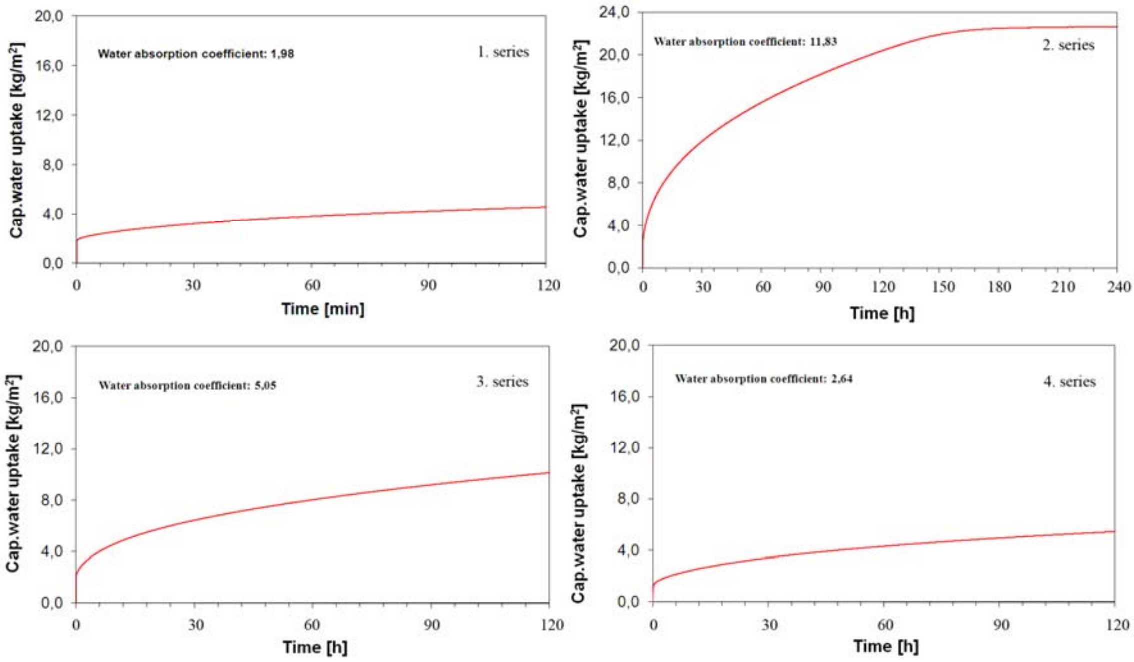

Figure 3. Capillary water absorption of the four studied mortar (1 -4 . series)

Actually saturation and drying did not cause visible damage in these first stages, and very often an increase in the uniaxial compressive strength was also recorded (Figure 8, series 1 and 3). After the 3 cycles of salt crystallization the specimens of the 2 and 4 series showed a reduced compressive strength (see Figure 8). However after the 15th cycles all the samples were destroyed except the 1 series. Surprisingly a minor increase in strength was measured on these samples. Actually the initial strength increase in 3. series after the 3rd salt crystallization cycles was followed by a rapid loss in weight after the 4th salt crystallization cycle (see Figure 6). The samples of the 3. series lost the 50% of weight after the 7th cycles of immersion. The specimens of the 4. series also lost the 50% of weight after the 11th cycles. As compared to salt weathering, the freeze-thaw test showed different trends (Figure 9). It is clear, that after 50 freeze-thaw cycles a loss in compressive strength was measured with the exception of the 3. series of samples.

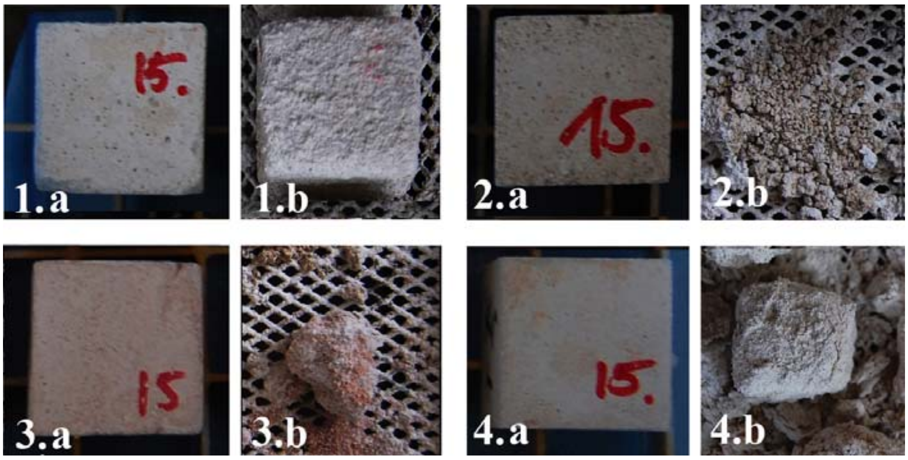

Figure 4. Visual assessment of damages caused by salt decay: before (left) and after salt crystallization cycles (right) (1-4 numbers refer to sample sets listed in Table 1).

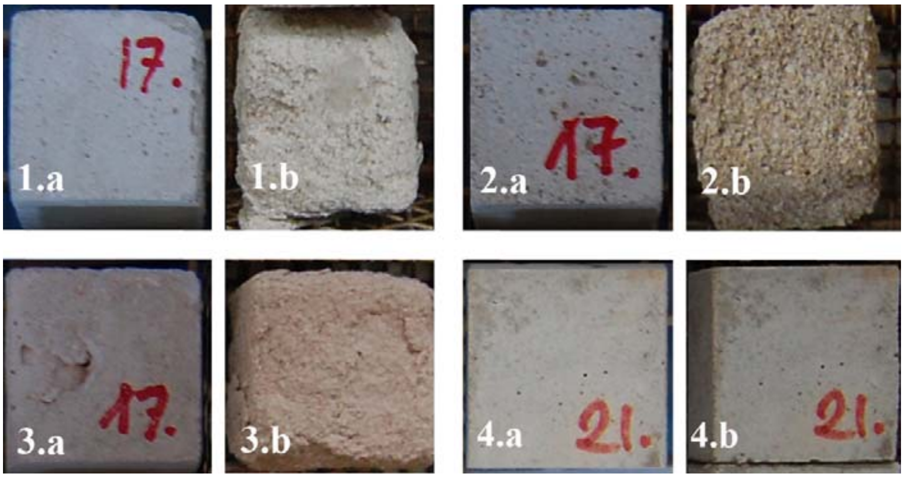

Figure 5. Visual assessment of damages caused by freeze-thaw cycles: before (left) and after 50 freeze-thaw cycles (right) (1-4 numbers refer to sample sets listed in Table 1).

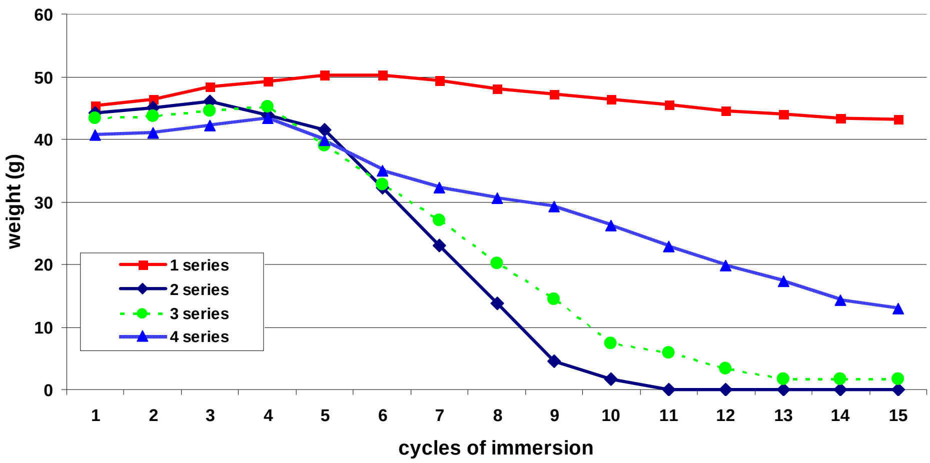

Figure 6. Weight loss of the four mortars (1 -4 . series) during the 1 to 15 salt crystallization cycles

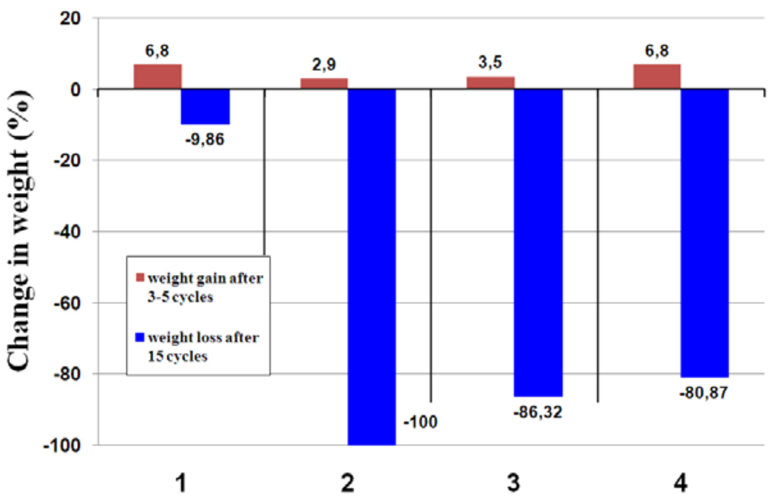

Figure 7. Weight gain of repair mortars after 3 to 5 and weight loss after 15 cycles of salt immersion test (1-4 numbers refer to sample sets listed in Table 1).

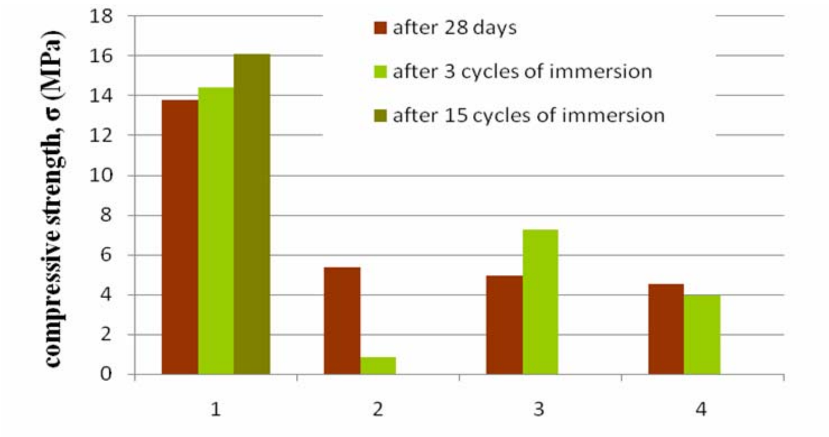

Figure 8. Compressive strength of repair mortars: from left to right: air dry after 28 days, 3 cycles and 15 cycles of salt immersion, note that samples of 2-4 series were damaged after 15 cycles, thus no strength tests were made (1-4 numbers refer to sample sets listed in Table 1)

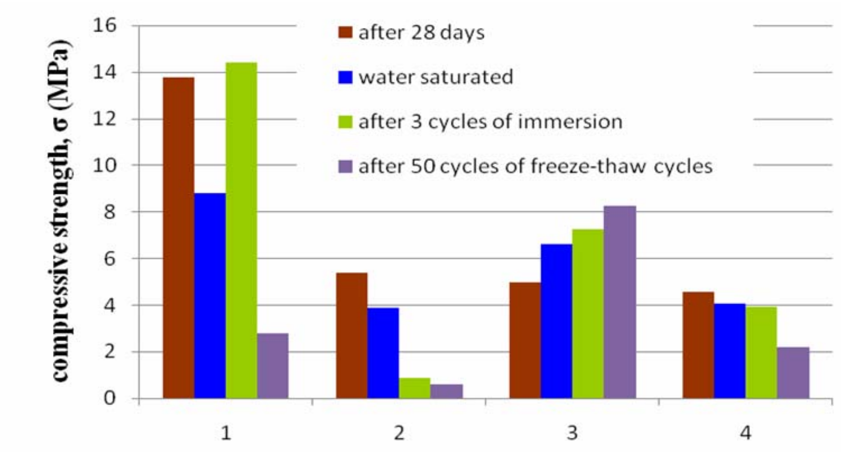

Figure 9. Compressive strength of repair mortars: from left to right: air dry after 28 days, water saturated, 3 cycles of salt immersion and 50 freeze-thaw cycles (1-4 numbers refer to sample sets listed in Table 1)

4 DISCUSSION

The weight changes during salt crystallization tests did not show a uniform trend and not a continuous loss in weight was measured. To the contrary, all of the samples gained weight during the first 4 cycles, but than some sets of samples behaved differently. When the total porosity of mortar samples is compared (Table 1) it is clear that samples belonging to series no. 2. have the highest amount of open porosity (38.57%). However, the amount of open porosity does not inversely proportional with salt durability. A good example for this is the comparison of 3rd series and 4th series of samples, since the open porosity is 34.89% while that of the 4th series is 32.72%, respectively. In this case the more porous samples (4th series) are more salt resistant than the less porous ones (3rd series). Previous studies (La Iglesia et al. 1997, Bartsoletti et al. 2001) have shown that salt crystallization in porous media begins in the largest pores and than continues in the smaller pores. Steiger (2005) has demonstrated that in case of very small pore entrances a permanent equilibrium crystallization pressure able to damage porous building materials. By studying the results it is suggested that not only the open porosity but also pore-size distribution is important in terms of controlling salt durability of repair mortars and construction materials. It is in agreement with previous findings, since the pore size distribution and role of micro-pores in the salt susceptibility of building stones were also emphasized by studying the salt exposure of Japanese building stones (Yu & Oguchi 2010). These differences in pore-size distribution are also shown by capillary water absorptions (Figure 3), since the 3rd series of samples showed slower water absorption, than the 4th series. The air dry compressive strength of studied repair mortars are related to open porosity as it was suggested for lime-pozzolan mortars by Papayianni & Stefanidou (2006), however in these tests there were mortars with higher porosity and higher strength (2. series), which indicate that composition is also important factor in controlling the strength of repair mortars. The durability of repair mortars against freeze-thaw does not necessarily synchronous with the durability against simulated salt crystallization (compare Figure 4 and Figure 5). Our observations show that there are some repair mortars that are durable in terms of salt weathering, but these mortars might perform very weakly under freeze-thaw conditions (Figure 9). One example for this is the 1st series of samples, with 14.44 MPa of compressive strength after 3 salt cycles, but low strength after 50 freeze-thaw cycles (2.80 MPa). The strength change due to salt crystallization is ambiguous for the first three salt crystallization cycles. Two sets of samples (namely set no. 2 and 4) show a decreased compressive strength when water saturated and salt weathered samples are compared, while the 1st and 3rd series of samples had an increased compressive strength after 3 cycles (Figure 8). When this data set is compared with the changes in weight (Figure 6) it suggests that weight change, (ie. increase in mass) is not proportional with the changes in strength (Figure 8). Additional salt crystallization cycles (up to 15) lead to a complete damage of all but one set (1 series) of mortar samples resulting in the complete disintegration of samples (Figure 4). The most resistant mortar against salt weathering had the highest apparent density, lowest open porosity and lowest water absorption, but has a significant loss in strength when subjected to 50 freeze-thaw cycles.

5 CONCLUSIONS

Sodium sulfate proved to be extremely destructive for the tested repair mortars and it was observed that most of the damage occurred after the 5th and 6th cycles. Surprisingly, a few percent of weight increase of the samples was detected during the first few salt crystallization cycles, indicating that weight measurement is not necessarily the best indicator of early stage salt damage susceptibility. The durability of the studied mortars against sodium sulfate and frost are different and there are mortars that seem to perform well under freeze-thaw conditions but have very low durability against salts. The major parameters influencing durability are total porosity and pore-size distribution. The micro-pores are more sensitive to salt damage, while larger porosity and rapid capillary water uptake are also indicators of the sensitivity of the repair mortar against salt weathering. These tests have shown that freeze-thaw damage and salt crystallization damage cannot be merely estimated by capillary water uptake or open porosity.

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