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STONE PROPERTIES AND DAMAGE INDUCED BY SALT CRYSTALLISATION IN SOME JORDANIAN STONES

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Abstract

Limestone and basalt samples were selected from four archaeological sites in north and northeast Jordan. The selected stones were investigated with physico-mechanical methods and ultrasonic technique and the changes in their properties after artificial weathering by salt crystallisation test were studied in order to obtain information about their weathering behavior and durability.

It was found that the susceptibility of the studied stone samples to salt damage is determined by their petrophysical rather than mechanical properties. In terms of loss of stone material, the damage induced by the crystallisation of salt in the stones seems to be dependent on their proportion of micropores and free porosity. Durability estimators for the evaluation of the weathering resistance of stone were consequently developed.

Keywords: durability, salt crystallisation, Jordanian stones.

1. Introduction

The assessment of the intensity of stone deterioration is an essential aim for preservation and conservation purposes (Siegesmund et al., 2002). For the quantification of deterioration, a fundamental understanding of stone weathering mechanisms and their influence on stone structure is necessary. Weathering processes affect the physical and mechanical properties of stone and induce various changes in its structure (Nicholson, 2001; Benavente et al., 2004). Changes in stone due to weathering might include modification of porosity and pore structure, development of cracks and loss of stone cohesion (Tuğrul, 2004). The study of these changes in stone properties helps to provide information about the weathering of the stone and its durability.

However, stone deterioration processes are controlled by multiple factors; intrinsic factors inherent to the stone and its natural heterogeneity and extrinsic factors related to the surrounding environment (Siegesmund et al., 2002). The interactions between the various properties of stone and the weathering processes affecting them do create a complex system. In such a complex system there is no single controlling parameter, but rather a multiplicity of factors is actually involved (Nicholson, 2001).

A simple and good approach to understand the weathering of stone and to assess its durability is, therefore, to consider a certain type of weathering processes and try to determine the most important parameters controlling this weathering (Bourgès, 2006). Such an approach has been widely used for testing building stone in the field of civil engineering and architecture (Nicholson, 2001; Benavente et al., 2004; Angeli et al., 2007; Yu and Oguchi, 2009; 2010).

In this work, the changes in stone properties upon artificial weathering by salt crystallization test are studied in order to provide the necessary information for understanding and assessing the deterioration of the selected stones and their durability.

2. Materials and Methods

To study the effects of artificial weathering on the properties of stone, five samples of limestone and basalt were selected. The petrographic properties of these stone samples are described in table 1 and table 2 below.

Table 1. The petrographic description of the limestone samples

Sample	*Site*	*Geological formation*	*Microstructure*	*Porosity*	*Color*
LA	Ajlun	Wadi As-Sir Limestone Formation	Massive unfossiliferous recrystallised sparry limestone	Differential intercrystalline porosity	Yellowish grey
LJ1	Jarash	Na'ur Limestone Formation	Dolomitic intraclastic biosparite	Minor intercrystalline and intracrystalline porosity	Reddish yellow
LUQ1	Umm Qeis	Umm Rijam Chert Limestone	Sparse intrapelbiomicrite	Minor moldic porosity and intergranular micro-porosity	Whitish grey

Table 2. The petrographic description of the basalt samples

Sample	*Site*	*Stone type*	*Texture*	*Phenocrysts*	*Groundmass*	*Porosity*
BUQ	Umm Qeis	Early Pliocene (Plateau basalt)	Doleritic medium-grained with sub-ophitic texture	Olivine, plagioclase and some carbonate	Plagioclase, pyroxene, some olivine, carbonate, opaque minerals and apatite	Secondary, Some pores contain carbonates
BUE	Umm El-Jimal	Late Tertiary (Neogene) basalt	Ol-doleritic medium-grained	Olivine and plagioclase	Pyroxene, some olivine, carbonate and opaque minerals	Secondary, Some pores contain carbonates

These stone samples were artificially weathered by salt crystallisation test which was carried out by total immersion in a solution of sodium sulfate decahydrate ($Na_2SO_4 \cdot 10H_2O$) according to the standard test DIN EN 12370. 25 salt weathering cycles were performed on the limestone and basalt samples. At the end of the test, the samples were submerged in distilled water that was changed daily before eventually rinsed thoroughly in water to remove all the salt from their pores. The samples were finally dried in oven and the loss of stone material after the test is calculated from the change in the mass of specimen as a percentage of initial mass.

Different laboratory tests were carried out to characterise these stone samples and to study their properties before and after salt weathering test. The porosity and pore structure properties were measured by water absorption method (according to the RILEM standards) and Mercury intrusion porosimetry (MIP). MIP measurements were carried out using the porosimeter combination PASCAL 140/240 (from Porotec) with a pressure in the range from 10 Pa to 200 MPa, whereby pore radii in the range of about 58 µm–3.7 nm can be measured.

The biaxial flexural strength (β_{BFS}) and static modulus of elasticity (E_{stat}) of the studied stones were measured on 5 mm thick drill core slices following the method of Wittmann and Prim (1983). Measurements were performed using a universal *Zwick Z010* apparatus with a preload of 5 N at a rate of 0.5 mm/min.

The velocity of longitudinal ultrasonic waves (V_p) was measured with portable ultrasonic device UKS 12 from Geotron-Elektronik. The system is composed of an ultrasonic generator USG 20 and 50 MHz Philips scopemeter. The dynamic modulus of elasticity (E_{dyn}) was determined on prismatic specimens by the extensional wave measurement procedure (Erfurt and Krompholz, 1996), which involves measurements of the travel time of longitudinal wave and the resonance frequency of the base extensional wave. Measurements were carried out using the portable ultrasonic system UKS 12 with USG 30 ultrasonic generator and 100 MHz Fluke 99B scopemeter.

The fracture density (F_D) of the stones was also measured. It is a measure of the total surface area of fractures per unit volume of stone (Nicholson, 2001). It affects the mechanical strength of the stone and its other properties, particularly the elastic properties. The fracture density can be estimated using the following stereological equation (Karcz and Dickman, 1979).

(1)

= fracture density (fracture surface area per unit volume) [mm^2/mm^3]; = number of point intersections of fractures per unit length of grid line [mm^{-1}].

3. Results and Discussion

The properties of the studied limestone and basalt samples before and after salt weathering test are described below.

3.1 Visual examination

The stone samples were visually inspected during and at the end of the weathering test. Signs of damage started to appear on the stones beginning from the 5th weathering cycle. Besides salt efflorescence which appeared on all stone samples and which could be removed by washing, some samples suffered other forms of weathering. For example, some macrocracks started to appear on the limestone samples LJ1 and LA after the 5th and 8th cycle respectively. Sample LUQ1 started to disintegrate gradually, indicating an ongoing loss of cohesion between grains.

At the end of salt crystallisation test, the limestone samples exhibited two different weathering behaviors. The two samples LA and LJ1 were subject to fracturing without significant loss of stone material. On the contrary, the sample LUQ1 showed mainly granular disintegration and preferential weathering in form of pitting, and suffered relatively greater loss of stone material. The basalt samples exhibited no considerable macroscopic signs of damage.

3.2 Porosity and pore size distribution

The limestone samples exhibited a slight continuous increase in total accessible porosity (N_t) with increasing number of weathering cycles. The accessible porosity after 25 weathering cycles increased by 10%, 3% and 2% for samples LA, LJ1 and LUQ1 respectively. This indicates a continuous breaking up of grain contacts due to weathering, leading thereby to the development and enlargement of cracks and pores (Fitzner, 1988). On the other hand, the basalt samples showed a decrease in porosity, particularly at the beginning of the test. This might be attributed to pore-clogging by trapped salt crystals (Nicholson, 2001; Yu and Oguchi, 2010). Table 3 shows the MIP porosity values and the pore size distribution of the samples before and after salt weathering test.

Table 3. Mercury intrusion porosimetry data of the stones before (B) and after (A) salt weathering

Sample		*LA*		*LJ1*		*LUQ1*		*BUE*		*BUQ*	
		B	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*	*A*
Pore class [%]	*r<0 .01 µm*	0.00	0.42	1.40	3.79	1.18	7.21	0.00	4.19	0.00	3.56
	0.01-0.1µm	2.43	9.16	23.96	17.75	63.60	73.92	3.03	4.02	5.07	6.76
	0.1–1 µm	14.39	18.09	61.43	63.90	13.37	8.51	5.68	8.47	13.21	12.14
	1–10 µm	61.46	29.29	3.50	8.52	11.35	4.97	30.27	25.82	30.95	23.94
	10–100 µm	21.72	43.03	9.71	6.04	10.50	5.39	61.01	57.50	50.77	53.60
Avg. pore radius [µm]		4.89	41.09	0.23	0.30	0.03	0.04	41.07	61.87	33.60	41.08
Total porosity (P_c) [%]		7.45	12.23	5.87	9.63	6.24	11.48	6.87	3.93	4.47	3.77
Specific surface area [m²/g]		0.06	0.39	0.50	1.07	1.02	3.14	0.05	0.22	0.05	0.24
Microporosity ($P_{m0.1}$) [%]		0.18	1.17	1.49	2.07	4.05	9.31	0.21	0.32	0.23	0.39
$P_{sCap.}$ (0.1<r<5 µm) [%]		4.10	4.50	3.64	6.76	1.33	1.36	1.59	0.92	1.56	1.00
P_{m5} (r <5 µm) [%]		4.28	5.67	5.13	8.83	5.38	10.68	1.80	1.25	1.78	1.39
$P_{L.Cap}$ (r >5 µm) [%]		3.17	6.56	0.74	0.79	0.87	0.80	5.07	2.68	2.69	2.38

In general, salt appeared to crystallise in pores of varied sizes and modified them in different ways. Pore enlargement and crack developments can be seen in all weathered samples, albeit to varying extents. In the basalt samples, salt remained trapped in pores even after extensive rinsing with water. The remaining salt was either deposited in pore entries resulting in peak shifts towards smaller pores or inside pore cavities reducing thereby the total pore volume, particularly the volume of capillary pores.

3.3 Fracture density

The sound limestone samples showed varying degrees of cracking with the highest fracture density being 0.018 mm²/mm³ for LA. The fracture density of the limestone samples increased continuously with increasing number of weathering cycles. The samples LJ1 and LA suffered substantial fracturing with percentage increase of 165% and 90% respectively. The sample LUQ1 exhibited a relatively lower percentage of increase in fracture density (35%). The basalt samples, however, showed no visible macrocracks within 25 cycles of salt weathering.

3.4 Biaxial flexural strength and moduli of elasticity

The biaxial flexural strength (β_{BFS}) and moduli of elasticity (E_{stat} and E_{dyn}) of the stones before and after weathering are shown in table 4. All the samples showed a decrease of biaxial flexural strength after weathering. This is clearly evident for the limestone samples LA and LJ1, which underwent percent decrease of 40% and 30% respectively. A corresponding decrease in the static modulus of elasticity of all weathered samples is also evident, particularly for the samples LA and LJ1. The elastic and mechanical properties of a stone are highly influenced by microcracks and fracture density (Walsh, 1982). Therefore, the reduction in biaxial flexural strength and elasticity modulus was higher for the stone samples which were subject to greater fracturing and microcracking (LA and LJ1) as indicated by fracture density and MIP measurements. The dynamic modulus of elasticity of the stones was also reduced after weathering. However, the reduction in the static modulus of elasticity was much greater.

Table 4. Biaxial flexural strength and moduli of elasticity before and after salt weathering

Sample		*β_{BFS} [N/mm²]*	*E_{Stat} [kN/mm²]*	*E_{Dyn} [kN/mm²]*	*$\Delta\beta_{BFS}$ [%]*	*ΔE_{Stat} [%]*	*ΔE_{Dyn} [%]*
LA	*Before*	15.45±1.54	64.90±18.74	37.38±11.35	-40	-48	-9
	After	9.24±3.82	33.51±8.91	34.04±9.49			
LJ1	*Before*	18.53±3.64	96.38±14.83	68.72±3.18	-30	-55	-2
	After	12.91±3.48	42.95±16.15	67.27±5.12			
LUQ1	*Before*	17.36±1.91	67.54±13.20	49.54±4.94	-13	-10	-4
	After	15.06±3.98	60.52±4.78	47.57±4.75			
BUE	*Before*	20.01±1.06	115.89±20.85	64.66±4.60	-17	-35	-1
	After	16.69±3.01	75.27±21.89	63.80±4.97			
BUQ	*Before*	19.74±0.65	114.22±11.51	58.70±3.72	-13	-4	0
	After	17.10±3.23	109.54±17.67	58.70±3.24			

3.5 Total loss of stone material

The total loss of stone material (or dry weight loss DWL) is the parameter most frequently used to evaluate salt damage to building stone in durability tests (e.g. Benavente et al., 2004; Yu and Oguchi, 2009; 2010). The dry weight loss was calculated for cubic and prismatic specimens after extensive desalination with water and drying to constant mass by comparing the initial and final mass (Tab. 5).

Table 5. Total dry weight loss (DWL) after 25 cycles of salt weathering

Sample	*DWL [%]*	
	Cubes	*Prisms*
LA	0.241 ± 0.050	0.536 ± 0.056

LJ1	0.160 ± 0.022	0.344 ± 0.044
LUQ1	2.222 ± 0.608	2.065 ± 0.464
BUE	0.170 ± 0.009	0.248 ± 0.076
BUQ	0.098 ± 0.006	0.259 ± 0.040

Except for the heterogeneous allochems-rich sample LUQ1, the prismatic specimens were subject to slightly greater loss of material compared to the cubic ones. This might be attributed to the smaller dimensions of these specimens and their geometry, which facilitate the evaporation and crystallisation of salt and make them thereby more prone to damage during the drying phase (Angeli et al., 2007).

However, the ranking of the stone samples with respect to weight loss is the same for cubic and prismatic specimens. Sample LUQ1 exhibited the greatest loss of stone material, followed by LA and LJ1 and finally the basalt samples.

In terms of total dry weight loss, the studied stones showed generally quite good resistance to 25 cycles of salt weathering. This might be attributed to their relatively low porosity, pore space characteristics, and good mechanical resistance.

3.6 Ultrasonic velocity

The velocity of longitudinal ultrasonic waves (V_p) was measured on cubic specimens of each sample along three orthogonal directions before and after weathering. The anisotropy of each specimen was calculated from the maximum and minimum velocity measured in the different directions. Measurements were carried out both in dry and water saturation conditions. The results are shown in table 6.

Table 6. Ultrasonic pulse velocity in dry and water saturated cubes before and after 25 salt weathering cycles

Sample		*V_p-dry [m/s]*	*Anisotropy [%]*	*V_p-saturated [m/s]*	*$\Delta V_{p(sat-dry)}$ [%]*
LA	*before*	4676 ± 200	3.93	5042 ± 194	7.84
	after	3653	7.70	4806	31.55
LJ1	*before*	5185 ± 343	3.02	5258 ± 365	1.41
	after	4699	4.42	5084	8.19
LUQ1	*before*	4598 ± 124	3.32	4661 ± 110	1.38
	after	4257 ± 304	0.78	4470 ±197	5.01
BUE	*before*	5098 ± 97	1.43	5196 ± 30	1.92
	after	4913	1.10	4968	1.11
BUQ	*before*	5125 ± 112	1.57	5218 ± 116	1.82
	after	4969	2.11	5023	1.10

The limestones, and to a lower extent the basalt samples, showed slight anisotropy (up to 5%). The anisotropy of the samples LA and LJ1 increased after weathering, which might indicate preferred fracturing and crack propagation along certain directions. The other samples showed generally a decrease in anisotropy after weathering.

For all stone samples, the velocity of longitudinal ultrasonic waves in water saturated specimens is higher than that in dry specimens. The increase of velocity in water saturated specimens before weathering was below 2% for all the stone samples, except sample LA which showed an increase of 7.84%. This sample exhibited already the highest fracture density.

After weathering, all the samples showed a reduction in ultrasonic velocity due to development and widening of cracks and fissures. The stones with the highest degree of cracking (LA and LJ1) suffered the highest reduction in ultrasonic velocity. These samples showed also a considerable increase of velocity in water-saturated specimens compared to dry ones. This confirms the mitigation of the influence of cracks on ultrasonic velocity in water saturated stones.

The basalt samples exhibited a lower reduction in ultrasonic velocity after weathering. No visible fracturing could be noticed in these samples and the damage in stone structure was limited; only small proportions of cracks that might affect ultrasonic velocity were developed after weathering as shown by MIP results. The increase in ultrasonic velocity in water-saturated condition for the basalt samples was lower after weathering, probably because of the reported reduction in porosity.

3.7 Estimation of stone susceptibility to salt damage

In this section, the susceptibility of the studied stone samples to salt damage is going to be estimated based on their properties in the sound condition. The aim is to develop durability estimators from the physico-mechanical properties of the sound stone that can be used to predict and assess stone resistance to damage without the need for performing the time-consuming and costly accelerated weathering tests. This can be useful for durability tests that are intended to test the resistance of building stone to damage for a particular use under certain environmental conditions. It has also important applications in the field of conservation for replacing damaged stones and selecting suitable restoration materials.

For this purpose, the physico-mechanical properties of the stone samples before weathering are characterised and the induced damage after salt weathering test is to be evaluated using suitable parameters. Many studies have been dedicated to develop durability estimators from the different properties of stone and its pore structure characteristics (e.g. Benavente et al., 2004; Yu and Oguchi, 2009; 2010). In most of these studies, total dry weight loss (DWL) of stone is the only parameter used to indicate damage. A few authors have been considering the use of other additional parameters to provide a more reliable assessment of damage. For example, Nicholson (2001) used the change in fracture density besides DWL to evaluate damage. Angeli et al. (2007) proposed two parameters to quantify the alteration and weathering of stone.

In this study, the total dry weight loss (DWL) and the change in fracture density (ΔF_D) after weathering are used to indicate the damage induced in the tested stones in 25 cycles of salt weathering. These damage indicators are correlated with the petrophysical and mechanical properties of stone before weathering in order to understand the influence of the various properties on stone susceptibility to deterioration and to develop suitable durability estimators. Table 7 lists the Pearson correlation coefficients between total dry weight loss (DWL), percentage change of fracture density ($\%\Delta F_D$) and some physico-mechanical properties of stone.

Table 7. Pearson correlation coefficients between stone damage and physico-mechanical properties

	DWL	$\%\Delta F_D$	N_{48}	$W_{abs.48}$	$P_{m0.1}$	P_{Cap}	P_{m5}	β_{BFS}	E_{stat}	E_{dyn}	$V_{P\text{-}dry}$	ΔV_P
DWL	1.00											
$\%\Delta F_D$	-0.16	1.00										
N_{48}	0.96	0.12	1.00									

$W_{abs.48}$	0.96	0.12	1.00	1.00								
$P_{m0.1}$	0.94	0.10	0.99	0.99	1.00							
P_{Cap}	-0.72	0.03	-0.75	-0.74	-0.83	1.00						
P_{m5}	0.56	0.71	0.75	0.76	0.71	-0.41	1.00					
β_{BFS}	-0.30	-0.44	-0.35	-0.37	-0.22	-0.15	-0.68	1.00				
E_{stat}	-0.59	-0.37	-0.63	-0.65	-0.52	0.14	-0.80	0.95	1.00			
E_{dyn}	-0.31	0.07	-0.20	-0.23	-0.08	-0.19	-0.28	0.86	0.80	1.00		
V_{P-dry}	-0.72	0.07	-0.63	-0.65	-0.52	0.15	-0.53	0.80	0.90	0.87	1.00	
$\%\Delta V_P$	-0.26	0.20	-0.29	-0.26	-0.42	0.68	0.11	-0.78	-0.55	-0.80	-0.49	1.00

In terms of total dry weight loss (DWL), stones with high values of water absorption (W_{abs48}) (or free porosity (N_{48})), saturation coefficient, and microporosity, as well as low values of ultrasonic velocity showed generally higher degrees of damage. In its turn, fracture density influences mainly the mechanical and elastic properties of stone; higher fracture density implies lower strength, moduli of elasticity (particularly static modulus) and ultrasonic velocity. The increase in fracture density is also responsible for the increased difference between ultrasonic velocity in dry and water saturation conditions.

Based on the above mentioned correlations with stone properties, durability estimators for damage as indicated by DWL and change in fracture density are proposed. The dry weight loss in the tested stones (DWL) correlates very well with the product of microporosity (in this study $P_{m0.1}$ ($r < 0.1$ µm)) and water absorption (W_{abs48}), that is with (W_{abs}* P_{micro}); the Pearson correlation coefficient $r = 0.98$.

This durability estimator can be well interpreted by considering the nature of stress from salt crystallisation on pore walls and the influence of pore structure characteristics. Sufficiently high stresses to damage stone are mainly expected in very small pores. Micropores facilitate, therefore, the generation of high crystallisation pressure and have to be considered for estimating the durability of stone. On the other hand, the capacity of stone to absorb water (or its free porosity) determines the uptake of salt and contributes correspondingly to stone damage.

This implies that stones which have both considerable amount of micropores and large free porosity are more susceptible to damage by salt crystallization. This agrees partly with the classical idea that stones with higher amounts of micropores are more susceptible to damage. However, this idea is valid as long as we are comparing stones with nearly the same porosity. Cardell et al. (2003) and Buj and Gisbert (2010) found that stones with high porosity and low proportions of micropores are more susceptible to salt weathering than stones with low porosity and higher proportions of micropores. This estimator takes into account both the microporosity of stone (the proportion of micropores expressed as a percentage of total porosity) and its water absorption (or free porosity), and it seems to provide a reliable estimation of the resistance of stone to salt weathering and its durability.

The fracturing behavior of stone depends on its mechanical and elastic properties. The percentage increase of fracture density ($\%\Delta F_D$) of the tested stones in this study correlates very well ($r = 0.99$; $R^2 = 0.98$) with the estimator that represents the multiplication product of the porosity of small capillaries (P_{sCap}), the ratio of micropores smaller than 5 µm (P_{m5}) to total accessible porosity (N_t), and the ratio of the dynamic modulus of elasticity to the static one (E_{dyn}/E_{stat}), that is [P_{sCap}*(P_{m5}/ N_t)*(E_{dyn}/E_{stat})].

This could be interpreted as follows: P_{sCap} ($0.1 < r < 5$ µm) expresses the ratio of small capillary pores which control salt uptake. Small capillaries seem to be the most effective pores in salt absorption, and they work synergistically with micropores under equilibrium conditions to induce damage (Yu and Oguchi, 2010). P_{m5} ($r < 5$ µm) indicates the proportion of micropores and small capillaries, where salt precipitation mainly occurs (Zehnder and Arnold, 1989; Yu and Oguchi, 2010). These pores are subject to greater crystallisation pressure, and they are particularly important for salt uptake by total immersion (Yu and Oguchi, 2010). The fraction of these pores to total porosity (P_{m5}/N_t) may thus determine the extent of the stress field, i.e. the area of pore walls that is subject to stress. As pointed out by Scherer (1999), stress from salt crystallization must spread over a sufficiently large area of the porous network to allow for crack development and propagation; stress generated in single pores cannot induce fracturing. The ratio of the dynamic modulus of elasticity to the static one (E_{dyn}/E_{stat}) may reflect the degree of fracturing, because microcracks seem to influence E_{stat} more than E_{dyn}. The variation between the two moduli becomes larger with increasing microcracking and may thus be used to indicate the amount of available microcracks in the stone. As an alternative to the ratio (E_{dyn}/E_{stat}), the percentage difference in ultrasonic pulse velocity between dry and water-saturated conditions can be used to estimate the density of open cracks of stone in a non-destructive and simple way. In dry specimens, ultrasonic velocity depends on the intrinsic characteristics of the stone and its pore space. In water saturated conditions, the effects of pore structure on the propagation of ultrasonic waves is mitigated and the measured velocity is more related to the intrinsic velocity of the stone (Strohmeyer, 2003). The difference between these two velocities provides, therefore, information about the pore space of stone and can be used to estimate fracture density (Schild et al., 2001; Strohmeyer, 2003).

As fractures propagate progressively, stone might be prone to greater loss of material due to the loosening of stone structure (splitting of larger pieces may then occur). At this stage, DWL may implicitly reflect the degree of cracking and could be solely used to indicate damage. Fracture density can be mainly seen as a separate indicator at the early stages of weathering. In this connection, Nicholson and Nicholson (2000) point out that pre-existing cracks are particularly important in the deterioration of stronger stones, whereas their direct influence diminishes in weaker ones as the influence of other properties and factors is more relevant.

4. Conclusions

The aim of this study was to investigate archeological stone samples from jordan with physico-mechanical methods and ultrasonic technique in order to study their deterioration upon accelerated weathering and to assess their durability. The selected stone samples were characterised by physico-mechanical methods and their microstructure was studied.

The study of the changes in the properties of the stone samples upon artificial weathering by salt crystallisation test helps to understand their weathering behavior and to evaluate their resistance to deterioration. The studied limestone samples exhibited weathering in form of granular disintegration and pitting or cracking. The damage induced in the stones after salt crystallisation test was evaluated by two indicators; total dry weight loss of stone material (DWL) and change in fracture density (ΔF_D). On the one hand, the petrophysical properties of the stones seemed to be very important for determining their susceptibility to salt damage. The proportion of micropores and the water absorption capacity (or free porosity) of the stones were the most important parameters that determined the induced damage in terms of DWL. On the other hand, the mechanical and elastic properties were not directly correlated with stone damage indicated by loss of stone material. These properties were instead more related to the fracturing behavior of the stones.

Based on these results, durability estimators were developed to assess the susceptibility of stone to weathering. The size of the samples used to develop these estimators was, however, small. Further research with a larger number of samples and various stone varieties would be required for confirming the results.

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