Limestone weathering on historical monuments in Cairo, Egypt

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Abstract: Since Pharaonic times local limestones have been used in Cairo for monument construction. Weathering damage on many historical stone monuments in Cairo is alarming. Studies on properties and weathering behaviour of the limestones were carried out by means of laboratory tests and in situ investigation of many historical monuments. The laboratory studies reveal for the Middle Eocene limestones considerable petrographical variations. The limestone weathering was assessed with respect to weathering forms, weathering products and weathering profiles. A classification scheme of weathering forms and their intensities was tailored to optimal applicability for all Cairo historical monuments constructed from limestones. Monument mapping has been applied for the detailed registration of weathering forms and as a basis for the quantitative rating of stone damage by means of damage categories and damage indices. For the historical monuments in the centre of Cairo the combined evaluation of weathering forms, weathering products and weathering profiles shows clear correlations between the development of weathering damage and salt loading of the limestones as a consequence of air pollution and rising humidity. They exhibit the need and urgency of monument preservation measures.

In Greater Cairo, Egypt (comprising the governorates of Cairo, Giza and Qalubiyya) are located monuments of outstanding historical and artistical importance, ranging from pharaonic monuments to Roman, Coptic and Islamic monuments (Fig. 1). The pyramids of Giza as part of ancient Memphis, the capital of the Old Kingdom of Egypt, represent the most famous pharaonic monuments. In ancient time, the pyramids were considered one of the Seven Wonders of the World. In 1979 UNESCO inscribed the 'extraordinary funerary monuments of Memphis and its necropolis' into the World Heritage List. Only few Roman and Coptic monuments have remained in Cairo city, located in the quarter of Old Cairo. The Islamic monuments represent the main group of historical monuments in Cairo. More than six hundred Islamic monuments are concentrated in the centre of Cairo (Fig. 2). The majority of these monuments such as mosques, madrasas, city walls, gates, fortifications, aqueducts, monumental tombs, palaces, minarets, domes, residences, warehouses, hospitals or fountains date back to the periods of the Fatimids, Ayyubids, Mamluks and Ottomans (Behrens-Abouseif 1992; Williams 1993). In 1979 Islamic Cairo was inscribed by UNESCO into the World Heritage List as 'one of the world´s oldest

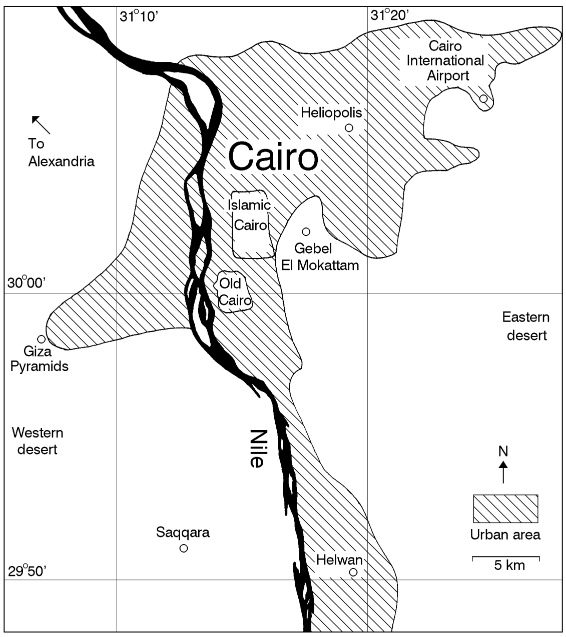


Fig. 1. Greater Cairo.

Islamic cities, which – founded in the 10th century – became the new centre of the Islamic world, reaching its Golden Age in the 14th century'.

Tertiary porous limestones from local quarries have been used for construction of monuments in Cairo since Pharaonic times until today (Fig. 3). In monument preservation practice the limestones are still used for stone replacement or rebuilding works at Cairo historical monuments. Porous limestones represent a stone type that was commonly used for the construction of historical monuments in the whole Mediterranean area.

Fig. 2. Islamic centre of Cairo

Fig. 3. Limestone quarry, Mokattam mountains west of Cairo city.

Fig. 4. El-Merdani Mosque.

Fig. 5. Weathering damage on a lower part of the El-Merdani Mosque.

Many historical limestone monuments in the Cairo area are seriously threatened by damage and are in need of intervention. Stone weathering represents an important cause of damage. Systematic studies were carried out for the petrographical characterization of the limestones and for the analysis of their weathering behaviour. These studies comprised laboratory analyses of the limestones and in situ investigation of quarries and Islamic monuments and, additionally, pilot studies of the Giza pyramids. The in situ investigation included survey, classification and mapping of weathering forms and in situ measurements. Very detailed studies were carried out on the El-Merdani Mosque in the frame of the Concerted Action 'Study, characterization and analysis of degradation phenomena of ancient, traditional and improved building materials of geologic origin used in the construction of historical monuments in the Mediterranean area' (ERB-IC18-CT98-0384), funded by the European Commission. The El-Merdani Mosque in the quarter of Tabbana was built in the 14th century as one of the finest examples of Islamic architecture in Cairo (Fig. 4). The mosque was restored a century ago by the Arab Antiquities Conservation Committee (Williams 1993). Preservation measures such as reconstruction, structural reinforcement and renovation of walls were carried out, but today the mosque is again in need of intervention. Especially, the considerable weathering damage on the lower parts of the monument is striking (Fig. 5). This state of damage is very characteristical for many Islamic monuments in the centre of Cairo (Fig. 6 and 7).

In the following results are presented on provenance and petrographical properties of the limestones used in the construction of the historical Cairo monuments, on weathering forms, weathering profiles and weathering products and on causes, development and rating of weathering damage on the monuments.

Fig. 6. Weathering damage. Mausoleum of Sultan Al-Mansur Qalawun.

Provenance, stratigraphy and petrographical properties of the limestones

Eocene outcrops in the area of Greater Cairo predominantly provided the limestones for the construction of the historical stone monuments in this region. Especially, these were the Mokattam limestone plateau east of Cairo city, the Helwan limestone plateau in the southeast and the Giza limestone plateau in the western part of Greater Cairo (Fig. 1). The pyramids mainly were constructed from local Giza limestones. Limestones from the Mokattam area were used additionally, like for the facing dimension stones of the Great Pyramid of Cheops (Khufu), only few of which have remained (Klemm & Klemm 1993). In the Mokattam area and in the Helwan area limestones were quarried for the historical monuments in Cairo city. They are still being used for stone replacement or rebuilding works at these monuments as well as for modern buildings (Fig. 8 and 9).

The following information on the geological setting refer to Said (1990). Most of the limestones used on historical monuments in Greater Cairo are related to the Mokattam Group of the Middle Eocene (Fig. 10). The Gebel Mokattam represents the type locality of this group. The Mokattam Group is subdivided into the older Mokattam Subgroup and the younger Observatory Subgroup. Type section of the Observatory Subgroup is the Observatory plateau at Helwan. At Gebel Mokattam the Mokattam Group comprises from bottom to top the two formations of Lower Building Stone and Gizehensis (Mokattam Subgroup) and the two formations of Upper Building Stone and Giushi (Observatory Subgroup). The Mokattam Subgroup does not seem to have an equivalent in the Helwan area. The Observatory Subgroup at Helwan is subdivided into Gebel Hof formation and Observatory formation. The Gebel Hof formation and the lower part of the Observatory formation are correlated with the Upper Building Stone formation at Gebel Mokattam, the upper part of the Observatory formation with the Giushi formation. The thickness of the beds of the Observatory Subgroup at Helwan is significantly greater than at Gebel Mokattam. At Giza the Mokattam Subgroup comprises the Mokattam formation. The lowermost members of this unit are considered as the oldest section of the entire Cairo area. Beds equivalent to the Observatory Subgroup are very thin at Giza. The Subgroup comprises the Observatory formation which correlates with the Upper Building Stone formation at Gebel Mokattam, whereas the presence of beds equivalent to Giushi formation is still questionable.

Fig. 7. Weathering damage and elevated water table. Mausoleum of Sultan Al-Mansur Qalawun.

Fig. 8. Stone replacement. Hospital of Sultan Al-Mansur Qalawun.

Laboratory studies were carried out on limestones from quarries at Gebel Mokattam and at Helwan, from outcrops at the Giza plateau and from El-Merdani Mosque in the Islamic center of Cairo. The limestones from the Helwan area are currently used for the restoration of monuments in the centre of Cairo. Results on mineral composition and classification of the limestones – based on microscopical studies – are presented in Table 1. All limestones can be characterized as almost pure limestones. Calcite $CaCO_3$ represents the predominating carbonate mineral. As X-ray diffraction analysis has shown, dolomite $CaMg\ (CO_3)_2$ and ankerite $Ca(Mg, Fe)(CO_3)_2$ may occur subordinately as further carbonate minerals. The limestones – except some limestones from Gebel Mokattam – show low contents of quartz. A low content of opaque matter is characteristical for the limestones. Additionally, in most of the limestones small amounts of salt minerals - halite and / or gypsum - were detected by means of X-ray diffraction analysis. This confirms the findings of Elhefnawi (1998), according to which primary salts are very characteristical for the Eocene limestones in Egypt.

Petrographical variations of the limestones concern their proportions of the carbonate components micrite (microcrystalline carbonate), sparite (coarsely crystalline carbonate) and bioclasts (fossil fragments). According to the limestone classification established by Folk (1962), the limestones range from fossiliferous micrite to sparse biomicrite, packed biomicrite and poorly washed biosparite.

Fig. 9. Restoration works. Northern wall of Cairo.

Results on porosity properties of the limestones are presented in Table 2. They are based on the joint evaluation of data obtained by mercury porosimetry, nitrogen adsorption (BET-method) and transmitted light microscopy with image analysis.

The results reveal remarkable differences between the limestones regarding their porosity characteristics such as total porosity, pore size distribution, pore radius, radius of pore entries and pore surface. Further laboratory tests have shown that considerable differences between the limestones also concern their strength / hardness properties and their water absorption / desorption behaviour. Each region of origin (Mokattam, Helwan, Giza) is characterized by significant petrographical variations of its limestones. The case study of El-Merdani Mosque and the studies on many further monuments in Cairo have shown that different limestone varieties often were used at the same monument. Limestones with considerable petrographical variations are still used for monument restoration.

Weathering forms on the limestone monuments

Weathering forms are the visible result of weathering processes which are initiated and controlled by interacting weathering factors. By means of weathering forms the weathering state of stone surfaces can be described according to phenomenological-geometrical criteria at cm to m scale. Weathering forms represent an important parameter for the characterization, quantification and rating of stone deterioration.

GROUP	SUBGROUP	GEBEL	HELWAN	GIZA
MOKATTAM	OBSERVATORY	Giushi 33 m	Observatory 136 m	Giushi (?) Concealed
		Upper Building Stone 70 m	Gebel Hof 121 m	Observatory 16 m
	MOKATTAM	Gizehensis 6 m		Mokattam 90 m
		Lower Building Stone 27 m		

Fig. 10. Rock units of the Mokattam Group – Middle Eocene (Said 1990).

Table 1. *Mineral composition and classification of limestones used for construction or restoration of monuments in the Cairo area. Transmitted light microscopy*

Lithotype	Mineral composition (%)						Classification (Folk, 1962
		Calcite*		Quartz	Opaque Matter	Others**	
	Micrite	Sparite	Bioclasts				
Limestone M1		99		1	< 0.1	-	Poorly washed
	54	*39*	*6*				biosparite
Limestone M2		84		15	1	< 0.1	Poorly washed
	32	*17*	*35*			f, h	biosparite
Limestone M3		99		1	< 0.1	-	Poorly washed
	14	*12*	*73*				biosparite
Limestone M4		92		8	< 0.1	-	Poorly washed
	31	*34*	*27*				biosparite
Limestone M5		91		8	1	-	Poorly washed
	40	*29*	*22*				biosparite
Limestone H1		99		< 1	< 1	-	Sparse biomicrite
	70	*7*	*22*				
Limestone H2		99		< 1	< 0.1	-	Fossiliferous micrite
	66	*32*	*1*				
Limestone E1		99		< 1	1	-	Fossiliferous micrite
	73	*21*	*5*				
Limestone E2		99		< 1	< 1	-	Fossiliferous micrite
	72	*25*	*2*				
Limestone E3		99		< 0.1	1	-	Fossiliferous micrite
	88	*10*	*1*				
Limestone E4		98		1	1	-	Poorly washed
	26	*46*	*26*				biosparite
Limestone G1		99		1	< 1	-	Sparse biomicrite
	70	*5*	*24*				
Limestone G2		99		1	< 1	-	Sparse biomicrite
	52	*5*	*42*				
Limestone G3		99		< 1	< 1	-	Poorly washed
	23	*29*	*47*				biosparite
Limestone G4		99		< 1	< 1	-	Sparse biomicrite
	75	*6*	*18*				
Limestone G5		97		3	< 1	-	Packed biomicrite
	37	*8*	*52*				
Limestone G6		99		1	< 1	-	Poorly washed
	40	*27*	*32*				biosparite

* subordinately dolomite or ankerite may occur
** f – feldspar, h – heavy minerals.
Limestones M1 – M5: Quarries, Mokattam mountains. Limestones H1 – H2: Quarries, Helwan. Limestones E1 – E4: El-Merdani Mosque, Cairo. Limestones G1 – G6: Outcrops / pyramids, Giza plateau.

The objective and reproducible survey and evaluation of weathering forms require a standardized classification scheme of weathering forms. Such a classification scheme was developed, based on investigation of stone monuments worldwide considering different stone types and environments (Fitzner et al. 1995; Fitzner & Heinrichs 2002). Based on a systematic survey of weathering forms on historical monuments in Cairo (e.g. pyramids, tombs and temples at Giza, old wall of Cairo, aqueduct, city gates Bab Zuwayla, Bab al-Nasr and Bab al-Futuh, citadel, al-Aqmar mosque, complex of Sultan Al-Mansur Qalawun, al-Azhar mosque, Sultan Hasan mosque, Blue mosque, Sultan Barquq school, dome of Sultan Qansuwa Abu Said, madrasa and dome of Al Salih Nadjmed), this classification scheme of weathering forms was updated and tailored to optimal applicability at all Cairo historical ashlar monuments made of limestone. The optimization of the classification scheme for the Cairo monuments has included an intensity classification of the weathering forms.

Table 2. *Porosity properties of limestones used for construction or restoration of monuments in the Cairo area. Joint evaluation of data obtained by mercury porosimetry, nitrogen adsorption (BET) and transmitted light microscopy with image analysis.*

Lithotype	Total porosity (Vol.-%)	Porosity in pore radii classses 0.001-0.1 µm (Vol.-%)	0.1-10 µm (Vol.-%)	10-1000 µm (Vol.-%)	Median pore radius (µm)	Median radius of pore entries (µm)	Pore surface ($m^2 \cdot g^{-1}$ / $m^2 \cdot cm^{-3}$)
Limestone M1	18.6	1.5	14.0	3.1	2.2	0.7	1.8 / 4.0
Limestone M2	20.0	0.8	12.6	6.6	5.3	0.9	1.0 / 2.2
Limestone M3	25.3	0.9	6.4	18.0	39.0	1.1	1.4 / 2.7
Limestone M4	25.3	1.3	18.0	6.0	2.8	0.9	1.8 / 3.7
Limestone M5	26.8	1.8	19.4	5.6	2.7	0.7	2.9 / 5.9
Limestone H1	8.5	1.7	6.5	0.3	0.6	0.1	1.8 / 4.5
Limestone H2	37.4	5.1	28.1	4.2	1.2	0.8	7.2 / 12.3
Limestone E1	10.8	0.8	9.6	0.4	0.8	0.3	0.5 / 1.3
Limestone E2	22.0	1.0	17.5	3.5	2.1	1.0	0.5 / 1.1
Limestone E3	22.9	1.9	18.1	2.9	1.7	1.0	1.4 / 2.9
Limestone E4	24.5	0.5	6.3	17.7	40.0	5.7	0.3 / 0.6
Limestone G1	12.0	1.7	8.9	1.4	1.2	0.3	1.9 / 4.5
Limestone G2	18.6	1.3	11.0	6.3	5.0	0.9	1.4 / 3.2
Limestone G3	19.2	0.8	8.2	10.2	12.5	1.1	0.8 / 1.7
Limestone G4	24.8	2.0	20.8	2.0	1.3	0.5	3.3 / 6.8
Limestone G5	25.6	2.2	13.4	10.0	6.0	0.5	2.4 / 5.0
Limestone G6	34.1	1.2	27.0	5.9	2.4	1.0	2.1 / 3.9

Limestones M1 – M5: Quarries, Mokattam mountains. Limestones H1 – H2: Quarries, Helwan. Limestones E1 – E4: El-Merdani Mosque, Cairo. Limestones G1 – G6: Outcrops / pyramids, Giza plateau.

A section of the classification scheme summarizing the frequent weathering forms observed on the limestone monuments in Cairo is presented in Table 3. Examples of weathering forms are shown in Fig. 11-15. Examples of the intensity classification of weathering forms developed for the Cairo limestone monuments are presented in Table 4. The intensity classification has been differentiated for limestone monuments composed of small- to medium-sized dimension stones (Table 4, intensity classification A) and limestone monuments composed of huge dimension stones (Table 4, intensity classification B) considering the different ranges of intensities.

Based on the classification of weathering forms and their intensities, the monument mapping method was applied for registration, documentation and evaluation of weathering forms. The mapping method represents a non-destructive, well-established procedure, which allows to evaluate quantitatively complete stone surfaces according to type, intensity and distribution of weathering forms. It means an important contribution to rating of weathering damage, weathering prognosis, information on causes and processes of stone weathering and to sustainable monument preservation (Fitzner, Heinrichs & Kownazki 1995 and 1997). As an example for the computer-enhanced illustration of weathering forms registered by monument mapping the map of all weathering forms of group 1 – 'loss of stone material' is shown for a lower masonry part of the El-Merdani Mosque (Fig. 16 and 17). In the same way maps were prepared for all stone surfaces of monuments that were studied in Cairo showing the weathering forms of group 2 – 'discoloration / deposits', group 3 – 'detachment' and group 4 – 'fissures / deformation'. All weathering forms and their combinations were evaluated quantitatively.

Table 3. *Typical weathering forms on limestone monuments in Cairo.*

Groups of weathering forms	Main weathering forms		Individual weathering forms
	Terminology	Definition	
Group 1 – loss of stone material	Back weathering (W)	Uniform loss of stone material parallel to the original stone surface.	Back weathering due to loss of scales (sW), due to loss of crumbs (uW) or due to loss of crusts (cW).
	Relief (R)	Morphological change of the stone surface due to partial or selective weathering.	Rounding / notching (Ro), alveolar weathering (Ra), weathering out dependent on stone structure (tR), weathering out of stone components (Rk), clearing out of stone components (Rh).
	Break out (O)	Loss of compact stone fragments.	Break out due to anthropogenic impact (aO), due to constructional cause (bO) or due to natural cause (nO).
Group 2 – discoloration / deposits	Discoloration (D)	Alteration of the original stone color.	Coloration (Dc).
	Soiling (I)	Dirt deposits on the stone surface.	Soiling by particles from the atmosphere (pI) or from water (wI).
	Loose salt deposits (E)	Poorly adhesive deposits of salt aggregates.	Efflorescences (Ee), subflorescences (Ef).
	Crust (C)	Strongly adhesive deposits on the stone surface.	Dark-colored crust tracing or changing the morphology of the stone surface (dkC, diC), light-colored crust tracing or changing the morphology of the stone surface (hkC, hiC).
Group 3 – detachment	Granular disintegration (G)	Detachment of individual grains or small grain aggregates.	Granular disintegration into sand (Gs).
	Crumbly disintegration (P)	Detachment of larger compact stone pieces of irregular shape.	Crumbling (Pu).
	Flaking (F)	Detachment of small, thin stone pieces (flakes) parallel to the stone surface.	Single flakes (eF) or Multiple flakes (mF).
	Contour scaling (S)	Detachment of larger, platy stone pieces (scales) parallel to the stone surface, but not following any stone structure.	Single scales (eS) or multiple scales (mS).
	Detachment of crusts with stone material (K)	Detachment of crusts with stone material sticking to the crust.	Detachment of dark-colored crusts tracing or changing the morphology of the stone surface (dkK, diK), detachment of light-colored crusts tracing or changing the morphology of the stone surface (hkK, hiK).
Group 4 – fissures / deformation	Fissures (L)	Individual fissures or systems of fissures due to natural or constructional causes.	Fissures independent of stone structure (vL) or fissures dependent on stone structure (tL).

Classification of weathering forms based on Fitzner et al. (1995) and Fitzner & Heinrichs (2002)

Table 4. *Intensity classification of weathering forms on limestone monuments in Cairo. Examples: weathering forms 'relief' (R), 'break out' (O) and 'contour scaling' (S).*

Weathering form	Parameter for intensity classification	Intensity classification A*		Intensity classification B**	
Relief (R) Morphological change of the stone surface due to partial or selective weathering.	Depth d of relief (cm)	Intensity 1	$d \le 0.2$	Intensity 1	$d \le 5$
		Intensity 2	$0.2 < d \le 0.5$	Intensity 2	$5 < d \le 15$
		Intensity 3	$0.5 < d \le 1$	Intensity 3	$15 < d \le 25$
		Intensity 4	$1 < d \le 3$	Intensity 4	$25 < d \le 50$
		Intensity 5	$3 < d \le 5$	Intensity 5	$50 < d \le 75$
		Intensity 6	$5 < d \le 10$	Intensity 6	$75 < d \le 100$
		Intensity 7	$d > 10$	Intensity 7	$d > 100$
Break out (O) Loss of compact stone fragments.	Volume v of break out (dm^3)	Intensity 1	$v \le 0.01$	Intensity 1	$v \le 1$
		Intensity 2	$0.01 < v \le 0.125$	Intensity 2	$1 < v \le 10$
		Intensity 3	$0.125 < v \le 0.5$	Intensity 3	$10 < v \le 25$
		Intensity 4	$0.5 < v \le 1$	Intensity 4	$25 < v \le 50$
		Intensity 5	$v > 1$	Intensity 5	$50 < v \le 100$
				Intensity 6	$100 < v \le 250$
				Intensity 7	> 250
Contour scaling (S) Detachment of larger, platy stone pieces parallel to the stone surface, but not following any stone structure.	Thickness t of scales (mm)	Intensity 1	$t \le 2$	Intensity 1	$t \le 5$
		Intensity 2	$2 < t \le 5$	Intensity 2	$5 < t \le 10$
		Intensity 3	$5 < t \le 10$	Intensity 3	$10 < t \le 20$
		Intensity 4	$10 < t \le 20$	Intensity 4	$20 < t \le 50$
		Intensity 5	$t > 20$	Intensity 5	$t > 50$

* Intensity classification A: For limestone monuments composed of small to medium dimension stones, e.g. Islamic monuments in the center of Cairo
** Intensity classification B: for limestone monuments composed of huge dimension stones, e.g. pyramids of Giza

The investigation of weathering forms on limestone monuments in Cairo has shown a wide range of weathering forms and their intensities. Back weathering (W), relief (R) and break out (O) represent very frequent weathering forms characterizing loss of stone material. The depth of back weathering and relief on the monuments in the centre of Cairo may amount to more than 10 cm. Especially on the lower parts of many of these monuments very often the depth of relief and back weathering is strikingly high. On the huge dimension stones of the Giza pyramids relief and back weathering can occur with depths of even up to more than 1 m. Break out of compact stone fragments on the Cairo monuments as well as fissures (L) frequently indicate structural instabilities. The impact of earthquakes like in 1992 should be considered as additional cause of break out and fissures. According to Badawi & Mourad (1994) 140 Islamic monuments in Cairo were severely affected by this earthquake.

Soiling (I), loose salt deposits (E) and crusts (C) are the main weathering forms characterizing deposits on the monuments. Soiling by pollutants from the atmosphere – poorly adhesive, mainly grey to black deposits of dust and soot – and crusts are very characteristic for the monuments in the centre of Cairo, however, are less significant on the monuments in the outer parts of Greater Cairo like the Giza monuments. Dark grey to black crusts (Fig. 13) often affect especially the middle and upper parts of monuments in Cairo city, whereas compact whitish crusts (Fig. 14) as well as efflorescences mainly prevail on the lower parts of many monuments.

Granular disintegration (G), crumbly disintegration (P), flaking (F) and contour scaling (S) as well as transitional forms between these like granular disintegration to flaking (G-F), granular disintegration to crumbly disintegration (G-P), flaking to contour scaling (F-S), flaking to crumbly disintegration (F-P) or crumbly disintegration to contour scaling (P-S) represent very frequent weathering forms characterizing current detachment of stone material. Additionally, detachment of crusts with stone material (K) can be observed on many monuments in the centre of Cairo. The studies show some trend that increasing loss of stone material corresponds to decreasing size of detaching stone elements. This indicates an increasing incoherence of the stone components in the course of weathering progression.

Considerable loss and detachment of stone material not only affects the outer walls, but also inner walls of many monuments in Cairo city.

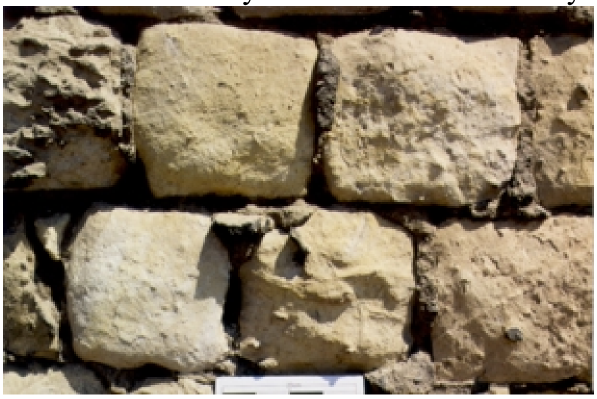


Fig. 11. Weathering form ‘relief (R)’. Image width appr. 90 cm.

Fig. 12. Weathering forms ‘back weathering (W)’, ‘crust (C)’ and ‘flaking (F)’. Image width appr. 70 cm.

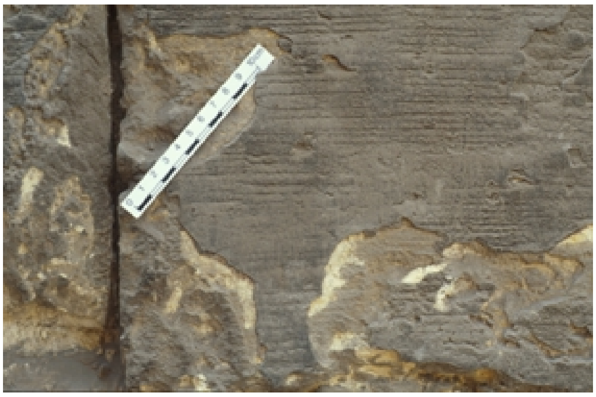


Fig. 13. Weathering forms ‘back weathering (W)’, ‘crust (C)’ and ‘detachment of crusts with stone material (K)’. Image width appr. 30 cm.

Fig. 14. Weathering forms ‘back weathering (W)’, ‘crust (C)’, ‘detachment of crusts with stone material (K)’ and ‘granular disintegration (G)’. Image width appr. 30 cm.

Fig. 15. Weathering forms 'relief (R)', 'break out (O)', 'crumbly disintegration (P)' and fissures (L)'. Image width appr. 70 cm.

Rating of stone damage

While weathering forms allow the detailed, objective and reproducible description and mapping of stone deterioration phenomena, damage categories and damage indices were integrated into the monument mapping method as tools for the rating of stone damage (Fitzner et al. in press, Fitzner & Heinrichs in press, Heinrichs & Fitzner 1999). For the rating of individual stone damage, six damage categories were defined: 0 – no visible damage, 1 – very slight damage, 2 – slight damage, 3 – moderate damage, 4 – severe damage, 5 – very severe damage. A correlation scheme of weathering forms and damage categories was developed for the limestone monuments in Cairo considering the high historical and artistical value of these monuments. In this correlation scheme, damage categories were proposed for all weathering forms in dependence upon their intensities. A section of this correlation scheme is shown in Table 5. The correlation scheme of weathering forms and damage categories was differentiated for limestone monuments composed of small to medium dimension stones and limestone monuments composed of huge dimension stones considering the different intensity ranges of several weathering forms. Based on the correlation scheme, damage categories were derived for all weathering forms and their combinations registered by means of monument mapping. The damage categories were illustrated in maps and were evaluated quantitatively. Maps of damage categories are shown for parts of the El-Merdani Mosque (Fig. 18) and the Great Pyramid of Cheops (Fig. 19-21) as examples.

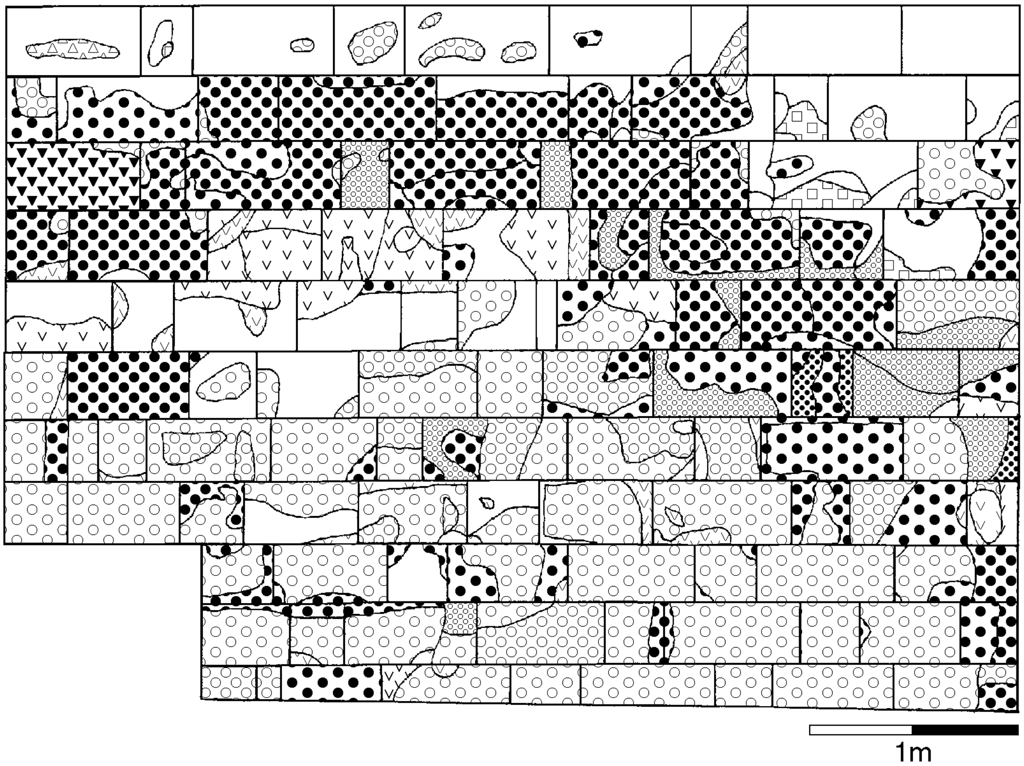
Fig. 16. El-Merdani Mosque - lower part of the SE-façade.

Table 5. *Correlation scheme for weathering forms and damage categories. Example: relating of the weathering form 'back weathering' (W) to damage categories considering different intensity ranges of the weathering form.*

Weathering form Back weathering (W)	Damage categories				
	1 very slight damage	2 slight damage	3 moderate damage	4 severe damage	5 very severe damage
Back weathering on small to medium dimension stones (e.g. Islamic monuments) *	$0 < d \leq 0.2$	$0.2 < d \leq 0.5$	$0.5 < d \leq 1$	$1 < d \leq 5$	$d > 5$
Back weathering on huge dimension stones (e.g. Pyramids of Giza) *	$0 < d \leq 5$	$5 < d \leq 15$	$15 < d \leq 25$	$25 < d \leq 50$	$d > 50$

* Values for depth d of back weathering (in cm)

Damage indices - linear damage index DI_{lin} and progressive damage index DI_{prog} - were calculated for conclusive quantification and rating of stone damage. Their calculation is based on the quantitative evaluation of the damage categories (Fig. 22). According to the calculation mode, both damage indices range between 0 and 5. The linear damage index corresponds to average damage category, whereas the progressive damage index emphasizes the proportion of higher damage categories. There is the following relation between the damage indices: progressive damage index ≥ linear damage index (Fitzner & Heinrichs 2002).



WEATHERING FORMS	INTENSITIES

Back weathering (W)	Intensities according to depth d of back weathering (cm)						
	Intensity 1 $d \le 0.2$	Intensity 2 $0.2 < d \le 0.5$	Intensity 3 $0.5 < d \le 1$	Intensity 4 $1 < d \le 3$	Intensity 5 $3 < d \le 5$	Intensity 6 $5 < d \le 10$	Intensity 7 $d > 10$
sW							
cW							
zW							

Relief (R)	Intensities according to depth d of relief (cm)						
	Intensity 1 $d \le 0.2$	Intensity 2 $0.2 < d \le 0.5$	Intensity 3 $0.5 < d \le 1$	Intensity 4 $1 < d \le 3$	Intensity 5 $3 < d \le 5$	Intensity 6 $5 < d \le 10$	Intensity 7 $d > 10$
Ro							

Break out (O)	Intensities according to volume v of break out (dm^3)				
	Intensity 1 $v \le 0.01$	Intensity 2 $0.01 < v \le 0.125$	Intensity 3 $0.125 < v \le 0.5$	Intensity 4 $0.5 < v \le 1$	Intensity 5 $v > 1$
oO					

Fig. 17. Map of weathering forms. Group 1 of weathering forms, 'loss of stone material'. El-Merdani Mosque, lower part of the SE-façade.

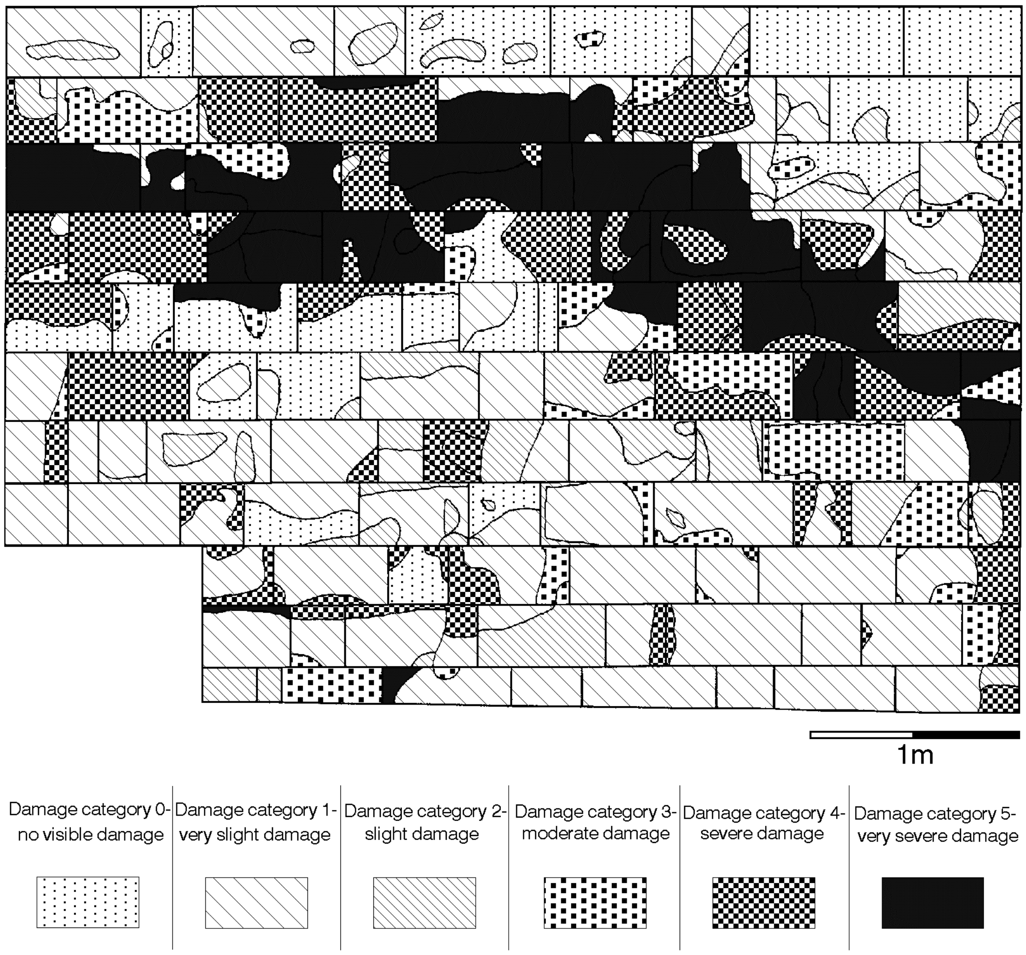


Fig. 18. Map of damage categories. El-Merdani Mosque, lower part of the SE-façade.

With respect to monument preservation, damage categories and damage indices are very suitable indicators for need and urgency of interventions. Maps of damage categories locate those parts of monuments on which interventions have to focus.

Examples of results on damage indices in addition to damage categories are presented considering: rating of stone damage for entire parts of monuments; characterization of damage zonation on monuments; and comparison of stone durability.

Visible stone damage was found on all historical limestone monuments in Greater Cairo. Regarding the monuments in Cairo city, considerable proportion of moderate, severe or even very severe stone damage (damage categories 3, 4 and 5) were found especially on the lower parts of the monuments. The linear damage index DI_{lin} calculated for such lower parts ranges between 2.2 and 3.1, the progressive damage index DI_{prog} between 2.6 and 3.2. Considering the range of the damage indices between 0 and 5.0 per definition, these results indicate a rather alarming state of damage and the need and urgency of preservation measures. Frequently, a zonation of damage was observed at these lower parts of the monuments in Cairo city, very similar to the example shown in Fig. 18 for the El-Merdani Mosque: a lower zone with mainly very slight, slight or moderate damage, a middle to upper zone with mainly severe or even very severe damage and an uppermost zone with mainly very slight or slight damage.

Fig. 19. Great Pyramid of Cheops, Giza (investigation area marked).

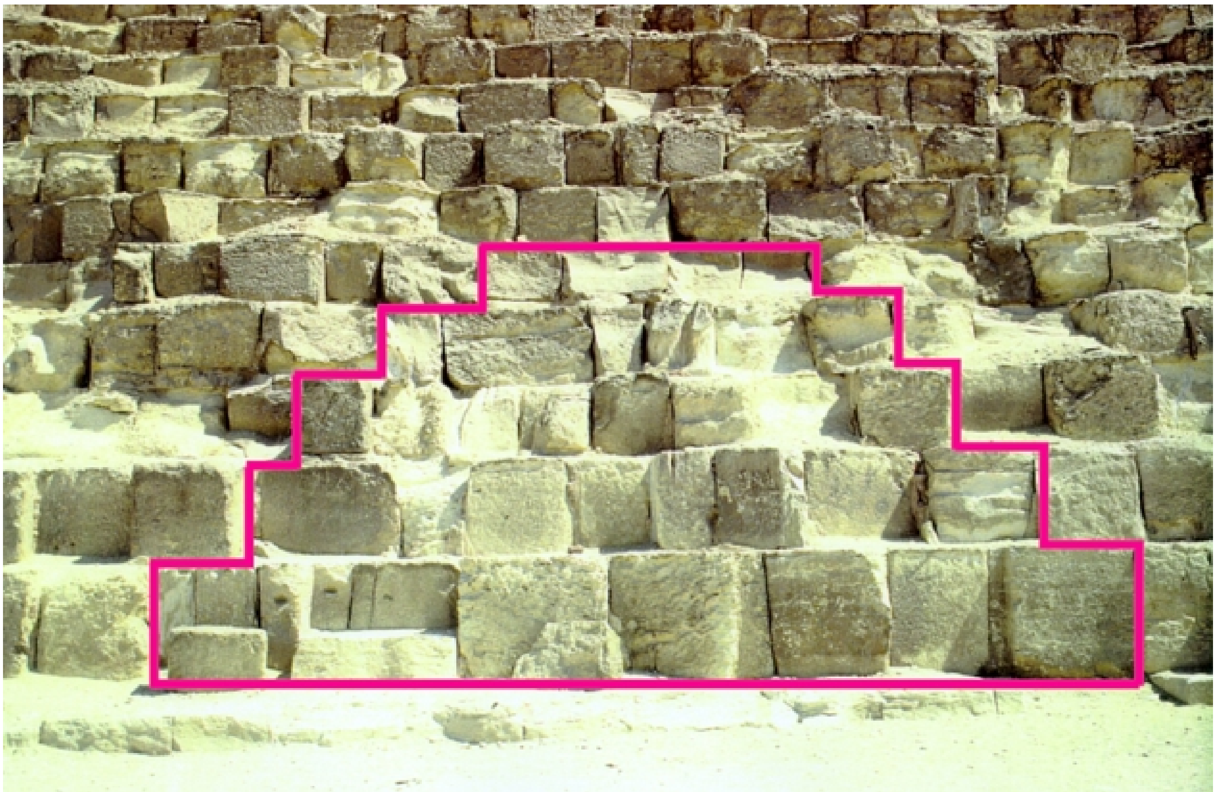


Fig. 20. Great Pyramid of Cheops, lower part of the southern side
(investigation area marked).

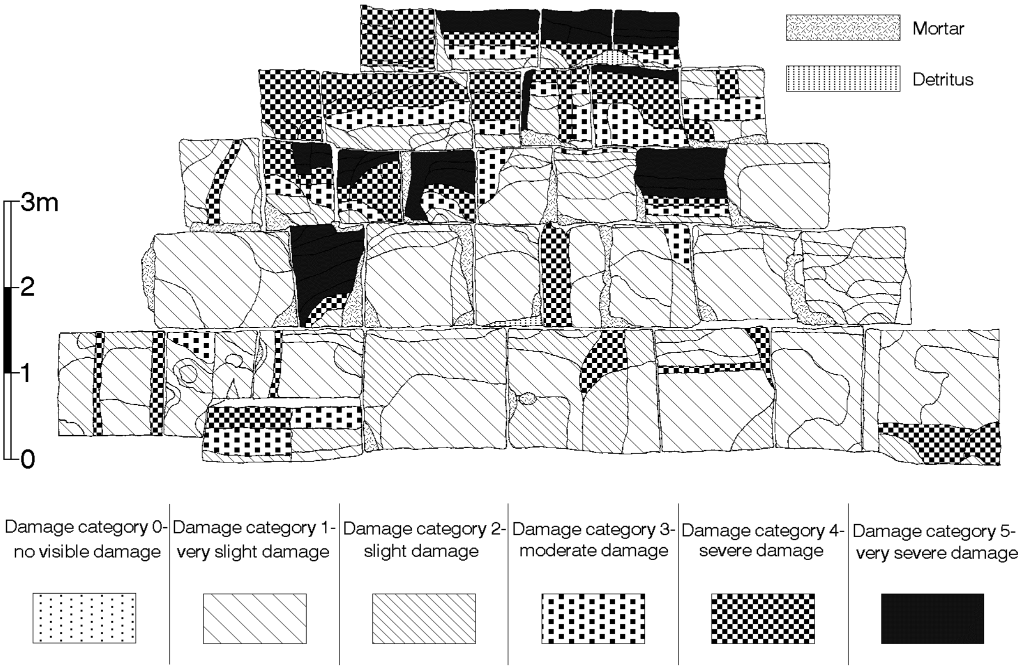


Fig. 21. Map of damage categories. Great Pyramid of Cheops, lower part of the southern side.

LINEAR DAMAGE INDEX DI_{lin} =	PROGRESSIVE DAMAGE INDEX DI_{prog} =
$\frac{(A \cdot 0)+(B \cdot 1)+(C \cdot 2)+(D \cdot 3)+(E \cdot 4)+(F \cdot 5)}{100}$ ↓ $\frac{B+(C \cdot 2)+(D \cdot 3)+(E \cdot 4)+(F \cdot 5)}{100}$	$\sqrt{\frac{(A \cdot 0^2)+(B \cdot 1^2)+(C \cdot 2^2)+(D \cdot 3^2)+(E \cdot 4^2)+(F \cdot 5^2)}{100}}$ ↓ $\sqrt{\frac{B+(C \cdot 4)+(D \cdot 9)+(E \cdot 16)+(F \cdot 25)}{100}}$
A = Area (%) – damage category 0 *B* = Area (%) – damage category 1 *C* = Area (%) – damage category 2	*D* = Area (%) – damage category 3 *E* = Area (%) – damage category 4 *F* = Area (%) – damage category 5
$\sum_{A}^{F} = 100$	
$0 \leq DI_{lin} \leq 5$	$0 \leq DI_{prog} \leq 5$

Fig. 22. Damage indices.

In order to quantify this zonation of stone damage, damage indices were calculated individually for rows of dimension stones (Fig. 23). Maximum damage indices - DI_{lin} up to 4.2, DI_{prog} up to 4.3 - were found at a height in the range between 2.0 and 2.5 m above ground level. It is striking that at El-Merdani Mosque and many other monuments, this zonation of stone damage can superpose the heterogeneous distribution of different limestone varieties in the walls of the monuments.

In contrast, the distribution of damage categories and the damage indices derived for the pilot investigation area at the Great Pyramid of Cheops clearly trace the four different limestone varieties found there and their different durability:

- compact limestone: mainly very slight or slight damage (damage categories 1 and 2), DI_{lin} = 1.2, DI_{prog} = 1.4, high durability,
- soft limestone: mainly severe or very severe damage (damage categories 4 and 5), DI_{lin} = 4.4, DI_{prog} = 4.5, very low durability,

- two intermediate limestones: mainly very slight to severe damage (damage categories 1 - 4), DI_{lin} = 2.2 – 2.5, DI_{prog} = 2.5 – 2.9, low to moderate durability.

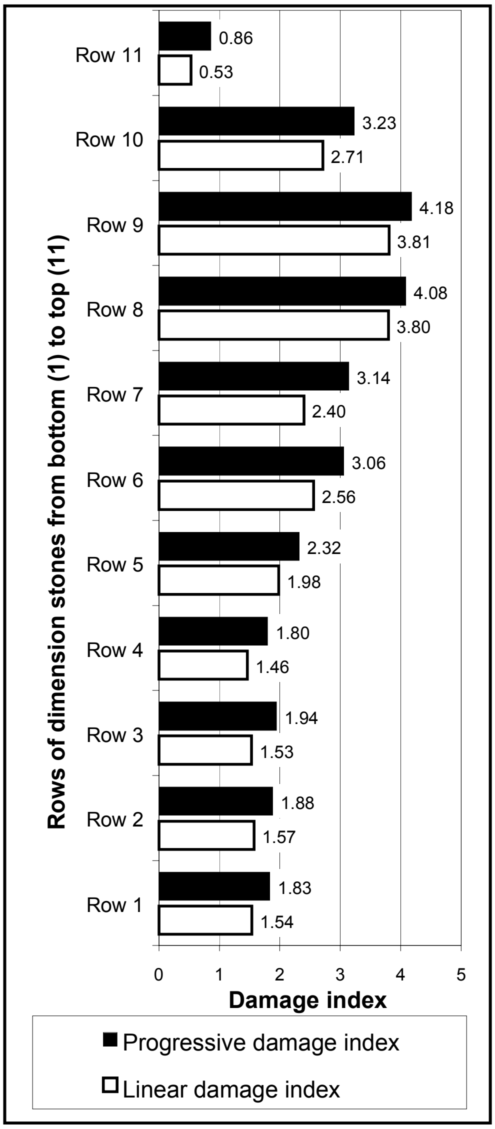


Fig. 23. Damage indices according to rows of dimension stones. El-Merdani Mosque, lower part of the SE-façade.

Weathering products and weathering profiles

In addition to weathering forms and their rating by means of damage categories and damage indices, weathering products and weathering profiles characterize the weathering state of natural stones and provide information on factors and processes of stone weathering.

Studies on lower parts of the El-Merdani Mosque – considered to be very representative for the lower parts of many limestone monuments in the historical centre of Cairo – have shown a considerable salt loading of the limestones by halite (NaCl) and gypsum ($CaSO_4 \cdot 2\ H_2O$). This concerns the outer walls and walls in the interior of the monument in the same way. Surface samples were analysed by means of X-ray diffraction with respect to salt minerals. Different weathering forms were considered, in particular different types of deposits and detachment. Results on salt minerals related to weathering forms are summarized in Table 6.

In the early phases of stone weathering a higher content of gypsum correlates with the detachment of larger-sized stone elements, whereas in the advanced phases of stone weathering the higher content of halite correlates with decreasing size of detaching stone elements.

Additionally, powder samples collected in the course of drilling resistance measurements on lower parts of the El-Merdani Mosque were studied geochemically. The samples correspond to the outermost 4 cm of the dimension stones. In all samples halite and gypsum were found. The content of halite in the surface zone of the dimension stones (0 – 4 cm) ranges between 2.5 and 7.0 weight-%, the content of gypsum between 0.5 and 4 weight-%.

Table 6. *Salt minerals related to weathering forms. El-Merdani Mosque.*

Groups of weathering forms	Weathering forms		Salt minerals
Deposits	Loose salt deposits	Efflorescences	Halite prevailing, rarely gypsum
		Subflorescences	Halite and frequently gypsum
	Crust	Dark-colored crust	Gypsum significantly prevailing
		Light-colored crust	Halite significantly prevailing
Detachment	Contour scaling		Gypsum prevailing (back side of the scales)
	Flaking to contour scaling		Gypsum and halite
	Granular disintegration to crumbly disintegration		Halite, rarely gypsum
	Granular disintegration to flaking		Halite, rarely gypsum
	Granular disintegration		Halite, subordinately gypsum

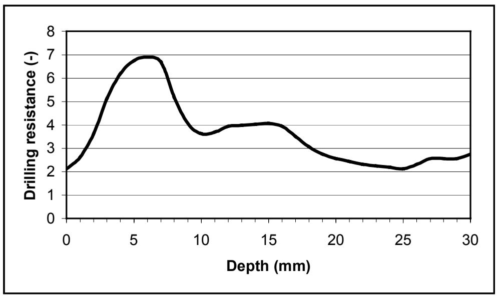


Fig. 24. Weathering profile type 1. Drilling resistance.

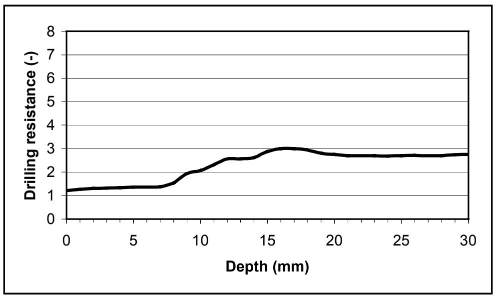


Fig. 25. Weathering profile type 2. Drilling resistance.

Weathering profiles were studied for information on causes and development of stone damage on the limestone monuments. Depth weathering profiles on dimension stones obtained by in situ drilling resistance measurements and by laboratory studies on drill cores and vertical weathering profiles on monument walls obtained by laboratory studies on salt load and by mapping and evaluation of weathering forms are presented in the following.

Drilling resistance measurements were carried out in situ considering different states of weathering. By means of this method, drilling with drill bits of 3 mm in diameter is made with constant pressure, energy supply and rotation speed. The drilling depth is monitored versus drilling time. The drilling resistance as parameter of stone hardness is calculated as a function of depth. Examples of drilling resistance profiles obtained from measurements at the El-Merdani Mosque are presented in Fig. 24 and 25. Two main types of profiles were found:

Type 1: profiles with decrease of drilling resistance from the stone surface to the stone interior (Fig. 24),

Type 2: profiles with increase of drilling resistance from the stone surface to the stone interior (Fig. 25).

Profiles of type 1 indicate accumulation of salt in the surface zone of the dimension stones. As example, the drilling resistance profile in Figure 24 can be characterized as follows:

- the outermost zone with low drilling resistance corresponds to the light-colored crust of almost pure halite;
- the zone with the first maximum peak of the drilling resistance corresponds to a hardening by cementation in the contact zone salt crust – limestone;
- the zone with the first minimum peak of the drilling resistance already traces the zone of the future detachment of the crust with adherent stone material;
- the zone with the second maximum peak of the drilling resistance traces a secondary zone of salt accumulation;

- the backward zone with decreasing drilling resistance corresponds to the transition to the unweathered limestone.

Table 7. *Vertical weathering profile (0 – 3.5 m above ground level). Outer façades, El-Merdani Mosque.*

	Lower zone (0 – 1.2 m)	Middle to upper zone (1.2 – 2.8 m)	Uppermost zone (2.8 – 3.5 m)
Loss of stone material*	frequent, mainly low intensities	very frequent, often high intensities	very rare, low intensities
Deposits on the stone surface*	very frequent, low to high intensities	very frequent, low to high intensities	very frequent, low to high intensities
Detachment of stone material*	rare, mainly low intensities	very frequent, often high intensities	very rare, low intensities
Rating of damage*	mainly very slight, slight or moderate	mainly severe or even very severe	mainly very slight or slight
Damage indices*	1.0 – 2.0	3.0 – 4.3	0.5 – 1.5
Salt load (depth: 0 – 4 cm)	moderate	very high	low to moderate
Halite – gypsum relation (depth: 0 – 4 cm)	halite ≥ gypsum	halite >> gypsum	halite ≤ gypsum

* Evaluation based on mapping of weathering forms

Profiles of type 2 indicate stone disintegration in the surface zone of the dimension stones. As example, the drilling resistance profile in Figure 25 can be characterized as follows:

- the outer zone with low drilling resistance correlates with considerable stone disintegration, especially granular disintegration;
- the zone with the maximum peak of the drilling resistance traces a zone of salt accumulation;
- the backward zone with almost constant drilling resistance corresponds to the transition to the unweathered limestone.

Ultrasonic studies and porosity studies of the drill cores from El-Merdani Mosque have confirmed these two main types of depth weathering profiles (Fig. 26). With respect to weathering profiles of type 1, increasing ultrasonic velocity, decreasing total porosity and median pore radius and decreasing density – considering the lower density of the salts – from the stone interior towards the stone surface indicate the accumulation of salt in the surface zone of the limestone. Regarding weathering profile of type 2, decreasing ultrasonic velocity and increasing porosity and median pore radius and the decreasing density from the stone interior towards the stone surface indicate increasing disintegration in direction of the stone surface in combination with salt loading of the limestone.

With respect to the historical limestone monuments in Cairo city, it was mentioned that considerable stone damage especially affects their lower parts. The results presented for these parts of the monuments have shown that all detachment of stone material and subsequent loss of stone material is linked to salt loading of the limestones. The comparison of results obtained from in situ investigation and laboratory analyses have allowed to evaluate vertical weathering profiles of these lower parts of the monuments characterizing the interrelation between salt loading and stone deterioration. A characteristical example is shown in Table 7. Three zones of the vertical profile are distinguished. The lower zone is characterized by very slight to moderate stone damage and moderate salt loading by halite and gypsum. Halite is slightly prevailing as salt mineral. The middle to upper zone shows severe to very severe stone damage and very high salt loading by gypsum and halite. Compared to gypsum, the content of halite is significantly higher. The uppermost zone is characterized by very slight to slight stone damage and low to moderate salt loading by gypsum and halite. The gypsum-halite relation increases upwards. Comparison of quantitative information on salt load and state of stone damage by means of vertical weathering profiles have proved the clear correlation between salt loading of the limestones and their state of damage (Fig. 27). It can be seen that stone damage increases as salt load increases.

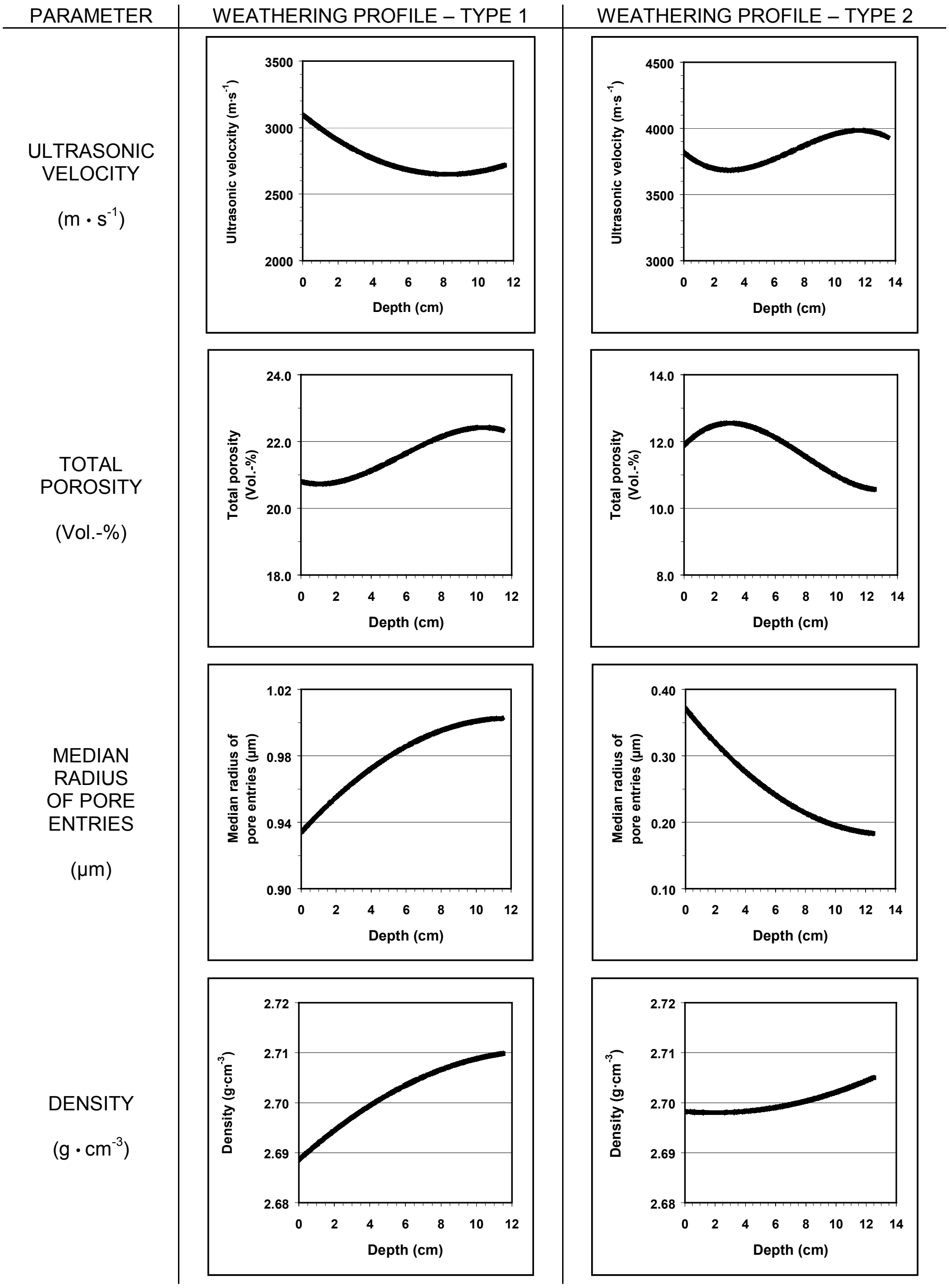


Fig. 26. Weathering profiles type 1 and type 2. Ultrasonic velocity, total porosity, median radius of pore entries, density.

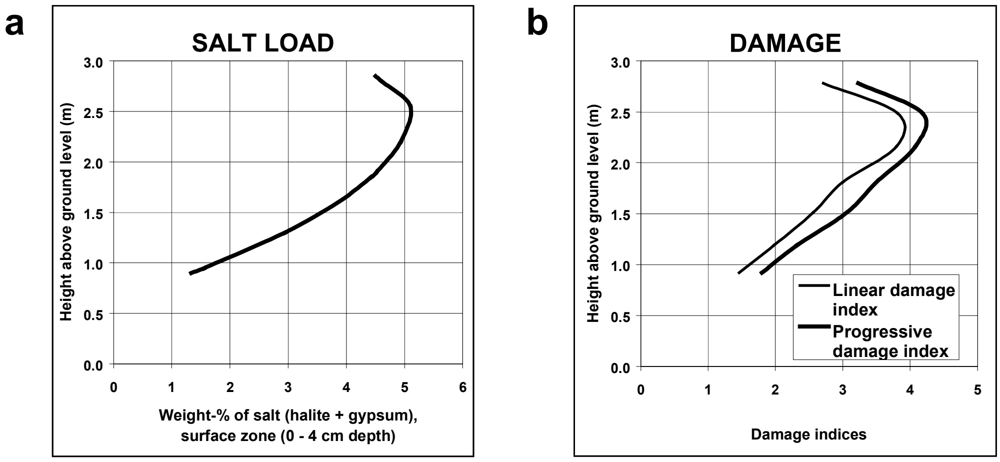


Fig. 27. Correlation between salt load (a) and stone damage (b) across a vertical profile. El-Merdani Mosque, lower part of the SE-façade.

The zonation of the stone damage and the type and intensity of salt loading indicates that salt weathering processes in the lower and in the middle to upper zone are mainly induced by salt-loaded rising humidity, whereas the uppermost zone represents the transitional zone to the upper parts of the monuments mainly affected by gypsum related to air pollution.

Discussion and conclusions

All historical limestone monuments in Cairo are affected by weathering. Studies on the weathering of the limestones were carried out comprising laboratory analysis and in situ investigation, the latter including detailed survey of weathering forms, registration and evaluation of weathering forms by means of monument mapping and in situ measurements. The studies were aimed at the petrographical characterization of the limestones and at the characterization and quantification of weathering forms, weathering products and weathering profiles, which in combination represent the state of weathering and which provide information on factors and processes of stone weathering. The methodological approach has guaranteed information on all scales of stone weathering ranging from nanoscale (< mm), to microscale (mm to cm), mesoscale (cm to m) and macroscale (> m). Rating of stone damage was an additional important objective of the studies.

The laboratory studies of the local Eocene limestones used on the monuments in Cairo since Pharaonic times until today have revealed a wide range of different limestone varieties with considerable variation of their petrographical properties.

Based on a systematic survey of historical monuments in Cairo, a detailed classification scheme of weathering forms was worked out, tailored to optimal applicability at all Cairo historical monuments constructed of limestones. The monument mapping method was applied as an established and internationally accepted non-destructive procedure for the precise registration, documentation and quantitative evaluation of weathering forms. Damage categories and damage indices were established as very suitable tools for the quantitative rating of stone damage on the Cairo historical monuments. A correlation scheme of weathering forms and damage categories was developed, applicable to all historical monuments in Cairo. Weathering forms, damage categories and damage indices were applied to Egyptian monuments for the first time. This systematic approach now can be transferred to all historical limestones monuments in Cairo.

A great variety of weathering forms characterizing loss of stone material, deposits, detachment of stone material and structural discontinuities were found on the limestones as well as a considerable range of their intensities.

At the pyramids of Giza east of Cairo city partly remarkable recession of the stone surface up to meter-range in combination with intense current detachment of stone material was found on the huge dimension stones.

Weathering forms such as soiling, black crusts and whitish crusts are very characteristical for the limestone monuments in the centre of Cairo. The black crusts – mainly composed of gypsum – very frequently occur on the middle and upper parts of the monuments, whereas the whitish crusts – almost purely composed of halite – mainly are limited to the lower parts of the monuments. Considerable loss of stone material in combination with intense current detachment of stone material is very characteristical for the lower parts of many monuments in Cairo city. Frequently, this also concerns stone structures in the interior of the monuments. The results obtained from in situ investigation and laboratory tests have shown that all kind of stone detachment and subsequent loss of stone material is linked predominantly to salt loading of the limestones. The significance of salts has become obvious in all results on weathering forms, weathering products and weathering profiles. Two paths of stone detachment and subsequent loss of stone material can be distinguished as consequence of salt loading:

(1) Accumulation of salt on the stone surface with formation of salt crusts. Reaching a critical thickness, the crusts begin to blister and then detach with adherent stone material. Texture in the front zone of the remaining stone material is already weakened. Salt accumulation continues causing further detachment of stone material.

(2) Salt deposits in the pore space of the limestones cause disintegration resulting in detachment of stone material. Type, quantity and depth of the salt deposits control intensity and velocity of stone detachment and the size of the detaching stone elements. The velocity of stone detachment increases in the course of weathering progression, whereas the size of the detaching stone elements decreases at the same time. This indicates increasing textural weakness of the limestones in the course of weathering progression.

Two very important sources of the salts can be distinguished, in accordance with findings of other authors (e.g. Croci 1994; Hawass 1993). (1) The increase of air pollution in Cairo as a consequence of the rapid expansion of the city (industry, traffic etc.) results in increasing deposition of pollutants from the atmosphere on the monuments with subsequent salt formation, especially gypsum – on the stone surface or in the pore space of the limestones close to the surface. (2) The water table (ground water, subsoil water) has significantly risen during the last decades. It can be observed that in extreme cases the water table has reached the ground floor of monuments (see Fig. 7). Insufficient or leaking sewage systems have caused increasing water pollution. Salt solutions from the subsurface intrude by capillary rise into the walls of the monuments and salts are precipitated – especially halite - on the stone surface or in the pore space of the limestones close to the surface.

Additionally, the natural content of salts in the limestones must be taken into account. Lime mortar and plaster – the latter especially used on the walls in the interior of many monuments – must be considered as further sources of salts. Detailed quantitative information on air pollution, subsurface conditions and quality of subsurface water is required for further improvement of knowledge as well as for suitable environmental management in the context with monument preservation activities.

Regarding the lower parts of monuments in the centre of Cairo, most severe stone damage was found at those zones of the walls which correspond to the main level of salt precipitation from rising humidity. A clear correlation between extent of salt loading and degree of stone damage - following a vertical profile - was shown for such lower parts of Cairo monuments.

Stone damage on numerous monuments in Cairo is alarming. This exhibits need and urgency of preservation measures. Preservation measures like control of capillary rise, desalination, cleaning, stone repair, fixation or consolidation of loose stone material, structural reinforcement and stone replacement are under consideration. Environmental management and rehabilitation aspects will have to be considered additionally.

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