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INVESTIGATIONS ON LIMESTONE WEATHERING OF EL-TUBA MINARET EL MEHALLA, EGYPT: A CASE STUDY

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ABSTRACT

The weathering phenomena that have affected El-TUBA Minaret, one of the most important Islamic stone minarets in middle delta in Egypt; that has suffered from several factors of deterioration due to weathering phenomenon. The present investigations concern the weathering factors that may have affected the minaret via the following methods and techniques: a) Contact-free methods used to study the chemical and mineralogical composition of building materials before and after weathering effects such as SEM-EDX and XRD, b) Non-destructive methods to find out percentage of range of decay which has affected these materials as well as the deteriorating roles of the surrounding environment. This method has been used to make an anatomical scheme of these features especially to specific deteriorated parts by GIS and other digital imaging techniques. All results confirm that the degradation factors affecting the minaret building materials are essentially attributed to direct effects of weathering phenomena. These weathering phenomena arise from physical and chemical mechanisms which have lead to many deterioration forms on the following two scales: a) *Macro scale* of weathering phenomena (e.g. structural damages, crakes, loss of plumb and walls bulging), b) *Micro scale* of weathering phenomena (e.g. hydrated salts, bursting, flaking, coloration, scaling, skinning, exfoliation and soiling). Discussion on the management and rehabilitation of this monument is made, since it is one of the religious shrines in Egypt.

KEYWORDS: Crusting, Flaking, Limestone, Pitting, Scaling, Soiling, Weathering.

INTRODUCTION

Throughout the history of mankind natural stones have been widely used as a material for buildings, monuments and art objects. In the course of time, all these natural stones have been affected by several weathering factors. So the interaction between stone materials and natural or anthropogenic weathering factors controls the type and extent of stone decay (Fitzner and Heinrichs, 2002). Weathering as a general term is applied to all mechanisms of alteration of building materials. It can be classified according to its origin as fallows:

- Chemical weathering: concerning the stone solubility or its reactivity with other factors of deterioration such as air pollutants.
- Physical weathering: concerning the stone resistance to expansive stress within the pore structure such as salt crystallization (Livingston, 1988). Both kinds of weathering lead to many deterioration appearances affecting the stone monuments. Such investigations are useful also in the dating of limestone buildings by surface luminescence dating (Liritzis et al., 1997; Liritzis & Galloway, 1999; Liritzis, 2001).

All these deterioration forms are closely related to weathering factors either exogenous or endogenous (El-Gohary, 1996 & Brüggerhoff and Mirwald, 1992), extended for centuries, sometimes for millennia (Lehmann, 1970). Particularly, the stonework with a lime basis is very sensitive to many of deterioration and weathering factors such as soling, pollution, oxidation, air temperature and relative humidity especially in industrial environment (Winkler, 1970). Limestone, mainly composed of calcium carbonate, contains small proportions of other ingredients "silica, clay, iron oxide and magnesium carbonate". It was not only used as building blocks for ancient Egyptian temples and tombs (MAGS, 2003), but also it was used to construct large number of mosques and churches. In this paper, due to the special nature of middle delta, where there are many aggressive weathering factors along time, the study focuses on the most dominant of these factors through investigating their mechanisms and resulting forms. This is achieved by studying the only steadfast Limestone minaret located in El Mehalla city.

Historical and monumental background of the study area

"El-Tuba" minaret, figure (1-a, b) is considered a unique archaeological stone minaret that still exists in El Mehalla town, which is about 110 km north Cairo. It was built by Abi El-Abas Al-Ghamry in 899 A.H. - 1493 A.D. The general body of the minaret was composed of two parts as fallows:

- The original "Mamluk" part, built between 899 - 905 A.H., 1493-1499 A.D. from softens and shaped Limestone. It consists of two levels with total height of 15.4m above the street level. This part includes Foundation and Octangular floors. All components of these parts have been completely hidden behind recent surround houses.
- The added "Alawian" parts, built in 1265 A.H., 1848 A.D., are 7.3m higher than the edge of the Mamluk part. This part includes many architectural features as three rows of stalactite, cylindrical stone body that contains entrance of "Muethin" (i.e. one who calls for prayers), as well as cylindrical nick carrying pointed conical top made of wooden gypsum. All of these features are made of rough Limestone and ornamented gypsum.

Fig (1- a, b) Map of study area and the minaret

Building materials of the minaret

According to different analytical studies, the minaret is built of three types of raw materials: limestone, as an essential material" used in the whole shaft of minaret both in Mamluk part and in Alawian part, wood and gypsum plaster which were used in the ornamental parts of muqarnas and window frames.

Environmental background of the study area

From geological perspective, the area is characterized by the presence of sandy gravels formation covered by a layer of silt precipitations through the last 7000-8000 years. According to the graduation of the geological development between erosion and destruction in the whole region this happened during Nile floods (Said, 1981). From the environmental perspective, the study area is characterized by some aggressive environmental features such as high levels of pollutants resulted from the industrial activities (N.E.C, 2008). The area is also characterized by high percentage of moisture content all over the year. Moreover, the evaluation of the area by GIS program proved that the micro surrounding environment is characterized by aggressive sources of deterioration factors and mechanisms resulted from the effects of domestic waste water of surrounding small workshops and old houses. This has led to the creation of several deterioration mechanisms and forms, Figure (2-a, b).

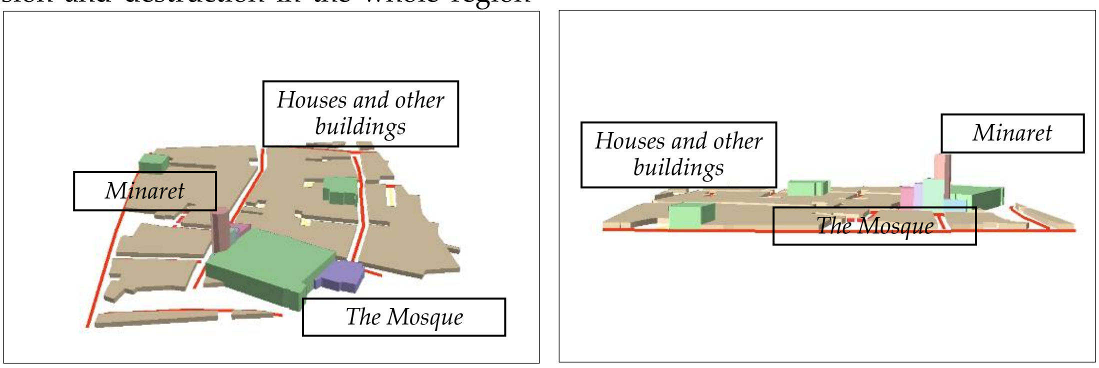

Fig (2-a, b) Environmental situation of the minaret and surround area by GIS digitizing.

Furthermore, the analysis of metrological database of E.M.O, dominating in the area of study, along the pervious 30 years shows that there is a high dissimilarity between air temperature records (*T*) during different seasons. It shows that the low average was 11.7°C in winter 1992, whereas the high average was 27.7°C in summer 1988 (E.M.O, 2005).

The study also concludes that there is an increase in the value of relative humidity (RH) all the year especially in winter, where the low average was 52% in spring 1965 and the high average was 77% in winter 1985, 1986, 1991 and 1992. This database also point out great differences between recorded rain falling (*RF*) quantities. Therefore, the low average has been in 0 mm all years and the high average was 26.9 mm in winter 1992.

All of these features have led to the creation of several deterioration and weathering mechanisms that, in its turn, led to the presence of several weathering forms.

MATERIAL & METHODS

According to (Douglas and McConchie, 1994; Tite, 1975), the following analytical techniques and scientific methods have been used to investigate all intrinsic and extrinsic factors that have affected the minaret weathering in order to define their deterioration mechanisms and their harmful forms.

Sampling

To capture any local variables in weathering forms and control the samples against any potential and anomalous interferences, (Riebea, et. al, 2004) several and random samples were taken from three different points of the minaret according to C.N.R–I.C.R of Rome, (NORMAL 3/80, 1980), with defined details (types, altitudes, orientations, description and percentage of decaying range). All these data are shown in Table 1 and are divided according to their altitude into three categories. The first category is taken between 11.5-12m.; the second is taken between 9.5-10m, and the third is taken between 2.2-3m.

Table (1) Detailed description of different samples collected from the monument under study

Samples	Samples details and visual observations				
	Samples types	Samples altitude*	Samples orientation	Samples description (Visual and touch)	Decaying range %
1	Limestone	11.5 m	E direction	Highly disaggregated surface crust	80%
2	Stone surface	12 m	E direction	Disintegrated surface	70 - 80%
3	Limestone	9.5 m	W direction	Contaminated Calcite particles	80 - 90%
7	Stone surface	10 m	W direction	Highly disintegrated surface	80 - 90%
5	Limestone	2.30 m	N direction	Deteriorated stone surface	70%
6	Stone surface	3 m	N direction	Salty and highly disaggregated crust	100%
7	Plaster	2.20 m	N direction	Highly contaminated surface layer	Over 95%
8	Plaster	2.65 m	N direction	Salty crust highly deteriorated	Over 95%

All altitude of the samples taken from street level

Instrumental analysis

Collected samples were analyzed and studied to identify the different weathering forms, their products such as salt profiles and salt types (Bläuer Böhm, 2005), and the weathering state affecting the minaret. The analysis is based on non-destructive methods such as photographic recording digital image processing (PRDIP), contact-free methods have been also used to evaluate the stone surface and its components such as EDX, XRD and SEM.

EDX and SEM techniques

According to (Koller, et. al, 1986; Moses, 1996) various samples had been coated with gold (20nm) and were analyzed using an EDAX-Oxford unit equipped with JSM 5300 scanning electronic microscope at acceleration voltages of 10-30 kV. The obtained results were calculated by excel, in order to identify and quantify surface characteristics of building materials. The analytical data are listed in table (2-a, b, c). In addition, SEM has been used for studying the morphological features of the same samples. The investigation captures show that there are wide range of deterioration features as shown in Figures (3- a, b, c, d, e, f) such as dusting, small fissures and micro-cracks, smoothing in outer surface of calcite grains, eroded pits, and the presence of some salty crystals as halite and gypsum.

Table (2-a) XRF analytical results of samples "highest between11.5-12 m"

Samples	Analytical results								
	Na	Al	Si	S	Cl	K	Ca	Fe	Total
1	-	3.20	11.29	12.94	-	-	70.68	1.90	100.01
2	-		8.18	13.87	-	-	74.88	3.07	100.00

Table (2-b) XRF analytical results of samples "highest between 9.5-10 m"

Samples	Analytical results								
	Na	Al	Si	S	Cl	K	Ca	Fe	Total
3	4.13	-	8.99	21.79	-	-	60.22	4.86	99.99
4	4.13	-	8.21	20.83	3.13	1.88	58.40	3.41	99.99

Table (2-c) XRF analytical results of samples "highest between2.20-3 m"

Samples	Analytical results								
	Na	Al	Si	S	Cl	K	Ca	Fe	Total
5	6.38	-	26.50	2.90	7.80	5.33	48.57	2.53	100.01
6	40.27	2.50	-	-	55.78	-	1.44		99.99
7	21.24	-	13.27	9.09	34.54	-	19.06	1.47	100.00
8	10.21	-	6.05	6.09	15.17	1.95	57.56	2.96	99.99

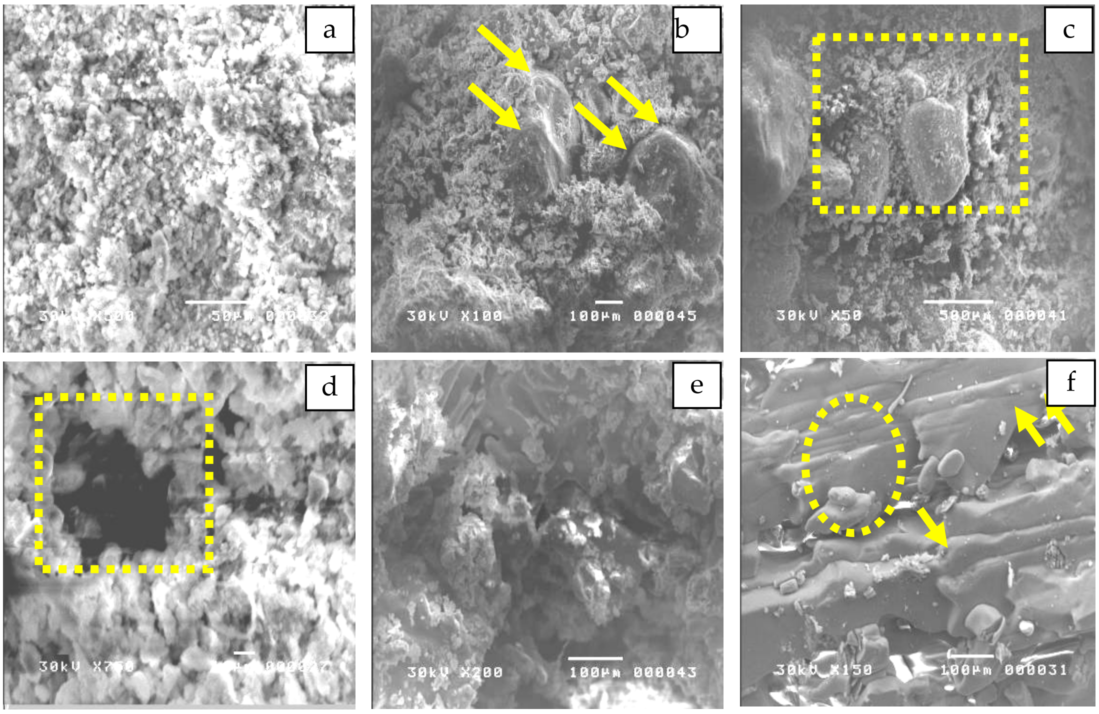

Fig (3) Electro-micrograph of investigated samples by SEM a dusting form covering all stone surface b some small fissures and micro-cracks around and within the grains, c smoothing in outer surface of calcite grains, d eroded pits, e growthing of some salty crystals, f surface of halite crystals

XRD technique

Several samples taken from different locations of the minaret have been examined by XRD through using instrumental model (XRD-600 Shimadzu X- Ray diffractometer with Cu k-α radiation) to define its different mineralogical composition, the results are listed in table (3- a, b, c) and fig. (4).

Table (3-a) XRD analytical results of samples "highest between11.5-12 m"

Samples	Analytical results		
	Major minerals	Minor minerals	Trace minerals
1	Calcite	Siderite and Fayalite	Halite, Hematite and Gypsum.
2	Gypsum and Calcite	Siderite and Fayalite	Halite, Hematite, Anhydrite, Sylvite and Soda niter

Table (3-b) XRD analytical results of samples "highest between 9.5-10 m"

3	Calcite	Siderite and Fayalite	Halite, Hematite and Gypsum.
4	Gypsum and Calcite	Siderite and Fayalite	Halite, Hematite, Anhydrite, Sylvite, Soda niter

Table (3-c) XRD analytical results of samples "highest between2.20-3 m"

5	Calcite	Siderite and Fayalite	Halite, Hematite and Gypsum.
6	Halite	--	--
7	Calcite and Quartz	Siderite and Fayalite	Halite, Hematite, Gypsum, Anhydrite, Goethite.
8	Gypsum and Calcite	Siderite and Fayalite	Halite, Hematite, Anhydrite, Sylvite and Soda niter.

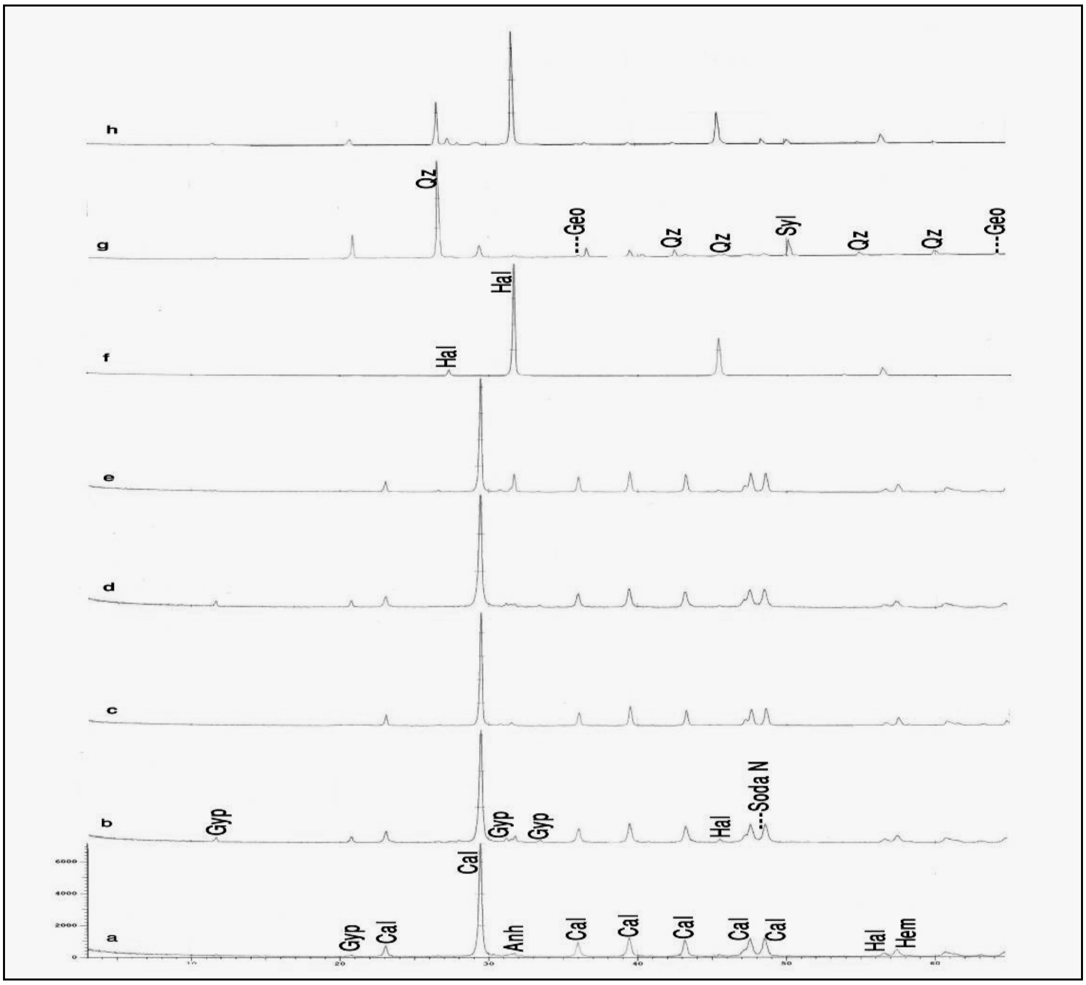

Fig. 4- (a- h) XRD Patterns of investigated samples.

WEATHERING FACTORS AND DESTRUCTION MECHANISMS

Weathering phenomena of stone monuments can be defined as "A process of alteration occurring under the direct influence of many deterioration factors (Karpuz and Paşamehmetoğlu, 1992), internally or externally, that affect the different properties of these stones". In this part of the study all destruction factors dominating in the study area and the main components of weathering phenomena "mechanism and resulted forms" have been observed, studied and explained.

The study proved that the deterioration factors affecting the minaret could be concluded as fallows:

Architectural situation of the minaret

According to the guidance methods in the architectural field (Kühlenthal and Fischer, 2000) (Kühlenthal, 1996), architectural structure and surrounded area of the minaret have been studied by close inspection and complimentary survey (CICS) is a simple method and its main focus is a search for evidences of different past activities in the study area, particularly studying the whole landscape through realizing three essential levels (*identification*, *evaluation* and *treatment*). This could be achieved through using handy and electronic measurements especially in the inner part of the minaret. The results indicate that there are some structural deterioration forms such as structural damages, crakes, and loss of plumb and bulging of the walls.

Conditions assessment of weathering phenomena

Observation and data analysis have revealed the authentic relations between the minaret building materials and the dominating deterioration factors. These relations represent real complicated problems especially with synergetic interactions between these different factors. Therefore through making a specific anatomical scheme (weathering map that was made by facsimile on tracing paper), photographical and drawing documentation (Nardi, 1986), in addition to the above described techniques are used to study such relations to assess the different deterioration factors (D'ossat, 1982). The assessment results have shown that the minaret has been affected by several deterioration factors, for example:

- Alternative processes between air temperature and different sources of moisture (Viles, 1993)
- Aggressive human activities either intended or un-intended (D'ossat, 1982).
- Chemical effects resulting from groundwater and domestic waste water "water quality" (El-Gohary, 2003). All the above listed factors and their mechanisms have affected the minaret with many internal and external deterioration forms.

Weathering forms affecting the minaret

The anatomical scheme, fig (5) points out the several forms of deterioration that have affected the minaret through different physical and chemical mechanisms. These forms are as follows:

- Scaling of some inner parts of the minaret, fig. (6-a), coloration to dark colored crust of the minaret external surface, fig. (6-b), and soiling and crusting, fig (. 6-c).
- Weathering out dependent on stone structure, fig. (7-a), salt crystallization, fig. (7-b), in addition to effective cracks, fig. (7-c).
- Clearing out of stone components, fig. (8-a), crumbling and splintering forms, fig. (8-b), and breaking out due to natural causes, fig (8-c).

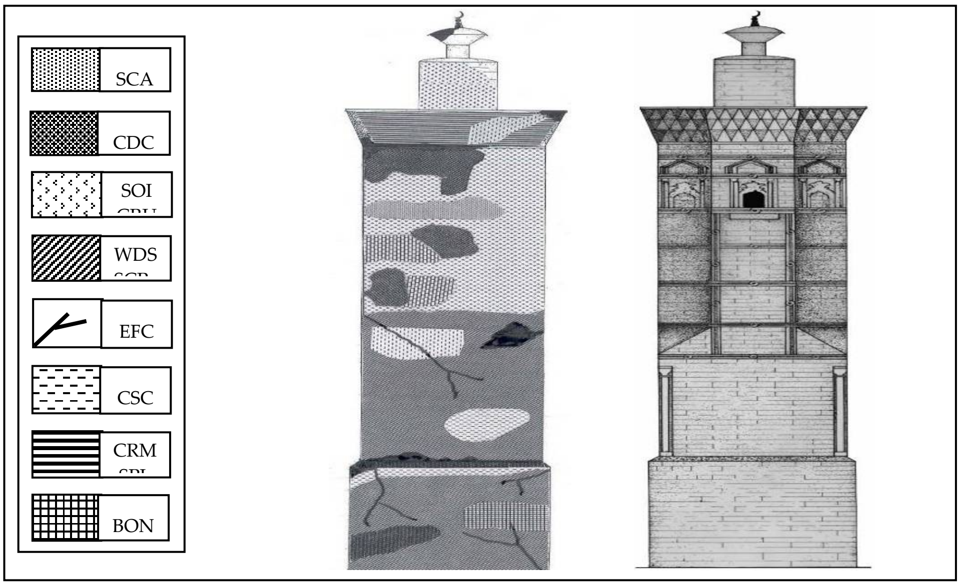

Fig. 5. Anatomical scheme with and without weathering forms affecting El-Tuba minaret

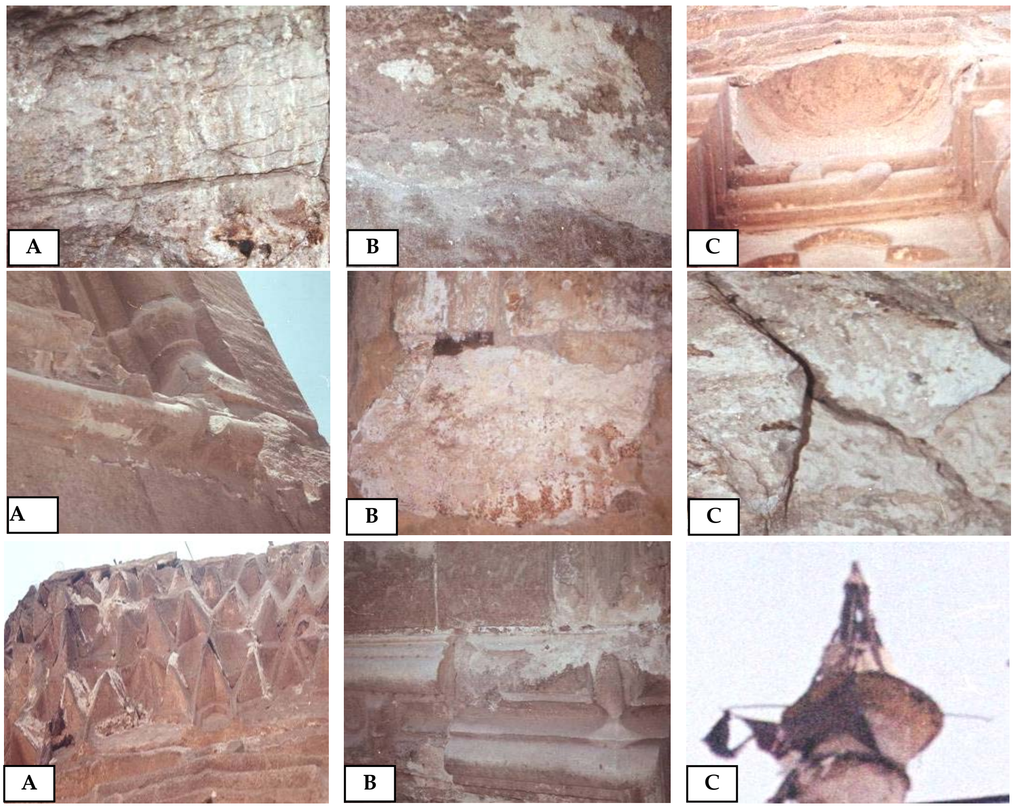

Fig (6, 7, 8) Different weathering forms affecting the El-Tuba minaret

DISCUSSION

The statistical and analytical data obtained by the previous techniques and the different research methods might be sufficient and accurate to identify the harmful factors that have affected the minaret building materials and the resulted deterioration forms. This is shown as follows:

Chemical composition by EDX

As previously mentioned in fig (9) There are differences in the element ratios that are responsible for deterioration forms (Al, Si, S and Fe) and they are relative to the essential element of building materials (i.e. Ca). Such element ratios indicate the different deterioration mechanisms affecting the stone surfaces and resulting from different deterioration factors dominating in the area of study. These ratios could be classified according to their deterioration degree into 3 categories as follows:

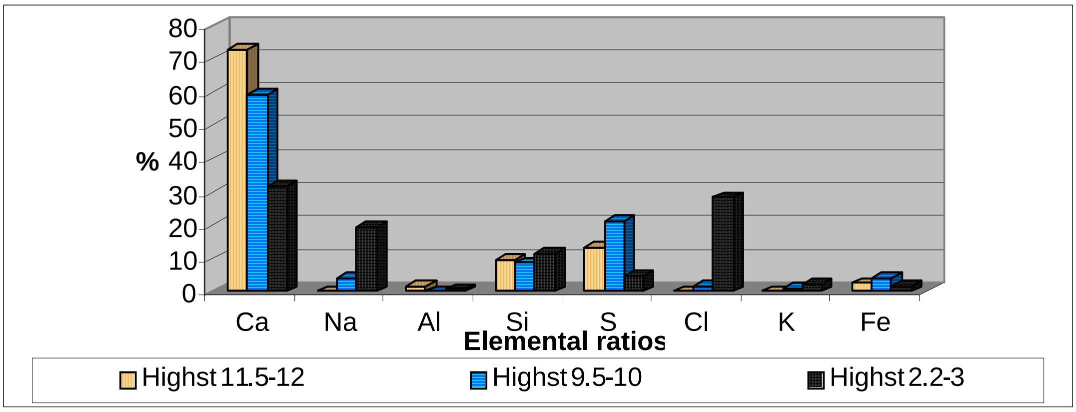

Fig. 9. Average of different analytical data of minaret building materials by EDX

- 1st category, in which the existing ratios refer to deterioration processes are about (27.20%). These ratios are divided into (1.6% Al, 9.74% Si, 13.41% S and 2.49% Fe) and relative to (Ca 72.80%), fig (10-a). The presence of such elements in such noticeable ratios is mostly ascribed to direct effects of soiling, dusting, artificial particulates and metal accumulations which spread in this direction that face the main road in the study area, "Al-Marwa Street".

- 2nd category, in which there are changes in both quality and quantity of different element ratios affecting the deterioration processes. These ratios increase to (40.69%). Where they are divided into (4.13% Na, 8.60% Si, 21.31% S, 1.57% Cl, 0.94% K and 4.11% Fe), and relative to the essential element of building materials (Ca 59.31%). Moreover, it marked the appearance of some new elements responsible for salt efflorescence (Na, K, Cl), and the disappearance of some other elements responsible for soiling and dusty accumulation (Al), as shown in fig (10-b). Therefore, these differences may be ascribed to the wetting and drying cycles caused by the alternative processes between air temperature and different sources of moisture (groundwater, domestic waste water or relative humidity). Moreover, some deterioration forms stem from synergetic effects among different activities of random, traditional activities (e.g. using ovens and small workshops of dyeing).

- 3rd category, in which the effect of deterioration factors are highly increasing as indicated by the different values of elements indicate either salt efflorescence or other forms of deterioration. These elements are about (68.34%) as (19.53% Na, 0.63% Al, 11.46% Si, 4.52% S, 28.36% Cl, 2.16% K, and 1.74% Fe), compared to the essential element of building material (31.66%), fig (10-c). All these deterioration forms are due to different mechanisms of aggressive deterioration factors such as alternative cycles between AT and RH, hydraulic pressures of salt crystallization, swelling of different incompatible material of new repairing mortars, and chemical weathering resulted from salinity ground water. Furthermore, it is clear that the high ratio of degradation, which exists only in the uncovered part in the minaret foundations, is directly related to many aggressive factors of deterioration that are dominate in the study area.

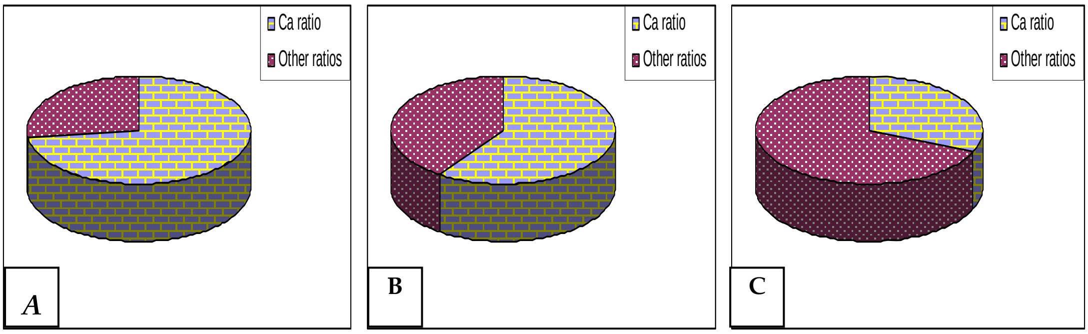

Fig (10- a, b, c) The relation between ratios of deterioration elements and essential elements of all building material.

Morphological description by SEM

Different SEM micrographs show that all parts of the minaret have been exposed to several aggressive deterioration factors. These factors have led to the creation of different features of soiling, either on stone surfaces or between different grains. Also, in the stone samples *halite* exists as a major salt since it is considered the predominant salt species in the Egyptian soil. Moreover, the gypsum and anhydrite salts, indicating the existence of sulfur ion, exist as a result either of environmental pollution or microbiological activities, especially with the presence of aggressive alternative cycles of drying and wetting. The presence of micro-cracks plays an important role in the physical behavior of stone and other building materials. They result from several factors. The first factor is the direct effect of the mechanical actions of groundwater, where the amount of water within the porous stones is the most powerful origin of historical buildings decay (Giorgi, 2000 & Lewin and Charola, 1979). The second is hydration pressures which result from salt crystal growth. The third is the effect of soil pressure.

Mineralogical composition by XRD

Different results obtained by this technique completely agree with others obtained by XRF where the weathering products affecting the body of the minaret vary both in their quantity and quality according to the differences in their altitudes and direction. In the 1st category, the presence of Calcite as a major mineral in different samples represents the main component of limestone used as a building material in the minaret. Whereas Gypsum mostly refers to the main component of plaster used in ornamental surfaces. Within the same context, the presence of Halite, Sylvite and Soda Niter, as trace minerals, result from a chemical reaction between calcite and different contamination ions (Wilson, 1994) that characterize ground water (e.g. SO_4, NO_x and Cl), particularly with alternative cycles between air temperature and different sources of moisture. 2nd category shows that all minerals that resulted from the deterioration of surface crusts are similar to those found in the samples taken from previous category. However, they are higher in value because of the combination between different deterioration factors affecting this façade, especially domestic waste water that results from human activities and houses lacking waste water net. Furthermore, it could be noticed that all surface crusts in the 3rd category represent the major forms of deterioration affecting the minaret, especially with the increase of the salty minerals affecting this part such as Halite, Gypsum and Anhydrite. These salty minerals result, in their turn, from alternative (daily, seasonally or annually) wetting and drying cycles (El-Gohary, 2001). The presence of some other weathering products result from soiling and dusting mechanisms, or from hydration phenomena that affect some minerals. This leads to some chemical transformation as the change of (Hematite) to (Goethite) (Gribble and Hall, 1992).

The analysis of surrounding environment of the building

The analysis of the architectural and structural situation of the minaret has revealed that all of the structural defects and damages are due to the *macro scale* effects of weathering phenomena. This scale results essentially from synergistic effects of soil pressure, severe loads resulting from new surrounding houses, mechanical movements of the ground and domestic waste water actions (i.e. water quantity and water flow) (Winkler, 1982) (El-Gohary, 2000).

Discussion of the weathering phenomena affecting the minaret stones

After assessing all results of weathering forms that have affected the minaret stones, it could be said that these forms have been the result, through *micro scale,* of synergetic deterioration factors dominating in study area. As for the scaling form (SCA), it is a serious physical weathering form that affects the stones. It results essentially from the effects of anthropogenic activities and chemical transformations. It is also ascribed to the sensitivity of its materials to deterioration processes especially in the presence of some aggressive sources of salts as halite and sulphate, which characterize the ground water of this area. These salts have led to the formation of some crumbling zones at a depth less than 1mm (Lubica, 1996). They also have created black and hardened scaling forms in some serious points especially in some unsheltered areas in the Alawian parts (Halsey, et. al, 1996). The effects of crusting (CRS) and soiling (SOI) as two major forms of deterioration are essentially attributed to the aggressive effects of air pollutants and some anthropogenic activities. *Crusting* as a symptom refers to firmly adhesive deposits, (in dark or light color), on the stone surfaces (Sebastián, et. al, 1992). In our case, the crusts aggressively affect all minaret surfaces through accumulations of gypsum and calcite mixed with quartz grains, in addition to air born ash coming from some hydrocarbon materials characterizing the study area. Another deterioration form is *Soiling*, dirt deposits which are divided, according to their nature, into soiling by pollutants, particles, droppings or direct anthropogenic influences (Halsey, et. al, 1996 & Pavia Santamaria, 1996). In our case, these dirt deposits are soiling by particles which result from the effects of urbanization and industrialization processes in certain areas. These deposits are mainly composed of coal fly ash and quartz grains which characterize not only the study area but also all the industrial town. Crumbling (CRM) represents the major form of deterioration affecting the minaret body through complex deterioration mechanisms such as salt migration, which is slower than the drying rate. It appears as a direct result of solute crystallizes within the pores at varying depth. This has led to a stone crumbling and powdering in some specific areas of the minaret body, as well as a detachment of large compact stone elements in the form of crumbs.

Furthermore, this deterioration form may have resulted from flaking, and may have changed into splintering or contour scaling (Van Grieken, 1998 & Storemyr, 2000). Splinter (SPL) is another serious deterioration form affecting the minaret and resulting from the detachment of large compact stone through breaking the stone surfaces into many small fragments (Russell, 2005). This mechanism has affected the elements in the splinters shape in irregular fractured across the usual zones of weakness-bedding planes in few centimeters and joints. It mostly occurs as a direct result of the signature of the crystal wedging process (White and White, 2003). Salt crystallization (SCR) is a widespread weathering process that affects porous building materials and causes the main deterioration mechanisms (Bala Awi, 2006). This form is considered the most serious form affecting the monumental buildings through poorly adhesive deposits of salt aggregates on the surfaces either in efflorescence or sub-efflorescence phases (Backbier, et. al, 1993; Esbert, 1991 & Winkler, 1972). In our case, these deposits are direct results of both aggressive sources of soluble salts characterizing the ground in the study area and some components of acid rains. These effects have led to the creation of some sever chemical deterioration cycles especially with the presence of the alternative cycles of wetting and drying. Excessive analytical investigation proves that the main families of salts are essentially composed of some species of chlorides and sulphates which are considered the common types of salt decay that come from un-welcomed sources of building materials (El-Gohary, 2003 & Arnold and Zehnder, 1987). Within the same context, the saline groundwater in the study area is essentially composed of different materials. It contains a number of chemical anions that are characterized by high concentration levels; particularly SO_4^{--} and Cl^- which, in turn, have led to the creation of sever deterioration forms and salty crusts (El-Gohary, 2003). These sources of water leaks into the minaret body through capillary rising as well as infiltration mechanisms particularly in that part encompassed by different typical houses.

In addition to other salts resulted from the reactions between limestone and dominated pollutants (sulphur and nitrogen oxides) created in the study area of through some industrial activities. These pollutants are considered significant sources of salts that affect porous building materials especially with high values of RH that exceed 75% in winter. RH is crucial in the salt damage process since it plays a major role in the transition states of salt weathering. This has led to the transformation of salt crystals into salt solution which directly controls the dynamics of weathering and damages cycles, in turn, their affect porous building materials (Arnold and Zehnder, 1987). Otherwise, these oxides are generally captured by raindrops and return to stone surfaces as acid precipitations (De Nevers, 2000). The previous factors have led to several deterioration mechanisms: salt problems, swelling and shrinkage processes, or microbiological contamination (Von Plehwe-Leisen, 1994).

Another main factor of weathering that has affected the stone components of the minaret, especially in the lower parts is the salt of inappropriate repair materials (gypsum and black Portland cement) which have been still used by the inhabitants through improper techniques for repairing and strengthening the foundations of the minaret. Moreover, windblown salt-laden dust is one of the primary agents of environmental damage to building materials that depends on different characteristics of each salt, particularly equilibrium relative humidity (Pender, 2000), in addition to other environmental factors such as temperature and wind speed which control the quality and quantity of deterioration mechanisms (Lubelli, 2006).

For, example the mechanisms of salt weathering by Halite and its different patterns that affect the minaret body are strongly affected by such environmental parameters. Within the same context, there are some minor forms of deterioration affecting the study area of such as weathering out dependent on stone structure (WDS). This form results from direct effect of some intrinsic factors of deterioration that are essentially due to the defects of stone composition and some errors of stone employment. These defects have mostly led to several forms of deterioration especially in the internal structure (Agrawal, 1986 & Blaeur, 1985). In our case, this form is represented in the shape of granular desegregation, then into individual components grains which develop to micro cracks. This is due to the effect of thermal expansion and contraction mechanisms particularly in all inner parts of the minaret. Effective cracks and micro fissures (ECM), is another serious deterioration form affecting the minaret body. According to some previous studies (Piniñska and Attia, 2003; Doehen, 1994 & Matteoli, 1981), cracks in archaeological building represent the most obvious feature of deterioration resulting from the mechanical stress which is due to crystal growth, hydration pressure, mechanical effects of earthquake or other mechanical actions.

Furthermore, it may be in individual fissures as bedding, foliation and banding that result from geological defects of the stone itself. The minaret has suffered for along time from these deterioration forms, especially those of the internal lower parts. These forms play an important role in the deterioration phenomena, affecting both the physical and mechanical properties of building materials.

Moreover, most of these cracks especially those found underlying the covering structures, have led to some displacement, which might be ascribed to the scouring of the minaret foundations by rain water in winter as already been mentioned in similar cases (Rossi and Tucci, 1991 & Dengler, 1976). Within the same context, clearing out of stone components (CSO) is considered one of the secondary deterioration forms that have affected some specific areas of the minaret through severe deterioration mechanism. This mechanism is known as loosing of stone material in parallel to the original stone surface as a relief in a form of protruding compact stone components, which is due to partial or selective weathering, in addition to the effects of alternative heating and cooling cycles. The break out due to natural causes (BNC) is considered one of the effective deterioration forms have affected the minaret. It owes some effects to seismic action created by earthquakes especially that happened in October 1992 and led to several features of deterioration, in addition to some other features created through intended man-made damages such as theft and vandalisms.

Finally, it is clear that the fieldwork observation, analytical data as well as laboratory experiments indicate that all these forms of deterioration have worked as a unique unit in completing the deterioration cycle that has affected the minaret. These cycles may lead to a full collapse of all the architectural features of the minaret unless a suitable conservation plan should be to stop the aggressive effects of deterioration factors and their mechanisms.

CONCLUSION

The previous study clarifies that the minaret as well as all the surrounding area have been exposed to aggressive deterioration factors mainly due to air temperature, air pollution and different sources of moisture (i.e. groundwater and domestic waste water) containing high level of different harmful ions. This gave rise to salt precipitation upon water evaporation because of the drying cycles that resulted either from air temperature or air currents, besides the above described deterioration forms. Therefore, the following recommendations should be taken for protecting the minaret such as:

1. The surrounding houses should be removed as they do not give any chance for the aesthetic appreciation of the minaret.
2. A partial pre-consolidation should be carried out only on the stone blocks that have heavy deterioration. This should be done after suitable experimental laboratory tests on different consolidated materials to avoid unfavorable reactions between treated stones and such materials. According to experimental tests, Paraloid B-82 as MMA copolymer is the best consolidant material to apply in this environment, because of its good obtained results.
3. Dirts, unfavorable surface accumulations and different species of salt crusts should be removed by suitable scientific techniques. Experimental studies have proved that the Japanese paper poultices are the best technique and material for achieving this purpose.
4. Structural repairs of the minaret (i.e. strengthening the soil, deepening foundation and sealing the inner cracks) should be carried out as important parts of architectural conservation plan.
5. External and internal wall surfaces of the minaret should be cased, especially those surfaces that are located beside the minaret foundations. This could be achieved by using new tested materials that are characterized by good physical and mechanical properties.
6. All old and incompatible conservation materials should be removed (black cement and gypsum); especially the materials used in the Mamluk part. New tested materials should be applied as gap fillers. Our experiments have proved that the best material for this target is Acryloid 2020, which belongs to epoxy resin and which is mixed with fine powder of Limestone.
7. After finishing all these steps, the whole body of the minaret should be

treated by water repellents for protection it against the extrinsic harmful effects. In this case, it has been found that RC 80 and Phase are the best materials used for this purpose because of their good chemical resistance and excellent exterior durability, in addition to its good visual appearances.

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REFERENCES

Agrawal, O. P., Singh, T. and Jain, K., (1986) Study and conservation of spotted red sandstone of Mathura', *Case Studies in the Conservation of stone and Wall Paintings*, IIC, London, 151-154

Arnold, A and Zehnder, K., (1987) Monitoring wall paintings affected by soluble salts, Cather, S. (ed.), 1991, *Proceedings of a Symposium of the conservation of wall paintings*, London, pp: 103-135

Backbier, L., Rousseau, J. and Bart, J. C. J., (1993) Analytical study of salt migration and efflorescence in mediaeval cathedral, *Analytical Chimica Acta*, Vol. 283, 855-867

Bala Awi, F., (2006) Salt damage at Petra, Jordan: a study of the effects of wind on salt distribution and crystallization, Ph.D., University of College London.

Blaeur, C., (1985) Weathering of Bernese Sandstone, *5th Inter. Cong. on deterioration and* conservation of stone, Presses Polytechniques Romandes, Lausanne, 79-87

Bläuer Böhm, C., (2005) Quantitative salt analysis in conservation of buildings, Restoration of buildings and monuments, Vol. 11, No., 6 1-10

Brüggerhoff, St. Mirwald, P., (1992) Examination of complex weathering processes on different stone materials by field exposure studies, *7th international congress on deterioration and conservation of stone*, Rodrigues, D., Henriques, F. and Jeremias, F.T., (eds.), Lisbon, 715-724.

D'ossat, G., (1982) Study of monuments from the historical artistic and technical point of view, ICCROM, Italy

D'ossat, G., (1982) Guida allo studio metodico dei monumenti e delle loro cause di deterioramento, ICCROM, Italy, 5-24

De Nevers, N.: (2000) Air pollution control engineering, 2nd ed., McGraw Hill, Boston.

Dengler, L., (1976) Micrograms in crystalline rocks, Electron Microscope in mineralogy, Berlin.

Doehen, E., (1994) In situ dynamics of sodium sulphate hydration and dehydration in stone pore: observation at high magnification using the Environmental Scanning Electron Microscope, *La conservazione dei monumenti nel bacino del mediterrneo*, Venezia 143-150

Douglas, W.L. and McConchie, D., (1994) Analytical sedimentology, Chapman & Hall, New York

Egyptian Metrological Organization, (2005) *Database of air temperature, relative humidity and rainfall*, Al-Gharbia unit, Egypt

El-Gohary, M., (2001) The effect of groundwater on the acceleration of weathering processes in Edfu temple area, *1st conference, faculty of archaeology*, Al-Fayoum, Egypt, 377-387

El-Gohary, M.A., (1996) Comparative study of deterioration causes and methods of conservation and maintenance of stone monuments in site with application on Ramsis II Temple in Abydos and Nektenbo II Temple in Abydos and Nektenbo II temple in Bahbit El- Haggara, M.A, Conservation dept. Cairo University.

El-Gohary, M.A. (2000), Effect of groundwater on sandstone used in some Egyptian temples in upper Egypt with scientific and application methods for its conservation and maintenance, Ph D, Conservation dept., Cairo Univ.

El-Gohary, M.A., (2003) Synergetic effects of sea water on monumental Limestone in Alexandria-Qait bey citadel as a case study, *3rd conference, faculty of archaeology*, Cairo, Univ, Al-Fayoum, Egypt 1-13

Esbert, R. M., (1991) Mechanical stresses generated by crystallization of salts inside treated and non-treated monumental stones; monitoring and interpretation by acoustic emission/microscopic activity, *Symposium of Material Research Society*, 185, 285-296

Giorgi, R., Baglioni, P., Alesiani, M., Capuani, S., Manicini, L. and Maraviglia, B., (2000) New results in the application of innovative experimental techniques for investigation of stone decay's processes, *9th international congress on deterioration and conservation of stone*, Fassina, V. (ed.)., Venice 79-87

Gribble, C.D., and Hall, A.J., (1992) Optical mineralogy principles and practice, UCL, London.

Halsey, D., Dews, S., Mitchell, D. and Harris, F., (1996) Influence of aspect upon Sandstone weathering: the role of climate cycles in flaking and scaling, *8th international congress on deterioration and conservation of stone*, Riederer, J. (ed.), Berlin, 849-860

Halsey, D., Dews, S.J., Mitchell, D.J., Harris, F.C., (1996) The black soiling of Sandstone buildings in the West midlands England: regional variations and decay mechanisms', *Processes of Urban stone decay*, Smith, B.J., Warke, P.A. (eds.), Donhead Publishing, London, 53-65

Karpuz, C. Paşamehmetoğlu, A. G., (1992) Rock mechanics characteristics of Ankara Andesite in relation to their degree of weathering, 7th international congress on deterioration and conservation of stone, Rodrigues, D., Henriques, F. and Jeremias, F.T. (eds.), Lisbon 39-46

Koller, M., Paschinger, H. and Richard, H., (1986) Work in Austria on history stucco technique, coloring preservation, *Case studies in the conservation of stone and wall paintings*, Smith, Perry (ed.), London, 27-33

Kühlenthal, M., (1996) Petra-the preservation concept for the tomb facades, *8th international congress on deterioration and conservation of stone*, Riederer (ed), J., Berlin, 1117-1122

Kühlenthal, M., and Fischer, H., (2000) Guidelines and procedures for the restoration of the monuments in Petra, Kühlenthal, M., and Fischer, H. (ed.), *Petra*, Arbeitshefte des Bayerischen Landesamtes für Denkmalpflege, München, 84-86

Lehmann, J., (1970), Damage by accumulation of soluble salts in stonework, *New York conference on conservation of stone and wooden objects*, 2nd Ed, Vol. I, New York, 35-45

Lewin, S.Z., Charola, A. E., (1979) Scanning electron microscopy in the diagnosis of "diseased", stone, *Scanning Electron Microscopy*, Vol. I, 695-703

Liritzis, I., (2001) Searching for precision of a new 'luminescence clock' in dating calcitic rocks. *J. Radioanal. & Nucl. Chemistry*, 247, 3, 727-730.

Liritzis, I and Galloway, R.B., (1999) Dating implications from solar bleaching of thermoluminescence of ancient marble. *J. Radioanal. Nucl. Chemistry*, 241, 2, 361-368.

Liritzis, I, Guibert, P, Foti, F and Schvoerer, M., (1997) The Temple of Apollo (Delphi) strengthens new thermoluminescence dating method. *Geoarchaeology International*, 12, 5, 479-496.

Livingston, R., (1988) The application of petrology to the predication of stone durability, *VIth international congress on deterioration and conservation of stone*, Nicholas Copernicus University Press, Torun, 432-445.

Lubelli, B., (2006) Sodium chloride damage to porous building materials, PhD thesis, Politecnico di Milano, Italy.

Lubica, W., (1996) Study of salt–frost attack on natural stone, *8th international congress on deterioration and conservation of stone*, Riederer, J. (ed.), Berlin, 563-571

Matteoli, U., Piacenti, F., Frediani, P., Tiano, P. and Manganellidelfa, C., (1981) Humidity in stones -II- humidity and temperature determinations in various lithotypes, *The conservation of stone* II 475-481

Memphis Archaeological and Geological Society, (2003) Mags explorer, Vol. 2, No 2, Greece, 1-6

Moses, C. A., (1995) Methods for investigating stone decay mechanisms in polluted and clean environments, Northern Ireland, *Processes of urban stone decay*, Smith, & Warke (eds.), Belfast, 212-227

Nardi, R., (1986), Conservation of the earth of septimus severus: work in progress, *Case studies in the conservation of stone and wall paintings*, London, 3-7

National Egyptian Center, (2008) Database of air pollution, Delta unite, Egypt

NORMALE 3/80, (1980) Materiali Lapidei: Campionamento, Raccomandazione, C.N.R–I.C.R, Roma

Pavia Santamaria, S., Cooper, T.P., Caro Calatayud, S., (1996) Characterization and decay of monumental sandstone in La Rioja, Northern Spain, *Processes of Urban stone decay*, Smith, B.J., Warke, P.A. (eds.), Donhead Publishing, London, 125-132

Pender, R.J. (2000) The behaviour of moisture in the porous support materials of wall paintings: an investigation of some environmental parameters, PhD thesis, University of London.

Piniñska, J., Attia, H., (2003) Use of geomechanical research in the conservation of stone monuments (Maadi Town Temple, Fayoum, Egypt), *Geological Quarterly*, 47 (1) 1–12

Riebea, C. S., Kirchner, J.W. and Finkel, R.C., (2004) Erosional and climatic effects on long-term chemical weathering rates in granitic landscapes spanning diverse climate regimes, *Earth and Planetary Science Letters* 224, ELSEVIER, 547-562

Rossi, M.R. and Tucci, A., (1991) Pore structure and destructive or cementing effect of salt crystallization in various types of stone, *Studies in Conservation* (36) 53-58

Russell, S.S., Zoleensky, M., Righter, K., Folco, L., Jones, R., Connolly, H., Monica G. and Grossman, J., (2005) The Meteoritical Bulletin, No. 89, 2005 September, The Meteoritical Society, USA, 201-263

Said, R., (1981) *The geological evaluation of the River Nile*, Springer Verlag.

Sebastián, E., Rodriguez-Navarro, C., Velilla, N., Rodriguez, J., Zezza, U. and Salmeron, P., (1992) Petrographic study, evaluation of the state of decay and proposals for preservation of stone materials from Jaen cathedral (Spain), *7th international congress on deterioration and conservation of stone*, Rodrigues, D., Henriques, F. and Jeremias, F.T. (eds.), Lisbon, 29-38

Storemyr, P., (2000) Weathering of Soapstone at Norwegian monuments an overview of current knowledge, The restoration workshop of nidaros culture, Trondheim, Norway, 1-22

Tite, M.S., (1975) *Methods of physical examination in archaeology*, 2ed Ed., Seminar Press, London.

Van Grieken, R. Delalieux, F. and Gysels, K., (1998) Cultural heritage and the environment, *Pure & Appl. Chem. 70 (12)*, Great Britain, 2327-2331,

Viles, H.A., (1993) Observations and explanations of stone decay in Oxford, UK, Conservation of stone and other materials, Thiel, M.J. (ed.), Vol. I, RILEM, UNESCO 115-120

Von Plehwe-Leisen, E., Wendler, E., Senthlage, R., Klemm, D., David Castello, H., and dos Santos, A., (1994) *Investigation into water and humidity transport properties*, IDEAS project, Germany, 127134

White, W. B. and White, E. L., (2003) Gypsum wedging and cavern breakdown, studies in the Mammoth cave system, Kentucky, *National Speleological Society Journal of Cave and Karst Studies* 65 (1), 43-52.

Wilson, M. J., (1994) Clay mineralogy: spectroscopic and chemical determinative methods, Glasgow.

Winkler, E. M., (1982) *Problems in deterioration of stone, Conservation of historic stone building and monuments*, Washington D.C., USA, 108-119

Winkler, E., (1972) Crystallization pressure of salt in stone and concrete, *Geol. Soc. of Amr, Bull* (83), 3509-3513

Winkler, E.M., (1970), Decay of stone, *New York conference on conservation of stone and wooden objects*, 2nd Ed, Vol., I, New York, 1-14