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Assessment of Salt Damage Based on Crystallization Test due to High Groundwater Level in Sandstone Monuments, Luxor, Egypt

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Abstract— The destruction of the stone-built architectural Luxor's heritage is becoming more and more obvious. A laboratory salt decay simulation is widely recognised as a well-established method to assess the relative durability of the stone-built architectural heritage. In this research, the destructive changes in which white and red sandstone, due to groundwater rising effects, were experimentally evaluated using crystallization test. Specimens of white and red sandstone were subjected to salt crystallisation tests with sodium sulphate and sodium chloride as the two most common destructive salts in the groundwater in the study area. In the case of white samples, the presence of detritical, non-carbonate (especially clay) rich zones seems to promote decay. Results show that, effects of sodium sulphate crystallization in the white spotted sandstone show higher destructive effect than the reddish spotted sandstone. This might be due to the water free-phase, thenardite (Na_2SO_4), and the hydrate phase, mirabilite ($Na_2SO_4.10H_2O$). Moreover, the calcareous matrix and the coarse grained may help in increasing destructive effects of sodium sulphate. of the observed and measured responses of these two sandstones to the cycling salt crystallization. The durability of studied stones was evaluated by determining the normalized weight changes during the applied cycles.

Index Terms— Anthropogenic Activities, Egypt. Salt Crystallization, Nile.

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1 INTRODUCTION

The Soluble salt crystallization within the pores of the stone is an important decay factor causing aesthetical problems and generates severe damage in building stone of architectural heritage. Soluble salts may significantly influence drying of porous building materials of Luxor's heritage which may endanger the structural safety of the Heritage. Laboratory salt crystallization tests have a long tradition as a way of assessing the relative quality and durability of weaker and porous rock building stone such as limestones and sandstones [1], [2], [3], [4], and [5],. The effects of soluble salts depend on environmental conditions, characteristics of solutions and properties of the affected materials [5]. In the study area (Fig. 1) which has the world's most precious archaeological treasures, the problem of salts crystallization in the ancient sandstone monuments of Luxor and Karnek Temple, is caused by rising groundwater level which is eating away at the monuments. As the water table rises the porous sandstone of the monuments soak it up through capillary water transportation. When water entries into the temples walls and pillers, it then evaporates leaving salt crystals in the pores of the stone that degrade its surface (Fig.2 and 3). These crystallize into destructive white lesions, which combined with the changing day and night time temperatures, cause paint and layers of heritage rock to separate [6].

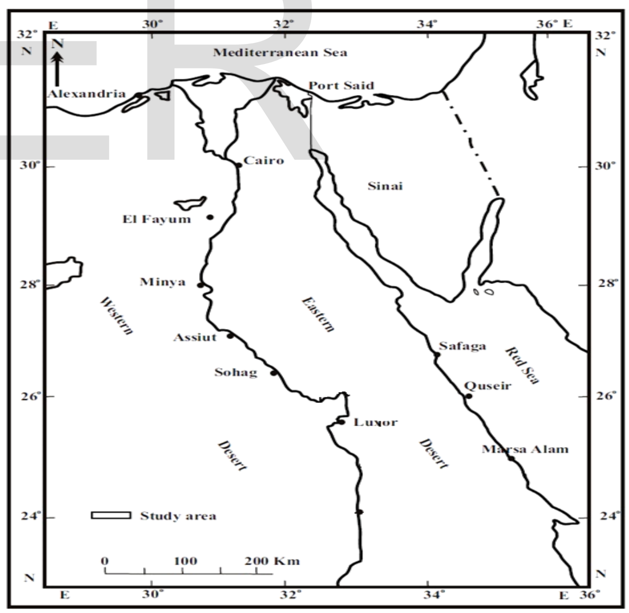

Fig. 1. Location map of the study area.

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Fig. 2. Field photograph showing discoloring in Karnak Temple.

Fig. 3. Field photograph showing salt efflorescence and damage in Luxor temple

The ionic origin can have either natural sources, e.g. soils, or anthropogenic features such as fertilizer and sewage. Concerning the salt weathering, the cations Na, Mg and Ca as well as the anions Cl and SO4 are of crucial importance since they are the constituents of most destructive salts [7]. In the study area, the most common types of the ion encountered in groundwater are chloride and sulphates, and these normally occur as halite and thenardite. These salts are water soluble and are thus transported by groundwater where the porous sandstone soaks it up. This salty water is absorbed by the stones of the monuments and it then evaporates leaving behind the salts.

Different types of salt occur in the sedimentary rocks along the Nile Valley, weathering and deteriorations of the rocks distribute the salts to the alluvial deposit. Since the climate in the Nile valley in Upper Egypt is characterized by low precipitations and high evaporations in most parts of the year, and the capillary zone normally reaches the ground surface. Continuous transport of salt takes place in an upward direction resulted in the concentration of salts in the upper soil strata.
Moreover, movements of water and salts can also occur in rock located above the capillary zone and the surface layer of the rock also can take up water from the humidity of the air. Variations in humidity and temperatures in the air cause the moist zone to move into the rock or retreat towards the surface. The result of these fluctuations is a concentration of the salts which are dissolved in the evaporating water, the volume increases as compared to the fluid phase. The result of this expansion can mash the stone matrix and often materializes as deterioration of the rock surface. Salt weathering affects buildings, engineering structures, rocky outcrops and minerals within the soil profile and there is compelling evidence that its influence will increase due to the global climate change and human impacts [5] and [8]. Since temples building materials (sandstones) are porous, any increase in soil moisture will result in greater salt mobilization and crystallization during drying, leading to damage the walls and pillars of the temples. The salts can be naturally present in the stones, get trapped inside the porous material for instance by imbibitions with salt-containing groundwater, it can in addition be present in the mortars used for construction. In this paper, a quantitative method is followed to assess groundwater level rise risks in addition to the few chemical risks associated with sulfate and chloride solids.

1.1 Scope of the Present Study

The focus of the current study was to monitor and evaluate the salts crystallization problems in monuments foundations for the two most common destructive salts in the groundwater aquifer in the study area. The aim of this work was to compare the morphologies of the two most common destructive salts (sodium sulphate and sodium chloride) crystals within blocks of sandstone, because of different experimental heating regimes in a climatic cabinet. The methodology was based on chemical analysis of groundwater samples taken from boreholes located within and around the temples area and salt laboratory experiments contributes greatly to the degradation of monuments.

2 Study Area

The study area has many conspicuous archaeological sites. The study is concerned with two of the most famous and the most affected ones; Karnak and Luxor Temples. Karnak Temple is one of the most famous reverence places in the world. It is situated at about 3 Km north of Luxor City (25°43′7″N 32°39′27″E) and covers an area about 60100 m². The history of the temple goes back to the Third Dynasty. The raw materials used for constructing the temple are granite derived from Aswan and Nubian Sandstone of grey and reddish- brown color derived from Gabel El- Silsila near Aswan [9] and [10]. The foundations of the temple are quartizitic sandstone derived from Gabel El-Ahmr locality near Cairo [11] and limestone which was derived from Torra near Cairo [12].

2.1 Geology and Hydrogeology

The area of study is essentially occupied by sedimentary rocks belonging to the Upper Cretaceous, the Tertiary and Quaternary (Fig. 4). According to [13] and [14] the Recent, Pleistocene and Pliocene deposits present in the Nile valley can be subdivided into the following sediments:
1- Recent to sub recent alluvial cover.

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2- Neonile sediments (Dandara Formation- Pleistocene age).
3- Prenile sediments (Qena Formation -Pleistocene age).
4- Paleonile / Protonile sediments (Armant and Issawia Formations)
5- Paleonile sediments (Pliocene age).

Concerning the hydrogeological sitting of the studied sites, there are three main groundwater aquifers in the study area (Fig.5) from bottom to top (summarized after [15], [16] and [17] as the following:

- Upper Cretaceous Nubian sandstone aquifer.
- Eocene fissured limestone aquifer.
- The Quaternary alluvial aquifer.

The Quaternary aquifer includes the main groundwater wells in the study area.

The Quaternary aquifer extended in the study area along the River Nile and is considered as the main aquifer. It is composed of graded sand and gravel with some intercalated clay lenses (Holocene and Pleistocene age). The thickness of the Quaternary aquifer in the study area varies from 95 m to about 5 m near the fringes of the Nile valley [18].

An upper silty clay layer (Holocene age) with an average thickness of 13 m semi-confines the Quaternary adjacent to the River Nile, then the aquifer becomes unconfined where the capped silty clay layer is terminates near the fringes of the River Nile.

Accordingly, the Quaternary aquifer comprises a semi-confined silty clay layer which is local and moderately to low productive aquifer and underlain by gravels, sand and clay which is extensive and highly productive aquifer through the River Nile course.

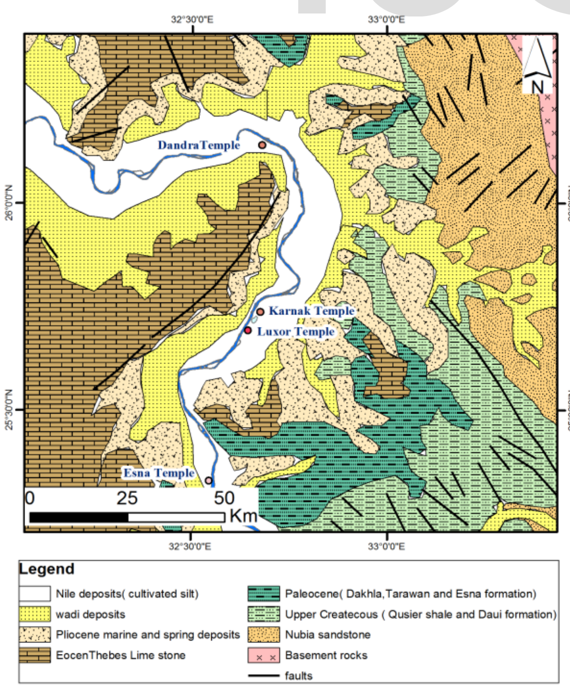

Fig. 4. Geological map of the study area after [13] and [14].

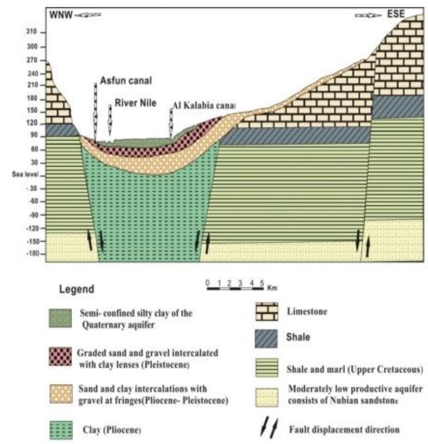

Fig. 5. Hydrogeologic cross-section in Luxor study area (re-drawn after [15] and [16].

3 Materials and Methods

The study is carried out with the help of two major components; field and laboratory. Forty five groundwater samples were collected from different sites of the study area especially in and around the archaeological for chemical analysis. This is to determine the most common destructive salts in the groundwater in the study area. In order to provide information about the fabric dependence of salt weathering, salt crystallization tests according to the German Verein Deutscher Ingenieure (VDI 3797) standard were performed. Two types of temple building sandstones, reddish spotted sandstone (ferru

TABLE 1

THE RESULT OF SODIUM SULPHATE CRYSTALLIZATION TEST WITH THE WHITE SPOTTED SANDSTONE.

Experiment cycle	Initial weight (gm)	Saturated weight (gm)	Dries weights (gm)	Weight loss (gm)
1	43.5	52.66	43.9	0.4
2	43.9	52.91	44.06	0.16
3	44.06	53.1	44.03	-0.03
4	44.03	51.1	42.83	-1.2
5	42.83	45.3	38.2	-4.63
6	38.2	41.3	34.2	-4
7	24.2	29.5	19.1	-5.1
8	19.1	24.8	17.2	-1.9
9	17.2	22.3	15.2	-2
10	15.2	20.8	13.6	-1.6

TABLE 2

THE RESULT OF SODIUM SULPHATE CRYSTALLIZATION TEST WITH THE REDSISH SPOTTED SANDSTONE.

Experiment cycle	initial weight (gm)	Saturated weight (gm)	Dries weights (gm)	Weight loss (gm)
1	45.73	51.16	46.2	0.47
2	46.2	51.11	46.36	0.16
3	46.36	51.3	46.33	-0.03
4	46.33	51.26	46.84	0.51
5	46.32	50.31	45.44	-0.88
6	46.29	50.19	45.16	-1.13
7	45.16	49.3	45.13	-0.03
8	34.08	38.5	30.5	-3.58
9	30.5	27.5	26.5	-4
10	26.5	24	20.4	-6.1

TABLE 3

THE RESULT OF SODIUM CHLORIDE CRYSTALLIZATION TEST WITH WHITE SPOTTED SANDSTONE.

Experiment cycle	initial weight (gm)	Saturated weight (gm)	Dries weights (gm)	Weight loss (gm)
1	45.69	51.16	45.9	0.11
2	45.9	51.11	45.86	0.14
3	45.86	51.3	45.83	-0.03
4	45.83	48.3	44.63	-1.2
5	44.63	47.7	44.5	-0.13
6	44.5	45.9	42.75	-1.75
7	35.75	39.7	30.65	-5.1
8	30.65	33.2	28.75	-1.9
9	28.75	28.8	26.75	-2
10	26.75	27.6	25.15	-1.6

TABLE 4

THE RESULT OF SODIUM CHLORIDE CRYSTALLIZATION TEST WITH REDDISH SPOTTED SANDSTONE.

Experiment cycle	initial weight (gm)	Saturated weight (gm)	Dries weights (gm)	Weight loss (gm)
1	45.79	51.16	46.2	-0.41
2	46.2	51.11	46.36	-0.16
3	46.36	51.3	46.33	0.03
4	46.16	49.3	45.83	0.33
5	45.83	47.5	44.5	1.33
6	44.5	46.54	43.2	1.3
7	43.2	45.69	40.85	2.35
8	40.84	44	38.65	2.19
9	38.65	40.9	36.7	1.95
10	36.7	39.5	35.82	0.88

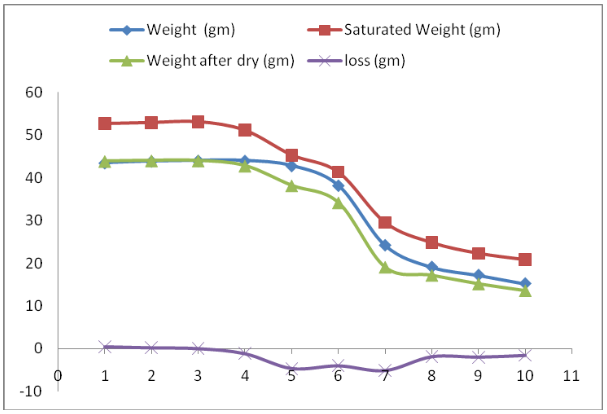

Fig. 6. The result of sodium sulphate crystallization test with white spotted sandstone.

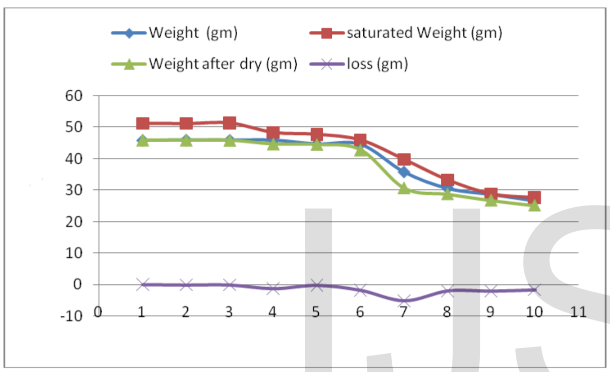

Fig. 7. The result of sodium chloride crystallization test with white spotted sandstone.

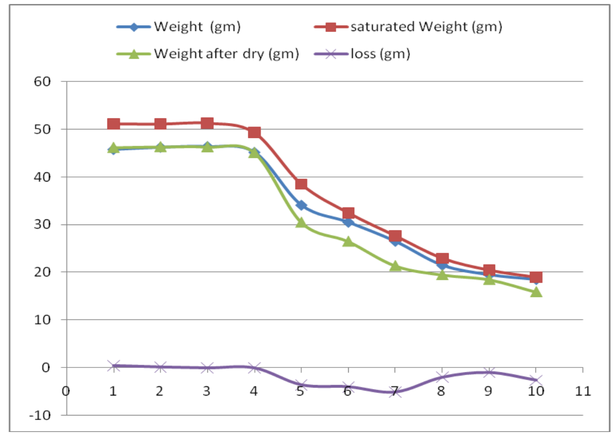

Fig. 8. The result of sodium sulphate crystallization test with reddish spotted sandstone.

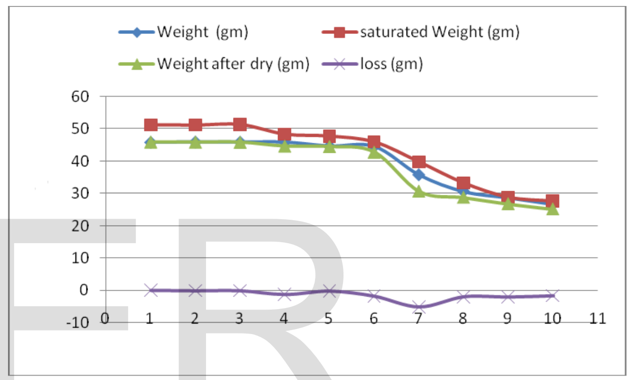

Fig. 9. The result of sodium chloride crystallization test with white spotted sandstone.

ginous) and white spotted (calcareous) sandstones were used in the salt crystallization test with sodium chloride and sodium sulphate 10% saturation solutions. Initial weights, saturation weight, dries weight and loss of weight are measured for each individual cycle. Changes in the specimens were visually controlled during the experiment with naked eye and weight loss through the drying of the samples was also controlled throughout the experiments.

The tests were carried out on sandstone cubic samples (36 mm edges length), which were cycled loaded with a sodium sulphate and sodium chloride 10% solution. For the capillary solution uptake, a period of 4 hours was chosen, and the drying required 16 hours at 60°C in a drying chamber. After a cooling phase of 2 hours, the loaded samples were weighed. Two samples of each sandstone type were used in the experiments. The specimens are subjected to cycles of soaking in a solution and drying; their deterioration is expressed as the specimen's weight loss in percentage and the visible changes of the sample surfaces and the change of weight after each cycle of loading. To get further information about the change of pore space after the salt crystallisation test for the respective sample, samples of the stone types were also studied by optical microscopy (petrographic characterization,), scanning electron microscopy (SEM) and by X-ray diffraction. For the various sandstone samples, differences of salt distribution (efflorescence or subflorescence), damage forms, and material loss behaviour are observable during the salt crystallization

4 Results and Discussion

Based on the results of the chemical analysis of the collected groundwater samples in the study area and analysis of the accumulated salt layer taken from temples walls, specimens of white and red sandstone were subjected to salt crystallization tests with the two most common destructive salts in the groundwater aquifer in the study area: sodium chloride which crystallize to form the halite (NaCl) and sodium sulphate which can crystallize to form the mirabilite $Na_2SO_4 . 10H_2O$ at high humidity or the thenardite Na_2SO_4 at low humidity [19] and [3].

Fig. 10. Effects of sodium sulphate crystallization with white spotted sandstone.top)- after one cycle, middle)- after five cycles and bottom)- after 10 cycles.

4.1 Sodium sulphate Na2SO4

Sodium sulphate is a frequent salt type found in all studied groundwater samples. It can be considered as extremely destructive [20] and [21]. From the sodium sulphate solution, two crystal phases can develop. The water free-phase, thenardite (Na_2SO_4), and the hydrate phase, mirabilite ($Na_2SO_4.10H_2O$). The phase transition from thenardite to mirabilite at water absorption is associated with a volume increase of about 300% [22]. Consequently, if the salt is deposited in the pores of sandstone, the dimensional changes can lead to destructive pressures and powdering of the surface. This hydration process takes place in a climate range which is often found in nature [23]. The conversion at 20°C takes place at 75% relative humidity, whereas thenardite is stable in the lower and mirabilite in the higher humidity range and the hydration process normally takes place during a short period.

The changes of initial weights, saturation weights, dry weights and loss of weight in both white and reddish spotted sandstone samples through ten cycles are illustrated in Tables (1 and 2) and Figures (6 and 7) respectively. These changes show that weights are nearly stable until the forth cycle, then there are rabid decreases of weights starting from the fifth cycle. The loss of weigh is much higher in white spotted sandstone than the reddish spotted sandstone. These differences may be due to the calcareous matrix and the coarser grain size of the white spotted sandstone than the reddish spotted sandstone.

Fig. 11. Effects of sodium sulphate crystallization with reddish spotted sandstone.top)- after one cycle, middle)- after five cycles and bottom)- after 10 cycles.

4.2 Sodium Chloride NaCl

Halite is a highly water soluble salt compared with other salts, and the pressure generated by crystallization of halite is twice as large as that generated in the process of gypsum crystallization. Therefore, rocks with a high content of halite are often more weathered. After salt crystallization tests, the mass loss of each specimen was measured and macroscopic and SEM studies were developed. All these measurements and analyses were carried out at the laboratories of South Valley University. The changes of initial weights, saturation weights, dry weights and loss of weight in both white and reddish spotted sandstone samples through ten cycles are illustrated in Tables (3 and 4) and Figures (8 and 9) respectively.

The calculated saturation weights showed that there is increase in the weight for all samples in the first loading cycle. The highest salt enrichment is observable for the white spotted sandstones compared with the reddish spotted sandstones which exhibit low salt enrichment. Remarkable is that the sandstones which are characterized by a high salt enrichment are only slightly affected by salt deterioration.

These changes showed that the samples weight is nearly stable until the seventh cycle, and then there is a rabid decrease of weights from the eighth cycle. The total loss of weights is much higher in white spotted sandstone than the reddish spotted sandstone. These differences may be due to the calcareous matrix and the coarser grain size of the white spotted sandstone than those of the reddish spotted sandstone.

4.3 Destructive Effects on Sandstone Subjected to Crystalline Test

This part deals with the destructive effects measured as lose of weight on the two types of temple building sandstones, reddish and white spotted sandstones that were subjected to salt crystallization test using sodium chloride and sodium sulphate. These effects can be summarized as follows:

Effects of sodium sulphate crystallization in the white spotted sandstone (Fig. 10) showed the highest destructive effects. The weight decreases from 43.5 to 13.6 gm in ten cycles. The loose of weight is begun early in the third cycle. This higher destructive effect is due two effective; the water free-phase, thenardite (Na_2SO_4), and the hydrate phase, mirabilite ($Na_2SO_4.10H_2O$). Moreover, the calcareous matrix and the course grained may help in increasing destructive effects of sodium sulphate.

Effects of sodium sulphate crystallization in the reddish spotted sandstone (Fig. 11) showed less destructive effects than those of white spotted sandstone. The weight decreases from 43.73 to 20.4 gm in ten cycles. The loose of weight is begun early in the third cycle. These low destructive effects are due to its finer grains, higher silicate content and absence of calcareous matrix.

In general, effects of sodium chloride crystallization are much lower than that of sodium sulphate where, its effects just appear as a surface efflorescence especially in the first five cycles.

Effects of sodium chloride crystallization in the white spotted sandstone (Fig. 12) showed lower destructive effects than that of sodium sulphate. The weight of the sample of the white spotted sandstone decreases from 45.69 to 25.15 gm in ten cycles. The loose of weight is begun lately after the sixth cycle. The relatively higher destructive effects than that of reddish sandstone is also due to the calcareous matrix and the course grained may help in increasing destructive effects of sodium sulphate.

Effects of sodium chloride crystallization in the reddish spotted sandstone (Fig. 13) showed less destructive effects than that of white spotted calcareous sandstone. The weight decreased from 45.79 gm to 35.85 gm in ten cycles. The loose of weight is appeared to be gradationally. These low destructive effects are due to its finer grains, higher silicate content and absence of calcare-

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ous matrix.

The destructive effects increase from sodium chloride in the reddish spotted ferruginous sandstone, sodium chloride in the white spotted calcareous sandstone, sodium sulphate in the reddish spotted ferruginous sandstone to sodium sulphate in the reddish spotted ferruginous sandstone.

From the result of the crystalline test, the most effective salt in the studied temple is sodium sulphate. Sodium chloride, although its abundance, having smaller destructive effects.

The building rock types are playing a great role in the magnitude of weathering in the study temples.

Fig. 12. Effects of sodium chloride crystallization with white spotted sandstone.top)- after one cycle, middle)- after five cycles and bottom)- after 10 cycles.

Fig. 13. Effects of sodium chloride crystallization with reddish spotted sandstone. (top)-after one cycle, (middle) -after five cycles and (right)- after 10 cycles

7 Summary and Conclusion

The crystalline salts from the temple walls were found to consist of halite NaCl, thenardite Na_2SO_4 with a small amount of sylvite KCI and in addition to trace amounts of nitrate KNO_3, gypsum $CaSO_4.2H_2O$, bassanite $2CaSO_4.H_2O$ quartz and kaolinite are also present in the salt sample. The effects of sodium chloride crystallization are much lower than that of sodium sulphate where, its effects just appear as a surface efflorescence especially in the first five cycles. The most effective salt is sodium sulphate, where sodium chloride has smaller destructive effects. The effects of both sodium sulphate and sodium chloride are higher in white spotted sandstones because of its calcareous composition and coarser grained. Finally, slices of naturally formed salt layer and thick salt layer collected from inside the Karnak Temple beside slides from different sandstone samples that subjected to the crystalline test are examined using Scanning Electron Microscopy (SEM) in South Valley University central laboratory. The most common salts layer collected from the studied temple walls are halite, thenardite and kaolinatie. Thenardite mineral appears in the SEM micrograph between quarz distinguished with its known fibrous crystal habit while, halite cubic crystals also, are easily could be distinguished in the thick salt layer. Studying the salt layer resulting from sodium sulphate and sodium chloride crystallization test showed a strike similarity with those neutrally collected from the studied temple walls.

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