SCIENTIFIC CULTURE
www.sci-cult.com

SCIENTIFIC CULTURE, Vol. 5, No. 2, (2019), pp. 37-48
Open Access. Online & Print

DOI: 10.5281/zenodo.2649505

ASSESSMENT OF THE AGING TREATMENTS OF SANDSTONE GREYWACKE ROCK ART (WADI HAMMAMAT) BY PETROGRAPHY, SEM, XRD, EDX

Abd El-Hakim A. El-Badry[1], Mona F.Ali[2], Badawi M.Ismail[3]

[1]Ministry of Antiquities, Cairo, Egypt
[2] Faculty of Archaeology, Cairo University, Egypt
[3] South Valley University, Faculty of Archaeology, Luxor, Egypt

Received: 30/09/2018
Accepted: 02/03/2019
Corresponding author: (hakimelbadry76@gmail.com)

ABSTRACT

Greywacke is a very important ornamental stone that was widely used in ancient Egypt for various purposes such as statues and sarcophaguses in addition to the rock-cut panels which suffered from the aggressive damage as the result of the physical-chemical and anthropogenic deterioration factors. The present study used the techniques of X Ray diffraction (XRD), scanning electron microscope -energy dispersive X rays (SEM-EDX) and polarised microscope (PM) to identify the deterioration phenomena of weathered greywacke. Several chemical consolidates have been used for treatment of the greywacke rock art at Wadi-Hammamat site. The aim of this paper is evaluation the effectiveness of those consolidates after the cycles of artificial aging using the examination by scanning electron microscope. SEM technique reveals the assessment of the treated greywacke samples after artificial thermal aging and artificial salt weathering using sodium sulfate Na_2SO_4. From obtained results, it is found that the treatment with Wacker OH 100 is more appropriate one.

KEYWORDS: Treatment, Greywacke, Rock Art, Wadi Hammamat, Artificial Aging, Scanning Electron Microscope, consolidant, SEM-EDX, XRD, chemical

1. INTRODUCTION

1.1 Uses of Greywacke in Ancient Egypt

Greywacke is one of the most famous ornamental stones that were widely used in ancient Egypt after limestone, sandstone and granite for various and splendid archaeological objects such as; internal wall veneer, pavement, and columns for temples, small statue shrines (naoi), obelisks, offering tables, small vessels and figurines, sarcophagi, small to colossal statues and other sculptures, scarab and shabti figures, stelae, cosmetic and ceremonial palettes (Harrell, and Storemyr, 2009). In addition to a great quantity of scattered unfinished and broken objects (sarcophagi) still at the quarry site as a result of carving and polishing processes (Klemm and Klemm, 2001). Furthermore, hundreds of rock art panels were carved on the greywacke stone in Wadi Hammamat site.

1.2 Geographical location of Wadi Hammamat

The famous and the main quarry for the greywacke or *bekhen-stone* as called by the Egyptians in ancient Egypt was the Wadi Hammamat site in the eastern desert of Egypt (Shiah, 1942). The site is located about 83 km east of Qift district in Upper Egypt, between (25°58.9´- 26°0.0´ N) and (33° 33.8´- 33° 34.6´ E) (Harrell et al.,1996). Furthermore, the quarry contains other similar varieties rocks such as siltstone and conglomerate (Aston et al., 2000).

1.3 Geologically and petrographically of greywacke at Wadi Hammamat

The name of greywacke or graywacke derived from the Dutch word (Grauewacke) which means the sandstones from Palaeozoic in Harz (Helmbold, 1952). The origin of greywacke at Hammamat sediments argued by several studies as follows:
Akaad, 1958 reported that it represents the clastic sediments formed by the erosion of moderately high relief volcanic rocks and pyroclastics. Samuel, 1978 stated that the rocks were deposited in local fresh water basins filling the low relief area after transportation by water. The other studies reported the rocks that originated from geosynclinal sediments or turbidity currents (Dott, 1964; Sakran, 1989). On the other hand the previous studies reported that, the greywacke at Wadi Hammamat was subjected to a very low grade regional metamorphism so, it's better to call it meta-greywacke (Aston, et al., 2000). Greywacke rocks are grayish green in color, and are composed mainly of clastic sediments; sharply-angular grains of quartz, feldspars (plagioclase) of sand-grains and lithic fragments (Andre, G.,1939), cemented by chlorite, mica, epidote, magnetite and calcite, and embedded in a clay matrix. The grains of greywacke range from fine to very fine-grained sediments between 0.06 - 0.2 mm in diameter (Dunham, 1962). The greywacke rocks are hard and dense due to compaction and characterized by folding, fracturing and foliation (Blatt, 1979; Sakran, 1989) as a result of the parallel alignment of the lithic fragments, quartz, plagioclase, muscovite and chlorite.

1.4 Rock art at Wadi Hammamat

Wadi Hammamat site contains about 600 rock art (inscriptions) carved in the greywacke bedrock documenting different and various themes of ancient Egyptian history (Hikade, 2006), and vary in their formulas, length and elaborateness such as themes of the quarrying and mining activities to the area from the fourth dynasty to the third year of the Roman Emperor Maximus which divide to the inscriptions of the royal expeditions and personal inscriptions which record the aim of the expedition and the number of the participants, sometimes the texts were accompanied by scenes such as the offerings of the kings to the gods (Sweeney, 2014) and the worshiping to the Cartouches of the kings (Fig. 1(a and b)).

The natural cleavage of *bekhen-stone* facilitated work using layers to separate the blocks by means of stone hammers (Hikade, 2006).Some of the rock inscriptions representing some birds and animals dating back to the prehistoric times, while the other rock inscriptions recording Coptic and Islamic graffiti.

2. CONSERVATION STATE OF ROCK ART AT WADI HAMMAMAT

The rock art at Wadi Hammamat have been subjected to a complex series of weathering and degradation factors (Meiklejohn, 1995) (MacLeod, 2000) (MacLeod, et al., 1995) such as natural environment, natural disasters and anthropogenic deterioration factors in addition to structural and geological aspects as the following;

The natural environmental deterioration factors such as violent wind, extreme temperatures, intensive solar radiation predominant at the site which lead to the drastic thermal fluctuations.

The studied area was subjected to heavy rains in 1925, 1960, 1979, 1987, 1991, 1994 and 1996 and the average amount of rainfall over the area was about 40-300×10^6 (Ismaiel,1996) which caused several aggressive flash floods and led to severe damage and destruction of rock art at the site. The anthropogenic deterioration factors at the site represented in utilizing the Portland cement mortars for filling the fractures and joints in greywacke bedrock this result in crystallization of soluble salts (especially gypsum and anhydrite), the detachment and separation parts of the bedrock which called the bossing phenomenon (Kmally, 2011). The other factor of anthropogenic deterioration represented in using un-appropriate treatment which caused the disfigurement of the rock art (El-Badry, 2018).

Figure 1. Themes of rock art at Wadi Hammamat ; (a) The king Seti II (19th Dynasty) present offerings to the gods; Min, Horus and Isis (b) The Vizier Paraemheb worship to the Cartouche of Seti II.

Greywacke displays several vertical and horizontal joints that range from tens of centimetre of a number of meters that helped to obtain suitable blocks for work pieces in ancient Egypt. And also caused the breaking off and falling away several parts of rock art on the bedrock (Klemm and Klemm, 2008). Also, the bedrock at the site is characterized with structural and geological aspects such as; lamination, bedding planes, oval and spherical nodules sets which consider weakness zones, caused sliding movements, cracking, collapse of the bedrock in addition to weathering and separation of rock art panels from the bedrock (El-Badry, 2014).

The type and the rate of decay largely depend on both the intrinsic properties and extrinsic factors (Rodrigues, 2001). The intrinsic properties such as chemical composition, physical and mechanical properties particularly the porosity and pore size distribution. While the extrinsic factors include the previously mentioned deterioration factors predominant in the area which caused a severe deterioration phenomena of rock art (Fig.2 (a-d)) such as; cracks, granular disintegration, fissures, fractures, exfoliation, scaling, collapse and rock sliding in addition to the change of the physical properties and the chemical alteration of the rock components and the crystallization of the salts. These deterioration phenomena required (need) to the treatment of the stone by consolidation products to improve the cohesion of deteriorated stones (Pinto and Rodrigues, 2008).

The consolidant products must also have the ability to penetrate inside the stone at enough depth and consolidate the weathered stones, give a good adhesion to the stone, coating the walls pores, be permeable to water vapor, as well as not change the color of the stone surface (Botteghi et al., 1992).

The consolidation of stone can be a risky action due to its irreversibility and it can cause undesired effects of some stones (Al-Bawab et al., 2017).

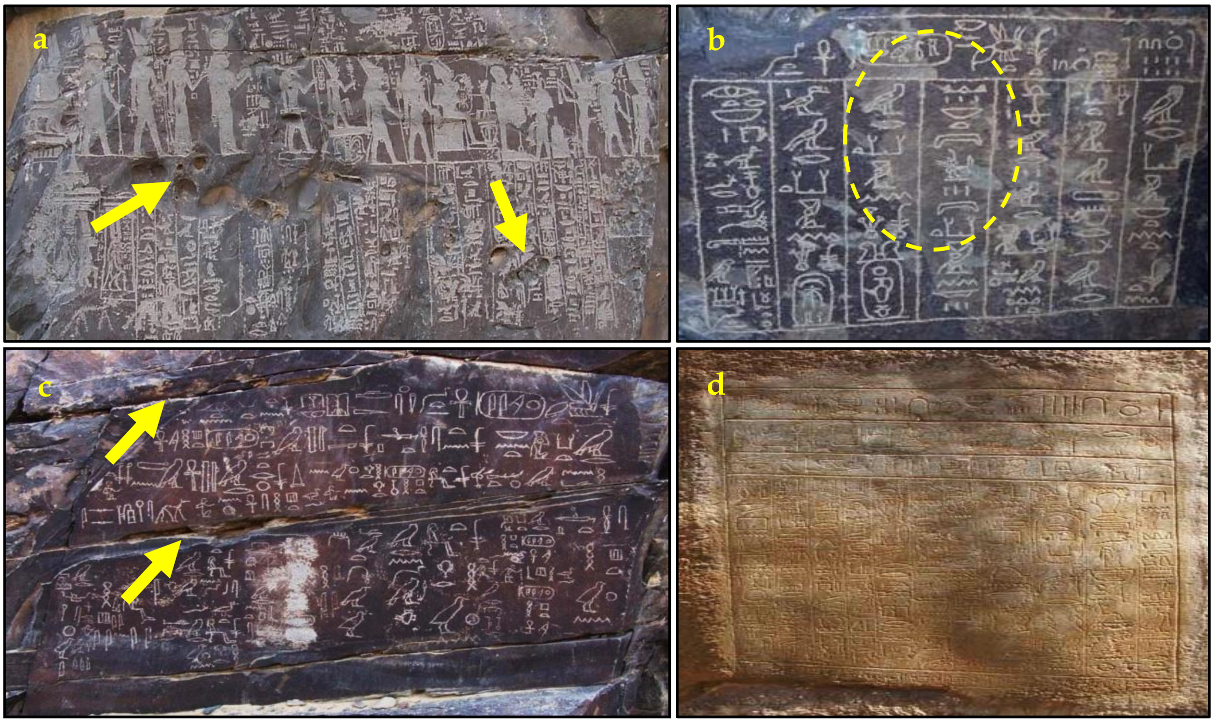

Figure 2. Deterioration phenomena of rock art at Wadi Hammamat ; (a) nodules (b) exfoliation (c) fractures and fissures (d) disfigurement due to un-appropriate treatment.

The effectiveness of the stone treatment depends on several parameters such as; the properties of treated stones, the microenvironment, the type of product used, product concentration, solvent type, application technique, and contact time (Pinto and Rodrigues, 2012). Although the variety of the products of stone conservation in the markets, some specific consolidants have been used practically and frequently as stone consolidation of greywacke rock art in Wadi Hammamat because of their easily obtainable, they are plentiful in the commercial markets and the easily of their application . These chemical consolidants are Silo 111, Wacker W-290, Wacker OH 100 (SILRES® BS OH 100), Paraloid B 82 and Paraloid B 66. The previous studies stated that, the treatment of greywacke stones resulted in very thin layer (few millimetres) of coating with all the treatments because of very low porosity and a very fine size of the stone pores (Rosario, et al.,2000). It's worth to mentioning that a low viscosity and a low contact angle are sought and required for the previous mentioned consolidant products, and also must be stiffish in their place after the application; for this reason that consolidants pre-diluted (De Buergo et al.,2004). There are several experimental methods and techniques for determining the above properties required, one of them is scanning electron microscope (SEM) which be considered a very useful tool to assess the efficiency of the treatments applied to weathered stones for conservation purposes (De Buergo et al., 2004).The technique offers the possibility of determining the porous system of the untreated stones.

The surface morphology and the penetration depth of the products in the stone (Al-Dosari et al., 2016), defining the products' filming capacity, observing the distribution and behavior of the treatment products on both the treated and treated aged samples (Darwish, 2013) and their conservation degree through time.

The aim of this paper is evaluating the effectiveness of the consolidants used in the present study after the accelerated aging tests through the examination by scanning electron microscope (SEM) to find the best ones for the treatment of the greywacke rock art at Wadi Hammamat particularly there is no any practical study carried out to evaluate their effects on the greywacke stone after treatment, after artificial aging tests and/or after natural aging at the site. For this purpose the previous mentioned consolidation products were subjected to tests as follows: they take code numbers a,b,c,d and e in the current study to facilitate reporting them (Table 1). Several greywacke samples were prepared for the treatment process, after that the treated samples were submitted to the accelerated thermal and salt aging tests to evaluate their behavior through their examination by scanning electron microscope as the following methodology.

Table 1. Selected conservative treatments.

Products	Code Number	Manufacturer	Solvent	Chemical Family	Composition
Silo 111	a	CTS (Italy)	ready to use	Organo Siloxane Oligomers	Oligosiloxanes
Wacker W-290	b	Wacker Chemie (Germany)	5% in White spirit	Siloxane	ethyl silicate
Wacker OH 100 SILRES® BS OH 100	c	Wacker Chemie (Germany)	5% in White spirit	Silane	silicone esters
Paraloid B.82	d	CTS (Italy)	2% in Toluene	Acrylic	co-polymer
Paraloid B.66	e	CTS (Italy)	2% in Toluene	Acrylic	co-polymer

3. MATERIALS AND METHODS

3.1 Sample preparation for treatment

Several greywacke blocks were collected from the Wadi Hammamat site, then those blocks were cut as regular cubic of 5× 5×5 cm, before the treatment the samples were washed with deionized water and brushed clean of any soil and salt deposits with tooth brushes, after that the samples were dried in an oven at 105 ˚C for 24 hours when the samples achieved a constant weight or mass (mass difference between two successive weightings did not exceed 0.1g). Then the samples were left at room temperature for 2 hours and then were brushing by acetone to open the porous of the stone and were weight again for achieving a constant weight.

The consolidation products tested in this work were applied by brushing at room temperature and pressure (Doehne and Price, 2010). The procedure was repeated three times with interval 48 hours between each application. At the end the treated samples were left at room temperature for about a month (28 days) to allow for the polymerization process to take place. The treated samples were divided into three groups; treated, and the other samples were divided into two groups which were submitted to both artificial thermal aging and salt weathering.

3.2 Laboratory tests

3.2.1 Artificial Aging Tests

The accelerated artificial aging tests such as; artificial thermal aging and artificial salt weathering (soundness) were carried out to assess the durability, stability and behavior of the treated samples and the consolidants against the artificial aging tests and find the best consolidant of greywacke at the site.

3.2.2 Artificial thermal aging

The samples were subjected to 30 cycles as the following; 2 hours of immersion in water at room temperature, 2 hours of drying at ambient temperature, 18 hours of drying in an oven at 105°C and 2 hours of cooling in ambient temperature (Franzoni et al., 2013; Shashaua, 1993) in this test the samples are weighed after each cycle and at the end the samples were left to cool in the air temperature for 48 hours.

3.2.3 Artificial salt weathering

The samples were subjected to 15 cycles of soundness test according to ASTM Designation: C88-05, using sodium sulfate Na_2SO_4 (ASTM, 1997; (Sheftick, 1989; Marschner, 1978) formed by; 16 hours total immersion in 10% sodium sulfate solution (it's necessary to cover the samples in the solution with polyethylene sheets for forbidden evaporation of the saline solution), 2 hours of drying in air temperature, 4 hours of drying in drying oven at 105°C, 2 hours of cooling in room temperature.

4. RESULTS AND DISCUSSION

4.1 Petrographic Examination (PM)

Polarizing microscope (PM) has revealed that (Fig.3 (a-c)) , the rock consists of quartz, plagioclase in addition to potash feldspars and perthite as main components of the rock, while the secondary minerals represented in chlorite, calcite, epidote, muscovite, zircon and iron oxides which also form the groundmass or fine grained matrix that cemented the rock, in addition there are rock fragments of various kinds. The deterioration products represented in the alteration of plagioclase to epidote, muscovite and sericite. Also, both kinds of feldspars transformed partially or completely to kaolinite, sericite and calcite. Furthermore the change of iron oxides to hydrated iron, which caused the staining and dark-brownish pigmentation of the mineral grains in the rock, in the same manner the green pigmentation is due to the chlorite. The petrographic investigation showed also that, the rock was subjected to mechanical deformation of the grains resulting from the physical weathering, which represented in micro fissures, cracks inside and among the grains in addition to the veins which were filled by calcite and carbonates and also, disintegration, eroded the boundaries of the quartz grains due to the strong stresses.

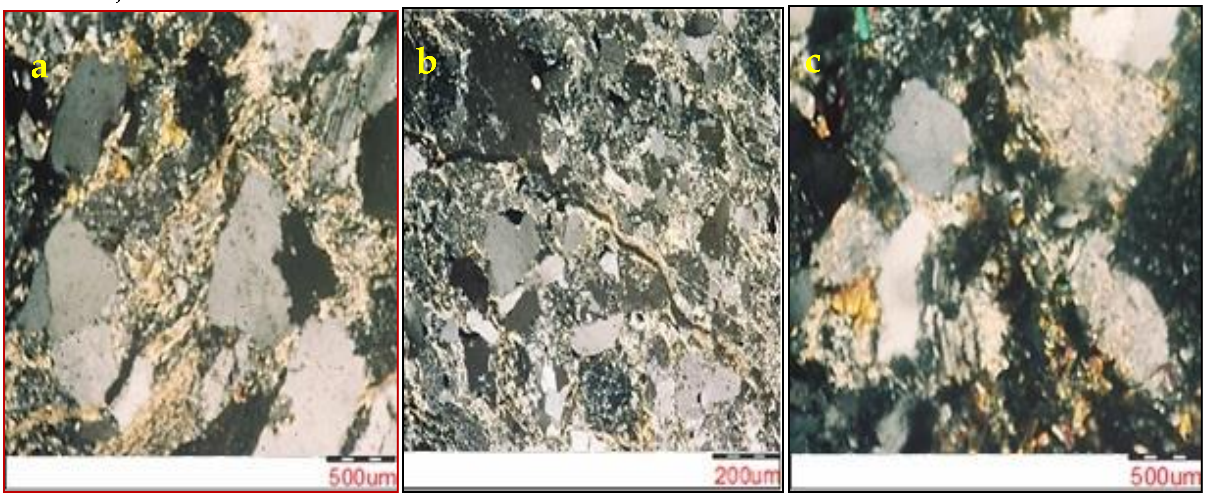

Figure 3. PM micrographs of greywacke samples: (a) Angular grains of quartz and plagioclase, (b) Fine grained matrix of clay and chlorite and veinlet, (c) Strongly altered feldspar to sericite.

4.2. Scanning Electron Microscope (SEM)

The weathered samples were cut at 50mm with flat surfaces, coated with a thin gold and were investigated using SEM that was performed using a Fei device (version Quanta 200), with following specifications: 24.98 kV, 0.00 tilt, 36.47 take-off, 35.0 ampt, SUTW-sapphire detector type, 129.87 resolution, according to the processing instructions. SEM have revealed that (Fig.4 (a-c)), destruction, the collapse of the internal structure of the stone, the deformation of quartz grains, the evolution of the fissures, cracks and de-cohesion among the grains in addition to the residual pores in the secondary minerals due to the effect of saline solutions. The SEM investigation has also shown that, the presence of clay minerals and crystallization the salt of sodium chloride among the grains of the stone.

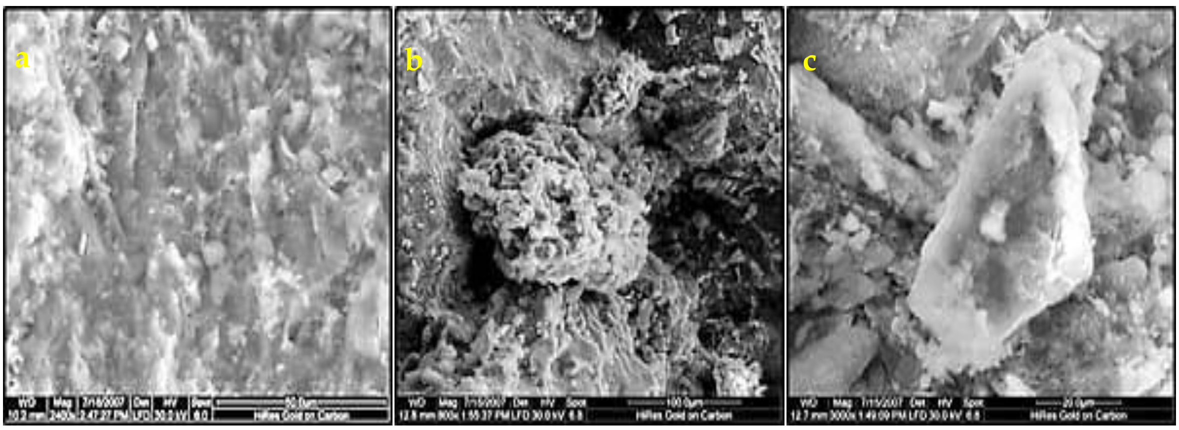

Figure 4. SEM micrographs of untreated greywacke samples.

4.3. X-Ray Diffraction Analysis (XRD)

The greywacke samples were studied by X-ray diffraction (XRD) to find their mineralogical and natural aging products, so that the samples were ground to a fine powder in an agate mortar and pressed into the specimen holder. XRD analysis of the samples was performed with a Philips X'Pert PW3710 Diffractometer, using Cu Kα radiation (40kV, 30mA), high-resolution graphite monochromator, rotating sample holder and proportional detector. Measurements were carried out in the range 5° < 2θ < 90° with a step of 0.02°; the ICDD data bank of standard X-ray powder spectra was used for phase identification (Uda et al., 2005).

XRD results of greywacke samples (Fig.5 (a-d)) have identified, the rock composes of quartz SiO_2, plagioclase (albite,$NaAlSi_3O_8$), clay minerals such as kaolinite $Al_2Si_2O_5(OH)_4$ and chlorite (Fe^{2+}, Mg, $Mn)_2Al_4Si_2O_{10}(OH)_4$, the other minerals are represented in calcite $CaCO_3$ and halite (NaCl).

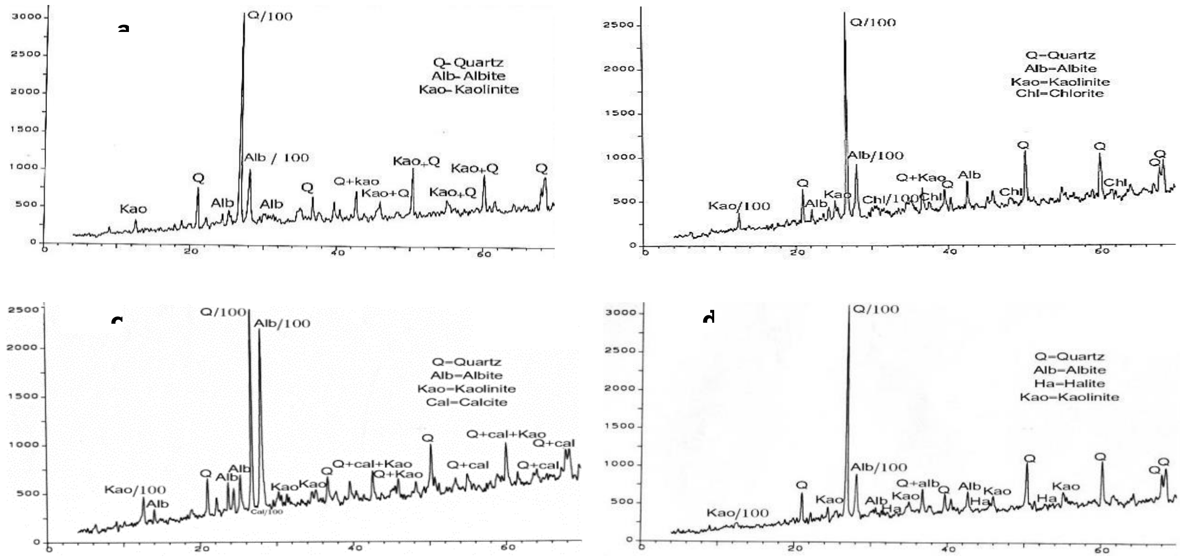

Figure 5. XRD patterns of weathered greywacke samples from Wadi- El-Hammamat site.

4.4. *Energy Dispersive X-ray analysis (EDX)*

Five deteriorated greywacke samples were studied by energy dispersive X-ray analysis (EDX) attached with scanning electron microscope (SEM) to determine the major mineral constituents and identifying unknown phases of the studied weathered greywacke samples. The scanning electron microscope used was a Quantom 3D 200 I) (FEI Philips – Holland) coupled with EDX. Column pressure 60PA, low vacuum, in back scattered mode (BSED) with a feature to obtain images and showing the distribution of the elements. The results in table (2) have shown that, the loss of silica (Si) content in the greywacke samples is due to the alteration process, the high iron (Fe) content may from ferromagnisum minerals and / or from the alteration process of iron oxides; convert ferrous-irons to ferric irons. On the other hand the presence of chlorine (Cl) and sodium (Na) ions in the samples suggested that the deterioration of greywacke was also due to the crystallization of sodium chloride (NaCl) salt. EDX analysis reveals significant quantities of silica with accessory aluminum (Al) calcium (Ca) magnesium (Mg), potassium (K),and sodium (Na) attributed to the quartz, clay minerals and plagioclase feldspars the main constituents predominate in the greywacke stone, while the loss ignition of calcium is due to the leaching of calcite.

Table.2.EDX analysis of weathered greywacke from Wadi Hammamat site.

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Cl	MnO	P_2O_5
A	69.00	0.52	13.33	5.30	2.06	5.17	3.50	0.90	---	0.04	0.17
B	65.00	0.68	13.80	6.88	5.15	4.70	2.66	0.95	---	0.04	0.13
C	52.50	1.14	13.48	8.91	5.16	10. 04	3.66	0.15	4.70	0.16	0.09
D	50.24	1.70	13.82	9.65	5.33	12. 91	1.97	0.09	3.99	0.21	0.08
E	49.20	0.31	12.30	11.34	12.37	10. 04	1.88	0.22	2.10	0.17	0.06
Total	**57.188**	**0.87**	**13.346**	**8.416**	**6.014**	**8.572**	**2. 734**	**0.462**	**2.158**	**0.124**	**0.106**

4.5. Assessment of the effectiveness of testing stone consolidants by SEM

4.5.1 Samples treated with Silo111

The treatment with Silo 111 covered the mineral grains in a dense and total form and also formed incomplete links or bonds between the grains due to partial filling in the spaces between the grains which caused the cracks in the consolidation film (Fig.6 (a1)). After the artificial thermal aging the consolidated material appeared a kind of partial stability and resistance against the effect of thermal aging, some cracks developed in polymer film due to the expansion and shrinkage of this material under the influence of high temperature (Fig.6 (a2)). After the artificial salt weathering the treatment with Silo 111 showed a partial cracking and fragmentation in the polymer film and several gaps developed between the mineral grains as a result of the growth and crystallization the salts of sodium sulfate (Fig.6 (a3)).

4.5.2 Samples treated with Wacker W-290

The treated samples with Wacker W-290 showed that; a heterogeneous in the polymer coat and although the consolidant gave fairly good coverage of some of the grains, while the other grains, the pores and the spaces between the mineral grains appeared free of consolidated polymer (Fig.7 (b1)). After the artificial thermal aging the consolidant appeared in dense and shrinkage concentrations which caused several clear cracks and gaps between the mineral grains (Fig.7 (b2)). After the artificial salt weathering the treatment with Wacker W-290 revealed many cracks in the spaces between the mineral grains in addition to clear detachments and separations between the rock grains as a result of the damage and fragmentation of the consolidation film due to the salt aging and crystalized sodium sulfate salt (Fig.7 (b3)).

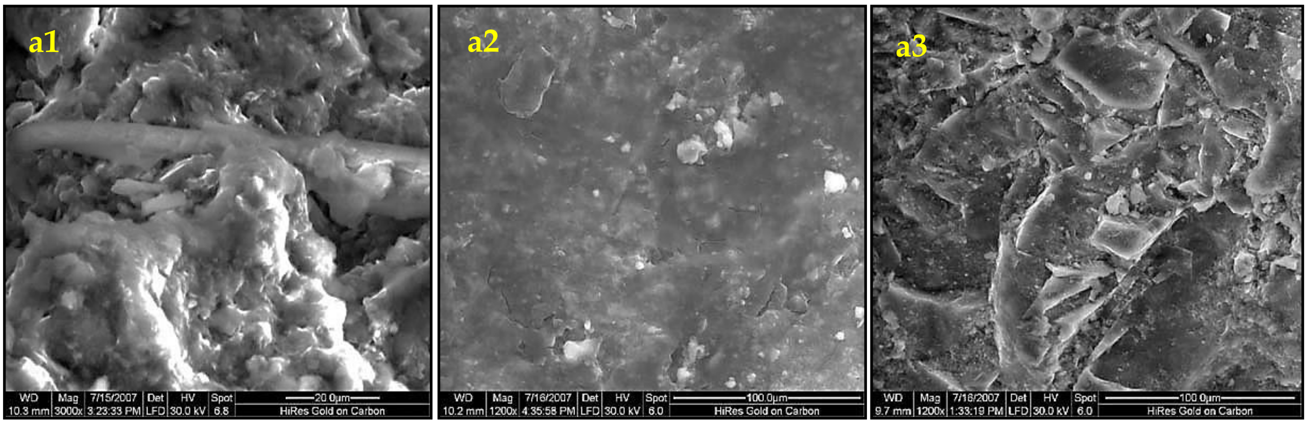

Figure 6. SEM micrographs of the samples treated with (a1) Silo 111, (a2) after thermal and (a3) salt ageing.

4.5.3 Samples treated with Wacker OH 100 (SILRES® BS OH 100)

The treatment with Wacker OH 100 forms a fairly uniform film and heavy coating on the boundaries of stone particles, more than that thick and dense polymer film deposited and relative filling the spaces and interfaces between the mineral grains (Fig.8 (c1)). After the artificial thermal aging that treatment revealed a high stability against the effects of heat also, a very good coverage, clear encapsulation of the mineral grains of the rock, as well as the relative filling and good penetration of the consolidant inside the cracks still appears (Fig.8 (c2)). After the artificial salt weathering the consolidant showed a good stability against the effects of the salt through the good coverage and bonds between of rock grains (Fig.8 (c3)).

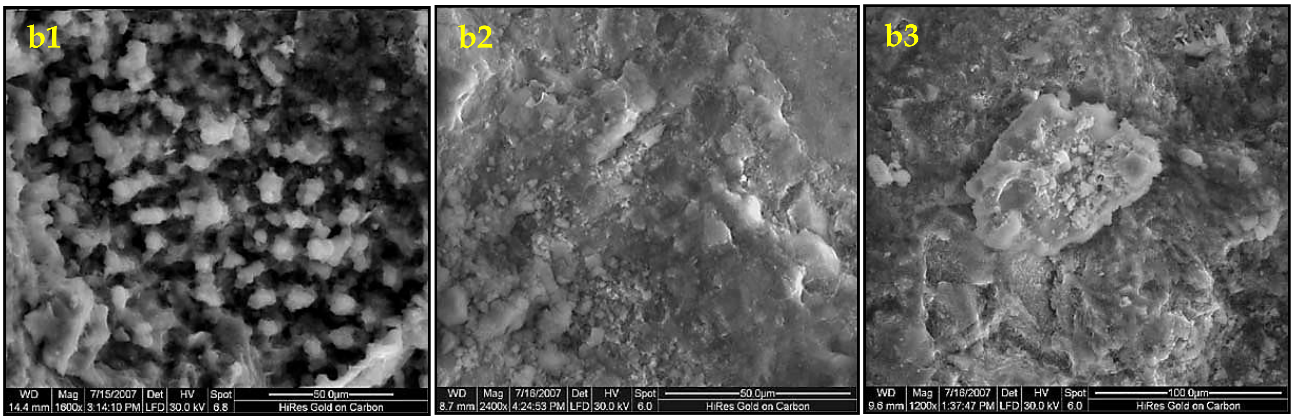

Figure 7. SEM of greywacke samples treated with Wacker W-290 (b1), after thermal (b2) and salt ageing (b3).

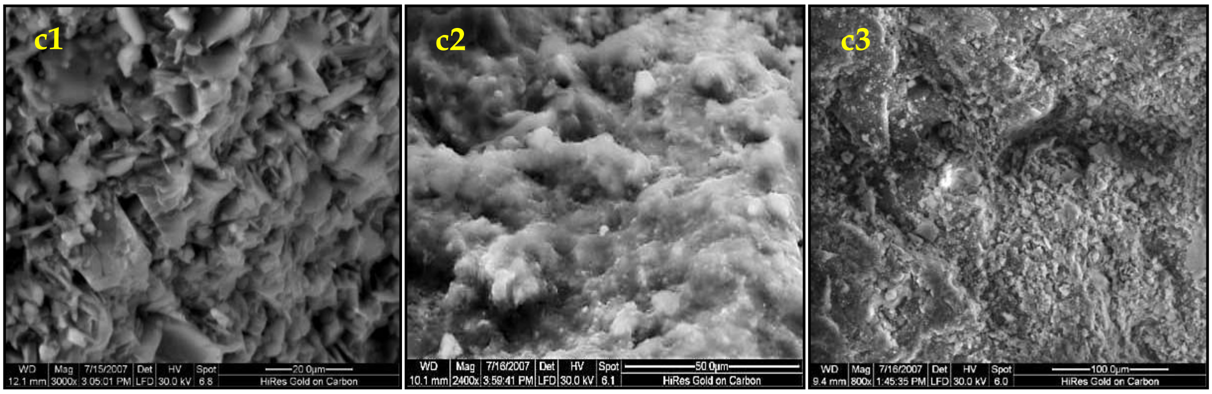

Figure 8.SEM of greywacke samples treated with Wacker OH 100 (c1), after thermal (c2) and salt ageing (c3).

4.5.4 Samples treated with Paraloid B 82

The treatment with Paraloid B 82 showed that; a good coverage and encapsulation of mineral grains by depositing the polymer in the form of thick film layer with full filling and form thick net of bonds in the spaces between the mineral grains (Fig.9 (d1)). After the artificial thermal aging SEM has revealed a great contrast in the consolidation polymer which was strongly affected by heat ,the consolidant showed a lack of good coverage of the grains as well as the non-filling of the spaces between the grains, therefore, the samples showed a clear separation among the grains due to the shrinkage of this consolidant , its damage by heat and turned it into a fragile material that loses the ability to bind the mineral grains in the rock (Fig.9 (d2)). After the artificial salt artificial salt weathering the treatment appeared weak strength of the effect of salt aging, several gaps and cracks were developed due to the fragmentation in the polymer film in addition to the detachment and crystallization the salts between the mineral grains (Fig.9(d3)).

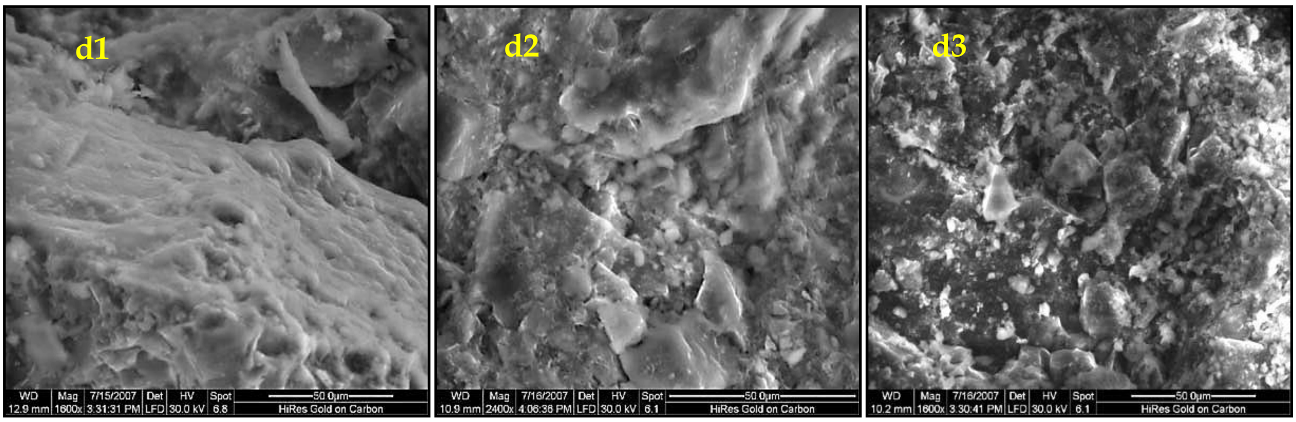

Figure 9. SEM of greywacke samples treated with Paraloid B 82 (d1), after thermal (d2) and salt ageing (d3).

4.5.5 Samples treated with Paraloid B 66

The treatment with Paraloid B 66; the consolidant covers the mineral grains with incomplete form (partial coverage) and heterogeneous distribution of the consolidation film between the grains; so several gaps and vugs were developed as a result of non-filling of polymer film and may be due to the properties of the consolidant and tensile strength between its molecules (Fig.10(e1)). After the artificial thermal aging various cracks, fissures were developed due to damage and fragmentation of consolidation polymer which cause the appearance several gaps and vugs in addition to erosion and etching the consolidation film (Fig.10(e2)). Many gaps and fissures were formed in the consolidation polymer causing the etching of the polymer and crystallization heavy salts after the artificial weathering (Fig.10 (e3)).

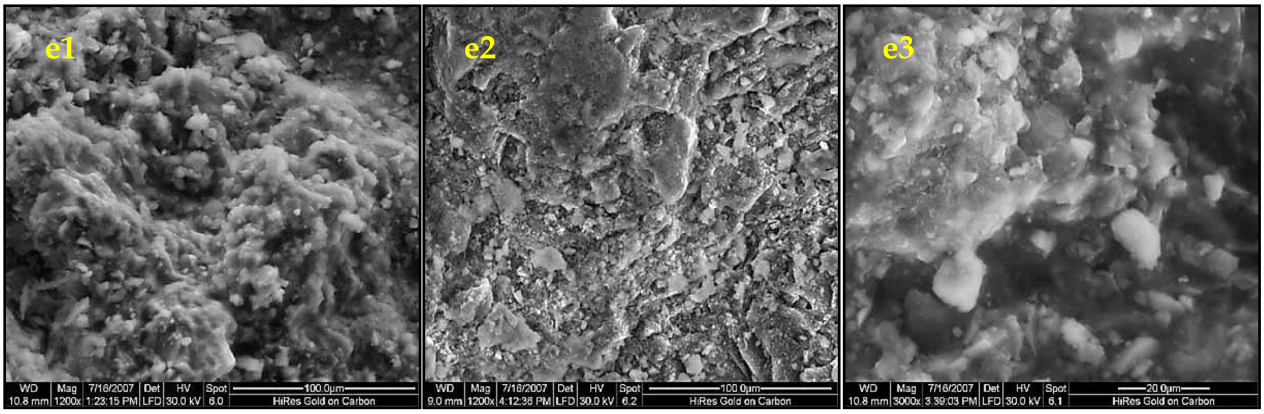

Figure 10. SEM of greywacke samples treated with Paraloid B 66 (e1), after thermal (e2) and salt ageing (e3).

5. CONCLUSION

The weathering and the deterioration of the greywacke rock art were studied utilizing PM, SEM-EDX and XRD as the following;

Petrographical studies showed that, the rock composes essentially from quartz, plagioclase and potash feldspars. Chlorite, calcite, epidote, muscovite, zircon and iron oxides represented as the secondary minerals.PM also revealed the transformation of the feldspars to clay minerals (kaolinite, sericite) and alteration of iron oxides. SEM revealed that, the rock suffered from the deterioration features such as the destruction and the collapse of the internal structure of the stone, the deformation of quartz grains, the evolution of the fissures, cracks and de-cohesion among the grains. The presence of clay minerals and crystallization of sodium chloride were also detected. XRD showed that, the greywacke consists mainly of quartz SiO_2, plagioclase (albite, $NaAlSi_3O_8$), clay minerals such as kaolinite $Al_2Si_2O_5(OH)_4$ and chlorite $(Fe^{2}+, Mg, Mn)_2$ $Al_4Si_2O_{10}(OH)4$, in addition to calcite $CaCO_3$ and halite (NaCl). EDX revealed, that, the greywacke is highly weathered due to the loss of silica (Si), the alteration of iron oxides (Fe) and the crystallization of sodium chloride (NaCl).

The SEM technique was used to assess the effects of five stone consolidants; Silo 111, Wacker W-290, Wacker OH100 (SILRES® BS OH 100), Paraloid B 82 and Paraloid B 66 which were applied on the greywacke samples from Wadi Hammmamat site, after the consolidation, and after the cycles of artificial thermal aging and salt weathering. The results showed that the treatments with Wacker OH100 is the more appropriate one.

REFERENCES

Abd El- Hakim, A. El- Badry (2014) Study on deterioration factors of rock arts carried out on the archaeological quarries sites and the methods of treatment and conservation applied on Gabel El-Silsilah and granite quarries at Aswan. Ph.D., Conservation Dep., Faculty of Archaeology, Cairo University.

Abd El-Hakim, A.El-Badry (2018) Environmental degradation of granite stoneworks, Karnak temples, Egypt. *International Journal of ChemTech Research,* Vol.11 No.9, pp. 340-352.

Akaad,M.K (1958) Seven new occurrence of Igla Formation in the Eastern Desert of Egypt. Geology Survey, Egypt, paper 3.

Al-Bawab, A., Abd-Allah, R., Al-Hamati, H., Odeh, F.and Bozeya,A (2017) Consolidation of archaeological basalt stone: A new experimental protocol by using different dispersions formulation. *International Journal of Conservation Science*, Vol. 8, No 2, pp. 187-198.

Al-Dosari, M.A., Darwish, S., Abd El-Hafez, M., Elmarzugi, N., Al-Mouallimi, N. and Mansour, S. (2016) Effects of adding nanosilica on performance of ethyl silicate (TEOS) as consolidation and protection materials for highly porous artistic stone. *Journal of Materials Science and Engineering A 6 (7-8)*, pp. 192-204.

Andre, G. (1939) The Greywacke of the eastern desert of Egypt. *Bull. Inst, Egypt.21*, pp.153-190.

ASTM, (1997) ASTM C88-90, Standard test method for soundness of aggregate by use of sodium sulfate or magnesium sulfate, Annual Book of ASTM Standards 4.2. *ASTM,* pp. 37-42.

Aston, B., Harrell, J.A. and Shaw, I. (2000) Stone. In: Nicholson, P.T. and Shaw, I. (eds.), Ancient Egyptian Materials and Technology, Cambridge University Press, Cambridge, pp. 5-77.

Blatt, H., Middleton, G.& Murray, R. (1979) Origin of sedimentary rocks. 2ed, New Jersey, pp. 417-420.

Botteghi, C., Matteoli, U., Paganelli, S., Arbizzani, R., Ciardelli, F., Aglietto, M., Taburoni, E. and Fassina, VI (1992) Polyfluoalky methacrylates as materials for the protection of stones. *Sci Technol Cultural Heritage 1*, pp. 111–122.

Darwish, S.S. (2013) Evaluation of the effectiveness of some consolidants used for the treatment of the XIXth century Egyptian cemetery wall painting. *International Journal of Conservation Science. Volume 4, Issue 4*, pp. 413-422.

De Buergo, M.A., Fort, R.and Gomez-Heras,M (2004) Contributions of scanning electron microscopy to the assessment of the effectiveness of stone conservation treatments. *Scanning*, Vol. 26, pp. 41- 47.

Doehne, E. and Price, C.A. (2010) Stone Conservation: An Overview of Current Research.2^{ed}, The Getty Conservation Institute, Los Angeles, p.36.

Dott, R. H. (1964) Wacke, Greywacke & Matrix, What Approach to Immature Sandstone Classification? *Journal of Sedimentary Petrology. 34*, pp. 625-632.

Dunham, R. J (1962**)** Classification of Carbonate Rocks According to Depositional Texture. *American Association of Petrolem Geologists Memoir. I,* pp. 108 – 121.

Franzoni, E., Sassoni, E., Scherer, G.W., Naidu, S. (2013) Artificial weathering of stone by heating**.** *Journal of Cultural Heritage*, Vol. 14, No *3,* pp .85-93.

Harrell, J.A., Brown,V.M.& Masoud,M.S. (1996**)** Survey of Ancient Egyptian Quarries . Egyptian Geological Survey and Mining Authority, Paper 72, p. 17.

Harrell, J.A. and Storemyr, P. (2009**)** Ancient Egyptian quarries—an illustrated overview. *In* Abu- Jaber, N., Bloxam, E.G., Degryse, P. and Heldal, T. (eds.) *QuarryScapes: ancient stone quarry landscapes in the Eastern Mediterranean*, Geological Survey of Norway, Special Publication 12, pp. 7–50.

Helmbold, R (1952) Beitrag Zur Petrographie der Tanner Grauwacken . *Heidel Beitr Miner Petrogr., 3*, pp 253 - 280.

Hikade, T (2006) Expeditions to the Wadi Hammamat during the New Kingdom. *The Journal of Egyptian Archaeology (JEA)* 92, pp.153-168.

Ismaiel, B.M. (1996) Geoarchaeological Study on Rock Art Sites, with Special Emphasis on Gabel-El Silsilah and Wadi Hammamat, Faculty of Arts , South Valley University, Qena, 7(2), pp. 7-59.

Klemm, D.D. and Klemm, R. (2001) The building stones of ancient Egypt- a gift of its geology. *Journal of African Earth Sciences 33*, pp.631-642.

Klemm, R and Klemm, D. (2008) Stones and quarries in Ancient Egypt. The British Museum Press, pp. 297-311.

Kmally, H.A. (2011) Deterioration and rates of weathering of the monumental rock inscriptions at Wadi Hammamat, Egypt. In *e-conservation, No.21*, pp.67-79.

MacLeod, I. (2000) Rock art conservation and management: The past, present and future options. *Reviews in Conservation 1*, pp. 32–45.

MacLeod, I., Haydock,P.,Tulloch, D. and Ford,B. (1995) Effects of microbiological activity on the conservation of Aboriginal rock art. *AICCM Bulletin 21* (1), pp. 3–9.

Marschner, H. (1978) Application of salt crystallization test to impregnated stone, in: *UNESCO/RILEM International Symposium on Deterioration and Protection of Stone Monuments* Vol. 3.4, Reilure, Paris, pp. 1 -15.

Meiklejohn, K. I. (1995) The deterioration and preservation of rock art in the KwaZulu/Natal Clarens Formation: A geomorphological perspective. *Pictogram 8*, pp 1-13.

Pinto, A.P.F. and Rodrigues, J.D. (2008) "Stone consolidation: The role of treatment procedures." *Journal of Cultural Heritage 9*, pp. 38-53.

Pinto,A.P.F., and Rodrigues, J.D. (2012) Consolidation of carbonate stones: Influence of treatment procedures on the strengthening action of consolidants. *Journal of Cultural Heritage 13,* pp. 154-166.

Rodrigues,J.D.(2001) Consolidation of decayed stones. A delicate problem with few practical solutions. Historical Constructions, P.B. Lourenço, P. Roca (Eds.), Guimarães, pp.3-12.

Rosario, VS., Jesus, E-G. and Moreno, MA (2000) Study of weathering factors and evaluation of treatments for the stones of "Santa Maria de la Encarnacion" Church, Constantina (Sevilla, Spain). *9th International congress on deterioration and conservation of stone,* Venice, pp. 697-705.

Sakran, M.M.S (1989) The Schist Mudstone Greywacke Rocks & Their Associated Mafic &Ultramafic Rocks in Some Localities of The Eastern Desert, Egypt. A Thesis for Master Degree, Geology Dep., Faculty of Science, Cairo University.

Samuel,M.D (1978) Lithological and sedimentological studies on the Red Beds of Wadi Igla, Eastern Desert, Egypt. *Nat.Res. Center Bull.,2*, pp.287-297.

Shashaua, S. (1993) Mechanical testing of resins for use in conservation. *ICOM Committee for Conservation*, Washington, 58.

Sheftick, W. (1989) Na_2SO_4 Soundness Test Evaluation. *Cement, Concrete and Aggregates*, Vol.11, No. 1, pp. 73-79.

Shiah, N. (1942) Some Remarks on The Bekhen stone. *A.S.A.E. 41*, pp 199-205.

Sweeney, D. (2014) Self-representation in Old Kingdom quarrying inscriptions at Wadi Hammamat. *The Journal of Egyptian Archaeology (JEA)* 100, pp.275-291.

Uda, M., Demortier, G., Nakai, I (2005) *X-rays for Archaeology*, Springer, Netherlands, pp.159-162.