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Diagnostic Investigation of the building materials and Conservation Proposals of Al-Ashraf Khalil Mamluk Mausoleum Dome - Historic Cairo - Egypt

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ABSTRACT

The Al-Ashraf Khalil bin Qalawun mausoleum in Cairo is an exceptional example of Mamluk architecture, and an important monument in the rich cultural landscape of Historic Cairo. This article provides an architectural description of the mausoleum including an assessment of its current condition using modern methods of documentation, and provides a proposed conservation plan. The archaeometric study of the building materials of the mausoleum and their deterioration was done using X-Ray Diffraction (XRD) analysis, a Polarizing Microscope (PM), and Scanning Electron Microscope equipped with an X-ray energy dispersal unit (SEM-EDX). This archaeometric study revealed that the limestone fabric of the mausoleum comprises mainly micritic calcite, traces of sand, as well as, traces of halite. The analysis also revealed the use of lime mortar and confirmed that halite is the main destructive salt of the building materials. The mechanical properties of the limestone used were evaluated by measuring its compressive strength. The results of this analysis formed the baseline data for a restoration plan that would address the deteriorating parts of the building.

1. INTRODUCTION

Historic Cairo was declared a World Heritage UNESCO Site in 1979. Since then, the authorities in charge have been undertaking many programs to preserve the site. However, the area has suffered from continuous deterioration. There are many reasons, which combined cause this deterioration. The continuous rise of groundwater is one of the main adverse factors.

(Elyamani et al., 2021) Ahmed Elyamani (2021), mentioned some of the reasons for this phenomenon. The aquifer of Historic Cairo is a confined to semi-confined system, which allows the groundwater to rise with water infiltrating from external sources. (El-Habashi and Ahmed, 2019) The leakage from the modern systems of water supply and sewage is the main source of the infiltration (Shahin, 1990; El-Sayed, 2018; El Arabi, 1999). The large earthquake of 12 October 1992, is another factor, which resulted in the damage of several historic structures (Badawi and Mourad, 1994; Osman, 2010). The lack of maintenance is also another reason for the deterioration of the structures in Historic Cairo (Elyamani and Amer, 2017).

For these reasons, there is an increasing need to research the deterioration of Historic Cairo's structures and how to preserve them. Adam et al. (2015) studied the construction materials of the Al-Tangoha Al-Mardany mosque in Historic Cairo. His results confirmed that the stone of the mosque suffered from several factors of deterioration, such as pollution and groundwater. El-Midany and Mahmoud (2015) Studied many samples of the building materials from the Mamluk building, Tekia Taki El-Din El-Bostamy in Historic Cairo. The results of their confirmed the wide spreading of halite (Na Cl) as a soluble salt. Hemeda et al. (2018) carried out a detailed physical, mechanical and chemical study of the building materials (the bricks and mortar) of the Roman Babylon located near Amr Ibn Al-A'as Mosque in Historic Cairo. They found that the mortar showed some hydraulic properties due to the addition of pozzolanic materials such as natural furnace slag, brick powder, and its fragments, as well as limestone aggregates. While the bricks consisted of mainly quartz and feldspars, and iron oxides.

The focus of this article is the Al-Ashraf Khalil bin Qalawun mausoleum, one of the masterpieces of Mamluk architecture in Historic Cairo. The Al-Ashraf Khalil mausoleum (Monument no. 275; figure 1a) is located on Al-Ashraf Street in the Al-Khalifa region beside the mosque of Al-Sayeda Nafisa. It was built in 1288 A.D. under the order of Al-Ashraf Salah ad-Din Khalil ibn Qalawun who was the eighth Mamluk Sultan. The dome of the mausoleum was built by the architect, Prince Alam al-Din Singer al-Shoja'i who was one of the most important pioneers in the field of Mamluk architecture. It is worth noting that there was a project to restore the archaeological site in 2017 by the Ministry of Tourism and Antiquities, which aimed to implement risk reduction procedures to the mausoleum dome, restore the site, and transform the vacant land facing the site into a public park and a recreational area that includes an open theater, a café, a children's play area, a children's library, and an administrative building. The project, moreover, aimed to repair the water and sewage network in the historic area, ensuring that the problem of surface water and salts in the archaeological site, which led to the erosion of some of its architectural parts, was resolved. But not all work on this project has been completed. It is hoped that this study will form part of an overall conservation program that preserves the mausoleum for future generations.

The mausoleum (Figure 1b) is essentially composed of a smooth cupola reinforced by vertical, cylindrical pillars reposing on a high octagonal drum. The walls supporting the drum are made of limestone, with recent restoration accounting for the differences in the color of the blocks. However, the dome and the drum are made of fired brick. The dome, which has an outside diameter of 11.3 meters(m), height of 6 m, and a wall thickness of 0.50 m, is supported by a curved plinth that, with the exception of the eastern corner, has almost totally vanished. The top of the dome has a slight taper which is tiered by cresting at its highest point. The dome has eight circular buttresses that alternate with four windows in a parabolic design. A drum octagon supports the dome and has an internal diameter of 5.2 m, a height of 6 m, and a wall thickness of 1 m. On the inside of the drum and below a series of circular widows are Surat a'l-Umran Naskh inscriptions (4:189-193) (Figure 2a). The straight walls below the dome are 14 m long, 1.9 m thick, and 10 m high. At the top of the external face of the walls is an inscription that glorifies sultan al-Ashraf Khalil (figure 2b). Figure 3a shows a plan of the mausoleum, figure 3b is a drawing of the external elevation, and figure 3c is an internal elevation drawing of the mausoleum.

(a)The mausoleum of al-Ashraf Khalil (1912)
(Photograph (unknown). "The Mausoleums of Mamluk Sultan Al-Ashraf Khalil and Fatima Khatun (Umm al-Salih), Cairo." V&A Collections. Accessed May 2, 2023. https://collections.vam.ac.uk/item/O1075535/the-mausoleums-of-mamluk-sultan-photograph-unknown/.)

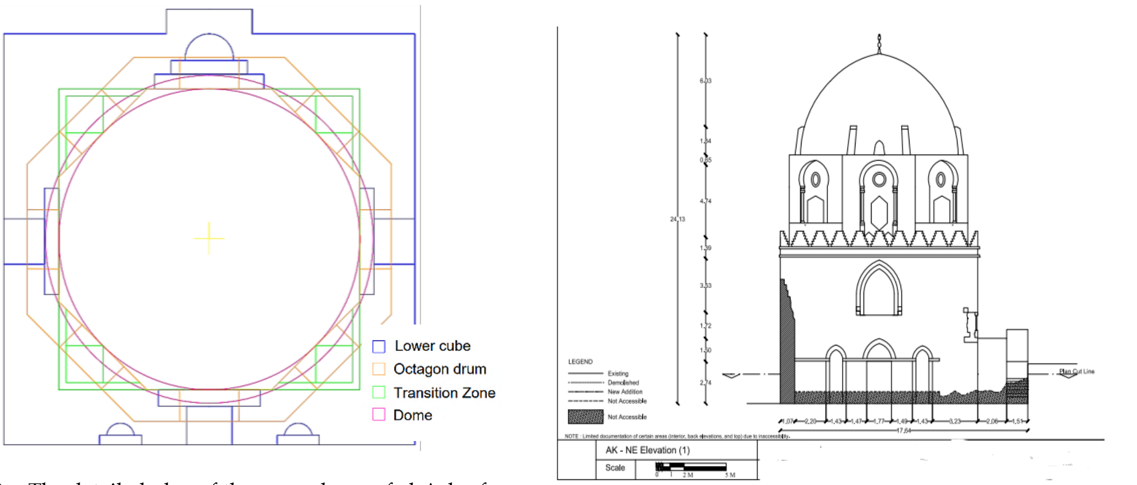
(b)The mausoleum of Al-Ashraf Khalil (2020)
(Taken by authors, Photographic documentation of Al-Ashraf Khalil mausoleum domes was carried out using cameras CANON 6D Mark II, and CANON D800 with lenses 18-55, 55-250 and 35-14.)

Figure 1. (a & b) Old and recent photos ofthe mausoleum of al-Ashraf Khalil.

(a) Surat a'l-Umran Naskhi inscriptions (4:189-193) in the interior of the mausoleum.

(b) The exterior inscriptionthat glorify Al-Ashraf Khalil.

Figure 2. (a & b) Inscriptions outside and inside the dome.(Taken by authors)



(a) The detailed plan of the mausoleum of al-Ashraf Khalil.
(Made by authors)

(b) The Northern-West architectural elevation of Al-Ashraf Khalil dome.
(after: Megawra conservation studies, 2017)

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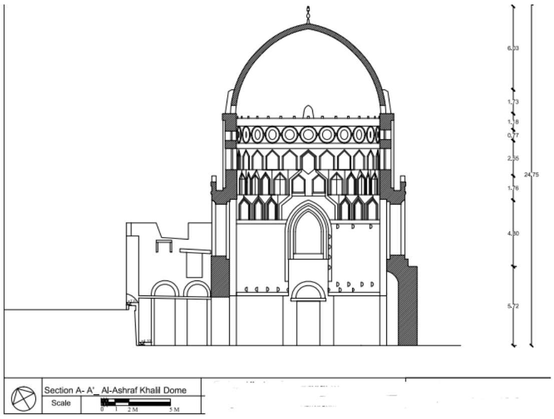


(c) The architectural section of the mausoleum (Megawra conservation studies, 2017)

Figure 3. (a,b & c) Drawings for the mausoleumof al-Ashraf Khalil.

2. CLIMATE AND GEOLOGY OF CAIRO

2.1. Climate

Cairo city is categorized as having a dry climate, which is marked by little precipitation and wide diurnal temperature variations (Koppen classification - group B), and it almost totally belongs to the subgroup: BWh - hot, arid, or desert climate (Peel, Finlayson, & McMahon, 2007). In the summer, Cairo's highest temperature ranges between 37 to 46 degrees Celsius, while the minimum temperature is between 13 and 21 degrees Celsius (°C). In the winter, the maximum temperature ranges between 25 to 28 °C, and the minimum temperature ranges between 6 and 9 °C. The altitude varies from 15 to 110 meters above mean sea level. There is a wide range in humidity, from 32% to 84%. Global radiation varies from 550 to 750W/m2 in the winter and from 940 to 1050W/m2 in the summer (Ayman, 2011). Ventilation plays a vital part in delivering comfort through natural ventilation, according to the Housing and Building Research Centre (HBRC, 2006) in Egypt (26.00%), just 9.00% of the cooling is provided by evaporation.

2.2. Geology

Egypt's northern region, where Cairo is located, developed geologically as the northern edge of an older, more stable craton. The Quaternary sediments predominate in the urban area and they include the Nile River alluvial sediments in particular. Mesozoic layers cover the crystalline basement in the subsoil (Tawadros, 2011). The Mokattam Plateau and the alluvial deposits of the Nile Valley meet close at the location of Old Cairo. There are two bedrock formations are outcrops from the Upper Eocene on the Mokattam Plateau. The first is the Maadi Formation, which also contains hard dolomitic limestone as well as soft clastic rock units (clay, silt, and sand). The Giushi Formation is the second, and is made up of white fossiliferous limestone with marl intercalation (NARSS, 1997).

Tertiary sedimentary rocks and Quaternary soils with a thickness of slightly more than 1000 meters form the foundation of Cairo. At El Khanka in north Cairo and at Abu Rowash to the west of Cairo, tertiary-aged basalts are exposed. Only a crumpled section to the west has exposed Mesozoic sedimentary strata. The pre-Cambrian basement is the base of the sedimentary sequence, which is around 2000 meters thick and has predominantly formed into an upper carbonate component and a lower clastic portion. The ground water flows under semi-confined as well as under unconfined free water table conditions. The change in the groundwater level in the area of the Al-Ashraf Khalil mausoleum was recorded in the years 1956, 1977, and 1980, and are shown in Table 1.

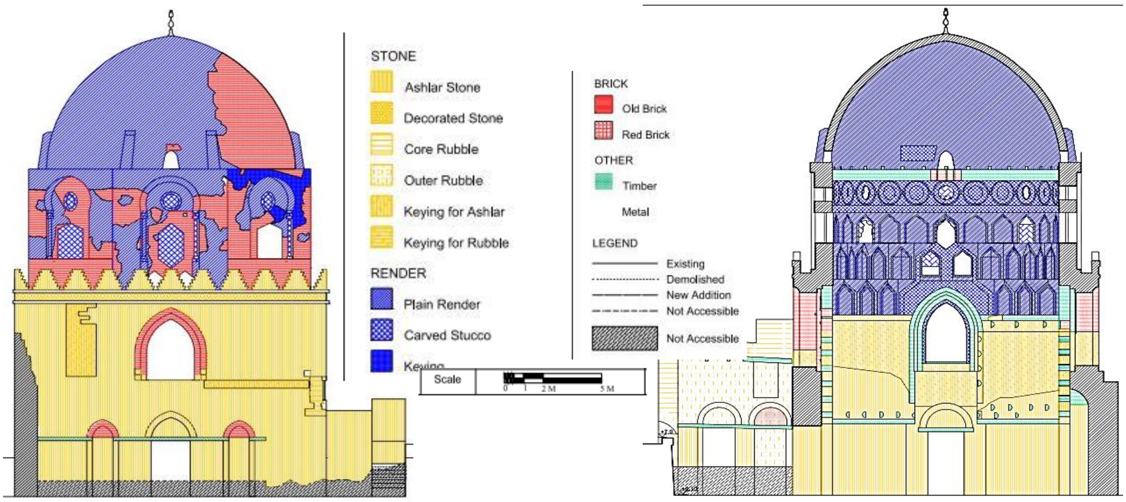
Table 1. the groundwater level change rate in the years of 1956, 1977, 1980 and 2017(Shata, 1988)

Year	Time interval	Ground water level (m)	Increase in water level (m)	Rate of rise (m/y)
1956	-	15.5	-	-
1977	21	17.5	2	0.096
1980	3	20	2.5	0.833
2017	39	35	15	0.385

3. MATERIALS AND METHODS

3.1. Visual inspection:

Undertaking an on-site visual inspection is an important part of the conservation assessment process. This method is essential to identify building materials, previous restoration attempts and the various forms of damage that have affected the building. Deterioration can be in form of decay, loss of some parts of the building fabric, cracks, and subsidence. The results of a visual inspection give the restorer a complete idea about the current state of the building which will help them to develop an integrated plan for restoration and conservation of the structure in the near and long term. (Figure 4)



(a) The external material survey of the mausoleum. (b) The internal material survey of the mausoleum

Figure 4. (a & b)Material survey of the mausoleum. (Megawra conservation studies, 2017)

3.2. Laboratory examinations and analyses:

Samples of the materials used in the construction of the mausoleum were taken for analysis to determine their type and composition. The results of this analysis will help to determine the appropriate material to use during the conservation process, and provide valuable information on how the building was constructed. One limestone block was supplied from the dome of the mausoleum on July 13, 2019 in order to perform mechanical, physical, chemical, and mineralogical tests. Cylindrical samples with a length of 88 mm and a diameter of 44 mm, and in the form of cubes 5x5x5 cm^3 according to the dimensions of the block were also taken according to the standards mentioned in ASTM (A.S.T.M., 2007) and ISRM (I.S.R.M., 2007). In total three limestone samples with code A-L-1, A-L-2 and A-L-3 (Figure 5a), two mortar samples (vertical and horizontal) with codes A-M-1 and A-M-2 (Figure 5b), and one salt sample with code A-S-1 (Figure 5c) were taken for analysis. The tests and analysis was carried out at Faculty of Engineering at Cairo University on August 8, 2019.

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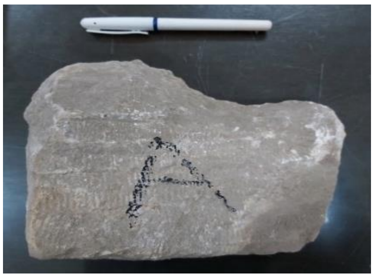
(a)Limestone sample (a 14 cm pen used as scale).


(b)Mortar sample.

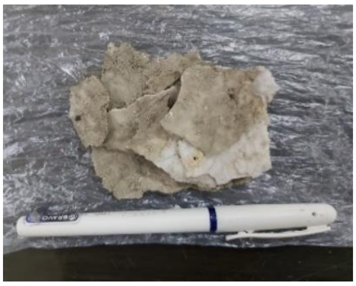
(c)Salt sample.

Figure 5. (a,b& c)Material samples collected from the mausoleum. (Taken by authors)

3.2.1. Compressive strength test

This test is important in determining the mechanical durability of building materials. The test was conducted to determine the compressive strength of the samples. Cubic samples were prepared from the original samples for testing with a compression machine.

3.2.2. Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray Analysis)(EDX)

The morphology of the studied samples (limestone, mortar and salt) and their chemical composition were recorded using: SEM Model Quanta FEG 250 attached to a EDX unit, with accelerating voltage of 200V-30K.V, and a magnification of 14x up to 1000.000x.

3.2.3. Polarizing (light) Microscope Petrography (PM)

The Polarized Microscope (PM) was used to identify the mineral structure of the material, the nature of the components of the material, the compatibility of these components with each other, and the physical or chemical changes that occurred due to the interaction with the material with ambient deterioration factors, and with the resulted deterioration phases. The device used for this analysis was a Leitz Labor Lux 11 POL S, Periplan 10x/18 eyepieces, both focusing with one cross-hair scale reticle, EF POL Strain Free 4x, 10x, 40x.

3.2.4. X-ray Diffraction (XRD)

This method is considered the most important analytical method used for analyzing building materials, as it identifies the mineralogical components of the material and their deterioration. The X-ray diffraction patterns of the four samples were obtained using a Philips PW3710/31 diffractometer at 40 kV and 30 mA. The sample used is typically very small and may be less than 50 micrograms.

3.3. In-Situ Methods

There are three piezometers located on el-Ashraf Street to monitor groundwater levels (figure 6). Three piezometers were installed at the location of the three executed boreholes. Therefore, the location of old piezometers that were installed by an earlier contractor were examined. Two piezometers were found, one of them was located near Piezometer No. 1.

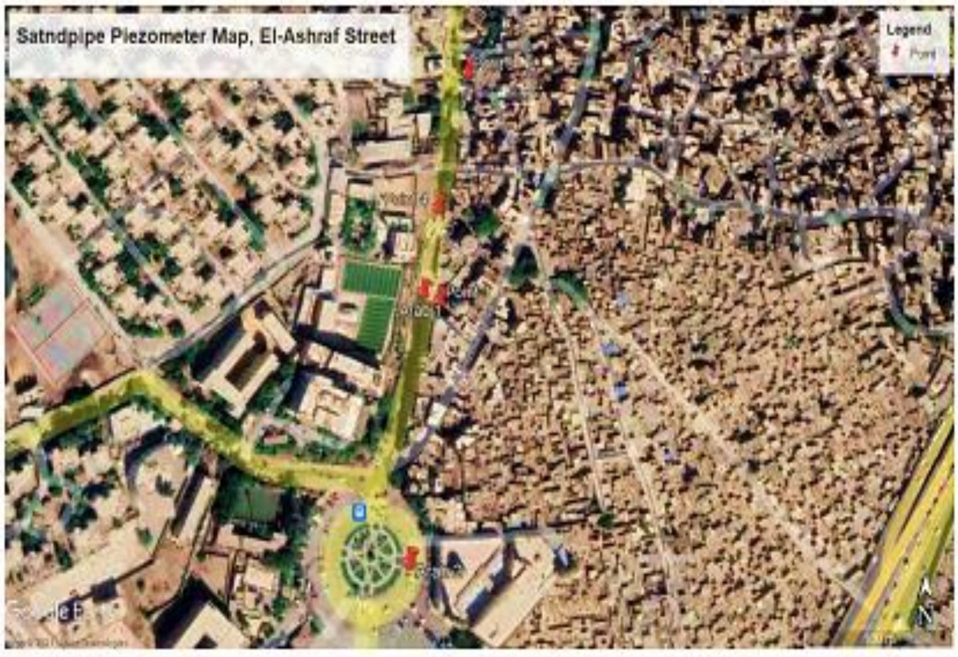

Figure 6. Locations of the piezometers (Marked with the red signs)

Table 2: piezometers locations and coordinates

PZ	Location	Easting	Northing	Natural ground level
1	Near Al-Ashraf Khalil mausoleum	639141.278	812657.518	33.861
4	Near Fatma Khatoun mausoleum	639136.420	812725.962	32.374
5	Near Ibn Sirin mausoleum	639155.721	812837.401	29.222
Existing 1	Near Al-Ashraf Khalil mausoleum	639138.699	812663.154	33.297
Existing 2	Near Al-Sayeda Nafisa Mosque	639128.617	812488.590	34.210

Water levels were monitored between August 28, 2021 and January 1, 2022. On the monitoring day, a technician unlocked the piezometer protection cap and used a water level indicator to take the reading.

4. RESULTS AND DISCUSSION

4.1. Laboratory examinations and analysis results:

4.1.1. Compressive strength test results:

The limestone samples showed relatively scattered results with an average of 22.78 MPa. The two samples A-L-1 and A-L-2 showed near results and near failure mode. (Figure 7, a& b). The third samples crashed more than these two samples (Figure 7, c) and showed lower resistance. The variability in the mechanical properties of such natural stone can be accepted because of the heterogeneity of its components.

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(a) Sample A-L-1 after the compressive strength test

(b) Sample A-L-2 after the compressive strength test

(c) Sample A-L-3 after the compressive strength test

Figure 7. (a,b& c) Compression test for samples (Taken by authors)

Table 3. Results of the mechanical compressive strength of limestone samples

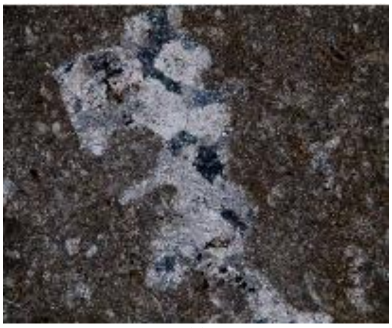
Sample no.	Compressive strength (MPa)
A-L-1	30.07
A-L-2	22.02
A-L-3	16.24

4.1.2. Polarizing (light) Microscope Petrography (PM):

Sample A-L-1: photomicrograph of nummulitic wackestone microfacies using the polarized microscope. For magnification (a, b, c = 10x), all photos are in crossed Nichols. Nummulites sp. with their well-preserved structure of high magnesium calcite as shown in Figs. 8a and8b. Blocky calcite crystals filling a fracture. Few crystals of these blocky show calcite are affected by dissolution as shown in Fig. 8c.

(a)

(b)



(c)

Figure 8. (a,b& c)Sample A-L-1: photomicrographs of nummulitic wackestone microfacies using the polarized microscope.

4.1.3. X-Ray Diffraction (XRD)results

- The XRD mineralogical results show that the main mineralogical composition of limestone sample (A-L-1) is calcite and traces of quartz and halite. The detection of halite shoes that the limestone sample was affected by saline solution from the soil) Figure 9 a). The vertical mortar sample A-M-1 and the horizontal mortar sample A-M-2) Figure 9 b & c) showed quartz as a major component as well traces of halite and calcite. The high ratio of quartz in the two mortar samples may indicate deterioration of the mortar through dissolution of calcite as a binding material and separating from the sand (Kamel et al, 2015). The detection of halite as the main component of the salt sample (A-S-1) indicates that the salt came from the soil. (Figure 9, d).

Table 5. XRD analysis mineralogical results of the studied samples of stone, mortar and salt.

Mineral	A-L-1	A-M-1	A-M-2	A-S-1
Calcite ($CaCO_3$)	***	*	*	-
Halite (NaCl)	*	*	**	***
Quartz (SiO_2)	*	***	***	-

Major=*** , Minor = ** , Traces = *

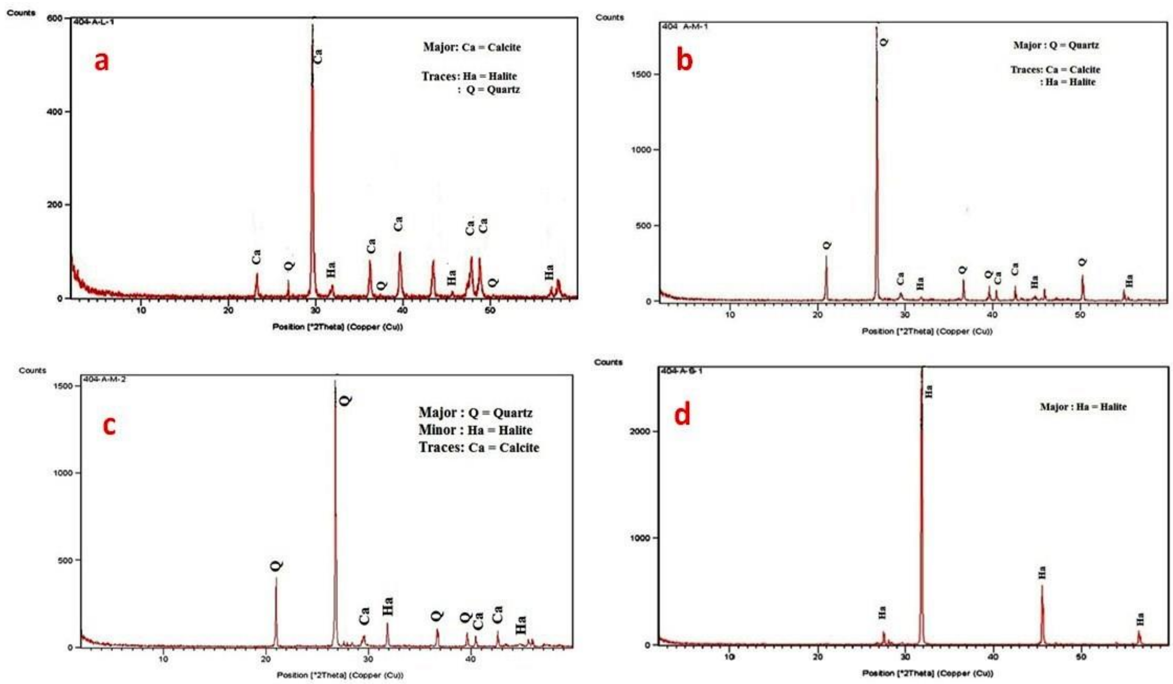


Figure 9. XRD analysis results of the studied samples of stone, mortar and salt

4.1.4. SEM-EDX results:

The examination and analytical observations made by SEM-EDX of the four samples showed the following :

- Sample (A-L-1) was shown to be micritic limestone, which is characterized by its low - Mg, its calcite crystals with sub-rhombic shape, and its size, which was frequently below 4µm (Volery et al, 2011). The detection of Ca, C, O, Cl and Si elements in the EDX analysis testifies to the presence of calcite, quartz, and halite,(figure 10 a).
- Mortar samples (A-M-1 & A-M-2) showed the wide spreading of quartz crystals and scattered pores over the surface of the samples, which may prove the dissolution of the binding material of the mortar separating from the sand. EDX analysis of the mortar samples showed the detection of Si, O, Ca, C, Na and Cl elements which confirm the occurrence of quartz, halite and calcite(figure 10 b & c).
- Salt sample (A-S-1) showed the wide spreading of halite crystals. Halite is a water soluble salt and its detection in all the samples may confirm that it is one of the main deterioration factors affecting the building (Kamel et al, 2014). The EDX analysis of the salt sample

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detected elements of Na and Cl, which confirm the occurrence of halite salt, while the detection of Ca,O and Si elements showed the trace presence of calcite and quartz (figure 10 d).

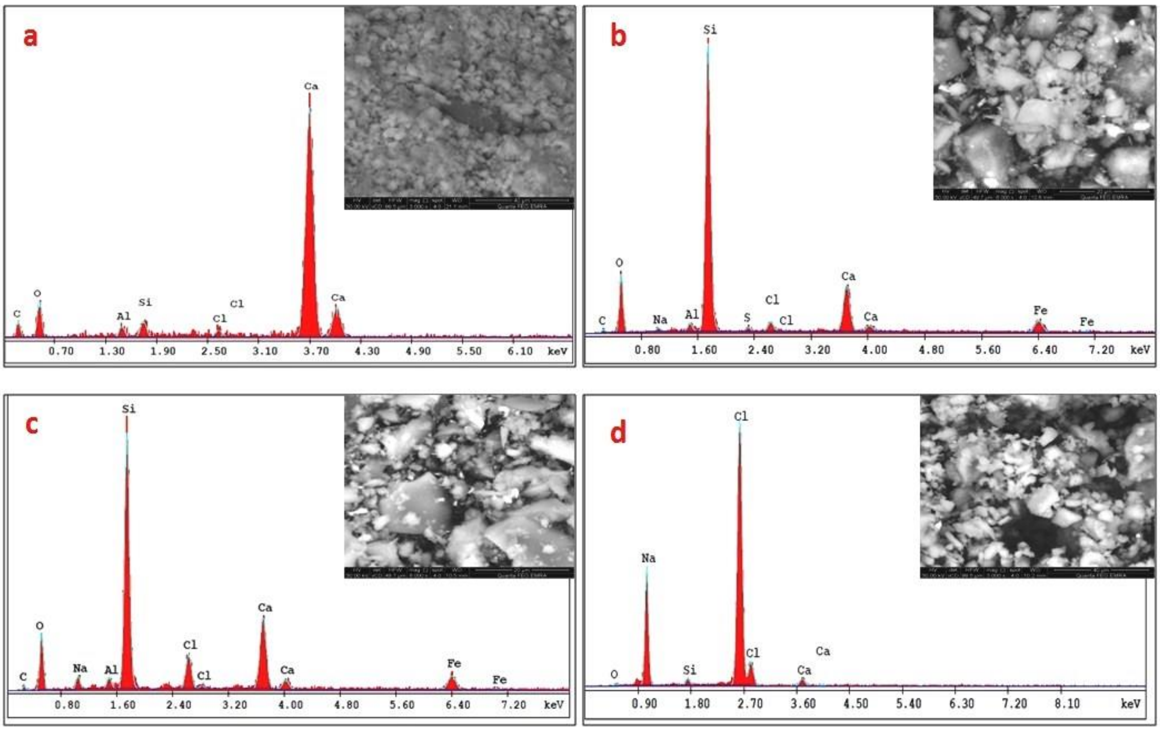


Figure 10. SEM –EDX analysis results of the studied samples of stone, mortar and salt

4.2. In-situ results:

4.2.1. Piezometers

The groundwater levels ranged between 1.32 m and 2.40 m below the ground surface. The groundwater levels range between 27.26 m asl and 32.49 m asl as shown in figure 11.

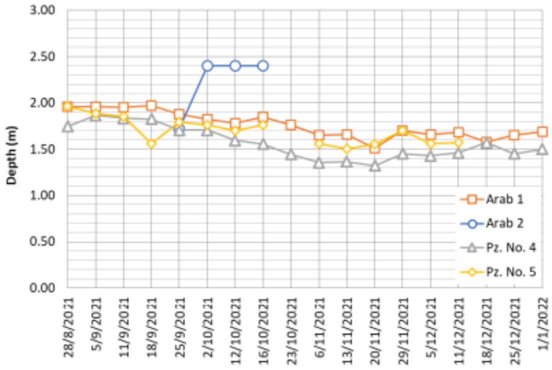


Figure 11.Groundwater depths versus time.

5. CONSERVATION TREATMENTS

Conservation treatments are interdisciplinary tasks that need input from a historian, architect, environmental, geotechnical, and structural experts. They also need an understanding of the different techniques required to treat the monument and its components. It is suggested that the following steps are taken in order to implement a conservation plan for the Al-Ashraf Khalil mausoleum:

1. Immediate structural interventions to keep the building from further deterioration or collapse. These measures are necessary to ensure the structural integrity of the building and the ensure the safety of the public. It is essential that the inner and outer walls of the mausoleum are reinforced with appropriate shoring before the start of conservation work (Figure12). It was clear from the visual inspection that the walls are bulging and there are a lot of missing and friable stones, especially in the lower parts of the walls. Shoring of door and window openings may be achieved using wooden frames in order to remove the damaged doors and windows for conservation in a specialized workshop. A structural design for the shoring appropriate for this building needs to be formulated considering the weight of the walls as well as the dead and live loads supporting the walls.

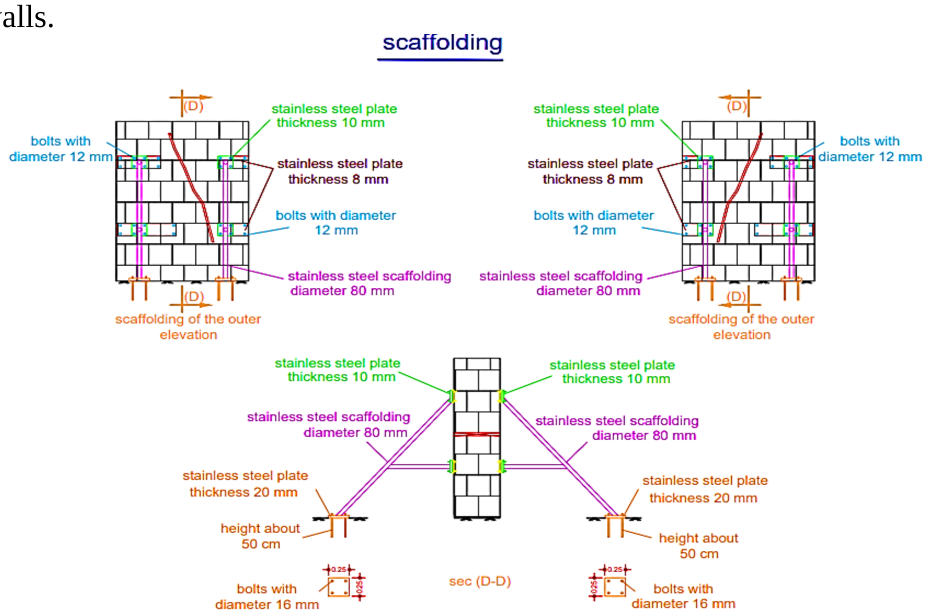
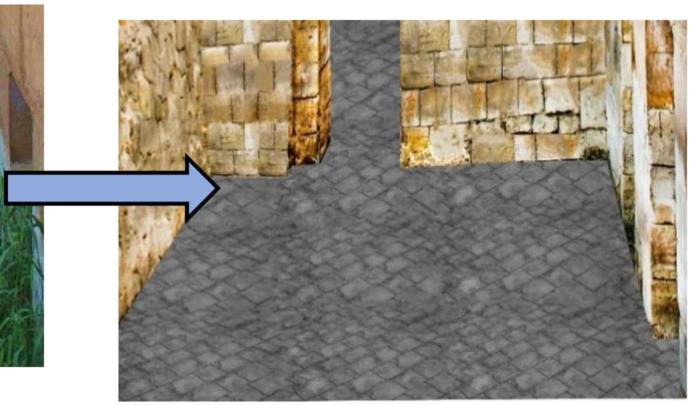


Figure 12.Shoring proposal for the inner and outer walls of Al-Ashraf Khalil mausoleum. (Made by authors)

2. The installation of a dewatering system such as portable pumps to lower the groundwater. In addition, all the vegetation and waste need to be removed from the site. These two steps are critical in order to proceed with the conservation treatments (Figure 13).

(a) Current status of entrance.



(b) Proposed treatment for entrance.

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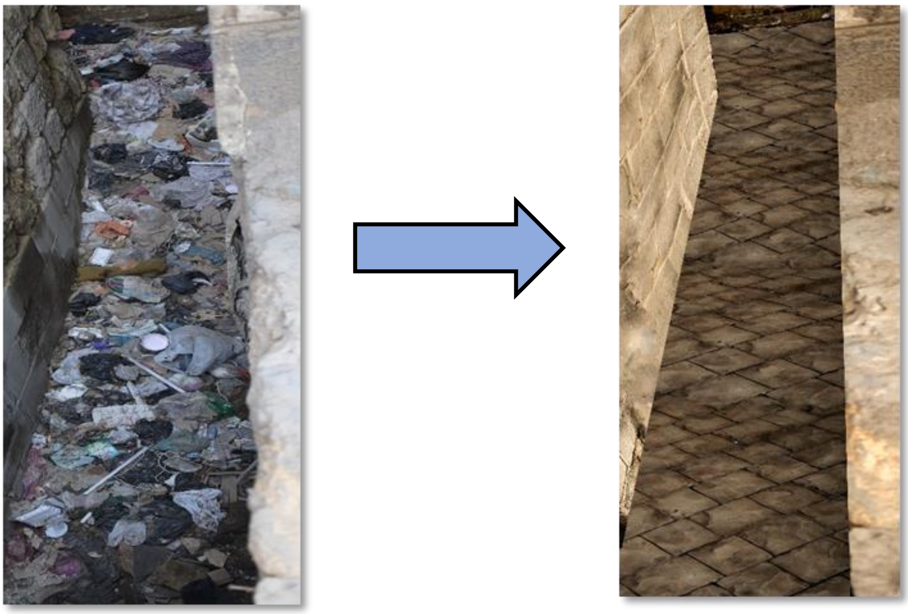
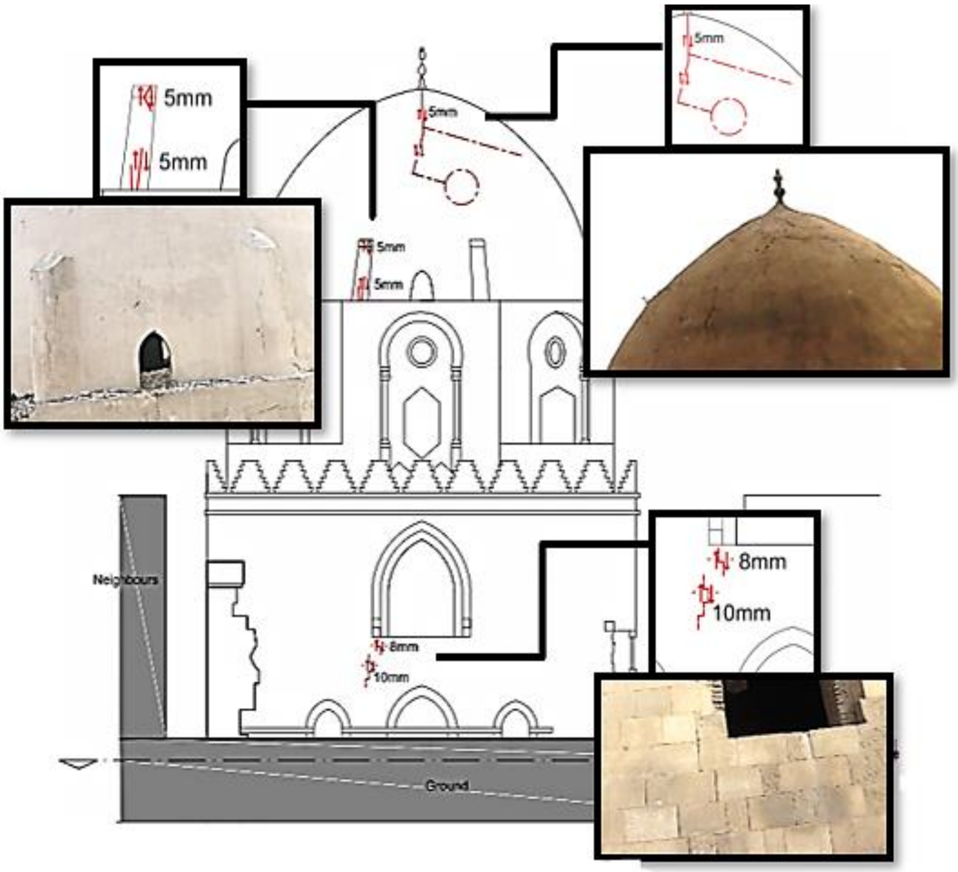


(c) Present status of corridor (d) Proposed treatment of corridor.

Figure 13. Current status and proposed restoration.
(Made by authors)

3. Lowering the groundwater is a complex process requiring coordination with the relative authorities and professionals to achieve a satisfactory result without causing structural damage to the mausoleum, or environmental damage. One suggestion, is for a trench to be made l m parallel to the outer wall parallel with the street with a width of 0.3m to 0.5m and a depth that reaches the foundations of the mausoleum. A PVC perforated tube would then be placed in the trench at an appropriate angle of inclination to collect and drain the groundwater. Finally, the trench should be filled with large stones at the bottom of the trench overlaid by a layer of small pebbles (Elyamani et al, 2020). This method can protect the foundations and the surrounding soil from humidity, and stop the chemical activity of the soluble salts that are harmful to the building materials.
4. The grouting of the moist clay soil is a petroleum material to decrease the humidity ratio and isolate the soil (Awad, 2002). Grouting the soil below the foundation of the mausoleum may be necessary to improve the characteristics of the soil and enable the soil to sustain present and new loads. The grout material should increase the porosity and permeability of the soil and help resist different forms of settlement.
5. The cracks in the fabric of the mausoleum need to be addressed. Figure 14 shows the current status of the structure and describes the cracks that appear on the walls of the mausoleum. The cracks should be monitored to discover whether they are active by using traditional technique such as Crack Gauges or modern technique such as Fiber Optic Sensors. The cracks should be classified based on their depth and width. In some cases, the assembly and reassembly of stones around the crack will be a suitable method of repair as shown in figure 15a, b,and c. Stitching or connecting the cracks using wooden ties is another method that could be used to address the cracks as shown in figure 15d. The cracks should be cleaned, and wooden beams inserted across the width at a spacing of 500mm between the ties, provided the ties are drilled inside the wall to at least the middle of the wall. The ties are fixed using the appropriate mortar, and after the mortar is dry, the location of stitches is concealed by rendering. The wall may then be grouted by suitable mortar to strengthen the inner core of the cracked wall (Figure 15e and f). For wide cracks (more than 3 mm wide) , metal clips may be used for

stitching by attaching epoxy resins, such as araldite, or addibonde, conface 2F. In some cases, if the reason for the cracks was an earthquake, the main structural elements may need confinement, or closing some or all of the openings as they are considered weak points.



(a) Photographical and architectural documentation of the cracks of the North-west elevation of Al-Ashraf Khalil mausoleum dome

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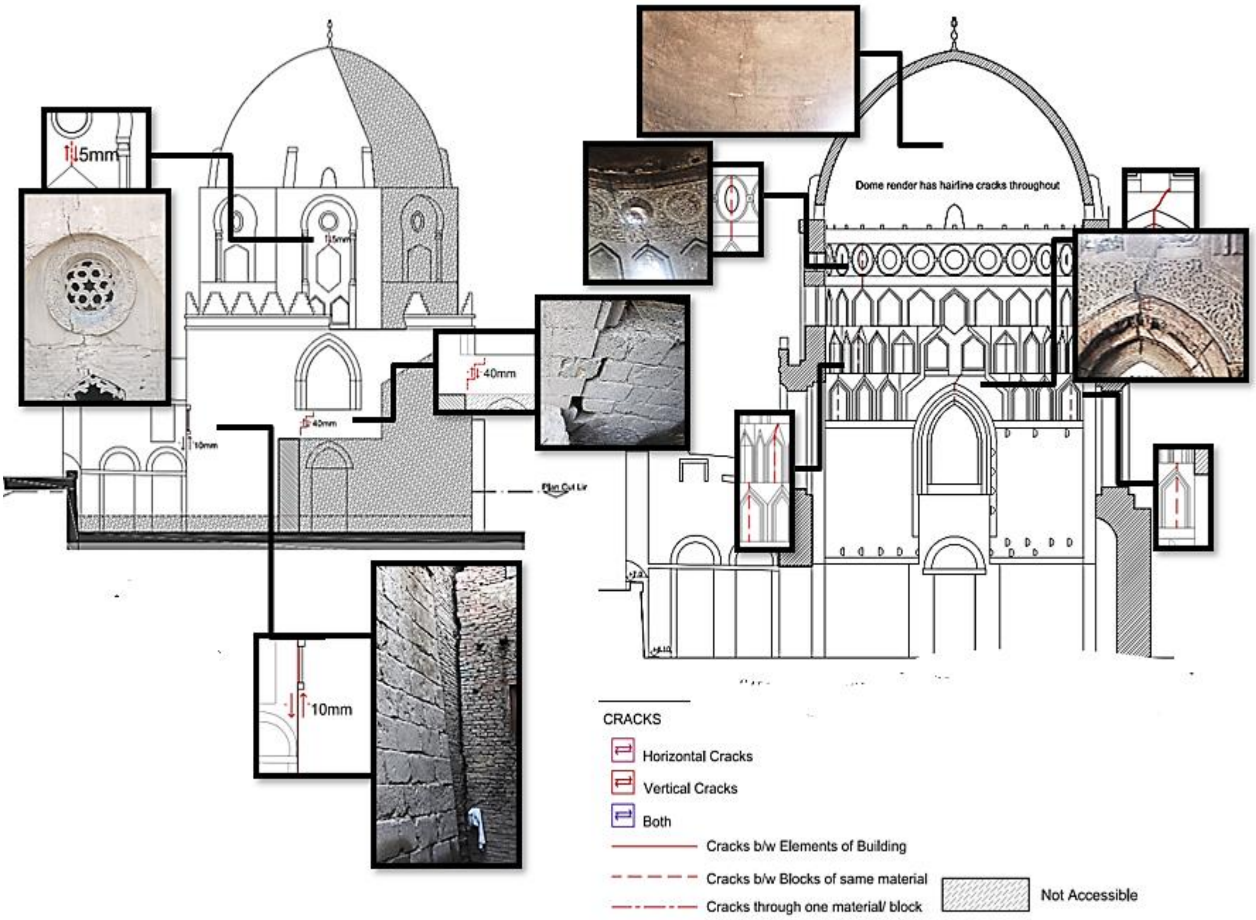
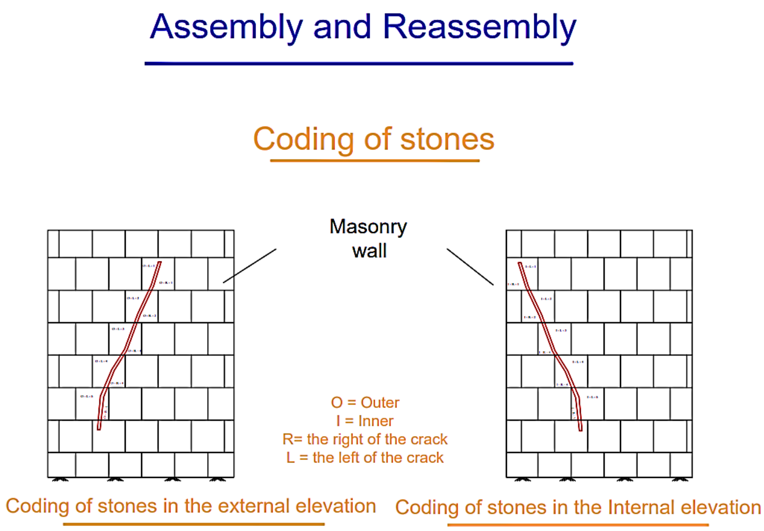


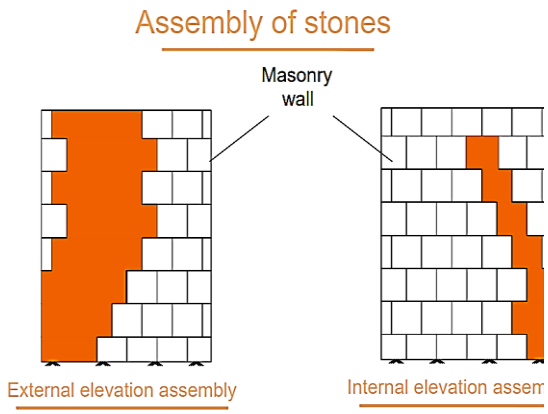
(b)Photographical and architectural documentation of the cracks of the South-West elevation.

(c)Interior section of Al-Ashraf Khalil mausoleum dome.

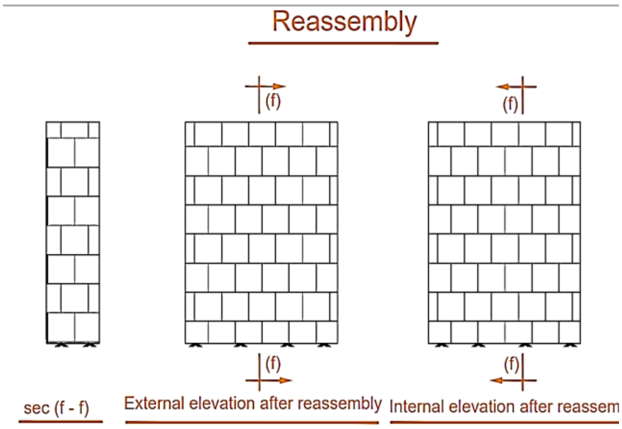
Figure 14. Documentation of deterioration.
(Made by authors)



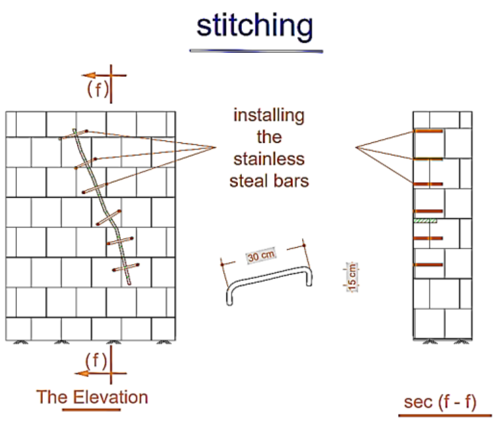
(a) Coding of stone.



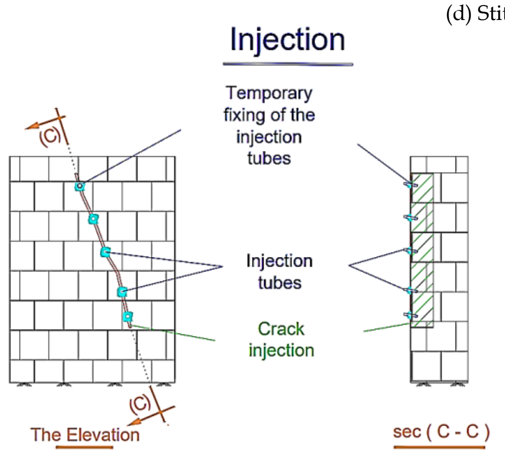
(b) Stone disassembly



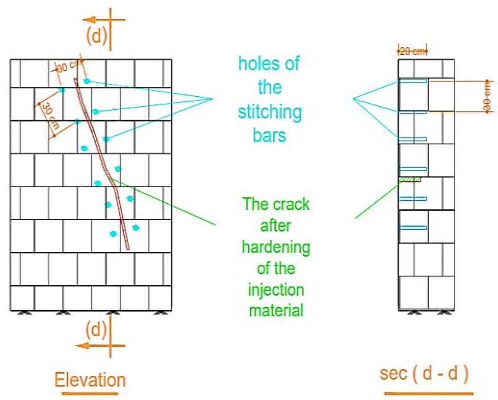
(c) Stone reassembly.



(d) Stitching of cracks.



(e) Injection of cracks – step 1.



(f) Injection of cracks – step 2.

Figure 15. Proposals for treatment.
(Made by authors)

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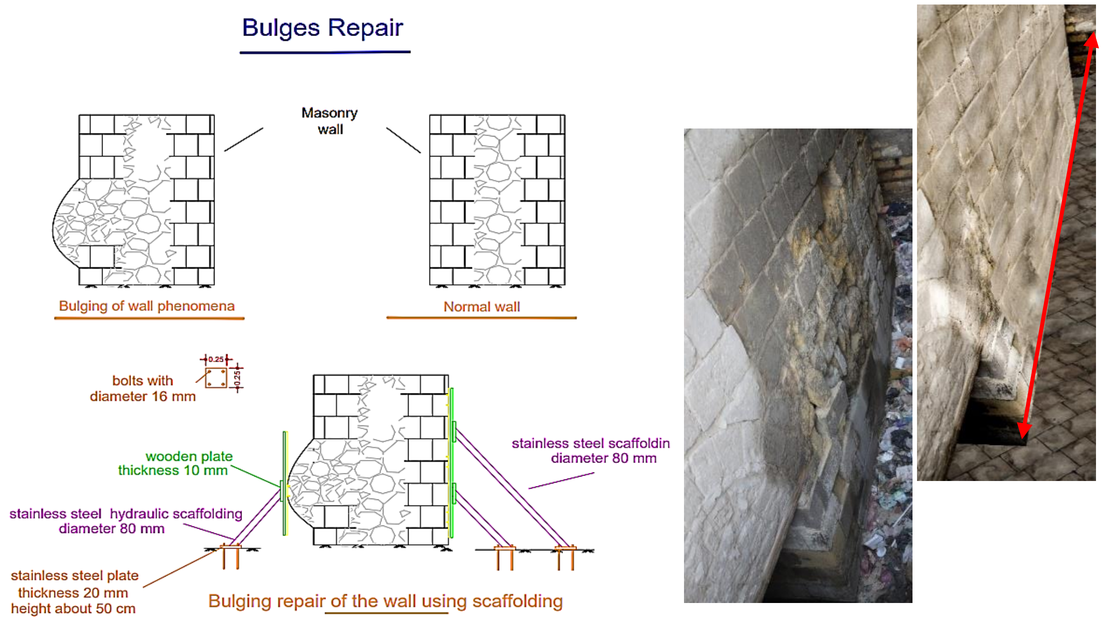


(a)Illustration for the bulges repair method in the conservation

(b)The status of the bulges wall before the conservation.

(c)An imagination to the wall of Al-Ashraf Khalil dome after conservation

Figure 16. Repair of wall bulging.
(Made by authors)

7. The dome of the mausoleum should be cleaned by using different mechanical methods that involves brushes of different sizes and hardness of bristle. Air abrasive cleaning, laser cleaning and ultrasonic cleaning may also be used. These processes should be followed by chemical cleaning using distilled water, soap and organic solvents. Trichloroethylene, ethyl alcohol, methyl alcohol, or acetone may be used depending on the nature of grime stuck on the surface of the monument. Water with zero salts is the most secured material in cleaning, followed by washing with organic solvents such as alcohol or acetone

8. The completion and strengthening of the mortar is necessary in the conservation process by cleaning and re-filling the joints between stones. The new mortar must be compatible with the old one, in color and composition, and have more permeability than the existing building materials to allow moisture to evaporate. A mortar that consists of, 1:2:1 sand: palm: lime, can be used based on the experimental work results in Maqaad Radwan in historic Cairo (Ali et al, 2016).

9. Cleaning with poultice is considered as one of the safe and effective methods. Historic masonry suffering from soluble salt has typically been desalinated using clay poultices with fine particle sizes in the range of 50mm or Mora poultice (Alessandrini et al., 1993) (Woolfitt, 2002) (Figure 18).

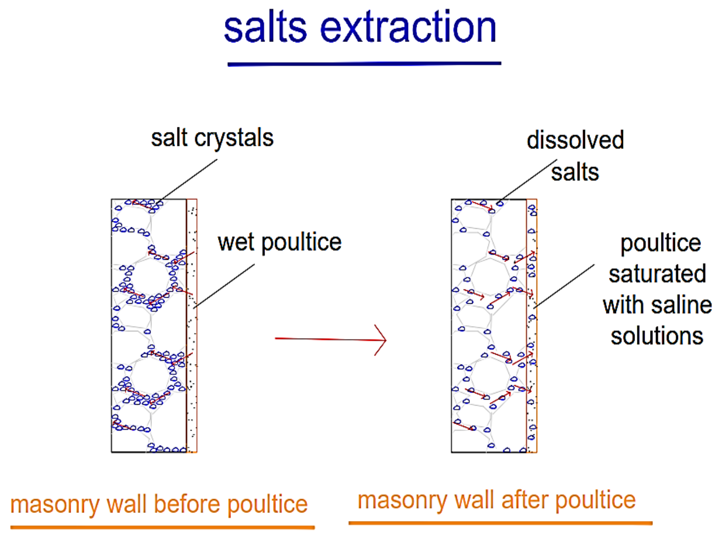
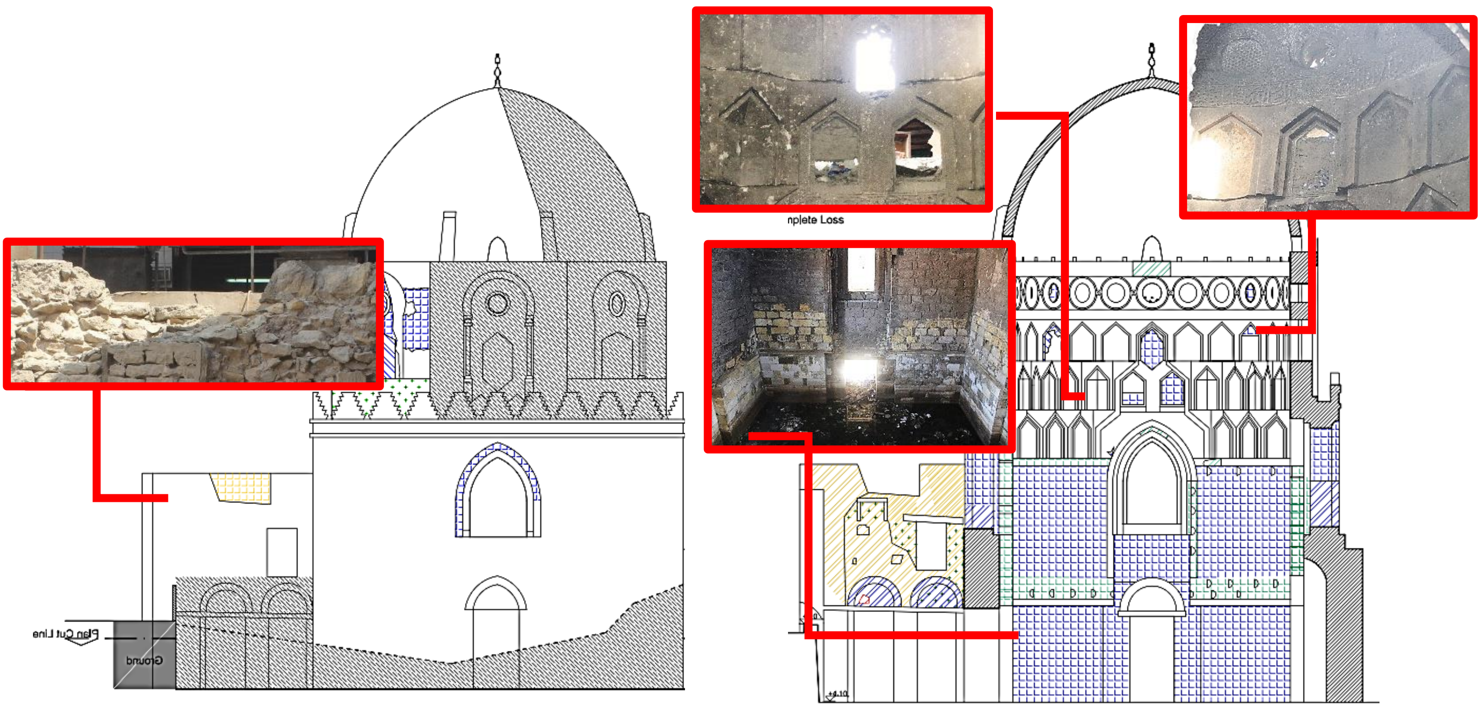


Figure 18.Proposed salt extraction method using poultice in Al-Ashraf Khalil dome. (Made by authors).

10. Building material strengthening, re-bonding, and cohesion improvement of the mausoleum fabric that has been subjected to weathering, and has lost its cohesionmay can be achieved by using one of the following techniques: immersion, injection, spraying, paper facing, or the tubes technique (Al-Banna, 1990). Different types of strengthening material can be used: Inorganic materials such as calcium hydroxide (lime water), barium hydroxide, nano materials. Organic materials such as thermoplastic resins, vinyl resins, acrylic resins, thermosetting resins, epoxies, polyester resins, polyurethane resins, can also be used. Silane-based materials such as tetra-alkoxysilanes, alkyl-triakoxysilane (Brethane), polysloxanes, silicon hydrate, and halogen bearing silanes are also effective substances to use.



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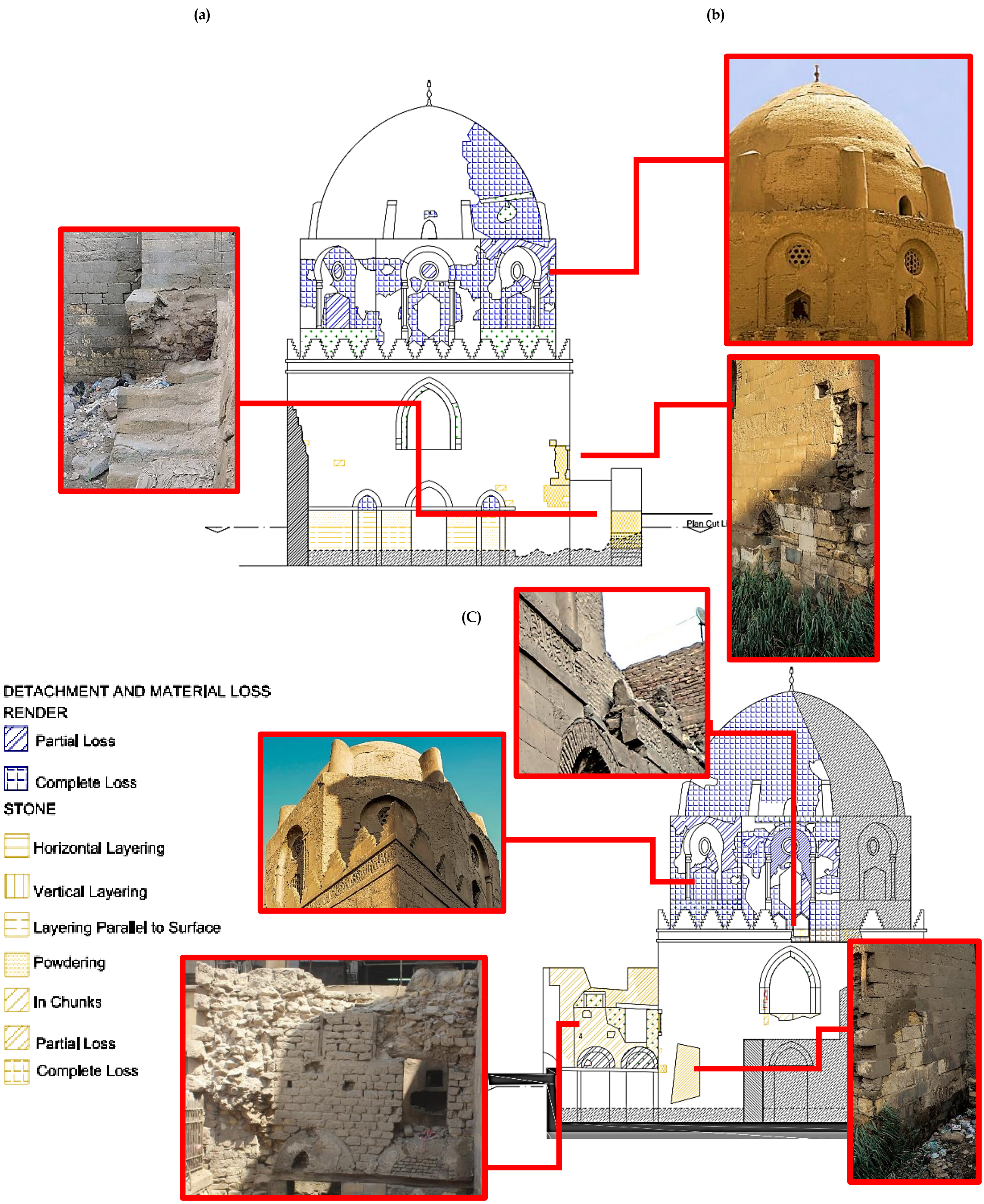


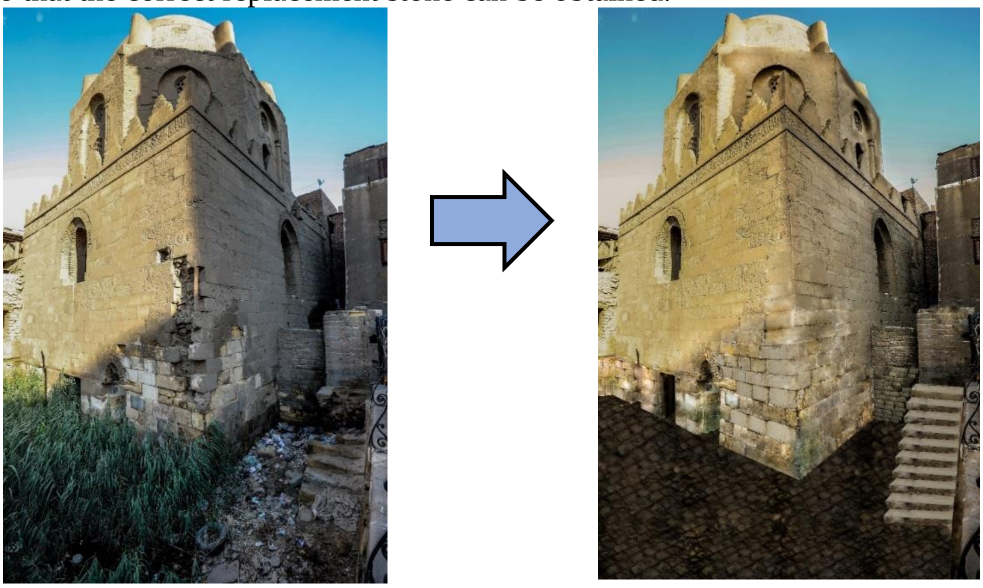
Figure 19.Layering and loss of rendering layers in Al-Ashraf Khalil mausoleum dome (Made by authors).

11. Suitable materials should be used to sensitively clean the painted surfaces. A suitable solution for this process is by usingpure water mixed with ethyl alcohol or acetone or ammonia at a ratio of 1:1. This solution is applied using a soft brush, which is then removed with water, or water mixed with alcohol to get rid of residual ammonia. The chormaline T solution 2% can also be used to clean the painted surfaces, which is removed by water. To clean organic material such as bird and bat waste from the surfaces, a solution of 1000 cm^3 water mixed with 100 cm^3 sap and 20 cm^3 ammonia can be used (Awad, 2002).

12. Over time the rendering layers that provide protection to the surfaces of the building have become separated. These layers increase the cohesion of the core fabric of the building and protect the fabric from exposure to environmental damage from wind, sand, rain, salts and biological material (Matero, 1995). The separation of the rendering layers can be fixed using suitable consolidation and filling materials. The separations can also be fixed by pinning the layers back together with stainless steel or nylon pins/dowels, or bars (Forster, 2010).

13. Missing stones in the calligraphic and crests of the outer elevation of the dome should be replaced using stone that matches the original fabric of the building.

14. Replacement of deteriorated stone should be done using stone that matches the parts being replaced. This work will give the monument a longer life span (Figure 20). This work is a complex intervention and requires samples being taken from the mausoleum so that the correct replacement stone can be obtained.



(a) Present view of the corner wall. (b) A rendered image for the corner wall after treatment.

Figure 20, Treatment and replacement of deteriorated stones.

(Made by authors).

15. The rehabilitation of the surroundings of the mausoleum is an integral part of the conservation of the monument. It is suggested that discussions take place with the owners of an ice cream factory, which is adjacent to the monument to explore ways to reduce vibrations from their machinery and the waste water from the factory adversely affecting the mausoleum. It is suggested that two adjacent residential buildings, are painted the same color as the mausoleum to to enhance their compatibility with the monument and the surrounding environment. Discussions should take place between the local residents and relevant authorities on how domestic waste can be managed. A new sewage system must be installed to allow the reuse of the water for plants. The knoll in front of the mausoleum is surrounded by a wall. It is recommended to paint

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this wall with historic paintings relevant to the history of the area and the mausoleum as shown in Figure 21.

(a) Current status. (b) Render of proposed treatment

Figure 21. Landscape treatment.
(Made by authors).

CONCLUSION

In this paper the conservation treatments for the Al-Ashraf Khalil mausoleum were presented. These included urgent structural intervention, reinforcing deficient structural elements, removing waste, dewatering operations in order to lower the ground water level, grouting and strengthening of soil, repair of cracks, local tilt or bulging treatment, cleaning dust and dirt, completion and strengthening mortar, salt extraction, and replacement of deteriorated stone. The rehabilitation of the area surrounding the mausoleum are important components of the overall conservation of the monument. The solutions proposed to improve the condition of the mausoleum will ensure its protection and survival for future generations. The methodology outlined in the paper for Al-Ashraf Khalil mausoleum may be applicable to other similar mausoleums, if the necessary materials and human resources are available.

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دراسة تشخيصية لمواد البناء ومقترحات الحفاظ على قبة الأشرف خليل الضريحية في العصر المملوكي - القاهرة التاريخية – مصر

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الملخص

تتناول هذه الدراسة قبة الأشرف خليل بن قلاوون، وهي واحدة من أهم قباب الاضرحة في عصر المماليك في القاهرة. تقدم الدراسة وصفًا معماريًا للموقع الأثري، وتقييمًا لوضعه الحالي باستخدام وسائل التوثيق المعماري الحديثة، مع توثيق مظاهر التلف وتصور عام لحالة المبنى بعد أعمال الترميم. بالإضافة إلى ذلك، تم إجراء دراسة أركيمترية لمواد بناء الضريح وجوانب تدهورها باستخدام تحليل حيود الأشعة السينية (XRD)والميكروسكوب المقطعي (PM)والميكروسكوب الإلكتروني الماسح المزود بوحدة انتشار الطاقة بالأشعة السينية (SEM-EDX).أظهرت هذه الدراسة أن الحجر الجيري الذي تم دراسته يتكون أساسًا من الكالسيت الميكريتي وآثار من الرمل، وآثار من الملح الصخري. كما كشف عن استخدام الجير الملاط، وتم التأكد من أن الملح الصخري هو الملح الذي يسبب تدهور مواد البناء المدروسة. وقد تم تقييم الخصائص الميكانيكية للحجر الجيري المستخدم من خلال قياس قوة الضغط. وحددت الدراسة خطة علمية لترميم التلف واستعادة الأثر.

بيانات المقال

تاريخ المقال

تم الاستلام في ٢٥ فبراير ٢٠٢٣
تم استلام النسخة المنقحة في ١ اكتوبر ٢٠٢٣
تم قبول البحث في ٢٨ اكتوبر ٢٠٢٣
متاح على الإنترنت في ١٠ يونيه ٢٠٢٤

الكلمات الدالة

المنشآت التاريخية،
الأضرحة المملوكية،
مواد البناء،
الميكروسكوب الالكتروني الماسح،
حيود الأشعة السينية،
خطة ترميم