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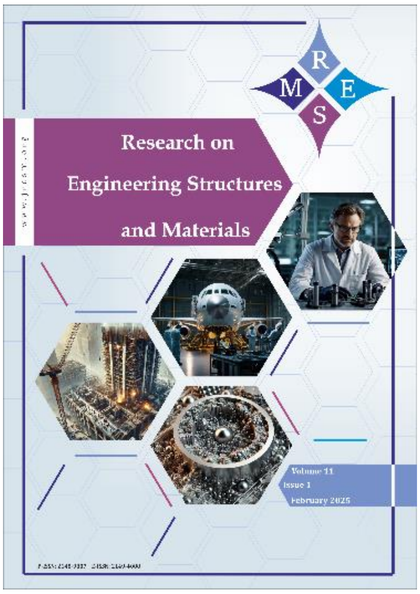

An experimental study on consolidated sandstone by accelerated salt crystallization cycles: A case study of Dendera Temple, Qena, Egypt

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Research Article

An experimental study on consolidated sandstone by accelerated salt crystallization cycles: A case study of Dendera Temple, Qena, Egypt

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Abstract

The purpose of this study is to look at the behavior of sandstone used in the Dendera temple's construction under the effects of weathering and salt crystallization. To achieve our objective, (40) cycles of salt crystallization testing were performed on the selected sandstone samples consolidated by Paraloid B-72 enhanced with ($Ca(OH)_2$ – SO_2) nanoparticles using sodium sulfate (Na_2SO_4) and sodium chloride (Nacl) solutions. Sandstone specimens were subjected to physical and mechanical properties tests, as well as Polarized Light Microscopy (PLM), Scanning electron microscopy (SEM) coupled with X-ray energy dispersive system (EDS) examination, Transmission electron microscope (TEM) and X-ray diffraction (XRD) analysis, this procedure was repeated four times after 10, 20, 30, and 40 cycles. Results of the study indicated that saline solutions containing Na_2SO_4 cause more damage to sandstone used in Dendera temple, The salt weathering test conducted on sandstone specimens consolidated with paraloid B-72 enhanced with nano-silica have shown superior results compared to other Nano-materials. The study concluded that Paraloid B-72 enhanced with Nano silica achieved the mean weight of 154.5 g, an increase of 7.4% over the untreated specimens, average density of 2.75 gr/cm^3, an increase of 7.2% over the untreated specimens, average Porosity of 9.85 % decrease of 27.03% over the untreated specimens and the mean compressive strength of 24.7 MPa an increase of 9.3 MPa over the untreated specimens, it also achieved resistance to salt weathering, indicating that this compound was well suited to the condition of the sandstone used in the Dendera Temple.

1. Introduction

The Temple of Goddess Hathor is located in the village of Dendera, on the west bank of the Nile River, west of Qena city. It is situated at latitude 26° 8' 29.96" E and longitude 32° 40' 14.08" N. (Fig. 1. a, b, c). Dendera's Temple of Goddess Hathor stands out for its archeological, architectural, and historical significance. The temple was built during the reign of King Khufu (4th dynasty), who established a temple for the goddess Hathor on the land of Dendera [1]. This was followed by King Pepi I (6th dynasty), and the temple was rebuilt during the reign of King Thutmose III (18th dynasty). In the late 2nd century BC, Ptolemy IX (116-107 BC) ordered the removal of the old temple, which was built by King Nectanebo I, and constructed a new temple for the goddess Hathor, whose worship had spread widely during the Ptolemaic period. Several Roman emperors also added to the temple during their reign. Most of the temples in Upper Egypt were built with sandstone rocks taken from the Gebel el-Silsila region. These rocks were also employed as a necessary building material for the Dendara temple. Sandstone quarries can be found in the Gebel

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el-Silsila region of southwest Egypt, which is situated 50 kilometers from Aswan and Luxor and spans the east and west banks of the Nile [2]. The rock fabric of sandstones controls their petrophysical properties and degradation behavior. Geological processes such as sedimentation, compaction, diagnosis, and post-diagenetic modification all influence the rock fabric. It offers useful details about cementing material quality, including grain size, sorting, roundness, and contacts [3]. The primary cements found in Egyptian sandstones are quartz, iron oxides, calcite, and clay minerals. The presence and abundance of these cements significantly impact the rock's durability. When cements are sparse, the sandstone is prone to breakage, whereas an abundance of cements results in a well-indurated and robust rock. Sandstone with a high quartz cement content, known as 'silicified sandstone', is particularly notable for its exceptional hardness and durability, making it a highly sought-after material in ancient Egypt [4, 5].

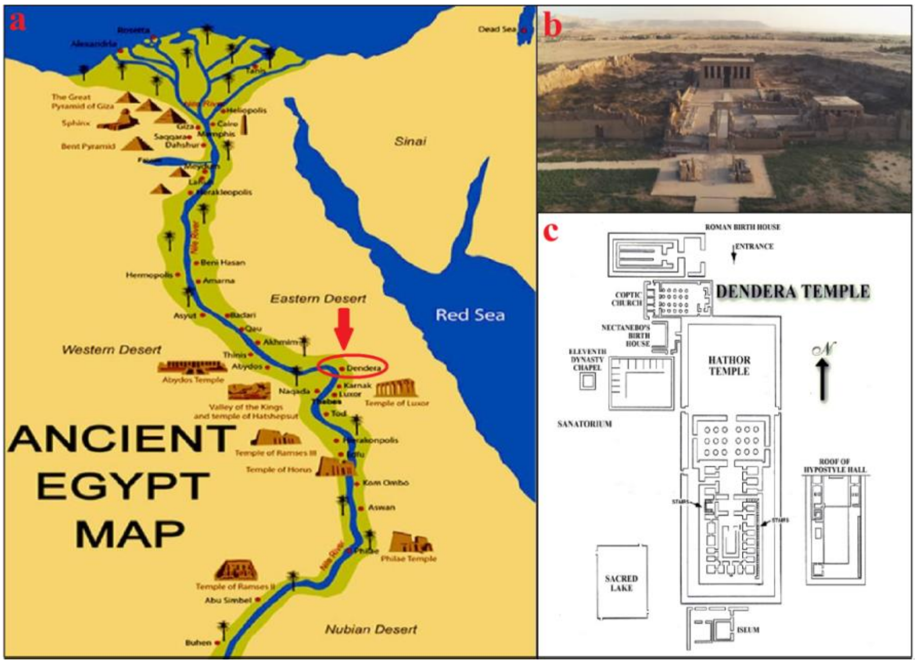


Fig. 1. (a) Egypt map, the circle indicates the site of Dendara temple. (b) General view of the temple and its urban surrounding. (c) Horizontal projection of the temple, after: http://www.touregypt.net/featurestories/seti1temple.htm

A number of factors contribute to the degradation to the Dendara Temple, such as increasing plant growth, pollution, urban encroachment, rising groundwater levels, and salt contamination of the groundwater beneath the temple. Together, these factors create a complicated deterioration mechanism that degrades the temple's fundamental building material [6]. Salt solutions can enter the pores of sandstone through its capacity to absorb moisture from the air or soil. This can result in physiochemical damage, especially when the dissolved salts crystallize in the stone's pores and cause internal pressures to cause structural fissures [7]. The binding materials break down and separate as a result of the dissolved salts' reaction with the constituents of the sandstone [8,9]. The mineral and chemical composition of monumental stones plays a crucial role in determining their durability and resistance to weathering. The mineral composition directly affects the stone's bearing capacity, with harder minerals contributing to increased strength. The presence of minerals like clay minerals, salts, and manganese and iron oxides in sandstone can impact its stability and susceptibility to damage. Repeated cycles of wetting and drying cause significant mechanical damage, particularly when salts are present within the stone's pore structure [10]. The stone's high porosity facilitates the absorption of moisture from the environment, this permits water containing salt to seep into its constituents and cause physicochemical deterioration. Further degradation may result from interior stone fissures caused by the dissolved salts crystallizing to different sizes. The clay content in the cement binding sandstone grains together renders it highly prone to deterioration, especially in environments with repeated wetting and drying cycles. This is particularly problematic in environments where the stone is exposed to repeated cycles of wetting and drying, causing the clay minerals to expand and contract [11]. In a study by Mohamed E.H found that certain minerals and salts in stone can cause it to break down faster. When these minerals and salts get wet, they dissolve and then recrystallize again after the water evaporates. This process can cause mechanical damage to the stone, the study focused on sandstones rich in clay minerals, mineral salts, and iron oxides [12]. It found that these substances can absorb moisture from the air, which can lead to damage to the stone [13]. Consolidation is a treatment process that strengthens and stabilizes deteriorated objects, yielding a durable and cohesive material resistant to environmental stressors. Effective consolidants should possess specific properties, including durability, penetration depth, minimal impact on porosity, and compatibility with the object's material composition [14].

Recent studies have consistently demonstrated the effectiveness of Paraloid B-72 (as a Co-polymer of methyl methacrylate/ethyl acrylate (MMA/EA) monomers with a composition Ratio of 70/30) in consolidating and preserving building materials, ensuring their durability and longevity. It is often cited as a reference standard due to its notable properties, including relative stability, transparency, mechanical resistance, and reversibility, it can be used to consolidate and strengthen deteriorated stone, improving its mechanical properties, also it can be applied as a protective coating to prevent further deterioration and damage from environmental factors.

These characteristics make it a reliable and versatile material for various applications, particularly in conservation and restoration projects. Nano materials and synthetic Nano composites have been increasingly used in conservation of monumental stones, including ancient buildings, monuments, and artifacts. These materials have shown great promise in enhancing the durability and sustainability of cultural heritage materials, while also preserving their original characteristics and integrity. Nano lime is one of the materials used to consolidation archaeological stones, it can be synthesized through a chemical precipitation process at elevated temperatures, utilizing supersaturated aqueous solutions of calcium chloride ($CaCl_2$) and sodium hydroxide (NaOH). Specifically, sodium hydroxide, employed as a precipitating agent, is added drop wise to the calcium chloride solution, which is maintained at a high temperature [15]. Nanoparticle suspensions of calcium hydroxide are gaining popularity as a protective coating for preserving historical materials, offering an alternative to traditional limewater solutions. The reaction between calcium hydroxide ($Ca(OH)_2$) and atmospheric carbon dioxide (CO_2) leads to the formation of insoluble calcium carbonate ($CaCO_3$) through carbonation. The carbonation process results in the formation of a hard, consolidating layer that enhances the stone's strength and stability of sandstone. The transformation of calcium hydroxide into calcium carbonate renders it an appropriate surface treatment, especially for historical building materials with a calcareous composition. Additionally, the nanoparticles' small size makes it easier for them to deposit and penetrate nano lime suspensions through the surface's exterior pores. [16].

In stone consolidation, silica-based consolidant products particularly those based on tetraethyl orthosilicate (TEOS) have become commonly used, leading to a notable decrease in material porosity. The preferred consolidants for stone consolidation are silicic acid esters (SAE), which hydrolyze to produce amorphous silica, which is defined by disordered lattices of tetra-coordinated silica. When humidity is present, this silica functions as a consolidant to create ethyl silicate [17, 18]. Recent studies have consistently shown that nano-silica improves the strength and consolidation of construction materials and the creation of restoration mortars. Additionally, research has shown that nano-silica and nano-lime can greatly increase the strength and consolidation efficiency of traditional building materials.

This study aims to investigate the extent to which nano-silica and nano-calcium hydroxide enhanced with Paraloid B-72 preserve the physical and mechanical properties of sandstone used in Dendera Temple after accelerated salt weathering test. The objective of this study is to conduct experimental tests to evaluate the durability of consolidated sandstone with nano composites using accelerated salt weathering tests, with the aim of identifying the most effective strengthening material for enhancing the durability of sandstone affected by salt weathering.

2. Materials and Methods

2.1. Sandstone *U*sed in Dendera Temple

The petrophysical properties of sandstone, such as grain size and cementation quality, directly influence the patterns of deterioration caused by environmental factors. Poorly cemented sandstones may more easily undergo granular weathering, while those containing clay minerals may be more affected by wetting and drying cycles. The main components of the sandstone used in the Dendera Temple include quartz grains, carbonate minerals (such as calcite), clay minerals and iron oxides. This mineralogical structure is an important factor that determines the resistance of the sandstone to deterioration caused by salts and other environmental factors.

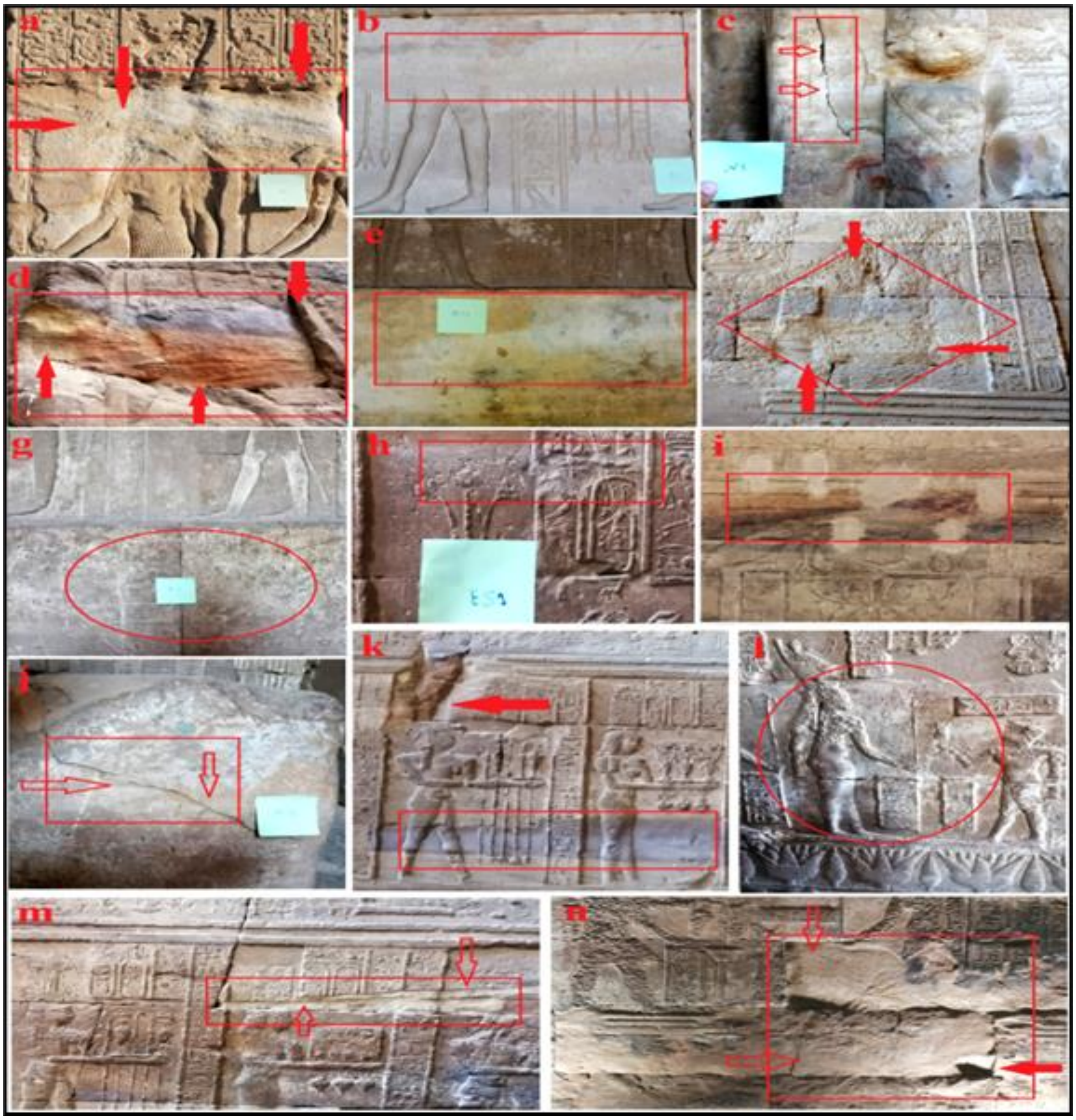


Fig. 2. (a), (b) Weathering out "granular disintegration into sand", (c) Efflorescence salts on stone surface and fissures, (d) Weathering out of stone components and coloration due to migration of iron oxides, (e)(h)(i) Efflorescence salts on stone surface, (f) Weathering out dependent on stone structure, g. Relief due to the effect of salts, (i) Coloration due to the effect of iron oxides, (j) Efflorescence salts and crack in the stone surface, (k) (m) The arrow indicates the loss of stone components and the rectangle indicates coloration due to migration of iron oxides, (n) Granular disintegration and scaling of the stone due to salt crystallization.

The sandstone that was used to build Dendera Temple has been exposed to variations in groundwater level and high temperatures, and infection of groundwater beneath the temple by salts. These factors combine to form a complex damage mechanism that negatively impacts the sandstone used in the temple. By studying the effect of salt weathering, as well as observing the deterioration patterns of the sandstone used in the Dendera Temple, it was found that it suffers from many different forms of deterioration, which are indicated in (Fig.2), and which include the following symptoms: efflorescence salts, granular disintegration into powder as a result of the effect of salt crystals, which led to the erosion of the inscriptions that were on the stone (Fig.2.a,b). Weathering out of stone components and multiple scaling were occurred, coloration due to migration of iron oxides. Weathering out occurred dependent on stone structure, separation of crusts or thin sheets of stone surface, loss of stone material, exfoliation, bleeding of stone, fissures, cracks and chipping of the stone to pieces.

2.2. Preparation of Selected Sandstone

Twenty-four cubic sandstone specimens of 4 cm side were used in this study. The sandstone specimens were brought from the ancient quarry in Aswan where the stone used to build temple was extracted. Six sandstone cubes were selected for each type of consolidating material, totaling 12 cubes. Six consolidated sandstone cubes were identified for each type of accelerated ageing tests by salt weathering, totaling 12 cubes (Fig.3).

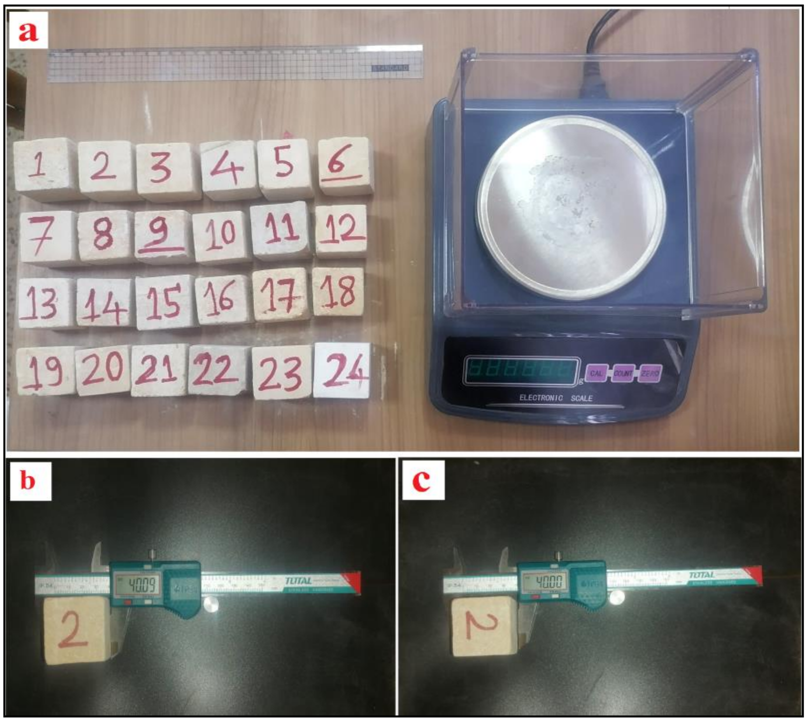


Fig. 3. (a) The sandstone prepared into cubes approximately in ($4 \times 4 \times 4$ cm^3), (b)(c) Measure the dimensions of the cube through digital caliper (150 mm), dimension measurement of the cube carried out digital caliper (150 mm)

2.3. Consolidating Treatments

In light of the environmental circumstances around the study building, two nano composite materials were chosen based on the characteristics of sandstone and a more thorough, uniform penetration of the consolidants into the substrate. The first is paraloid B-72 enhanced with nano-silica (SiO_2), while the second is paraloid B-72 enhanced with $Ca(OH)_2$ nanoparticles of. Nano-silica (SiO_2) and Nano-calcium hydroxide ($Ca(OH)_2$) materials were prepared at the central laboratory, South Valley University.

2.3.1. Paraloid B-72 enhanced with SiO_2 Nanoparticles

A solution was prepared by dissolving 10 g of sodium silicate in 200 mL of deionized water, stirred for 30 minutes using a magnetic heating stirrer, then hydrochloric acid (HCl at concentration of 0.1-0.5 ml) is slowly added to the previous solution with continuous stirring. The previous solution was treated with 1 gram of 25% ammonia (NH3), added slowly, and then stirred for 3 hours at 80°C in a water bath. Following that, the white product was filtered and cleaned using alcohol and deionized water until Cl^- was found. Then, chlorotrimethylsilane was used to chemically alter the SiO_2 nanoparticles [19]. After dissolving the white product and 0.05 moles of CTMS in 200 milliliters of alcohol, the resulting solution was heated to 80°C in a bath of water and stirring it for three hours. Following the reaction, the resultant product was filtered and vacuum-dried for 24 hours at room temperature to produce a powder of 40–50 nm-sized SiO_2 nanoparticles. (Figure 4. a). 1.5 g of powdered SiO_2 nanoparticles were mixed to paraloid B-72 (as a 70/30 co-polymer of methyl methacrylate/ethyl acrylate (MMA/EA) monomers). To create Nano composite, it was dissolved in 250 milliliters of acetone and then agitated with a magnetic stirrer set at 500 rpm for 30 minutes in a water bath at 80°C (Figure 5. a, b, c, d, e, f); Table 1 [20, 21].

2.3.2. Paraloid B-72 enhanced with $Ca(OH)_2$ Nanoparticles

Nano lime was obtained by a chemical precipitation process, by mixing 10 g of calcium chloride ($CaCl_2$) to 200 mL of deionized water with stirring by magnetic heating stirrer for 60 minutes, then hydrochloric acid (HCl at concentration of 0.1 - 0.5 ml) is slowly added to the previous solution with continuous stirring. 1 gram of sodium hydroxide (NaOH) at a concentration of 25% is slowly added to the previous solution, the solution was stirred for 2-4 hours in a water bath at 90°C. After that, the white product was filtered and washed with deionized water and alcohol until Cl^- could be detected [22].

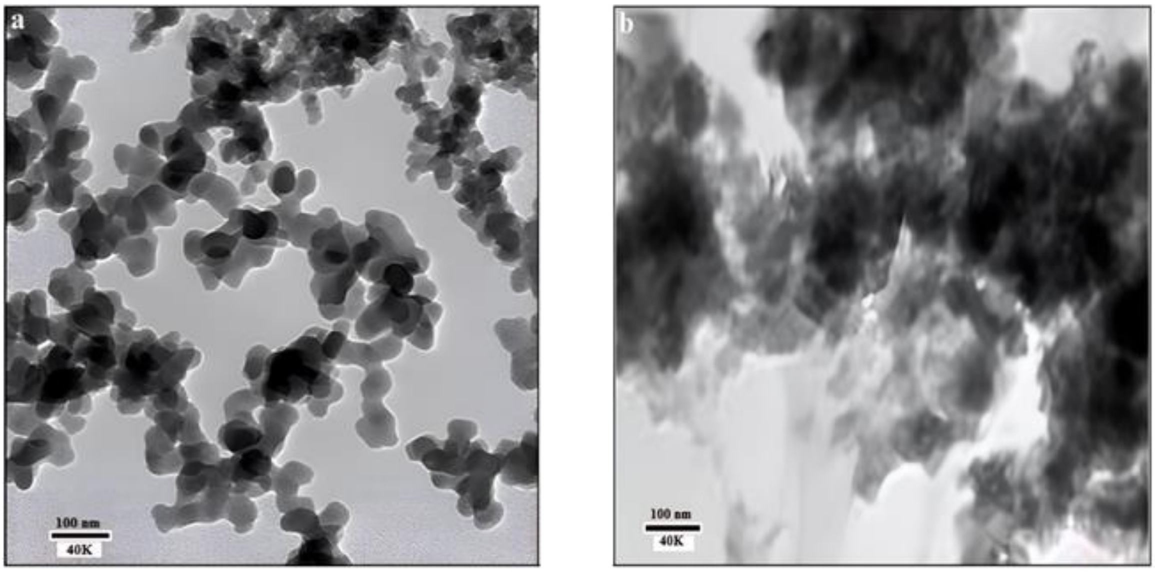


Fig. 4. (a) TEM image is show Nanocomposite of SiO_2 nanoparticles and paraloid B-72. (b) TEM image is show Nanocomposite of $Ca(OH)_2$ and paraloid B-72

Table 1. Concentrations of Nano composite materials

Consolidation materials (Code)	Ca $(OH)_2$ nanoparticles concentration	SO_2 nanoparticles concentration	Polymer solid content	The obtained nanocomposite
Nano lime (N.L) + Paraliod B-72 (P)	5%	--	3gm/ 100 ml	Ca $(OH)_2$ nanoparticles / polymer nanocomposites (5%)
Nano silica (N.S) + Paraliod B-72 (P)	--	5%	3gm/ 100 ml	SO_2 nanoparticles / polymer nanocomposites (5%)

The resulting product was filtered and dried in a vacuum at room temperature for 24 hours to obtain powder of $Ca(OH)_2$ nanoparticles (size 10- 40 nm) (Fig. 4. b). 1.5 g of $Ca(OH)_2$ nanoparticles powder added to paraloid B-72 (as a Co-polymer of methyl Methacrylate/ethyl acrylate (MMA/EA) monomers with a composition Ratio of 70/30) dissolved in 250 ml of acetone to prepare nanocomposite, the solution was mechanical stirred for 60 minutes at 90°C in a water bath using a magnetic stirrer (600 rpm) (Fig.5. g, h, i; Table 1).

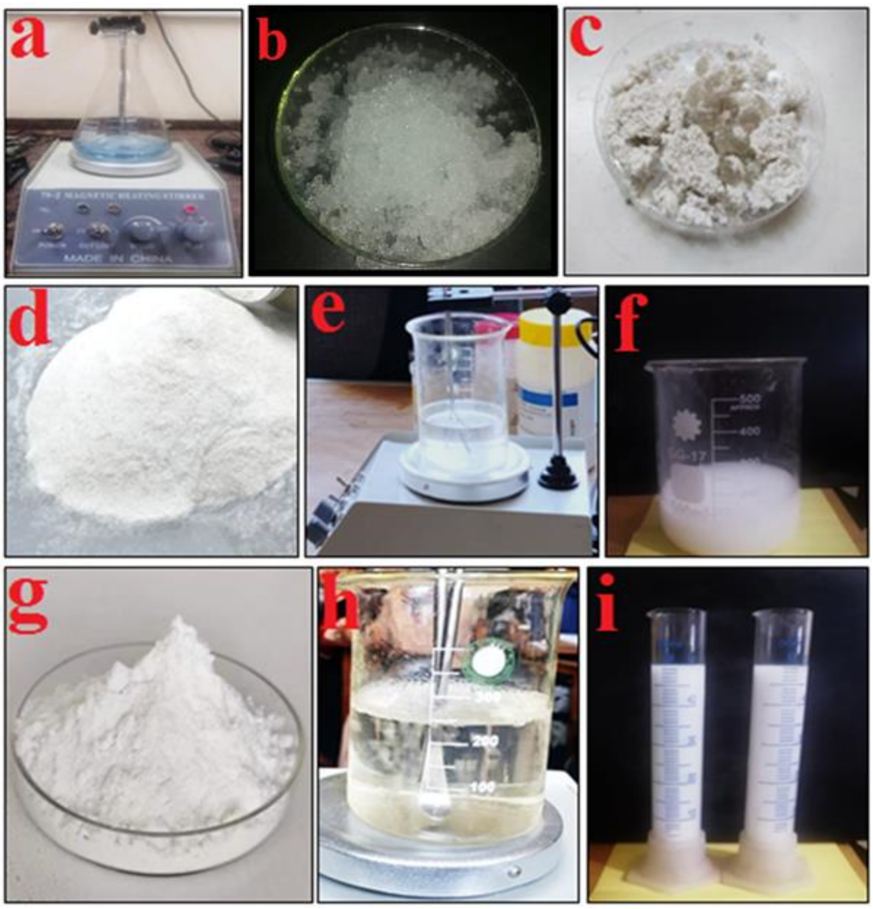


Fig. 5. (a) preparation of silica gel, (b)(c) silica gel, (d) SiO_2 nanoparticles powder, (e)(f) Nanocomposite of SiO_2 nanoparticles and paraloid B-72, (g) $Ca(OH)_2$ Nanoparticles, (h)(i) Nanocomposite of $Ca(OH)_2$ nanoparticles and paraloid B-72

2.4. Methods of the Study

2.4.1. Polarized Light Microscopy (PLM)

Thin sections of the deteriorated sandstone were examined using Polarized Light Microscopy (PLM) LEITZ WETZLAR (GERMANY), with a LEICA Cam Max. 100 W (307-148.002-514687). Thin sections of sandstone for use in polarizing microscopy conducted at faculty of science, Cairo university, Egypt. The purpose of examining sandstone samples using a polarizing microscope to identify the mineral composition of the sample, including the type of minerals and their crystal structure.

2.4.2. Transmission Electron Microscope (TEM)

TEM images were obtained by a JEM-1230 electron microscope operated at 60 KV (JEOL Ltd., Tokyo, Japan) conducted at the National Research Centre in Dokki , Egypt. The mixture of Paraloid B-72 enhanced with $Ca(OH)_2$ nanoparticles and the mixture of Paraloid B-72 enhanced with SO_2 nanoparticles were examined using (TEM) to determine particle size, shape, crystallinity, agglomeration, and dispersion as an indicator of mixture homogeneity.

The specimens were cut into small pieces (micrometers in size). Fixing the sample using chemicals like glutaraldehyde or osmium tetroxide. Embedding the sample in a special resin (like epoxy) to enhance stability. Cutting the sample into thin sections (50-100 nanometers) using an ultramicrotome. Placing the thin section on a metal grid specifically designed for TEM.

2.4.3. Scanning Electron Microscope (SEM)

The microstructure of the deteriorated sandstone and consolidated specimens (before and after 40 cycle of artificial ageing cycles) were investigated using a Quanta 250 Field Emission Gun (FEG) Scanning Electron Microscope (SEM) coupled with an X-ray Energy Dispersive System (EDS). The SEM was operated at an accelerating voltage of 30 kV, with a magnification range of 30x to 300,000x. The EDS system was operated at an accelerating voltage of 30 kV, with a magnification range of 14x to 1,000,000x. The samples were coated with a thin layer using a K550X Sputter Coater, UK.

2.4.4. X-ray Diffraction (XRD)

X-ray diffraction (XRD) analysis was carried out using a Philips PW 1840 X-ray diffractometer, employing Cu-Kα radiation at 40 kV and 40 mA. The XRD patterns were collected over a 2θ range of 5° to 50°, providing information on the mineralogical composition of the specimens. XRD was used to identify the mineral phases of the sandstone samples (Quartz, Calcite, Kaolinite, etc.) and to determine the effect of weathering processes on mineralogical changes.

2.4.5. The Physical and Mechanical Properties Tests

Physical properties tests were conducted in accordance with (ASTM C97-18) [23], to determine the physical properties (bulk density, water absorption, and porosity). The physical properties were calculated using the following equations:

Bulk density (ASTM C97-18): (Equation 1)

$$\rho\ dry = M(solid)/V(total) \tag{1}$$

where ρ = density, M = mass, and V = volume. Apparent porosity (ASTM C97-83): (Equation 2)

$$n = V(pore\ space\ )/\ V(total) \tag{2}$$

Compressive strength of the specimens was carried out according to (ASTM C170) [24], calculate the compressive strength of the specimens carried out as follows: (Equation 3)

$$C = F/A \tag{3}$$

where (C) compressive strength of the specimen in Mpa, (F) total load at which failure occurs in kg, (A) calculated area of the bearing surface in cm^2.

3.Laboratory Study

3.1. Applying Consolidation Treatments

Before applying consolidants, sandstone specimens underwent a (24) hour oven-drying process at 110°C, followed by a (30) minute cooling period at room temperature to reach constant mass weight [25]. Subsequently, the weights of the specimens' cubes were recorded before undergoing the consolidation treatment. Specimens numbered 1 to 12 (Denoted by the symbol N.S+P) were selected for the application of Paraloid B-72 enhanced with SiO_2 Nanoparticles, specimens numbered 13 to 24 (Denoted by the symbol N.L+P) were selected for the application of Paraloid B-72 enhanced with $Ca(OH)_2$ Nanoparticles.

The consolidation process was conducted under controlled laboratory conditions (T = 25 ± 2 °C, R.H = 50 ± 5%). The consolidation treatment methodology used for the stone specimens was designed to replicate the natural conditions of solution absorption and diffusion within the stone. The specimens were immersed in the consolidation solution within a plastic box, which was covered to prevent solvent evaporation. Each specimen was partially immersed in the solution to a depth of 5 mm and allowed to absorb the solution through capillary action for 30 minutes per side, totaling 180 minutes per all sides of stone specimen. To ensure uniform treatment, the specimens were subjected to consolidation from all sides, allowing for accurate assessment of physical properties, mechanical properties, and accelerated aging cycles [26]. Then the specimens were left to dry for 30 days at room temperature to allow polymerization to occur, after the polymerization process was complete, the weights of the specimens' cubes were recorded and the physic-mechanical tests were conducted on the specimens to compare the properties before and after treatment, furthermore, the performance of the consolidants was assessed using scanning electron microscopy (SEM).

3.2. Accelerated Salts Crystallization Tests

Salt crystallization tests were determined using the standard method in accordance with TS EN 12370 (Natural stone test methods-determination of resistance to salt crystallization) [27, 28, 29]. Two types of salts, sodium sulfate (Na_2SO_4) and sodium chloride (NaCl), were selected for the ageing tests to simulate the effects of salt weathering on sandstone used in Dendera Temple. Each test comprised of 40 cycles, wherein the specimens numbered 1 to 6 and 13 to 18 were submerged in a 14% solution of sodium sulfate (Na_2SO_4) for a period of 2 hours, the specimens numbered 7 to 12 and 19 to 24 were submerged in a 14% solution of sodium chloride (NaCl) for a period of 2 hours, then the specimens were dried in oven at 110°C for 16 hours, and subsequently were cooled at room temperature for 6 h. The previous steps were repeated for 40 cycles, during which the texture and morphology of the specimen surfaces were examined, and their weights were recorded after cycles 10, 20, 30, and 40 (Fig.6). Following the completion of the 40th cycle. All the specimens subjected to aging tests due to crystallization of salts were immersed in distilled water for 24 h, and then brushed, to remove the loose deposited efflorescence from the specimens surfaces. Subsequently, the specimens were dried in oven at 110°C until constant mass [30]. Then the specimens underwent evaluation through examination with a digital microscope and scanning electron microscope, as well as testing for density, porosity, and compressive strength.

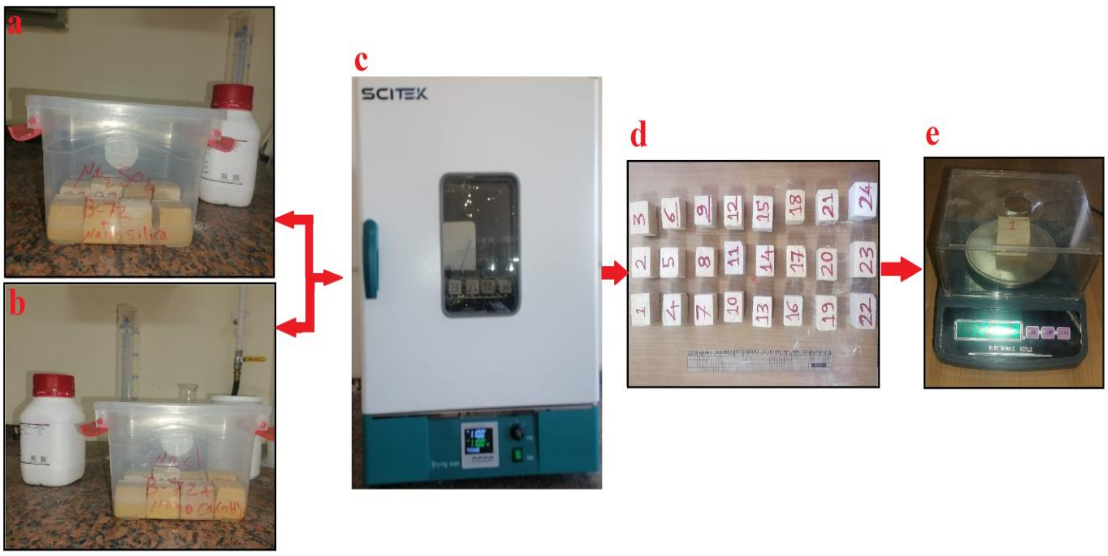
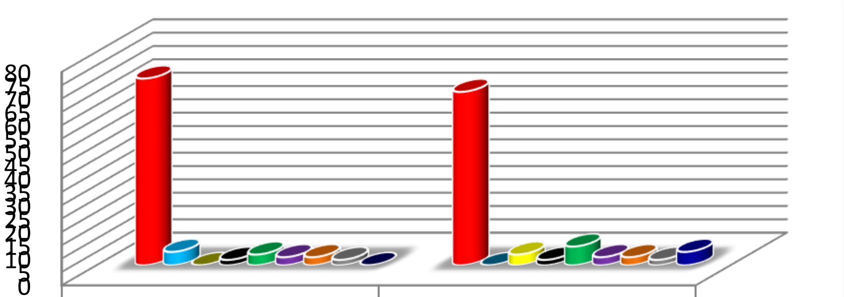


Fig. 6. (a)(b) immersing the sandstone specimens in a saline solution (Na_2SO_4 - NaCl) for two hours. (c) drying in oven at 110°C for 16 hours. (d) cooling at room temperature for 6h. (e) The weight of specimens were recorded after cycles 10, 20, 30, and 40

4.Results and Discussion

4.1. Examination and Mineralogical Composition of The Studied Sandstone

Polarized light microscopy (PLM) examination of the sandstone used in Dendera Temple revealed a complex composition, primarily consisting of quartz grains, along with rock fragments, carbonate minerals such as calcite, clay minerals including kaolinite, opaque matter, feldspar minerals comprising microcline and albite, bassanite and iron oxides. Notably, the sandstone exhibited relatively low quartz and rock fragment content, but high concentrations of clay minerals and opaque matter. Characteristic features included color banding, alignment of mica and elongated quartz grains, and a distinctive texture. These findings provide valuable insights into the composition and properties of the sandstone used in the construction of Dendera Temple.



	b	d
Quartz	70	65
Calcite	5	0
Kaolinite	0	4
Albite	2	2
Bassanite	4	7
Magnetite	3	3
Hematite	3	3
Gypsum	2	2
Halite	0	5

Fig. 7. Chart shows X-ray diffraction analysis results of deteriorated sandstone specimens that represent case study

X-ray diffraction (XRD) analysis of the sandstone samples revealed that they are primarily composed of Quartz (SiO_2 65 -70%), Calcite ($CaCO_3$ 5%), Kaolinite ($Al_2Si_2O_5(OH)_4$ 4%), Albite ($NaAlSi_3O_8$ 2%), Bassanite ($CaSO_4.0.5H_2O$ 4-7%), Magnetite (Fe_3O_4 3%), Hematite (Fe_2O_3 3%), Gypsum ($CaSO_4.2H_2O$ 2%) and Halite (NaCl 5%), as shown in Fig.7-8. Petrographic examination reveals that the sandstone is comprised of three distinct components: framework grains, cementing materials, and pore spaces. The sandstone samples obtained from Dandara Temple exhibit a low concentration of feldspars in most samples, indicating that the sandstone samples have undergone chemical weathering and recycling. Furthermore, The XRD analysis confirmed that the studied sandstone suffers from a low concentration of feldspars and high concentration of clay minerals in most samples suggest that the sandstone have undergone chemical weathering. It is worth noting that the high concentration of halite, gypsum, and bassanite was a contributing factor to the activation of chemical weathering, which led to the deterioration of the sandstone (Fig.8).

SEM examination of sandstone samples revealed an abundance of clay minerals, halite, bassanite, and gypsum. The SEM micrograph of the sandstone shows presence of disintegration in the quartz mineral crystals as a result of the crystallization of salts, as well as the loss of the binding materials, in addition to the presence decomposition of the clay minerals within the stone structure. The results of EDX microanalysis confirmed the presence of Al, Si, Mg, Fe, Ca, Ti, K, S and Na. the presence of Na, Ca, indicate to halite and bassanite (Fig.9). The presence of bassanite salts indicates that chemical weathering has occurred, resulting in the conversion of calcium carbonate to calcium sulfate, which is soluble in water. Furthermore, the presence of halite salts has caused the transformation of calcium carbonate, the binding material of quartz grains, into calcium chloride, which is also soluble in water and has contributed to increased porosity, disintegration, loss of cohesion, reduced durability and weathering of the sandstone.

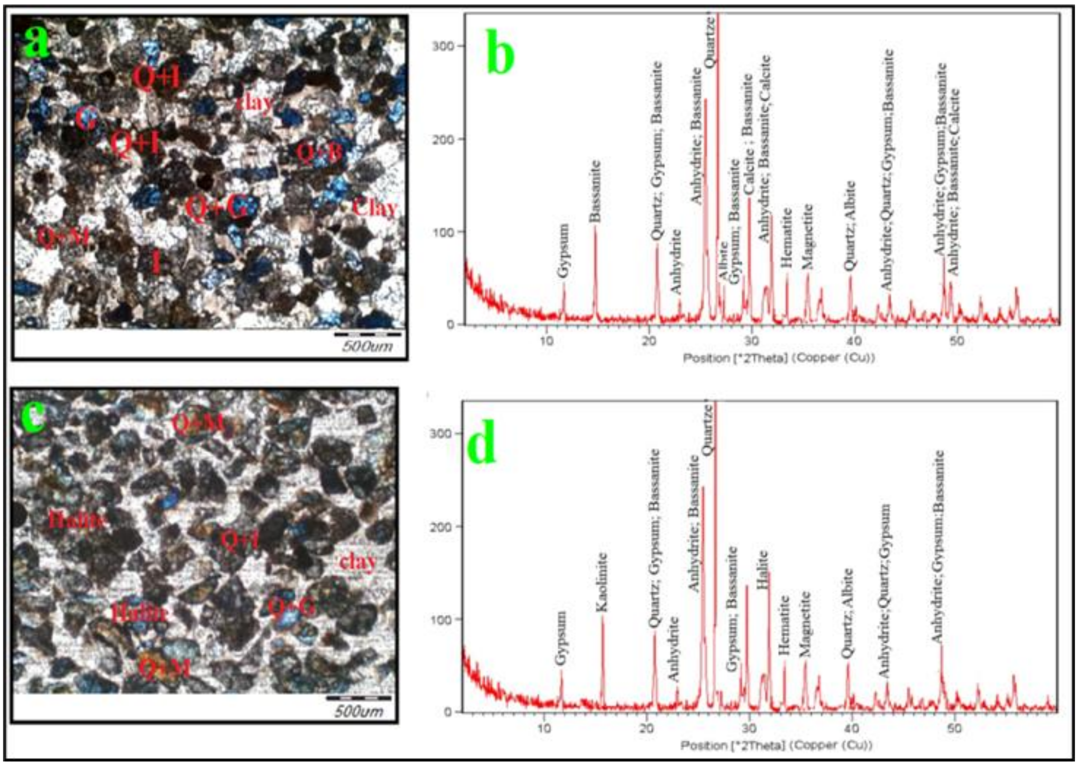


Fig. 8. (a) (c) Photomicrograph of thin section of deteriorated sandstone shows quartz grains that are medium to coarse-grained, rounded to sub rounded. iron oxides, clay minerals, salts and iron oxides were found. (b)(d) XRD pattern of deteriorated sandstone samples of case study

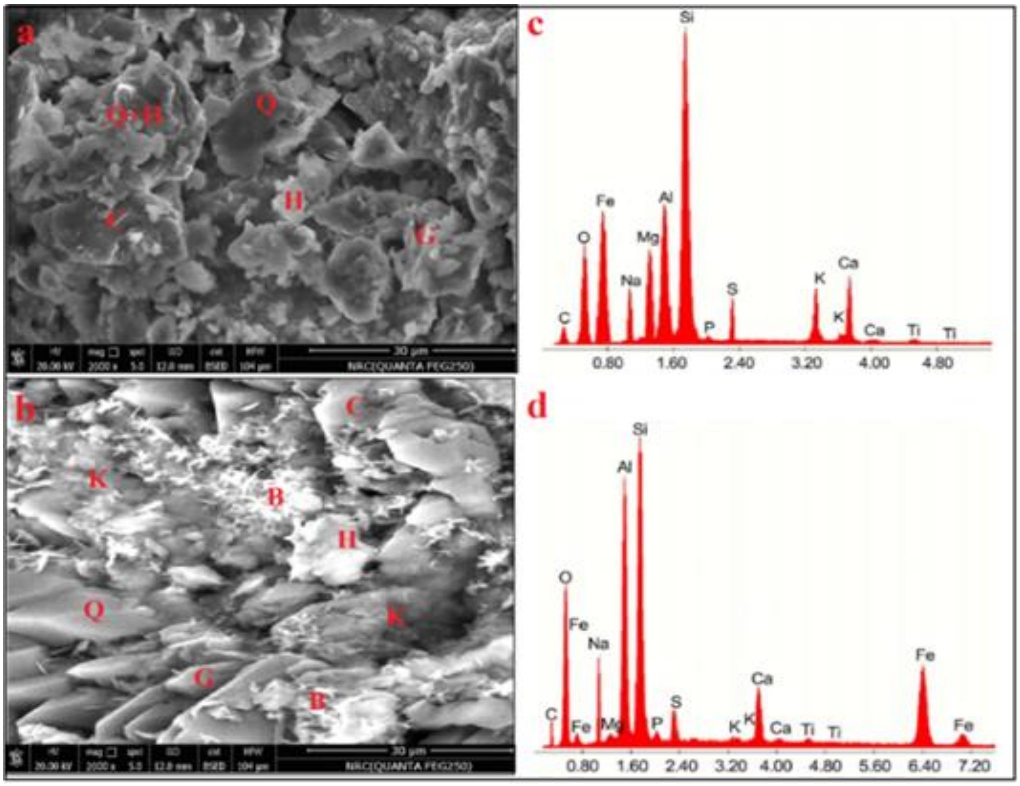


Fig. 9. (a) (c) SEM photomicrograph of deteriorated sandstone shows erosion in quartz crystals and abundance of salts (Nacl - CaSO4.0.5H2O) and clay minerals. Letters indicate the following: Q. quartz, C. calcite, K. kaolinite, B. bassanite, H. halite, and G. gypsum. (b)(d) EDX pattern of deteriorated sandstone samples of case study

4.2. Evaluation of Consolidation Materials Before Ageing Test

In addition to mechanical properties, the evaluation approach includes physical properties like density, porosity, and water absorption, as well as investigation using scanning electron microscopy. (Fig.10, a) The degraded sandstone's mineral grains were coated with consolidation materials to make them hydrophobic, which stopped chemical weathering brought on by salts in the stone's pores. SEM examination showed that the Nano-silica enhanced with Paraloid B-72 treatment achieved effective penetration into the stone's pores and coated the mineral grains without causing pore clogging or densification, and nano-calcium hydroxide enhanced with Paraloid B-72 achieved good coating of the mineral grains without causing pore clogging (Fig. 10 b,c). This is consistent with a number of scientific investigations that have validated the advantages of employing nanoparticles distributed inside polymers to strengthen, preserve, and enhance the characteristics of archaeological construction materials [31, 32, 33, 34].

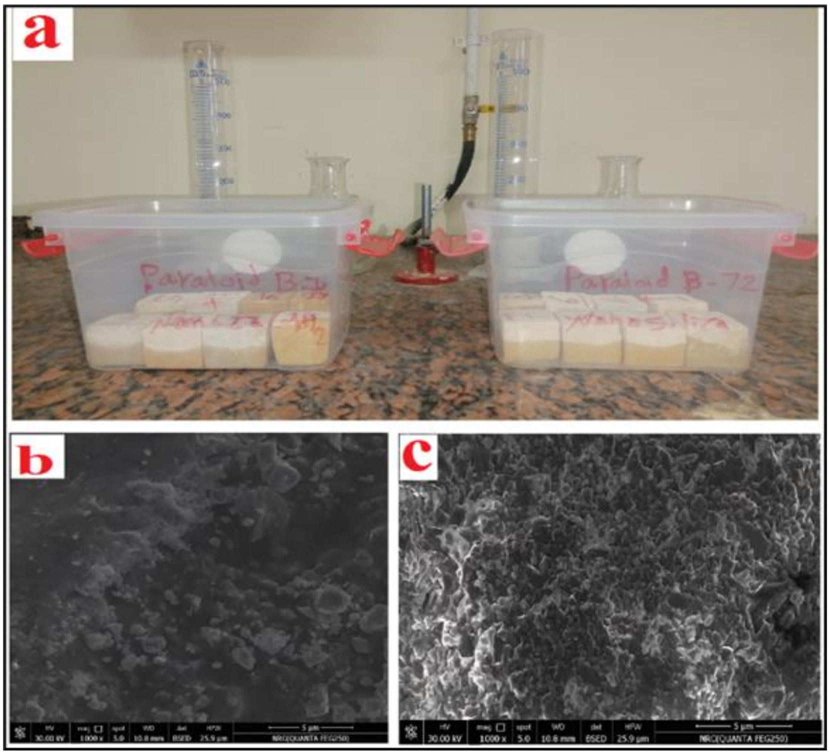


Fig. 10. (a) Applying consolidation treatments under controlled laboratory conditions. (b) SEM micrograph shows a good coating of the mineral grains of the sandstone with SiO_2 nanoparticles enhanced with paraloid B-72. (c) SEM micrograph shows a good coating of the mineral crystals with $Ca(OH)_2$ nanoparticles enhanced with paraloid B-72

Table 2 presents the minimum, maximum, and average results obtained of physico-mechanical properties of sandstone before and after consolidation. The results indicate that the weight of un treated samples varied between (140.8) g and (145.3) g with an average of (143.05) g. Moreover, the test results showed that the dry density of the samples varied between (2.2) and (2.9) g/cm^3, with a mean density of 2.55 g/cm^3. The porosity test results indicated that the values ranged from (12.5) % to (14.2)% with an average of (13.5)%.

The treated specimens with (N.S+P) achieved the mean weight of 154.5 g, an increase of 7.4% over the untreated specimens, average density of 2.75 gr/cm3, an increase of 7.2% over the untreated specimens, average Porosity of 9.85 % decrease of 27.03% over the untreated specimens and the mean compressive strength of 24.7 MPa an increase of 9.3 MPa over the untreated specimens.

The treated specimens with (N.L+P) achieved the mean weight of 149.7g, an increase of 4.4% over the untreated specimens, average density of 2.57gr/cm3, an increase of 0.77% over the untreated specimens, average Porosity of 10.95% decrease of 18.8% over the untreated specimens and the mean compressive strength of 23.6MPa an increase of 5.08 MPa over the untreated specimens.

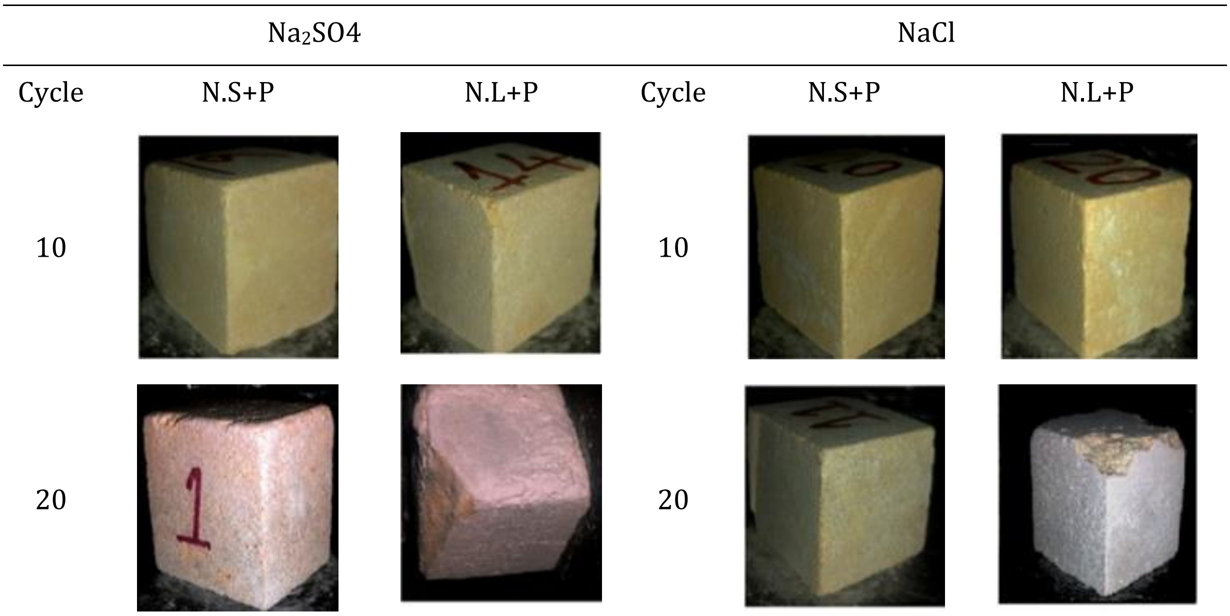
Table 2. Physical and mechanical properties of the sandstone specimens before and after applying consolidation treatments

Specimens/ Tests	Weight of Specimens			Porosity (%)			Dry density (gr/cm3)			Compressive strength (MPa)		
	Min.	Max.	Aver.	Min.	Max.	Aver.	Min.	Max.	Aver.	Min.	Max.	Aver.
Untreated	140.8	145.3	(143.05)	12.5	14.2	(13.5)	2.2	2.9	(2.55)	20.3	24.5	(22.4)
N.S+P	153.6	155.5	(154.5)	9.2	10.5	(9.85)	2.4	3.1	(2.75)	22.8	26.5	(24.7)
N.L+P	147.2	152.2	(149.7)	10.2	11.7	(10.95)	2.3	2.85	(2.57)	21.5	25.8	(23.6)

4.3. Evaluation of Consolidation Materials After Ageing Test

The artificial weathering of the consolidated sandstone was monitored using six parameters: (1) weight loss in the specimens, (2) visual deterioration, (3) examination of internal structural (4) bulk density (5) porosity and (6) compressive strength. These parameters were studied to determine the changes in petrophysical values and to assess the degree of deterioration that occurred. Table 3 shows a comparison of the mean values of weight, density, porosity, and compressive strength of sandstone samples after artificial weathering caused by the crystallization of salts using sodium sulfate and sodium chloride after cycle (10), cycle (20), cycle (30) and cycle (40). Visual examination revealed that the consolidated sandstone specimens with Paraloid B-72 enhanced with SiO_2 Nanoparticles exhibited excellent resistance to salt weathering using sodium chloride and a good resistance to salt weathering caused by sodium sulfate, compared to the consolidated sandstone specimens with Paraloid B-72 enhanced with $Ca(OH)_2$ Nanoparticles. The formation of salt crystals within the pore spaces resulted in an initial weight increase in some samples (N.L+P (Na_2SO_4)) up to the tenth cycle. However, from the twentieth cycle onwards, the sandstone specimens displayed a weight loss and began to deteriorate, exhibiting various weathering forms, including efflorescence, fracture, flaking, and material loss. Additionally, all samples exhibited superficial granular disaggregation, and some samples showed superficial flaking, leading to the loss of thick sheets on the sample surfaces (Fig.11).

Accelerated salt crystallization test



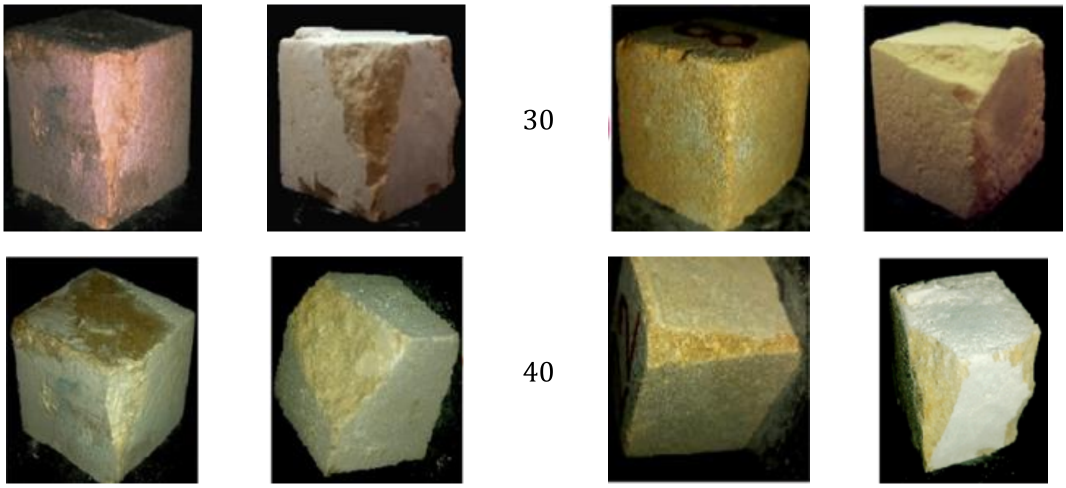
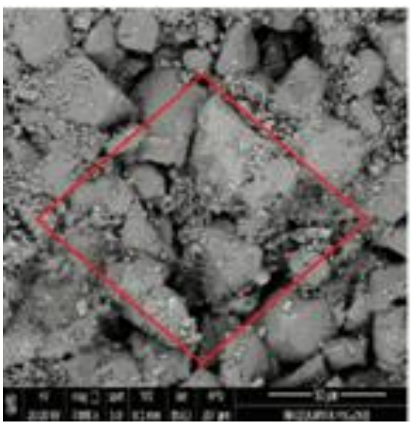
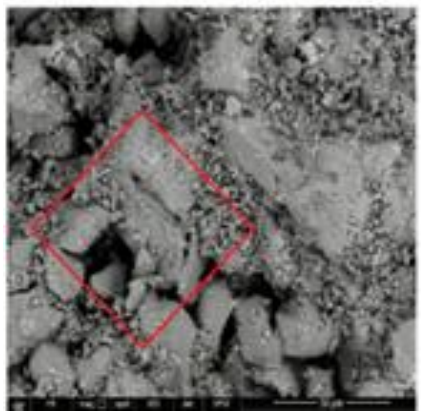
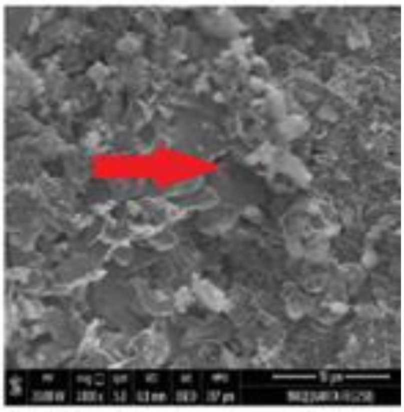
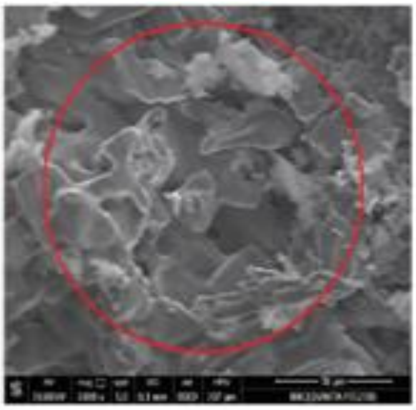
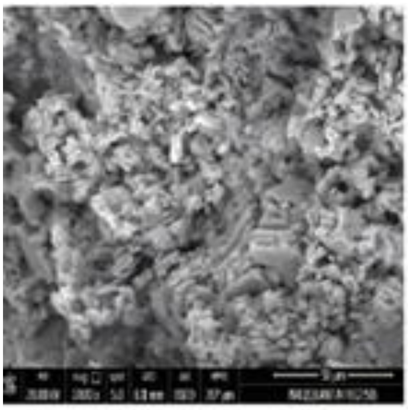
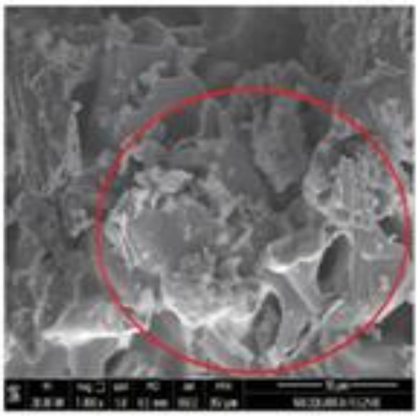
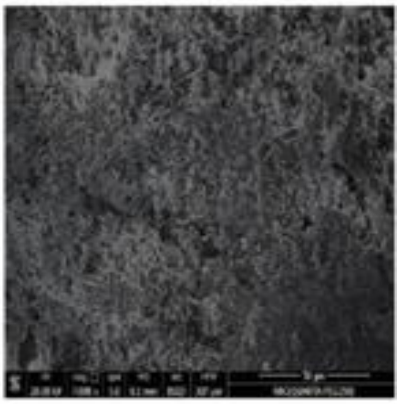
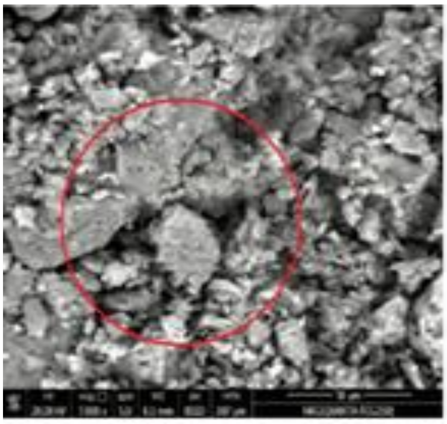
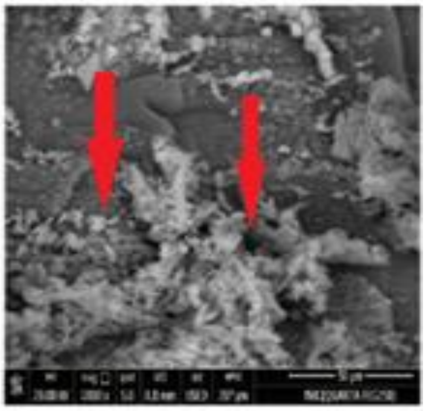
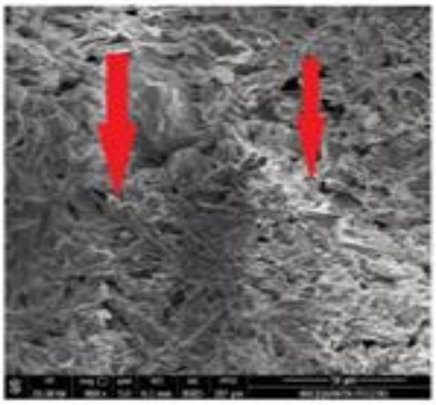


Fig. 11. Appearance of the consolidated specimens after being subjected to accelerated salts crystallization cycles

Table 3. Physical and mechanical properties of the consolidated sandstone specimens after ageing tests

Specimens/ Tests	Weight of Specimens				Porosity (%)				Dry density (gr/cm3)				Compressive strength (MPa)			
	C.(10)	C.(20)	C.(30)	C.(40)	C.(10)	C.(20)	C.(30)	C.(40)	C. (10)	C.(20)	C. (30)	C.(40)	C.(10)	C.(20)	C.(30)	C.(40)
N.S+P (Na2SO4)	155.4	152.3	148.2	145.3	6.5	8.2	10.5	14.7	2.5	2.1	1.92	1.87	20.2	19.5	17.4	15.8
N.S+P (NaCl)	155	153.2	150.2	148.02	7.5	8.5	9.85	11.6	2.5	2.3	2.15	1.95	20.7	19.8	18.3	17.5
N.L+P (Na2SO4)	154.2	146.5	134.7	122.8	9.6	12.7	14.75	19.5	2.3	1.85	1.57	1.46	18.5	17.2	15.6	13.5
N.L+P (NaCl)	153.1	147.5	138.2	125.8	8.4	11.9	13.5	17.8	2.28	1.92	1.78	1.65	18.7	17.5	15.8	14.2

NaCl		
Cycle	N.S+P	N.L+P
20		

30		
40		
	Na_2SO4	
Cycle	N.S+P	N.L+P
20		
30		

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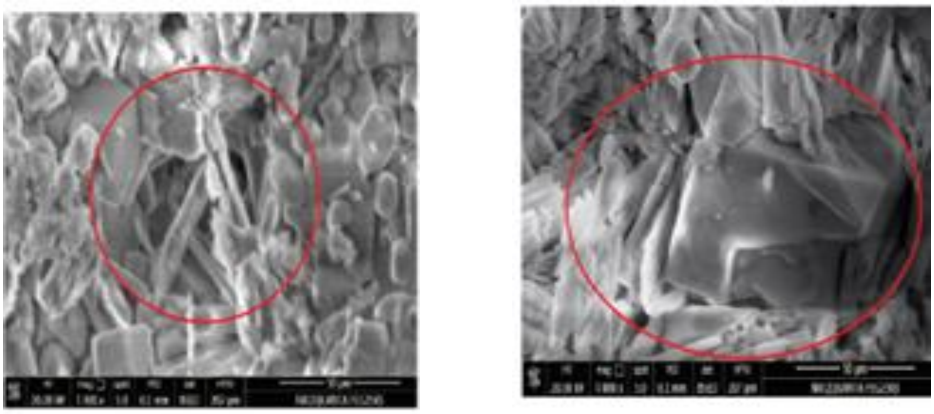

Fig. 12. SEM micrograph shows of the consolidated sandstone specimens after being subjected to accelerated salts crystallization cycles

According to Fig.12, SEM examination shows the accumulation of sodium chloride crystals within the pores of the sandstone specimens (N.L+P (NaCl)) after the tenth cycle of artificial weathering. In the fortieth cycle, the examination shows the deterioration of the mineral crystals constituting the sandstone due to the chemical reaction between sodium chloride and the binding materials of the mineral crystals, resulting in the loss of the binding materials. In contrast, the sandstone (N.S+P) showed resistance to salts weathering caused by sodium chloride due to the effect of SiO_2 nanoparticles, which coated the mineral crystals and prevented sodium chloride crystals from penetrating the quartz crystals, the main component of the sandstone. SEM examination of consolidated stone specimens (N.L+P (Na_2SO_4) exposed to salts weathering caused by sodium sulfate (Na_2SO_4) showed severe deterioration, while the examination revealed cohesion in the mineral crystals of sandstone specimens (N.S+P (Na_2SO_4)) and minor damage, confirming the resistance of SiO_2 nanoparticles enhanced with paraloid B-72 to the effects of sodium sulfate.

5. Conclusions

The aim of this study is to conduct experimental tests to evaluate the durability of consolidated sandstone with nano composites using accelerated salt weathering test, with the aim of identifying the most effective strengthening material for enhancing the durability of sandstone used in Dendera temple and affected by salts weathering. After subjecting the specimens to 40 cycles of the salt's crystallization test (Na_2SO_4 - NaCl), visual observations indicated that Na_2SO_4 has a greater impact on weathering of the studied sandstone more than NaCl. Additionally, the study of the physical and mechanical properties of the sandstone specimens revealed that the (N.S+P) specimens exhibited significant improvement in physical and mechanical properties compared to the (N.L+P) specimens. Also, showed significant improvement in resistance to salts weathering compared to the (N.L+P) specimens. The treated sandstone with (N.S+P) showed resistance to salts weathering caused by sodium chloride and sodium sulfate due to the effect of SiO_2 nanoparticles enhanced with paraloid B-72, which coated the mineral crystals and prevented sodium chloride crystals from penetrating the quartz crystals, the main component of the sandstone.

The study concluded the paraloid B-72 enhanced with SiO_2 nanoparticles achieved superiority in resisting salt weathering, making it very suitable for strengthening the sandstone used in the Dendera Temple for the following reasons: (1) Nano silica's ability to produce siloxane linkages (Si-O-Si) through hydrolysis, condensation, and polymerization enables it to restore the inter-granular cohesiveness in stone. This process involves reacting with moisture to form hydrolysis, which is then polymerized to form a robust "gel" with properties similar to those of the silicate minerals found naturally in stone. (2) Paraloid B72 is a widely used acrylic resin in stone consolidation, valued for its distinctive mechanical properties and user-friendly nature. It does not cause surface discoloration, and it enhances the water-resistance of stone surfaces, rendering it a reliable and acceptable material for preserving monumental stones.

Future studies could examine the effects of different types and concentrations of Nano materials under different salt types and aging conditions. Also, factors such as consolidation depth and long-term durability could be investigated in detail.

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