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Sustainable Techniques Using Eco-Friendly Materials In The Restoration Of Ancient Egyptian Heritage - A Case Study

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ABSTRACT

This study investigates the application of sustainable, eco-friendly consolidation materials in the restoration of ancient Egyptian limestone, with a focus on the Sphinx Temple at the Giza Necropolis. Given the vulnerability of limestone to environmental degradation, particularly under the arid conditions and urban pollution surrounding the Giza Archaeological Site, the research explores natural materials such as eggshells, seashells, and fired brick powder (Homra)—both in their raw forms and as nanomaterials—as potential alternatives to conventional chemical consolidants.

Experimental procedures involved preparing standardized limestone cubes and treating them with the selected materials. A series of physical and mechanical tests—including bulk density, porosity, water absorption, and compressive strength—were conducted. In addition, Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Analysis (EDX) were used to examine the microstructural integration of the consolidants within the stone matrix.

The results revealed that Nano Eggshell performed most effectively, achieving the highest compressive strength (29.2 MPa), lowest porosity (7.92%), and lowest water absorption (3.32%). SEM analysis confirmed deep and homogeneous penetration of the consolidant into the stone's microstructure, with reduced voids and enhanced cohesion. The material also proved to be non-toxic, compatible with the original substrate, and environmentally safe.

The study concludes that green nanomaterials—particularly Nano Eggshell—offer a promising and sustainable solution for consolidating deteriorated limestone in heritage monuments. Their successful application aligns with current goals for environmentally responsible conservation practices and supports long-term strategies for preserving Egypt's architectural legacy.

KEYWORDS

Sustainable restoration, eco-friendly materials, nanomaterials, limestone conservation, ancient Egyptian heritage, green technologies, Shells, Eggshell, Homra, Sphinx Temple.

INTRODUCTION

The Conservation of ancient Egyptian heritage represents a critical challenge in the field of architectural restoration, particularly amidst escalating environmental pressures and the limitations of conventional restoration materials. Limestone, as one of the most commonly used construction materials in ancient Egypt, is highly susceptible to deterioration caused by weathering, pollution, and salt crystallization, Given that the concept of sustainability is inherently tied to environmental protection, a growing shift has emerged toward the adoption of green restoration materials in the conservation of heritage buildings. This direction now constitutes a vital and forward-looking approach within the broader efforts to preserve historic and archaeological structures in a sustainable and environmentally responsible manner [1].

The need for innovative, environmentally friendly materials suitable for the restoration of historic buildings has recently become the subject of numerous research studies. This study explores the application of sustainable and environmentally friendly materials in the restoration of ancient Egyptian limestone monuments at the Great Sphinx in the Giza Necropolis. It examines the potential of naturally available materials—Eggshells, Shells, and Homra—both in their raw form and as green nanomaterials.

These materials were selected based on their chemical and mineral compatibility with limestone, their environmental sustainability, and their economic feasibility. Laboratory analyses evaluated their effectiveness using a series of physical, chemical, and mechanical tests to assess their performance in terms of compressive strength, porosity reduction, surface cohesion, resistance to environmental degradation, and long-term durability when applied to damaged limestone surfaces.

The results indicate that these green materials, particularly their nanostructures, can enhance the cohesion and protection of historic buildings and stabilize limestone surfaces while reducing environmental impact, offering a promising and environmentally friendly alternative to traditional restoration methods. This case study highlights a practical and applicable model of the potential of green nanomaterials to promote sustainable heritage conservation practices, particularly in archaeologically and climatically sensitive areas such as Egypt.

MATERIALS AND METHODS

The Sphinx Temple at the Giza Necropolis is subject to numerous deterioration factors, making its preservation an urgent and unavoidable necessity, as it represents an integral part of Egypt's rich historical and cultural legacy, Accordingly, the significance of this experimental study lies in its investigation of appropriate restoration techniques and materials, their application methods, and the compatibility of such materials with the original substrate [2], The primary aim of this research is to identify suitable eco-friendly consolidants for the restoration of limestone—the temple's principal construction material—based on the results of comprehensive analytical, physical, and mechanical testing conducted on the temple's building materials.

To ensure the reliability of the findings and applicability of the materials, the study was carried out on experimental samples that closely simulated the original stone materials of the monument,

[1] Andrea Macchia, Loredana Luvidi, Fernanda Prestileo : Green Conservation of Cultural Heritage International Workshop,Rome, Italy, October 27th -28th, 2016, P.3.

[2] Ji& I Burs, Petrkotlik: consolidation of stone by mixture of alkoxy silane and acrylic polymer, studies in conservation vol. 41, No2, 2007, p.109.

This allowed for an accurate assessment of the efficiency and impact of the proposed treatments, thereby supporting the implementation of safe and effective conservation practices.

The experimental methodology involved a comparative evaluation of green restoration materials in their natural form versus their nano-sized equivalents. Uniform limestone blocks were cut into cubes measuring 5 cm × 5 cm × 5 cm for use in the study, Following treatment with the respective materials, all relevant physical and mechanical properties were measured to determine their impact on the stone and to select the most effective formulation for use in the conservation process.

Consolidation Materials

Limestone primarily consists of calcium carbonate (Ca Co3), or a combination of calcium and magnesium carbonates as in dolomite, with minor amounts of other constituents such as iron oxide, silica, and clay [1], The classification of limestone depends largely on its purity [2], particularly the proportion of calcium carbonate it contains. Based on this chemical composition, the selection of eco-friendly green restoration materials was directed toward those that naturally contain calcium carbonate as a primary component, In addition, materials with sources and chemical properties similar to limestone were prioritized to ensure compatibility.

The chosen materials were also assessed for their potential to enhance the structural integrity of limestone, increase its density, and reduce water absorption within its pores. These materials include:

- *Shells*
- *Eggshells*
- *Homra*

The use of these materials aims to protect archaeological buildings and sites in a manner that preserves cultural heritage, minimizes environmental impact, respects historical authenticity, and ensures long-term sustainability. The intrinsic properties of these green materials make them particularly suitable for sustainable conservation of historical sites, while maintaining the integrity of the original substrate.

Evaluation of Eco-Friendly Green Consolidation Materials

Mineral Composition:

- ***Shells***

Most shells are composed of three distinct layers: the prismatic layer (outer layer), the lamellar layer (middle layer), and the nacreous layer (inner layer), Each of these layers contains a specific crystalline form of calcium carbonate. In most shells, the minerals present within these structural layers are responsible for imparting strength and durability to the shell [3].

- ***Eggshell***

The term "Eggshell" refers to two primary components:

The hard outer shell, which is rich in calcium along with other minor constituents.

The soft, transparent membrane, located between the outer shell and the egg white, which is composed primarily of proteins and collagen.

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1 Haydar, Farouk Abbas. *Construction of Buildings – Civil and Architectural Engineering*. Al-Maaref Establishment for Publishing, 8th ed., Alexandria, 2005, p. 159.

2 *Mehran, Anwar Fouad Suleiman. Completion as a Fundamental Structural Requirement and an Implicit Technical Aspect in the Restoration of Historic Buildings. Master's thesis, Department of Restoration, Faculty of Archaeology, Cairo University, 2003, p. 18.*

3 Jacksonville Shells- August 2017 - www.Jaxshells.Org, 10-1-2023, 1:46 Pm.

Eggshells contain approximately 2.2 grams of calcium in the form of calcium carbonate crystals. Calcium carbonate constitutes about 93% of the dry eggshell, Phosphorus accounts for about 3% of the shell's composition, with magnesium contributing a similar proportion. Additionally, trace amounts of sodium, potassium, zinc, manganese, iron, and copper are also present [1].

- ***Homra***

It is composed of a mixture of lime, alumina clay, sand, iron oxide, and magnesium, with certain components derived from natural soil sources used in its production[2] , It is also considered an eco-friendly material due to its low generation of environmentally harmful residues during application.

Chemical Composition:

- ***Shells***

Calcium Carbonate (Ca Co3**):**Calcium carbonate constitutes approximately 95% to 99% of the total composition of the shell.

Organic Materials: These represent about 1% to 5% of the shell's composition and consist mainly of proteins and complex compounds that function as a binding matrix, linking calcium carbonate crystals together. They contribute to the shell's flexibility and mechanical strength.

Trace Minerals: Shells also contain small amounts of other minerals such as magnesium and iron, which can influence their physical properties[3].

These elements play a role in enhancing the crystalline stability of calcium carbonate, thereby improving the shell's hardness and mechanical performance [4].

- ***Eggshell***

Calcium Carbonate (Ca Co3**):**Eggshells are composed of approximately 90% calcium carbonate, which serves as the primary component responsible for their rigidity and structural strength[5].

Proteins: Eggshells contain a variety of proteins involved in the formation of the shell membranes, most notably albumin and collagen.

Other Mineral Compounds: They also include trace amounts of minerals such as magnesium, potassium, phosphorus, sodium, iron, and zinc.

Organic Compounds: Small quantities of organic compounds, including amino acids, are also present within the eggshell matrix.

- ***Homra***

It is a byproduct obtained by crushing bricks or terracotta that have undergone firing at high temperatures, It is commonly used in various applications such as restoration and insulation.

Silicon Dioxide (SiO_2): Contributes to the material's strength and enhances its resistance to heat.

Calcium Oxide (CaO): Considered a fundamental component, it supports structural stability and contributes to overall hardness.

Aluminum Oxide (Al_2O_3): Typically makes up 10% to 20% of the fired brick composition and improves resistance to erosion and thermal stress.

Iron Oxide (Fe_2O_3): Present in concentrations ranging from 5% to 10%, it enhances the brick's hardness and durability.

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1 Gary Butcher and Richard Miles:"Concepts of Eggshell Quality", University of Florida, Institute of Food and Agricultural Sciences, 2018.

2 Aac Blocks Vs Red Bricks: How To Make The Right Choice - 2018,(Www.Gharpedia.Org) 11-1-2023, 8:22 Pm.

3 Pearlmutter D, Theochari D, Nehls T, et al.: Enhancing the circular economy with nature-based solutions in the built urban environment: green building materials, systems and sites. Blue-Green Systems 2020; 2 (1):PP. 46–72.

4 Yonatan Ayele Abera : Sustainable building materials: A comprehensive study on eco-friendly alternatives for construction, Composites and Advanced Materials ,Volume 33, 2024, PP. 1–17.

5 Michele Baglioni, Giovanna Poggi, David Chelazzi and Piero Baglioni : Advanced Materials in Cultural Heritage Conservation, Molecules, Basel, Switzerland, 2021,PP. 26-39.

Other Components: May also contain minor quantities of potassium oxide (K_2O), sodium oxide (Na_2O), titanium, and magnesium, which further improve properties such as mechanical strength and absorbency[1].

Preparation and Processing of Samples and Materials

Figure 1 : Illustrates the preparation and processing of experimental limestone cubes prior to the consolidation treatment

- Limestone blocks were cut into regular cubic shapes with dimensions of 5 × 5 × 5 cm, with three stone samples allocated for each consolidant material, as shown in Figure (1).
- The study adopted a comparative approach to evaluate the performance of green restoration materials in consolidating limestone, testing each material in both its natural form and its nano-sized version. This comparison was based on the understanding that the behavior of particulate materials varies significantly depending on particle size, morphology, and internal distribution. The effectiveness and penetration capacity of consolidants increase substantially when particle sizes are reduced to below 100 nanometers. Accordingly, top-down synthesis techniques were employed to reduce the particle size of the three selected materials to the desired nano scale.
- The consolidant materials were prepared in liquid form at a concentration of 3% for each material. The nano-sized versions were standardized at approximately **50 nanometers**, in accordance with nanotechnology material specifications.
- The consolidation treatment was applied using the immersion method, where the stone cubes were fully submerged in individual glass beakers containing each consolidant.
- The treated samples were then left to dry under ambient conditions—at a temperature of 25°C and relative humidity of approximately 31%—for a period of 21 days. The immersion process and sample treatment procedure, conducted on 29 January 2023.

RESULTS

Study of the Physical Properties of Experimental Limestone Samples

The measurements of these properties were conducted at temperatures ranging between 17°C and 19°C, with relative humidity levels ranging from 34% to 38%, during February 2023. This took place approximately 21 days after the drying of the samples, ensuring the complete polymerization process between the consolidant materials and the limestone specimens, Table (1) presents the values obtained following the consolidation of the samples.

[1] Marta Gueidão; Eduarda Vieira; Rui Bordalo; Patrícia Moreira: Available green conservation methodologies for the cleaning of cultural heritage: an overview, Estudos de Conservação e Restauro, January 2021, PP. 22-44.

Table 1 : The Results Of The Physical Properties Of The Limestone Samples After The Application Of The Consolidation Materials

No.	Consolidation Material	Sample Code	Bulk Density (g/cm3)	Water Absorption (%)	Porosity (%)
1	Standard sample	M	2.15	6.86	14.72
2	Shells	S	2.28	4.80	10.96
3	Eggshell	E	2.26	4.78	10.8
4	Homra	H	2.19	5.09	11.2
5	Nano Shells	NS	2.32	3.72	8.64
6	Nano Eggshell	NE	2.38	3.32	7.92
7	Nano Homra	NH	2.29	3.97	9.12

The study of the physical properties of the limestone samples after the application of the consolidation materials revealed the following results:

- Samples treated by immersion in Shell-based material recorded a bulk density of 2.28 g/cm³, porosity of 10.96%, and a water absorption rate of approximately 4.80%.
- For samples treated with Eggshell-based material, the bulk density was 2.26 g/cm³, porosity was 10.8%, and water absorption was 4.78%.
- In contrast, samples consolidated using fired brick powder (Homra) showed a bulk density of 2.19 g/cm³, porosity of 11.2%, and water absorption of 5.09%.

Upon treatment with green nanomaterials, the results varied more significantly:

- Samples immersed in nano-shell material recorded a bulk density of 2.32 g/cm³, porosity of 8.64%, and water absorption of 3.72%.
- When consolidated with nano-eggshell material, the bulk density reached 2.38 g/cm³, porosity was 7.92%, and water absorption was 3.32%.
- Finally, samples treated with nano-Homra material showed a bulk density of 2.29 g/cm³, porosity of 9.12%, and water absorption of 3.97%.

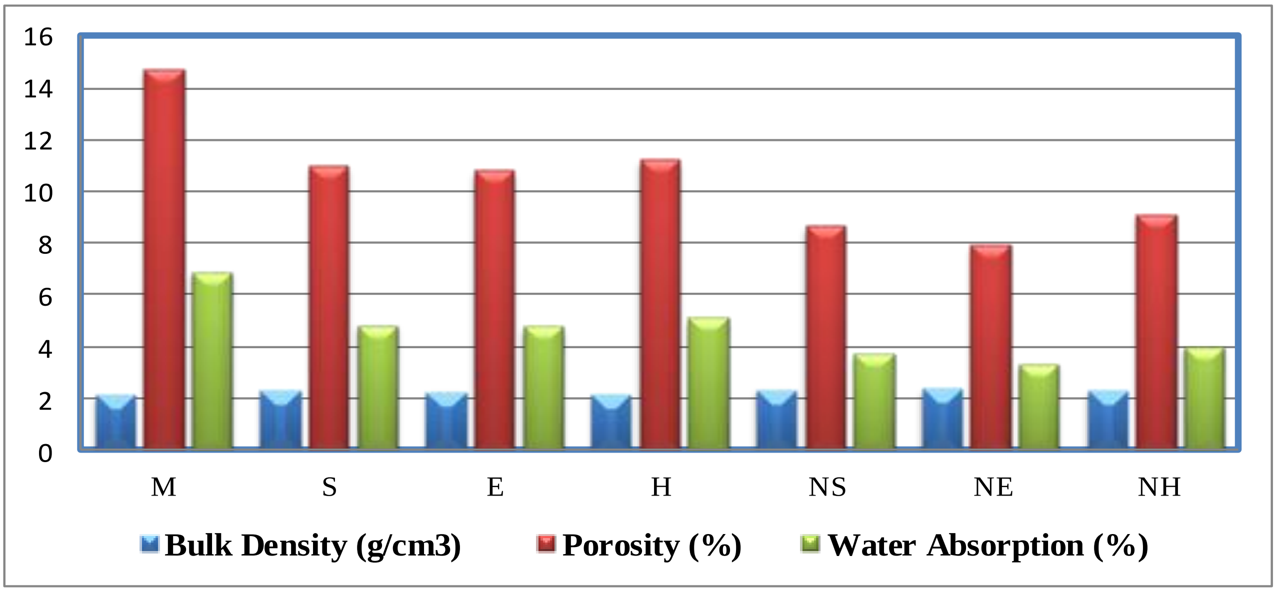
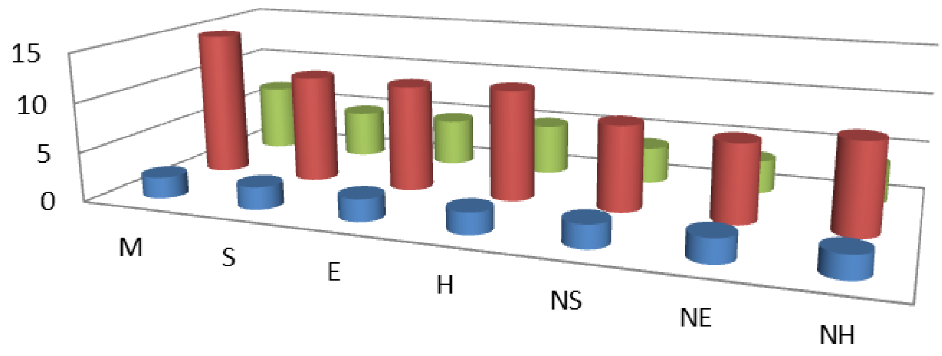


Figure 2 : Illustrates A Comparative Overview Of The Average Values Of The Physical Properties Of The Limestone Samples After Consolidation



	M	S	E	H	NS	NE	NH
درجة الكثافة جم/ سم3	2.15	2.28	2.26	2.19	2.32	2.38	2.29
نسبة المسامية %	14.72	10.96	10.8	11.2	8.64	7.92	9.12
نسبة امتصاص الماء %	6.86	4.8	4.78	5.09	3.72	3.32	3.97

Figure 3 : Illustrates Levels Of The Physical Properties Of Limestone Samples After Consolidation

Study of the Mechanical Properties of Experimental Limestone Samples

The compressive strength of the experimental limestone sample cubes was measured in order to evaluate their mechanical performance under various conditions. These properties were assessed approximately 21 days after complete drying of the samples, ensuring the full completion of the polymerization process between the consolidant materials and the limestone. The results are presented in Table (2).

Table 2 : The Results Of the results of the mechanical properties of the experimental limestone samples after consolidation

No.	Consolidation Material	Sample Code	Compressive Strength (MPA)
1	Standard sample	M	16.5
2	Shells	S	21.6
3	Eggshell	E	23.8
4	Homra	H	19.8
5	Nano Shells	NS	27.4
6	Nano Eggshell	NE	29.2
7	Nano Homra	NH	25.1

The mechanical property analysis of the experimental limestone samples revealed that the average compressive strength varied depending on the type of consolidation material used.

- Samples consolidated with shell-based material exhibited a compressive strength of 21.6 MPa, while those treated with eggshell-based material achieved a higher strength of 23.8 MPa. In contrast, samples treated with fired brick powder (Homra) showed a lower compressive strength of 19.8 MPA.
- However, when green nanomaterials were applied for consolidation, a notable improvement in compressive strength was observed. Samples treated with nano-shell material reached a compressive strength of 27.4 MPa, and the strength increased further with nano-eggshell material, reaching 29.2 MPa. Samples consolidated with nano-Homra exhibited a compressive strength of 25.1 MPA.

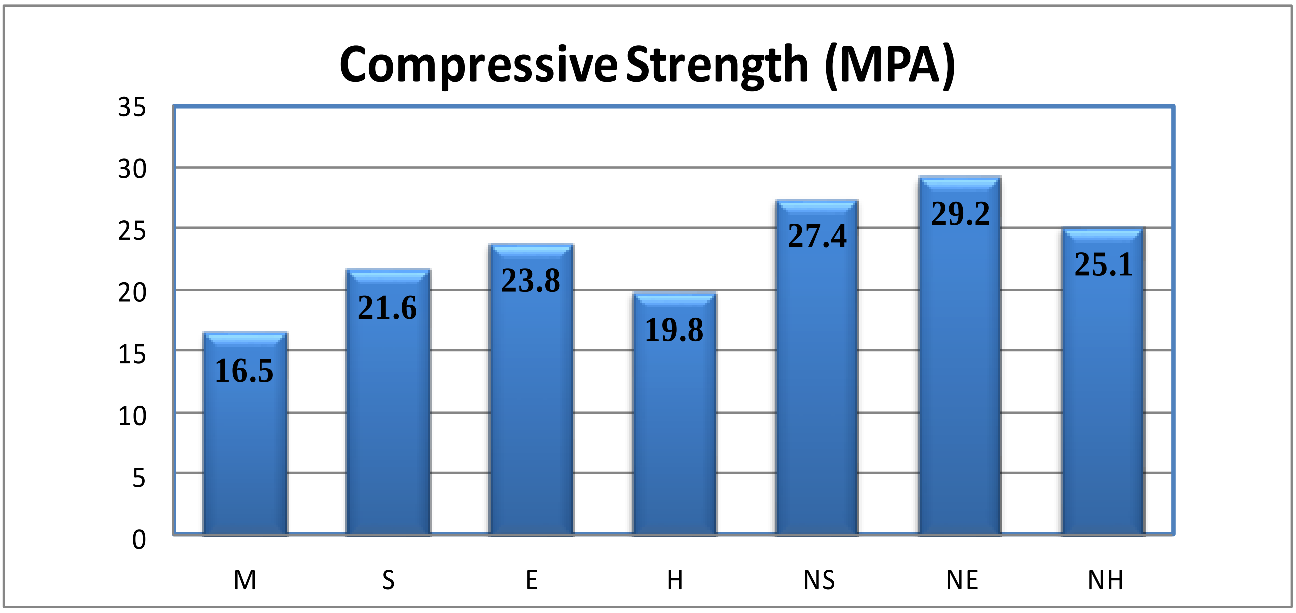


Figure 4 : Illustrates a comparison of the average compressive strength of limestone samples after the application of different consolidation materials

- Examination of the Experimental Limestone Samples Using Scanning Electron Microscopy (SEM)

The internal microstructure of these samples was examined and analyzed using Scanning Electron Microscopy (SEM) to assess the effectiveness and compatibility of the applied materials and to identify the most suitable one for potential future use in the restoration of the walls of the Sphinx Temple, as shown in Figure 5.

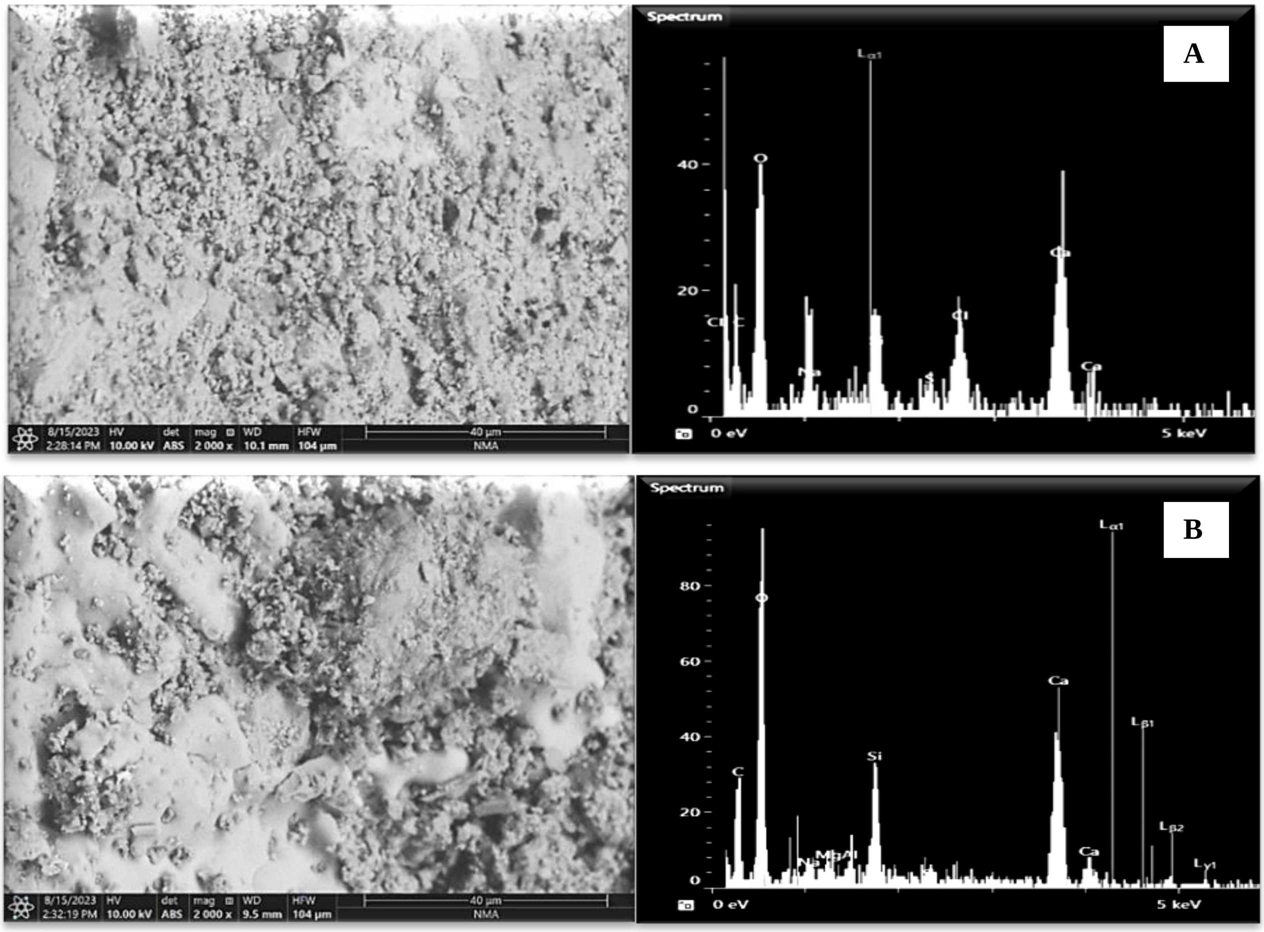


Figure 5 **:** Illustrates (A) the SEM examination and analysis of sample consolidated with Nano Eggshell at a magnification of 2000×. The elemental analysis using the EDX unit indicates an increased concentration of calcium carbonate, along with the presence of silica, alumina, and sulfur. The microstructural observation reveals that the consolidant material has crystallized uniformly between the mineral grains, resulting in reduced voids and decreased porosity within the sample.

And (B) The sample consolidated with Nano Shell, revealed—through elemental analysis using the EDX unit—an increased concentration of calcium carbonate, along with the presence of silica, alumina, sulfur, and magnesium. The microstructural analysis shows that the consolidant has penetrated and distributed uniformly throughout the internal matrix of the sample.

CONCLUSIONS

Upon completion of the comprehensive experimental study on the physical and mechanical properties of the limestone samples, as well as the microstructural analysis using Scanning Electron Microscopy (SEM) before and after the application of all consolidation materials—both in their natural green form and as green nanomaterials—it becomes evident that the most effective and appropriate material for application in the restoration of the Sphinx Temple at the Giza Pyramids Necropolis is the limestone sample consolidated with Nano Eggshell.

The sample consolidated with Nano Eggshell exhibited a bulk density of 2.38 g/cm³, a porosity of 7.92%, and a water absorption rate of 3.32%. Among all the consolidation materials tested, this sample recorded the highest compressive strength, reaching 29.2 MPa. Microscopic analysis further revealed that the internal mineral grains of the limestone appeared as though integrated within a unified matrix with the consolidant. The Nano Eggshell material had clearly penetrated between the inner grains, significantly reducing internal voids and forming a cohesive surface with the capacity to resist various deterioration factors affecting limestone. These findings were supported by the values of both the physical and mechanical properties, which demonstrated high resistance to compressive stresses, an increase in density, and a notable decrease in both porosity and water absorption. These effects are attributed to the minimal void spaces between grains and the crystallization of the consolidant within the microstructure of the stone.

The samples consolidated with this material are distinguished, first and foremost, by the fact that it is a natural, eco-friendly nanomaterial that poses no harm to the environment, the monument, or the conservator during application. Moreover, experimental testing clearly demonstrated its strong resistance to deterioration factors, weathering, and various environmental changes affecting the Giza Necropolis.

The use of green restoration materials represents one of the modern approaches in the field of heritage conservation and restoration. These materials contribute to reducing the reliance on chemical substances in restoration processes and promote the shift toward environmentally friendly alternatives. This aligns with key principles of sustainable development and supports the preservation of archaeological temples.

It is recommended to use natural materials rich in calcium carbonate, such as seashells, eggshells, and fired brick powder (Homra), for the consolidation of limestone and lime-based mortars, particularly in their nano-sized forms, as they have demonstrated both efficacy and sustainability in strengthening the materials while preserving the environment.

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