Comparison between Nanolime and Plexisol P550 as Two Consolidants for the Preservation of Humidity Saturated Monumental Limestone

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[Abstract]

The tomb of "Senusret-Ankh" in Lisht, which is considered to be one of the tombs that was built from limestone, was found next to the pyramid of the Senusret I in 1933. The limestone of the tomb is exposed to humidity that may reach 90% in some cases, leading to its damage and degradation. Two consolidants, nanolime and Plexisol P550, were carefully chosen to reinforce the humidity saturated limestone of the tomb. Three standard limestone samples coded A1, B1, and C1 were collected to investigate their mineralogical composition, textural, physical, and also mechanical properties. The samples were subject to three time intervals of humidity acceleration, ranging from one month to three months. The physical and mechanical properties were also measured after three months of humidity acceleration and after consolidation of the samples using nanolime and Plexisol P550. The obtained results are more promising for nanolime than for Plexisol P550 when both are applied to humidity saturated limestone such as that of the "Senusret-Ankh" tomb.

1 Introduction

Lisht was known as "Itj-Tawy" in the ancient Egyptian language, which means controlling on both upper and lower lands (Hayes 1953). The tomb of "Senusret-Ankh" in Lisht is considered to be one of the tombs that was built from limestone. This tomb was found next to the pyramid of the Senusret I in 1933 (Breasted and Debevoise 1934), as shown in Fig. 1. The tomb includes pyramid texts, Fig. 2, which are a collection of ancient Egyptian religious texts dating back to the Old Kingdom. The

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aim of the texts was to protect the owner of the tomb and also to revive his body after death and help him to reach paradise in the afterlife; they are also used to seek the help of the gods (Richard 2003). Limestone is considered to be one of the stones that was widely used in constructions throughout the Pharaonic age. It was used in the construction of the pyramids, temples, tombs, and burial chambers. Humidity in the tomb, the subject of this study, can reach 90%. This is evident from the humidity existing on the walls, Fig. 3, so, the humidity test system (device) that was used to measure the percentage humidity inside the tomb. It is necessary to carefully select consolidants to protect the walls of the tomb from the effects of humidity, even high humidity. Therefore, Nanolime and Plexisol P550 consolidants were used to reinforce the humidity saturated limestone of Senusret-Ankh.

Fig. 1 Panoramic view of the tomb of Senusert-Ankh relative to the pyramid of Senusret I

Fig. 2 Close-up view of pyramid text on the wall of the tomb

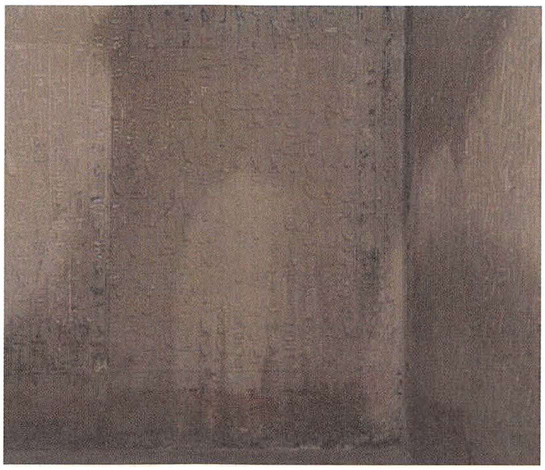

Fig. 3 The presence of humidity and its effect on the north wall

2 Methods and Materials

2.1 Materials

In the recent research standard limestone samples were collected from inside the tomb as hard, white-to-creamy crushed limestone free from any texts and pigments. Three standard rock samples coded A1, B1 and C1 were collected to investigate their mineralogical composition, textural, physical, and also mechanical properties. The effect of humidity, quantified by the percentage humidity before and after treatment by two consolidant materials, nanolime and Plexisol P550, was also investigated. These standard samples were prepared in different shapes and dimensions, as required by the previous diverse tests.

2.2 Nanolime

Nanolime is made up of very fine particles of calcium hydroxide suspended in an organic solvent, usually alcohol. The average diameter of the particles is 150 nm, with a range of 50–300 nm. The smaller particle size of nanolime compared with traditional lime has the advantage of realizing deeper penetration into pores, and the higher surface area/volume ratio permits greater reactivity. The consolidation of carbonate rocks such as limestone by nanolime is based on the conversion of calcium hydroxide carbonates to calcium carbonate through the following reaction:

$$\underset{\text{(lime)}}{Ca(OH)_2} + \underset{\text{carbonic acid}}{(H_2O + CO_2)} \Longrightarrow \underset{\text{calcium carbonate}}{CaCO_3} + \underset{\text{water}}{2\,H_2O}$$

Finally, nanolime can be used for the consolidation of archeological materials and for repairing lost binder or matrix in natural stone and plasters, increasing their strength and integrity.

2.3 Plexisol P550

Plexisol P550 is a material made of pure acrylic resins. It is known to be lightweight and resistant to imprescriptible and fungi, it comprises the derivative butyl, which allows it to dissolve in aliphatic hydrocarbon solvents, and it is used to strengthen archeological materials, including stone. Its glass transition temperature, T_g, is 34 °C (Sinopia 2007), and it is soluble in organic solvents. Trichloroethylene is a colorless liquid. It is used for metal cleaning and as a lubricant (Foxall 2008), and its composition is C_2HCl_3. Its molecular weight is 131. It can be used at a temperature of 25 ° C (Crse 2012).

3 Methodology

To achieve the aim of this study, standard limestone was characterized using various techniques. First, the mineralogical composition was determined using a transmitting polarizing microscope (Olympus BX50, Japan) and X-ray diffraction (X-ray model X′Pert ProPhillps MPD PW 3050/60 X-ray diffractometer). Transmission electron microscopy (TEM) with a JEOL JEM-1230, model Oregon (Japan), at 80 kV was used to investigate the size of the nanolime particles.

Moreover, the physico-mechanical properties (bulk density, water absorption, apparent porosity, and compressive strength) were measured for both standard samples and samples treated with nanolime or Plexisol P550, which were based on the following international test methods and standards: bulk density and apparent porosity followed ASTM C-20, water absorption followed ASTM C-97, and compressive strength followed ASTM C-170.

Artificially accelerated humidity tests were conducted for both standard and treated samples in the same manner. Cubic limestone samples measuring 3 cm × 3 cm × 3 cm were placed in a box made of polycarbonate with dimensions of 70 cm width, 50 cm height, and 60 cm depth containing a container filled with water to produce a humidity inside the box of about 95%, thus simulating the high humidity environment of tomb (Fig. 4). Samples were subjected to this test for different periods of time ranging from one month to three months. The physical and mechanical properties of the studied samples were measured after each period of immersion and the average properties were compared with the average properties of the standards as a measure for following the effect of humidity on the studied samples during each period of time.

Fig. 4 Photograph showing that the percentage humidity in the test system was 90%

4 Consolidation

The consolidation by both nanolime and Plexisol P550 was applied to the studied limestone in the same way by the following procedure. On the first day, the limestone subjected to 3 months humidity acceleration was consolidated by brushing all of its sides (Fig. 5). It was then left for one hour in an airtight polyethylene box. This brushing process was repeated again in the same way two times with time intervals of one hour between each application. Finally, the samples were left inside a sealed box for two weeks. After consolidation, nearly complete cubes of consolidated limestone were subjected to physical and mechanical property measurements to compare the results before and after consolidation, as well as to compare the two consolidants used.

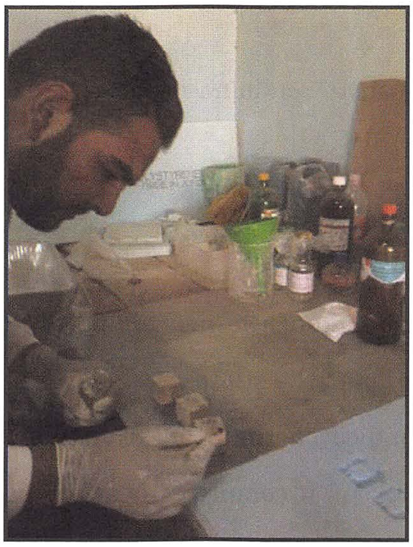

Fig. 5 The consolidation of limestone by brushing

5 Results and Discussion

5.1 XRD

The representative standard limestone samples were mineralogically investigated using X-ray diffraction. The results revealed that the studied limestone essentially comprises calcite, as this carbonate mineral can be detected by its main peak at 2θ = 29.45, and quartz was present as a minor non-carbonate constituent of the studied sample, as show in Fig. 6. Quartz can be detected in XRD diffractograms by its main peak at 2θ = 26.65. Based on previous obtained results (XRD) the studied limestone can be classified as high-calcium limestone, as described in (Carr et al., 1994).

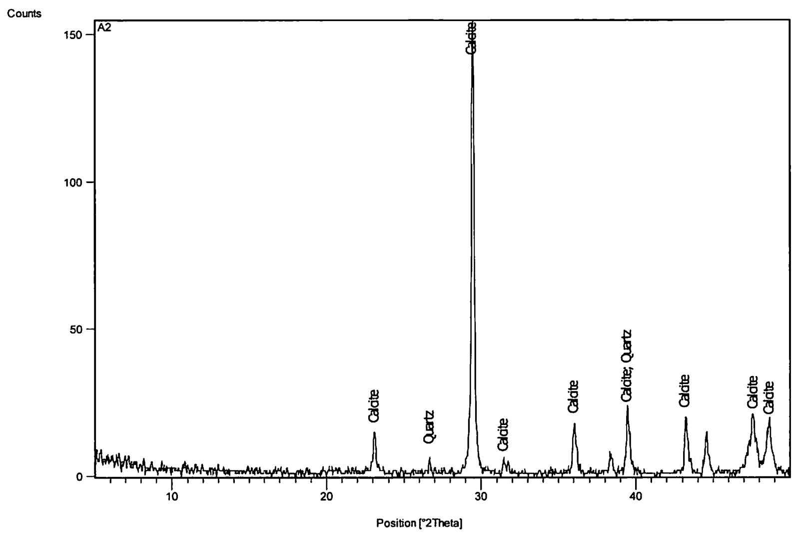

Fig. 6 Representative X-ray diffractogram of the studied samples

5.2 Petrographical Examination

Petrographical examination is one of the most important techniques used to investigate the grain size, shape, and textural relation of the studied standard limestone sample before consolidation. The results of the investigation indicated that the studied limestone was *Packstone microfacies* (Kendall, 2005 after Dunhum, 1962). As it comprises over 50% allochems (interaclast and bioclasts) grains such as foraminifera ranging in size from microsparitic to sparitic (Fig. 7), i.e., from 4 μm to 15 μm and more than 15 μm, respectively. These grains embedded in a micritic matrix represent over 2/3 of these facies with less sparry calcite cement (Fig. 8, so they can be classified as *Packed biomicrite* facies based on (Kendall, 2005 after Folk, 1959).

5.3 Transmission Electron Microscop

Transmission electron microscope (TEM) was used to characterize the studied nanolime in more detail (Fig. 9). Aggregates of nanolime particles in the size range 150–350 nm with a mean size of 250 nm were observed. Most of the nanoparticle agglomerates comprised hexagonal crystals with regular edges.

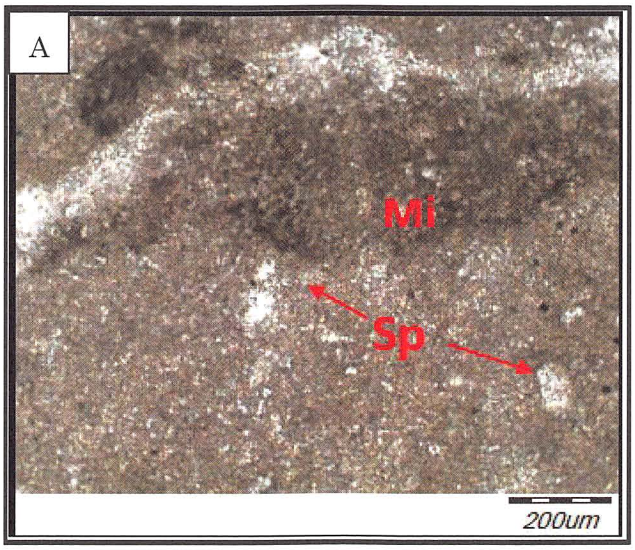

Fig. 7 Photomicrograph of the studied limestone

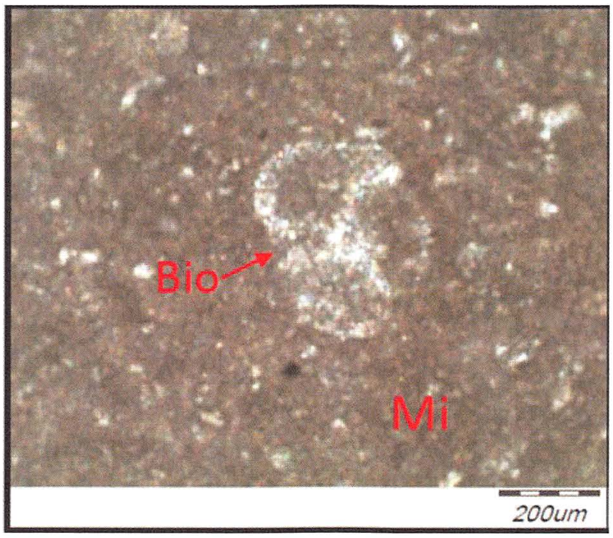

Fig. 8 Photomicrograph of the studied limestone
Bio:Bioclasts; Mi:Micrite; Sp:Sparite

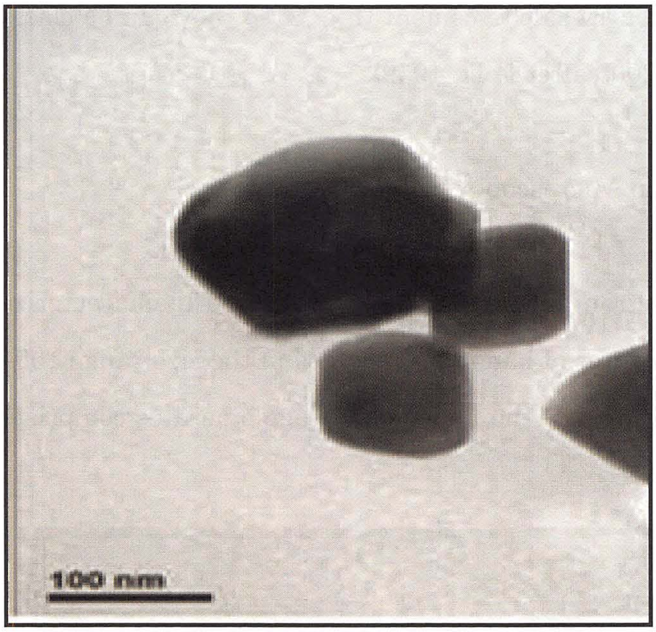

Fig. 9 TEM micrograph of nanolime particle agglomerates

5.4 Physico-Mechanical Properties

The averages of all the measured physico-mechanical properties are given in Table. 1 and plotted graphically in Figs. 10, 11, 12, and 13. Based on the obtained results it can be concluded that:

- The average bulk density (Fig. 11) is 2.3 gm/cm^3 for both standard and accelerated humidity samples. Physically, this means that this limestone is classified as medium-dense limestone according to (ASTM C-568, 2000).
- Both the water absorption and apparent porosity percentages gradually increase from A1 to A4. The average water absorption of A1 is 7.0% and finally reaches 12.5% for A4 (Fig. 12). On the other hand, the average of the apparent porosity also increased from 16.1 for A1 to 27.5% for A4 (Fig. 10).
- The average values of the compressive strength decreased for the standard samples from 190 kg/cm^2 for A1 to 111.8 kg/cm^2 for A4 (Fig. 13).

Table. 1 Average values of selected physico-mechanical properties for standard and humidity saturated limestone samples at different interval times

No.	Bulk density (gm/cm^3)	water absorption (%)	Apparent porosity(%)	Compressive strength (kg/cm^2)
A1	2.3	7.0	16.1	190.5
A2	2.3	9.7	22.2	179.3
A3	2.3	10.6	23.9	119.6
A4	2.3	12.5	27.5	111.8

A1: Standard sample
A2: After one month of humidity acceleration
A3: After two months of humidity acceleration
A4: After three months of humidity acceleration

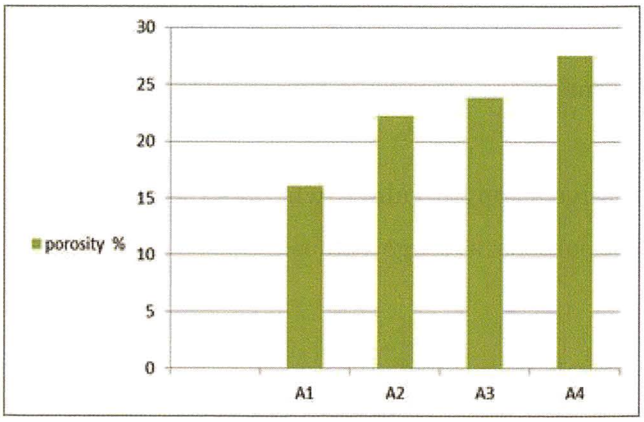

Fig. 10 The variation in average apparent porosity between standard and humidity accelerated samples

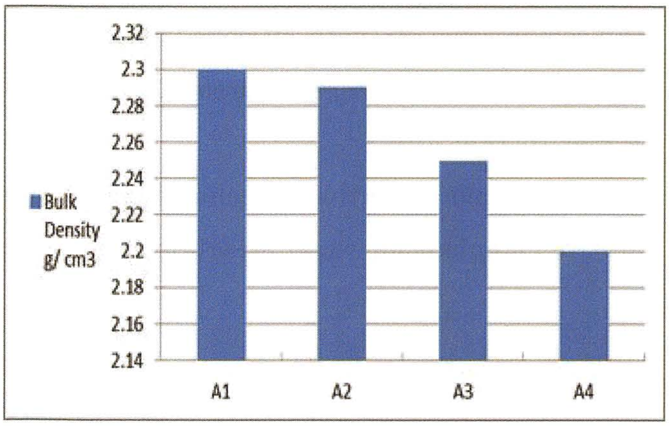

Fig. 11 The variation in average bulk density between standard and humidity accelerated samples

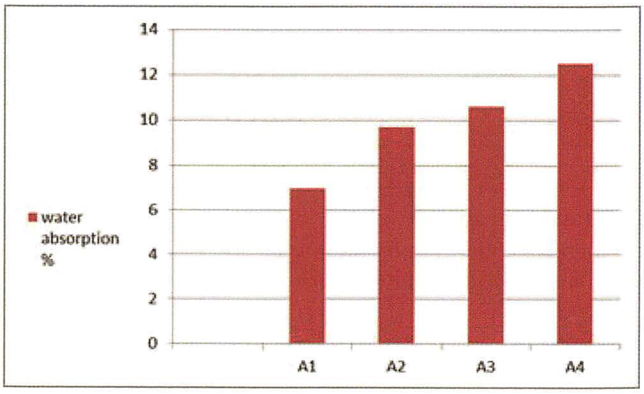

Fig. 12 The variation in the average water absorption between standard and humidity accelerated samples

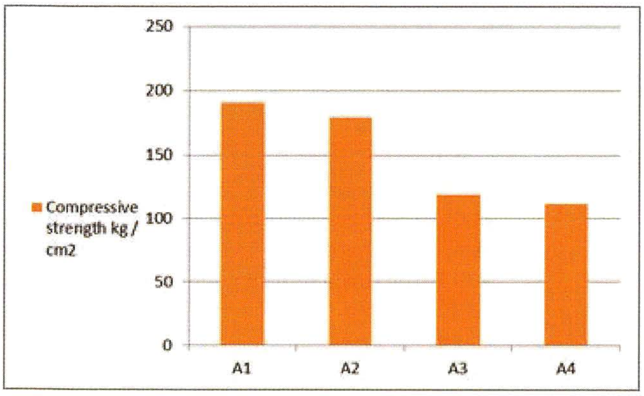

Fig. 13 The variation in the average compressive strength between standard and humidity accelerated samples

5. 5 After Consolidation by Nanolime and Plexisol

The same physico-mechanical properties were measured and averaged again after consolidation by each consolidant, considering A4 as the standard sample. The obtained results are given in Table. 2 and plotted graphically in Figs. 14 and 15.

- The average value of bulk density is approximately constant and does not show any enhancement after consolidation for either nanolime or Plexisol.
- Both the average values of water absorption and apparent porosity show an enhancement after consolidation by nanolime and plexsiol. Moreover, plexsiol is more effective for this hygroscopic properties according to Table. 2, where it is shown to reduce the water absorption average value from 12.5% to 1.2% and the apparent porosity from 28.8% to 2.6%. On the other hand, nanolime consolidation is less effective as it reduces the water absorption average value from 12.5% to 5% and the apparent porosity from 28.8% to 11.5% (Fig. 14).
- The compressive strength average values are enhanced with both nanolime and Plexisol, as the compressive strength increased from 111.8 to 249.8 kg/cm^2 in the case of nanolime and to 169.1 kg/cm^2 for Plexisol (Fig. 15).
- Nanolime is more effective for enhancing the compressive strength values, whereas Plexisol is more effective for enhancing water absorption and apparent porosity average values.

Table. 2 Variation in average values of selected physico-mechanical properties between standard samples and samples consolidated by nanolime or Plexisol

No.	Bulk density (g/cm^3)	water absorption (%)	Apparent porosity(%)	Compressive strength (kg/cm^2)
A4	2.3	12.5	28.8	111.8
A5	2.3	5	11.5	249.8
A6	2.2	1.2	2.6	169.1

A4: After three months of humidity acceleration (standard sample)
A5: After three months of humidity acceleration then consolidation by nanolime
A6: After three months of humidity acceleration then consolidation by Plexisol P550

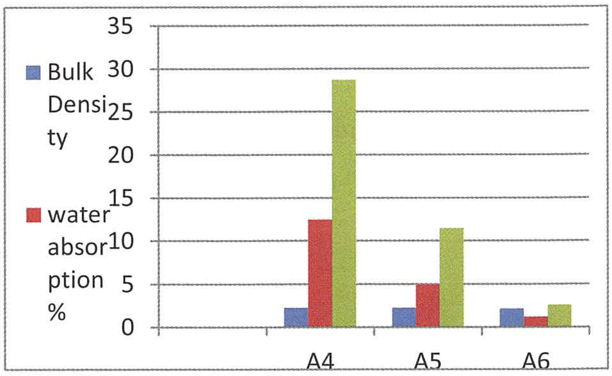

Fig. 14 Variation in different measured physical average values after consolidation by nanolime and Plexisol

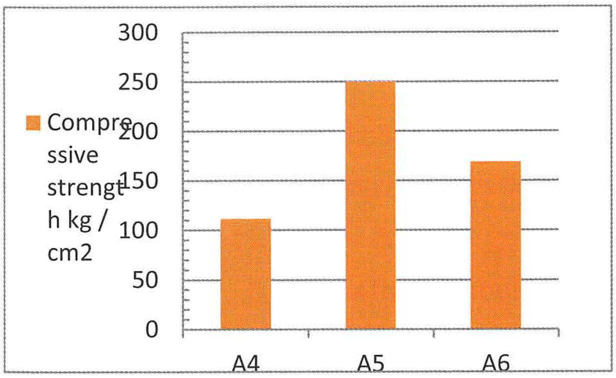

Fig. 15 Comparison of the enhancement in average compressive strength values between nanolime and Plexisol

6 Discussion

The variation in the mechanism of consolidation between nanolime and Plexisol leads to variation in the affected physico-mechanical properties and, ultimately, their compatibility with humidity saturated limestone. As consolidation by nanolime depended mainly on its deep penetration through the pores and formation of $CaCo_3$, acting as cement between the original grains, it leads to a greater increase in the average compressive strength values than Plexisol. On the other hand, Plexisol leads to only surficial consolidation, which results in the formation of a thin-film coating surrounding the humidity saturated limestone and, consequently, decreases or prevents the entrance of water through the limestone pores, thus decreasing the average values of both water absorption and apparent porosity.

7 Summary and Conclusions

-The limestone of "Senusret-Ankh" tomb is exposed to humidity that may reach 90% in some cases, leading to its damage and degradation.

-Two consolidants, nanolime and Plexisol P550, were carefully chosen to reinforce the humidity saturated limestone of the tomb.

-Mineralogically, the tomb limestone is classified as high-calcium limestone.

-Based on its bulk density, the tomb limestone is classified as medium-density limestone.

- Nanolime enhanced the average compressive strength more than Plexisol.

-The most promising results were obtained for nanolime consolidants.

8 Recommendation

It is recommended that humidity saturated limestone be consolidated with nanolime as it is more effective and compatible with the limestone of the "Senusret-Ankh" tomb than Plexisol.

Acknowledgements

Thanks to Mr. Mustafa Ahmed, Director of Giza Restoration.
Thanks to Mr. Ashraf Youssef, Director of Saqqara Restoration.
Thanks to Mr. Maged Saleh, Conservator in the Lisht Area who has helped me greatly.
Thanks to Prof. Hiroshi Suita, Director of the Center for the Global Study of Cultural Heritage and Culture.

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