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GEOMECHANICAL INVESTIGATIONS FOR ARCHITECTURAL HERITAGE PRESERVATION. THE HABIB SAKAKINI PALACE IN CAIRO, EGYPT

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Abstract

The understanding of the geotechnical problems and failure mechanisms of stone structures of Sakakini palace (1897 AC) entails a comprehensive study on the mechanical behavior of the stones and other construction materials. In addition to micro analysis, geological and geomorphologic interests, several investigations on stone deterioration and engineering geology were performed. First phase included more advanced techniques, which provided additional information on particular aspects of site deterioration and it included laser analysis (*LIBS*)*, electron probe micro analysis, micro XRD and XRF analyses, scanning electron microscope analysis coupled with EDX probing, transmission electron microscopy and grain size distribution analysis, permeability and pore size distribution of stone, mortars, core binders and other construction materials. Second phase included the determination of mechanical properties of building stones, such as compressive strength, modulus of elasticity, tensile strength, and shear strength. To obtain reliable values for these properties, a suitable number of samples should be extracted, prepared for testing, and properly tested. The test results are then analyzed to establish the investigated stone properties. The testing program includes extracting seven cylindrical cores from the basement stone walls of Sakakini's mansion in down town Cairo. The cores are extracted using rotary cylindrical diamond blade coring machine. The top and bottom surfaces of every core were prepared to be flat circular surfaces perpendicular to the vertical axis of the core. Because the palace is functioning as a museum/ is a museum and is also an attractive place for the tourists, the core sampling could be carried out only at a limited number of locations under official permission. For the purpose, cylindrical specimens with a diameter of 42-44mm and height of 90-100mm, prepared by the use of a core drilling machine and some collected blocks from the archaeological site under investigation were taken to determine the bulk structure, physical, short and long-term mechanical properties of the stone and other construction materials in the laboratory. A number of specimens prepared from these blocks were employed for testing. Furthermore, limitation due to the number of blocks was overcome by the determination of the in situ characteristics of the stones by Schmidt hammer tests, geo-tomographic investigations and rock mass classification on some stone rock structures where testing has been permitted. The objectives of the study are to provide a characterization of micro structures and the mechanical properties of the stones of Sakakini's Mansion; to describe the required testing plan and results of the basic mechanical properties of the building stones. The following sections provide detailed descriptions of the steps taken to achieve the objectives of the study. The purpose of the present research is to provide recommendations regarding the strengthening and the safety of architectural heritage under long and short-term loading. For this purpose, a set of experimental tests and of advanced numerical analyses are to be carried out.*

Keywords: *Architectural heritage; Habib Sakakini palace; geotechnical; mechanical properties; stone deterioration; LIBS.*

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Introduction

The site of Habib Sakakini's palace (Fig. 1) is considered to be one of the most important sites) that have drawn the attention of a lot of historians, especially at the Mamluk's and Ottoman's. In the past next to the palace was a water pond which was located at eastern side of Egyptian gulf beside the Sultan Bebris Al-Bondoqdary mosque and the pond was called "Prince Qraja al-Turkumany pond". That pond became important when it was filled down by Habib Sakakini in 1892. On that place he built his famous palace in 1897 AC.

Fig. 1. Sakakini Palace in Cairo, Egypt.

Chalky stones and other kinds of construction materials (which are under investigation) are porous rocks with complex behavior. There can be identified two main deformation mechanisms in these rock types depending on the applied stress conditions: fracture propagation, associated with volumetric dilatation and brittle behavior, which is dominant in compressive stress paths at no or low confining pressure; pore collapse, which dominates at higher stress conditions, producing large contracting plastic deformations.

The high fossils content, due mainly to shells of foraminifers and some mollusks, give rise to structural heterogeneity, which is reflected in the variability of the mechanical properties and in the poor reproducibility of the experimental results [1, 2].

There is no generally accepted theory concerning the strength of the brittle rock based on an examination of the formation process of micro cracks and deformation. Therefore, the key of interest is represented by the initiation and the development of the stress-induced microfractures in the EDZ.

Some of the main concerns regarding the stability of the monumental structures of soft rocks, include the implications of potential ground disturbance by the construction method and the redistribution of in situ stresses. Both of these factors relate to the initiation and propagation of brittle fractures and the extent of the *excavation-disturbed zone* (EDZ), which could adversely affect the stability of the stone structures boundary and could increase the permeability of the near-field host rock. In structural Geology and Tectonics, experimental rock deformation is important in determining the evolution of natural structures and tectonic features.

A considerable effort has been extended towards the understanding of brittle fracture processes and mechanisms. Much of this focus has been extended to laboratory testing and the measurement/quantification of brittle fracture thresholds [3-7]. Of these the crack damage threshold (marked by the onset of dilatation) and taken as the point of reversal in the volumetric strain curve is of specific interest as several studies have associated the threshold with unstable crack propagation in brittle rocks [8]. Unstable crack propagation corresponds to the point where the relationship between the applied stress and the crack growth velocity, take control of the propagation process. Under such conditions crack propagation will continue until failure even if the applied load is stopped and held constant. As such, Martin and Chandler [9] and Read et al [10] have equated the crack damage threshold to the long-term in situ strength of brittle rock, a practice they note that has been similarly adopted in the concrete industry.

Thus, the identification of these processes and their associated mechanisms are of key interest in predicting both the short and long–term strength of soft rock. This research focuses on these processes by presenting the results from several short and long-term laboratory tests.

In general, the propagation of a brittle fracture can be equated with the irreversible destruction of molecular cohesion along the generated fracture path. In this sense, the microfracturing process acts to "damage" the rock material. As the number of propagating fractures multiplies, the damage can be viewed as accumulative and can be correlated to observed decreases in the elastic stiffness and cohesive strength of the material.

In this work, we highlighted some important characteristics of the geotechnical behavior of structured soft rock and showed that these characteristics are quite common in many natural rocks. Based on such concepts, research into soft rock materials has intensified during the last two decades [11-16].

Methodology

The evaluation methodology for the geomechanical characterization of the stone structures included: *Assessment of geological, hydraulic data***:** Lithology, Weathering and Groundwater table; *Assessment of geotechnical data***:** Strength, deformability of geomaterials, possible stability problems, mechanisms, Stress regime, Engineering Rock mass quality classification (RMR, RSR, RQD).

Bulk Structure and Durability Aspects of Stone, Mortars and Core Binders

Various techniques were used to establish the causes of the stone deterioration in Sakakini palace. The first group of techniques was used to establish the site parameters and it included photographic recording, petrographic analysis of the stone type, microclimate data, ground water composition and ultra violet radiation levels.

The second group included advanced techniques, which provided additional information on particular aspects of site deterioration and it included laser analysis (LIBS) [17, 18], micro XRD (Table 1) and XRF analyses (Table 2), Scanning Electron Microscope analysis (SEM) coupled with EDX detector, and grain size distribution analysis of rock samples, permeability and pore size distribution of stone, mortars and core binders.

Results and discussions

Chalky limestone

The limestone can be characterized as medium grained with uniform relative grain size, angular to sub angular grain shape with equidimensional form and rough surface texture. Sound or non weathered pieces of stone can be characterized of medium compactness and durability and the weathered pieces characterized of low compactness and durability. It must be mentioned that the weather variations affected strongly the masonry units, starting from the surface and continuing inward thus loosing the mineral fabric.

The EDX micro analysis indicated that, the elemental arrangement for the chalky limestone samples collected from Sakakini place can be put in a decreasing order according to their concentration as follow: Ca (33.50%), O (29.80%), S (16.94%), K (9.01%), C (6.53%), Fe (1.76%), Si (1.48%), Al (0.55%), Mg (0.44%) (Figs. 2 and 3).

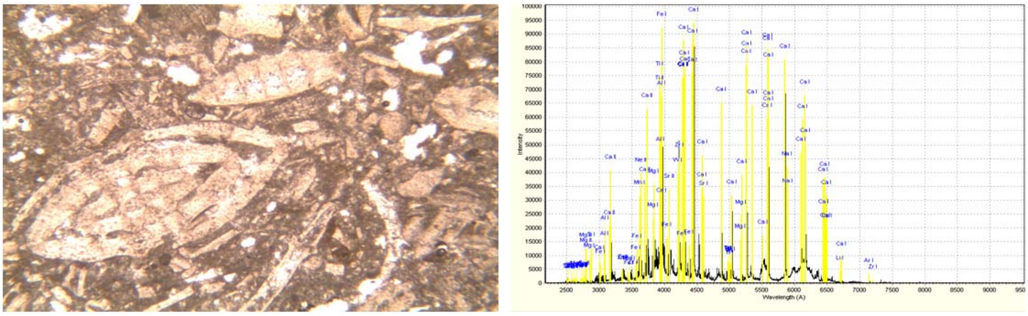

Fig. 2. Thin section and laser analysis (LIBS) results of chalky limestone.

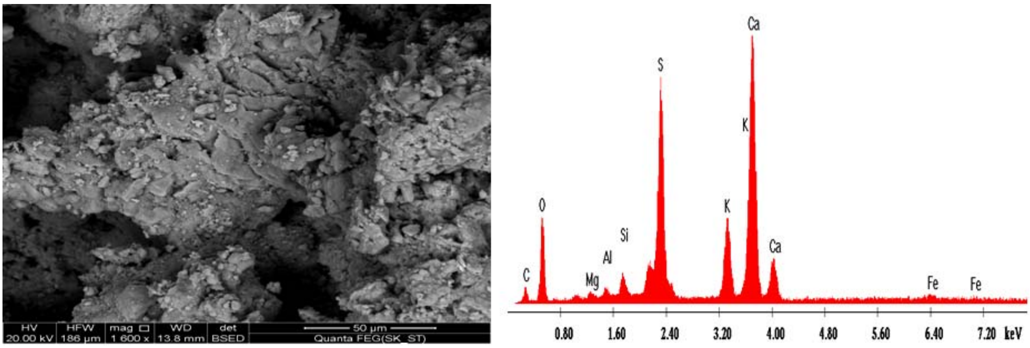

Fig. 3. SEM with EDX analysis results of chalky limestone

Mortars between stone blocks

Mortars between stone blocks are coarse to very fine grained, compact, and poorly sorted. It is composed of quartz as the essential mineral constituents with rare amounts of rock fragments, hornblende, collophane, epidote, gluconite and opaques all cemented by very fine grained calcite (micrite) mixed with traces of iron oxides and clay materials. Quartz occurs as coarse to fine-grains of rounded to subangular outlines, and some quartz grains are polycrystalline. Feldspars and rock fragments are detected in the rock as coarse to medium grains.

The EDX micro analysis indicated that, the elemental arrangement for the Mortars between stone blocks samples collected from Sakakini place can be put in a decreasing order according to their concentration as following: Ca (49.21%), O (32.70%), Si (6.77%), C (5.85%), Fe (2.25%), Al (2.25%), K (0.67%).

Plaster or Render layers

The renders layers are medium to fine-grained, compact. The renders are composed mainly of quartz, Gypsum with rare amounts of feldspars, clay minerals and iron oxides. Quartz occurs as medium to fine-grains of rounded to subangular outlines, and some quartz grains are polycrystalline. The matrix is composed of a mixture of micrite with minor amount of clay minerals and iron oxides.

The grade of disintegration and deterioration usually goes with the salt content, it was also found that pollutants from car traffic, attack mortars as well as chlorines from the ground water, and the lower parts covered for long time with ground also present high percentage in NaCl and NO_3^- and SO_4^{2-} salts.

The EDX micro analysis indicated that, the elemental arrangement for the renders layers samples collected from Sakakini place can be put in a decreasing order according to their concentration as following: O (37.50%), Si (26.60%), C (11.72%), Ca (10.42%), S (9.52%), Mg (1.23%), Na (1.21%), Cl (1.1%), Al (0.71%).

Core binders between leave masonry walls

The core binders between two leaves are coarse to very fine grained compact. It is composed of quartz as the essential mineral constituents-with minor amounts of feldspar and rare amounts of rock, stone and brick fragments, collophane, glauconite and opaques all cemented by very fine grained calcite (micrite) admixed with traces of iron oxides and clay materials. Quartz occurs as coarse to fine-grains of rounded to subangular outlines, and some quartz grains are polycrystalline. Feldspars and rock fragments were detected in the rock as coarse to medium grained.

The grade of disintegration and deterioration usually goes with the salt content. Although the research was not oriented to estimate the degree of deterioration, it was found that pollutants from car traffic, attack mortars as well as chlorines from the ground water. The lower parts covered for long time with ground also present high percentage in NaCl and NO^- and SO_4 salts.

The EDX micro analysis indicated that, the elemental arrangement for the Core binders between leave masonry walls samples collected from Sakakini place can be put in a decreasing order according to their concentration as follow: Ca (39.29%), O (29.44%), Si (17.13%), C (5.17%), Al (4.73%), Fe (3.16%), S (9.52%), Cl (0.58%), Mg (0.49%).

Table 1. XRD analysis Results for stone and other construction materials

Material	Major const.	Minor const.	Trace const.
Chalky Limestone	Calcite	-	Calcite
Mortars between stone locks	Calcite	Calcite	Gypsum
Render or Plaster layers	Quartz, Halite, Gypsum	-	Illite
Core Binders between leave masonry walls	Quartz	Calcite	Calcite

Table 2. XRF analysis Results for stone and other construction materials

Compound	Limestone Masonry units	Mortar Between stone blocks	Renders or plaster layers	Core binders between two leave masonry walls
	%	%	%	%
SiO_2	0.81	63.28	30.18	65.28
TiO_2	0.05	0.25	0.06	0.55
Al_2O_3	1.13	3.90	0.63	7.27
Fe_2O_3	0.17	1.65	0.28	3.48
MnO	0.002	0.02	0.003	0.05
MgO	1.01	1.17	0.90	1.28
CaO	52.50	14.08	10.28	11.13
Na_2O	0.12	0.81	12.01	0.87
K_2O	0.15	0.73	1.94	0.88
P_2O_5	0.10	0.13	0.09	0.19
Cl	0.24	0.65	12.07	0.94
SO_3	0.90	1.85	11.34	1.76
L.O.I.	42.45	10.83	20.1	5.97

L.O.I.: loss-on-ignition

Mechanical testing program

The basic mechanical properties of building stones are compressive strength, modulus of elasticity, tensile strength, and shear strength. To arrive at reliable values for these properties, a suitable number of samples should be extracted, prepared for testing, and properly tested. The test results are then analyzed to establish the investigated stone properties.

The testing program includes the extraction of seven cylindrical cores from the basement stone walls of Sakakini's mansion in down town Cairo (Fig. 4 and 5). The cores are extracted using rotary cylindrical diamond blade coring machine. The top and bottom surfaces of every core were prepared to be flat circular surfaces perpendicular to the vertical axis of the core.

Fig. 4. The Core Samples extraction from the basement of the palace

Fig. 5. Some Core Samples after Preparation for Mechanical Testing

Three cores were equipped with strain gauges to measure the longitudinal strain corresponding to compressive stresses. The results of testing these three cores in compression will be used to determine the stones compressive strength and modulus of elasticity.

Three cores were tested in splitting tension to determine the tensile strength of the stone samples. One core was tested in single shear to determine the stone’s shear strength.

Compressive Strength

Three samples were equipped with 100 mm long electric strain gauges. One strain gauge was fixed to the core parallel to its vertical axis to measure the longitudinal compressive strain corresponding to the applied compressive stress. The vertical compressive stress was increased gradually until failure (Fig. 6). The compressive strength of every core was determined. Table 3 shows the results of the compressive strength of the three cores.

Table 3. Compressive strength test results

No.	Diam. (mm)	Height (mm)	Cross-section Area (mm^2)	Failure Load (kN)	Compressive Strength (MPa)
1	44.7	132	1569.3	16.50	10.5
2	42.7	117	1432.0	14.90	10.4
3	44.1	136	1527.5	16.22	10.6
4	49.1	140	1886.3	17.80	9.44
5	49.1	161	1886.2	22.90	12.14
6	49.1	168	1886.2	13.30	7.05
7	49.1	200	1886.2	15.70	8.32

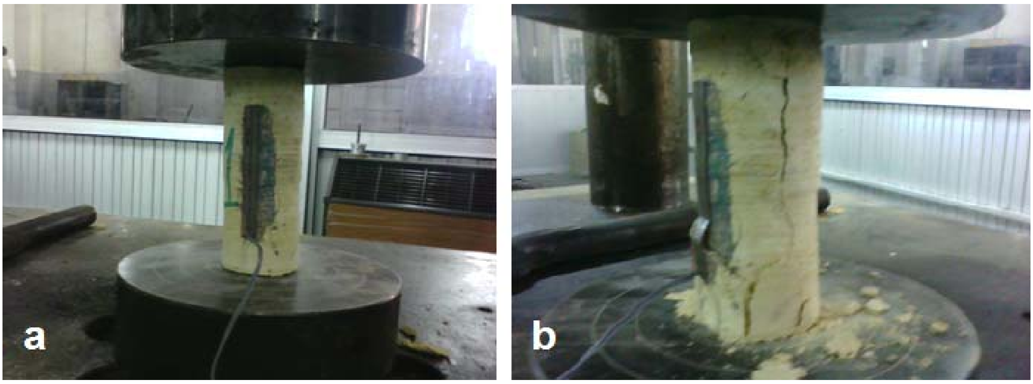

Fig. 6. Compressive Strength Sample in the Test Set-Up (a) and failure (b)

Modulus of Elasticity

The recorded stress-strain data for the three samples are graphed as shown in figure 7. From these figures, the value of the modulus of Elasticity can be obtained. For brittle materials with non-linear stress-strain relationship; the modulus of elasticity may be determined as the chord modulus between a low stress value (0.5 MPa) and a stress value equals one third of the compressive strength. For such definition the values of the modulus of elasticity obtained for the three tested samples are given in Table 4.

Table 4. Modulus of Elasticity for the Stone Samples

Sample No.	Strain at 0.5 MPa ($x10^{-6}$)	Ultimate Strength f_{ult} (MPa)	Strain at $f_{ult}/3$ ($x10^{-6}$)	Modulus of Elasticity (GPa)
1	10	10.5	301	17.182
2	13	10.4	213	22.500
3	4	10.6	250	18.293

Average value for Modulus of Elasticity = 19.325 GPa

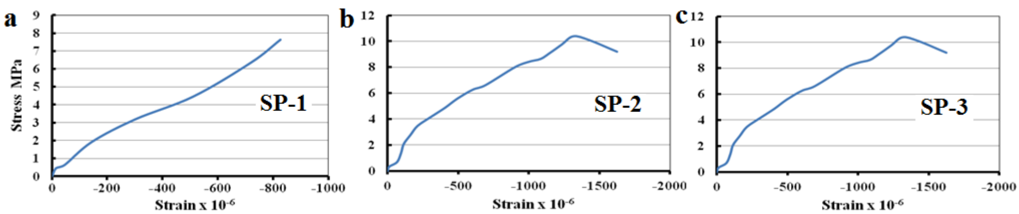

Fig. 7. Stress-Strain Curve for Samples: a – Sample 1, b – Sample 2, c – Sample 3

Splitting tensile strength

Three samples were tested to determine the average splitting tensile strength of the stone. Table 5 gives the details of the test results.

Table 5. Splitting Tensile Test Results

No.	**Diam. (mm)**	**Height (mm)**	**Ultimate Load (kN)**	**Splitting Tensile Strength (MPa)**
1	44	101	10.35	1.48
2	44	117	15.02	1.86
3	44	117	12.07	1.49
4	49	12.2	10.90	1.16
5	49	11.0	15.00	1.77
6	49	13.6	11.70	1.12
7	49	13.2	13.57	1.34

Shear Strength

One sample was tested in single shear to determine the shear strength of the stone. The obtained shear strength equals 1.63MPa.

Pathology assessment and causes of deterioration and degradation

The structure of the vast complex of the palace is unusually complicated. These buildings are of non-homogenous structural features, their elements are made of different construction materials and its foundations are of various levels and configurations.

An inspection of the palace revealed that while the deterioration seems to be geotechnical, seismic and moisture/weathering problems, other instances of deteriorations are caused by structural systems of the buildings. The structural system is a largely (to be regarded as a free shear –wall system), in which the load –bearing walls are neither always placed on top of each other nor upon strong beams transmitting their load to other continuous structural components.

The foundations were found to be built on different levels. Under a certain wall, the footing was found to be partly supported on the remains of the underground structure while the other parts are in the fill layer. The foundations in some locations were not found. The visual cracks that were observed prooved that the foundations of the building had been subjected to different settlements.

The stability problems of these structures are mainly related to the damage caused by the earthquake & seismic and geotechnical hazards. Also the foundation subsidence and deformations and fractures on the walls, as well as the weathering of stones and others construction materials by ground water, polluted atmosphere, temperature variations and the mechanical action of wind, where historical building stones exposed to atmospheric factors are subject to the action of various agents causing their deterioration and degradation. A complex combination of mechanical, chemical, biological factors played an important role in the deterioration and degradation of the building stones of palace

Type of damage recognized: flakes or scaling at the surface, loss of mass, changes in shape (worn rectangular angles), efflorescence, changing in colour (smoked brick), presence of fungus, pulverization.

The symptoms of building stones disintegration usually go in parallel with the high humidity of the walls. Salts are often concentrated in the voids without cracking around them. In many cases recrystallization takes place in the cracks which constitute the veneers of liquid faces. Salt crystals are usually in microcrystalic form and rarely in well developed crystal shape. It seems that the high content in salts has a detrimental effect on stone strength.

The process of the mechanical deterioration affecting the structures are abrasion, polishing, scouring, scratching splitting, cracking fragmentation and stone fall. These processes are reflected by striations, polished surfaces, undulating surfaces, cracks, fissures and joints and finally rock loose. Water/salt combination activated by fluid circulation and evapo-transpiration, is one of the main factors which provoke weathering and decomposition of a stone, by reaction of shrinking-expansion phenomena of pore water.

We can see decays by supply of matter such as brown crust, damages by loss of matter such as dissolution, other degradations by loss of matter such as granular disintegration and contour scaling (on parts exposed to rains), the presence of salts leads to dissolution and crystallization cycles of salts, especially inside the porous network, this mechanism occurs: a) by capillary transfer of water and salt from the ground and b) by fixation of water vapor by sea salt deposited on the stone by the wind. The action of plant's root in a particularly porosity material of construction. The building was affected by some human activities, since some building stones were subjected to scratch, breaking down or removing and reuse of stones.

Conclusions

A testing program was planned and executed to determine the basic mechanical properties of Sakakini's Mansion Building Stones. Micro structure analysis, the compressive strength, Modulus of Elasticity, Splitting tensile Strength and Shear Strength were determined as shown in the previous sections of this report.

The purpose of work concerns the geotechnical characterization of the building stones of the Sakakini building. The mechanical behavior of building stones is compared with that of soft rocks in outcrop, in particular being studied the propagation of fractures in order to predict their stability. It is reported that the stability of the materials in buildings is tightly correlated to the characteristics of the foundations, to the construction technique and therefore to the redistribution of stress in situ. It is stated that the building materials have a high heterogeneity and that this leads to a high variability of the mechanical characteristics of the materials and to a low reproducibility of the experimental data. It was also reported that given the particular historical importance of the building, only few cores have been drilled.

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