ORIGIN AND STONE MATERIAL CHARACTERISTICS IN THE PROTECTION OF MONUMENTS. THE CASE OF THE ARCAEOLOGICAL SITE OF ELEUSIS, IN ATHENS

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Abstract

In the present paper the Temple of Eleusis was used as an example in order to show the necessity of the materials description and origin as a first step in the investigation of the deterioration of stones and the protection of monuments, in addition to the study of their physical and mechanical properties. Having this as a guide, different techniques and methodologies were used for the investigation of the building stones. Furthermore, there was an attempt to localise quarries in the broader area of Attica and correlate the monument's rock material with the geological formations of the area. For obtaining a complete picture of the existing situation of the Eleusis rock materials the following investigation methods were used. a) Detailed mineral identification and petrographical observations of the natural stones, b) mineralogical and chemical study of the black crusts, dusts, efflorecences and pittings and c) physical and mechanical properties of the rock materials.

1. Introduction

The greatest dangers for the historical monuments are weathering and air pollution. Building stones are susceptible to various atmospheric factors causing their destruction, especially in Mediterranean basin, where the marine spray is a permanent cause of natural pollution, not only on the coast but also further inland. Ground stability investigation, at the foundation area of a monument, contributes also to the definition of the protection measures. Mediterranean countries present very complicate geotectonic related to important natural hazards.

In this framework no protection measures can be taken without previous petrographical characterization of the stone material. These data will not only be used in the decision of the more proper conservation technique but also in exploration of the quarry which could offer material for restoration. Furthermore the use of testing material from the quarry is very useful, given that only a minimum quantity of original material is possible to be used. The study of the physical and mechanical properties is also important. These properties are related not only to the weathering but also to the stability of the building.

In the present paper the Temple of Eleusis was investigated regarding the above characteristics in the framework of the EU project "Marine spray and polluted atmosphere as factor of damage to monuments in the Mediterranean coastal environment (EV5V-CT92-0102)".

The Temple of Eleusis is situated in one of the most historical and significant ancient cultural centres of Attica, the city of Eleusis, the mother country of the philosopher Aeschylus. In the Temple, the Athenians used to worship the goddess of agriculture, Ceres, and her daughter Persephone, by extraordinary ceremonies which constituted the "Eleusis Mysteries". Recent excavations proved that this sacred centre existed during the prehistoric period and was active till the 4^{th} AD century. In the existing ruins of the Temple, one can distinguish the traces of successive constructions, representing all the periods of antiquity, from pre-Mycenae to Roman period. The site corresponds to a typical urban-centre profile of intense and diversified industrial activity as well as that of climatic conditions favouring photo-chemical pollution in the presence of an atmosphere highly charged by suspended particles

2. Geological setting of Attica and origin of the stones used in Eleusis Temple

Attica is characterised by a complicated geological structure consisted of several alpine rock units which form different tectonic napes (Katsikatsos et al. 1986). Figure 1 illustrates a geological map of this area. Different views of the Eleusis Temple ruins, as well as the identified rock types on the building stones and sampling sites are shown in Figures 2 and 3.

From base to top we distinguish the autochthonous Attico-Cycladic crystalline complex, the Neohellenic tectonic nape and the Subpelagonian unit.

The autochthonous system of metamorphic formations is represented by schists and gneisses with horizons and intercalation of marbles (SAMPLES B and C, in Table 1) and crystalline dolomites, with a total thickness up to 2500 m. The age of these metamorphic formations is Triassic to Upper Cretaceous (Marinos & Petrascheck 1956, Papadeas 1970, Katsikatsos 1976, 1977).

The Neohellenic nape consists of phyllites, shists and quartzites with intercalation of crystalline limestone and metabasic igneous rocks as well as serpentinite bodies. The upper formations are including Upper Cretaceous crystalline limestones (Lepsius 1893, Kober 1929, Marinos & Petrascheck 1956, Leleu & Newmann 1969, Katsikatsos 1977). The total thickness exceeds 400 m and overthrusts the autochthonous units.

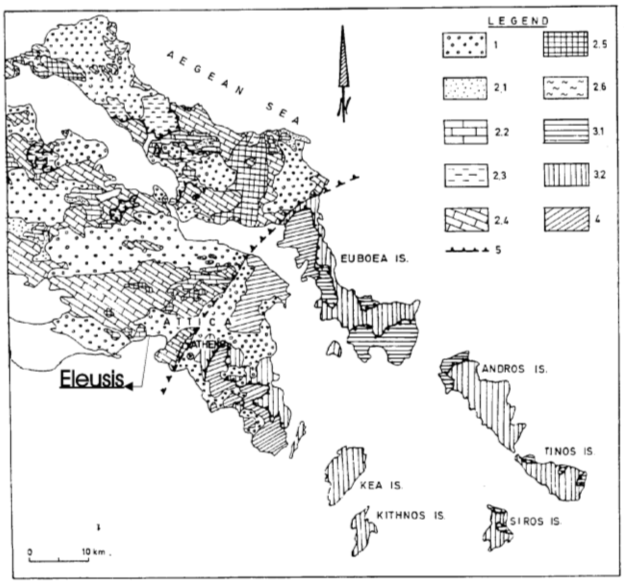

Figure 1. Geotectonic map of Euboea-Attica and N. Cyclades. (after Katsikatsos, 1977). 1. Neogene and Quaternary formations; 2. Pelagonian zone; 2.1. Flysch; 2.2. Upper Cretaceous limestones; 2.3. Eohellenic nape formations; 2.4. Middle Upper Triassic-Upper Jurassic limestones and dolomites; 2.5. Neopalaeozoic-Middle Triassic formations; 2.6. Crystalline basement; 3. Neohellenic nape; 3.1. Ochi unit; 3.2. Styra unit; 4. Autochthonous system; 5.

The Subpelagonian unit, which is the main tectonic unit of Eleusis area, overthrusts the Neohellenic nape and the autochthonous units. According to Dounas (1971), Katsikatsos(1977) and Katsikatsos et al. (1986) it consists of the following formations (Figure 1):

a) The Palaeozoic crystalline basement (two-mica gneisses, migmatites and amphibolites) overlain by clastic sediments of Permian and Carboniferous age with visible thickness of 800 m.
b) The lower-Middle Triassic group of a thickness exceeding 500 m, consisted of argillaceous shales and metasandstones, basic igneous rocks and limestone intercalation.
c) The upper Triassic - Upper Jurassic neritic limestones and dolomites with a thickness of more than 1000 m. They consist of a lower unit of white to white grey, massive to thick bedded, crystalline karstic limestone (SAMPLE E, in Table 1) and dolomite, strongly connected, and fractured. The upper unit consists of greyish to dark-grey limestone (SAMPLE A, in Table 1) and dolomite containing calcareous chert layers and nodules.

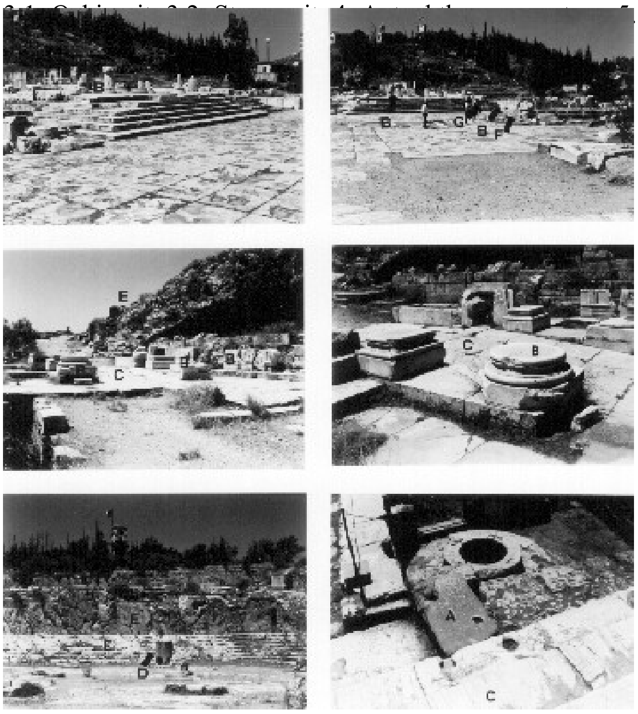

Figure 2. Views from the archaeological site of Eleusis. The sites of the different rock types are also figured.

d) The Eohellenic tectonic nape comprising deep sea sediments, volcanic and ultrabasic rocks.
e) The Upper Cretaceous limestones of Cenomanian - Maestrichtian age, with a thickness ranging from 150 m to 800 m, transgressivelly lying over the older formations. Red-brown bauxite deposits occur under the limestones. Red clays (terra - rossa) are intercalated between the bauxite and the overlying limestones. In the lower horizons the limestone is white-yellow (SAMPLE D, in Table 1) to green-brown, thin-bedded, often nodulous, alternating with marly limestones and marls. In the upper hori-

zons the limestone is greyish brown, medium to thick-plated, locally dolomitised (SAMPLE G, in Table 1), with chert nodules and microfossils. In the upper-most horizons, the limestone is thin bedded brown (SAMPLE F, in Table 1) to greenish-brown alternating upwards with conglomerates and sandstones.

f) The Maestrichtian flysh with sandstones, siltstones and limestone intercalation.

g) These alpine rocks are overlain by Neogene and Quaternary deposits (Dounas 1971). The Neogene sediments are divided into two systems. The lower system of marine blackish and lacustrine deposits which consists of marls, clays, sandstones, marly limestones and conglomerates, containing thin layers of lignite. The upper system of continental facies, consists of a) red-brown clays, sandy clays and mud alternating with sandstones and conglomerates, b) thick-bedded conglomerates with pebbles of Mesozoic limestones connected by reddish to reddish - brown sandy marl. The Quaternary deposits consist of torrential deposits and alluvial fans containing compact conglomerates and cemented screes, very cohessive, mainly of limestone debris.

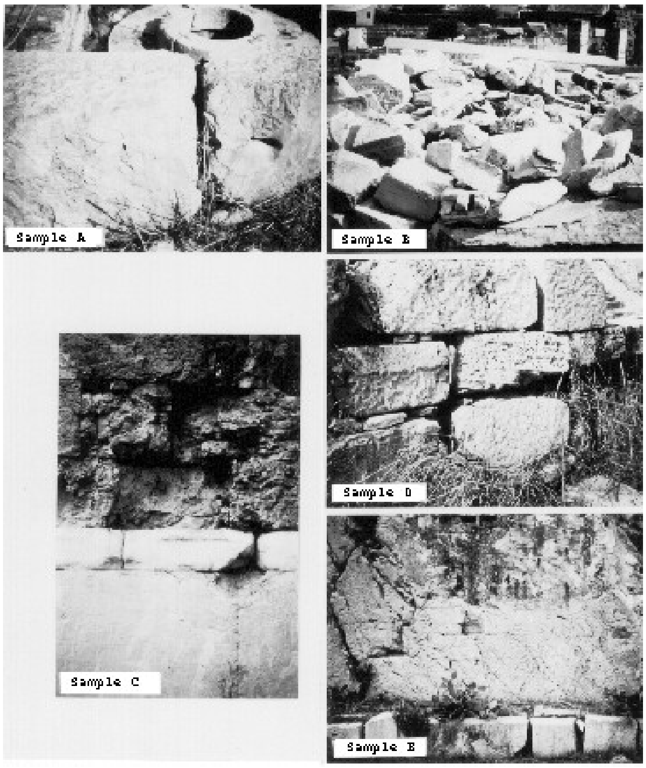

Figure 3. Sampling sites of the rock types determined in Eleusis Temple

Table 1. Rock types used in Eleusis Temple and samples studied

ROCK TYPE	MONUMENT
Grey micritic limestone, SAMPLE A	Kallichoron Well, Telestirion
White "Pentelic" marble, SAMPLE B	Temple of Artemis (Columns), Greater Propylaea, (Columns), Smaller Propylaea (Columns)
White grey marble, SAMPLE C	Kallichoron Well, Smaller Propylaea (Floor)
Yellow microsparitic limestone, SAMPLE D	Plutoneion, Telestirion
Grey biosparitic limestone, SAMPLE E	Smaller Propylaea
Yellow-brown oosparitic limestone, SAMPLE F	Artemides temple (Basement), Kallichoron Well, Smaller Propylaea (Walls)
Yellow-brown biomicritic dolomite, SAMPLE G	Greater Propylaea (Basement), Smaller Propylaea (Walls), Artemides temple (Basement).

3. Mineralogy - Petrography of stomess

4. 3.a. Analytical tecniques

The petrographical investigation of the Eleusis Temple rock material, included a) observation of thin sections under the polarizing microscope and b) X-ray diffraction analysis.

The X-ray diffractograms were obtained on randomly oriented samples, using a Philips diffractometer, Ni-filtered $Cu_{K\alpha}$ radiation. The scanning speed was 1^{o} per minute over the interval 3-60^{o} of 2θ.

3.b. Microscopic observations

The microscopic observation of the samples from Eleusis Temple gave the following results:

SAMPLE A: Grey micritic limestone. Very fine-grained limestone, including few fossils (sponge spicules, radiolaria, ostracods, crinoid ossicles, echinodermal stem plates and bivalve filaments), which though often deformed, are still recognisable. Medium-grained recrystallized calcite in forms of veins and nests, is observed in places. The calcite veins crosscut the fine-grained matrix. Some vugs and stylolites are cemented by sparry calcite. Thin veins of iron oxides ramify in several places of the rock.
Constituents: Calcite, traces of quartz.

SAMPLE B: White marble. Medium-grained well recrystallized marble with granoblastic polygonal texture. The grain size indicates increasing intensity of metamorphism, that is, possible high temperature and low deformation rates. Tangential to structural contacts between grains are observed. The porosity is very low (< 5%) of intercrystalline type according to rhomboedral cleavage planes. Porosity occurs inside the calcite crystals and between the grains there is no visible anisotropy.
Constituents: Calcite mainly in polygonal isometric grains, frequently multitwinned. Dolomite is a minor phase. Few prismatic needles of muscovite participate also as accessories as well as some quartz grains, zircon and opaques, indicating impurities in the primary rock.

SAMPLE C: White-grey marble. Fine- to medium- grained marble with a banded, granolepidoblastic texture. Calcite appears sometimes recrystallized. Multitwinning of calcite crystals is frequently observed. Structural or slightly tangential contacts between grains are observed. Porosity is very low (5-10%). Parallel fractures developed following the most fine-grain bands, which produce a very important channel porosity. There is also intercrystalline porosity according to the rhomboedral cleavage. Alteration borders in fractures are observed.
Constituents: Calcite, traces of quartz, retaining their detrital character and indicating siliceous impurities in the primary limestone. Traces of thenardite and white mica are also present.

SAMPLE D: Yellow limestone. Very fine-grained, patchily recrystallized microsparitic limestone with many pellets, pseudopelloids, very small calcareous intraclast, and bioclast (echinodermal "ghost" fragments, sponge spicules, radiolaria, mollusc filaments-possible gastrops). Cryptocrystalline lenses are observed to develop. Porosity is medium (25%), and intercrystalline, moldic and geode type. Bioclasts and original matrix have undergone a dissolution-recrystallization process.
Constituents: Calcite and dolomite in equal quantities and minor quartz.

SAMPLE E: Micritic limestone. Strongly tectonized, deformed and recrystallized single-phase limestone. Fine- to medium-grained. The calcite crystals have bent cleavages, deformation twins and deformation lamellae. Veins of tectonized, recrystallized calcite grains crosscut the matrix. Big bioclasts composed of fragments of mollusk shells (bivalves, possible oysters) with prismatic, radial and interbreed texture. Cement is granular sparitic. No porosity was observed.
Constituents: Calcite.

SAMPLE F: Oosparitic yellow-brown limestone. Microcrystalline, oolitic single phase limestone. Recrystallization of calcite in form of nests is locally observed. Dissolved fossil remains corresponding to bivalves, ostracodes, gastropods and bryozoos are observed. In addition, ooids and pelloids are found. Intraclasts occur. Micritic mud is absent. Porosity (interparticle, intraparticle and moldic type) is high.
Constituents: Calcite. Quartz, zircon, rutile as terrigenous.

SAMPLE G: Biomicritic yellow-brown dolomite. Micro- to crypto-crystalline dolomite. Few spherical to ellipsoidal quartz crystals are observed. Dissolved fossil remnants corresponding to bivalves, ostracodes, echinodermal stem plates, are found. Detrital grains and bioclasts are less than 10% of the rock. Porosity is moldic.
Constituents: Dolomite, quartz as minor phase, traces of feldspars and white mica.

3.c. Results of X-Ray diffraction analysis

X-ray diffraction analysis was applied on all samples derived from the Eleusis Temple (Greece). The X-ray method was used in order to verify the microscopic observations and determine the mineralogical composition of the very fine grains. The XRD results are presented in Table 2.

Table 2. Eleusis Temple - XRD analysis of the samples studied.

Samples/Minerals	A	B	C	D	E	F	G
Calcite	M	M	M	M	M	M	-
Dolomite	-	m	-	M	-	-	M
Quartz	tr	m	tr	m	-	-	m
Muscovite	-	m	-	-	-	-	-
Thenardite	-	-	tr	-	-	-	-
Feldspars	-	-	-	-	-	-	tr

M : Major phase, m : minor phase, tr : traces, - : absent
C=calcite, Q=quartz, M=muscovite, D=dolomite, H=halite, T=thenardite, F=feldspars, G=gypsum, A=anhydrite.

4. X-Ray diffraction and infra-red spetroscopic and X-ray fluorescence study of black crusts, yellow and gray dusts, white efflorescences and pink pittings

During the field work at Eleusis archaeological site, besides the characterization of the main seven rock-types used in the Temple, a lot of samples such as black crusts, white efflorescence, pink pittings and several type of coloured dusts, taken from Prostilio in Roman Court as well as from the Greater Propylea and Telesterion have been studied by XRD and IRS and XRF. In Tables 3 and 4 the main conclusions obtained from this study are presented.

5. Physical and mechanical properties

The rock samples from the Eleusis Temple were measured for their dry density (d), water absorption (Ab), dry compressional wave velocity (v_p), compressive strength (σ_c), tensile strength (σ_t), modulus of elasticity (E), cohesion (c), angle of internal friction (φ) and abrasion resistance (AR) (Table 5). Tests were applied on minicores of 1 in. diameter and $\oplus$30 mm height, prepared using a core drilling machine. Abrasion resistance was measured on specimens of 1 in diameter and 10 mm height. Minicores without visible fractures were collected carefully to be representative of the lithology. The surfaces of the minicores were shaped to ensure flat ends. The height to diameter ratio of specimens generally required for mechanical tests is 2:1 to 2.2:1 (Jaeger and Cook, 1979) but the specific conditions (material derived from the monument) obliged us to use specimens with the above dimensions. All tests were performed acording to ASTM specifications (Christaras, 1996); the abrasion resistance was measured according our previous technique (Christaras, 1995).

Table 3. The Temple of Eleusis (Greece). Mineralogical results of the black crusts, dusts and pik pittings

SAMPLE	MINEROPETROGRAPHY	XRD STUDY	IRS STUDY
No 1-Floor of Greater Propylea. "Black ampoules"	Black crusts and ampoules on the floor. Limestone trans-fprmed by acid rains (?)	Outer black crust -cc + qz (tr) Black oolithes -cc + qz (tr) Yellowish crust -cc + qz + gt (tr) Crystalline agregates -cc	cc + qz cc + qz cc + qz + altered silicates cc
No 2-Floor of Greater Propylea. Samples from a fracture	Like sample No 1	Yellowish zone -cc + qz Black zone - cc + qz	cc + qz cc + qz
No 3-Pentelic marble	White marble formed by a mosaic of equant calcite. Small grains of quartz and a few mica flakes	Pinkish face - cc +qz Black face brown crust - cc + qz + gt black crust - cc + qz White efflorescences - cc	cc + qz cc + qz + gy cc + qz + gy cc + gy + qz(tr) + oxl(tr)
No 4-Yellow limestone 4th Column Telesterion	Yellowish micritic limestone decayed in yellow dust	Yellow dust - cc + qz Black crust - gy + qz + cc(tr)	cc + qz + gy(tr) + nitrates cc + gy + qz(tr) + nitrates
No 5-Prostilio	Like sample No 3	Brown crust - cc + qz Light pinkish dust - cc + gt + qz Black crust - cc + qz White efflorescences - gy + cc	cc + qz cc + qz cc + qz gy + cc + oxl
No 6-Rose pentelic marble. Column in Greater Propylea 1st column, 3rd row	Like sample No 3, rich in pink pitting	Light pinkish face - cc + gt + qz Brown-yellowish zone - cc + gt	 cc + altered silicates
No 7-Yellow limestone Stepped Terrace	Yellow micritic limestone	Whitish zone - cc + dl Romboedral crystals - cc + qz(tr) Yellow dust - gy + cc(tr) Botrioidal grey crusts - gy + cc + qz(tr)	cc + dl + altered silicates cc + dl(tr) + qz(tr) + sulphates(tr) cc + qz(tr) + sulphates(tr)

cc: calcite, qz: quartz, gy: gypsum, gt: goethite, oxl: oxalates, dl: dolomite, and tr: traces

Table 4. The temple of Eleusis (Greece) . XRF results of crusts, dusts and efflorescences.

	ELEMENTS																		
SAMPLE	Na	Mg	Si	P	S	Cl	K	Ti	V	Cr	Mn	Fe	Zn	Br	Rb	Sr	Y	Pb	Cu
No 1																			
White sample				tr	tr		o	tr				tr				tr		tr	
Black crust				tr	o	tr	o	tr	tr			o	o			tr		o	
No2																			
Yellow dust			tr	tr	tr		o	tr	tr	tr		tr				tr			
Black dust		tr	o	o	yt		o	o	tr	tr	o	+	o	tr	tr	o	tr	o	
No 3																			
Pinkish face			tr	o	tr	tr	o	o	tr	tr	tr	o	tr			o			
Black crust			tr	o	tr		o	o	tr	o	tr	o	o			o		tr	
No 4																			
Pelletized sample	++	tr	o	o	o	++	+	tr		tr	o	o	tr	tr		++	o	o	tr?
No 5																			
Brown crust			tr	o	o	tr	o	tr	tr	tr	tr	tr				o			
Black crust		tr	tr	o	o	tr	o	o	tr	tr	tr	o	tr			o		o	
Green (lichenic) crust		tr	tr	o	o		+	o	tr	tr	tr	tr	tr			o		tr	
No 6																			
Rose Pentelic marble	Like sample No 5																		
No 7																			
Brown dust			tr	o	o	tr		tr	tr	tr		o		o		o		tr	
Pelletized sample	o	+	tr	o	o	o		tr	tr	o	o	+	tr	tr		+	o	++	

Present o
Abundant +
V.m. abundant ++
Traces tr
Note: All samples have been tested directly by XRF
Sample 4 and 7 have been previously powdered and pelletized

Table 5. Physical and mechanical properties of samples studied, from the Temple of Eleusis. d: density, Ab: water absorption, σ_c: compressive strength, σ_t: tensile strength, c: cohesion, φ: angle of internal friction, E: Young's modulus (c, φ and σ_t were measured using the "Brazilian method")

ROCK TYPE	Vp (m/s)	d (gr/cc)	Ab (%)	σ_C (MPa)	σ_t (MPa)	φ^o	c (MPa)	E (MPa)	AR %
SAMPLE A Gray micritic limestone	6486	2.68	0.68	77.4	9.73	42	17.38	20650	3.56
SAMPLE B White "pentelic" marble	5833	2.71	0.22	99.5	11.50	44	20.90	38480	1.40
SAMPLE C White gray marble	5776	2.73	0.35	88.5	10.62	43	19.00	33200	3.07
SAMPLE D Yellow limestone	4237	2.48	5.19	48.7	6.20	41	10.96	15480	5.08
SAMPLE E Gray biomicritic limestone	5300	2.56	0,41	57.5	6.64	44	12.07	17600	4.00
SAMPLE F Yellow-brown limestone	5073	1.76	1.2	50.9	5..50	45	10.43	14500	5.72
SAMPLE G Yellow-brown fossilif. limestone	3893	2.42	3.51	48.7	5.50	45	10.05	14500	5.98

6. Conclusions

This research was performed in the framework of the EU project "Marine spray and polluted atmosphere as factor of damage to monuments in the Mediterranean coastal environment (EV5V-CT92-0102)". The aim of the project was to establish a common methodology in investigating the deterioration of stones. In the frame of this investigation, it was verified that without the detailed description of the existing situation of a monument's construction material, it is not easy to proceed to protection measures. Having this as a guide, different techniques and methodologies were used for the investigation of the Eleusis building stones. All these methods were used in order to determine the degree of deterioration of the Eleusis monument, which is situated in an area of high industrial pollution impact.

Furthermore, there was an attempt to localise quarries in the broader area of Attica and correlate the monument's rock material with the geological formations of the area. For obtaining a complete picture of the existing situation of the Eleusis rock materials the following investigation methods were used. a) Detailed mineralogical and petrographical observations of the natural stones, b) mineralogical and chemical study of the black crusts, dusts, efflorecences and pittings and c) physical and mechanical properties of the rock materials.

The detailed mineralogical and petrographical investigation of the studied rock samples matches very well with the physico-mechanical values, measured for the same samples. This means that the resistance of the rock material is closely dependent on the mineralogical composition, corrosion, texture etc.

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