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# The Engineering Geology of Ancient Works, Monuments and Historical Sites

## *Preservation and Protection*

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# Building stones of ancient monuments in Attica; an outline

## Principales pierres de construction utilisées pour les monuments anciens de l'Attique

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ABSRACT: Extensive urban development and vast creation of sculpture works in ancient Athens and Attika was facilitated by the almost inexhaustible ammounts of material available. Building stones were cut from limestone, marble and other rock formations encountered in the area. An outline of the minerological composition, the weathering features, the physical and mechanical properties of representative types of building stones of the classical era is given in this paper. Results are based on laboratory rock testing and in situ observations.

RESUME: Le développement urbain extensif et la production immense des œuvres d'art de l' ancienne Athènes et de l'Attique, ont été facilités par les presque inépuisables quantités des pierres employées en construction, qui étaient disponibles, produites par les calcaires, les marbres et autres formations rocheuses qu'on rencontre dans la région. On donne une esquisse de la composition minérale des caractéristiques d'érosion et des qualités physiques et méchaniques des types représentatifs des pierres employées en construction, basée sur les résultats des expériences de laboratoire et les observations sur place des auteurs.

## 1 GEOLOGICAL SETTING AND SOURCES OF ANCIENT BUILDING STONES

The urban development in ancient Attica was facilitated by infinite supplies of construction materials derived from the mountains surrounding Athens, the local hills, on one of which the Acropolis is founded, the coastal area and the nearby islands like Aigina. As Strabo in his Geographics (9.1.15) comments, "The city itself is a rock situated in a plain and surrounded by dwellings". On the other hand Xenophon in his work Poroi (1.4), is adding that, "Attica has a plentiful supply of stone from which are made the fairest temples and altars, and the most beautiful statues for the gods".

The geological setting of Attica may be summarized in the following simplified geological section (Lepsius, 1893; Marinos, 1971; Papadeas, 1986):

- Quaternary
- Tertiary (fluviolacustrine and shallow sea)
- Athens schist formation (including Acropolis limestone)
- Kara beds - SE Attica phyllites
- Upper marble beds (Hemittus, Ag.Marina) interbeded with schists
- Lower marble (Penteli, Lavrion)

Limestones and other carbonate rocks had been used during the antiquity for the construction of foundations and walls while the high quality marbles, for the construction of ornamental members and sculpture works.

As Strabo says in his Geographics (9.1.23), "Near the city are the most excellent quarries of marble, the Hymmettian and Pentelic". Indeed, most of the stones were usually quarried in the antiquity, not far away from the sites of major constructions. The various sources of ancient building stones, the locations of some ancient quarries and main archaeological sites in Attica, are shown in Figure 1.

## 2 LITHOLOGICAL CHARACTERISTICS

The lithological types of the ancient building stones used in various ancient monuments are presented in Table 1. They may be grouped as follows:

1. breccias or conglomerates; they consist of coarse gravels and pebbles within a reddish to reddish brown matrix material;

2. soft carbonate rocks; they are rocks of variable strength; a subyellowish, relatively hard, fossiliferous limestone (Koghyliates), the relatively weak yellowish brown soft porous limestone from Aigina and a compact yellowish white to reddish brown oolitic limestone from Piraeus belong to this category;

3. limestones; the following types of stones may be included in this category; gray with a tinge of red limestone of the Acropolis hill, a lacustrine limestone from the foot hills of Hymettos, Kara district which is greyish white, a durable limestone from the Piraeus coast and the so called dark stone from Eleusis;

4. marbles; the lower marble, white to gray white and the upper marble, gray to bluish white are included in this category; the quality of the latter marble is relatively lower than that of the former; local types of marble used in the antiquity are the white marble of Ag.Marina and that of Agryleza, Sounio.

## 3 MINERALOGICAL COMPOSITION AND PETROGRAPHIC DESCRIPTION

A number of representative samples were collected from actual ancient building stones or from ancient quarries and assocciated rock outcrops. Selected samples were examined under the petrographic microscope and were analysed by means of standard X-ray diffraction techniques, using Cu-Ka radiation, a Ni filter, 20mA intensity, 40KV potential and angular velocity of goniometer equal to 1°/min. The results of the above examinations are presented in Tables 2 and 3.

Based on the above results, carbonate rock materials are differentiated to dolostones and limestones. The fine grained dark Eleusinian stone may in places contain clay minerals. The Pentelic marble characterized by certain archaeologists as "suffering from a desease" due to the easiness of its deterioration is that marble with a relatively high percentage of muscovite. In the marble sample from the Sounion site traces of magnetite were detected. According to Lepsius (1890), no Fe-minerals are likely to be present in this marble. In a paper by Lazzarini et al (1980), samples of the upper marble formation are referred to contain quartz, white mica and Fe-minerals. These authors attribute the grey colour of the marbles to the presence of graphite. Detailed petrographic studies of the marbles of Attica had been made by Papageorcakis (1967).

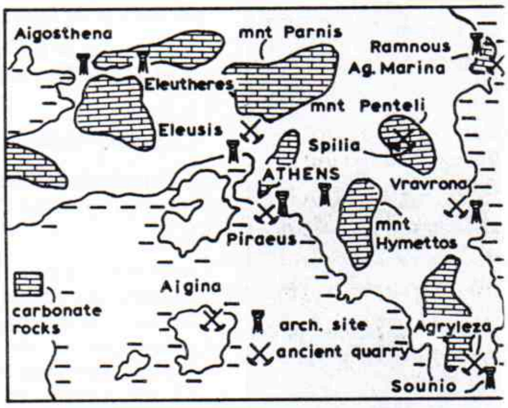



Figure 1. Locations of main archaeologica sites, ancient quarries and stone sources in Attica.

## 4 PHYSICAL AND MECHANICAL PROPERTIE

The physical properties of a number of representative rock samples from ancient building stones or from assocciated geological formations were determined by a seri of laboratory tests based on the standard methods described in A.S.T.M., D:C97-47 (1982), B.S.,812:Part 2 (1975), B.S. 1377 (1977) and the I.S.R.M.: Suggested method for determining water content, porosity, density absorption and related properties (1979). The results of the above tests are presented in Table 4.

The uniaxial compressive strength and t point load strength index of similar sampl were defined in accordance with the I.S.R. Suggested methods for determining the uni xial compressive strength of rock materia and the point load strength index (1972). T results are shown in Figure 2, where the rock materials are classified in six grou with respect to their strength parameters

## 5 PRINCIPAL MODES OF WEATHERING AN DETERIORATION OF STONE MATERIALS

In this chapter an attempt is made to elu cidate the relative susceptibility to weathering of the different rock material used as building stones in Attika during the antiquity. The main modes of weather and parameters on which its rate depends, are examined in the next paragraphs.

### 5.1 Degree of weathering

The relative degree of weathering of a se

Table 1. Use of building stones in different architectural members of ancient monuments in Attika*

| Ancient names of stones | Lithological type and location | Sites | Monuments | Use |
|---|---|---|---|---|
| Arouraios | Breccia or Conglomerate | Athens | Theater of Dionysos | Substructure, retaining walls |
| | | | Mon.of Lysicrates | Foundations |
| | | Eleusis | Great Propylea | Support of floor slabs |
| | | | Fortifications | Walls |
| | | Ramnous | Temple of Nemesis | Foundations |
| Poros lithos Koghyliates | Shell Calc | Athens | Temple of Hephaistous | Foundations, Krepis |
| | | | Hecatompedon | Walls |
| | | | Olympieion | Foundations of the inner columns |
| | | | Parthenon | Foundations, subbase |
| | | Vravrona | Stoa** | Columns, architrave, triglyphes, pavilion |
| | | Sounion | Temple of Poseidon | Krepis*** |
| Poros lithos Aiginaeos | Soft limst. Aigina | Athens | Agora, Middle Stoa | Steps, columns, walls |
| | | Eleusis | Stoa of Philon | Foundations |
| Epichorios lithos | Limestone of Acropolis | Athens | Hecatombedon | Foundations |
| | | | Pelasgic fortifications | Walls |
| Agryleikos | Cara Limestone | Athens | Olympieion | Krepis, Foundations |
| Aktites lithos | Crystalline porous limestone | Athens | Pyrgos of Athena Nike | Walls |
| | | | Propylaea | Great terrace walls |
| | | Piraeus | Arsenal of Philon | Columns and Krepis |
| | | Athens | Stoa of Attalos | Walls |
| | | Eleusis | Kefissos Hadrian bridge | The whole |
| Eleusiniakos Melas lithos | Eleusinian dark Limestone | Athens | Propylaea | Decorative band within base and side walls |
| | | Eleusis | Fortifications of Pisistrate | Walls |
| | | | Telestirion | Retaining wall |
| Penteleikos Lefkos lithos | Pentelic Marble | Athens | All mon.of Acropolis | Superstructure |
| | | | Olympieion | Columns |
| | | | Parthenon | |
| | | Eleusis | Telestirion | |
| Hymettios lithos | Hymettian Marble | Athens | Stoa Basileios | Columns |
| | | | Stoa of Attalos | Columns |
| Lefkos lithos | Agryleza Marble | Sounion | Temple of Poseidon | Krepis, columns, walls |
| Lefkos lithos | Ag.Marina Marble | Ramnous | Temple of Nemesis | |

*Data from Orlandos (1958), Marten (1965) and Wycherley (1978)
**Stoa: Arcade, Portico
***Krepis: Base

Table 2. Microscopic examination results of ancient building stones and associated rock samples

| N° | Provenance | Mineral constituents* | | | Grain size | Petrographic description |
|---|---|---|---|---|---|---|
| | | Secondary | Accessory | Trace | | |
| 1 | Vravrona q. | Quartz | | Sericite | Coarse | Arenaceous oolitic fossiliferous Limestone. Possible geol. age: Tertiary (algae Lithothamnium). |
| 2 | Sounio s. | | Quartz | Zircon | Fine to medium | Microfossiliferous oolitic Limestone. Vugs secondarily filled with sericite. |
| 3 | Piraeus q. | | | | Fine | Crystalline Limestone. |
| 4 | Athens, Agora s. | Quartz | | | Coarse | Arenaceous neritic fossiliferous Limestone. Breccious, non homogeneous and stiff in places. |
| 5 | Eleusis s. | | Clay min. | Limonite Magnetite | Fine | Marly fossiliferous Limestone. Isotropic in places, primary fissures filled with recrystallized calcite and secondary with the same or with Fe minerals. |
| 6 | Penteli (spilia) q. | Muscovite | | | Coarse | Marble, intensively crystallize Thin muscovite laminae parallel to the slight schistosity of the rock. |
| 7 | Ramnous q. | | | Magnetite | Medium to fine | Marble moderately crystallized, with visible cleavage. |
| 8 | Sounio s. | | | Magnetite | Medium to coarse | Marble monomict, with visible cleavage. |
| 9 | Sounio q. | | Quartz | Magnetite | Fine | Crystalline Limestone. Locally recrystallized along fissures. |

* except calcite which is the primary s.: archaeological site, q: ancient quarry

es of representative rock samples was estimated by measuring their quick absorption index, $I_{QAI}$.

This index is correlated with water absorption and porosity and hence with the rock weathering characteristics. It was measured according to the suggested procedure presented by Hamrol (1961). The results are presented in Figure 3.

Comparing Figures 2 and 3 it is evident that there is a rather inverse correlation between the logarithm of $I_{QAI}$ of the rock materials tested anf their corresponding strength parameters.

### 5.2 Chemical weathering due to atmospheric pollution

The artificial change of the atmosphere in the basin of Athens and the industrial area of Eleusis due to the continuous emission of various gaseous pollutant is the reason for the severe deterioration of the ancient building stones during the last decades. The problem has been examined in detail by Skoulikidis (1981) as concerns the monuments of the Acropolis.

In the present study the relative behaviour of the building stones encountered in Attika under the attack of $SO_2$ in the form of sulphuric acid is examined by using the experimental methods described by Snethlage (1981).

The following samples from representative carbonate rock materials were tested:

Carbonate rock from Agrileza quarry, Sounion
Arenaceous limestone from Vravrona
Pentelic marble
Dark Eleusinian limestone
Dolomitic limestone

Concentrations of 0.1, 0.01 and 0.001m of sulphuric acid have been used for the dissolution of the above samples to simulate different concentrations of sulphuric acid in the rain water. A mean value of 0.001±0.01m (range: 0.0-0.006) is reported from a raingauge out of 43 recording measurements which is located at the Agricultura University of Athens.

The experimental condition that was established and which approximates natural conditions is as follows:

Table 3. Results of XRD analysis of ancient building stones or associated rock samples.

| N° | Provenance | Mineral contituents | Lithological type |
|---|---|---|---|
| 1 | Athens, Agora s. | (1): calcite, (3): quartz, illite, chlorite | Marly Limestone |
| 2 | Athens, Agora s. | (1): dolomite, (3): calcite, quartz, illite, (4): chlorite | Fossil. Dolostone |
| 3 | Athens, Agora s. | (1): calcite, (4): dolomite, illite | Gray Limestone |
| 4 | Athens, Agora s. | (1): dolomite, (4): quartz, mica | Gray Dolostone |
| 5 | Athens, Agora, s. | (1): calcite, (4): muscovite | Marble |
| 6 | Penteli, Spilia q. | (1): calcite, muscovite, (3): quartz chlorite | Marble |
| 7 | Eleusis s. | (1): calcite, dolomite, (2): illite, (3): quartz, epidote, (4): chlorite | Marly Limestone |
| 8 | Eleusis s. | (1): dolomite, (3): quartz | Dolostone HW |
| 9 | Eleusis s. | (1): dolomite, (3): quartz, (4): muscovite | Dolostone MW |
| 10 | Eleusis s. | (1): calcite, (4): quartz | Dark Limestone |
| 11 | Eleusis q. | (1): calcite, (3): illite, chlorite, (4): quartz | Dark Marly Limestone |
| 12 | Eleusis s. | (1): calcite, (3): muscovite, (4): quartz | Pentelic Marble |
| 13 | Sounio s. | (1): calcite, (3): quartz, illite, (4): aragonite | Oolitic Limestone |
| 14 | Sounio s. | (1): calcite, (3): quartz, illite | Marly fossiliferous Limestone |
| 15 | Sounio q. | (1): calcite, (3): muscovite, chlorite | Crystalline Limestone |

s: archaeological site  q: ancient quarry
(1): primary, (2): secondary, (3): accessory, (4): trace
HW: highly weathered, MW: moderately weathered

Powdered rock of 0.2 gr weight of different grain sizes was brought into contact with the sulphuric acid in a glass flask. After stirring, samples were taken in certain intervals. The contents of $Ca^{2+}$ were measured by means of a titration method.

The dissolution of calcite in the different concentrations of sulphuric acid as a function of time, is shown in Figure 4. The reaction ceases when all calcite is dissolved. After 60 hours 3/4 of the calcite has reacted. The attack of the 0.001 m $H_2SO_4$ is much slower in all cases. On the basis of an ideal behaviour, the $Ca^{2+}$ concentration which is necessary to reach the solubility product of gypsum, decreases with increasing $H_2SO_4$ concentration. In the experiments the formation of gypsum was observed in almost all cases under the condition 0.1 m $H_2SO_4$. From this, it can be concluded that the formation of a gypsum cover protects the carbonate grains, so that a higher concentration of sulphuric acid is finally less aggressive than a more diluted one.

The reactions led to a nearly complete consumption of the acid after 150 hours for samples 1,2 and 3. The solubility curves of calcite (Figure 5) for the different samples at 150 hours gave the best fitted curves with their equations (computer simulation). All demonstrated very high correlation coefficients.

Finally taking the value of 2.72 gr/cm³ as the mean density of marbles and limestones, the diameter elimination of a temple column can be extracted assuming a rainfall of 0.001 m $H_2SO_4$. The dimensions of the column were arbitrarily taken to be, diameter equal to 40 cm and the height equal to 5 meters. The radius elimination was found to be between 6 and $9 \times 10^{-4}$ cm/100 years.

### 5.3 Salt attack

The relative resistance of various types of ancient building stones to weathering agents, and especially to damage caused by the crystalization of salts, was estimated by means of weathering simulation tests.

Table 4. Physical properties of ancient building stones and associated rock samples, laboratory test results.

| N° | Lithological type | $\gamma_d$ $\frac{gr}{cm^3}$ | $\gamma_{sat}$ $\frac{gr}{cm^3}$ | $\gamma_s$ $\frac{gr}{cm^3}$ | $A_w$ % | $A_v$ % | $n_t$ % | $n_{ef}$ % | e % | $S_r$ % |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Physical properties | | | | | | | | |
| 1 | Arenaceous Limestone Sounio (out) | 2.53 | 2.63 | 2.81 | 4.05 | 11.40 | 10.26 | 10.23 | 11.44 | 99.70 |
| 2 | Arenaceous Limestone Vravrona (s) | 2.41 | 2.49 | 2.61 | 3.04 | 7.93 | 7.42 | 7.34 | 8.02 | 98.20 |
| 3 | Soft Limestone Eleusis (s) | 2.34 | 2.43 | 2.58 | 3.94 | 10.15 | 9.36 | 9.20 | 10.32 | 98.30 |
| 4 | Marble (micaceous) Penteli, Spilia (q) | 2.71 | 2.71 | 2.72 | 0.18 | 0.49 | 0.50 | 0.49 | 0.23 | 91.40 |
| 5 | Conglomerate Aigosthena (out) | 2.56 | 2.70 | 2.98* | 5.43 | 16.17 | 14.04 | 13.90 | 16.34 | 99.00 |
| 6 | Marly Limestone Eleusis (s) | 2.51 | 2.53 | 2.58 | 1.11 | 2.85 | 2.80 | 2.77 | 2.88 | 99.20 |
| 7 | Crystalline Lmst Piraeus (q) | 2.40 | 2.51 | 2.71 | 4.81 | 13.05 | 11.61 | 11.54 | 13.13 | 99.40 |
| 8 | Oolitic Limestone Sounio (out) | 2.70 | 2.73 | 2.78 | 1.05 | 2.93 | 2.92 | 2.84 | 3.01 | 97.40 |
| 9 | Marble Penteli, Spilia (q) | 2.72 | 2.72 | 2.72 | 0.07 | 0.19 | 0.20 | 0.19 | 0.20 | 96.10 |
| 10 | Gray Limestone Athens (out) | 2.78 | 2.79 | 2.79 | 0.17 | 0.46 | 0.50 | 0.46 | 0.50 | 91.90 |
| 11 | Dark Limestone Eleusis (q) | 2.73 | 2.74 | 2.74 | 0.09 | 0.26 | 0.27 | 0.25 | 0.27 | 94.10 |
| 12 | Gray Limestone Eleutheres (out) | 2.73 | 2.73 | 2.74 | 0.12 | 0.33 | 0.34 | 0.33 | 0.34 | 96.70 |

$\gamma_d$: dry apparent density, $\gamma_{sat}$: saturated apparent density, $\gamma_s$: mineral grain specific gravity, $A_w$: water absorption by weight, $A_v$: water absorption by volume, $n_t$: total porosity, $n_{ef}$: effective porosity, e: void ratio, $S_r$: degree of saturation, s: archaeological site, q: ancient quarry, out: outcrop, * non representative value due to the mineral variability of the rock fragments

Representative samples were tested according to the specifications of A.S.T.M., D: C-88-71A (1972) and Commission 25-PEM Protection et érosion des monuments: Test N°V.1, Crystallisation test by total immersion (1980). The samples were shaped to form cubes but also rock aggregates were employed. A saturated solution of sodium sulphate decahydrate ($Na_2SO_4 \cdot 10H_2O$) was infiltrated within the voids of each stone and the destructive result after five continuous cycles of recrystalizations and dissolutions was recorded. The results are presented in Figure 3 and reported in terms of a weight loss index $I_c$, expressed as a percentage of initial dry weight.

It can be seen from Figure 3 that there is a rather direct correlation between $LogI_{QAI}$ and $logI_c$. Both these logarithms are approximately inversely related in a linear sense with the corresponding strength parameters shown in Figure 2.

## 6 PRESENT BEHAVIOUR OF ANCIENT MONUMENTS IN A RELATION WITH THE PHYSICAL CONDITION OF THEIR BUILDING STONES

The static behaviour of ancient monuments in Attika or the corresponding behaviour of their individual architectural members is to a large account controlled by the physical condition of their building stones. Some indicative examples of relative problems encountered in the most important archaeological sites of Attica are given here below.

In the Acropolis, since the Pentelic marble

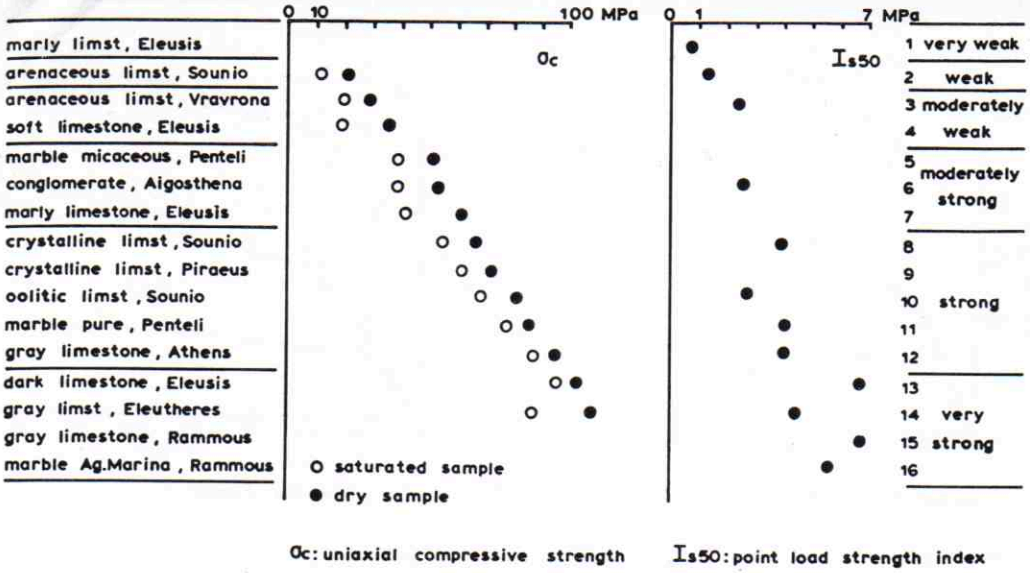



Figure 2. Uniaxial compressive strength and point load strength index of rock materials associated with ancient building stones.

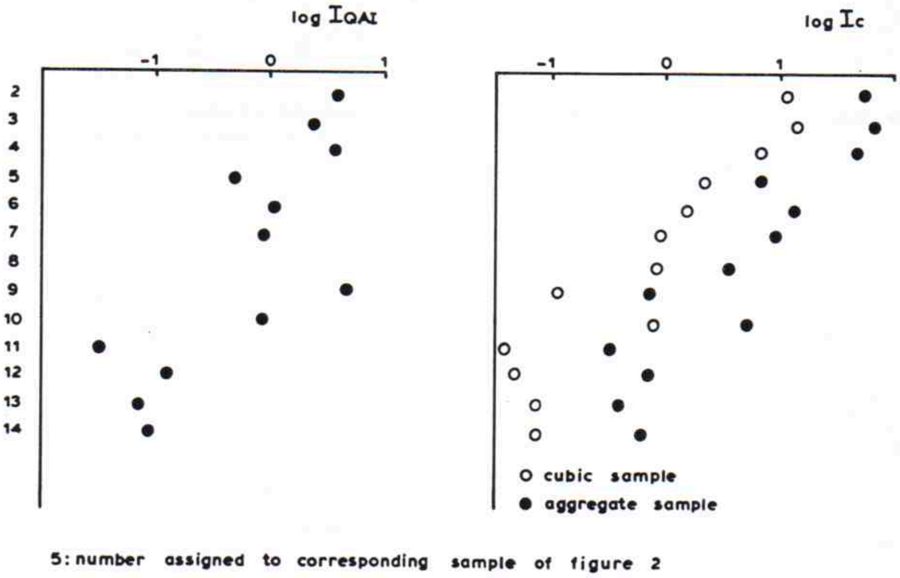
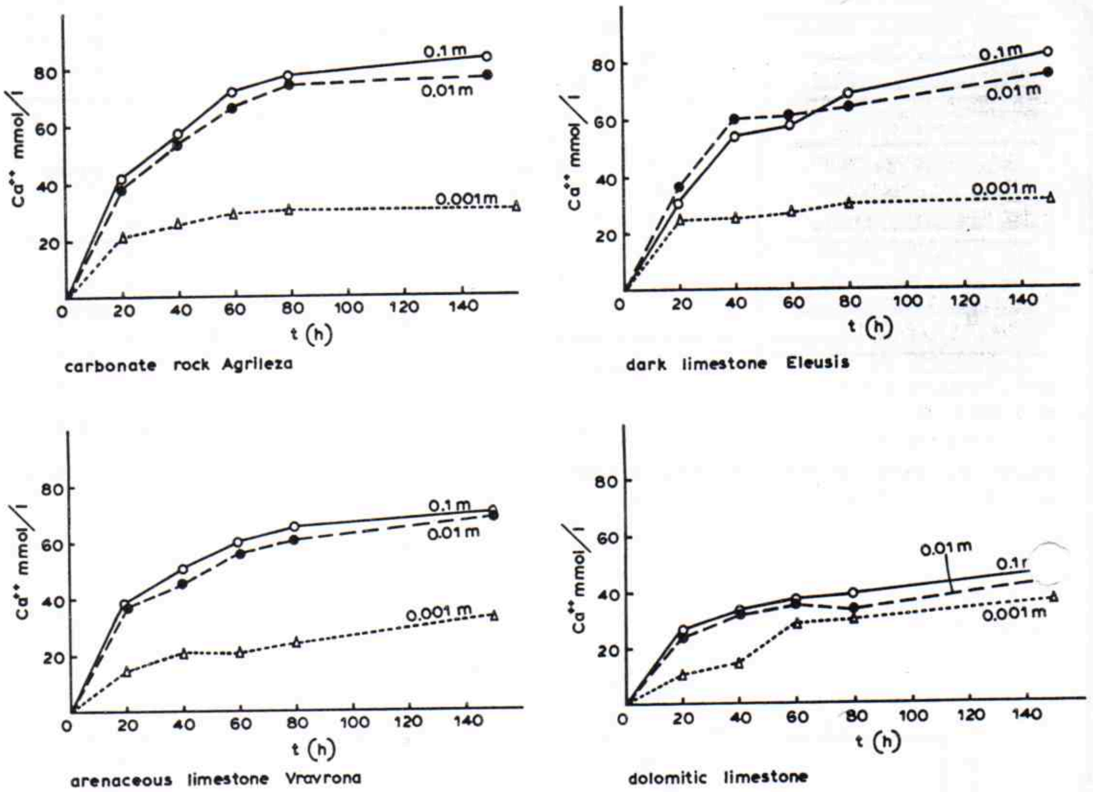



Figure 3. Relationship between quick absorption index $I_{QAI}$ and weight loss index $I_C$.



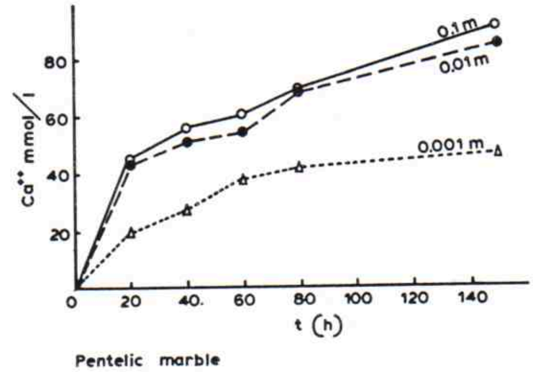




Figure 4. Dissolution rates of calcite for different sulphuric acid concentrations as a function of time.

is abundant, most of the problems of the structures are associated with its behaviour. Thus chemical weathering due to pollution and the gypsum film formation on the surface of building stones and sculptures is a primary problem. Also flaking, exfoliation and cracking of different members made of marble, is frequently observed.

In Eleusis site apart from similar problems like the above, a serious one is caused by the action of cement powder originated from a cement factory located near the archaeological site. The latter with the action of water, is forming thin tight films which subsequently are inducing flaking phenomena. Another severe problem is the intensive dissolution of the relatively soft carbonate rocks. They are transformed to powder by the action of water. The phenomenon is more intensive in the infras-

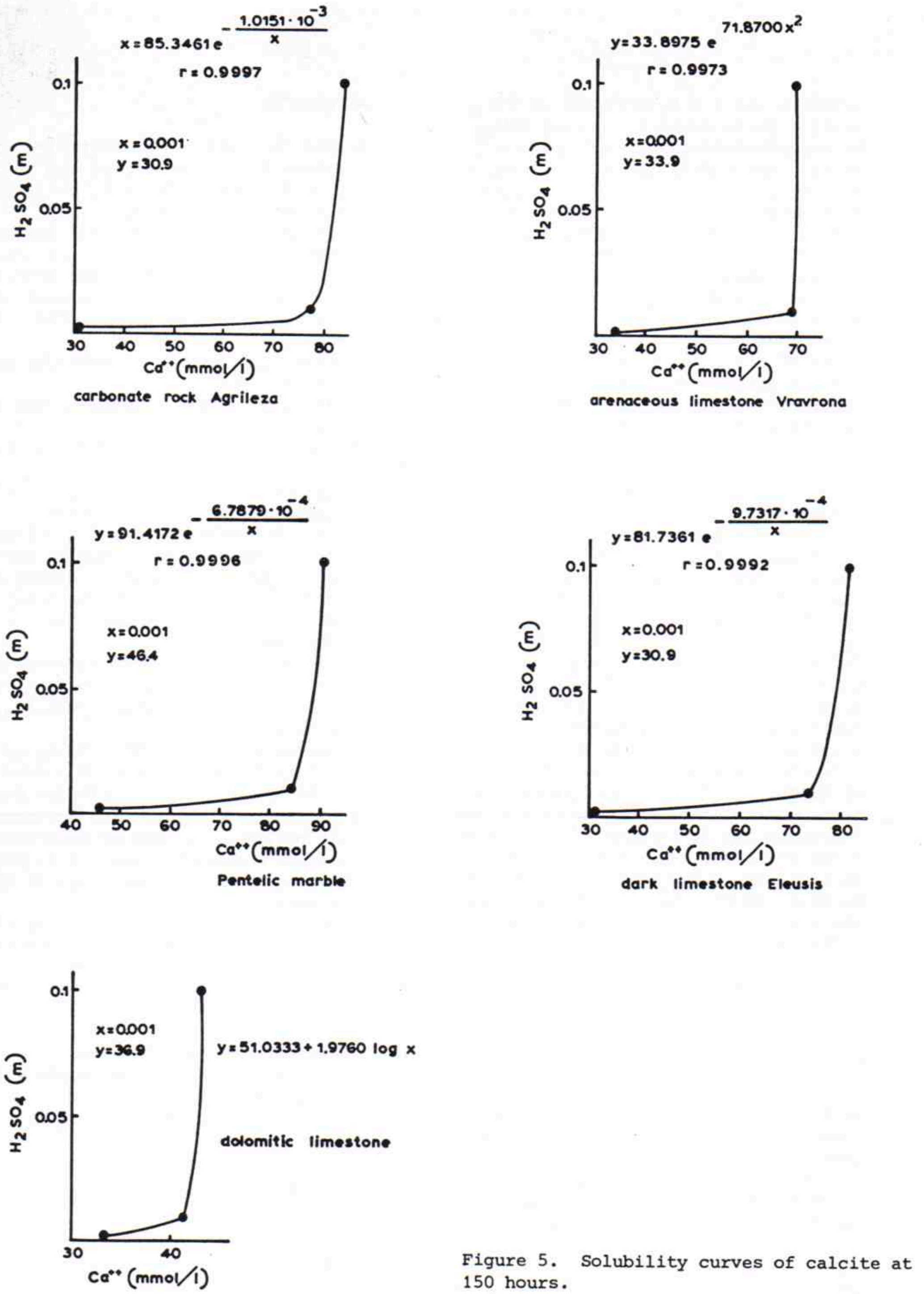



Figure 5. Solubility curves of calcite at 150 hours.

tructure and the foundations of the monuments. These members, consist frequently of soluble dolostones, soft porous limestones and sometimes marls. After the excavations and the loss of the protective soil cover they have been exposed to the action of the natural agents. In many instances there is an increased hazard for the superstructure to fail due to undercutting because of the dissolution of these soft building stones.

At the Sounion site, the geological structure of the local marble, being largerely anisotropic, is responsible for the present condition of the Temple of Poseidon. Intensive weathering is taking place along joint planes of the drums and the slabs due to salt attack by the action of saline moisture attributed to the proximity of the sea. Dissolution and recrystalization phenomena are visible. The penetrative weathering causes the opening of preexisting discontinuities, thus resulting to the reduction of the shear and the tensile strength of the above stone blocks. On the other hand the high weatherability of the building stones of site fortifications which consist of a weak oolitic limestone has already caused extensive dissolution of the individual structural members, and local undercutting and dismantling of the walls.

In the Vravrona site the long term effects of weathering on the local arenaceous limestone construction material, are evident by comparing the difference in size of the ancient drums and those constructed using identical but fresh building construction material during the restoration works. The high weatherability of the rock material is reflected on the irregular shape of the columns and the presence of numerous secondary cracks and solution vugs.

Intensive cracking of some of the remaining drums of the columns of the Temple of Nemesis at Ramnous site, made of Ag.Marina marble, has also been observed. On the contrary, the base and the retaining wall made of stones from a local durable limestone apart from some local fractures, seem to be quite stable.

At Aigosthena site a source of instability of the fortification walls made of stones from a local conglomerate, outcroping in the sea, is the disintegration of the stones especially those near the base, mainly due to solution of the rather semicalcareous-semiargelaceous matrix material.

Finally the high durability of the limestone construction material of the Eleutheres fortification complex is reflected to the very good preservation of this monument.

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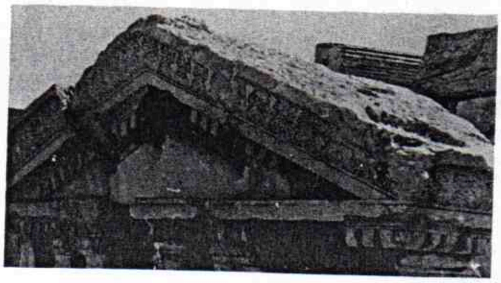
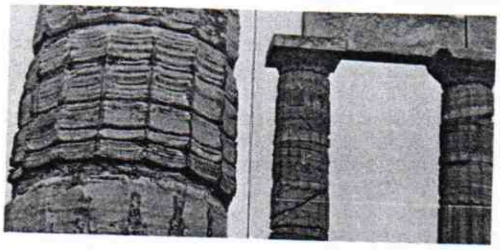
Quarry of Aktites lithos, Piraeus coast



Chemical and mechanical weathering of an ornamental architectural member, Eleusis

Undercutting of a wall due to dissolution of its building stones, Eleusis site

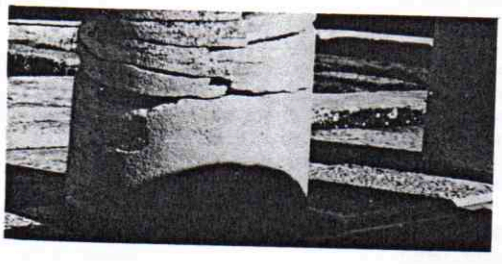


Weathered and cracked columns and slubs, Temple of Poseidon, Sounion site

Intensive dissolution of oolitic carbonate building stones, Sounion site

Dismantling of the fortification walls, Sounion site

Weathered ancient columns and intercalated recently constructed drums, Stoa, Vravrona



Cracked marble columns of the Temple of Nemesis, Ramnous site

Marinos, Paul G. & George C.Koukis (eds) 90 6191 793 X
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During the last years people have become more and more interested in the protection and restoration of ancient monuments and structures and have appreciated the value of historical sites.
These four volumes of the proceedings of the international symposium held by the Greek National Group of the International Association of Engineering Geology in Athens, relate the experience acquired so far worldwide in this field. The contribution afforded by the geosciences and geotechnical engineering has often been shown to exceed expectations. The proceedings include as many interdisciplinary interests as can be covered by the term 'Engineering geology' and related to the subject of ancient works, monuments and historical sites. Soil and rock mechanics, foundation engineering, structural geology, geomorphology, geophysics and seismology are actively present. On the other hand, in all themes multidisciplinary contributions are included by papers prepared after a collaboration among geologists, engineers, architects and archaeologists.
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