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PARTICULARITIES IN STUDYING THE PHYSICAL AND MECHANICAL PROPERTIES OF STONES IN MONUMENTS. EXAMPLES FROM THE MEDITERRANEAN BASIN

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Abstract:

The investigation of the physical and mechanical properties of stones in monuments needs non destructive methods and small quantity of testing material. The non destructive methods can be divided in laboratory and *in situ* techniques. P & S wave ultrasonic velocities and Schmidt hammer can be used for both *in situ* and laboratory measurements, in contrast to the compressive strength and abrasion resistance that can be used only for investigation in the laboratory. In the present paper the above methods were used for the study of properties like the mechanical anisotropy, weathering degree, mechanical strength and deformation ability of stones, using data from The Cathedral of Bari, in Italy, the Temple of Eleusis, in Greece, the Cathedral of Cadiz, in Spain and the church of Sta Marija Ta Cwerra, in Malta. This investigation 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)".

1. Introduction

One of the greatest dangers for the historical monuments is weathering, caused by climatic changes and air pollution. Building stones are susceptible to various atmospheric factors causing their destruction, especially in Mediterranean basin, where the marine salts are 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.

Weathering effects on the physical and mechanical properties of natural stones of monuments causing stability problems. These properties cannot be easily studied using the common methods used for investigation in the modern construction, because these methods need a big quantity of testing material.

In this framework the use of non destructive techniques for determining the physical and mechanical properties of natural stones is very important because only a small quantity of testing material is needed. Methods using P & S wave velocities, Schmidt hammer resistance and abrasion resistance provide data related to the elasticity, uniaxial compressive strength, anisotropy and weathering resistance of the stones. Porosity, dry density and water absorption are physical characteristics that can also provide data related to weathering.

In the present paper the above methods were used for the study of properties like the mechanical anisotropy, weathering degree, mechanical strength and deformation ability of stones, using data from The Cathedral of Bari, in Italy, the Temple of Eleusis, in Greece, the Cathedral of Cadiz, in Spain and the church of Sta Marija Ta Cwerra, in Malta. This investigation 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)".

2. Physical and mechanical properties used

The physico-mechanical properties of the collected samples were measured according to the following methodology.

I. <u>DRY DENSITY (d, ASTM C 97-47):</u> It obtained by dividing the dry weight (after drying for 24h at $110^{O}C$) of the specimens by the total volume (solids and voids). Weights were determined using a FX-320, A&D automatic electronic balance (310 gr. x 0.01 gr. and 60 gr. x 0.001 gr.). The total volumes were measured using an EIJKELKAMP Vacuum Air Pycnometer. For total volumes, saturated samples were used.

II. <u>WATER ABSORPTION (Ab, ASTM C 97-47):</u> It was calculated by dividing the absorbed water weight (after a bath of 24h, in vacuum) by the dry weight of specimens.

III. ULTRASONIC VELOCITY (v_p, ASTM 597, ASTM D 2845- 83): It is a good index characteristic of the physico-mechanical behaviour of the rocks. For this purpose a PUNDIT ultrasonic non destructive digital tester was used. Measurements were applied along the axis of the core samples and the travel time of the 54-KHz source pulse was measured. Water pump grease, covered with a specific membrane, was used as coupling media, to improve the acoustic contact between the sample and the transducers. The instrument was calibrated with aluminium standards. Thickness and travel time corrections were calculated by performing a linear regression between the actual and the measured times. Ultrasonic velocity is related to the elastic moduli of rocks, such as Young's modulus and Poisson's ratio (Christaras et al, 1993, Topal, 1995). Furthermore, it is a very good index for rock quality classification and weathering determination. Tests were made using the direct or the indirect method, depending on the case. The direct method is referred to the arrangement of the transducers of the apparatus on the opposite surfaces of the specimen tested. The indirect method, used especially on in-situ measurements, is referred on arrangement of the transducers on the same surface of the stone. The direct transmission arrangement is the most satisfactory one since the longitudinal pulse leaving the transmitter are propagated mainly in the direction normal to the transducer face. In general, the pulse velocity determined by the indirect method of testing will be lower than that using the direct method. If it is possible to employ both methods of measurement then a relationship may be established between them and a correction factor derived. According to the manual of the apparatus used, when it is not possible to use the direct method an approximate factor of 1.05 could be used for the determination of the pulse velocity obtained using the direct method.

IV. ABRASION RESISTANCE (AR): It is an expression of hardness measured as "abrasion loss of weight (AR, %)". The method used is based on the calculation of the loss of weight of a pre-weighted sample after abrasion for a constant time under constant conditions. For this purpose a "LOGITECH - LP 30" thin-section lapping machine with constant rotation of 40 rpm is used. Tests are applied on mini-cores of 1 in diameter and 10-mm high, rather than 30 mm, which was the ordinary height used for the other tests, ensuring no damage of the edges. The polishing material (sand) is emery of grain size No. 400 and the specimens are loaded with 2 kg. The abrasion time is 1/2 hr. Test results are accurate and repeatable not only for fine-grained rocks, like the pentelic marble, but also for medium- and cross-grained rocks without very big phaenocrystals (e.g. trachyte etc.). Our previous studies on specimens of different rock types (Christaras, 1995) provided significant correlation between abrasion loss of weight and the other common physico-mechanical properties.

V. UNAXIAL COMPRESSIVE STRENGTH (σ_c or UCS): Uniaxial compressive strength (UCS, in MPa) was measured according to ASTM C 97-47 specifications by dividing the compressive force by the surface of the base of the cylindrical specimen. For this purpose a 100/450-KN Weber PW 40E compression machine was used, calibrated according to the instructions of the factory. The machine was equipped with an electro-hydraulic directly connected motor-driven pump, a solenoid valve, and a pressure valve. A low-pressure contact pressure gauge, inductively operated as desired (indication range 25 % of main contact pressure gauge: 100 KN), with automatic closing and shut-off valve.

VI. YOUNG'S MODULUS OF ELASTICITY (E): Deformation data for specimens undergoing strength tests may be obtained and used to calculate the static elastic moduli of intact rock. The modulus of elasticity, or Young's modulus is one of the most common used. The static modulus of elasticity, which is a form of Hook's law, is derived from applied axial compressive stresses and resulting axial strains ($E_s = \sigma_n/e$, where E: Young's modulus, in GPa, σ_n: normal stress and e: axial strain). Rate of stress application will result in different E-values, for the same material. The values for E-modulus may be obtained from stress-strain diagrams. Of the average modulus, tangent modulus and secant modulus referred to in the literature, the last one is more commonly used, as it predicts the maximum elastic deformation that would occur at 50 % of the ultimate strength (Johnson and De Graff, 1988). In the present investigation Young's modulus was measured using the secant modulus method. Unfortunately the small size of the specimens did not permit us the use of high-precision deformation gauges. Thus, deformation was measured using a "KYOWA" micrometer connected to an amplifier. The precision of the instrument was 0.01 mm; a third digit precision is given by an amplifier.

VII. TENSILE STRENGTH (σ_t), COHESION (c), ANGLE OF INTERNAL FRICTION (φ): It was measured according to the indirect "Brazilian method" (Duriez et Arrambide, 1962) consisted in breaking the dry minicores placed horizontally between the plates of a press. The tensile strength is obtained by dividing the applied compressive force by the half lateral surface of the cylindrical specimens. Besides a compressive stress, equal to $3\sigma_t$ is obtained in the same time. For each sample, two Mohr circles are traced, the first with $\sigma_c>0$ and $\sigma_t=0$ and the second with $\sigma_t<$) and $\sigma_c=3|\sigma_t|$. The angle of internal friction and the cohesion are also calculated according to the relationships $\tan^2(45^o-\varphi/2)=\sigma_t/(\sigma_c-3\sigma_t)$ and $c=(\sigma_c/2)\tan(45^o-\varphi/2)$.

VIII. SCHMIDT HAMMER VALUE (SHV): The Schmidt hammer is designed to carry out instant non destructive tests on in-situ concrete or stone without damage, to give an immediate indication of their compressive strength, using the calibration curve supplied with each instruction (linear regression). Test values is better to be used in relation to fresh values. The method can easily be used for hardness scanning and weathering mapping of a stone surface (Christaras, 1996).

IX. MECHANICAL ANISOTROPY: Stones do not behave mechanically in the same way along different directions. Orientation of minerals in rocks cause anisotropy phenomena, referred to the physical and mechanical properties. Deformation is one of the more important properties related to the rock fabric. This property is expressed by the Young's modulus (E), obtained either statically using loading techniques, or dynamically using ultrasonic and resonance frequency techniques. Weathering is also related to the rock fabric, causing different results in different directions (Zezza, 1991, Christaras, 1996).

3. The Temple of Eleusis in Greece

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 4th 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 (Moropoulou et al., 1994, 1995).

Figure 1. Columns of pentelic marble in the Temple of Eleusis

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) and angle of internal friction (φ) . Tests were applied on minicores of 1 in. diameter and ⌖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 the samples used were collected from the ruins of the Temple (walls, basement, columns, etc,). The test results are given in Table 1.

Table 1. Physical and mechanical properties studied samples 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°	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

Table 2. Density (d), Water absorption (Ab), Uniaxial compressive strength, (UCS, MPa), Young's modulus (E, GPa) and Ultrasonic velocities of limestones from Cadiz (quarry), along the x,y,z direction as well as Ratio z/x of the ultrasonic velocity (V, Km/s), uniaxial compressive strength (UCS, MPa) and Young's modulus (E, GPa.

No	d (gr/cc)	Ab (%)	UCSz (MPa)	UCSx .(MPa)	Ez (GPa)	Ex (GPa)	Vx(km/sec)	Vy(km/-sec)	Vz(km/-sec)	Vz/Vx	UCSz/UCSx	Ez/Ex
I	2.66	5.45	76.10	76.03	16.30	17.44	4.54	4.54	4.36	0.96	1.00	0.93
II	2.60	4.42	82.60	79.20	20.00	18.03	4.8	4.49	4.84	1.01	1.04	1.11
III	2.54	4.74	85.86	86.44	20.51	21.25	4.95	4.91	4.88	0.99	0.99	0.96
IV	2.53	4.41	76.98	83.53	17.12	19.92	4.89	4.9	4.34	0.89	0.92	0.86
V	2.63	3.6	90.69	89.52	25.06	24.03	4.97	5.1	5.11	1.03	1.01	1.04
VI	2.54	3.38	91.92	93.67	26.48	27.65	5.15	5.1	5.09	0.99	0.98	0.96
VII	2.48	3.63	78.58	89.32	21.34	24.95	5	4.89	4.46	0.89	0.89	0.86
VVIII	2.65	3.70	96.58	97.97	27.80	29.90	5.2	5.07	5.17	0.99	0.99	0.93
IX	2.56	3.63	89.46	90.35	27.90	26.38	5.1	5.07	5.11	1.00	0.99	1.06
X	2.60	3.95	93.11	89.23	28.26	25.79	5.1	5.15	5.17	1.01	1.04	1.10
XI	2.80	2.68	82.03	84.40	22.75	22.50	4.9	4.9	4.68	0.96	0.97	1.01

4. The Cathedral of Bari in Italy

The Basilica of St. Nicolas in Bari (Cathedral of Bari, Italy), is of the XII century and is located in the central Mediterranean where it is exposed to marine environment influenced by air currents both from the north and from the south-east. It is constructed with Cretaceous limestone and has four portals in marble, including the central one, and fifth portal in limestone. The monument shows notable phenomena of sulphurization of the marble and weathering of the limestone on both the external facade and inside the church.

The rock samples form Bari, were tested for their dry density (d), water absorption (Ab) and dry compressional wave velocity (Vp). The samples were very small, so the above physical properties were measured on specimens without specific dimensions. Test results are given in Table 3.

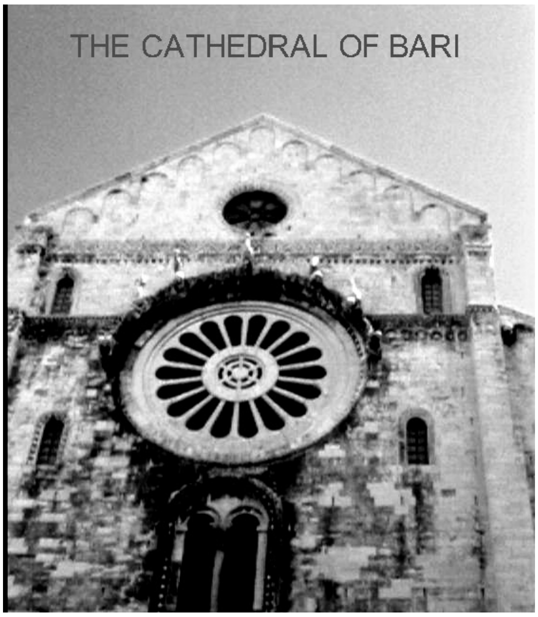

Figure 2. The Basilica of St. Nicolas in Bari.

Table 3. Physical properties of limestone samples from Cathedral of Bari. d: dry density, Ab: water absorption, Vp: ultrasonic velocity,

Samples	d (gr/c3)	Ab %	Vp(m/s)
30	1.85	4.10	4100
31a	2.30	2.10	4400
31b	2.31	2.48	4500
32	2.31	2.50	4500
41	2.29	2.58	4500

5. The Cathedral of Cadiz in Spain

The Cathedral of Cadiz (18^{th} and 19^{th} centuries) may be considered the masterwork of Vicente Acero y Arebo. The building's style is "post-dated". He planned the interior with three naves, an ambulatory surrounds the chancel, which is of circular plan and covered by a dome (upon tambour). The styles adopted during the Cathedral's construction can be summarised as follows: Baroque period for the ground-plan and interior elevations up to the capitals, Rococo in its ornamentation and of Neo-classical style in the shell of the principal facade, dome and towers.

Eleven representative specimens of limestone, collected from the quarry, probably used for the construction, were tested regarding their density (d), water absorption (Ab), ultrasonic velocity (V), uniaxial compressive strength (UCS) and elastic modulus (E). The specimens used were cubic, of dimensions 5x5x5 cm. The ultrasonic velocity was measured along the three axes x, y, z of the specimens, in order to determine the probable anisotropy existed. For the same reason the uniaxial compressive strength and the Young's modulus were measured along the axes x & z.

The test results, given in Table 2, were interpreted statistically in order to determine significant correlation between the properties examined. Furthermore correlation diagrams of the anisotropy of ultrasonic velocities, compressive strength and elastic modulus, measured along the different axes were made in order to determine a significant relationship between the results of these methods.

The changes of the magnitude of the properties studied as well as the correlation observed between these properties are given in the diagrams of the Figures 4 and 5. The diagram of Figure 4 provides a relationship between the properties tested. This relationship is more significant between the properties detected along the same direction. This relationship becomes more significant in the diagram of Figure 5 where the changes of the ratios Vz/Vx, UCSz/UCSx and Ez/Ex, along the z and x axes improve the dependence of these properties on the anisotropy of the rock material. Furthermore no significant relationships are observed, in Figure 4, between the "linear" properties, such as the ultrasonic velocity, the uniaxial compressive strength and the Young's modulus, and the "volume" properties, such as the dry density and the water absorption.

The relationships of the ultrasonic velocity with the uniaxial compressive strength and the elasticity (Young's modulus), along the same axis, is presented in Figure 5. These diagrams provide a very significant correlation between the above properties, separately for the axes z and x. The influence of the anisotropy on the physico-mechanical behaviour of a stone is more clear in the diagrams of Figure 5. In these diagrams a very significant correlation is observed between the ratios Vz/Vx, UCSz/UCSx and Ez/E. According to these diagrams, the use of the non destructive method of the ultrasonic velocity is possible for measuring the anisotropy of the material as well as the change of its compressive strength and elasticity.

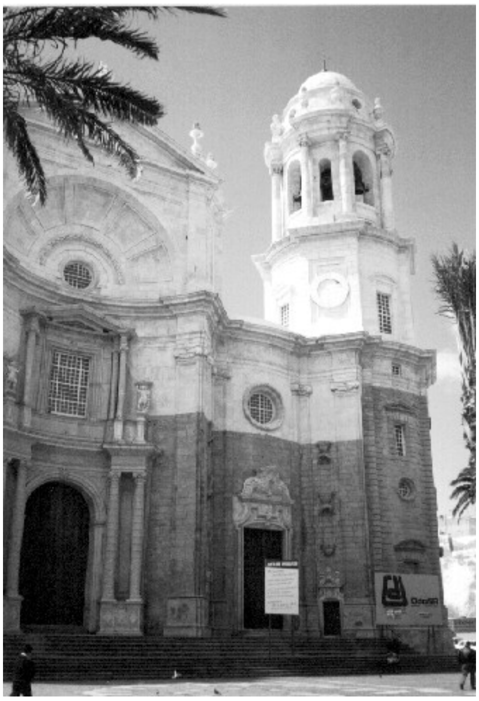

Figure 3. The Cathedral of Cadiz

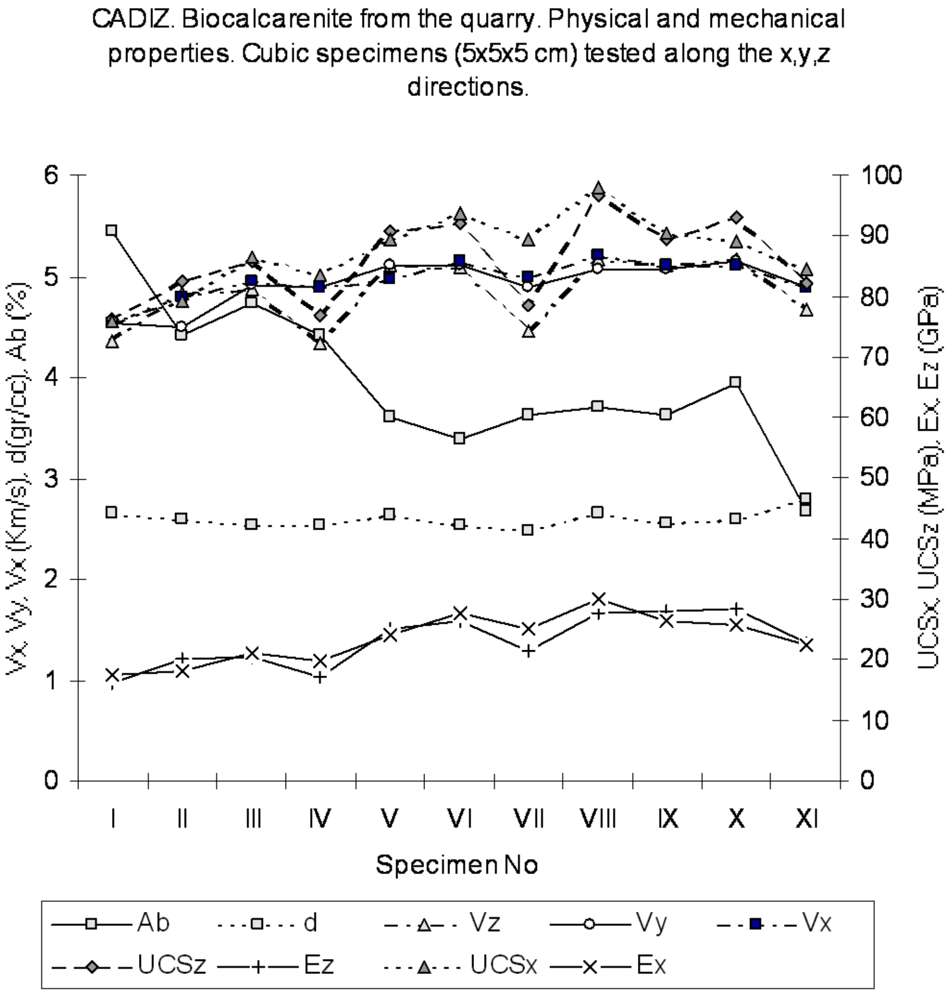

Figure 4 Changes of physical and mechanical properties of the biocalcarenite used in the construction of the Cathedral of Cadiz. The specimens were collected from the quarry.

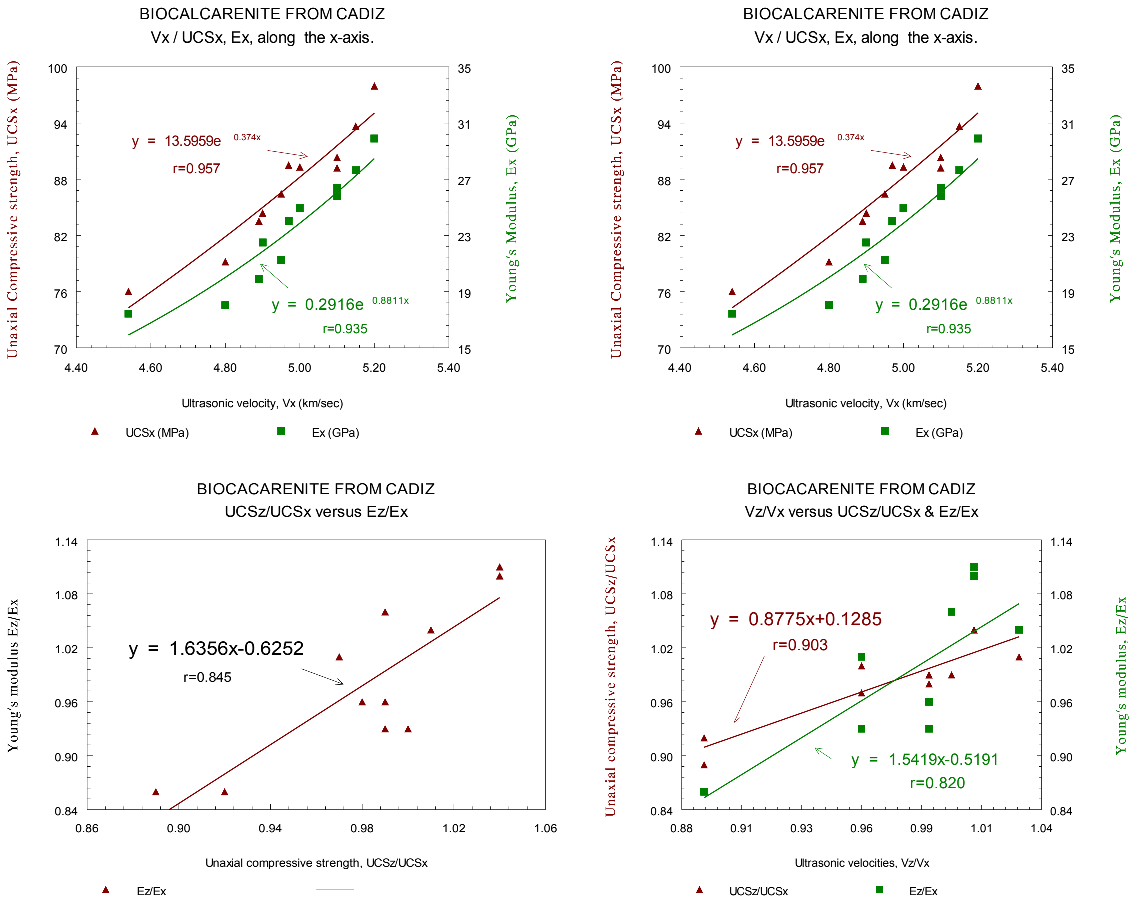

Figure 5. Biocalcarenite used in the Cathedral of Cadiz. Samples collected from the quarry. Correlation diagrams of the mechanical properties along the x and z axis

6. The church of Sta Marija Ta Cwerra in Malta

The Church of Sta Marija Ta Cwerra at Siggiewi, in Malta, is located on an island, in the centre of the Mediterranean, having a typical marine environment. The church is constructed with Globigerina limestone, which is the main rock type in the island. It is mentioned that this rock is the only raw material used in the construction of all the old and new buildings in the island.

Twenty representative specimens of limestone, collected from the Mqabba quarry in Malta, were tested regarding their density (d), water absorption (Ab), ultrasonic velocity (V), uniaxial compressive strength (UCS) and elastic modulus (Young's modulus, E). The specimens used were cubic, of dimensions 5x5x5 cm. The specimens were collected from two different geological layers, which are exploited for construction materials, in the same quarry. It is very probable that stones from both layers were used in the construction of the church in study. The specimens 1 to 10 correspond to the lower layer while the specimens 11 to 20 correspond to the upper layer. The ultrasonic velocity was measured along the three perpendicular axes, x, y & z while the uniaxial compressive strength and the elasticity were measured along the axis z, which corresponds to the z-axis of the rock formation in the field. This axis is perpendicular to the stratification of the limestone.

Test results are given in Table 4. These results were interpreted statistically in order to determine relationships that express the interaction of the physico-mechanical properties of the stones. Tests on specimens, well prepared, taken from the south wall of the church, gave the following mean values: d= 1.77 gr/cc, Ab=15.6 %, V= 2.986 Km/s, UCS= 40.93 Mpa, E= 10.20 Gpa.

According to Figure 8, the test results differ in the two layers. The uniaxial compressive strength, the elastic modulus, the ultrasonic velocity and the dry density are always higher in the upper layer while the water absorption is higher in the bottom. Consequently, the above properties provide significant correlation, separately in each layers (Figure 9). These diagrams show that the water absorption correlates significantly with the dry density while the ultrasonic velocity correlates with the uniaxial compressive strength and the Young's modulus, providing a possible use for the determination of the changes of the mechanical behaviour.

Figure 6. Apart of the external southern wall of the church. Numbers correspond the points of measurements.

In-situ measurements were also made, on the external part of the south wall, in addition to the above laboratory tests. This wall is strongly weathered and presents very important changes of weathering from place to place corresponding to probable changes of the mechanical behaviour. A part of the wall was investigated regarding the indirect ultrasonic velocity (V) (arranging the transducers on the same surface) in relation to the Schmidt hammer values (SHV). Test results are given in Table 5. The compressive strength (CS) corresponding to the Schmidt hammer values measured, are also given in the same Table. The significant correlation that presents the ultrasonic velocity with the Schmidt hammer values in Figure 7 provide a possible used of both of them in determining the weathering and the mechanical behaviour of a weathered surface. The points where the tests were applied on the wall are given in Figure 6. In order to measure the indirect ultrasonic velocity, a mean value of three measurements in different distance were used, and the results were verified to be similar, so as to avoid errors from cracks.

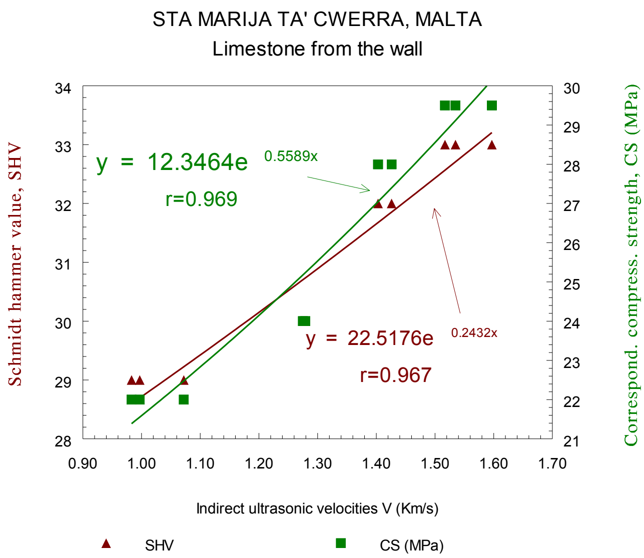

Figure 7. Correlation between the surface compressive strength and the indirect P-wave velocity measured on the external south wall of the church of Sta Marija Ta Cwerra.

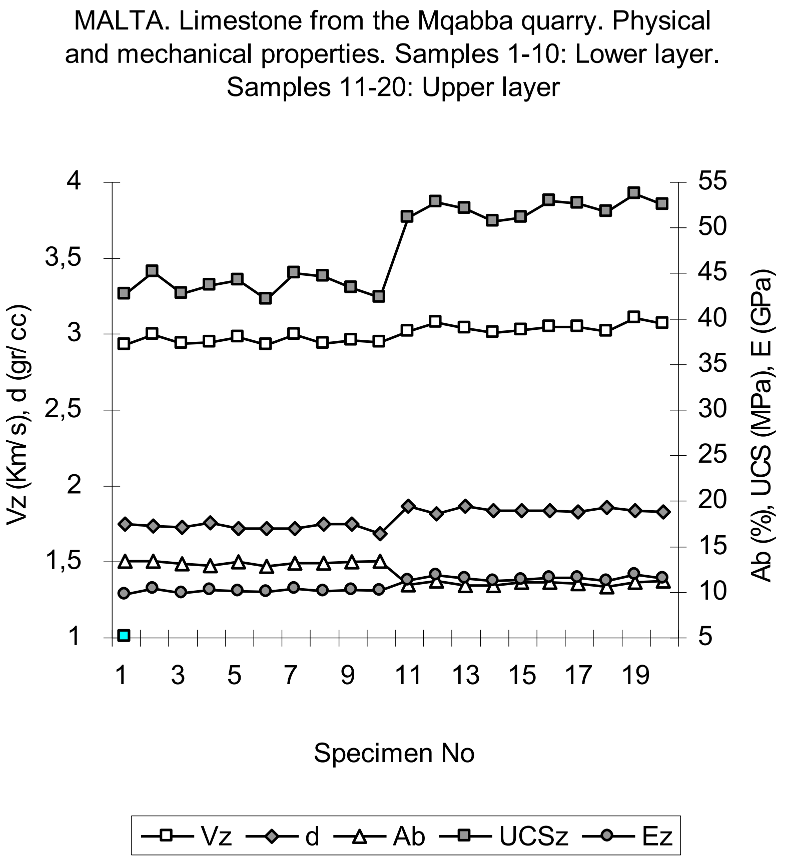

Figure 8. Limestone used in the construction of the church of Sta Marija Ta' Cwerra. Physical and mechanical properties of specimens from the Mqabba quarry. The tests were applied perpendicularly to the stratification. Samples 1-10: Loer Layer. Samples 11-20: Upper layer

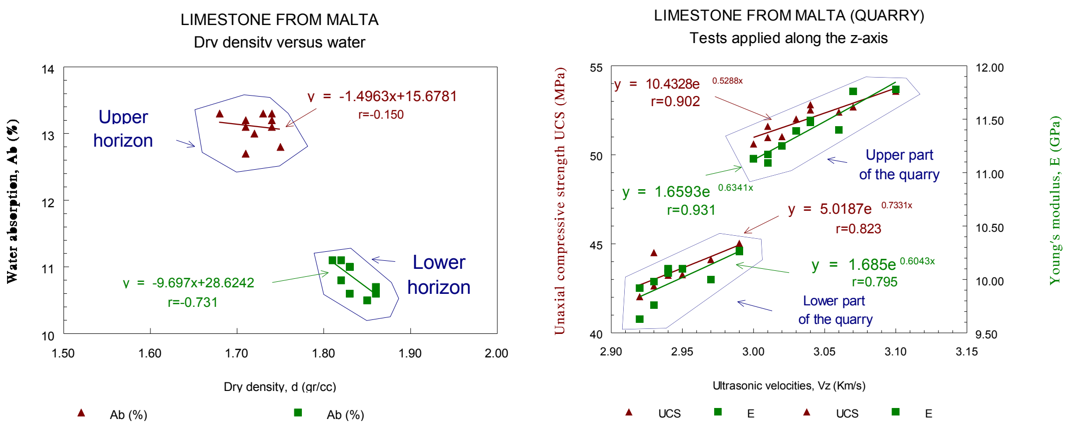

Figure 9. Limestone used in the construction of the church of Sta Marija Ta Cwerra. Samples collected form the Mqabba quarry. Correlation diagrams of the mechanical properties, separately for each layer

Table 4. Density (d), Water Absorption (Ab), Uniaxial compressive strength along z-axe (UCSz), Young's modulus along z-axe (Ez) and Ultrasonic velocities (Vx,y,z), along x,y,z directions, of the limestones from Malta (quarry),. Samples 1-10: Lower layer, Samples 11-20: Upper layer.

No	d (gr/cc)	Ab (%)	UCSz (MPa)	Ez (GPa)	Vx (km/sec)	Vy (km/sec)	Vz (km/sec)
1	1.74	13.3	42.55	9.63	2.85	2.86	2.92
2	1.73	13.3	45.03	10.27	2.98	2.99	2.99
3	1.72	13.0	42.64	9.76	2.89	2.99	2.93
4	1.75	12.8	43.54	10.10	2.98	2.94	2.94
5	1.71	13.2	44.12	10.00	2.75	2.78	2.97
6	1.71	12.7	42.04	9.92	2.85	2.70	2.92
7	1.71	13.1	44.92	10.26	2.97	2.95	2.99
8	1.74	13.1	44.51	9.98	2.90	2.80	2.93
9	1.74	13.2	43.27	10.10	2.86	2.77	2.95
10	1.68	13.3	42.24	10.06	2.86	2.84	2.94
11	1.86	10.7	50.97	11.17	3.05	2.99	3.01
12	1.81	11.1	52.69	11.76	3.07	3.12	3.07
13	1.86	10.6	52.01	11.39	3.07	3.03	3.03
14	1.83	10.6	50.61	11.13	3.11	3.07	3.00
15	1.83	11.0	51.02	11.25	3.03	3.03	3.02
16	1.83	11.0	52.81	11.49	3.07	3.08	3.04
17	1.82	10.8	52.52	11.47	3.02	3.06	3.04
18	1.85	10.5	51.60	11.09	3.04	3.00	3.01
19	1.83	11.0	53.57	11.78	3.13	3.08	3.10
20	1.82	11.1	52.40	11.40	3.04	3.11	3.06

Table 5. Indirect ultrasonic velocities (V), Schmidt hammer values (SHV) and the derived compressive strengths (CS) of the limestone external south wall of Sta Marija Ta' Cwerra (Malta). Velocities were measured . Samples 1-10: Lower layer, Samples 11-20: Upper layer.

No	Lenght/Time (cm/❍s)	Mean V (Km/s)	SHV	CS (MPa)
1	3/29.4 5/51.2 6/62.5	0.983	29	22.0
2	3/24.2 5/38.7 6/46.4	1.275	30	24.0
3	3/27.5 5/48.1 6/55.2	1.072	29	22.0
4	3/29.9 5/49.6 6/62.1	0.997	29	22.0
5	3/21.5 5/34.1 6/42.2	1.426	32	28.0
6	3/19.5 5/32.0 6/39.1	1.535	33	29.5
7	3/20.0 5/32.9 6/39.2	1.517	33	29.5
8	3/18.8 5/31.4 6/37.4	1.597	33	29.5
9	3/21.4 5/35.2 6/43.2	1.403	32	28.0
10	3/23.3 5/39.2 6/47.1	1.279	30	24.0

7. Conclusions

In the present paper four Mediterranean monuments were studied regarding the physical and mechanical properties of the building stones used. 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)".

During this study several non-destructive experimental methods were used in order to determine their ability in investigating the changes of the physico-mechanical behaviour of the stones regarding to their anisotropy and weathering conditions. The purpose was to establish a common methodology of research, in which the minimum testing material from the monument is necessary to be used.

The abrasion resistance proposed technique can provide data concerning the surface hardness of a rock sample. The knowledge of this property is very useful, especially after accelerated experimental weathering and consolidation.

The P & S waves velocities, using the direct and indirect methods, provide data not only for the mechanical behaviour and the deformation ability of a stone but also for its anisotropy, the weathering conditions and the depth of weathering at a stone surface. It can also be used to distinguish very similar geological layers, like in the limestone of Malta. It can be used for laboratory and *in situ* measurements.

The Schmidt hammer can be used in the weathering mapping of a stone wall surface, providing data which are related to the surface weathering conditions as well as to the surface compressive strength of the stones. The test results collected using this method are related significantly to that collected using the indirect ultrasonic technique, confirming so the accuracy of the method used.

The uniaxial compressive and tensile strengths as well as the dry density and water absorption were performed using only small specimens and the results were correlated with other acceptable properties.

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