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Estimation of damage at the surface of stones using non destructive techniques

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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. In this framework, P & S wave ultrasonic velocities can be used for both *in situ* and laboratory measurements. In the present paper the above methods was used for the study of properties like the mechanical anisotropy, weathering degree, mechanical strength and deformation ability of stones, using data from different countries, like France, Italy and Greece. The P-waves were also used, in indirect mode, for the estimation of the depth of weathering at the stone surfaces of three representative monuments in Greece.

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. So, 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 provide data related to the elasticity, anisotropy and mechanical and weathering resistance of the stones. Porosity, dry density, water absorption and abrasion resistance can also tested on small specimens, providing data related to weathering.

2 Ultrasonic velocity (V, ASTM 597, ASTM D 2845- 83)

It is a good index characteristic not only for determining the physico-mechanical behaviour but also for evaluating the weathering degree of the rocks. For this purpose a PUNDIT ultrasonic non destructive digital tester is used. Measurements are applied along the axis of the core samples and the travel time of the 54-KHz source pulse was measured (*for in situ* measurements a pair of small edge transducers of 500-KHz could give more reasonable results). Specific transducers of 300 kHz are used in the case of P and S wave velocity measurements. Water pump grease, covered with a specific membrane, is used as coupling media, to improve the acoustic contact between the sample and the transducers. The instrument is calibrated with aluminium standards. Thickness and travel time corrections are calculated by performing a linear regression between the actual and the measured times.

Ultrasonic velocity is related to the moduli of elasticity of rocks, such as Young's modulus and Poisson's ratio. Furthermore, it is a very good index for rock quality classification and weathering determination (Topal & Doyuran [10]).

Tests are 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, refers to 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 PUNDIT 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.

The ultrasonic velocity tests can also be used for the determination of the dynamic elastic moduli which express the deferability of rocks. The most common of them are the Modulus of Elasticity or Young's Modulus (E) and the Poisson's Ratio (ν) calculated using the following formulas:

$$\mathrm{E_d} = \mathrm{kdV_s^2}\,\frac{3V_p^2 - 4V_s^2}{V_p^2 - V_s^2}\,, \quad v_d = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}$$

Dynamic elastic moduli are obtained by rapid application of stress to the sample. Two different dynamic methods can be used for this purpose. The first method uses P & S wave ultrasonic velocity measurements, along core specimens

(Bruneau et al.[2]), while the second uses the excitation and detection of mechanical resonance frequencies in small cylindrical rods and prismatic bars (Spinner & Tefft[9], Glandus[7]). The procedure of the last method consists of exciting a specimen by means of a light external mechanical impulse and of the analysis of the transient natural vibration during the subsequent free relaxation (Mosse[8]).

Test results compared statistically each other in our previous work made using eight different lithotypes from France, determined regressions for an accurate expression of the static elastic moduli using dynamic, non-destructive techniques (Christaras et al.[4], Table 1). Typically the dynamic modulus of elasticity is greater than the static one, because the response of the specimen to very short duration strain and low stress level is essentially purely elastic (Clark[6]).

Table 1. Ultrasonic velocity and mechanical resonance frequency methods. (eight different rock types from France, Christaras et al.[4])

X / Y	Regression	Correl. Coef. (r)	Standard deviation
PUNDIT dynamic / Static Elasticity Modulus	E_{st}-3.16+1.05E_d	0.994	38.02
GRINDO-SONIC dynamic / Static Elasticity Modulus	$E_{st}=-3.12+1.05E_{dg}$	0.997	38.02
PUNDIT dynamic / Static Poisson's Ratio	$n_{st}+0.063+0.71n_d$	0.737	0.057
GRINDO-SONIC dynamic / Static Poisson's Ratio	$n_{st}=0.029+0.85n_{dg}$	0.962	0.057
PUNDIT / GRINDO-SONIC P-wave velocities	$V_{pg}=-270.85+1.05V_p$	0.988	1334
PUNDIT / GRINDO-SONIC S-wave velocities	$V_{sg}=45.72+1.01V_s$	0.982	801.9
GRINDO-SONIC / PUNDIT Elasticity Modulus	$E_d=0.83+0.98E_{dg}$	0.992	35.79
PUNDIT P-wave / Static Elasticity Modulus	$E_{st}=3.02e^{0.00055Vp}$	0.970	38.02

3 Surface weathering

The depth of weathering at a stone surface can be evaluated using the indirect ultrasonic velocity technique (Zezza[12]). In this case the transmitter is placed on a suitable point of the surface and the receiver is placed on the same surface at successive positions along a specific line. The transit time is plotted in relation to the distance between the centres of the transducers. A change of slope in the plot could indicate that the pulse velocity near the surface is much

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lower than it is deeper down in the rock. This layer of inferior quality could arise as a result of weathering.

The thickness of the weathered surface layer may be estimated as follows:

$$D = \frac{Xo}{2}\sqrt{\frac{Vs - Vd}{Vs + Vd}}$$

Where Vs: Pulse velocity in the sound rock (Km/s)
Vd: Pulse velocity in the damaged rock (Km/s)
Xo: Distance at which the change of slope occurs (mm)
D: depth of weathering (in mm)

The above method was performed on the building stones of the walls of Kapnikarea church and Osios Lucas Monastery (Greece, Figures 2 & 3). Some representative diagrams of this research are given in Figure 1, where the weathering depth was calculated, at the change of slope of the curve.

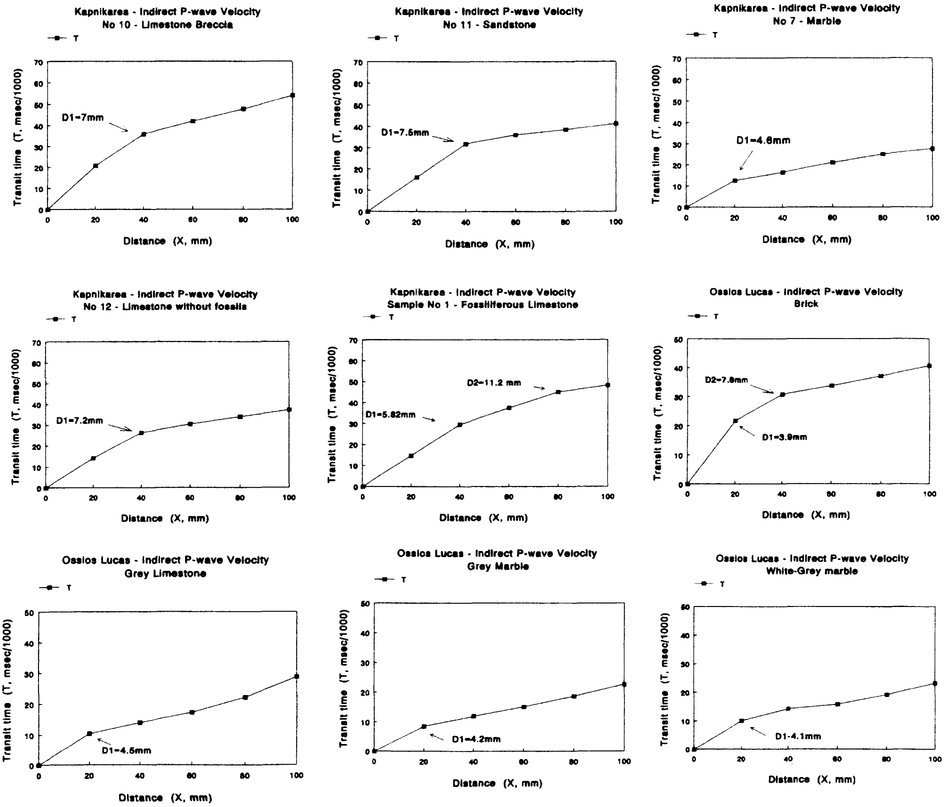

Figure 1. Estimation of the depth of wethering at the stones of Kapnikarea Church and Ossios Lucas Monastery

3.1 Compact or porous materials

Additionally to the previous examples two representative diagrams from the Macedonian Tomb of Anthemion (3rd c. BC, in Naousa City of N. Greece, Alamani[1], Christaras et al.[5]) are given in Figure 5. The first diagram corresponds to the marble of which the main door of the tomb is constructed (Figure 4). In this diagram the travel time of P-waves is constant in depths higher than 6.9 mm.

The second diagram corresponds to travertine, which is the construction material of the walls. The curve, in this diagram, does not present the simplicity of the previous diagram. The changes of the slope at the curve are related to the porous character of the material, in parts dipper than 6.38 mm. So, the two parallel lines correspond to the compact parts of the travertine, presenting similar soundness.

Comparing the above diagrams we could say that the estimation of the weathering depth is more accurate in compact

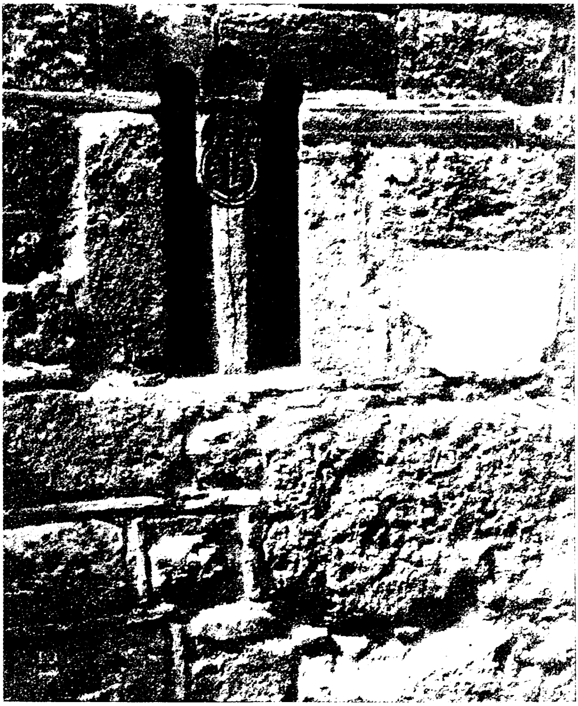

Figure 2. A part of the Kapnikarea Church

Figure 3. The church in the Ossios Lucas Monastery

materials than in porous ones.

4 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, related to weathering, is expressed by the Young's modulus (E). Ultrasonic velocity measured along different directions can determine the anisotropy of the physico-mechanical behaviour of rocks, according to the above mentioned results, between static and dynamic determination of the elastic moduli. Data obtained, using a provisional system of x,y,z axes, can determine the global reference ellipsoid of anisotropy in the space (Zezza[11]).

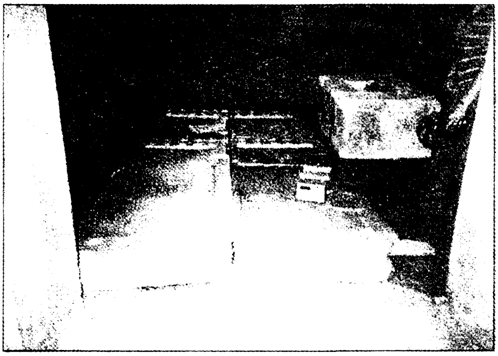

Figure 4. The marble front door in Anthemion Tomb

For this purpose, P and S are velocities (V_p, V_S) were measured along the main axis of cylindrical specimens oriented along the three perpendicular principal axes of rock-fabric. The cylindrical specimens are placed between the 300 kHz P & orthogonal S1, S2 wave transducers of the PUNDIT velocimeter. Measurements, for both P & S waves, are taken, in every 20 Gra, rotating the specimens around their main axis. Furthermore measurements of radial P wave velocities ($V_{p(rad)}$) are made in every 20 Gra (grades), around the cylindrical surface of the specimens, at every 1 cm of length. The specimens are of dia. 5 cm x 10 cm length. The anisotropy was expressed by the ratio of P-wave velocity along the axis of the cylinder versus radial P-wave velocities ($V_p/V_{p(rad)}$) as well as the ratio of P-wave versus S-wave velocities (V_p/V_s) (Christaras[3]).

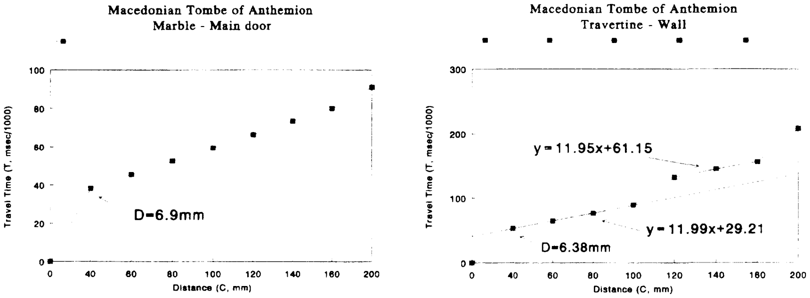

Figure 5. Estimation of the depth of weathering of stones from the Macedonian Tomb of Anthemion

Test results from our previous investigation on the anisotropic rhyolite of Vandeé (France) and the marble of Carrara strengthens the accuracy of the above non destructive methods in determining the anisotropy of the rocks (Table 2).

Table 2. Anisotropy of the Marble of Carrara and the rhyolite of Vandée. Relationships showing the accuracy of the use of the ratios Vp/Vp_{rad} and Vp/Vs as expressions of mechanical anisotropy.

Axis	Marble of Carrara (Italy)	Rhyolite of Vandée (France)
X	$E=66.23-22.21(Vp/Vp_{rad})$ $r=-0.968$	$E=81.86-5.90(Vp/Vp_{rad})$ $r=-0.931$
Y	$E=73.55-24.39(Vp/Vp_{rad})$ $r=-0.907$	$E=84.86-11.39(Vp/Vp_{rad})$ $r=-980$
Z	$E=56.57-9.53(Vp/Vp_{rad})$ $r=-898$	$E=83.15-21.52(Vp/Vp_{rad})$ $r=-0.779$
X	$(Vp/Vs)=0.91+0.73(Vp/Vp_{rad})$ $r=0.969$	$(Vp/Vs)=1.69+0.96(Vp/Vp_{rad})$ $r=0.932$
Y	$(Vp/Vs)=1.04+0.54(Vp/Vp_{rad})$ $r=0.797$	$(Vp/Vs)=1.54+0.19(Vp/Vp_{rad})$ $r=0.979$
Z	$(Vp/Vs)=1.3+0.30(Vp/Vp_{rad})$ $r=0.898$	$(Vp/Vs)=1.07+0.55(Vp/Vp_{rad})$ $r=0.774$

5 Conclusions

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, and the weathering conditions.

The depth of the weathered layer at the surface of a stone can be easily estimated using indirect ultrasonic techniques.

The accuracy of this method is higher in compact materials than in porous ones.

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