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P-WAVE VELOCITY AND QUALITY OF BUILDING MATERIALS

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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 waves ultrasonic velocities can be used for both *in situ* and laboratory measurements. These methods are used for studying properties such as the mechanical anisotropy, and the modulus of elasticity of the materials. In this paper, the P-wave velocities were used for the estimation of the depth of weathered or artificially consolidated layers as well as the depth of cracks at the surface of the building stone. This estimation was performed in relation to the lithology and texture of the materials, given that in many cases different lithological data create similar diagrams. All tests were performed on representative monuments in Greece.

INTRODUCTION

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 and the measured velocities.

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, 1995).

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.

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., 1995), while the second uses the excitation and detection of mechanical resonance frequencies in small cylindrical rods and prismatic bars (Spinner & Tefft, Glandus, 1961). 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, 1990).

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., 1994, 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, 1966).

Table 1. Relationships between dynamic and static modulus, according to the Vp, Vs data (measurements on eight different rock types from France, Christaras et al., 1994)

X / Y	Regression	(r)	St. D.
(Dynamic / Static) Elasticity Modulus	E_{st}-3.16+1.05E_d	0.994	38.02
(Dynamic / Static) Poisson's Ratio	n_{st}+0.063+0.71n_d	0.737	0.057
P-wave / Static Elasticity Modulus	$E_{st}=3.02e^{0.00055Vp}$	0.970	38.02

SURFACE WEATHERING AND DEPTH OF CRACKS

The depth of weathering at a stone surface can be evaluated using the indirect ultrasonic velocity technique (Christaras,1997, Zezza, 1993). 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 lower than it is deeper down in the rock. This layer of inferior quality could arise as a result of weathering.

According to this plot, the thickness of the weathered surface layer is estimated as follows {Vs: pulse velocity in the sound rock (Km/s), Vd: pulse velocity in the damaged rock (Km/s), Xo: horizontal distance at which the change of slope occurs (mm), D: depth of weathering (in mm)}:

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

The arrangement of the transducers at the same surface of a stone, but from the opposite sides of a

$$h = \frac{L}{2}\left(\frac{T_2}{T_1} - \frac{T_1}{T_2}\right)$$

crack can be used for estimating the depth of the crack. In the obtained diagram, a vertical displacement of the regression is occurred, due to the depth of the crack. This depth is estimated using the following equation {h: depth of crack, L: horizontal distance of displacement, T1, T2: times before and after the crack (at the point of the displacement)}:

Figure 1. Location of the investigation sites

APPLICATION OF THE METHOD

Two representative diagrams from the Macedonian Tomb of Anthemion (3rd c. BC, in Naousa City of N. Greece, Alamani, 1995, Christaras et al., 1997, Fig. 1) are given in Figures 2 and 4. The first diagram corresponds to the marble of which the main door of the tomb is constructed (Fig. 3). In this diagram the travel time of P-waves is constant in depths higher than 6.9 mm.

The second diagram (Fig. 4) corresponds to travertine, which is the construction material of the walls (Fig. 5). The curve, in this diagram, does not present the simplicity of the previous diagram but the pores of the stone causes parallel displacement of the regression line.

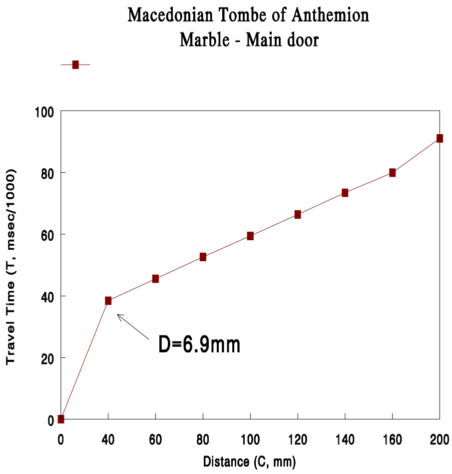

Figure 2. Estimation of the weathering depth at the surface of the marble door in Anthemion Macedonian Tomb

Figure 3. The marble door of the Anthemion Tomb (Lefkadia Macedonian Tomb, N. Greece).

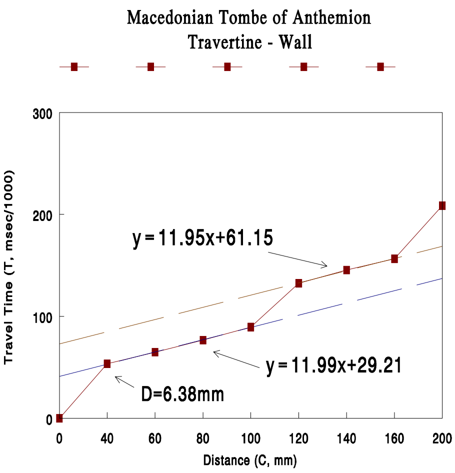

Figure 4. Ultrasonic velocities measured on the surface of travertine blocks from Lefkadia Macedonian tombs. The displacement of the curve corresponds to the big pores of the materials.

Figure 5. Travertine blocks from Lafkadia Macedonian Tombs.

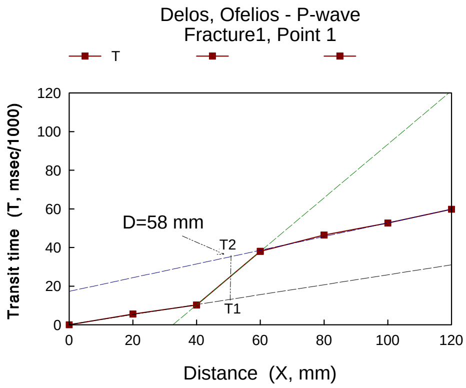

Figure 6. Ultrasonic velocities diagram on the surface of Ophelios marble statue (Delos island, Greece), for estimating the depth of a crack along its left leg.

Figure 7. Gaios Ophelios statue, in Delos island (Greece)

In the diagram of Figure 6, the depth of a crack was calculated along the leg of the statue of Gaios Ophelios in Delos Island (Fig. 7).

The above mentioned displacement of the regression line, cannot only related to the pores or the cracks but also to the conditions of a treated surface using consolidation liquids. These liquids produce a consolidation external zone which provides (?) mechanical characteristics, similar to the sound inner parts. This consolidation depth can also be estimated, giving information about the efficiency of the consolidation materials used. This application was performed on the walls of the Medieval City of Rhode and some representative results are presented in the diagrams of Figures 8 and 9. These diagrams correspond to measurements on two neighbouring sites on the same wall of St. Aikaterini monument (Fig. 10).

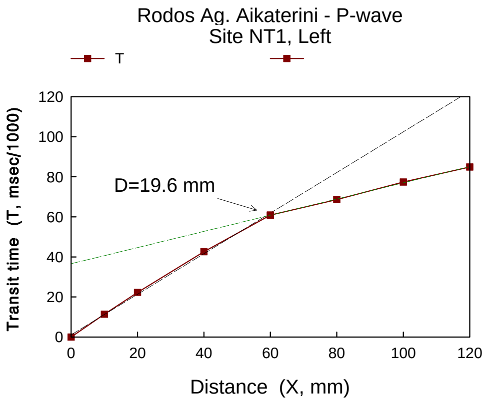

Figure 8. Ultrasonic velocities measured on untreated surface of calcarenitic blocks. The change of the regression slope corresponds to the depth of the weathered zone.

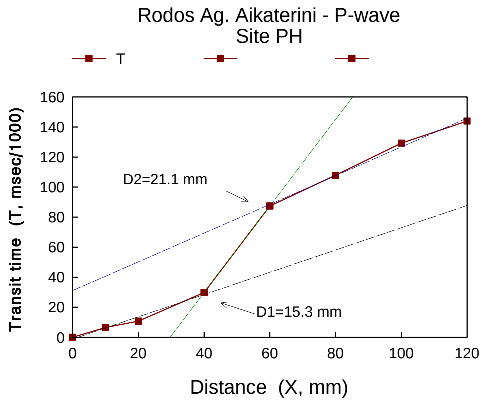

Figure 9. Ultrasonic velocities measured on the surface of calcarenite blocks, treated with consolidation liquid. The change of the regression slope corresponds to both consolidation and weathering depths.

Figure 10. The calcarenite blocks where the measurements of Figures 8 & 9 were performed.

USE FOR DETERMINING THE QUALITY CHANGES OF LIME DURING CALCINATION

The ultrasonic techniques were also used in order to determine quantitatively the quality changes of the lime during the calcination of the limestone. The tests were performed using the direct method, referred to the arrangement of the transducers of the apparatus on the opposite surfaces of the specimen tested. This method was selected because the final product is usually very weak and the static methods are impossible to be used. The P & S wave velocities were measured in different temperatures (650, 950 and 1,050^o C) and the determined high correlation coefficients improved the reliability of the method used (Kantiranis et. al, 2001, Figures 11, 12).

The quicklime produced from this process has very weak mechanical characteristics, so it is very difficult to determine the quality of this product using static methods. These methods are unable to be applied on the lime because they destroy the specimens and the results are not reliable.

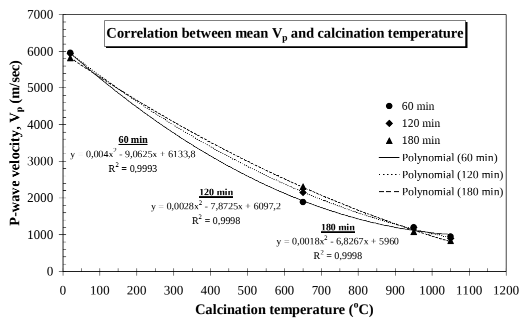

Figure 11. Correlation between mean P-wave velocity and calcination temperature at different retention times (Kantiranis et al, 2001).

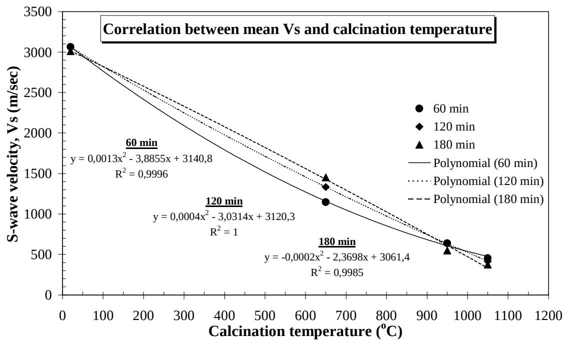

Figure 12. Correlation between mean velocity of S-waves (m/sec) and calcination temperature (^oC) at different retention times (Kantiranis et al., 2001)

CONCLUSIONS

The change of the P-wave velocity gives information for the depth of damage, or the quality change, at the external layers of a stone or mortar. The depth of cracks can also be evaluated.

The important is that different causes provide similar diagrams, with almost parallel displacement of the regression line. This displacement is due either to the pores and the cracks of the material or also to the artificial consolidation of the external layers. The presence of phenocrysts, causing higher or lower velocities than in the rest parts of a rock, can also provide similar diagrams to that described previously confirming that the accuracy of the method is directly related to the good knowledge of the lithology and the texture of the materials.

The significant correlation observed between the P & S waves velocities and the calcination temperatures improves that the ultrasonic technique gives reliable information on the quantitative conversion of limestone into lime, during a calcination process, in different temperatures. The use of this non-destructive technique is very useful, taking into account that the final material is very soft and humidity changes it easily into powder so as to be practically impossible to use static methods for tests.

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REFERENCES

Alamani, V., 1995. The ancient mieza. Kopanos, lefkadia, naousa. Municipality of Naousa & IZ Ephorate of Prehistoric & Classic Antiquities, Thessaloniki.

Bruneau, C., Forrer, A. & Cuche A., 1995. Une méthode d' investigation non destructive des materieaux pierreux: les mesures à l' ultrason. *Proceedings of the Congr. LCP '95: Preserv. and Restor. of Cultur. Heritage*, Montreux, 187-195.

Christaras, B., Auger, F. & Mosse, E., 1994. Determination of the elastic moduli of rocks. Comparison of the ultrasonic velocity and mechanical resonance frequency methods to the direct static one. *Materials & Structures*, 27, 222-228.

Christaras B., 1997, Estimation of damage at the surface of stones using non destructive techniques. *STREMAH V (5th Int. Congr. Structural Studies, Repairs and Maintaince of Historical Buildings).* San Sebastian, *in* Advances in Architectural Series of Computational Mechanics Publ., Southampton, pp. 121-128.

Christaras B., Mariolakos I., Foundoulis J., Athanasias S. & Dimitriou A., 1997. Geotechnical input for the protection of some Macedonian Tombs in Northern Greece. *Proceedings of the IVth International Symposium on the Conservation of Monuments in the Mediterranean Basin*, Rhodes, pp. 125-132.

Clark G.B. 1966. Deformation moduli of rocks.- *Am. Soc. Test.Mat., Spec. Tech. Publ.*, 402, 133-174.

Glandus jI.T., 1981. Rupture fragile et resistance aux chocs thermiques de ceramiques à usages mécaniques.- Th. doc. Univ. of Limoges, p.224.

Kantiranis N., Christaras B., Filippidis A. & Tsirambides A. 2001. The usage of ultrasonic techniques at calcination studies. "*Aggregates 2001 – Environment and Economy" – Proc. Int. Congr. of Finnish IAEG Nat. Group, Bull. of Tampere Univ. of Technology, ISBN 952-15-0636-9, V. 50(2), pp. 389-394.*

Mosse E., 1990. Relations entre vitesse du son, module d' elasticité et coefficient de Poisson, mesurés par des méthodes statiques et dynamiques. application aux matériaux pierreux.- D.E.A., Univesr. Poitiers, La Rochelle, 1-100.

Spinner S. & Tefft W.E.., 1961. A method for determining mechanical resonance frequencies and for calculating elastic moduli from these frequencies.- *Proceedings of the A.S.T.M.*, 61, 1229-1238.

Topal, T. & Doyuran V., 1995. Ultrasonic testing of artificially weathered cappadocian tuff. *Proceedings of the Congr. LCP '95: Preserv. and Restor. of Cultur. Heritage*, Montreux, Switzerland, 205-213.

Zezza, F., 1993. Evaluation criteria of the effectiveness of treatments by non destructive analysis. *Proceedings of the 2nd Course of CUN University School of Monument Concervation*, Heraklion, 198-207.