Application of non destructive ultrasonic techniques for the analysis of the conservation status of building materials in monumental structures

Basile Christaras[1], Francesco Cuccuru[2], Silvana Fais[2], Helen[1] Papanikolaou

[1] Lab. of Engineering Geology & Hydrogeology, School of Geology, Aristotle University of Thessaloniki AUTH (Greece), christar@geo.auth.gr

[2] Dipartimento di Ingegneria Civile, Ambientale e Architettura DICAAR, Università degli Studi di Cagliari (Italy), sfais@unica.it

Some examples of application of ultrasonic methods were chosen in different test areas located in Southern Sardinia (Italy) and Northern Greece coastal areas:

- Cagliari town (Southern Sardinia – Italy), masonry structure and architectural element of an ancient monument.
- Dion archeaological site (N. Greece).

The study on the above mentioned monument was focused on the application of ultrasonic techniques in the low frequency range (24-54 kHz), with the aim to verify the conservation status of their building materials by means of the study of the longitudinal ultrasonic pulses propagation.

Compressional velocity has been related to the physical, textural and mineralogical-petrographic features of the investigated materials, to correlate their intrinsic properties with the elastic ones.

On the base of the laboratory ultrasonic measures, in *situ* investigations have been performed to identify the areas affected by degradation, quantify the intensity of weathering and monitoring his evolution. In addition, the methodological approach used in this study has proved to be useful also to reconstruct the texture of walls under the plaster or in the outcropping masonry structures, where the degradation makes it difficult the macroscopic identification of building materials.

Keywords: Ultrasonic velocity, historical buildings, monument protection, weathering description.

1. Introduction

The need to recover the historical buildings for a reuse allowed a significant expansion of non-destructive diagnostic investigations. With non-destructive tests it is now possible to get all the qualitative and quantitative parameters useful to formulate a plan of recovery and preservation of a monumental structure.

Nowadays, the non-destructive ultrasonic method represents one of the most reliable diagnostic methods used in the building materials of monumental structures. The high relationship between propagation velocity of the ultrasonic pulses in stone materials and its physical, textural and mineralogical features is the strength of this method. The integrated analysis of ultrasonic method with the physical and mineralogical-petrographic data of building materials, allows obtaining important information about the conservation status of the monumental structures. The changes in time of the elastic properties, observed by means of ultrasonic measures, identify the evolution of degradation in building materials and provide useful information about the effectiveness of restoration works. In fact, alterations in the materials, normally, cause a decrease in the longitudinal pulse velocity values and therefore the longitudinal velocity values can be considered representative of the elasto-mechanical behaviour of the stone materials.

2. The case study of Cagliari (Italy)

2.1. Materials and methods

2.1.1. *Materials*

The stones used in the building of the monumental structures of Cagliari (Italy), come from a prevalently carbonate succession, cropping only in the town hills, known as "Calcari of Cagliari Auct". This sedimentary complex, attributed to Tortonian-Messinian, is formed by three different limestones which from top to bottom are called: *Pietra Forte*, *Tramezzario* and *Pietra Cantone*.

Pietra Forte is a bioclastic shelf limestone very compact, tenacious, very hard, poorly porous, even if in some cases can be intensely fractured and interested by many carsic cavities.

Tramezzario is a white, well lithified, bioclastic limestone without stratification. It can be characterized by an intense fracturation associated with the alteration and the disaggregation of the rock, making it very porous and making to assume it the characteristics of a loose rock.

Pietra Cantone is a bioclastic, limestone without stratification, frequently bioturbated. Generally it is a very soft stone, characterized by an elevated porosity and by an elevated percentage of matrix that make this rock very hygroscopic. The low cementation of the granules causes disaggregation in the rock, especially in conditions of strong humidity.

Samples of these limestones have been analyzed for determining their mineralogical and textural characteristics using respectively X-ray diffraction and thin sections observed to petrographic microscope.

The different textural characteristics of the three lithotypes regulate the intensity of the degrade process. In the cases of the *Pietra Cantone* and *Tramezzario*, that are characterized by a high porosity (>20%), the processes of erosion, alveolization, disaggregation and detachment (Fig. 2.1.1. a - b) are frequent. In the matrix supported limestones (*Pietra Cantone*) a large quantities of water can be accumulated. This fact causes the degradation of the stone. In the *Pietra Cantone* is frequent the alveolization, that causes the formation, on the stone surface, of cavities (alveoles) which may be interconnected and may have variable shapes and sizes. *Pietra Forte*, that is a shelf limestone, is more resistant than the *Pietra Cantone* and *Tramezzario*. However, if the *Pietra Forte* is fractured, the materials near the discontinuities are subject to the oxidation and to the detachment (Fig. 2.1.1.1 c).

Fig. 2.1.1.1. Differents types of degrade: a) Alveolization of the *Pietra Cantone*, b) Detachment of material from a wall of *Tramezzario,* c) Detachment of material from an architectural element of *Pietra Forte.*

2.1.2. Laboratory and in situ ultrasonic measurements

One of the most effective tools in restoration and rehabilitation of monumental structures is the ultrasonic inspection which includes the assessment of damaged or altered zones, cracks, defects and elasto-mechanical characterization of stone materials (Galan et al., 1991, Christaras B., 1997, Casula et al., 2009; Fais & Casula, 2010).

The ultrasonic techniques are effective both for laboratory and site conditions and they have increasingly been used to determine the dynamic properties of rocks and then their mechanical behaviour. In fact the ultrasonic velocity of a rock is closely related to the rock properties. Therefore, the velocities of longitudinal wave (Vp) have been calculated for the different type of limestones under study. The ultrasonic measurements have been performed on laboratory condition on prismatic unaltered specimens (12x12x24 cm) prepared for the application of the ultrasonic techniques according to C.N.R. - I C R - Normal - 22/86 (1986). The mentioned ultrasonic measurements were performed using the Portable Ultrasonic Non-Destructive Digital Indicating Tester (PUNDIT) by C.N.S. Electronics LTD.

Table 2.1.2.1. Ultrasonic Velocities measured in laboratory

Lithotype	**Vp (m/s)**
Pietra Cantone	3000
Tramezzario	4500
Pietra Forte	6000

On the basis of the results of the laboratory tests, in situ ultrasonic measurements on significant monumental structures in order to check zones of weakness, to assess the alterability of the investigated stones and evaluate the restoration effectiveness have been also carried out. In fact, as it is known, alterations in the material lower the ultrasonic velocity value, which can be considered representative of its elastic status. Longitudinal pulse ultrasonic velocities were measured in situ using the above mentioned portable ND indicating tester (PUNDIT) with 54 kHz transducers. As cases study, some architectural elements of the church of S. Chiara on the historical downtown of Cagliari, were tested. S. Chiara church is an important monument built in the seventeenth century in the historic district of Stampace. It was one of the most popular religious sites of the city in the past centuries. Nowadays, closed to worship, the church has become an important point of performance of cultural events such as visual art exhibitions, concerts and theatrical works.

3. Application

3.1. The case of the church of S. Chiara

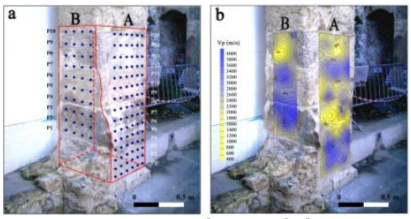

Fig.3.1.1. acquisition scheme and ultrasonic longitudinal velocity maps of faces A & B.

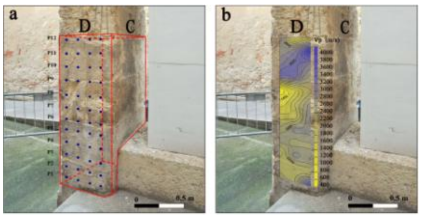

Fig. 3.1.2. Acquisition schemes and ultrasonic longitudinal velocity maps of faces C & D

In this paper the results obtained on an outside structural element (external pillar) of the church of S. Chiara are presented. Tests have been performed both by indirect (surface).

Ultrasonic measurements by indirect transmission have been carried out on the surfaces of the pillar to know the conditions of the building materials on its superficial parts. The measurements of the traveltime of the ultrasonic signal from transmitter to receiver were carried out along parallel profiles in a vertical direction and particular care was given to take measurements at the same level in all the profiles. Starting from the measured traveltime of the ultrasonic signal and considering as space the distance between transmitter and receiver, the apparent propagation velocity at each observation point along the profiles was computed. The values of the longitudinal ultrasonic velocity were contoured to represent the distribution of the velocity on the investigated surfaces with the aim of detecting damages and degradation zones by studying the velocity variations. In fact, ultrasonic signal characteristics change as the wave propagates through the carbonate materials with varying properties such as porosity, pore types, mineralogical and petrographical composition also as a result of degradation. In figures 3.1.1 (a,b) and 3.1.2 (a,b) are reported both the acquisition schemes and the ultrasonic longitudinal velocity maps of the accessible faces of the pillar respectively named A, B, C and D. The low velocity areas (yellow zones) in the map represent mainly degradation of the limestones and weakness zones, as can be also deduced both comparing the in *situ* velocity measurements with the laboratory results and considering the information from the petrographical study.

4. The case of Dion archaeological site (Greece)

4.1. Historical data

Dion in Pieria of Macedonia was one of the most important religious centers of the ancient Greeks from the 5th century BC. Built at the eastern foothill of Mount Olympus, it was on the road leading from Thessaly to Macedonia. In antiquity it was just 1.5 km from the coast of the Thermaikos Gulf. Vaphyras, a navigable river passing to the east of the ancient city, provided a link to the sea, through the extensive marshlands and shallow lagoons of its estuary.

4.2. Representative application of ultrasonic technique

The application was performed on conglomeratic blocks along the main street of the archaeological site. According to the mineralogical study, these conglomerates consist mainly of limestone. Dolomite is also secondary found, together with trace of quartz and micas.

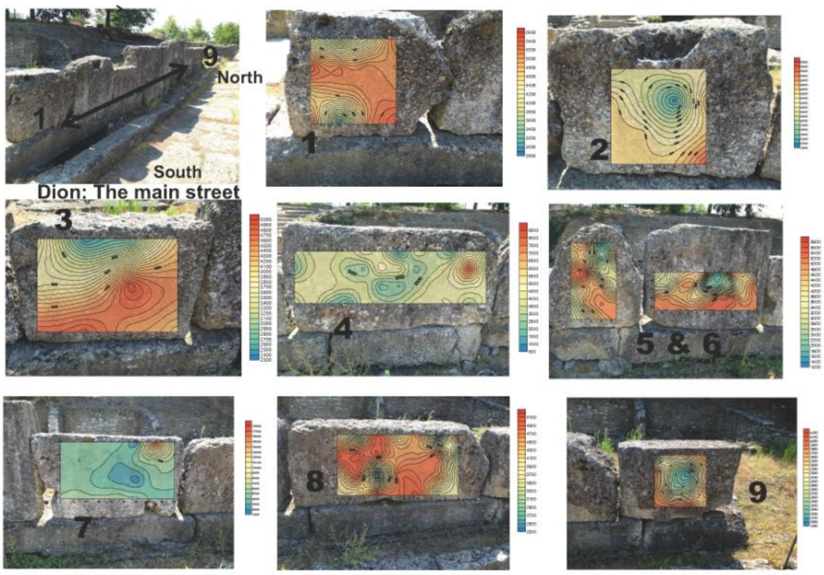

Fig. 4.2.1. Ultrasonic velocity mapping related to the surface weathering of stones, along the main street of Dion archaeological site

Ultrasonic velocity was used for mapping the weathering degree of the conglomeratic blocks (Fig. 4.2.1). For this purpose, a small portable UK140l ultrasonic tester was used in the present investigation, additionally to a "Pundit Lab ultrasonic tester" which was, also, used in our investigation. Measurements were applied, indirectly, on the same surface of the stones, which are located along the, S-N direction, street (Fig. 4.2.1). The measurements taken by indirect method (transducers placed on the same surface) are lower (about the 2/3) than those taken by direct method (transducers placed at the opposite sites of a stone), for the same stone, because the first measurements refer to the surface quality instead of the second which refer to the inner quality of the stone (Christaras 1998).

5. Conclusion

In this study, representative surfaces of calcareous pillars of Sta Chiara (Cagliari) and thin calcareous-conglomeratic plates of the main street of Dion archaeological site were mapped regarding to their surface weathering, using indirect ultrasonic technique.
The result of this weathering mapping can give information for the consolidation of these stones against weathering.

6. References

Casula, G., Fais, S. and Ligas, P. 2009. Experimental application of 3-D Laser Scanning and acoustic techniques in assessing the quality of stones used in monumental structures. *International Journal of microstructure and materials properties*, 4, 45-56.

Christaras, B. 1997. Estimation of damage at the surface of stones using non-destructive techniques. *Proceedings of the 5th International Congress of structural studies, repairs and maintenance of historical buildings*. San Sebastian, in Advances in Architectural Series of Computational Mechanics Publications, Southampton, 121-128.

Christaras, B. 1998. Non-destructive methods used for the estimation of the damage (weathering and cracks) of the building and ornamental stones. *PACT 55 (Revue du Conseil de l' Europe), pp. 213-219).*

Fais, S. and Casula, G. 2010. Application of acoustic techniques in the evaluation of heterogeneous building materials. *NDT & E International*, 43, 62–69.

Galan, E., Guerrero, M.A., Vasquez, M.A., Maert, F. and Zezza, F. 1991. Marble weathering: relation between ultrasonic data and macroscopic observations. The case of the columns of the court of the lions at the Alhambra in Granada, Spain. *Proceedings of the 2nd International Symposium "The conservation of monuments in the Mediterranean Basin"*. Geneve, Switzerland, 193-207.

Normal 22/86. 1986. *Misura della velocità di propagazione del suono*. Normativa Materiali lapidei, CNR-ICR, Rome.