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Non-Destructive Ultrasonic Testings on a Monumental Structure of The Historical Center of Cagliari (Italy)

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Abstract: *The Municipal Center for Art and Culture Exmà is an excellent result of the transformation of a mono-functional structure (the old abattoir of Cagliari) into a polyfunctional pole dedicated to art that has hosted major events since nineties. In order to monitor the conservation state of the building materials of this monument, mostly carbonate rocks, non-destructive ultrasonic analyses have been carried out since 2007. Ultrasonic data have been related to the physical and mineralogical-petrographic features of the investigated building materials, in order to correlate the elastic properties with their intrinsic ones. In situ ultrasonic investigations were performed on the outer walls of the main building of the monumental complex, subjected to various restoration works. The methodology used in this study proved useful to evaluate and monitor the weathering process, verify the effectiveness of the old restoration works and check the thickness of the weathered shallow part of the masonry by means of refraction techniques.*

Keywords: *degradation monitoring, monumental structures; refraction techniques, restoration effectiveness, ultrasonic velocity.*

I. Introduction

The work presented in this paper aims to highlight the diagnostic power of the non-invasive acoustic techniques, integrated by analysis of mineralogical and petrographic type, to formulate an interpretative model for the definition of elastic-mechanical characteristics and the conservative state of buiding materials.

As a case study is presented a diagnostic survey carried out in the old abattoir of Cagliari (Italy). This monument, now called Exmà (for *ex mattatoio, "mattatoio" being the Italian for "slaughter house"*), was one of the first urban spaces to be restored and handed back to the city. The complex was built between 1845 and 1852, using as building materials the calcareous stones from the historic quarries of the city. Restoration and modernization works made in 1993 converted the abattoir to a center of art and culture. Since then no conservative works have been carried out on the monument, except in the central building called *Sala delle Volte* (Fig. 1), where the external plaster was redone in 2014. The external masonry of the *Sala delle Volte* was monitored by acoustic non-destructive techniques in order to evaluate the conservation state of the building materials. Therefore, since 2007 a non destructive ultrasonic analysis, integrated with mineralogical-petrographic and petrophysical analyses, have been carried out in order to acquire the elastic-mechanical conditions of the building materials and understand the causes of their degradation. These integrated methods allowed to detect the evolution in time of the degradation, while taking into account the external factors (humidity, pollution, salts, etc.) as well as the physical and textural features of the materials.

Figure 1: Main building of the Exmà complex.

II. Materials And Methods

The non-destructive ultrasonic method is nowadays one of the most effective diagnostic methods for the monitoring of elastic-mechanical conditions and the conservation status of building materials of monumental structures [1, 2, 3, 4, 5, 6, 7, 8]. Thanks to the good relationship between propagation velocity of the ultrasonic pulses in building materials and its physical, textural and mineralogical - petrographic features it is possible to obtain important information about the degradation in monumental structures. By observing changes in time in the elastic properties by ultrasonic measures, it is possible to detect the evolution of the degradation forms in building materials and provide useful information about the effectiveness of previous restoration works. As a matter of fact, alterations in the materials normally cause a decrease in longitudinal pulse velocity values; thus the velocity values can be considered representative of the elasto-mechanical behaviour of the stone materials.

In order to know the intrinsic features of the building materials, *in situ* diagnostic surveys were preceded by laboratory tests on samples of the same unaltered carbonatic stones from the historical quarries of the city. Acoustic measurements in the 24kHz – 82kHz ultrasonic range were performed in laboratory on several specimens of the three different facies of limestones used as building materials, which were also studied from the mineralogical-petrographic and petrophysical point of view in order to correlate their intrinsic features with the elastic ones. Prismatic unaltered samples (12x12x24 cm) were prepared for the ultrasonic measurement according to CNR ICR Normal 22/86 [9] and for the study of the physical properties of the calcareous (carbonatic) rocks. A number of representative thin sections of the three lithotypes (*Pietra Forte*, *Tramezzario* e *Pietra Cantone*) were analyzed under optical microscopy in order to study their compositions, textural features and porosity. Based on the laboratory results, *in situ* diagnostic non-invasive analysis were planned and carried out to assess the elastic-mechanical conditions of the masonry building stone materials, identify the sectors affected by degradation, associate each building material to a different degradation susceptibility, evaluate the effectiveness of the restoration, quantify the intensity of weathering, and monitor its evolution.

2.1 Stone materials properties

The lithotypes used as building material in the Exmà complex belong to the Miocenic carbonate succession called "Calcari di Cagliari" [10], outcropping in the hills and along the coast of the city of Cagliari. This sedimentary complex, attributed to the Tortonian-Messinian [11], is made up of three different types of limestone, from top to bottom called: *Pietra Forte*, *Tramezzario*, and *Pietra Cantone*. These stones have different physical and textural features (Fig. 2) depending on the bathymetric changes in the sedimentation basin.

Pietra Forte (Fig. 2a) is a white gray, massive, well lithified, sometimes bioclastic, shelf limestone rich in Lithothamnium algae, formed in a littoral and sublittoral depositional environment, with high energy and paleobathymetry less than 30 m [12]. At microscopy observations *Pietra Forte* shows the typical textures of a boundstone [13], a shelf limestone with the carbonate components bound together by abundant Lithothamnium algae. In the *Pietra Forte* the porosity, which is about 1%-2%, is prevalently of a secondary type.

Tramezzario (Fig. 2b) is a white, bioclastic, well stratified, grain supported limestone, (grainstone, [13]), in which bioclasts mainly consist of algal fragments and mollusk macrofauna cemented by sparry calcite. According Leone [12] this lithotype seems to have been deposited at a maximum sea depth of 40 m. In the *Tramezzario*, the porosity, which is of a secondary type, is about 5%-10%.

Pietra Cantone (Fig. 2c) is a yellowish, poorly lithified, mud supported, bioclastic limestone (from mudstone to wackestone, [13]), without stratification, rich in pores (5%-20%), frequently bioturbated, with a fossiliferous content, consisting mainly of benthic and planctonic foraminifera. Its depositional environment is characterized by low-energy with paleobathymetry between 60m and 80m [12]. It is generally a very soft stone, which in conditions of strong humidity presents serious disaggregation problems. Among these three limestones some transition facies are present, with mixed textural features due to bathymetric variations of the sedimentary basin.

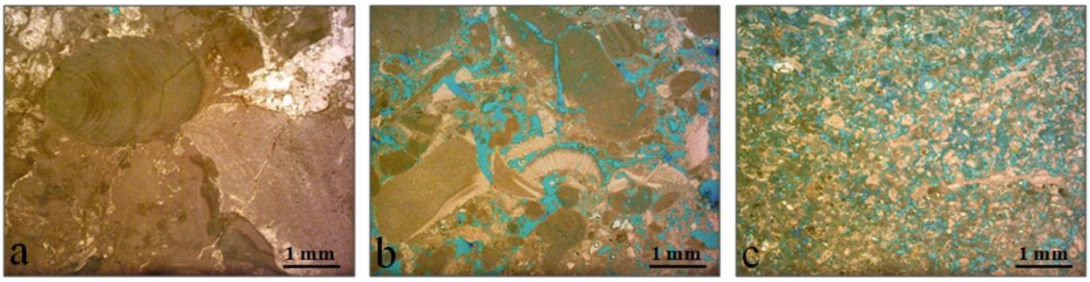

Figure 2: Textures of the *Calcari di Cagliari*: a) *Pietra Forte*; b) *Tramezzario*; c) *Pietra Cantone*. Thin sections treated with blue dye.

The petrophysical properties, such as apparent density and water content, were determined in laboratory according to UNI 9724/2-90 [14]. *Pietra Forte* presents a mean apparent density value of 2620 Kg/m^3 and a water absorption value of 2%. In the *Tramezzario* the apparent density is 2400 Kg/m^3, while the mean value of water absorption is 9%. In the case of *Pietra Cantone*, the presence of the microporous carbonate matrix causes an apparent density of 2230 Kg/m^3 and a water absorption of 12%.

The different textural and petrophysical properties of the three lithotypes determine the forms and intensity of the degradation process. In the cases of the *Pietra Cantone* and *Tramezzario*, which are characterized by a high porosity (>10%), processes of erosion, alveolization, disaggregation, detachment and pulverization are frequent. In the matrix supported limestones, such as *Pietra Cantone*, large quantities of moisture mixed with salts transported by the SE wind can accumulate causing alveolization in the stone. *Pietra Forte*, which is a poorly porous, well cemented shelf limestone, is more resistant than *Pietra Cantone* or *Tramezzario*. However, if the *Pietra Forte* is fractured, it can be affected by oxidation and detachment.

III. Results And Discussion

The laboratory ultrasonic tests were performed using the Portable Ultrasonic Non Destructive Digital Indicating Tester (PUNDIT) devices by CNS Electronics LTD and by Proceq (Fig. 3) in the 24kHz – 82kHz frequency range. Prismatic unaltered specimens were prepared to perform the ultrasonic measurements, using different acquisition techniques (direct, semi-direct and indirect) according to C.N.R. I C R Normal 22/86

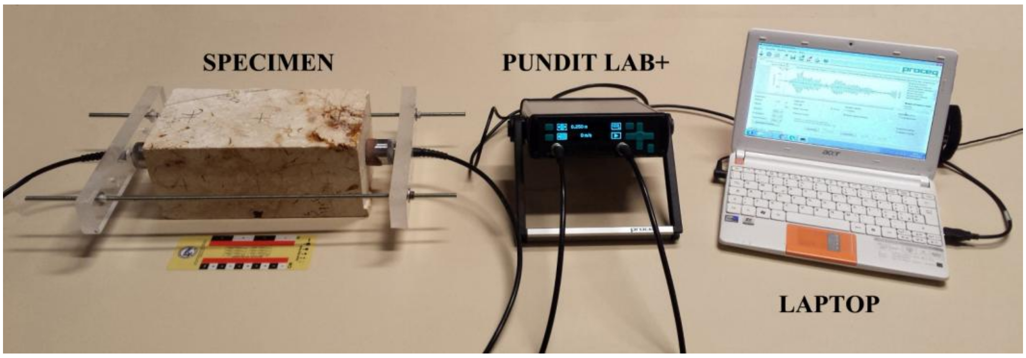

Figure 3: Equipment used for the ultrasonic measurements.

The measurements of compressional wave velocities (Vp), in dry and saturated samples, were carried out and the relationships between the elastic properties and the compositional, textural and petrophysical features were evaluated. As a matter of fact the propagation velocity of the ultrasonic pulses is closely related to the rock properties. In the *Pietra Forte* limestone, which is a well-cemented and poorly porous rock, the mean Vp values are 6000 m/s. In the *Tramezzario*, characterized by porosity and discontinuities among bioclasts, the mean longitudinal velocity is about 4500 m/s. In the porous and mud supported *Pietra Cantone*, the longitudinal velocity is 3000 m/s. In saturated samples of *Pietra Cantone* a significant reduction in the velocity values (from 3000m/s to 2200 m/s) was also observed. In this lithotype, the water brings on a decrease in cohesion among the particles of carbonate mud and determines a worsening of its elastic properties.

3.1 In situ diagnostic investigations

Diagnostic studies focused on the external walls of the *Sala delle Volte*, in the central building of Exmà. From 1993 to 2014, when the external plaster was restored, no maintenance was carried out on the structure. Until then, most of the plaster had broken away due to moisture held in the masonry, mainly *Pietra Cantone* blocks, which are highly hygroscopic.

Due to its inadequate collection and disposal of storm water, rainwater was discharged directly on the walls resulting in erosion and chemical weathering of the limestone blocks.

Another problem is the heterogeneity of the materials making up the masonries: i.e. fragments of brick and very friable mortar layers interconnected and overlapping with the original limestone blocks that led to phenomena of physical-mechanical incompatibility with consequent cracking and detachment of the plasters.

Considering the environmental aspects, the heterogeneity of the walls and the petrophysical characteristics of the stone building materials, it was decided to monitor the evolution of the degradation in time by non-destructive ultrasonic measurements. As an example, in this paper are present, the tests carried out on a panel of the south wall of the *Sala delle Volte*. Based on a preliminary investigation, a qualitative evaluation of the conservation status of the wall structure was carried out and ultrasonic surveys were designed in order to perform a quantitative diagnostic analysis of the elastic-mechanical properties of the building materials. The measurements were made by the ultrasonic "indirect" acquisition technique (Normal 22/86), positioning the transmitter and receiver on the surface to be investigated. The

reading of the transit times of ultrasonic pulses was achieved by PUNDIT and 54 kHz piezoelectric transducers. Ten horizontal profiles each of 24 observation points, were performed on the investigated panel. The velocity values for each observation point were calculated dividing the transmitter – receiver distance by the transit time of the longitudinal ultrasonic pulse. Thus, the velocity values obtained were contoured using a specific graphic software in order to achieve a bidimensional map of the distribution of the longitudinal ultrasonic velocity pulses. In order to facilitate the data interpretation, the map was overlaid in transparency on the digital image of the investigated panel. As deduced from different tests carried out in different conditions, the velocity values on the maps must be interpreted as relative. One possible tool to monitor the evolution of the weathering of the panel building materials is by in time ultrasonic monitoring. To determine the feasibility of the method, over a period of many years we acquired separate relative ultrasonic surveys that observed the distribution of the longitudinal velocity in time and in the same environmental conditions. As an example in Fig. 4, a,b, we show the 2007 and 2010 ultrasonic surveys.

Figure 4: Ultrasonic in time monitoring on an external panel of *Sala delle Volte* (Exmà): a) ultrasonic survey carried out in 2007; b) ultrasonic survey carried out in 2010; ultrasonic survey carried out in 2016 (after the restoration works of 2014).

The differences between the first (2007) and the second (2010) map is evident. An increase in low velocity areas can be observed in time. This is a consequence of the increase in weathering which affects the propagation of the longitudinal velocity through the materials.

The low velocity areas in the maps mainly represent degradation of the building materials and weakness zones. The analyzed masonry is predominantly made up of *Pietra Cantone* blocks, as can be deduced both by comparing the *in situ* velocity measurements with the laboratory results and by considering the information deduced from the petrographical study. The lower velocity values are in correspondence of the areas where the plaster detached. These sectors, which are more exposed to water infiltration and rising damp, are subject to an intense circulation of water and to a higher retention of it in the areas under the plaster, where the *Pietra Cantone* blocks are found.

Thanks to ultrasonic in time monitoring of the investigated structures, it was possible to make interesting deductions on the evolution in time of the conservation status of the heterogeneous wall materials. After the restoration works in 2014 (Fig. 4c), the elastic-mechanical conditions of the shallow part of the building materials improved slightly, which leads to the conclusion that the restoration was mostly aesthetic.

An additional diagnostic aid to the knowledge of the elastic conditions of the masonries was provided by the acquisition of ultrasonic data using the ultrasonic refraction techniques. Therefore, different refraction profiles were performed on representative areas of the investigated wall. The data were reported in a space-time graph (Dromocrone), from which the velocity values and the thicknesses of the different layers of the masonry were obtained. As an example in Fig. 5 are shown the dromocrone of two conjugate profiles carried out in a sensitive area of the masonry.

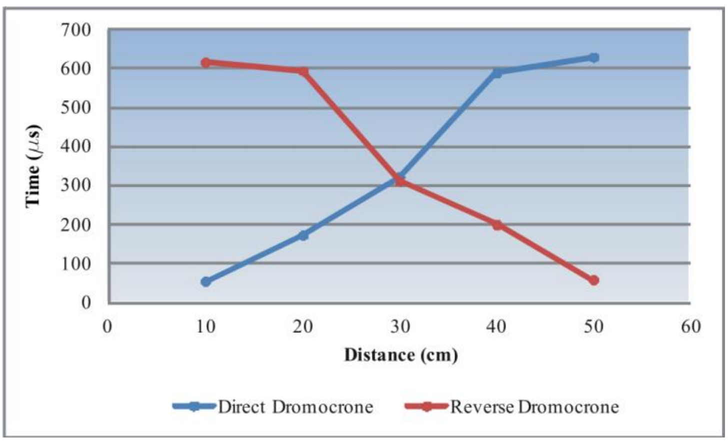

Figure 5: Dromocrone of two conjugate profiles carried out in a sector of the masonry.

Based on these analyses two layers with different elastic characteristics were detected: a) a 12 cm shallow low velocity layer (medium V_1 = 560 m/s) characterized by the plaster and the altered parts of the stone materials; b) an underlying high velocity layer (medium V_2 = 2900 m/s) characterized by less impaired stone materials (Fig. 6).

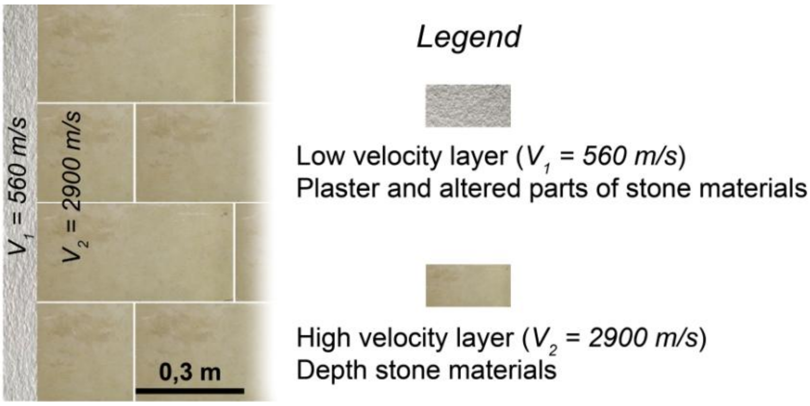

Figure 6: Result of the refraction ultrasonic investigation on the analyzed masonry panel.

IV. Conclusions

The dynamic elastic characterization of carbonate stone materials supported by petrophysical and mineralogical-petrographic analysis has proved to be an effective tool to evaluate the conservation state of the building materials of the heterogeneous masonry of the Exmà complex. The use of the elastic waves at 24kHz - 82 kHz ultrasonic frequency through the materials has been successful in checking their integrity.

The integrated petrophysical and petrographical study pointed out the compositional and textural characteristics that favour the alteration of carbonate building materials. The *Pietra Cantone*, which has a high content in pores and micrite, is the most alterable lithotype of the *Calcari di Cagliari Formation*. As opposed the *Pietra Forte*, which is porly porous and well cemented by sparry calcite, represents a durable building material.

As a matter of fact, hygroscopic characters of the *Pietra Cantone* cause serious degradation problems. Large quantities of water can be accumulated, causing alveolization, pulverization and the detachment of the overlying plaster on this lithotype. These features sensibly affect the propagation of the ultrasonic pulses which have a high diagnostic resolving power. In this study the *in situ* ultrasonic investigations has made an effective contribution to the recognition of the altered sectors and to the estimation of the elastic conditions of the building materials of the investigated masonry.

The results demonstrate that non invasive ultrasonic in time monitoring is also an effective tool to monitor the weathering evolution of the building materials and to evaluate the effectiveness of the restoration treatments. Moreover, by means of refraction techniques can be check the thickness of the weathered shallow part of the masonry and the depth of the degradation processes. In conclusion, the present diagnostic study was effective in assessing the conservation state of carbonate stone materials, but can be applied effectively on all natural stones, as well as on artificial materials that constitute the modern buildings.

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