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Ultrasonic pulse velocity for the evaluation of physical and mechanical properties of a highly porous building limestone

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ABSTRACT

UPV as non-destructive technique can effectively contribute to the low invasive *in situ* analysis and diagnosis of masonry elements related to the conservation, rehabilitation and strengthening of the built heritage. The use of non-destructive and non-invasive techniques brings all the times many advantages in diagnostic activities on pre-existing buildings in terms of sustainability; moreover, it is a strong necessity with respect to the conservation constraints when dealing with the historical–architectural heritage.

In this work laboratory experiments were carried out to investigate the effectiveness of ultrasonic pulse velocity (UPV) in evaluating physical and mechanical properties of Lecce stone, a soft and porous building limestone. UPV and selected physical–mechanical parameters such as density and uniaxial compressive strength (UCS) were determined. Factors such as anisotropy and water presence that induce variations on the ultrasonic velocity were also assessed. Correlations between the analysed parameters are presented and discussed.

The presence of water greatly affected the values of the analysed parameters, leading to a decrease of UPV and to a strong reduction of the compressive strength. A discussion of the role of the water on these results is provided.

Regression analysis showed a reliable linear correlation between UPV and compressive strength, which allows a reasonable estimation of the strength of Lecce stone by means of non-destructive testing methods such as the ultrasonic wave velocity. Low correlation between UPV and density was found, suggesting that other factors than density, related to the fabric and composition, also influence the response of the selected stone to the UPV. They have no influence on the UCS, that instead showed to be highly correlated with the packing density.

1. Introduction

The conservation, rehabilitation and strengthening of historical buildings are increasingly required by modern societies, due to the need of preserving the memory of the past and keeping a record of cultural changes. Based on the appropriate knowledge and diagnosis of materials and structures, proper interventions can be adopted. According to the international charters of Athens cited by Venice [1], the diagnostic analysis of historical buildings should be carried out with the lowest degree of intrusion and with the fullest respect for their physical integrity, as per the principles associated with preserving objects of architectural and cultural heritage. To abide by these restrictions, the scientific community has moved to propose alternative non-destructive testing (NDT) that is to be applied to the investigation of masonry and construction materials.

Sophisticated non-destructive techniques – such as ground penetrating radar, thermography, sonic and ultrasonic tomography, and laser scanner survey – have been developed and improved throughout the years. By using an integrated approach it is possible to reconstruct the morphology of the masonry structures and to detect the presence of structural failures, such as cracks and voids, in addition to the presence of water coming from rising damp or from seepage, thus achieving an accurate and reliable identification and diagnosis of the construction, which is the basis for the restoration design [2–4]. In the field of characterization and diagnosis of ancient buildings, the knowledge of the physical–mechanical properties of the constituent materials and their in-use conditions is of crucial importance; however, being able to obtain samples of these materials is still a major obstacle. To this

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regard, the ultrasonic pulse velocity (UPV) method can be conveniently used to obtain a variety of information on the material properties and state of conservation. Ultrasonic velocities are related to the properties of the stone and they can thus be applied to assess the quality of the stones [5,6], to detect any presence of microscopic fissuring and cracks [7,8], to evaluate the material decay [9–12] and to assess the effectiveness of consolidation products [13,14]. In material characterisation, UPV testing has been reported by several authors as a useful and reliable non-destructive tool for assessing the mechanical characteristics of concrete [15–20]; it has also been suggested in the field of rock analysis for the estimation of elastic and strength properties, as well as of physical parameters of the stones [21–27].

Intrinsic factors of the stone – including density, porosity, grain size, oriented structures, microcracks, etc. – affect the elastic wave propagation; external parameters associated with humidity, temperature, and mechanical stress are also involved and it is important to study in what manner and how much their variation may modify the characteristics of the waves being measured trough a specific material. This aspect is of crucial importance when *in situ* measurements are made so that the results of the measurements are interpreted properly.

In this paper UPV technique for the physical and mechanical characterization of Lecce stone – a soft and porous limestone used as construction material in Southern Italy – has been investigated under laboratory conditions. UPV measurements were performed and selected physical–mechanical parameters such as density and uniaxial compressive strength (UCS) were determined. The study was aimed to find correlations between them, as well as to evaluate factors that can affect correlations, such as anisotropy and water presence. The final aim was to verify the reliability of UPV as a tool for the estimation of the *in situ* compressive strength of Lecce stone, thus limiting destructive tests for the mechanical qualification and structural diagnostic analysis of ancient masonries in which this material is used.

2. Material description

Lecce stone is a soft, fine-grained biocalcarenite commonly used in the past as construction material in Southern Italy. In this area, buildings across multiple districts that are made with this stone can be found, such as those within the city of Lecce and surrounding historic towns, where it is the almost unique material used in Baroque architecture and minor buildings despite its low durability [28]. Similar soft limestones can be frequently found elsewhere within the historic built heritage [29,30] due to their high availability, easy extraction, and workability. Microscopically, Lecce stone consists of fine microfossil fragments – mainly planktonic Foraminifera and fossil debris within a micritic groundmass (Fig. 1) that also contains dispersed clay minerals. Grain size is mainly around a few tens of microns. Variable fabric relies on stone frameworks of wackestone and packstone types [31], densely packed, but poorly cemented by fine calcite with microsparitic texture; this is intimately mixed into the groundmass and irregularly distributed. The frequent presence of bioturbations contributes to alter the textural homogeneity of the stone.

Porosity is mainly intergranular; intragranular holes are sometimes present in the form of microfossil cavities. As reported in [28], porosity measured by Mercury Intrusion Porosimetry ranges between 30% and 43%, where the bulk of the pores (50–70%) is between 0.5 μm and 4–6 μm in radius; the remaining pores are mostly of smaller radii, up to 0.02 μm. The mineralogical composition of Lecce stone primarily consists of calcite with low magnesium content; a not carbonatic insoluble residue that accounts for 3% up to 11% in weight is made of clay minerals and amorphous compounds, quartz, and phosphatic grains. Clay minerals include glauconite, illite, kaolinite, chlorite, but also smectite which has an expandable lattice; their presence has been demonstrated to have an influence on the durability of Lecce stone [32].

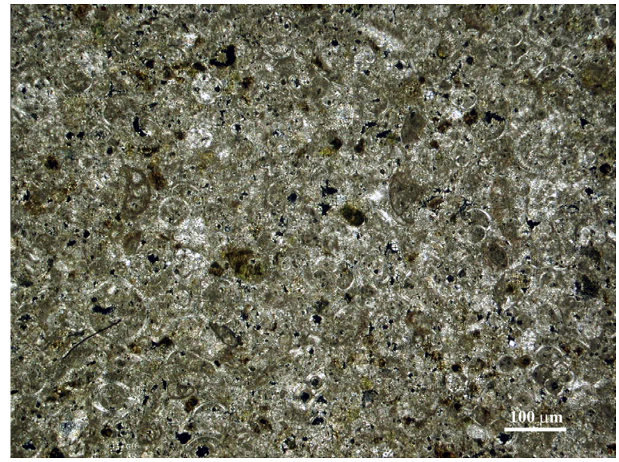

Fig. 1. Thin section image (crossed nicols) of Lecce stone showing the densely packed structure mainly consisting of fine fossil remains within a groundmass with a poor microcrystalline cement.

3. Experimental methods

In this research, nineteen blocks (50 × 25 × 25 cm) coming from three different quarries of the Lecce district were tested. Cubes having 70 mm sides were cut from the blocks, and 151 specimens were obtained in total.

Each cubic specimen (Table 1) is identified by a capital letter (A–N) followed by the number related to the block of provenance (1–19). The specimens are organized in four groups. Group 1 and Group 2 include specimens used to test density, UPV and UCS in dry and wet conditions, respectively. The specimens belonging to Group 3 were used for to assess the anisotropy by UPV measurements and its influence on the UCS. Group 4 was used to compare the density, UPV and UCS in dry and wet conditions of samples coming from the same block.

All the specimens were oven dried at 70 °C until constant weight measurements were reached [33]. Apparent density in dry and wet conditions was determined by mass volume ratio. Saturation of the samples was obtained by immersion in deionized water at room temperature, according to UNI EN 13755 [34]. The weight was determined by means of a digital balance with a precision of 0.1 g.

The dimensions of each specimen were exactly determined for the calculation of the apparent volume. All three dimensions of each specimen were measured by means of an analogic caliper with a precision of 0.01 mm. Four measurements were taken for each direction and then the mean value was calculated.

3.1. UPV measurements

The ultrasonic pulse velocity (UPV) test was performed according to ASTM D2845-05 [35] on dry and saturated samples. No coupling agents were used for the UPV measurements, in order to avoid the possible penetration into the pores before saturating the specimens. Velocities were measured by the direct transmission method using an Epoch 4 plus (Olympus) instrument and probes with a frequency of 1 MHz. They were recorded in each direction (x, y, z) of the cubic specimens and expressed as the average of three readings.