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Assessing the reliability of non-destructive and moderately invasive techniques for the evaluation of uniaxial compressive strength of stone masonry units

Emilia Vasanelli [a], Angela Calia [a,*], Donato Colangiuli [a], Francesco Micelli [b], Maria Antonietta Aiello [b]

[a] Institute for Archaeological and Monumental Heritage (CNR-IBAM), via per Monteroni, 73100 Lecce, Italy
[b] University of Salento, Dept. of Engineering for Innovation, via per Monteroni, 73100 Lecce, Italy

HIGHLIGHTS

- UPV and Schmidt Hammer were used as NDTs for strength estimation of building stones.
- Reliability in the stone strength assessment by the use of microcores was studied.
- Regression analysis and analysis of variability of the results were performed.
- UPV gives the best results in detecting strength variation among blocks.
- Results evidence some limits in the use of Schmidt Hammer and test on microcores.

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ABSTRACT

In this work Ultrasonic Pulse Velocity (UPV), Schmidt Hammer Rebound (SHR) test and strength assessment on microcores (UCS_m) and standard cubic samples (UCS_c) were used to detect the uniaxial compressive strength of stone masonry units. The analysis of the variability of the measurements allowed to investigate the significance of each test to differentiate the masonry blocks. The latter was evaluated by a Variability Index (VI), as the ratio between the variances at block scale and among the blocks. VI was found higher for UCS_c and UPV than for UCS_m and SHR measurements. A regression analysis aimed to the correlation of uniaxial compressive strengths evaluated by conventional destructive test on stone cubes with the other test results. The findings showed a good linear correlation among UCS_c and UPV values ($R^2 = 0.83$), thus supporting the reliability of UPV to screen the masonry units and to estimate their uniaxial compressive strength. The correlation of UCS_c with UCS_m was reasonable ($R^2 = 0.76$), while it was low with SHR results; some limits related to the use of SHR and UCS_m tests are also discussed.

1. Introduction

Nowadays, the preservation and rehabilitation of historical – architectural heritage is a theme of crucial importance and several branches of the scientific community are working on this complicated task. Repairing an historical building always requires a multidisciplinary approach to face a variety of problems before making decisions and adopting interventions, which have to be as non-invasive and reversible as possible, but durable and effective, at the same time [1].

When masonry structural elements of historic buildings are investigated, the strength assessment of the natural stone is a key issue and it can support many aspects of the masonry survey. In the case of regular stone wall texture, several formulations suggested by the literature and by the Codes allow calculating the strength and deformability properties of the masonry as a composite material, starting from the mechanical properties of the constituent stones and binding mortars [2–5]. Moreover, the compressive strength of the constituent stone is an input parameter for developing numerical models to describe the structural behaviour of stone masonry walls by using micromechanical approaches [6,7]. In micromechanical models, masonry units and mortars are separately analysed and mechanical properties of both these constituents are considered to perform the numerical analysis. The mechanical qualification of the stone within the buildings

* Corresponding author at: CNR-IBAM, University Campus, via per Monteroni, 73100 Lecce, Italy.
E-mail address: a.calia@ibam.cnr.it (A. Calia).

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also supports the evaluation of the effects of the weathering on the stone integrity and performance, and allows the selection of suitable materials for replacement [8].

A great number of specimens to be tested in laboratory conditions is necessary to have statistically representative results of the properties of a material within a stonework. This is a further limit for the use of destructive tests, as it does not comply with the necessary requirements of preservation of historical buildings. In such a situation, the use of non-destructive techniques (NDTs) is suitable to reduce sampling. The quality of the estimation of the strength is a key issue when NDTs are used. They provide indirect measurements of the mechanical strength, which are affected by several sources of uncertainties, so that results obtained with these methods needs the calibration through destructive tests. The precision of the estimation is strictly related to the number of the samples tested, as a large enough statistical basis is necessary to construct a reliable correlation between NDT parameters and strength values.

Ultrasonic Pulse Velocity and Schmidt Hammer Rebound tests offer an interesting approach to the analysis of historical buildings, since they give access to material properties while remaining rapid, of moderate cost and not invasive, thus supporting sustainable diagnostic procedures in terms of cost and time effectiveness, as well as with respect to the physical integrity of the artefacts. They have been widely used in the mechanical characterization of natural stones and correlations have been proposed for the estimation of UCS values of different stone types by non-destructive tests, with reference to both high and low strength rocks [9–19]. Nonetheless these correlations have been found to be dependent on stone varieties and test conditions, so that empirical relationships between UCS and both UPV and SHR tests need to be calibrated for each rock type [20]. Rebound and ultrasonic pulse velocity tests are among the most widely used non- destructive methods for strength assessment of concrete [21]. In this field, some standards have been recently drown up to provide the guidelines to estimate UCS through *in situ* non-destructive tests [22,23], including UPV and SHR. For both rocks [11,12] and concrete [24] it has been found that he combined use of these two non-destructive techniques may improve the development of mathematical models for the prediction of the material strength.

Besides the use of non-destructive techniques, there are some tests, such as the pull out, drilling, etc., which are more invasive but still considered as low or moderate destructive. They concern the measurements of different physical magnitudes, other than uniaxial compressive strength, which are related to the latter in a more or less complex manner. Compared with the previous moderate destructive tests, mechanical testing of few centimeters diameter cores (microcores) could offer the significant advantage of the direct measurement of the uniaxial compressive strength [25], along with low intrusion. Nevertheless, the small scale of the specimens may introduce a source of uncertainty. Many works in the literature in fact, report high dispersion of results due to both inhomogeneity of material at the scale of small specimens and to a proneness of microcores to be damaged during drilling, storage and handling operations [12,26–29]. Furthermore, sample size influences the compressive strength values [30,31]; therefore, international standards suggest minimum dimensions of 54 mm [32] or 47 mm [33] for rock core diameters, as well as fixed height to diameter ratios. Nonetheless, it is not always possible to drill cores of these standard sizes; thus, it can be useful to equate UCS values obtained on smaller diameter specimens with those, which would be measured on standard dimensions. Previous researches have investigated the relationships between UCS values and sample sizes [34], which should be calibrated on the various stone types [31]. Linear correlations among mean cube strengths and mean strengths of microcores having diameters of 28 mm have been established in the field of concrete [25,35,36]. In a similar vein, the possibility of using microcores out of the standard dimensions for the determination of the stone strength is explored in this work for a weak limestone (Lecce stone), by assessing correlations among the uniaxial compressive strengths measured for 28 mm diameter cores (UCS_m) and for the standard cubes (UCS_c). The UPV and the SHR tests as non-destructive methods have been also investigated. In particular, the study aims to test the reliability of these methods in detecting the compressive strength of Lecce stone masonry units and in identifying the presence of different kinds of stones based on significant variations of mechanical properties registered among them.

Lecce stone is a soft and porous calcarenite widely used as building material in the historic-architectural heritage of the South of Italy. Many old masonries built with the stone are blockworks having regular texture. A large variability of the physical-mechanical characteristics can occur among the block units. It comes from the intrinsic stone heterogeneity at small scale and from material variations at large scale due to the use of different stone varieties, as well as to variable states of conservation, which result from the different conditions of use and lifespan within buildings. It is worth noting that very often both original and replaced materials can be found in the historic masonries. This is the typical case of the masonries made of Lecce stone; due to the low durability of this stone, the replacement of block units is a common practice, frequently used since the past in the restoration of the building heritage of the area. The possibility of using UPV and SHR tests to detect mechanical properties of the stone units within the masonry, and their large scale variations, could help obtaining an overview of the strength properties within the investigated wall; this could limit the invasive impact of the diagnostic analysis, thanks to a well-focused sampling for destructive tests, based on the screening of the results obtained from the use of NDT. Moreover, the use of microcores may reduce the degree of sampling intrusion.

UPV, SHR measurements and UCS tests on both standard cubes and microcores were performed in laboratory conditions on stone masonry units coming from an old building. The UCS on standard cubic specimens was determined in accordance with the Codes [37], which suggest the standard specifications for the stone masonry units [38]. In a first step the significance of the variability of the measurements of the different parameters related to the tests was analysed at the scale of each block and at larger scale, namely among the different blocks. Then, correlations of SHR and UPV test results with the uniaxial compressive strength values were assessed by regression analysis as well as between the strength results obtained for different sample sizes.

2. Materials and methods

2.1. Stone material

"Lecce Stone", a soft, fine-grained calcarenite, widely used as building and decorative stone in the Baroque architectural heritage and in minor buildings of Salento, in the South of Italy [39], was used for testing. Microscopically, it consists of fine microfossil fragments – mainly planktonic Foraminifera and fossil debris within a micritic groundmass finely mixed to clay minerals. Grain size is mainly around a few tens of micrometres. The stone is densely packed, but poorly cemented. The cement is fine calcite with microsparitic texture; it is intimately mixed into the groundmass and irregularly distributed. Large heterogeneity of the stone relies on variable fabrics of wackestone and packstone types [40] and frequent presence of bioturbations which contributes to alter locally the textural homogeneity of the stone. It also comes from