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Combining non-invasive techniques for reliable prediction of soft stone strength in historic masonries

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HIGHLIGHTS

- UPV, Rebound and compressive microcore tests for stone masonry strength estimation.
- Statistical evaluation of accuracy of each test measurements is performed.
- Multivariable methods improves correlation models between direct and indirect tests.
- Iterative cross-validation is effective in evaluating model predictive performances.
- Combined UPV and microcore strength tests gives the best estimation of UCS.

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ABSTRACT

In this study, some NDTs (Ultrasonic Pulse Velocity UPV and Rebound Hammer) and uniaxial compressive test on microcores (UCS_m) as a moderately destructive test, were investigated as tools for assessing the uniaxial compressive strength (UCS) of a soft limestone. Correlations between UCS and results of each above-mentioned tests were determined by a univariable regression analysis. Artificial Neural Network and the Multiple Regression Analyses were considered to search correlations between UCS and combined results of the non-invasive tests. An iterative cross-validation procedure was implemented to validate the predictive performances of the models. It was found that combining UPV and UCS_m results gives the best reliability in the indirect estimation of UCS, with a notably reduced predictive error.

1. Introduction

The knowledge of the geometry, texture and mechanical properties of the masonry is an essential step in the safety analysis of an historical building in order to define the risk conditions and the necessary repair/strengthening measurements [1,2]. When stoneworks in historic buildings are investigated, the strength assessment of natural stone elements is a key issue. In the case of regular stone wall texture, several formulations suggested by the literature and the provisional Codes allow calculating the strength and deformability properties of the masonry as a composite material, starting from mechanical properties of the constituent stones and binding mortars [3–5]. Moreover, the compressive strength of the stone elements is an input parameter for developing numerical models to describe the in-plane behavior of masonry walls [6,7] and for implementing prototypes to be mechanically tested as representative of the real situations. The mechanical qualification of the stone within buildings also supports the evaluation of the weathering effects on its integrity and performance and allows the selection of suitable materials for replacement.

A great number of specimens to be tested in laboratory conditions is necessary to have statistically representative results of the material properties in a stonework. This is a limit for the use of destructive tests, as it does not comply with the necessary requirements of historical buildings preservation. In such a situation, the use of non-invasive techniques is suitable in order to reduce destructive sampling.

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Several experimental methods, such as ultrasonic pulse velocity, Rebound hammer, point load tests and compressive tests on microcores were investigated as non destructive and semi destructive tests (ND/SDT) to indirectly assess the uniaxial compressive strength (UCS) of different kinds of stones [8–13]. For each material, a correlation law between ND/SDT and UCS was calibrated in the attempt of using it to predict UCS from new indirect test results. However, an indirect measurement of the compressive strength by means of non-destructive tests may lead to uncertainties due to measurement and calibration errors. Moreover, passing from descriptive models of correlation between direct DTs and indirect NDTs to predictive ones, the uncertainty of the indirect measurements, which variably affect the different tests, needs to be evaluated as a basic safety aspect for assuming compressive strength values indirectly estimated. This aspect has been widely investigated in the field of concrete [14,15]: it was proved that the quality of the assessment depends on the quality of the measurement, the existence of uncontrolled factors, the number of data used for regression analysis and the range of UCS variation. Several statistical techniques have been proposed in the literature to overcome the above mentioned standard limitations and to obtain improved correlations. They include Bayesian inference analysis [16,17] and artificial intelligence techniques [18,19].

The present study tries to provide new contributions on these concerns of research in the specific field of natural stones.

In particular, in this paper, the Ultrasonic Pulse Velocity and the Rebound Hammer tests as non-destructive methods, and a compressive test on microcores, as a moderately destructive one, are investigated as tools for assessing the uniaxial compressive strength of Lecce stone, a soft and porous calcarenite. UPV and Rebound measurements were performed in laboratory conditions on stone blocks coming from an historical building. Compressive strength was determined on cubic specimens (UCS) and on small-scale cylindrical specimen, namely microcores (UCS_m). Some aspects concerning the accuracy of the measurements carried out by means of the different tests methods were discussed on the basis of statistical evaluations.

Correlations of the indirect test results with UCS were assessed by a univariable linear regression analysis. Multivariable Artificial Neural Network (ANN) and Multiple Regression Analysis (MRA) of the data were performed to combine the results of the different tests, in an attempt of reducing the errors in the assessment of the stone strength. A cross-validation procedure was implemented to evaluate the reliability of the developed correlations. It is a consolidated statistical method to compare the predictive performances of established models and it has a large application in several fields including medicine, biology, chemistry, finance, meteorology, etc. To the best knowledge of the authors, there are not previous applications of this method in civil engineering to support the diagnosis of existing structures.

2. Materials and methods

2.1. Materials

"Lecce Stone", a soft fine-grained calcarenite, widely used as building and decorative stone in the Baroque architectural heritage, as well as in minor buildings of Salento, in Southern Italy, was used for testing. Microscopically, it consists of fine microfossil fragments and fossil debris, with a grain size mainly around a few tens of micrometers. They are included within a micritic groundmass containing finely dispersed clay minerals and phosphate lumps. The stone is densely packed, but poorly cemented. The cement is a microsparitic calcite irregularly distributed and intimately mixed to the groundmass. A large heterogeneity of the stone comes from variable fabrics of wackestone and packstone types [20] and frequent presence of bioturbations, which concur to alter locally the textural homogeneity of the stone. Heterogeneity also characterizes physical and mechanical properties, such as porosity that ranges from 30 to 45% and compressive strength, varying between 7 and 30 MPa [21,22]. Fig. 1 shows the microstructure of the stone as observed by optical microscopy, along with the mineralogical composition, as determined by X-ray Diffraction analysis.

Twenty-three stone blocks, measuring 50x25x20 cm, were used. They come from a collapsed portion of walls of "Masseria Tagliatelle" in Lecce, an historic building of the XVI century, which has been subjected to several repair measurements over time (Fig. 2). The blocks were numbered and x, y, and z-axes were assigned with z and x corresponding to the minimum and maximum dimension of the block, respectively. The investigated blocks can be considered isotropic in relation to the ultrasonic wave propagation, since the anisotropy, calculated as $(UPV_{max} - UPV_{m}in)/UPV_{max}$ [23], was near 1%.

2.2. Compressive tests

Uniaxial compressive strength tests were carried out on microcores (UCS_m) and cubes (UCS). A universal testing machine with a load capacity up to 200 kN and a load speed 0.05 MPa/s was used.

Two microcores (28 mm diameter) were extracted from each block along the z axis. They were cut to obtain a total number of six cylindrical specimens per block, with the ratio between the height and the diameter equal to one [24]. A total number of 138 specimens was used.

Cubes having 70 mm sides [25] were cut from the blocks; six cubes for each block were obtained, with a total number of 138 specimens. Before the compressive tests, the dimensions of both small cores and cubes were measured by means of an analogic caliper with a precision of 0.01 mm. The specimens were oven dried at 70 °C until a constant weight was reached [25] and then they were tested under compression with the load applied along the z axis, until rupture.

2.3. Non-destructive tests (NDT)

UPV test was performed on each stone cube before the compressive test, following ASTM D2845-08 standard [26]. UPV was measured by the direct transmission method along the z-axis of each cube using an Epoch 4plus instrument, equipped with 1 MHz probes. Three UPV measurements for each side of the cubes were taken. The estimated relative error of the velocity measurements, obtained by combining the relative errors on time and thickness measurements, is about 0.3%.

Rebound Hammer test was performed on the blocks in laboratory conditions, according to ASTM D5873-14 [27]. A digital hammer with impact energy of 2.207 Nm, suitable for a compressive strength range from 10 up to 70 N/mm^2, was used. The test was carried out on the upper xy face of each block; 20 impacts per block were made at a distance of 2 cm at least. The mean value of the 20 Rebound Index (RI) readings was calculated, discarding measurements that differed for more than 7 units from the mean, according to the ASTM standard [27].

3. Test results and discussion

For each tested block the mean values and the standard deviation (SD) of the UPV, RI, UCS_m and UCS measurements were calculated (Table 1). UPVs considerably vary between the blocks, from 2411 to a maximum of 3184 m/s. RI values range between 20 and 28. The compressive strengths measured on the cubes vary between 8.3 MPa and 23.3 MPa; these values are comparable with the lowest ones obtained for the quarry Lecce stone in a previous work [22]. Microcores, although they came from the same block as the cubes, yielded UCS_m values from 30% to 70% lower than UCS, and a scale effect can be identified in the underestimation of the strength values when small diameter cores are tested [26].

3.1. Accuracy of the investigated test methods

Assessing the minimum number of non-invasive measurements, corresponding to a predefined degree of accuracy of the mean value, is a key issue. This minimum number represents the best compromise between the reliability of the measurements and the time-cost efficiency of the diagnostic plan. The value of the minimum number can be estimated by statistical evaluations. Let is $(x_1,\ldots,x_n)$ a sample of measurements from a normally distributed population with unknown mean $(\bar{x})$ and standard deviation. Thus, the mean of the population can be found in the confidence interval:

$$\left[\bar{x} - t_{(0.05,n-1)}\frac{s}{\sqrt{n-1}}, \bar{x} + t_{(0.05,n-1)}\frac{s}{\sqrt{n-1}}\right] \quad (1)$$