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Non-destructive techniques to assess mechanical and physical properties of soft calcarenitic stones.

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Abstract

One of the major goals in the field of rehabilitation and renovation of existing structures is to determine mechanical properties of materials as well as their level of damage, namely the presence of defects, cracks, weathering effects, etc., by means of non-destructive (NDT) techniques. NDT tests, in fact, are easier and more economics than destructive ones because they do not necessitate sample extraction and preparation; furthermore they are often the unique way to assess the material properties in case of historic and architectural buildings, where the possibility of extracting core samples is limited or not possible. The ultrasonic pulse velocity testing has been proved to be a useful and reliable non-destructive test for assessing the compressive strength and the elastic modulus of concrete in existing structures. Furthermore, the use of both ultrasonic tests and Schmidt hammer tests allow to have a good estimation of concrete compressive strength (SONREB method) by reducing the influence of the variables affecting the two technique when used alone. Both the technics have also been suggested to investigate mechanical and physical properties of rocks, but further experimental data are needed to confirm the reliability of the method. The present work is a part of a wider research aimed at set up non-invasive diagnostic procedures for the mechanical analysis and qualification of the ancient masonries; it is specifically devoted to verify the effectiveness and/or to point out critical aspects and limits of the above mentioned non-destructive tests - already applied in the field of concrete and compact stones - with reference to the characterization of soft stones.

*Keywords:*Non-destructive tests (NDT); soft stones; mechanical characterization.

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1. Introduction

Built cultural heritage plays an important role in the cultural life and identity of people and their countries. Conservation, rehabilitation and strengthening of historical buildings are clearly required by modern societies, as the result of the need of preserving the memory of the past and cultural changes. This means that proper intervention techniques on materials and structures should be available, based on appropriate diagnosis and understanding of the existing material properties.

The material physical and mechanical properties can be determined by in-situ and laboratory tests. In case of historical buildings, the principles of preserving architectural heritage, according to the international charters of Athens cited by Venice [1] recommend that the diagnostic procedures should be carried out on the building stone with the lowest degree of intrusion and fullest respect for their physical integrity. The sample extraction from existing structures is one of the major problems in the field of diagnosis of an ancient building and this has moved the scientific community to propose alternative non-destructive techniques to evaluate the mechanical and physical properties of construction stone. Ultrasonic pulse velocity (UPV) and the Schmidt hammer (rebound hammer) are two examples of simple and economic solutions that can estimate the mechanical properties and the weathering state of building stones [2].

In the present research the use of UPV and Schmidt hammer tests as NDT techniques to predict the mechanical behaviour of soft calcarenites has been analyzed. The results of the tests have been compared with those obtained by laboratory compressive destructive test, in order to assess the reliability of the two NDT methods to predict the compressive strength of the stones. The present work is a part of a wider research aimed to set up non-invasive diagnostic procedures for the mechanical analysis and qualification of the ancient masonries. One of the main goal of the research is to verify the effectiveness and/or to point out critical aspects and limits of the above mentioned non-destructive tests - already applied in the field of concrete and compact stones - with reference to the characterization of soft stones. This activity is carried out in an interdisciplinary way within the AITECH network (Applied Innovation Technologies for Diagnosis and Conservation of Built Heritage), a regional research laboratory infrastructure (Apulian region, Southern Italy) funded within the FSE and FESR programs and realized by the contribution of the Italian CNR and Salento University (Lecce, Apulia).

2. Materials and methods

2.1. Materials

Two kinds of soft calcarenitic stones, widely used in Puglia (region of the Southern Italy), have been investigated, "Gentile" and "Leccese" stones. In particular, the Gentile Stone (GS) used in the research came from two different quarries, "Melpignano" (MGS) and "Bianco Cave" (BGS) in the province of Brindisi, while the Leccese Stone (LS) was taken from several quarries of the province of Lecce.

GS stone, commonly named "pietra gentile", is a very fine calcarenite, white colored and with a massive appearance, used since the antiquity as ornamental stone and then as building material in many historic towns of the region. From a petrographic point of view, GS is a medium-fine wackestone [3]. It is made of fine fossil remains and lythoclasts with the average size of about 200 microns, within a micritic groundmass finely mixed with poor microsparitic cement. The open integral porosity is 28% (MGS) and 27% (BGS), with pore radius ranging mainly between 2 and 0,4 μm (MGS) and 4 and 0.5 μm (BGS). The chemical composition indicates that the rock consists of a content exceeding 90% of calcium carbonate and the insoluble residue is made of quartz, mica and clay minerals present in trace.

LS stone, usually named "Lecce stone", is a fine-grained calcarenite, with a characteristic pale-yellow color. It is widely used in the Baroque heritage of the Salento area, as well as in minor buildings. Petrographically, it is a wackestone [3], mainly composed of micritic fraction, mixed with fine clay minerals and poor cryptocrystalline

calcitic cement; itcontains fine microfossil fragments, grains of glauconite, sporadic quartz grains and phosphatic nodules [4]. The integral open porosity is around 40%, with pore radius mainly between 4 e 0,5 microns. The rock has around 80% of calcium carbonate and the insoluble residue is essentially made of clay minerals and glauconite.

2.2. Test procedure

Non-Destructive Test (NDT) and Destructive Test (DT) were carried out on 70 mm side cube samples. All the specimens were dried before being tested. In particular, they were heated at 70°C for about three days, until they reached a constant weight (the difference between two successive measurements was less than 0.1%).

For each sample, dimensional measurements (four per side) were recorded in order to calculate the specimen volume and apparent density.

UPV and Schmidt hammer tests were performed on cube specimens before destructive compressive tests.

In particular, the UPV measurements were carried out on 88 LS specimens and 40 GS specimens by means of the instrument Epoch 4plus (Olympus), using the method of direct transmission and probes of 1 MHz. The measurements were performed on cubic samples along the three directions x, y and z. For each direction a set of three measurements was taken. The velocity was calculated directly from the instrument through the formula $V = L / T$, where V is the velocity (m / s), L is the distance between the transducers (mm), and T is the time of arrival (s) required for the wave to pass through the sample. Data are reported as the average values calculated on the number of measurements made for each direction based on the size of each specimen.

The index of anisotropy was calculated using the equation of Ruedrich & Sigesmund [5] (ARS %= ((Vpmax-Vpmin)/(Vpmax) *100).

The Schmidt hammer test was performed on 22 PL specimens, while GS specimens were not investigated. A digital hammer, type DIGI_SCHMIDT 2, made by Proceq, with an impact energy of 2.207 Nm, suitable for a range of 10 to 70 N/mm^2 compressive strength, was used. A mesh of five points was marked on each side of the cube sample so that the impact location was sufficiently far from the edges and spaced by at least the diameter of the plunger (Figure 1). The mean value of the five rebound readings was calculated for each side of the specimen and the final rebound index was determined for each cube as the average of the six side readings. Since the specimens were cut by means of a saw machine, the influence of the roughness of the surface on the test was minimum.

The compressive tests were performed according to the UNI EN 772-1 standard [6], by means of an automatic servo-controlled press (Controls-Automax 5) with load capacity up to 3000 kN and a piston stroke of 50 mm.
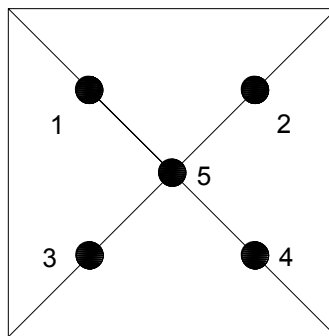

Fig. 1. Measurement points for Schmidt hammer test

3. Experimental results

3.1. Ultrasonic test results

In Figure 2a the velocity values of the P waves recorded for each sample in the three directions are reported. It can be seen a variability of the UPV results depending on the measurement direction. The anisotropy values are shown in Figure 2b. They let to identify two groups of samples, with the corresponding anisotropy of 14% and 5%. The total anisotropy, relative to all the samples has an average value of 9.3%. The results obtained confirm the heterogeneity of the LS along the directions investigated.
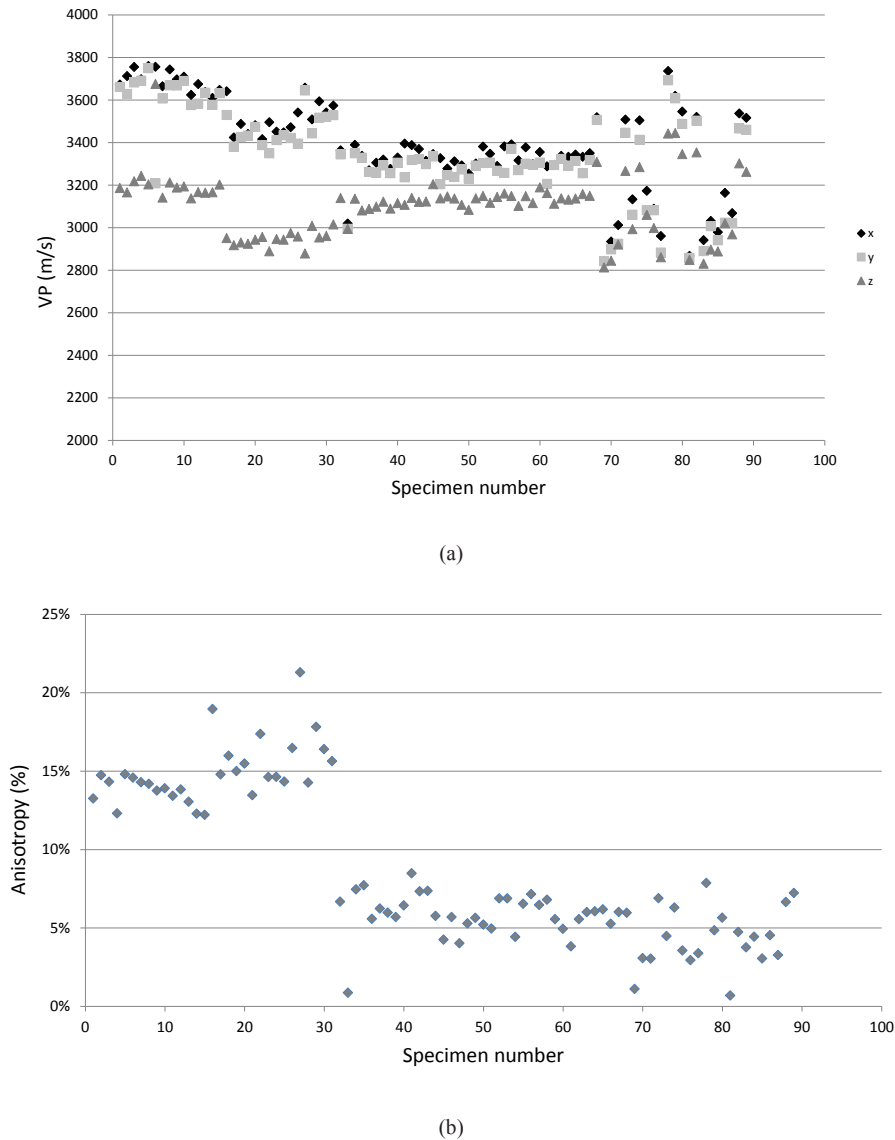

(a)

(b)

Fig. 2 (a) UPV results for LS specimens; (b) anisotropy values calculated for LS specimens

VP and anisotropy values are reported for GS specimens in Figure 3a and 3b. It can be observed that the samples show VP values very similar and close together along the three directions; no differences between the values of the anisotropy of the two types of stones investigated are evidenced and the average value stands at 4.4% ca. The results obtained indicate the GS stone as a material more homogeneous with respect to the LS stone.
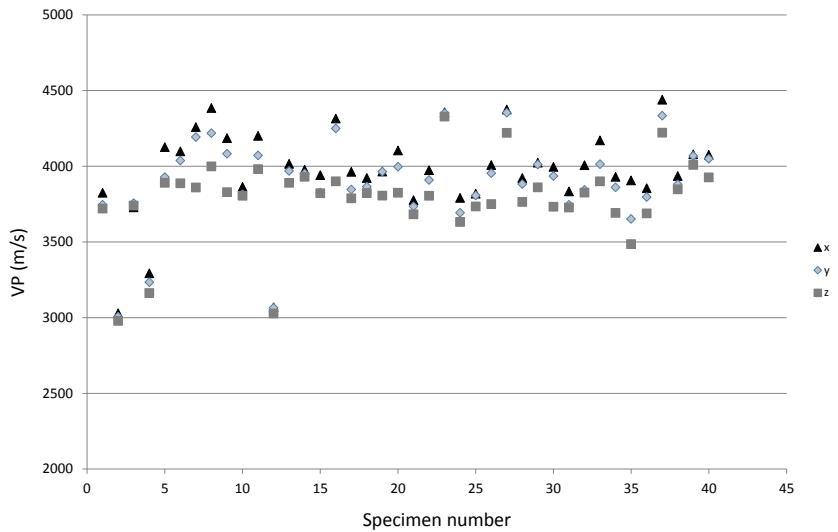
(a)
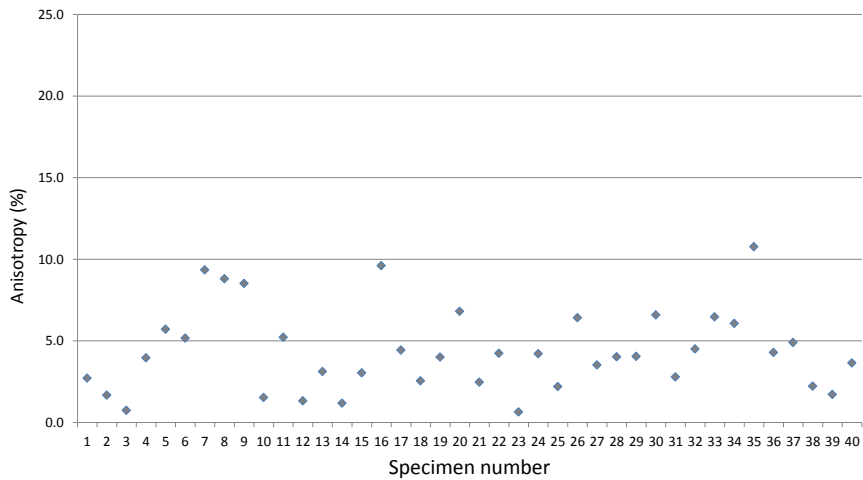
(b)

Fig. 3 (a) UPV results of GS specimens; (b) anisotropy values calculated for GS specimens

3.2. Schmidt hammer test results

As before mentioned (2.2) 22 LS specimens were investigated by the Schmidt hammer test. In table 1 the rebound indexes, the standard deviation and the coefficient of variation calculated on the readings of each specimen are reported.

Table 1. Schmidt hammer test results

Specimen number	Rebound Index	Standard Deviation	Coefficient of Variation
A1	23.8	2.23	9%
A2	22.8	1.72	8%
A3	22.7	1.21	5%
A4	22.8	1.72	8%
A5	23.2	2.04	9%
A6	22.7	0.52	2%
A7	22.8	1.47	6%
A8	23.0	1.67	7%
A9	23.5	1.38	6%
A10	22.3	1.21	5%
A11	24.0	1.26	5%
A12	24.5	2.43	10%
A13	24.7	1.03	4%
A14	21.7	0.82	4%
A15	22.5	1.76	8%
A16	22.7	0.82	4%
A17	21.8	1.33	6%
A18	21.0	1.79	9%
A19	21.0	0.63	3%
A20	22.2	0.75	3%
A21	22.5	1.05	5%
A22	23.7	1.97	8%
A23	23.8	2.23	9%
A24	22.8	1.72	8%

3.3. Compressive test results

GS and LS specimens were tested along parallel and perpendicular directions, with reference to the stratification planes that were identified on the basis of the UPV results. In fact, the stratification planes correspond to close values of VP along y and x directions.

The compressive strengths, measured along and perpendicular to the stratification planes, have been reported for the Leccese stone in Figure 4. 43 LS specimens were tested in the direction perpendicular to the stratification planes, while 45 specimens were tested with the load parallel to the stratification planes direction. The

compressive strengths measured along the two directions were very similar, this means that the material anisotropy, recorded by the ultrasound measurements, does not influence the compressive strength of the material.

As regards GS stone 20 specimens were tested for each load direction. In Figure 5 the results of the compressive tests are reported It can be noticed that the compressive strengths along and perpendicular to the stratification planes are very similar and this result is coherent with the homogeneity of the material recorded by the ultrasound measurements (3.1).

Comparing the compressive strength of GS and LS, no difference was found between the stones, in spite of the higher VP in the GS than in PL stone.
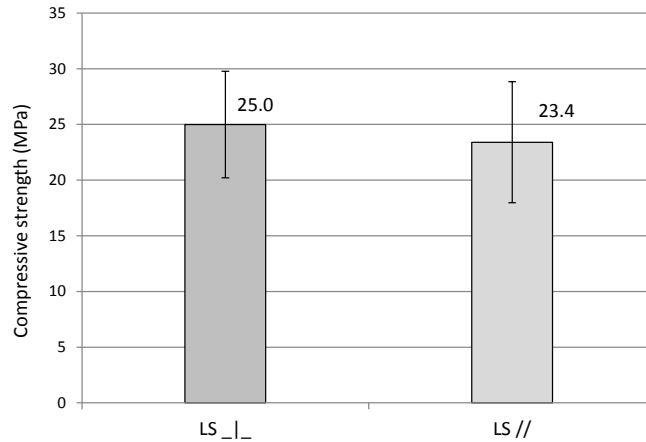

Fig. 4. Compressive strength of LS specimens (_|_ perpendicular to stratification planes, // to the stratification planes)
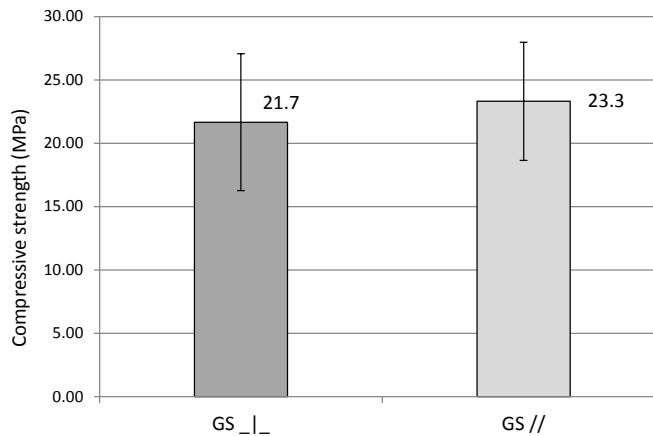

Fig. 5. Compressive strength of GS specimens (_|_ perpendicular to stratification planes, // to the stratification planes)

4. Analytical correlation of experimental results

4.1. Leccese Stone

In Figure 6 the results of compressive tests are reported versus the ultrasound velocity, calculated as the average of the velocities in the x, y and z directions.

Several correlation laws have been proposed in the literature to evaluate the compressive strength of rocks from the ultrasound velocity values [7, 8, 9]. In particular the laws are calibrated on different rocks, within an high range of compressive strength (30-180 MPa) and V_p velocities (2000-5000 m/s). These proposed laws roughly estimate the compressive strengths of the Leccese stone analyzed in this study.

On the basis of a statistical regression analysis, a good correlation factor has been found (R^2=0.85) (Figure 6), which indicates that a reliable estimation of compressive strength of the Leccese stone can be obtained from UPV results applying the proposed law.
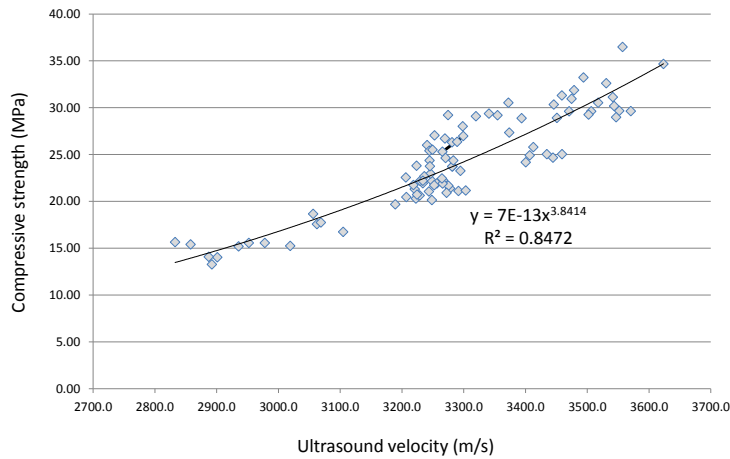

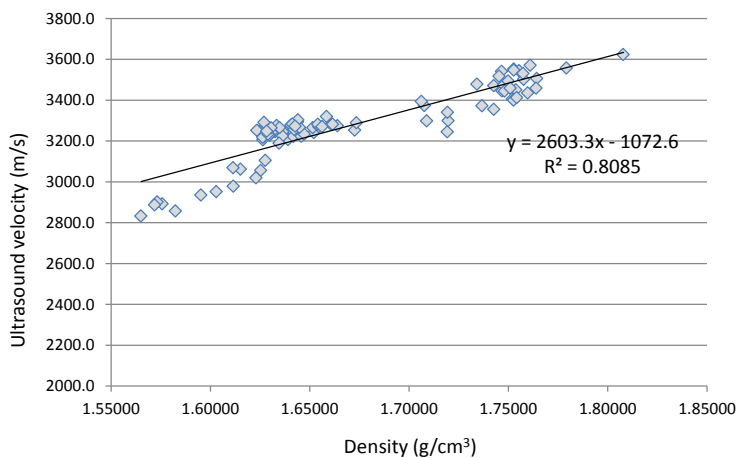Fig. 6. Correlation between compressive strength and UPV for "Lecce Stone"

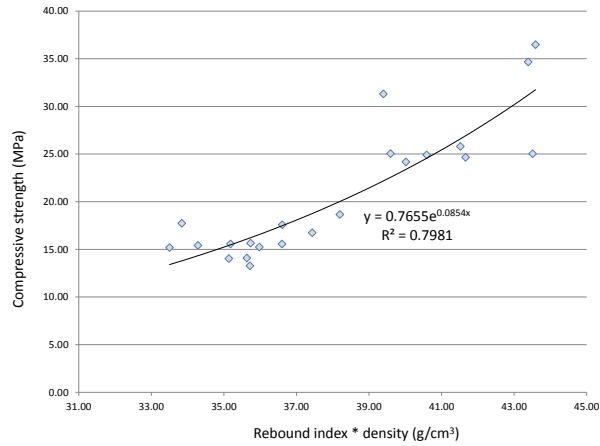Fig. 7. Correlation between UPV and density

Fig.8. Correlation between compressive strength and the product of the rebound index and density

A good correlation (R^2=0.81) was also found between the ultrasound velocity and the density values: a linear relationship has been proposed as the best curve that fit the experimental results (Figure 7).

In Figure 8 the compressive strength has been correlated with the product of the rebound index and the density of LS specimens. Multiplying the rebound number by the density improves the correlation with the uniaxial compressive strength: this increases exponentially with the product of the rebound number and the density [7].

4.2. Gentile Stone

In Figure 9 the correlation between the experimental values of compressive strength and ultrasound velocity is reported. As for LS a potential law is the curve that best fit the experimental results; with respect to the LS specimens in this case the correlation factor is lower, thus the proposed law can give a rough estimation of the compressive strength of the specimens. It is necessary to increase the number of the specimens in order to evaluate with more accuracy the reliability of the correlation. Furthermore, a worse correlation between the UPV test results and density was found compared to LS results (Figure 10).
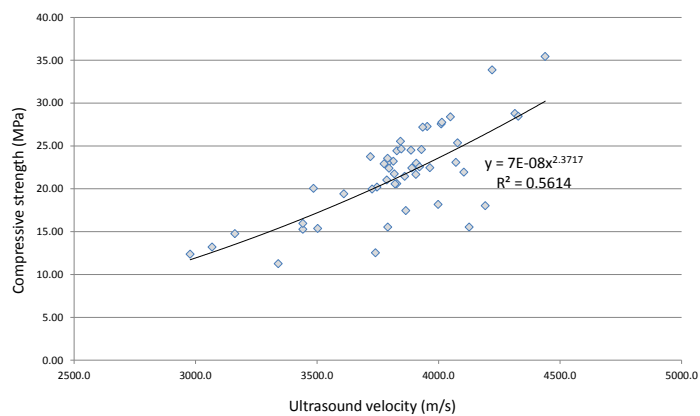

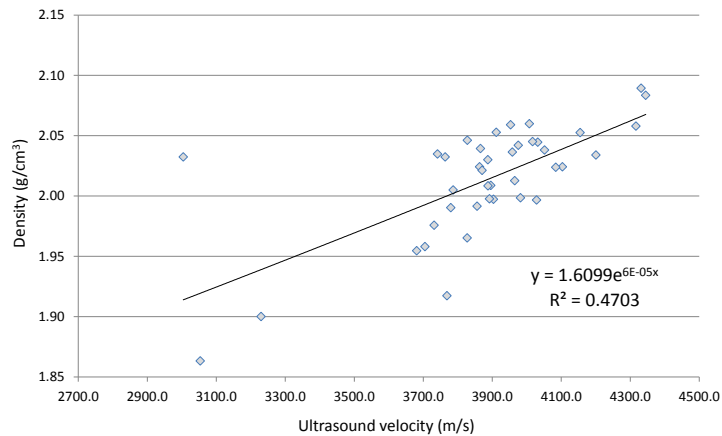Fig.9 Correlation between compressive strength and UPV

Fig.10 Correlation between UPV and density

5. Conclusions

The present research aimed at evaluating the reliability of the Schmidt hammer test and Ultrasound Velocity Test in predicting the compressive strength of two kind of soft calcarenitic stone: the Leccese Stone (LS) and Gentile stone, widely used in the Apulian region in the South of Italy. On the basis of the obtained results, analytical correlations between the ultrasound velocities and the compressive strength, as well as between the rebound index and the compressive strength have been proposed. In particular, the correlations obtained for the LS specimens had a significance quite high which indicates a good prediction of compressive strength using the proposed laws. On the contrary, lower correlation factors have been found for GS specimens; in this case the study needs the assessment on a larger statistical base and further research.

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