# Experimental investigations for the mechanical characterization of a soft calcarenite: the role of external factors on UPV measurements

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## Introduction

The use of non-destructive techniques to investigate the state of damage and the durability of historical masonry structures has rapidly increased in the last years. This was mainly due to the impossibility of invasive investigations because of the historical values of the surfaces and construction details.

Ultrasonic pulse velocity (UPV) method can be usefully employed to investigate the properties and quality of the stone blocks within the masonry system. In rockcharacterization, UPV testing has been reported by several authors as a useful and reliable non-destructive tool for assessing elastic and strength properties, as well as of physical parameters of the stones [Kaharaman 2001; Yasar& Erdogan 2004; Vasconcelos et al 2008; Aliabdo&Elmoaty 2012].

Several factors may affect the measurements and relationships between UPV and mechanical and physical properties of the investigated stones. Intrinsic factors are density, porosity, grain size, oriented structures, micro-cracks, presence of fossils, etc., while external parameters are related to humidity, temperature, and mechanical stress. These aspects are of crucial importance when in situ measurements are performed, in order to properly understand and use the obtained experimental results.

In this workUPV technique was used for the estimation under laboratory conditions of the compressive strength of a soft and porous limestone (Lecce stone) used as construction material in Southern Italy.The influence of some external factors on the mechanical characterization of the stone was previously studied [Vasanelli et al 2015; Vasanelli et al. 2017]. The research presented herein is focused on three parameters, namely the presence of water, the frequency used for the measurements and the application of a mechanical load.

## Influence of water

Nineteen blocks (50 x 25 x 25 cm) coming from three different quarries of the Lecce district were tested.Cubes having 70 mm sides were cut from the blocks, and 151specimens were obtained in total (Fig. 1).  All the specimens were oven dried at 70 °C until constant weight measurements were reached [UNI EN 772-1, 2011]. 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 [UNI EN 13755, 2008]. The weight was determined by means of a digital balance with a precision of 0.1 g. The ultrasonic pulse velocity (UPV) test was performed according to ASTM D2845-05 [ASTM D2845-05, 2005] 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.



*Fig. 1 Stone blocks; Ultrasonic Pulse Velocity measurements on stone samples*

A moderate correlation was found between compressive strength and UPV mean in dry condition ($R^2$ = 0.73, Fig.2). Regression analysis between the uniaxial compression test (UCS) and UPV mean values in saturated conditions showed a high value of $R^2$, equal to 0.82. The slopes of the two regression lines, obtained in dry and saturated conditions (Fig. 2), are not equal, showing that the presence of water influences UPV and compressive strength in a different way. In fact, both UPV and compressive strength are lower in the presence of water but a stronger reduction can be appreciated on the compressive strength. In the presence of water a decrease of the UPV was recorded:it was found between 5% and 10%. This effect has not an immediate response. An increase of UPV in the presenceof water has been shown for various types of rocks [Kahraman 2007;Vasconcelos et al 2008; Török&Vásárhelyi 2010] and itis consistent with the fact that the ultrasonic wave velocity is higherin water than in air, and thus in water filled pores. In case of Lecce stone a different effect, also reported by Atzeni et al. [Atzeni et al. 2006] for a similar highly porous limestone, may cause UPV reduction. In fact, the presence of water can influence the UPV within the rock skeleton. It canweak the calcium carbonate ionic bonds that hold the stone grainstogether, leading to the weakening of the solid/solid contactsbetween the grains with the consequent decrease of the ultrasonicwave velocity in the stone skeleton. This effect, could have great incidence on the microstructure of the Leccestone, consisting of a particle framework densely packed but weaklycemented by poor and fine microsparitic calcite mixed to thegroundmass; it could contrast the increase of the P-wave velocityin the pores filled by water, leading to the overall decrease of thevelocity. A contribution to this result of the clay minerals presentwithin the Lecce stone is not to be excluded. Water can changethe structure of clay minerals with an expandable lattice, by promotingswelling phenomena; ultrasonic velocity in expandable clay minerals is lower in wet conditions than in dry ones [Wilkens et al. 1986,Basma et al. 1996] and their presence in rocks contribute to the UPV decrease in saturated conditions [Karakul &Ulusay 2013].
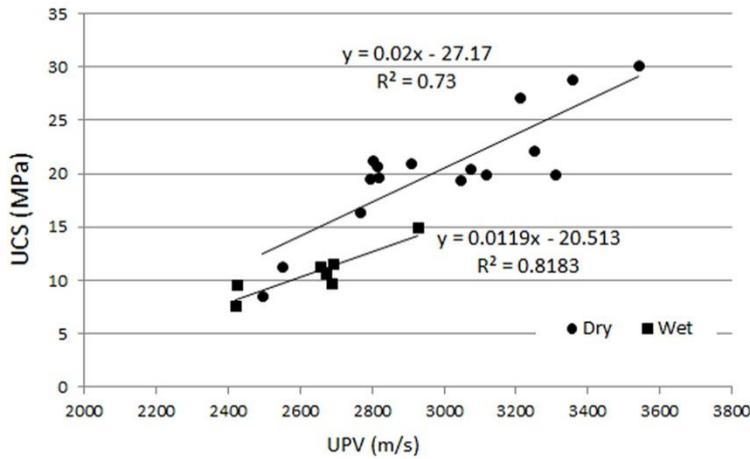
*Figure 2 UPV-UCS linear correlations of Lecce stone in saturated (wet) and dry conditions*

## Influence of frequency

The experimental research was carried out on stone specimens of three different dimensions: cubes of 70 mm (S cubes), 140 mm (M-cubes) and of 250 mm (L-cubes) side. All the cubes were cut from blocks coming from the same quarry. The blocks had dimensions of 500 x 300 x 250 mm, which were associated to x, y and z axes, respectively. The specimens were stored in laboratory conditions for 1 month at a temperature of 15 °C and a relative humidity of 65 %. Five S cubes (S1–S5), four M cubes (M1–M4) and four L cubes (L1–L4) were tested; the specimens were numbered and x, y, and z axes were marked, keeping the same directions assigned to the quarry blocks.

Ultrasonic pulse velocity was measured in direct transmission mode along x and z axes, following the American Standard ASTM D2845-08 [ASTM D2845-08 2008]. The probes were positioned in the center of each face of S and M cubes, while in the case of L cubes two points of measurement for each face were chosen. An ultrasonic gel was used as coupling agent. An Epoch 4 Plus (Olympus), with a pair of ultrasonic transducers of 1 MHz central frequency, and a DIO 1000 LF (Starmans) equipped with transducers of 120 and 55 kHz central frequencies were used. The pulser voltage of the instruments was 400 V and 100 V, respectively. 1 MHz, 120 and 55 kHz were employed for UPV measurements on L and M cubes; the lowest frequency was excluded in the case of the S sample size.

|  | 1MHz | 120kHz | 55kHz | Δ1-120 | Δ1-55 | Δ120-55 |
|---|---|---|---|---|---|---|
| Sx | 3091±10 m/s | 3065±32 m/s |  | 1% |  |  |
| Sz | 3402±34 m/s | 3340±45 m/s |  | 2% |  |  |
| Mx | 3075±156 m/s | 3041±162 m/s | 3020±184 m/s | 1% | 2% | 1% |
| Mz | 3313±43 m/s | 3264±68 m/s | 3266±67 m/s | 2% | 1% | 0% |
| Lx | 3166±22 m/s | 3127±10 m/s | 3105±28 m/s | 1% | 2% | 1% |
| Lz | 3127±28 m/s | 3086±6 m/s | 3082±16 m/s | 15 | 1% | 0% |

Tab 1 UPV mean values with standard deviation, measured on S, M and L cubes along x and z directions, using the wave frequencies of 1 MHz, 120 and 55 kHz. Δ is the percentage of variation between the UPVs obtained with the different frequencies.

Table 1 reports the UPV mean values of the UPV measured at the frequencies of 1 MHz, 120 and 55 kHz , along x and z directions for each S, M and L group; the standard deviations and the differences between the values obtained at the three frequencies (Δ), which was calculated as percentages of variation were also reported. Each sample group shows a slight decrease of the mean values of both UPV along x ($UPV_x$) and along z ($UPV_z$) related to the decreasing frequencies. However, the maximum values of the corresponding mean velocity variations did not exceed 2 %, thus indicating a negligible dispersion related to the frequency used.

**Influence of load**

The same specimens used to investigate the effect of frequency were used to evaluate the influence of the presence of load on the UPV. S cubes were loaded under displacement control by means of a hydraulic universal testing machine with a load capacity up to 150 kN, at a load speed of 0.2 mm/min. Every 15 kN the load speed of the machine was reduced to zero and the ultrasonic pulse velocity was measured. M and L cubes were loaded by means of a 120 tons hydraulic jack, controlled by a manual pump. During the test, the applied load signal was recorded by an electronic data logger. For the whole duration of the test, until the rupture, the load increase was stopped at every 50 and 100 kN for the M and L samples, respectively, to measure the ultrasonic pulse velocity. Samples were kept under load during these measurements. The cracking pattern of all the cubic specimens was visually inspected during loading; the load values and the position at which the crack formed were registered. Both the instruments were accurately set up by means of a calibration bar. The value of the gain was fixed on both the instruments in order to optimize the reading and reduce the noise on the screen; the gate was positioned at about 10 % of the first peak measured on each unloaded specimen. Both the values fixed for the gain and the gate position were kept constant during loading. The time of flight was recorded at the intersection between the gates and the wave front.

Representative curves of UPV versus applied load are reportedin Fig 3 for Sand M groups, which have a similar behavior, in Fig. 3 for L group.
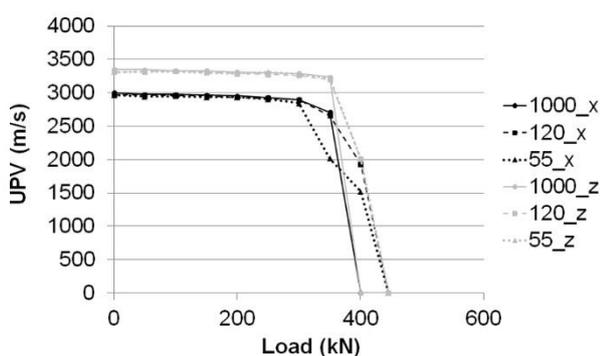


*Figure 3Representative curves of UPV versus applied load for S and M samples.*
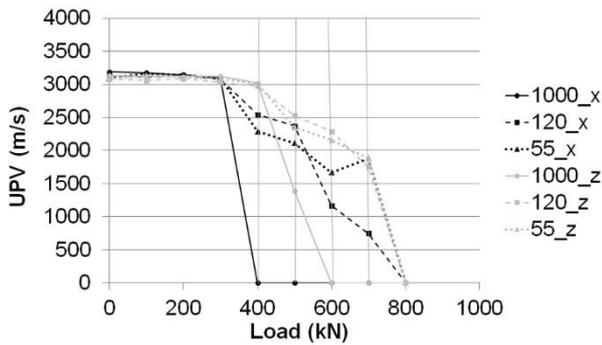
*Figure 4Representative curves of UPV versus applied load for L samples.*

A slight decrease of UPV (up to 6 %) with load was recorded before the visible crack formation along both x and z for all the S, M and L sample groups with the three frequencies used. Up to visible crack formation, the different frequencies record similar effects on the stone materials, as related to the load application. Then a stronger reduction of UPV with load is observed and here on the velocity trends vary with the frequencies used, showing their different abilities to follow the progression of the damage. In S and M groups, UPVs recorded with 1 MHz of frequency almost immediately dropped to zero (Fig. 3) as the appearance of visible cracking stopped the propagation of the elastic waves. The velocities showed a gradual decrease through a few steps, when they were measured at frequencies of 120 and 55 kHz; unstable crack propagation led to the rupture of these samples. In the case of L cubes, the first crack was earlier registered, namely at between 30 and 40 % of the ultimate load; further cracks grew until the collapse of the specimens (in Fig. 4 each vertical line corresponds to the formation of new cracks). Visible cracking and its propagation involved a strong reduction of UPVs along both z and x directions. All the three frequencies were able to detect the cracking evolution within most L samples, but each of them recorded variable extents of the UPV drops. 1 MHz elastic waves were strongly slowed down by the crack formation. The frequencies of 120 and 55 kHz followed the crack growth better than the previous one, through different steps before the collapse of the samples.

Different wave lengths behave differently in the presence of defects: the wave paths are modified depending on the ratio between the wavelength and the defect dimension, thus resulting in different arrival times [Aggelis 2013]. The obtained results suggest that the dispersion of the velocities obtained with the different frequencies can be used as a parameter to discriminate damaged and undamaged stone, as it increases with cracking. In the experiments presented herein, the threshold of 200 m/s has been found as a reference value for the detection of stress induced microcracking; higher dispersion values reveal the presence of important cracks, which seriously compromise the material integrity and thus its loadbearing capacity.

**Conclusions**

In the paper, the results of a wide experimental campaign on the influence of external parameters on UPV measurements on a soft stone are reported. In particular, the influence of three parameters was investigated, namely the presence of water, the employed frequency of measurement and the presence of load. Lecce stone samples were used in the experiments.

In the presence of water a decrease of the UPV was recorded: it was found between 5% and 10%. This effect has not an immediate response. One hypothesis may be that the presence of water weaks the calcium carbonate ionic bonds that hold the stone grains together, leading to the weakening of the solid/solid contacts between the grains with the consequent decrease of the ultrasonic wave velocity in the stone skeleton [Atzeni et al. 2006]. Another possible explanation is that water can change the structure of clay minerals with an expandable lattice, by promoting swelling phenomena; ultrasonic velocity in expandable clay minerals is lower in wet conditions than in dry ones [Wilkens et al. 1986, Basma et al. 1996] and their presence in rocks contribute to the UPV decrease in saturated conditions [Karakul &Ulusay 2013].

A negligible dispersion was observed using 1 MHz, 120 and 55 kHz frequencies of measurements, registering velocity variations which not exceed 2%. This result was independent of the specimen dimension: cubes of 70, 140 and 250 mm side were used in the experiments.

A slight decrease of UPV (up to 6%) with load was recorded before visible crack formation. A stronger reduction of UPV was observed after cracking and it varied with the frequencies used for the measurements. UPVs recorded with 1 MHz frequency almost immediately dropped to zero, as the appearance of visible cracking stopped the propagation of the elastic waves. The velocities showed a gradual decrease through a few steps, when they were measured at frequencies of 120 and 55 kHz. Different wavelengths behave differently in the presence of defects: the wave paths are modified depending on the ratio between the wavelength and the defect dimension, thus resulting in different arrival times [Aggelis 2013]. The obtained results suggest that the dispersion of the velocities obtained with the different frequencies can be used as a parameter to discriminate damaged and undamaged stone, as it increases with cracking.

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