High Frequency Sound Waves as Function of the Density and Water Content: Experimental Studies on Calcarenitic Stones of Southern Apulia

Leucci G.[1], Sileo M.[2], De Giorgi L.[3]

[1]CNR - IBAM, Lecce, giovanni.leucci@cnr.it
[2]CN.R.-IBAM, Potenza

Abstract— *In Apulia Region there is a dense historical-architectural and archaeological heritage built with soft calcarenitic stones. These materials present significant problems of conservation related to their low durability and therefore know the intrinsic characteristics is crucial to evaluate the performance properties and their susceptibility to degradation. To evaluate the physical-mechanical characteristics of the stone materials is very useful to use non-destructive and non-invasive technologies such as ultrasonic, applicable both in situ and in the laboratory.*

The factors influencing the propagation of elastic waves in the rocks are the structure, density, size and shape of the granules, porosity, anisotropy, the water content, stress and temperature. In this paper the effects of saturation on the elastic wave velocity and the relationship between density and elastic wave velocity were studied on some Apulia's porous calcarenites such as Leccese stone, the Ostuni stone and the calcareous "Tufo delle Murge". The ultrasonic P and S wave velocity measurements were performed on cubic samples, under natural condictions (e.g. without applying external pressure on the samples), using the transmission method. Variations of P and S wave velocity were related to density and percentages of water content. Furthermore in order to study the frequency influence on seismic velocities.

Keywords— P and S-wave velocity, bulk density, volumetric water content, sedimentary rock.

I. INTRODUCTION

Monumental structures represent our cultural and historical heritage. However, damage of historical buildings, monuments, works of art and other cultural properties is reported from all over the world. One of the greatest dangers for the historical monuments is weathering, caused by climatic changes and air pollution. Building stones are susceptible to various atmospheric factors causing their destruction, especially in Mediterranean basin, where the marine salts are a permanent cause of natural pollution, not only on the coast but also inland. Weathering effects on the physical and mechanical properties of natural stones of monuments. These properties can be studied using the microgeophysics methods that includes all the methodologies derived from geophysics with more or less miniaturized instrumentations. Particularly ultrasonic measurement is one of the non-destructive microgeophysical methods commonly used in order to provide data related to the elasticity, anisotropy and mechanical and weathering resistance of the stones, porosity, dry density, and water absorption. This method can be applied both in the laboratory. The study of P and S waves velocity has used in several area of application such as rock mass characterization (Boadu, 1997; Leucci and De Giorgi, 2006; Bery and Saad, 2012). There are several studies related to the application of ultrasonic method in order to study the damage of historical buildings and monuments (Zezza, 1993; Christaras et al., 1997; Christaras, 2003; Cosentino et al., 2009; Leucci et al., 2011; Leucci et al., 2012; Calia et al., 2013). Some authors have investigated on the relationship between seismic wave velocity and bulk density (Gardner et al., 1974; Miller and Stewart, 1991). Also the effect of water content on the ultrasonic velocities was studied by several authors (Wyllie et al., 2956; Wyllie et al., 1958; Thill and Bur, 1969; Nur and Simmons, 1969; Gregory, 1976; Carcione, 2001). Kahraman, (2007) performed P-wave velocity measurements were performed on 41 different rock types, 11 of which were igneous, 15 of which were sedimentary and 15 of which was metamorphic, he found a strong linear correlation between the dry- and wet-rock P-wave velocities.

Although several researchers have investigated both the effect of saturation and the variation of bulk density on elastic-wave velocity of different rocks, none of them has derived empirical equations between dry- and wet-rock P and S-wave velocities and between P and S wave velocities and bulk density. Furthermore these studies will be useful for the rock used in the construction of historical and monumental heritage in south Apulia region. In this paper, the predictability of both wet-and dry rock vs P and S-wave velocity and bulk density vs P and S-wave velocity was studied.

II. THE ROCK SAMPLES

The elastic velocity tests were performed on 120 samples related to three different rock types, generally used in the historical building and monumental heritage in southern Apulia. Rock blocks were collected from the stone quarries.

The rock types were:

The "*Pietra Gentile*" (kind stone), or Ostuni stone were collect from two different quarries, The Melpignano quarry (M) and the White quarry (B), respectively, in the towns of Ostuni and Carovigno (near Brindisi).

The kind stone is mined in the province of Brindisi and it is a white calcarenite. From the petrographic point of view it can be classified as *wackestone* (Dunham, 1962) and it is composed by fossilized remains of algae and recrystallized foraminifera and lithoclasts limestone with average size of about 200 microns embedded in a micritic matrix that gives to the rock a texture mud supported. The porosity, is variable from 25% (M type) to 28% (B type) approximately, with an average pore radius of 0.24 microns (M type) and 0.86 microns (B type). The uniaxial compression strength of such materials in the dry and saturated state are shown in table 1. The *"Pietra Gentile"* stone shows a good mechanical strength in the dry state (19 MPa, B type ; 24.13MPa M type) and a differential loss of resistance at the saturated state (15.74 % B type; 3,50 % M type).

TABLE 1
DATA OF COMPRESSION TESTS IN DRY AND WET CONDITIONS

Rock type	DRY		WET		loss of strength in %
	Uniassial compressive strenght (MPa)	Standard Deviation (MPa)	Uniassial compressive strenght (MPa)	Standard Deviation (MPa)	
Pietra gentile (B)	19,00	4,36	16,01	4,70	15,74
Pietra gentile (M)	24,13	7,90	23,28	4,84	3,50
Pietra leccese (PL)	25,54	2,89	14,72	1,61	42,36
Tufo delle murge (T)	3,34	0,84	1,99	0,34	40,42

The "*Pietra Leccese*" (PL – Lecce stone): was collect from Marti's quarry, in the municipality of Cursi (Lecce).

Widely cultivated in Salento, Lecce stone, white-yellowish, is a fine-grained limestone, classifiable as *wakestone*. From petrographic point of view, it is composed primarily of benthic and planktonic foraminifera fragments, numerous small greenish grains of "*glauconite"* and phosphate nodules. The dimensions of bioclastis vary between 100 and 150 microns, the matrix is composed of micrite and clay minerals, while the calcite cement is poor and has a cryptocrystalline texture. The porosity is mainly represented by pores type of inter- and intra-granular, with dimensions between a few microns and 200 microns. The porosity is 36%, with predominant pore radius between 0.9 and 1.0 microns. Leccese stone shows in the dry state a uniaxial compression strength of 25.54 MPa, while at the saturated state decreases strongly, in fact there is a loss of resistance that is on average to 42.36% (Table1), in agreement with Zezza (1974).

The "*Tufo delle Murge*" (T): was collect from a quarry in the territory of Montescaglioso (Matera).

Extensively used in Apulia and Basilicata, the "*Tufo delle Murge*" is a fine-grained limestone, classifiable as *grainstone*. Consisted lithoclasts and bioclastic limestone, represented by the remains of benthic foraminifera, briozoe, bivalves, gastropods, echinoderms and calcareous algae. The matrix is absent and the weaving is grain-supported. The microcrystalline cement is present in small amounts and it is of inter-intra granular type. The porosity observed at the microscope consists of pores ranging from tens of microns to 500 microns. The porosity is equal to approximately 45%, with most of the pores having a radius greater than 10 microns prevalent. The mechanical properties of "*tufo delle Murge*" are very low in the dry state (3.34 MPa) and at the saturated state decreases strongly with a loss of resistance of 40.42% in agreement with what found in the literature for these materials (Andriani & Walsh 2007) (Table1).

III. THE LABORATORY TEST

Both 70mm and 100mm cubes samples were used in the laboratory. Surfaces of the samples were cut and polished sufficiently smooth plane to provide good coupling (Fig. 1). In the measurements, the Epoch4 plus (by Olympus) and two transducers (a transmitter and a receiver) for both P and S wave having a frequency of 1 MHz were used. Transducers were pressed to either end of the sample and the elastic wave pulse travel time was recorded. The ultrasonic technique used was based on the transmitting pulse method. The propagation velocity was determined by measuring the specimen length and the travel time (time-of-flight) of the ultrasonic wave. Three readings were taken for each test specimen: in the center of the cross-section and on the upper and lower points of the cross-section. The ultrasonic velocity was calculated based on the average of the three measurements of time-of-flight and the length of the specimen, using the equation:

$$V = S/T$$

where V is the longitudinal ultrasonic velocity, S is the length of the specimen, and T is the time-of-flight of the pulse through the specimen. Estimated margins of error in the pulse measurements were ± 6 - 8m/sec in "*pietra leccese*" and "*tufo delle murge*" and ±3-5 m/sec in "*pietra gentile*" rock.

FIG. 1: THE LABORATORI TEST INSTRUMENTATION

In the first step Vp and Vs were measured on dry samples. In the second step the samples were saturated with distilled water for 216 h (9 days). In the first day P and S-wave velocity measurements were performed, after weighting a sample, for the 20 minutes (every 2 minutes for "pietra leccese" and "tufo delle murge"), 60 minutes (every 5 minutes for "pietra gentile"), and successively every one hour for all samples. In the successively 8 days measurements were performed one per day. The method was repeated for each sample. Bulk density was based on weight when oven dry. The experiment was carried out under natural condictions (e.g. without exerting pressure on the samples).

IV. P AND S-WAVE VELOCITY AS FUNCTION OF NORMALIZED SATURATION DEGREE

Figure 2 shows the average water absorption curve related to the three type of tested rock. As shown in Fig. 2, a rapid increase in the water absorption was occurred in the three type of tested rock. For the "pietra gentile" samples, the major absorption were obtained in 1 hour, while for "pietra leccese" and "tufo delle murge" the major absorption was obtained in 30 minutes and 10 minutes respectively. However, after this time there are no remarkable changes.

When the P-wave velocity plots as a function of normalized saturation degree was examined, it was shown that after initial increasing with increasing saturation degree, P-wave velocity values were remained approximately same up to a saturation degree value depending on the rock properties Figs 3a-5a. The P-wave velocity plots as a function of normalized saturation degree for "*pietra gentile*" rock is given in Fig. 3a. As shown in Fig. 2a, the saturation values vary between approximately 7.5% and 8.5%. It was found that the Vp values increase rapidly with the increase of normalized saturation degree.

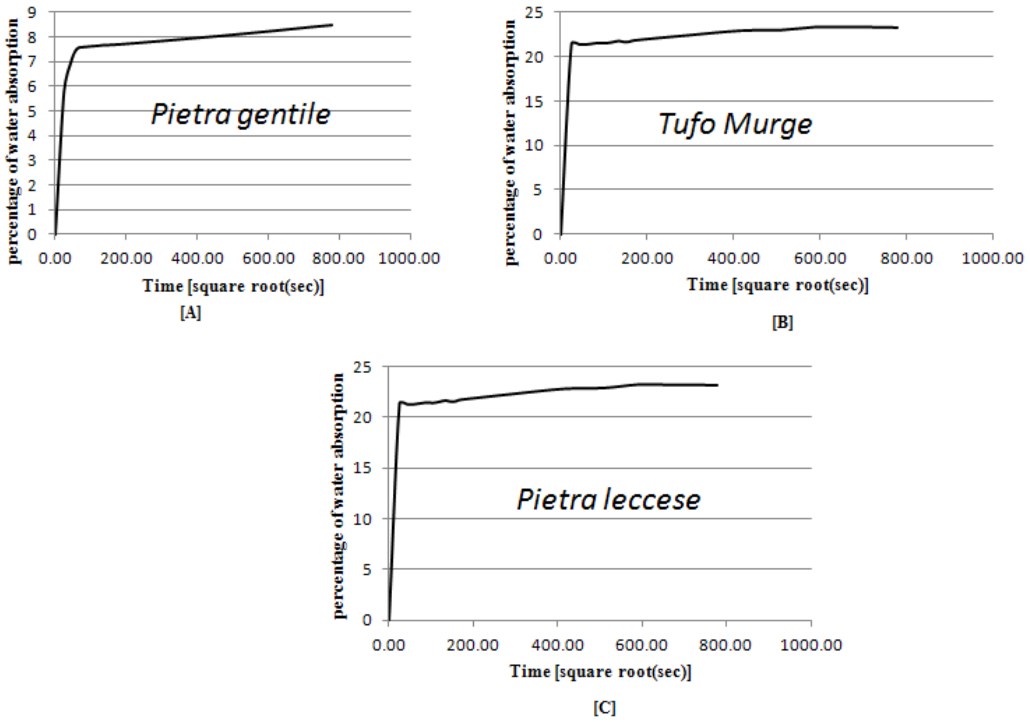


FIG. 2: AVERAGE WATER ABSORPTION CURVE RELATED TO: A) PIETRA GENTILE; B) TUFO DELLE MURGE; C) PIETRA LECCESE

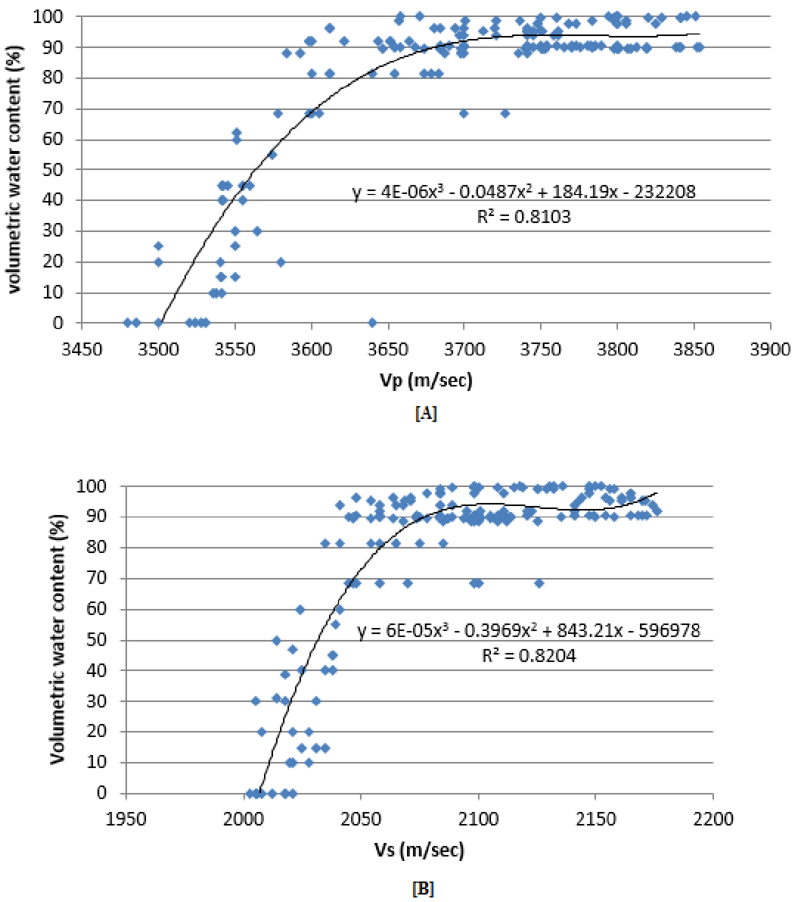


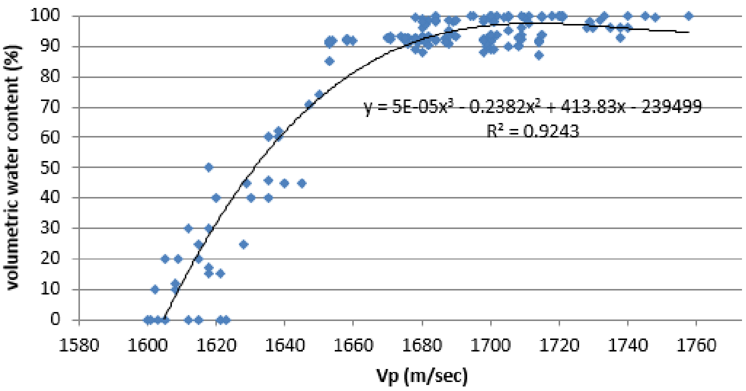
FIG. 3: PIETRA GENTILE: ULTRASONIC WAVE VELOCITY VS VOLUMETRIC WATER CONTENT: A) P-WAVE; B) S- WAVE

The correlation between Vp and normalized saturation degree (w) was evaluated using the method of least squares regression. Linear, polynomial, exponential and power curve fitting approximations were tried and the best approximation equation with highest correlation coefficient (R^2) was determined for each regression. There is a strong correlation between the Vp and w (Fig. 3a). The relation follows a polynomial function. The equation of the line is

$$w = 4*10^{-6}*Vp^3 – 0.0487*Vp^2 + 184.19 *Vp -232208 \qquad R^2 = 0.8103 \qquad (1)$$

The S-wave velocity plots as a function of normalized saturation degree for "*pietra gentile*" rock is given in Fig. 3b. The Vs values increase rapidly with the increase of normalized saturation degree. Also in this case the correlation between Vs and normalized saturation degree (w) was evaluated using the method of least squares regression. The relation follows a linear function. The equation of the line is

$$w = 6*10^{-5}*Vs^3 – 0.3969*Vs^2 + 843.21 *Vs -596978 \qquad R^2 = 0.8204 \qquad (2)$$



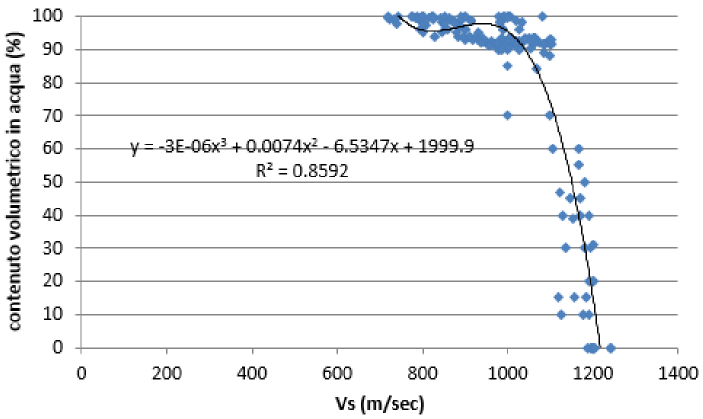


FIG. 4: TUFO DELLE MURGE: ULTRASONIC WAVE VELOCITY VS VOLUMETRIC WATER CONTENT: A) P-WAVE; B) S- WAVE

The P-wave velocity plots as a function of normalized saturation degree for "*tufo delle murge*" rock is given in Fig. 4a. As shown in Fig. 2b, the saturation values vary between approximately 21.1% and 22.5%. It was found that the Vp values increase with the increase of normalized saturation degree. The correlation between Vp and normalized saturation degree (w) was a linear function. The equation of the line is

$$w = 5*10^{-5}*Vp^3 – 0.2382*Vp^2 + 413.83 *Vp -239499 \qquad R^2 = 0.9243 \qquad (3)$$

The S-wave velocity plots as a function of normalized saturation degree for "*tufo delle murge*" rock is given in Fig. 4b. In this case the experimental results shows a different behavior than "*pietra gentile*". In fact the Vs values decrease with the increase of normalized saturation degree and the correlation between Vs and w was a polynomial function. The equation of the line is

$$w = -3*10^{-6}*Vs^3 + 0.0074*Vs^2 -6.5347 *Vs + 1999.9 \qquad R^2 = 0.8592 \qquad (4)$$

Same results were obtained for the “*pietra leccese*” rock. As shown in Fig. 2c, the saturation values vary between approximately 21.3% and 23.1%.

The P-wave velocity plots as a function of normalized saturation degree for “*pietra leccese*” rock is given in Fig. 5a. The correlation between Vp and w was the polynomial equation

$$w = 6.9*10^{-11}*Vp^3 – 1.8*10^{-8} *Vp^2 + 4.07*10^{-4} *Vp – 0.312 \qquad R^2 = 0.7792 \qquad (5)$$

As “*tufo delle murge*” in the “*pietra leccese*” rock the S-wave velocity decrease with an increase of normalized saturation degree (Fig. 5b). The correlation eqation was:

$$w = -5*10^{-6}*Vs^3 + 0.0121*Vs^2 – 10.881 *Vs +3367.2 \qquad R^2 = 0.9072 \qquad (6)$$

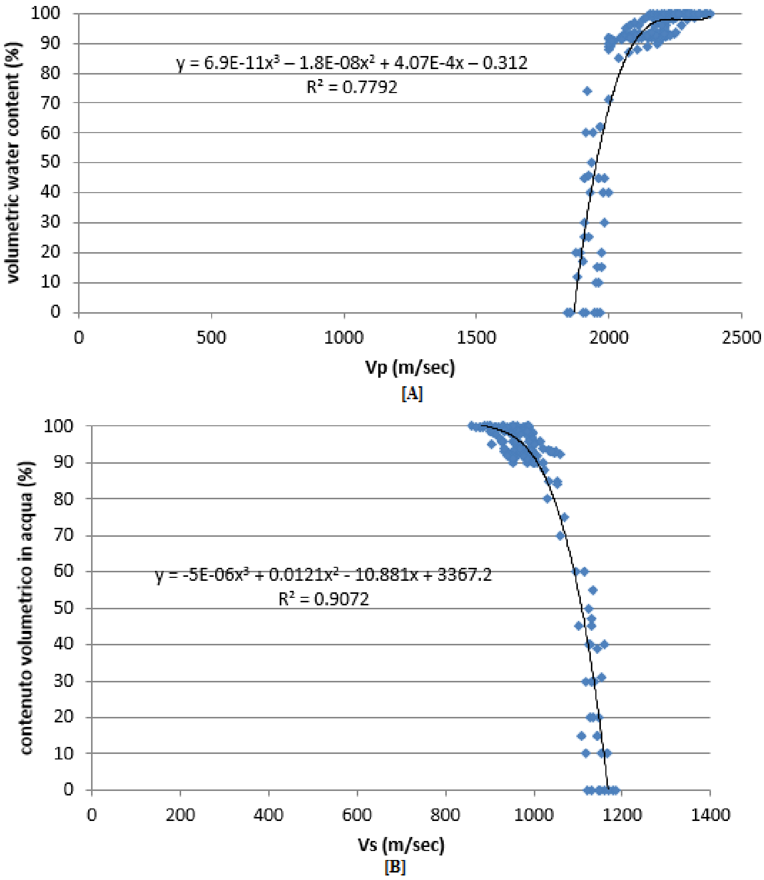


FIG. 5: PIETRA LECCESE: ULTRASONIC WAVE VELOCITY VS VOLUMETRIC WATER CONTENT: A) P-WAVE; B) S- WAVE

V. P AND S-WAVE VELOCITY AS FUNCTION OF BULK DENSITY

Bulk densities were determined by the weight-volume method. Statistical analysis procedures were used to examine the relationships between the P and S-wave velocity and density for the three studied rocks type. The results obtained are presented in Figs. 6-8. The relationship between density and velocity could be represented by linear regression models. The coefficients of determination (R^2) were found to be significant and ranged from 0.74 to 0.89. In all the studied sampled the relationship between ultrasonic velocity and bulk density indicate that the velocity tended to increase as the density of the samples increased.

However, when different rock type are considered, the correlation are different, as it can be observed in the experimental results.

For "*pietra gentile*" the results related to the analysis of Vp versus density (Fig 6a) show an increasing trend in Vp as density increases, the relationship was a linear equation as follow:

$$\text{density} = 0.2657Vp + 1030.9 \qquad R^2 = 0.7449 \tag{7}$$

The Vs versus density show a linear relationship (Fig. 6b) as follow:

$$\text{density} = 0.3581Vs + 1255.4 \qquad R^2 = 0.7513 \tag{8}$$

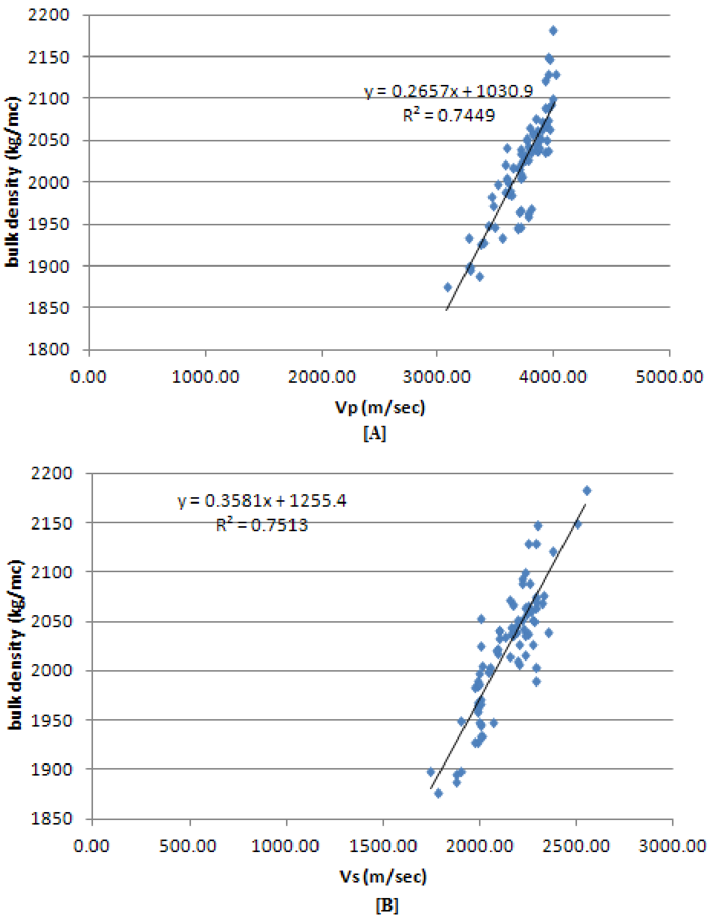


FIG. 6: PIETRA GENTILE: ULTRASONIC WAVE VELOCITY VS BULK DENSITY: A) P-WAVE; B) S- WAVE

For "*tufo delle murge*" Vp show an increasing trend as density increases (Fig. 7a), the relationship was a linear equation as follow:

$$\text{density} = 0.7884Vp + 363.27 \qquad R^2 = 0.8955 \tag{9}$$

The Vs versus density show a linear relationship (Fig. 7b) as follow:

$$\text{density} = 0.7068Vs + 1058.8 \qquad R^2 = 0.7521 \tag{10}$$

Also for "*pietra leccese*" Vp increase as density increases (Fig. 8a) with a linear equation:

$$\text{density} = 0.1997Vp + 1332.7 \qquad R^2 = 0.8153 \tag{11}$$

The Vs versus density show a linear relationship (Fig. 8b) as follow:

$$\text{density} = 0.2226Vs + 1324.9 \qquad R^2 = 0.8726 \tag{12}$$

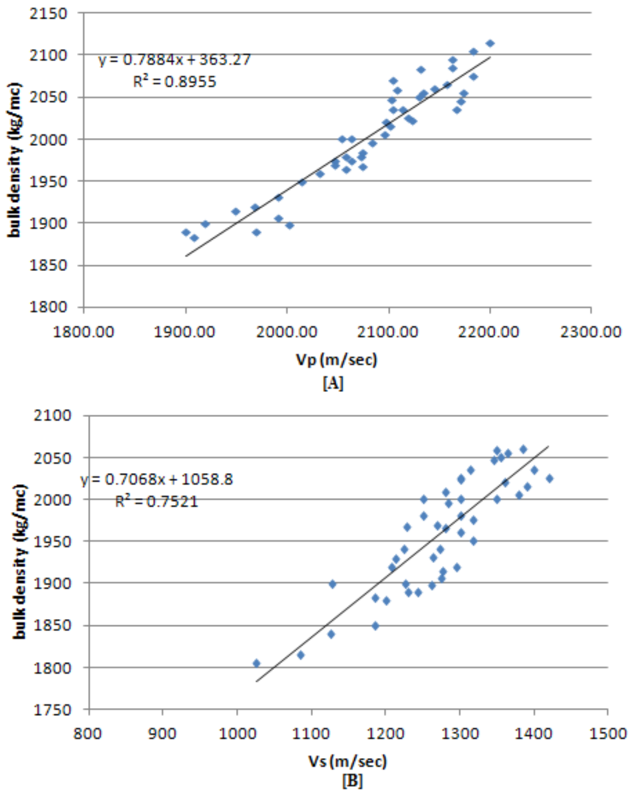


FIG. 7: TUFO DELLE MURGE: ULTRASONIC WAVE VELOCITY VS BULK DENSITY: A) P-WAVE; B) S- WAVE

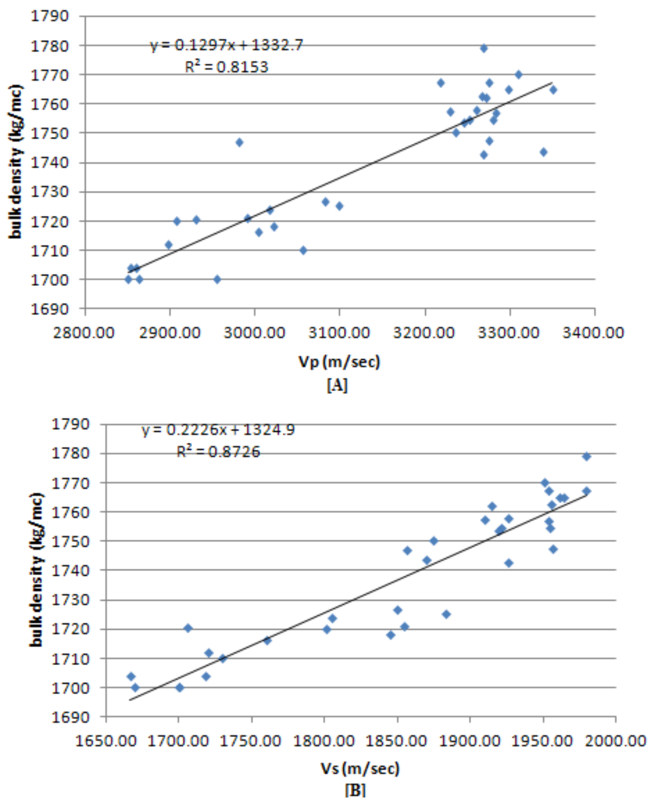
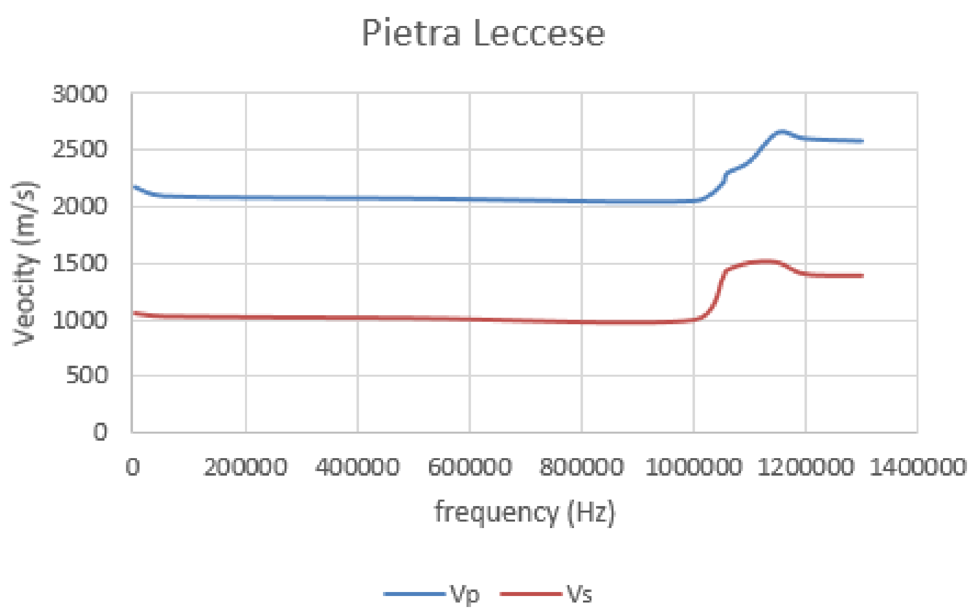
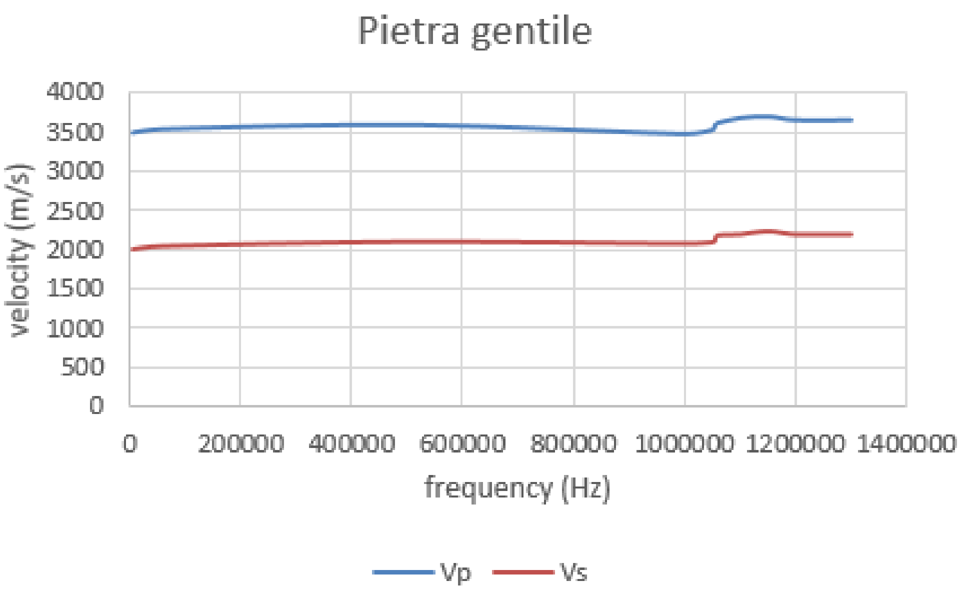


FIG. 8: PIETRA LECCESE: ULTRASONIC WAVE VELOCITY VS BULK DENSITY: A) P-WAVE; B) S- WAVE

Furthermore an experiment that consider the velocity variations as function of frequency was carried out using the same samples (dry and saturated) and the instrumental package contains additional electronics, including a digital oscilloscope, an impulse generator and a bandpass filter. The system was controlled by a PC, using Labview codes. The average velocities were used. The results (Fig. 9) indicate that the velocity variations are confined at frequencies greater of 1MHz.





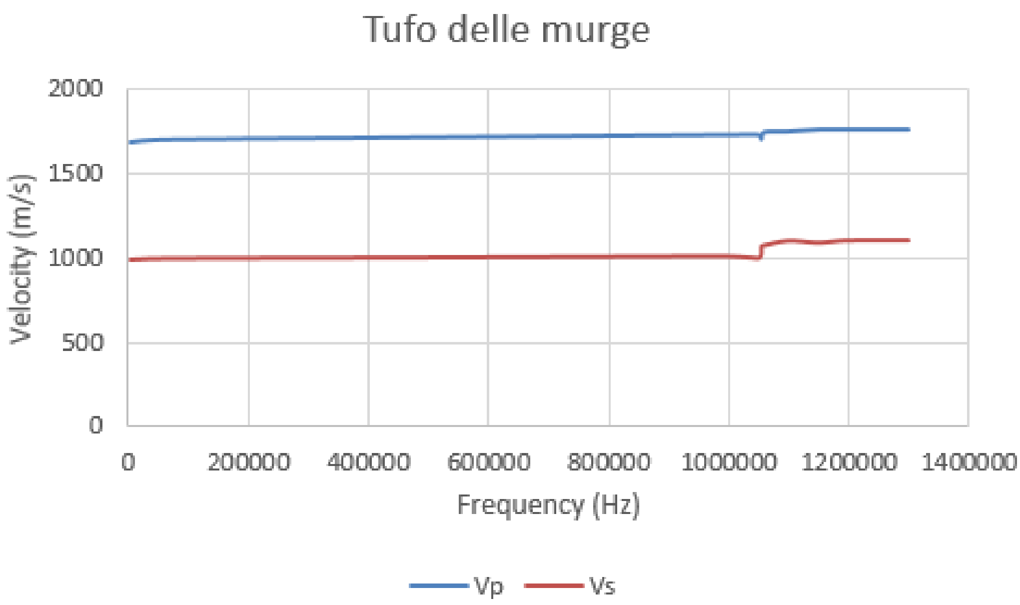


FIG. 9: ULTRASONIC WAVE VELOCITY VS FREQUENCY

VI. IN SITU MEASUREMENTS

In order to provide information on the quality and consistency of masonry structures of the important historic building in Lecce, the method of the sonic pulse velocity was applied. This method consists of the measurement and observation of acoustic waves reflected/transmitted inside the masonry. To perform the measurements, we have made use of a Boviar T-das multichannel ultrasonic instrument, composed of a data acquisition unit, piezoelectric transmitter (>1.6 kV), and piezoelectric receiver (at 55 kHz). To generate the seismic waves, we made use of a triggered hammer. The sampling rate was 1.25 MHz. Considering an average wave velocity, inside the surveyed medium, of about 1000 m/sec and the central frequency of the probe (55 kHz), we obtained a main wavelength of about 0.018 m. The acquisition was realized using 24 measurement points every profile with 24 shot points. The distance between two consecutive probe positions was of the order of 12 cm.

The sonic pulse velocity test was carried out with the direct transmission method, which involves the crossing of a pressure wave through the structure from a source (piezoelectric transmitter) to a receiving sensor (accelerometer receiver) located on the opposite sides of the masonry element. The resulting wave velocity is an average value of the local velocity along the path. The zero time calibration was performed using a bar sample with known length and seismic p-wave velocity. Measurements were performed on a series of pillars in "*pietra leccese*" rock (Fig. 10).

FIG. 10: IN SITU ULTRASONIC WAVE VELOCITY ACQUISITION ON PIETRA LECCESE PILLAR

The picking of the P-wave travel times was performed manually for each point. Then, the vector of the 'slowness', i.e. the inverse of the velocity, was calculated for each sub-segment identified between two consecutive crosses along the straight paths from the transmitters to the receivers. This was accomplished by inverting the system

$$t = Au \tag{13}$$

Where t is the vector of the measured comprehensive times, u is the unknown vector of the slowness and A is a matrix whose elements represent the length of the sub-segments along the straight paths where the seismic signal propagates. The choice of the paths is a trade-off between the accuracy and

The robustness of the result, and in particular it is a good role of thumb to have a number of rays (i.e. data) larger than the number of unknowns looked for. In our case, we have taken 576 data. The inversion is performed by means of the simultaneous iterative reconstruction technique (SIRT) method for curvilinear rays.

The P-wave velocity distribution is show in Fig. 11a. Vp values ranging from 1500 to 2200 m/sec. They were interpreted as follow: Vp<1800 m/sec damaged masonry; 1800 < Vp < 2500 masonry with average damage. This interpretation was related to the laboratory results obtained for the undamaged "*pietra leccese*" that show for Vp variation between 2800 m/sec and 3300 m/sec. Using relationships 5 and 12 water content and density were esteemed (Figs. 11 b and c).

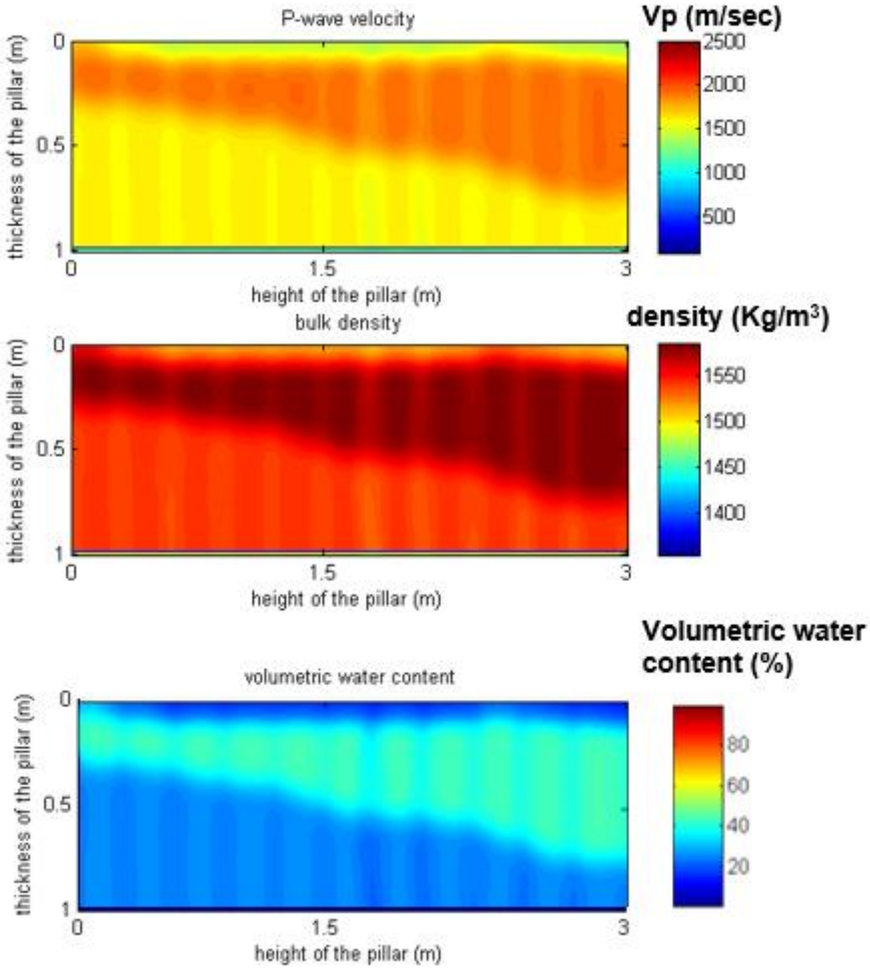


FIG. 11: IN SITU MEASUREMENTS: 2D DISTRIBUTION OF VP, BULK DENSITY AND VOLUMETRIC WATER CONTENT

The density distribution shows (Fig. 11b) values ranging from 1520 to 1554 Kg/m^3. While the water content distribution show (Fig. 11c) values ranging from 20 to 49%. These values were verified by core results that done a density values ranging from 1500 to 1540 Kg/m^3 and a volumetric water content values ranging from 0 to 41%.

VII. CONCLUSION

P and S wave velocity measurements were carried out on three different rock types used in the building construction in the southern Italy. The results were evaluated as function of bulk density and normalized saturation degree variations. The rock types were "*pietra gentile*", "*tufo delle murge*" and "*pietra leccese*". The following conclusions were obtained:

- The Vp values increase as the normalized saturation degree increase in the three type of rock; P-wave velocity values rapidly increases follow a liner equation that varies in the three types of rock;
- The Vs values increase as the normalized saturation degree increase in the "*pietra gentile*", while decrease as the normalized saturation degree increase in both the "*tufo delle murge*" and "*pietra leccese*" rock types; this anomalous behavior may be due to the intrinsic characteristics of studied rock types. In fact, this phenomenon is to be related to the framework which determines the natural resistance of the rocks . The "*Pietra Gentile*" stone shows values of uniaxial compressive strength in dry conditions similar to the "*pietra leccese*", while the Tufo delle Murge has poor resistance. In wet conditions the loss of strength of "*Pietra Gentile*" is relatively low (15.74% M; 3.5% B), while for the Leccese stone and "tufo delle Murge" has a fall of resistance even greater than 40% as seen from the values of uniaxial compressive strength shown in Table 1.
- The low porosity values of "*pietra gentile*" makes it very compact makes it very compact and consequently the velocity Vs insensitive to changes of fluid present within the pores;
- The Vp and Vs values increase as the density increase;
- Regression analysis indicated that P and S-wave values were strongly correlated with the normalized saturation degree and density. When the regression analyses were repeated for the three types rock, it was seen that correlation coefficients were increased using a linear correlation.
- The in situ measurements demonstrate the effectiveness of the relationships obtained from laboratory test.

REFERENCES

[1] Andriani G.F. & Walsh N., 2007 - The effects of wetting and drying, and marine salt crystallization on calcarenite rocks used as building material in historic monuments. In: Prikryl R. & Smith B. J. eds) Building Stone decay: From Diagnosis to Conservation. Geological Society, London, Special Publications, v. 271, pp. 179-188.

[2] Andy A. Bery, Rosli Saad, 2012. Correlation of Seismic P-Wave Velocities with Engineering Parameters (N Value and Rock Quality) for Tropical Environmental Study International Journal of Geosciences, 2012, 3, 749-757

[3] Boadu F.K., - 1997 - Fractured rock mass characterization parameters and seismic properties: analytical studies, J. Appl. Geophys. 36 (1997) 1– 19.

[4] Calia A., Lettieri M., Leucci G., Matera L., Persico R., Sileo M., 2013. The mosaic of the crypt of St. Nicholas in Bari (Italy): Integrated GPR 1 and laboratory diagnostic study. Journal of Archaeological Science 40, 4162-4169 10.1016/j.jas.2013.06.005

[5] Carcione J.M., 2001 - Wave Fields in Real Media. Theory and Numerical Simulation of Wave Propagation in Anisotropic, Anelastic and Porous Media, Pergamon Press, 2001.

[6] Christaras B., Mariolakos I., Foundoulis J., Athanasias S., Dimitriou A.,1997 - Geotechnical input for the protection of some Macedonian Tombs in Northern Greece, in: Proceedings of the 6th International Symposium Conservation of Monuments in the Mediterranean Basin, Rhodes, 1997, pp. 125–132.

[7] Christaras B., 2003 - P-wave velocity and quality of building materials, in: E. Yuzer, H. Ergin, A. Tugrul (Eds.), Proceedings of the International Symposium Industrial Minerals and Building Stones, Istanbul, 2003, pp. 295–300.

[8] Cosentino P L, Capizzi P, Fiandaca G, Martorana R, Messina P. 2009. Advances in Microgeophysics for Engineering and Cultural Heritage Journal of Earth Science, Vol. 20, No. 3, p. 626–639.

[9] Gardner G.H.F., Gardner L.W., Gregory A.R., 1974. Formation velocity and density: the diagnostic basis for stratigraphic, Geophysics 39, 770–780.

[10] Gregory A.R.,1976 - Fluid saturation effects on dynamic elastic properties of sedimentary rocks, Geophysics 41 (1976) 721–895.

[11] Dunham R.J., 1962. Classification of carbonate rocks according to depositional texture. Classification of carbonate rocks. Mem. American Association Petrology and Geology, 1, W.E. Ham Ed. 108-121.

[12] Kahraman S., 2007 - The correlations between the saturated and dry P-wave velocity of rocks. Ultrasonics 46, 341–348.

[13] Leucci G., De Giorgi L., 2006. Experimental studies on the effects of fracture on the p and s wave velocity propagation in sedimentary rock ("calcarenite del salento"). Engineering Geology, 84, 130–142; doi:10.1016/j.enggeo.2005.12.004

[14] Leucci G., Masini N., Persico R., Soldovieri F., 2011. GPR and Sonic Tomography for Structural Restoration : the Case of the Cathedral of Tricarico. Journal of Geophysics and Engineering, 8, 76-92; doi:10.1088/1742-2132/8/3/S08

[15] Leucci G., Masini N., Persico R., Quarta G., Dolce C., 2012. A Multidisciplinary Analysis of the Crypt of the Holy Spirit in Monopoli (Southern Italy). Near Surface Geophysics, 10, 1-8; doi:10.3997/1873-0604.2011032

[16] Miller S. L. M., Stewart R. R. 1991 -The relationship between elastic-wave velocities and density in sedimentary rocks: A proposal, CREWES Research Report, Consortium for Res. in Elastic Wave Explor. Seismol., Calgary, Canada. (Available athttp://www.crewes.org/Reports/1991/1991-17.pdf).

[17] Nur A., Simmons G., 1969 - The effect of saturation on velocity in low porosity rocks, Earth Planet. Sci. Lett. 7 (1969) 183–193.

[18] Thill R.E., Bur T.R., 1969 - An automated ultrasonic pulse measurement system, Geophysics 34 (1969) 101–105.

[19] Wyllie M.R.J., Gregory A.R., Gardner L.W.,1956 - Elastic wave velocities in heterogeneous and porous media, Geophysics 21, 41–70.

[20] Wyllie M.R.J., Gregory A.R., Gardner G.H.F., 1958 - An experimental investigation of factors affecting elastic wave velocities in porous media, Geophysics 23 (1958) 459–493.

[21] Zezza F., 1974 - Le pietre da costruzione e ornamentali della Puglia. Caratteristiche sedimentologico – petrografiche, proprietà fisico – meccaniche e problemi geologico – tecnici relativi all'attività estrattiva, Rassegna Tecnica Pugliese – Continuità, anno VIII, n.3-4.

[22] Zezza F., 1993 - Evaluation criteria of the effectiveness of treatments by non destructive analysis, in: Proceedings of the 2nd Course of CUN University School of Monument Concervation, Heraklion, 1993, pp. 198–207.