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Case study

Assessments on the material properties of the Pietraforte stone of Florence (Italy) in conservation, restoration and construction

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ABSTRACT

"Pietraforte" is the historic name of a turbiditic sandstone extensively used in monumental buildings of Florence from the Roman period to the early XX century. Today all the historical quarries are disused, and they have been reclaimed as urban areas or parks (e.g., Boboli Garden). No technical data on Pietraforte are available, although they would be valuable to drive the conservation of these exceptional monumental buildings. In this work the results of an experimental research are shown; the experimental campaign was aimed at investigating the mechanical properties of Pietraforte through both destructive and non-destructive tests. The analysed samples were extracted from some of the ancient quarries used for the historical buildings in the Florentine area. All the samples were tested according to international standards, in order to collect statistically consistent results in terms of the *ultrasonic velocity* of the *P*-waves and *uniaxial compressive strength*. A predictive model to relate the ultrasonic velocity and the uniaxial compressive strength is proposed on the basis of the obtained results. The collected experimental data refer to "fresh" intact rock and provide useful knowledge that can be used to design and calibrate the interventions on monumental buildings made of Pietraforte.

1. Introduction

"Pietraforte" is the historical name of the material used for the main stone buildings of Florence (Italy) since its settlement in 59 BCE by the Romans. It is light brown in colour, and was widely used for construction until the beginning of the XX century, when the growth of the city incorporated the last quarries inside its perimeter.

Despite its long historical use, and the various papers written about its adoption in Florentine buildings [1–6], the technical information on Pietraforte is not yet completely satisfactory. Indeed, while various comprehensive studies have been made on its physical properties, such as those by Banchelli et al. [7] in 1997, and by Pecchioni et al. in 2020 [8,9], no certified technical tests have been made on its mechanical properties. To date, only a few experimental investigations have been made to check the mechanical properties of this material. The first available data were found in 1883 at the Military Arsenal in La Spezia [10]. More recently, in 1986, Barbi et al. [11] provided some data found through cores drilled in the masonry of Brunelleschi's Dome. None of these data, however, were obtained according to the current testing procedures; furthermore, they differ from each other in the size and number of samples,

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and are therefore hard to compare.

The lack of data regarding the mechanical properties of construction materials used in a limited area is not so unusual. In past centuries, the use of local materials for construction was the most common choice, and there is, worldwide, much historical architecture built with materials which were very locally used, or which are no longer used. The knowledge of these materials is very

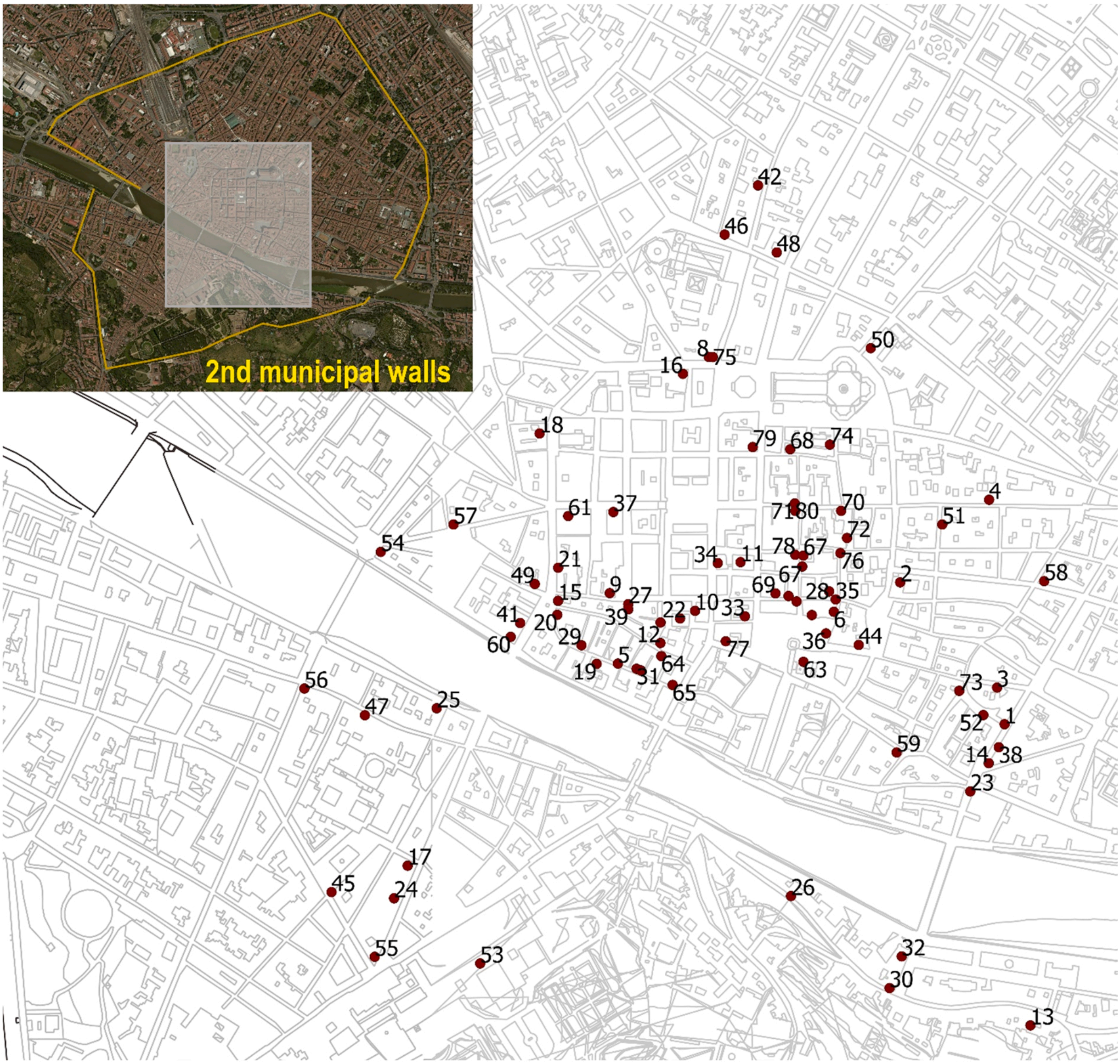

Fig. 1. Some of the mostfamous buildings made in Pietraforte until the XVI century. 1 Arco dei Peruzzi, 2 Bargello, 3 Bourbon del Monte, 4 Casa Altoviti, 5 Casa Buondelmonti, 6 Casa del Garbo, 7 Casa Guidacci, 8 Casa Marignolli, 9 Casa-torre dei Foresi, 10 Loggia del Mercato Nuovo, 11 Orsanmichele, 12 Palagio di Parte Guelfa, 13 Palazzo Alamanni, 14 Palazzo Alberti, 15 Palazzo Bartolini-Salimbeni, 16 Palazzo Bezzoli, 17 Palazzo Biliotti, 18 Palazzo Boni-Antinori, 19 Palazzo Borgherini, 20 Palazzo Buondelmenti, 21 Palazzo Cambi del Nero, 22 Palazzo Cavalcanti, 23 Palazzo Corsi-Horne, 24 Palazzo Corsini Suarez, 25 Palazzo Coverelli, 26 Palazzo da Uzzano, 27 Palazzo Davanzati, 28 Palazzo de' Cerchi, 29 Palazzo degli Altoviti, 30 Palazzo dei Mozzi, 31 Palazzo del Gran Siniscalco, 32 Palazzo Del Nero, 33 Palazzo dell'arte dei mercatanti, 34 Palazzo dell'Arte della Lana, 35 Palazzo della Condotta, 36 Palazzo della Mercatanzia, 37 Palazzo dello Strozzino, 38 Palazzo di Benedetto degli Alberti, 39 Palazzo Davanzati, 40 Palazzo Giandonati, 41 Palazzo Gianfigliazzi, 42 Palazzo Ginori, 43 Palazzo Giugni, 44 Palazzo Gondi, 45 Palazzo Guadagni, 46 Palazzo Lotteringhi della Stufa, 47 Palazzo Manetti, 48 Palazzo Medici, 49 Palazzo Minerbetti, 50 Palazzo Niccolini, 51 Palazzo Pazzi Quaratesi, 52 Palazzo Peruzzi-Lotti, 53 Palazzo Pitti, 54 Palazzo Ricasoli, 55 Palazzo Ridolfi, 56 Palazzo Rinuccini, 57 Palazzo Rucellai, 58 Palazzo Salviati, 59 Palazzo Soldani, 60 Palazzo Spini, 61 Palazzo Strozzi, 62 Palazzo Uguccioni, 63 Palazzo Vecchio, 64 Residenza dell'arte dei Galigai, 65 Torre de' Baldovinetti, 66 Torre de' Buondelmonti, 67 Torre de' Cerchi, 68 Torre de' Visdomini, 69 Torre degli Alepri, 70 Torre dei Donati, 71 Torre dei Ghiberti, 72 Torre dei Giuochi, 73 Torre dei Peruzzi, 74 Torre dei Pierozzi, 75 Torre del Vescovo, 76 Torre della Castagna, 77 Torre di Casa Ciacchi, 78 Torre Galigai, 79, 80 Torre degli Adimari.Some of the most famous buildings made in Pietraforte until the XVI century.

important for the scientific community, both for understanding the features of the historical buildings and their possible damage, and to preserve as well as possible such remains of architectural value. A lot of research has been done in the last few decades on the assessment of local materials.

Interesting studies have been carried out on single buildings, such as the study by Bozdağ et al. focused on the Eflatunpınar Hittite Water Monument in Konya [12], the one by Korkanç et al. on the Granaries located at Taşkale [13], or by Gökçe et al. on the Zengibar Castle (Bozkır, Konya, Central Anatolia) [14]. In these cases, the damage suffered by the buildings is related to the properties of the stones used for their construction and to the environmental conditions.

Other studies are instead focused on the stones typical of specific sites [15–17]; most of this research is focused on areas that have not been intensively occupied, which has preserved their main features, such as Nueva Tabarca island (Spain) [18,19], where it is possible to observe a strict relation between all the quarries used over the centuries, the state of conservation of the buildings and the vicissitudes that have occurred. This is not the case of Pietraforte; it was extracted from the banks along the hills that delimit the Arno River, and it was widely used for the buildings, bridges and towers of Florence. The use of Pietraforte reached its peak during the Renaissance, becoming a benchmark of the architecture in Florence. Many of the buildings made of Pietraforte across the centuries are still in use. Fig. 1 shows the location of the most important buildings made of Pietraforte until the XVI century (without considering churches); besides such constructions, however, many more residential buildings were built using Pietraforte.

Due to its easy availability and high strength, it was mainly used for structural purposes, to build monumental palaces and towers (see Fig. 2). However, it was used also for architectural details, such as angle-irons, gates, window frames, or the external details of facades, as can be seen in the images shown in Fig. 3.

The number of intact and still-in-use buildings made of Pietraforte proves the suitability of this material for architectural and structural purposes. For this reason, its use for renovating historical buildings is adequate and suitable and, therefore, the mechanical properties of the material need to be known.

This paper presents the results of experimental research aimed at investigating the main mechanical properties of Pietraforte. For this purpose, a wide experimental campaign has been performed on pieces of Pietraforte extracted from two of the quarries close to Florence, which were used in the past for extracting the material adopted in the historical buildings of Florence. The material has been taken from a superficial layer of the quarry, so it has been exposed to atmospheric agents, and it can be assumed to be similar to the stone used for the historical constructions. Some cuts have been extracted and used to make 110 cubic samples and 22 cylindrical ones. All the samples have been tested, with reference to their *ultrasonic pulse velocity* (V_{us}) and *uniaxial compressive strength* (UCS).

The strength is the most relevant information required by the Italian Code to use a material for structural purposes. For this reason, a correlation between the *ultrasonic pulse velocity* — which can be used without destructive tests – and the compressive strength has been checked in order to provide a practical device for performing structural analyses with regard to buildings made from Pietraforte. The provided V_{us}-UCS relationship has a satisfactory reliability level, presenting a mean *percentage difference* deviation from the predicted strength equal to 27%.

Fig. 2. Monumental buildings made in Pietraforte: a) Palazzo Vecchio, b) Torre della Castagna, c) Bargello.

Fig. 3. Some examples of the use of Pietraforte for architectural details. a, b. Palazzo Giandonati (base and arches), c. Palazzo Torrigiani (frame), e, f) Palazzo Rucellai (frame and base); g) Strozzino (string courses, vestment).

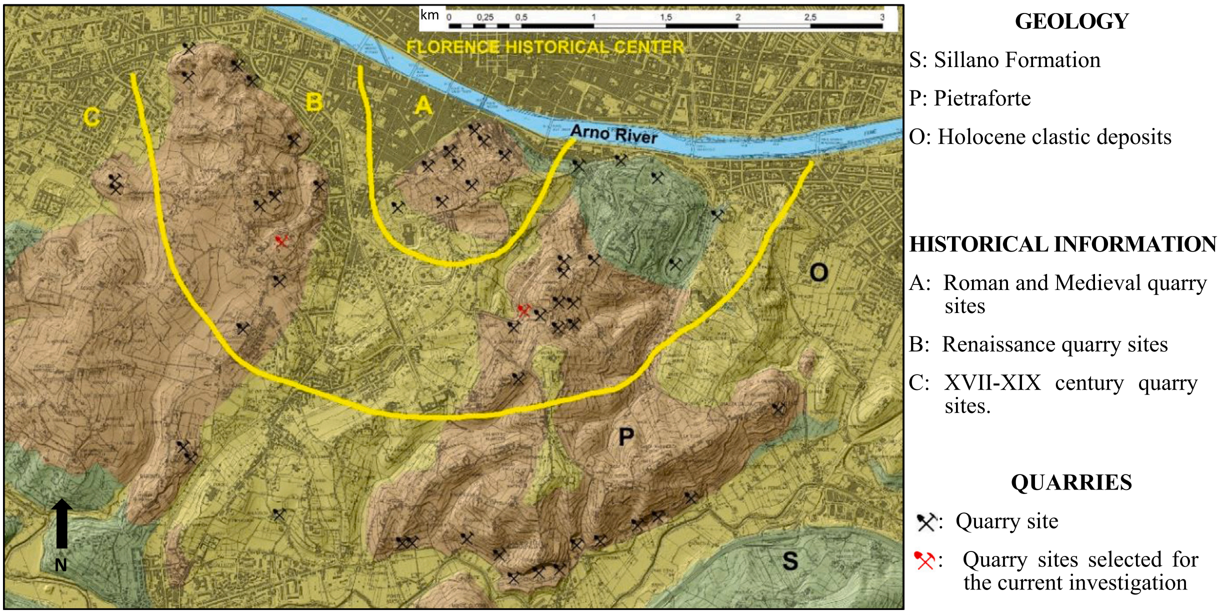

Fig. 4. Geological setting of the hills south of Florence.

2. The material properties

2.1. Geology

Pietraforte largely outcrops in the hills that delimit the Arno River, on its southern bank (Fig. 4), constituting a close and easy supply area for good building stone [7,20,21]. From a sedimentological point of view, Pietraforte is a turbiditic sandstone, Late Cretaceous in age, deposited as a turbiditic fan system within the Sillano Formation of the Monte Morello Units, External Ligurian Unit [22], of which it constitutes a member. Turbidites originate from the Southern Alps Inner Molasse basin [23].

Pietraforte has a grey colour when freshly cut, but due to quick oxidation, it assumes the light brown colour that characterizes the buildings of Florence [4]. It consists of a regular alternation of quartz-calcareous turbidites, with calcitic cement, and hard siltstone and claystone, with rare, intercalated beds of limestone and marly-limestone (Fig. 5).

Turbidites are usually in thin-bedded turbidites (*TBT*) facies with beds from fine to medium (5–50 cm) and rare intercalations of thick beds (80–100 cm, and a very few up to 150 cm). With reference to the Bouma Sequence [24], Pietraforte presents intervals T_b—$T_{c\text{-}e}$ with a ratio between arenaria and pelite of around unity; the T_c interval (see Fig. 6) is the most developed one, and it represents a peculiar characteristic of Pietraforte.

Petrographically, from thin section analysis Pietraforte is found to be a lithic arenite constituted by quartz (≈ 40%), feldspars (≈ 16%), carbonate (≈ 44%, mainly dolomitic) grains and magmatic rock fragments, cemented by recrystallized micritic calcite (see Fig. 7) [25]. Thin section analysis and clay mineral association, consisting of kaolinite, illite, illite/smectite, chlorite/vermiculite, are reported in [4].

2.2. Mechanical and physical information

As mentioned in the Introduction, there is a little available data provided by past experimental investigations. Table 1 lists the information provided by the experimental campaign carried out at the Military Arsenal in La Spezia in 1883 [10] and the one by Barbi et al. [11] in 1986.

This study focuses on the mechanical properties only, although within this research project the main physical properties have also been checked. Donigaglia [26] presents a detailed description of the obtained data, whilst Table 2 summarises the main data. The results presented in Table 2 are consistent with the mechanical properties presented in the next section, since the samples used have the same source used for the current analysis.

3. The campaign setting

3.1. The samples

Tests were performed on both cubic and cylindrical samples, to comply with the standard requirements provided by UNI EN 1926 [27] and the ASTM [28] respectively. The samples were prepared from 27 blocks of Pietraforte, collected from two ancient quarries still preserved: a private garden in the Marignolle hill and along the road cut of the Viale dei Colli (see the photo in Fig. 5).

The blocks were not extracted from inside the undisturbed rock-mass, but only from near the surface; therefore, they may present different grades of weathering and/or de-cohesion, similar to the material of the monumental buildings. The results obtained for the mechanical quantities can therefore be assumed to be suitable to describe their behaviour.

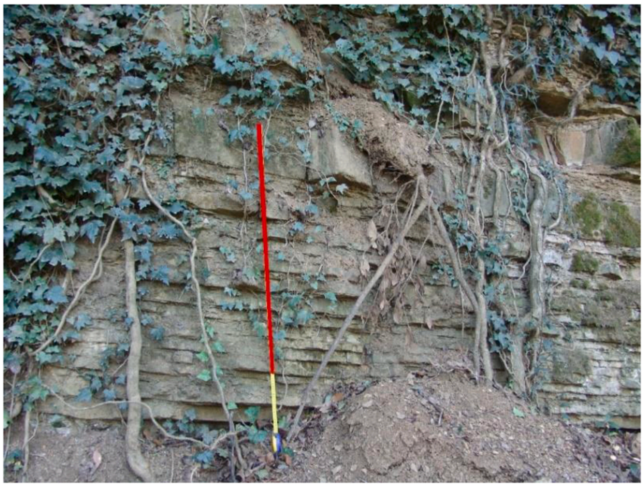

Fig. 5. A typical outcrop of the Pietraforte in one of the few quarry fronts still visible. The red line corresponds to 1 m.

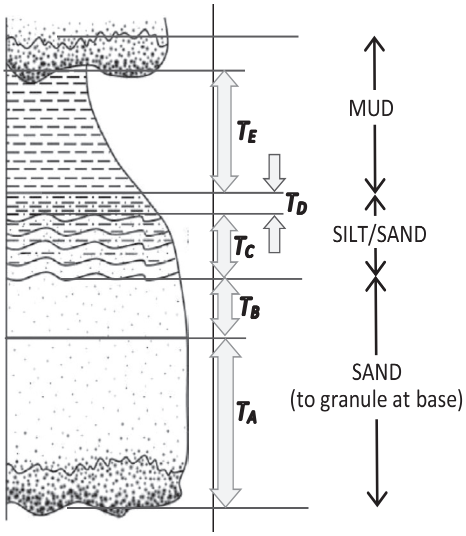

Fig. 6. Scheme of the Bouma intervals.

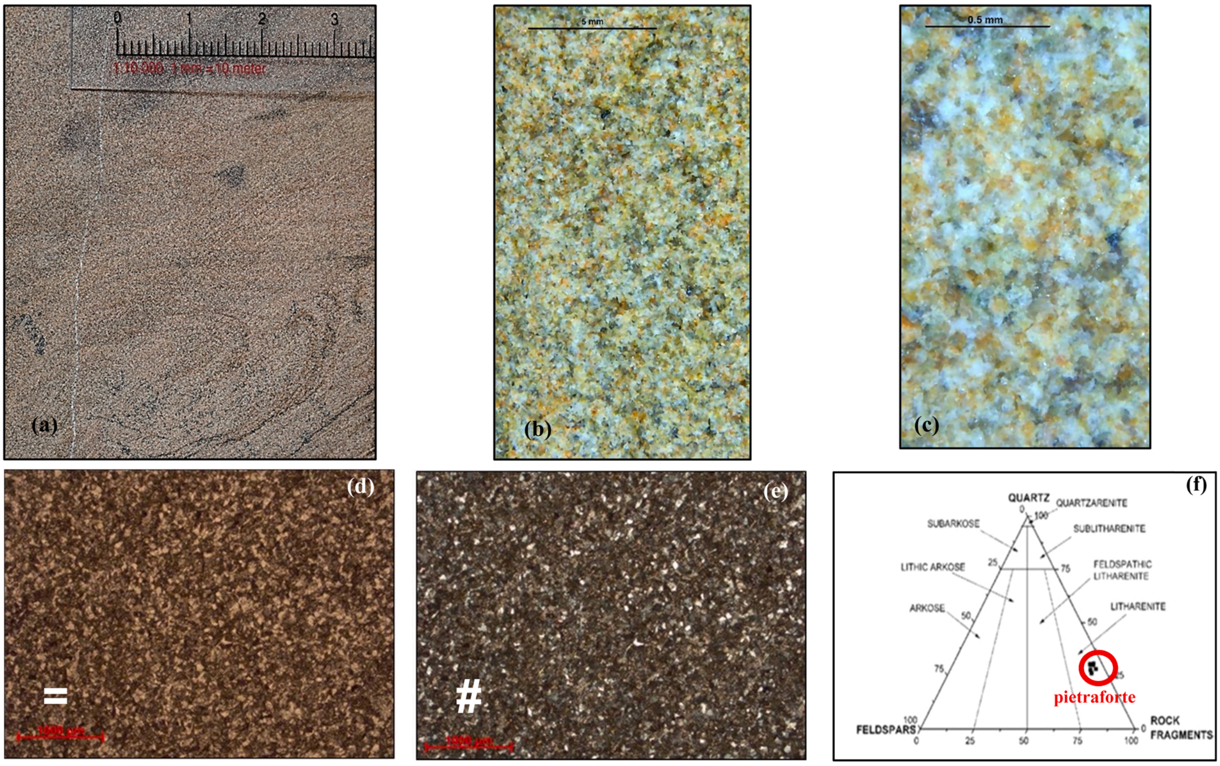

Fig. 7. a) Field observation of the Pietraforte textural assemblages. a) macrophotography of Pietraforte with well-developed Tc Bouma interval; b) microphotography at 150X; c) microphotography at 1000X; microphotography executed by portable digital microscopy d, e) Microphotography of a thin section of Pietraforte at the Transmission Optical Microscopy (TOM) at 2.5x (parallel and crossed); f) Ternary diagram (quartz, feldspars, rock fragments – modified after Folk, 1974) representing the petrographic classification of Pietraforte.

The extracted blocks consisted of bed slabs obtained by dismantling the bedding according to its natural discontinuities: the bedding and two sets of almost orthogonal joints. Each block represents a single Perforce bed, not subsequent, at a different level in the stratigraphic sequence. This stochastic sampling technique made it possible to obtain a representative sampling of the entire Pietraforte sequence.

Once in the laboratory, the 27 blocks were cut into smaller sizes from which the samples for the tests were obtained. Since each

Table 1
Main mechanical data provided by experimental investigation available in the scientific literature.

Experimental campaign	Samples number	Sample shape	dimensions	*UVW*	*UCS*	*Flexural Strength*	*Tensile strength*	*E*
			mm	*KN/m3*	*MPa*	*MPa*	*MPa*	*MPa*
Military Arsenal [10]	unavailable	unavailable	unavailable	27.46	119.64	11.96	–	–
Barbi et al. [11]	16	Cubic	30x30x30	–	93.9	–	9.0	–
	8	Parallelepiped	30x30x90	–	–	15.5	–	–
	24	Parallelepiped	30x30x60	25.75	–	–	–	1690

Table 2
Experimental data found for the same material tested in the current analysis (from [26]).

Property	unit	Value
Density	g/cm^3	2.6
Porosity	%	3.5–4.3
Imbibition coefficient	%	1.3–1.6
Water absorption at atmospheric pressure	%	1.15–1.55
Water absorption by capillarity	$g/m^2\ s^{1/2}$	0.9–1.9

block had a different bed-thickness and size, each one provided a different number of samples; 23 of the blocks provided 110 cubic samples, whilst from the remaining 4 blocks 22 cylindrical samples were extracted. The cylindrical samples have diameter $d=$ 54 mm, height $h=$ 108 mm and thickness $h/d=$ 2, while the cubic samples have all sides equal to 50 mm. In the analysis, the samples taken from the two quarries were not distinguished, and neither were any samples having flaws. All the samples were named based on their extraction block, with the number of blocks followed by a progressive number for the cubes and by a progressive letter for the cylinders.

Fig. 8 shows some of the samples. As can be noted, they differ from each other in colour and texture regularity; some of them show a good state of conservation, without any irregularity, whilst others show some degradation (see Blocks 12 and 22).

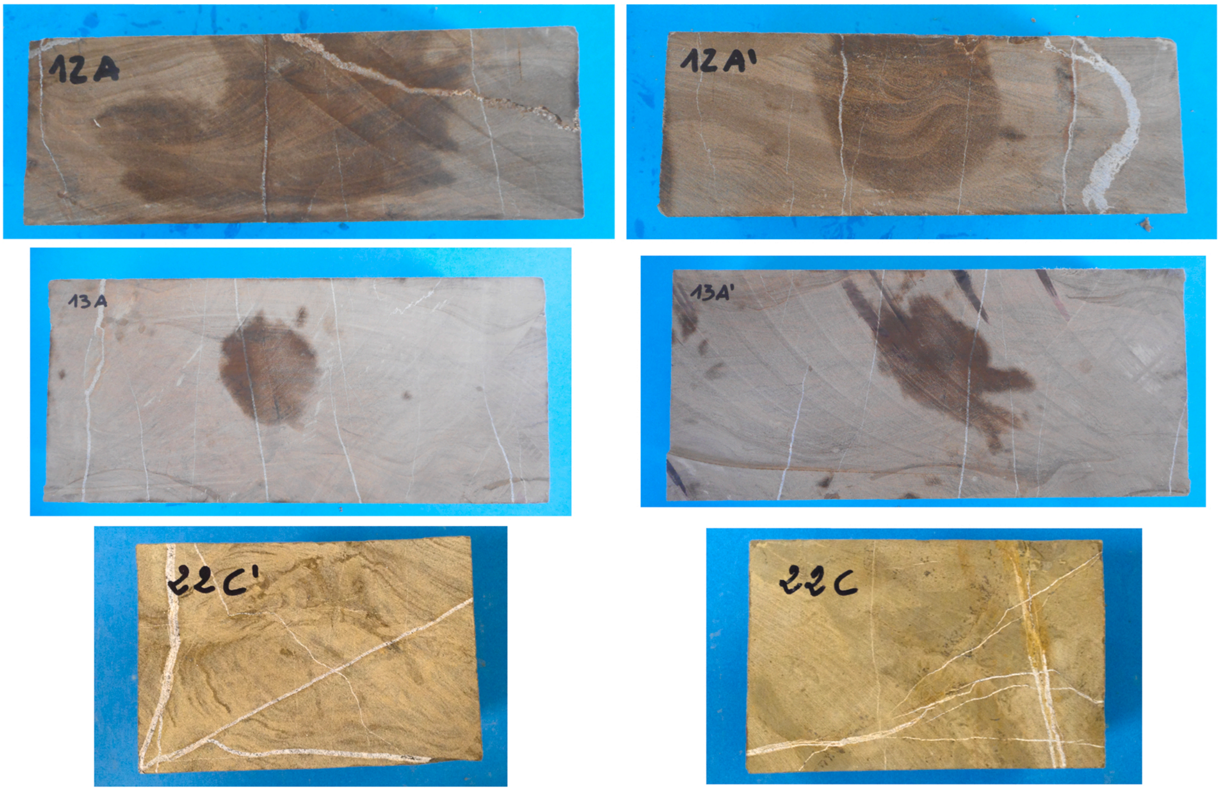

Fig. 8. Images of some of the blocks (the images refer to the two sides along the same direction).

3.2. The standards adopted for testing

As mentioned in the Introduction, the quantities tested are the ultrasonic pulse velocity (*UPV*) and the uniaxial compressive strength. Special attention was paid to selecting the tests to perform, in order to ensure repeatability and comparisons with other data [29].

In order to have data that were comparable at an international level, the UCS tests were executed according to UNI EN 1926:2007 [27] for the cubic samples and to the ASTM methods [28] for the cylindrical samples, while the determination of the ultrasonic pulse velocity for the cubic samples was according to UNI EN 12504–4 [30].

It should be considered, however, that the results found in terms of UCS can be affected by various factors, such as the loading rate, environmental conditions, samples size and shape [31–46]. All these factors vary as a function of the adopted "standard" procedures.

In Italy, Royal Decree no. 2232/1939 [47], issued about 70 years before the UNI rules and still in force, establishes that the UCS must be measured on four cubic 71 mm-sided samples for fine-grained stones, and on four cubic 100 mm-sided samples for coarse-grained stones. The axial load on the sample must be increased continuously at a rate of 20 kg/cm^2/s (2 MPa/s). According to UNI EN 1926:2007 [27], the axial load must be applied at a constant rate of 1 ± 0.5 MPa/s for cylindrical samples of 70 ± 5 mm with thickness equal to 1, or for cylindrical samples 50 ± 5 mm with thickness equal to 2. ASTM [28] requires cylindrical samples with thickness between 2 and 2.5 and a load rate leading to rupture in a time span between 2 and 15 min. The testing methods provided by ISRM [48] for cylindrical samples with a thickness between 2.5 and 3, diameter of at least 54 mm and a load rate continuously applied at a constant stress rate such that failure will occur within 5–10 min of loading; alternatively, the stress rate must be between 0.5 and 1.0 MPa. This short survey of the European and American regulations shows how the problem of having a standard and univocal procedure capable of defining comparable results in determining the UCS is still open.

In this study, the uniaxial compressive strength was measured by means of a hydraulic press INSTRON MODEL 5592 (Fig. 9), with a maximum load of 600 kN, at a constant rate of 1 ± 0.5 MPa/s, according to UNI EN 1926:2007 [27].

Before performing the UCS tests, the V_{us} values were read, and the relative UVW was determined according to UNI EN 12504–4 [30].

The ultrasonic pulse velocity was found by transparency, applying the transducers on the two opposite sides of the sample. It was measured using the digital instrument DSP-UTD 1004 model N034 by Boviar. A specially developed template guaranteed the accurate positioning of the transducers on the opposite sides of the samples. As regards the cubic samples, the ultrasonic pulse velocity was measured on the 23 squared blocks, before they were cut to obtain the cubic samples. Readings were taken for all the three pairs of opposite sides, obtaining three values (V_{us_A}, V_{us_B}, V_{us_C}, as can be seen in Fig. 10). In this case the average value (V_{us}) was found as the *mean* of the three values for each sample. As regards the cylindrical samples, the reading was instead taken on the samples after they had been cut. In this case, one reading only was taken for each sample, as can be seen in Fig. 10.

4. The results

In this section, the results of the experimental investigation are shown. Before proceeding with the ultrasonic readings and the UCS testing, *the Unit Volume Weight* was measured on the dry samples. The mean *UVW* of the cubic samples was 26.8 kN/m^3, while the mean *UVW* of the cylindrical samples was 26.29 kN/m^3; the single values are shown in Table 3.

Fig. 11 shows the *UPV* values found for the cubic and cylindrical samples, respectively. As already mentioned, for the cubic samples, tests were not performed on each cube, but on the single blocks, after having squared them. For each block, three readings were taken for each of the three directions. Fig. 11a shows both the mean V_{us} and the V_{us} along the three directions. Each directional value, in turn, is the mean value of three readings. As regards the cylindrical samples (Fig. 11b), the data (found as the mean of three

Fig. 9. Laboratory test on a sample.

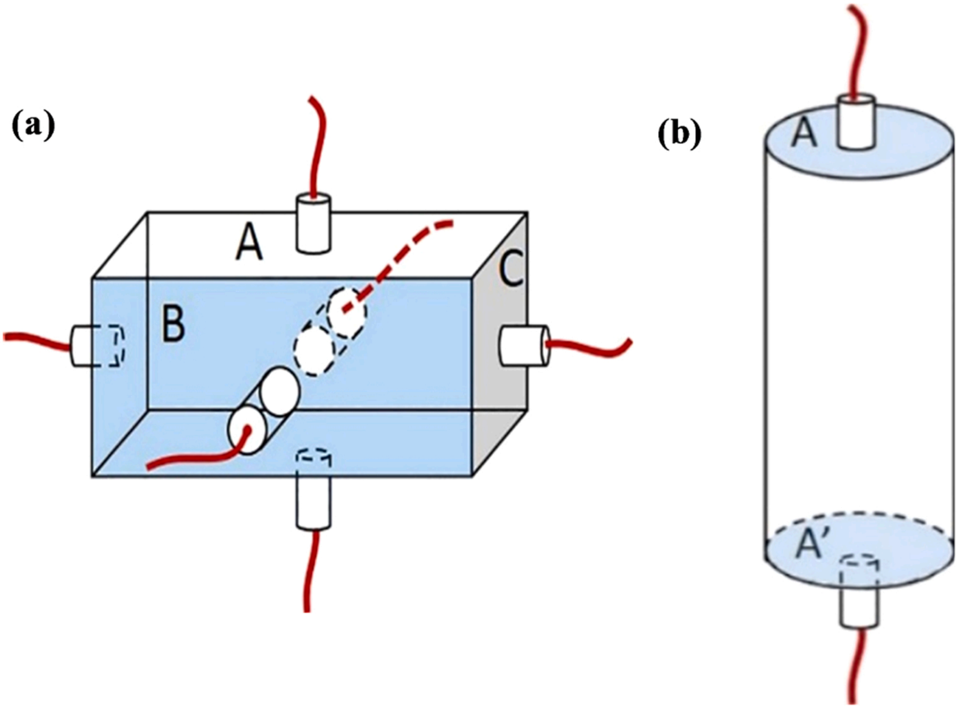

Fig. 10. Position of transductors:(a) squared blocks before cutting the cubic samples; (b) cylindrical samples.

Table 3
Values found for *UVW* for cubic and cylindrical samples.

Cubic samples										Cylindrical samples	
sample	UVW	sample	UVW	sample	UVW	sample	UVW	sample	UVW	sample	UVW
1_01	26,91	11_03	27,01	15_01	27,07	17_08	26,26	20_08	26,29	24_A	26,29
1_02	25,70	12_01	26,82	15_02	27,24	17_09	27,24	20_09	26,73	24_B	26,41
1_03	25,92	12_02	27,08	15_03	26,30	17_10	26,48	20_10	27,10	24_C	26,43
2_01	25,95	13_01	26,84	15_04	26,92	18_07	27,43	20_11	26,19	24_D	26,36
2_02	26,92	13_02	26,49	15_05	27,36	18_08	26,73	20_12	26,83	24_E	26,41
2_03	26,09	13_03	26,80	15_06	26,84	18_09	27,38	21_1	26,57	24_F	26,44
3_01	27,20	13_04	26,49	15_07	27,52	18_10	26,85	21_2	26,81	24_G	26,30
3_02	26,11	13_05	26,11	15_08	26,52	19_01	26,62	21_3	26,89	24_H	26,36
4_01	26,01	13_06	26,57	15_09	27,29	19_02	26,99	21_4	26,82	25_A	25,99
5_01	26,12	13_07	26,75	15_10	26,56	19_03	26,90	21_5	27,52	25_B	26,04
5_02	27,57	13_08	26,41	16_01	26,69	19_04	26,99	21_6	27,35	26_A	26,48
6_01	26,08	13_09	25,72	16_02	27,06	19_05	26,65	21_7	27,20	26_B	26,44
7_01	26,96	13_10	26,47	16_03	26,86	19_06	26,77	22_1	27,02	26_C	26,69
7_02	26,95	14_01	26,57	16_04	26,22	19_07	27,06	22_2	27,39	26_D	26,89
8_01	27,10	14_02	27,00	16_05	26,97	19_11	27,26	22_3	27,03	26_E	26,68
8_02	27,90	14_04	26,68	17_01	26,98	20_01	26,79	22_4	26,88	26_F	26,50
8_03	26,23	14_05	26,89	17_02	26,34	20_02	26,68	22_5	26,25	27_A	25,84
9_01	26,42	14_06	27,09	17_03	26,91	20_03	26,54	23_1	26,95	27_B	25,98
9_02	26,93	14_07	26,95	17_04	27,17	20_04	26,31	23_2	27,49	27_C	26,06
10_01	27,24	14_08	26,86	17_05	26,75	20_05	26,84	23_3	27,01	27_D	26,21
10_02	27,06	14_09	26,96	17_06	26,45	20_06	26,86	23_4	26,94	27_E	25,73
11_01	26,61	14_10	27,34	17_07	26,86	20_07	26,38	23_5	26,88	27_F	25,93

readings) refer to one direction only.

As can be observed, the values found for both the blocks and the cylindrical samples evidence a high spread, ranging between 2500 m/sec and 5300 m/sec.

Fig. 12 shows the stress—strain relationships found for the cubic and cylindrical samples through the UCS test, while Fig. 13 shows the results found for the compressive strength in each sample. Fig. 13 shows the *mean* and the *standard deviation* found for each block. The *UCS* values found for each block present a high variability, with a *coefficient of variation* ranging between 5% (block 9) and 52% (blocks 22 and 25). It should be observed that mean and standard deviation refer to samples having different sizes (from 2 to 12

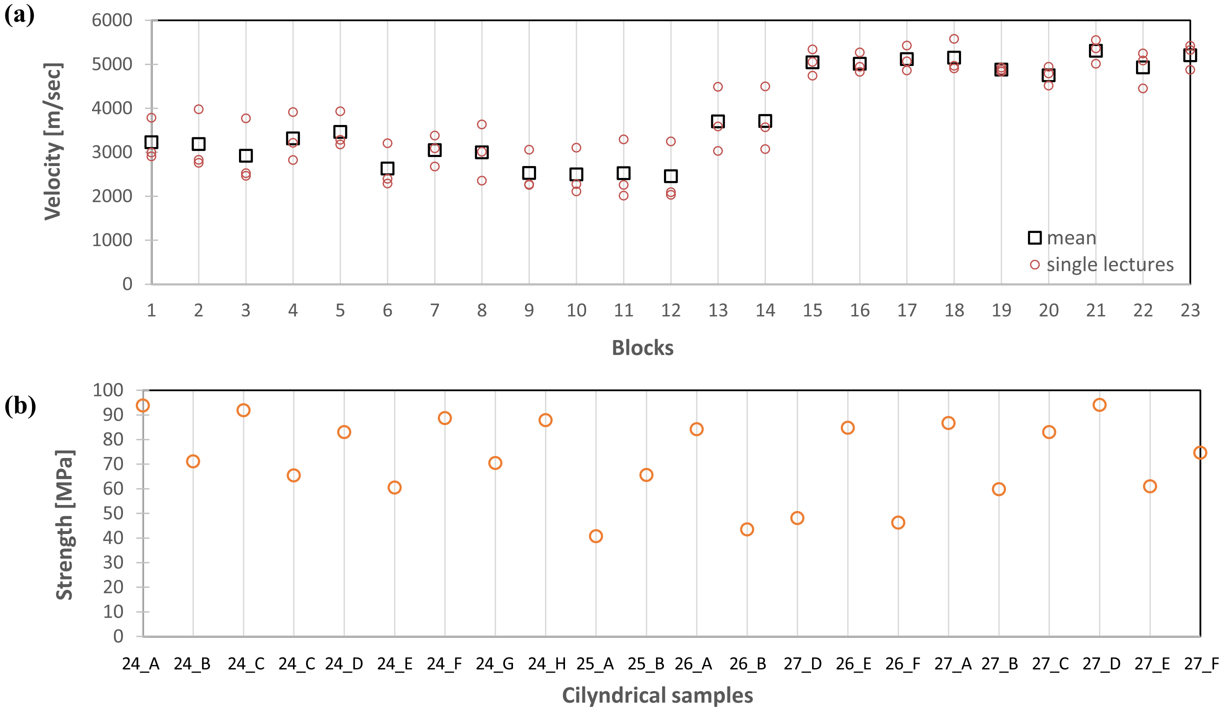

Fig. 11. Values of V_{us} (in m/s) for blocks (a) and cylindrical samples (b).

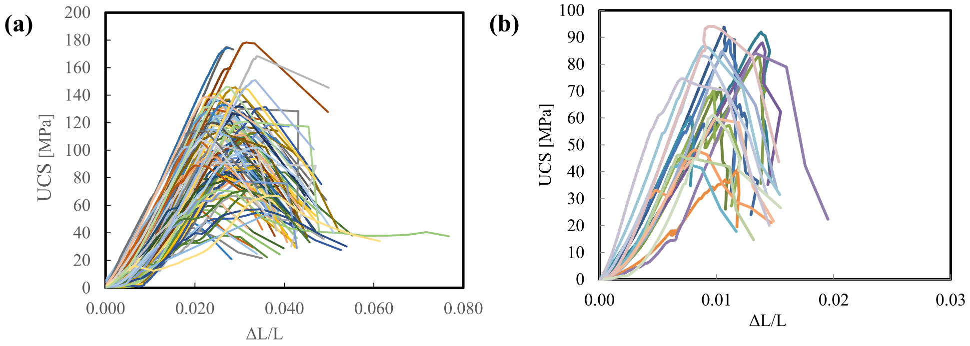

Fig. 12. Stress-strain relationship obtained through UCS test for (a) cubic and (b) cylindrical samples.

samples).

The high variability of the data provided by the *UCS* test is not surprising; indeed, the blocks were taken at different depths, and were affected by a certain degree of weathering. Furthermore, the samples were tested without excluding possible “flaws”, such as calcite veins.

Another possible source of randomness in the results of the UCS test is the orientation of the lamination angle. Pietraforte can easily present a well-developed convolute lamination of the T_c Bouma sequence; therefore, the role played by the angles between this sedimentary lamination and the applied force — which is assumed to be normal to the bedding — can affect the results obtained. Fig. 14 shows the relationship between the UCS and the sedimentary lamination angle; these two quantities do not evidence a strict mutual correlation. Such evidence can be caused by the strong fixing action caused by the calcite component, which overcomes the sedimentary layering, which only remains as a textural feature with no influence on the physical—mechanical properties of the rock.

5. Discussion of the results

One of the most useful pieces of information needed for design purposes is the compressive strength. Indeed, when a structural intervention is in need on existing buildings, the mechanical characterization of the structural material is the first step of the intervention. Since Pietraforte is mostly used for monumental buildings, which cannot be investigated though destructive tests, a prediction model to adopt based on non-destructive data would be very useful.

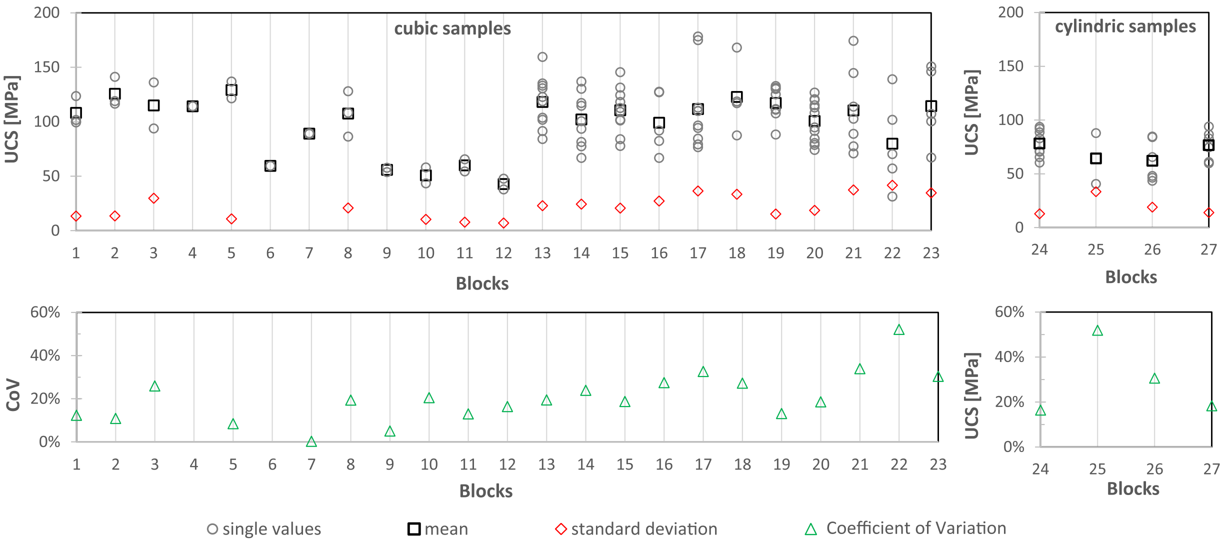

Fig. 13. UCS obtained for each sample.

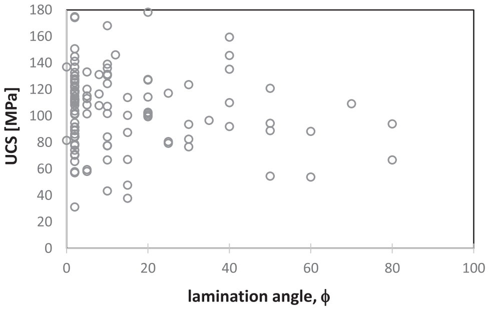

Fig. 14. Cubic samples: UCS of vs sedimentary lamination angle.

In order to find a predictive relationship between V_{us} and the UCS, the results of the experimental tests were compared. Fig. 15 shows this comparison for the blocks and for the samples (both cubic and cylindrical), respectively. In the plot referring to the cylindrical samples, the UCS values were scaled in order to compare them to those found for the cubic samples. The scaling was done through the simple approach proposed by EC2 [52] for concrete specimens, by assuming a scale factor equal to 0.8. As regards the cubic samples, since the V_{us} was not measured for each cube, the *mean* value of V_{us} was assumed for all the cubes taken from the same block.

The cylindrical samples – which have the V_{us} and UCS data referred to each specimen — were used to propose a predictive relationship to estimate the *UCS* based on the V_{us} readings. Fig. 16 shows the comparison between the *UCS* values predicted through the correlation relationship and the experimental ones.

The correspondence between the prediction and the experimental data has been measured in terms of *percentage difference*, defined as:

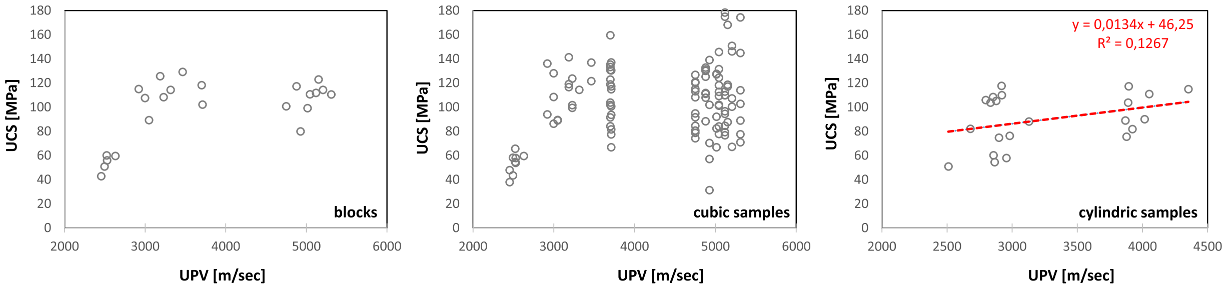

Fig. 15. Relationship between UPV and UCS.

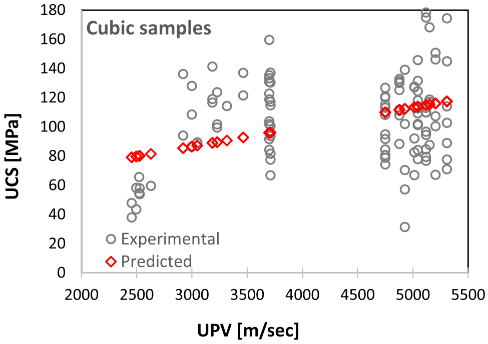

Fig. 16. Comparison between the experimental UCS and those provided by the predictive relationship.

$$\% \quad difference: \quad \frac{|\,\mathrm{experimental}UCS - predicted \quad UCS\,|}{experimental \quad data}$$

Fig. 17 shows the value of the percentage difference found for the UCS results on the cubic samples. As should be noted, the mean of the obtained percentage difference is equal to 27%, which is acceptable, since the experimental UCS data found for the cubes is equal to 29%, which is not much higher than the predictions made for concrete with more extensive investigations [49].

Although the *mean* prediction of the UCS is acceptable, some of the predicted values differ greatly from the experimental data. It can be noted that the predictions made for some of the samples taken from blocks 12 and 22 overestimate the UCS greatly. In such cases, the strength values found through the UCS test were very low; it could be observed (see the images in Fig. 8) that blocks 12 and 22 presented evident defects.

The variability of the strength of Pietraforte is hard to overcome; indeed, the presence of flaws can greatly reduce the strength. Some interesting studies have taken into account the possible flaws in the strength prediction by introducing a “degradation index” to correct the prediction. For determining the degradation index, Kahraman et al. [50] propose a relationship based on the ratio between the ultrasonic pulse velocity of the intact rock and the sample, while Salvatici et al. [51] suggest using the ratio between the hammer rebound value *R* of intact rock and that from in situ quoins and ashlars.

The current investigation, however, is aimed at providing a general approach for predicting the UCS of Pietraforte. When the strength capacity is assumed for the Pietraforte used in historical and monumental buildings, indeed, the possible flaws may not be visible from non-destructive testing.

6. Conclusions

Pietraforte stone has been widely used for construction since Roman times but, despite attracting the interest of many researchers over the years, its physical and mechanical properties have never been adequately defined. In this work, the results of an experimental campaign are reported, taking Pietraforte blocks extracted in the area of the historical quarry sites in the first nearby hills south of Florence.

After measuring the *Unit Volume Weight* of all (cubic and cylindrical) samples, the V_{us} and *UCS* have been checked. Ultrasonic tests were carried out on the squared blocks before the cutting of the cubic samples, and on the cylindrical samples. The V_{us} values found for the samples range between 2015 m/sec and 5580 m/sec. Neither the density nor the ultrasonic tests evidenced any sensitivity to the sample shape.

Uniaxial compressive strength tests were performed on the cubic and the cylindrical samples, according to the standard provided by

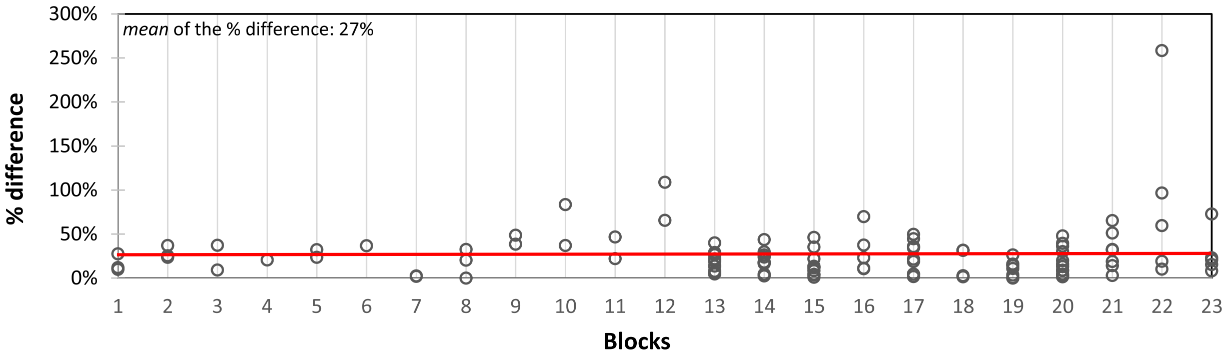

Fig. 17. Percentage difference found for *UCS* in the cubic samples.

EN 1926:2007 and ASTM, respectively. The *UCS* evidences a large variability, with values ranging from 32 MPa to 178 MPa. Such outstanding variability can be easily explained by observing the features of the samples. These were taken from superficial blocks, without excluding possible flaws or conservation damage.

In the paper, a prediction relationship is proposed, aimed at characterizing the strength capacity of Pietraforte on the basis of ultrasound readings only. The prediction analysis was based on the data found for the cylindrical samples; their prediction capacity was tested on the data of the cubic samples, providing a *percentage difference* equal to 27%; such prediction seems to be quite satisfactory, since the sample data is very variable itself, presenting a *coefficient of variation* equal to 29%.

Further analyses were focused on the relationship between the laminar sedimentary features and loading direction. This issue presented a surprise: Pietraforte is strongly cemented by its calcite component, and this feature overcomes the sedimentary layering, which only remains as a textural feature having no influence on the physical—mechanical properties of the rock.

Currently, these data are the only certified tests of the physical—mechanical properties of Pietraforte to be officially used for conservation purposes in the maintenance of the many historical and monumental buildings of Florence, according to the principles of their integrity and authenticity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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