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Defining a Non-Destructive In Situ Approach for the Determination of Historical Mortar Strength Using the Equotip Hardness Tester

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Abstract: The determination of mechanical parameters of historical mortars is a crucial aspect in the analysis of masonry in ancient buildings, especially for evaluating their quality and planning the appropriate restoration interventions. Due to conservation reasons, creating a comprehensive database is generally not possible because cutting out masonry specimens relates to damaging historical structures. This study starts with the need to characterize the mortar quality of different buildings in the town of Camerino (Central Italy) which has been strongly damaged by the 2016–2017 seismic sequence. A non-destructive collecting data strategy based on the use of the Equotip hardness tester (EQ) has been set up by evaluating the most appropriates impact strategy (single or repeated) and the range of measurements to calculate the basic statistics. The seismic damage suffered by the buildings allowed the rare opportunity to take samples from several walls and carry out laboratory tests to determine their Uniaxial Compressive Strength (UCS). The comparison between the results of the two types of tests made it possible to calibrate a relationship between the EQ values and the UCS. The Pearson's coefficient of determination derived from an exponential interpolation (R2 = 0.81) confirmed a strong relationship between the EQ values derived from the tests on the specimens and the UCS. Moreover, comparing the in situ EQ measurements with the ones performed on the specimens prepared for the compressive tests, a general underestimation of the in situ EQ values has been observed, possibly due to the presence of a superficial alteration layer of the exposed mortar. From these results, we propose a correction of the in situ measurements able to obtain a more appropriate strength estimate of the historical mortars.

Keywords: non-destructive testing; Equotip hardness tester; uniaxial compressive strength; historical mortar strength

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1. Introduction

Over the centuries, mortars have been highly used as bedding material in buildings construction and as valuable materials in frescoes and decorations. Indeed, mortars are characterized by ease of manufacture and application, a positive cost-benefit ratio, and a remarkable versatility that supported the widespread century-old use [1,2]. Recently, the attention on the role that ancient masonry mortars play in their earthquake resistance has risen for medieval cities and villages characterized by the presence of historical buildings [3], but also for archeological sites [4], which stand on high seismic hazard zones [5,6]. One of the main issues regarding the characterization of historical masonry buildings concerns their high heterogeneity [7,8], in fact, these are also often characterized by poor construction, with mixed masonry, made up of rounded and/or irregular stone elements [9]. In this regard, a rapid and exhaustive characterization is necessary for both decreasing their vulnerability and identifying guidelines for advanced restoration techniques [10–12]. In this context, the determination of the mechanical parameters of the mortars, such as compressive strength and Young's modulus, is crucial in the analysis of these types of structures. However, the high cultural and artistic value of ancient buildings is in contrast with the need to obtain a representative statistics-based collection of samples for laboratory tests, because the small thickness of mortar joints makes their extraction, collection, and subsequent creation of the prismatic samples required by the standards difficult [13–15]. To this aim, the use of non-destructive tests (NDT) has been proposed by many authors [16,17] and references therein, which have tried to provide interpretation of the deterioration mechanisms affecting these materials in a coordinated matter with the laboratory tests. The most popular ones, just to mention a few, are pulse transmission techniques, infrared tomography, tomographic imaging, and microwave radar. However, these techniques require operator experience and proper planning to provide reliable results. The methods based on rebound hardness instead, are relatively simple to conduct and the result processing is quick. At the same time, when dealing with low-strength materials such as the masonry of historical buildings, some of them such as the Schmidt hammer and the penetrometer cannot be considered as fully non-destructive. In fact, it can leave small depressions [17] or even cause fractures on the material giving no-rebound values [18]. With regards to the L-type Schmidt hammer, the impact energy (0.735 Nm) is too large for the characterization of the historical masonry mortars, and in fact, as reported by [19], it should be used with caution when the Uniaxial Compressive strength (UCS) of the material is less than 20 MPa. This value is generally one order of magnitude larger than the one of the historical mortars. At the same time, the penetrometer, which is based on the penetration of the steel needle into the masonry joint, cannot be considered as a non-destructive test when used on buildings with historical, artistic, or cultural value. For the reasons just mentioned, a rapid and non-invasive methodology for the estimation of the strength of ancient mortars is highly desirable.

In this study, we propose the use of the Equotip hardness tester (EQ), a non-destructive, easy to handle, and electronic rebound-based device, originally developed in the 1970s for testing metals [20], and then extensively tested for rock hardness determination [21–23] and weathering studies [24–27]. This method has been already extensively applied to the investigation of mechanical properties of weak rocks [18], natural materials that resemble the ancient mortars under several perspectives. The EQ has a low impact energy (1/66 of the Schmidt hammer) and it can be applied on materials having less than 0.1 MPa UCS [22]. For this study, EQ testing was carried out on a series of historical buildings in the medieval town of Camerino, in Central Italy, severely damaged by the 2016–2017 seismic sequence [28]. The buildings have been chosen with consideration of different historical periods, different architectural styles, and the possibility of collecting a series of mortar samples of adequate size for carrying out classic uniaxial compression tests [13]. The in situ measurements with EQ were carried out exclusively on the ancient mortars between stones and/or brick elements, on both the masonry face and core of the building's walls. This approach gave thus a complete mechanical characterization of the historical masonry mortars involved. The impact strategy and the range of measurements to calculate the statistics were discussed. Moreover, considerations on the discrepancy between the in situ EQ values and the ones derived by testing the specimens prepared for the UCS test in the laboratory have been made.

2. The Historical Masonry Mortars of Camerino Town

The town of Camerino is located on top of a hill, between the valleys of the Chienti and Potenza rivers, within the Camerino basin [29] and reference therein in the Marche Region. This area deserves particular attention for its great historical and cultural richness with human settlements dating back to prehistoric times, but which reached the period of maximum splendor in medieval times, under the lordship of the da Varano family. During this period, the town considerably increased its architectural value, due to its typical medieval layout with imposing defensive walls and numerous historic buildings. Three of these buildings were chosen to conduct this new mortar characterization approach (Figure 1): Palazzo Ducale Palace (XV century), Battibocca Palace (XVII century), and the Monastery of San Domenico (XIII–XVI century). This choice was determined not only by their historical period and type of masonry but also because the damage reported after the earthquakes of the 2016–2017 seismic sequence of Central Italy has permitted the testing of the core of the masonry, which now exposed to the surface.

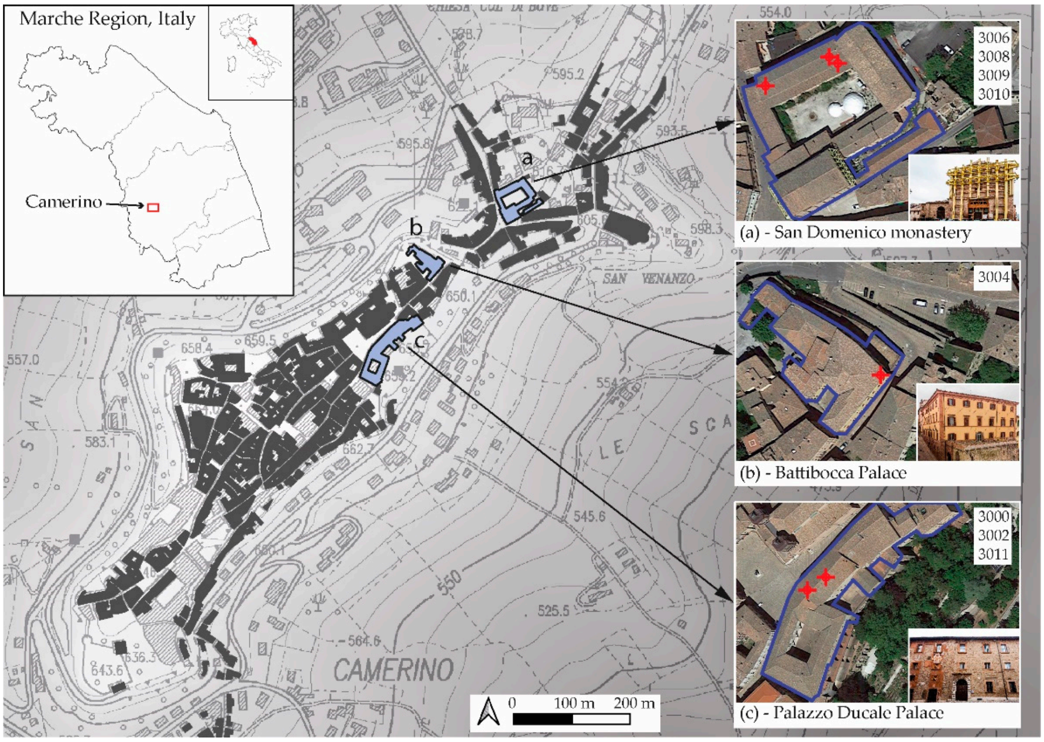

Figure 1. Map of the town of Camerino (base map "Carta Tecnica Regionale 1:10000" and DEM) with the buildings where in situ measurements and sample collection were undertaken. In the small boxes are shown the position and detail of the building façades: (**a**) "Convent of San Domenico" (**b**) "Battibocca Palace" and (**c**) "Palazzo Ducale Palace". Red dots represent measurement sites with related sample lists from Table 1.

The buildings chosen in this study are well representative of the built cultural heritage of the Marche Region, with their masonry walls representing a very common construction type for the area, composed of a three-leaf (stone or brick) masonry. Two external leaves made of stone or brick masonry are constructed at a distance, whereas an internal leaf is filled with a loose, low strength material, made of stone fragments and/or bricks and mortar (i.e., sack stone masonry) [30]. The main structural problems of this masonry type are: (i) the weakness of the internal layer, which has significantly poorer mechanical properties than the external leaves, (ii) the deterioration of the external joint mortar, and iii) the absence of connection between the leaves. In turn, this type of masonry is very vulnerable to seismic actions, in fact, as the bond between the external and the interior leaves has deteriorated or is inexistent, the masonry itself does not behave as a whole.

Consequently, they are very sensitive to brittle collapse mechanisms, which usually manifest, both under vertical and horizontal loads, as detachment of the leaves and out-of-plane deformation [31]. In this regard, collapsed walls made mortar sampling possible, on both masonry face (Figure 2a,c) and core (Figure 2b,d), with an adequate sample size to perform mechanical compression tests in the laboratory.

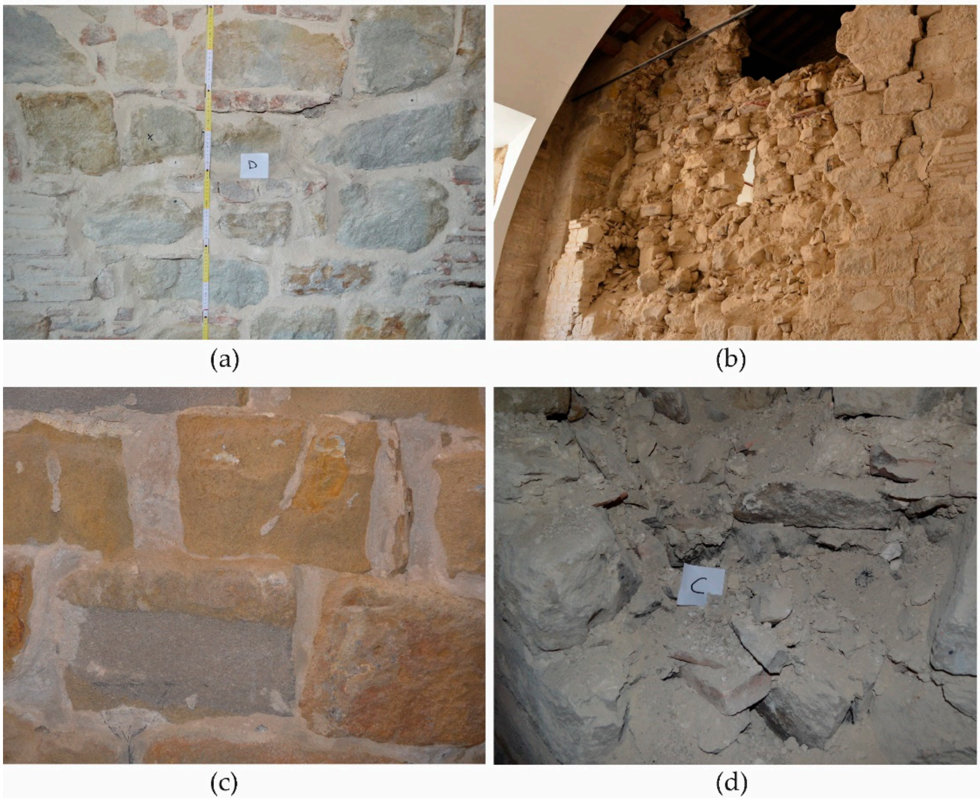
(a) (b)
(c) (d)

Figure 2. Pictures showing typical masonry face (internal and external) on the left and masonry core of collapsed walls of Palazzo Ducale Palace on the right side. (**a**) Internal masonry face. (**b**) Internal masonry core. (**c**) External masonry face. (**d**) Detail of internal masonry core.

The ancient mortar samples investigated are all composed of air lime whereas the masonry is generally characterized by rounded or irregular stone elements. Each wall examined has been identified through an *id* (Site ID in Table 1).

Table 1. Characteristics of building examined.

Building	Sampling Location	Site ID
Palazzo Ducale Palace	masonry core	3000
Battibocca Palace	masonry core	3004
San Domenico Monastery	masonry core	3008
San Domenico Monastery	masonry core	3009
Palazzo Ducale Palace	masonry face	3011
Palazzo Ducale Palace	masonry core	3002
San Domenico Monastery	masonry face	3006
San Domenico Monastery	masonry core	3009
San Domenico Monastery	masonry face	3010
San Domenico Monastery	masonry face	3011

3. Materials and Methods

3.1. Data Collection Strategy Using the Equotip Hardness Tester

The experimental phase of this study consists of non-destructive tests by using the EQ device to define a methodology for collecting rebound data on historical masonry mortars. A compact version of the EQ, named Piccolo 2 (produced by Proceq, Switzerland), has been selected for the evaluation of the mortar strength and it was tested both in situ and on the specimens prepared for the uniaxial compression test. This device is easy to handle because of its small size and weight (only 110 g). Thanks to its low impact energy (11 N/mm), EQ has been not only used on hard materials such as rocks and metals but also on very soft materials including fruits (to evaluate the ripening degree), demonstrating its capability to cover a wide range of rebound measurements. Compared to other hardness devices such as the L-type Schmidt hammer, Cone penetrometer, and Needle type penetrometer, the EQ has the widest measurement range [22] and thus it can be suitable for the strength evaluation of weak and soft historical mortars. The EQ's principle of operation is quite simple, and it is based on a tungsten carbide ball (3 mm of diameter) that constitutes the tip of a spring-driven piston. The carbide test tip is mounted in an impact body that strikes, under spring force, against the test surface from which it rebounds [32]. The EQ hardness value is expressed as the "L" index (Leeb number), calculated from the ratio of the rebound velocity to the impact velocity, multiplied by 1000.

In the analysis of ancient mortars coming from buildings of Camerino, the use of a non-destructive test (NDT) is essential to preserve the integrity of these monuments. For this reason, and to create a comprehensive dataset of the historical mortal quality, EQ was tested both on the bed joints (Figure 2a,c and Figure 3) and inside the walls involved in collapses due to the 2016–2017 seismic sequences, thus characterizing both the mortars inside the sack stone masonry (masonry core, Figure 2b,d) and the most external mortars (masonry face). The collapse of some sack stone masonry following the 2016–2017 seismic sequence allowed a sample to be taken for each wall tested with EQ, thus avoiding further damage to intact walls of historic interest. The samples for the UCS test were collected close to the EQ tests conducted to minimize compositional changes that may affect the correlation between the EQ's rebound and the UCS.

Figure 3. Non-destructive in situ survey with Equotip hardness tester on a masonry face of a building.

According to the hardness tester manufacturer's manual [33], the correction of the impact value with respect to the vertical direction is automatically made by the device. All the surfaces have been smoothed manually before testing to avoid the influence of roughness on the rebound and both single impact and repeated impact strategies have been adopted for comparison. To date, a reliable data collection methodology has not been defined, and, according to the literature, it is possible to choose between at least two main methods, namely, "repeated impact test" or "single impact test" [22,23]. The repeated impact test refers to multiple impacts on the same spot while the single impact test refers to individual impacts in one small area, in which each test is separated from the nearest one by at least one plunger tip. Besides, following [23], there is not a unique data collection methodology in the literature on how surfaces should be smoothed, how measurements should be taken, nor what size should be sampled, and whether extremes need to be removed. For this reason, we decided to take a high number of measurements for each Site ID, using both the impact strategies with the aim of defining the more appropriate methodology for the investigation of the historical mortars. In particular, the following procedure has been adopted in situ, for each masonry mortar examined within the bed joint, we performed 60 repeated impacts on the same point (i.e., "repeated impact test" method), then 10 single impacts separated by at least a plunger tip were carried out (i.e., "single impact test" method); in the laboratory, on each specimen prepared for the UCS test, we performed 60 repeated impacts on the same point (i.e., "repeated impact test" method). From now on, we refer to: (a) L60-situ as the 60 repeated impacts on the same spot on the in situ mortars; (b) L60-lab as the 60 repeated impacts on the same spot on the specimens prepared for the UCS lab analysis; (c) L10-situ as the 10 individual impacts in one small area on the in situ mortars. The single impact strategy was only tested in situ since the dimension of the specimens was not enough to properly perform the test in the laboratory. A typical example of the EQ measurements conducted on both the in situ mortars and the laboratory specimens is presented in Figure 4.

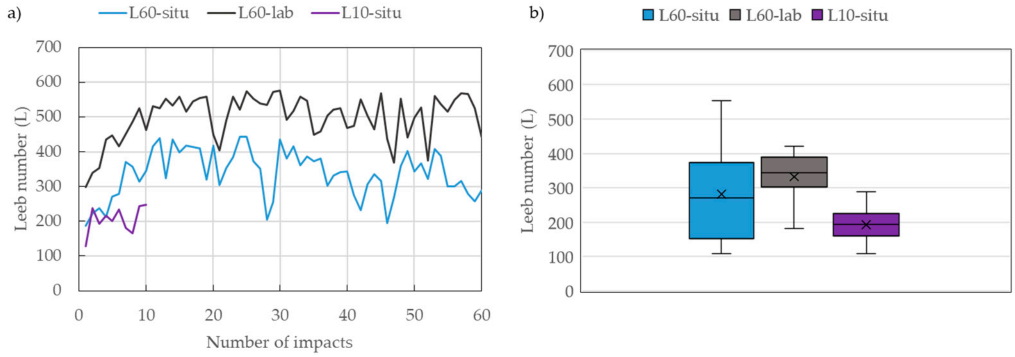

Figure 4. (**a**) rebound values of the EQ (Leeb number, L) for the repeated and single impact strategy for a representative sample of the dataset (sample 3011); (**b**) boxplots of the whole dataset.

As shown in Figure 4a, some typical behaviors have been detected: (1) the results of the "repeated impact test" shows a progressive increase of the rebound values for the first 10 impacts, followed by a general stabilization as the number of impacts increases; (2) beyond 30–40 impacts, a slight decrease of the rebound value was sometimes observed; (3) comparing the results of L10-situ with L60-situ, we can observe generally lower values of the single impact method; (4) the results of L60-situ and L60-lab mortars are different, with constantly higher rebound values for L60-lab.

These observations indicate that: (1) at the beginning of the rebound test, the result is affected by the settling between the tip of the instrument and the mortar surface. This may probably be due to the initial compaction of the material; (2) the decrease of rebound value after many impacts can be related to a progressive damaging of the tested mortar; (3) the results of L10-situ agree with the first values of L60-situ, indicating that the single impact is aimed at representing only the hardness of the most superficial portion of the material [22]; (4) the differences between laboratory test and in situ test are probably due to the real difference between the elastic properties of the mortar close to the surface and inside the mortar mass.

Moreover, trying to define a comprehensive methodology of data acquisition, changes in the EQ's rebound values with the number of repeated impacts at the same point have been investigated using the findchangepts function in Matlab®. This function is aimed to find the point at which the mean of a population changes the most significantly. This was tested regardless of both in situ mortars and specimens prepared for the UCS laboratory. Different behaviors have been recognized between the mortars of masonry core and masonry face (Figure 5a,b).

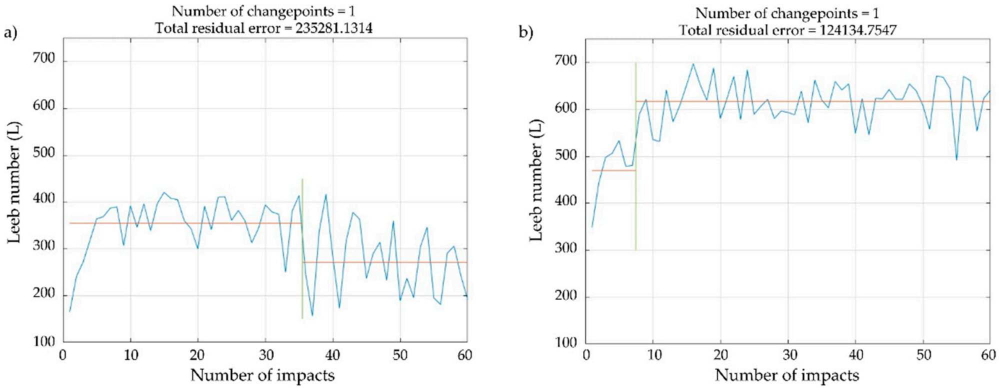

Figure 5. Changes in the rebound value of EQ with the number of repeated impacts at the same point for two mortar samples. (**a**) masonry core; (**b**) masonry face.

Examining the average values of the two types of mortars (red lines in Figure 5) it can be observed that the mortar of the masonry core is of lower quality (Figure 5a) compared to that of the masonry face (Figure 5b), with the former showing a mean value of ≈350 and the latter L ≈ 600. Moreover, in the mortar of the masonry core, after ≈40 repeated impacts, a sudden fall of the average value is evident, respectively indicating damage of the material caused by the repeated impacts at the same point, which could thus be explained with the formation of micro-fractures. The outermost mortar of the masonry face, on the other hand, is of higher quality and the average value is stable until the 60th repeated impact. As reported before, both mortars show very low values until the 10 repeated impacts, probably due to the initial compaction of the material.

Based on this evidence, it was chosen to adopt the "repeated impact test" method and assume the mean value of the 20 impacts located between the tenth and the thirtieth repeated impacts, as representative of the elastic properties of the mortar. From now on, we refer to $Lmean_{situ}$ and $Lmean_{lab}$ as the respective in situ and laboratory EQ measurements with the average value calculated with the just proposed criterion.

3.2. The Uniaxial Compressive Tests

To evaluate the mechanical properties of the study's historical mortars, several uniaxial compressive tests were carried out. A total number equal to 14 specimens were tested, and the corresponding stress-strain behavior was recorded. It should be noted that the opportunity of carrying out a standard test, that is, a uniaxial compressive test, on historical mortar samples is quite rare [34]. Due to preservation matters related to architectural value buildings, it is very difficult to collect volumes of material large enough to obtain prism-shape specimens to be tested. In this context, the experimental results of this study represent a precious dataset able to improve the knowledge about the mechanical characterization of ancient mortars. A hand-held electric angle grinder was used to obtain cuboid shape specimens from larger mortar blocks directly taken in situ. Due to the irregular starting geometry of the latter and the general tendency of the material to crumble, it was not possible to obtain the standard cubic samples (i.e., 40 × 40 × 40 mm). Since it is well-known that the sample geometry affects the value of the measured compressive strength [35], each obtained UCS value has been put in relation to the associated slenderness ratio, as will be discussed in detail in the dedicated section. In Table 2 the geometry of each specimen is shown where h is the height (that is the dimension parallel to the load application direction), l_{max} and l_{min} are the maximum and minimum dimensions of the cross-sectional area respectively, while h/d is the slenderness ratio. The latter was computed by dividing the height of the specimen for the diameter d of the circular area equivalent to the cross-sectional area of the specimen. In Figure 6 some of the tested samples are shown.

Table 2. Geometrical characteristics of the samples.

Site ID	Sample Name	h [cm]	l_{max} [cm]	l_{min} [cm]	h/d [-]
3000	3000	5.83	4.65	4	1.2
3004	3004	6.9	6	4.9	1.13
3008	3008	4.8	3.6	3.4	1.22
3011	3011	4.7	4.5	2.6	1.22
3002	3002-C	4.2	3.05	2.88	1.26
3006	3006-2	4.4	2.55	2.2	1.65
	3006-3	4.55	2.25	2.2	1.81
3009	3009	4.86	2.85	3.35	1.07
	3009-2	3.6	4.2	2.7	0.95
	3009-3	3.3	3.5	3.4	0.85
	3009-4	4.3	3.1	2.3	1.43
	3009-5	2.8	2.4	2.2	1.08
3010	3010-A	4.6	2.47	2.4	1.67
	3010-B	4.75	2.6	2.48	1.66

Each specimen was tested in dry condition and brought to breakage by imposing a constant vertical velocity equal to 0.5 mm/min. Consequently, the associated vertical stress was transferred to the upper face of the specimen through a swivel loading cap and registered by a bearing ring (maximum load equal to 1000 kg). Finally, the vertical displacement of the sample was recorded by a Linear Variable Displacement Transducer (LVDT).

Figure 6. Some of the tested mortar samples.

4. Results and Discussion

4.1. Uniaxial Compressive Strength of Mortar

According to the results of the compressive tests, the mortars analyzed in this study are characterized by UCS values ranging from 0.17 MPa to 1.49 MPa. For each specimen, the maximum of the stress-strain curve has been selected and identified as the compressive strength of the material. Such values are summarized in Table 3 and sorted from the smallest to the greatest. The sampling location is also reported to highlight that, except for the 3009-5 sample, the material coming from the masonry face furnished the highest values of UCS. This experimental evidence confirms that the inner part of such a type of masonry wall is the weakest one, made of a material having poorer mechanical properties than the ones of the outer parts. Even though this aspect is crucial in properly evaluating the overall mechanical response of the structural element, its quantification is generally impossible due to the impossibility of directly testing the inner material. In this context, therefore, the available measurements are very rare as well as important.

Table 3. Uniaxial compressive strength (UCS) of all specimens.

Sample Name	Sampling Location	UCS [MPa]
3008	masonry core	0.17
3004	masonry core	0.19
3000	masonry core	0.33
3009-4	masonry core	0.4
3009	masonry core	0.41
3009-2	masonry core	0.44
3009-3	masonry core	0.47
3002-C	masonry core	0.49
3006-3	masonry face	0.65
3006-2	masonry face	0.68
3009-5	masonry core	0.84
3010-B	masonry face	1.25
3011	masonry face	1.29
3010-A	masonry face	1.49

In order to evaluate the possible effect of the specimen geometry on the measured compressive strength, each UCS value was plotted against the corresponding slenderness ratio, as shown in Figure 7. Moreover, this comparison has been done by considering three different classes of mortar, identified based on the UCS values range: Class I (UCS < 0.5 MPa), Class II (0.5 MPa ≤ UCS < 1 MPa), and Class III (UCS ≥ 1 MPa).

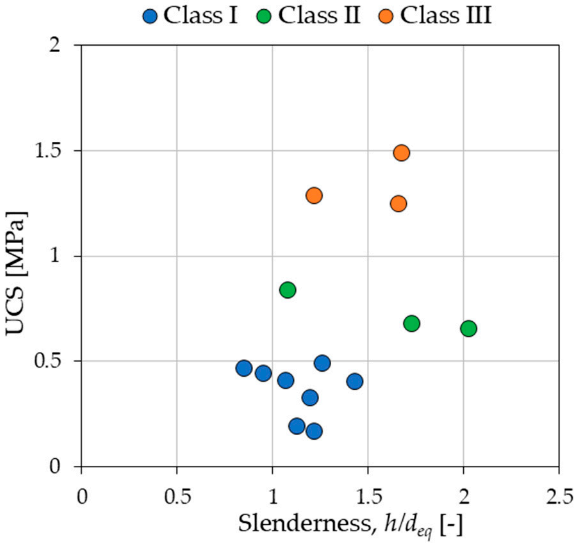

Figure 7. Comparison between UCS and slenderness for the three classes of mortar identified.

Even though the number of samples for each class is limited (especially regarding Class II and Class III), no evident dependency of the UCS value from the slenderness has been found, at least within the slenderness ratios considered in the experimental testing. For a given class, it seems that the variability of the compressive strength is more related to the intrinsic inhomogeneity of the material rather than the geometrical features of the samples. As far as Class I is concerned, for instance, it can be observed that the variability of the UCS value for a fixed slenderness ratio is greater than the variability found for different slenderness ratios. Such consideration can be also observed for the samples owing to Class III. Only for the data of Class II, an increase of the compressive strength as the slenderness decreases can be detected. However, based on the findings concerning the other two classes and the very limited number of specimens, such a relationship between the UCS values and the corresponding slenderness ratios seems not to be representative. Naturally, such an aspect requires further study, and the possibility of testing more samples characterized by different slenderness ratios could be useful. So, in conclusion, the measured UCS values can be considered representative as they are, without any correction in relation to the slenderness.

For the sake of completeness, in Figure 8 the stress-strain curves of the tested specimens are reported by considering the three classes previously described. It is worth mentioning that the samples owing to Class I (that is the weakest one) exhibited a markedly ductile behavior, showing a progressive increase of the compressive stress as the axial strain increases. On the contrary, the samples owing to the Class III (that is the strongest one) showed a clear brittle failure mode, highlighted by the presence of a peak of the stress-strain curve after which the material underwent a more or less pronounced softening. The samples grouped in Class II, finally, exhibited a mechanical response in between the two formers. The same findings, in terms of the mechanical response of the material, are reported in [34] regarding compressive tests carried out on Ancient Roman mortars coming from the archeological site of Pompei (Italy).

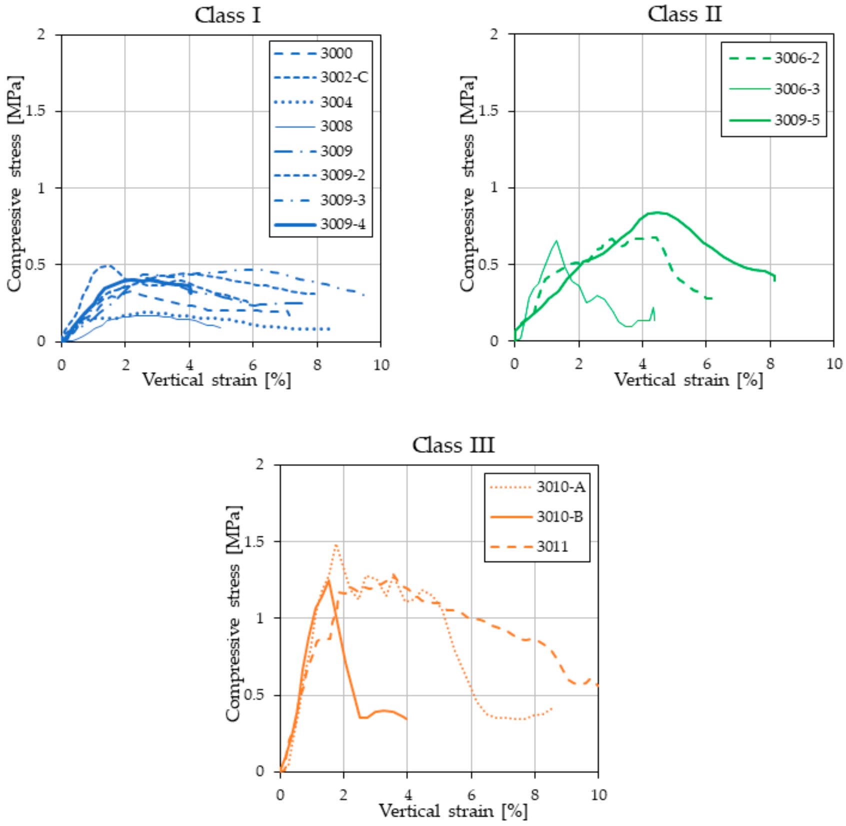

Figure 8. Axial stress-strain curves of the samples divided into the classes considered.

4.2. Results of the In Situ and Laboratory Tests

The results obtained using the proposed test method make it possible to plot the mean value of EQ of the specimens ($Lmean_{lab}$) vs. the UCS, expressed in MPa (Figure 9), proposing a correlation curve for the evaluation of the mortar compressive strength based on the EQ average values for each site examined. A strong positive exponential interpolation is evidenced by Pearson's coefficient of determination ($R^2 = 0.81$), and one sample (sample ID 3009-5) could be considered as an outlier. The latter has been visually identified on the plotting since it lies well above the correlation curve obtained by fitting the other experimental measurements. This is related to the fact that this sample furnished a higher UCS value in relation to the associated $Lmean_{lab}$. Moreover, if this datum is considered in the fitting process, the coefficient of determination drops significantly from 0.81 to 0.62. The interpolation law presented to correlate EQ values with the UCS is reported in Equation (1):

$$UCS = 0.08 * e^{0.01 * Lmean_{lab}} \tag{1}$$

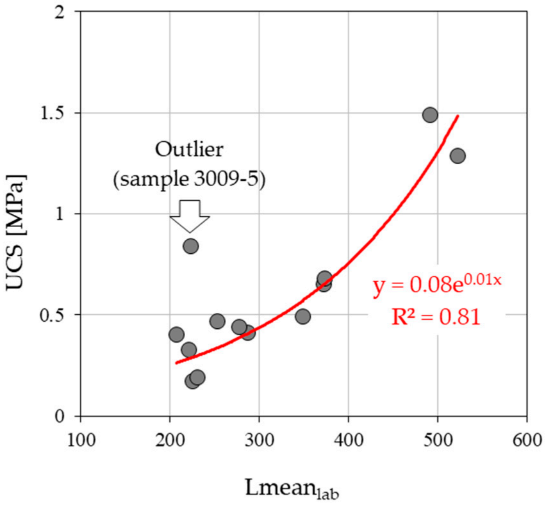

Figure 9. Correlation between $Lmean_{lab}$ and the UCS. Pearson's correlation coefficient is reported.

Results of the EQ testing on the in situ mortars and on the specimens are reported in Table 4, summarized with the UCS results.

Table 4. The list of EQ and UCS test results for each masonry examined. δ values are reported.

Sampling Location	Site ID	Number of Specimens (pcs.)	*$Lmean_{situ}$*		*$Lmean_{lab}$**		δ	UCS* [MPa]
			mean	**std**	**mean**	**std**		
masonry core	3000	1	160	15	221	42.1	0.72	0.33
masonry core	3002	1	263.5	91.2	349.5	30.9	0.75	0.3
masonry core	3004	1	143	23.5	230.6	20.5	0.62	0.19
masonry face	3006	2	290	54.9	372.7 *	34.5	0.78	0.67 *
masonry core	3008	1	143	71.3	225.3	63.3	0.63	0.17
masonry core	3009	5	143.2	74.2	250.0 *	107.1	0.57	0.51 *
masonry face	3010	1	369.6	46.5	491.4 *	55	0.75	1.37 *
masonry face	3011	1	375.6	37.9	523	43.8	0.72	1.29

* data referred to the averages data calculated on EQ and UCS for multiple specimens.

It should be noted that Lmean$_{lab}$* and UCS* values for each masonry mortar examined have been calculated averaging the values obtained for each specimen. At first, a discrepancy is clearly observed between Lmean$_{situ}$ and Lmean$_{lab}$*, with the site value always lower than the values obtained on the specimens in the laboratory. Based on that, the block volumes of the laboratory specimens have been assessed to see if they influence the rebound of the EQ, excluding its relationship with the inconsistency between Lmean$_{situ}$ and Lmean$_{lab}$ values. In Figure 10, the volumes of fourteen blocks of mortar sampled from the eight masonry sites examined were plotted against Lmean$_{lab}$. The volumes ranged between under 14 cm^3 to almost 200 cm^3. Based on the extremely low Pearson's coefficient of determination ($R^2 = 0.095$) there is no correlation, or relationship, between the block volume and Lmean$_{lab}$ (Figure 10), so the discrepancy in mean values cannot be attributed to the different volumes tested. This aspect is in accordance with [23] who tested the influence of block volume and edge effect on the EQ measurements.

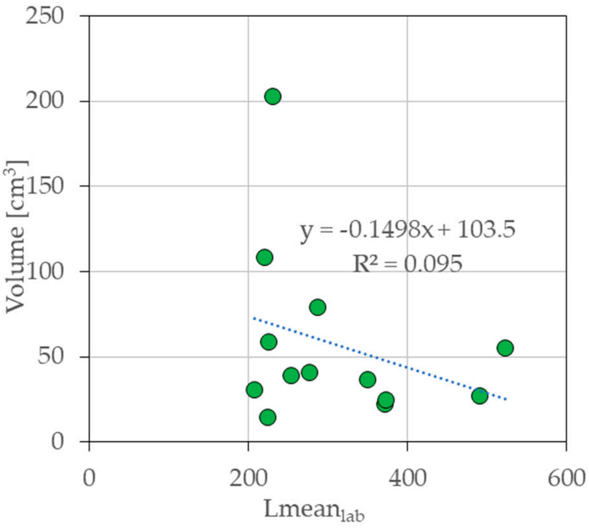

Figure 10. Lmean$_{lab}$ plotted vs the volume of specimens.

Having excluded the dependence between the volume and the EQ values on the specimens, it is plausible to attribute the decrease of the Lmean$_{situ}$ values to a real difference in strength between the external layer and the core of the in situ mortars, possibly due to surface phenomena of alteration. It should be considered, indeed, that the preparation of the laboratory samples implies the removal of the superficial altered layer, explaining why Lmean$_{lab}$ is always higher than Lmean$_{situ}$. Based on these assumptions, the ratio between Lmean$_{situ}$ and Lmean$_{lab}$ was calculated to estimate the amount of strength reduction δ (Equation (2)), that can be assumed to represent the degree of surface alteration of the in situ mortars (data reported in Table 4):

$$\delta = Lmean_{situ}/Lmean_{lab} \tag{2}$$

The δ values range from 0.57 to 0.78, indicating that the in situ mortars are characterized by a strength reduction due to surface alteration ranging from 22% to 43%. This aspect, coupled with the previous statistics evidence, confirms that the in situ mortars have generally higher variability of the mechanical properties in respect to EQ measurements on the laboratory specimens. As already evidenced in the literature [15,22], surface alteration generally lowers material's strength, as reflected in the rebound values indicative of surface hardness. Based on this evidence, we think that this aspect is crucial in the direct evaluation of the in situ strength properties and should be considered. In light of the results obtained, although the discrepancy between Lmean$_{lab}$ and Lmean$_{situ}$ is observed in the whole dataset, additional research deserves to be deepened, focusing on the influence of different methodologies on laboratory sample preparation. To substantiate all the consideration just made, the most striking observation that emerges plotting Lmean$_{situ}$ vs. Lmean$_{lab}$* (Figure 11) is that, although the depicted line of interpolation has a slope approximately equal to the reference line 1:1 and the correlation is strong (R^2 = 0.97), the intercept on the y axis is not on the origin. This demonstrated also that if using the in situ measurements as it is to empirically estimate the UCS with Equation (1), an incorrect UCS evaluation is made because it would be affected by the superficial altered layer. Based on our observations we can suggest correcting the in situ measurements of the historical mortars based on the linear interpolation formula of Figure 11 (Equation (3)) and then use these values to estimate the UCS with Equation (1):

$$Lmean_{lab} = 1.184 * Lmean_{situ} + 53.64 \tag{3}$$

This is a common problem of in situ non-destructive devices, i.e., the superficial evaluation of mortar properties [15].

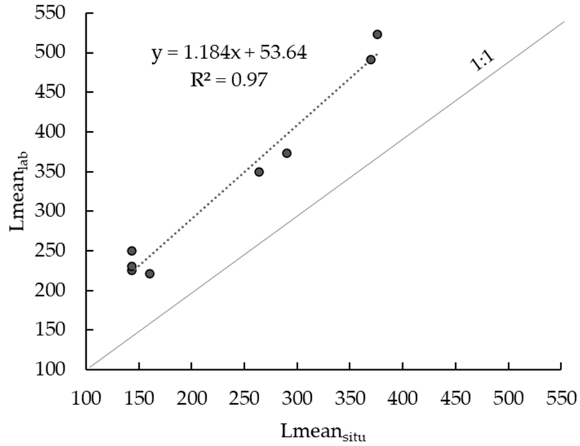

Figure 11. Linear interpolation of Lmean$_{situ}$ vs Lmean$_{lab}$. Pearson's coefficient of determination (R^2) is reported in the graph.

5. Conclusions

This study aims at defining a new non-destructive approach for historical mortar strength evaluation, focusing on a quick, easy to use, in situ, and relatively economic device, named Equotip hardness tester, applicable to any ancient masonry mortars. The proposed non-destructive testing (NDT) is useful in acquiring strength information which is often absent for widespread structural materials in territories with old and high value built cultural heritage. Within this context, this work shows the first results of an ongoing experience on the mortars of walls from different historic buildings in the town of Camerino (Italy).

The data resulting from the Equotip hardness tester were validated by the correlation with the data collected from the Uniaxial Compressive Strength test, allowing the following observations:

- the Equotip device, due to its low impact energy, is able to evaluate the mechanical properties of ancient mortars, characterized by low strength. In particular, the low dimension of the impact tip of the Equotip device investigates the mechanical properties of the first millimeters of the mortars;
- the data collected by using both the 'single impact test' and 'repeated impact test' methods; results indicate that the first one is strongly affected by the device settling, underestimating the real mechanical properties of the mortar differently;
- the "repeated impact test" method used in this paper allows monitoring of material behavior following repeated impacts and thus discarding initial values affected by settling and final values affected by artificial micro-fracturing of the material because

of the impacts. For this reason, the collecting methodology is fundamental to obtain reliable results;

- the comparison between EQ results and UCS laboratory test allowed the calibration of a relationship between the two parameters;
- the investigated mortars are characterized by low values of UCS, ranging from 0.17 MPa to 1.49 MPa, values largely lower than the strength currently required for new structural mortar; they were classified into three groups based on the UCS values and their different stress-strain response to the compression test; in particular, a brittle behavior has been observed for mortars with a higher UCS whereas a ductile behavior was noticed for mortars with lower UCS values; an evidently different mechanical behavior has also been observed between the mortar samples coming from the core of the masonry and the ones coming from the face. In particular, the mortar in the core of walls is generally weaker than the one coming from the wall face. The reasons for the lower strength of the masonry core can be related to a number of aspects such as the different ages of the mortars, their mineralogical composition, the manufacturing, and application method. Such aspects, not so documented in the literature, are of relevant importance in quantifying more realistically the structural behavior of historical masonry structures;
- the EQ data collected in situ always have a lower mean value comparing to the ones measured on the specimens in the laboratory. This is an important observation to consider in order to give a correct estimation of the real UCS. This aspect has been previously evidenced by [15], pointing out that the NDT may allow a superficial evaluation of the mortar properties and, more so of other materials [21–23]. In fact, natural environmental processes, with time, cause decay mostly at the most superficial portion of the mortar, in this study evidenced by the reduction in strength derived from the δ parameter.

For the reasons just mentioned, the in situ data should be corrected in order to obtain a more reasonable evaluation of the mortar compressive strength.

A possible limitation of the methodology proposed could be represented by the local representativeness of the test, starting from the fact that the investigated area is usually very limited and the existing constructions often present significant spatial variability and heterogeneity in the material properties. Nevertheless, this restriction can be potentially overcome by repeating the tests on different portions of the existing buildings, collecting thus a representative statistic of the mortar strengths. Future improvements of the proposed methodology could be linking the strength of the historical mortars with the chemical-physical and mineralogical investigation, developing a complete, multidisciplinary, non-destructive method for the evaluation of historical mortar quality.

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