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Evaluation of non-destructive techniques for mechanical characterisation of earth-based mortars in masonry joints

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A B S T R A C T

In this paper, the use of non-destructive tests for the mechanical characterisation of earth-based mortars in masonry joints is discussed. Four testing methods, namely the penetrometer, Schmidt hammer, pendulum hammer and scratch test, originally developed for other types of mortar, are reviewed. The methods are applied to the earth-based mortars at the Wupatki Pueblo archaeological site, in Arizona, US. The outcomes of the experimental programme allowed to assess the reliability of the methods and to identify their limitations. Finally, the methods are compared in terms of six qualitative indicators, namely easy-of-use, consistency of results, range and granularity of results, respect towards cultural value, depth of investigation under the visible surface and versatility in application. Overall, the penetrometer test is recommended as the preferable method to characterise the mechanical performance of earth-based mortars.

1. Introduction

As a bedding material between masonry units, mortar plays a key role. Important aspects are the bond capacity able to ensure a monolithic behaviour of the masonry, facilitate the stacking of the units by accommodating their geometric irregularity and distribute uniformly the compression stresses, limiting their concentration. Even if the contribution to masonry compressive strength is moderate, its tensile strength and shear strength depend to great extent on the mortar. In irregular masonry walls, the disintegration or local collapse are also much dependent on the mortar quality. The determination of the mechanical properties and durability performance of mortar is, therefore, fundamental in the analysis of historical masonry walls, in order to assess their structural integrity and identify possible deterioration mechanisms [1]. However, the heterogeneity of mortars, in terms of constituents, mixture composition, application process and actual conditions, often makes their characterisation difficult. This is more complex when dealing with earth-based mortars, given the variations in clay amount and composition, susceptibility to environmental humidity, and the frequent occurrence of extensive deterioration.

Raw earth is undoubtedly one of the most ancient and widely used materials by mankind to build houses and cities. Thus, an immense earthen-built heritage exists and is spread worldwide [2]. Several techniques have been developed over time and independently in different geographical contexts [3,4], adapting to different social and cultural features, as well as local resources [5]. In particular, earth-based mortars have been used as filling materials, plasters, and joints in adobe, fired brick, and stone masonry [6]. Earthen mortars share common main constituents, i.e., soil and water, nevertheless their physical and mechanical properties can be extremely different. This is partly due to the inherent heterogeneity of the raw materials, consisting of different soil constituents and fractions, as well as different mixing water contents, possible addition of sand and possible presence of admixtures (such as straw or other natural fibres, aerial lime, ground brick and biological products). The mortar preparation procedure, the experience of the workforce and the environmental conditions are other key affecting factors.

On this regard, a case specific characterisation of the mortar properties is needed for a correct diagnosis of existing constructions. However, collecting on-site mortar samples for destructive testing in laboratory environment is an invasive procedure, which is rarely feasible due to the historical and cultural value of the architectural heritage [1]. Moreover, the fragility of earthen materials makes sampling a delicate operation [7,8]. Indeed, the use of water, to which earthen materials are particularly sensitive, and the vibrations induced by the cutting device can significantly alter the mechanical and physical

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properties of the extracted samples [9,10]. The difficulties in sampling mortars are even greater if joints with small thickness are considered [11]. Therefore, the small number of samples, which may be taken at a few selected locations, is likely altered and inadequate to provide sufficiently representative results. The samples are also often different in shape and size, meaning that the results obtained cannot be compared without an appropriate correction [9]. Extracting non-disturbed samples is definitely invasive and challenging, so that other techniques have been developed in the last decades to mitigate the aforementioned issues, while ensuring an effective characterisation [11]. Minor-destructive (MDT) and Non-destructive Testing (NDT) methods are partially or fully non-invasive diagnostic strategies for assessing material properties, condition, geometry or details, causing easily repairable minor damage or no alterations, respectively. Effective tools and protocols to plan, conduct and interpret the results of these testing methods have been successfully developed for different materials and structural elements. Yet, research and application to earthen buildings is limited [12], and further studies are needed to ensure the repeatability of such methods, despite the heterogeneity and variability of earthen materials [9]. The few investigations conducted so far on this regard are mainly focused on rammed earth [7]. MDT methods, such as flat jack, hole-drilling, and mini-pressuremeter, have been successfully employed to assess mechanical properties of earthen walls [12]. Rammed earth walls have been also investigated through ultrasonic [13–15] and sonic tests [13]. The ultrasound transmission method was also used in [16] to evaluate raw earthen materials. Even if the aforementioned MDTs and NDTs allow to characterise the mechanical properties of walls, most of them can be hardly applied to the investigation of earth-based mortar joints. Indeed, some of them may be too invasive or even detrimental for very weak materials and require a regularity of the joints that is not always present in historic buildings. Moreover, the specific characteristics of the units may influence the results and the subsequent interpretation, thus some methods may provide a characterisation for the masonry as a composite material, rather than for the joints only. For these reasons, testing methods which rely on punctual measurements, may be more suitable. Devices like the Schmidt and pendulum rebound hammers measure specific parameters, but permit an indirect estimation of the mechanical properties through correlations with destructive laboratory tests. In some cases, correlation curves provided by the equipment manufacturers, and thus developed for other materials, have been assumed for earthen constructions [15,17,18], despite the debatable reliability of the estimation based on these curves. To this end, Bui [7] and Martin-del-Rio *et al.* [9] developed rammed earth correlation curves for the Schmidt and pendulum rebound hammers, respectively. Some rebound hammer tests applied to earthen materials have reported accurate results validated through laboratory tests [7,18], while in other studies, the results were not interpretable due to low rebound values [17].

The use of testing methods available for other materials to earthen ones can have further limitations. The testing protocol may be hardly adaptable to the specific characteristics of the elements to be tested *in-situ*, as, for instance, due to difficulties in accessing adequately earth-based mortar joints within very irregular masonry, or due to technical limitations of the available equipment (e.g. impact energy), which may not be compatible with the typical low strength of earth-based mortars [1]. For this reason, devices specifically developed for softer materials are preferred to test earthen materials, such as rammed earth [18] and renders on rammed earth walls [19], reducing but not eliminating the risk of damaging the surface without obtaining reliable measurements.

Considering the above, the research on the use of NDT methods to characterise earth-based mortars is currently limited. To advance this field, it is necessary to: (i) identify limitations and challenges in applying NDT methods to earth-based mortars; (ii) develop protocols tailored to the unique characteristics of earth-based mortars that enables accurate and reliable NDT measurements; (iii) calibrate the results based on destructive tests to improve their accuracy and enhance their reliability. The present work addresses the first point, which is considered a crucial preliminary step towards the development of the subsequent phases. The work aims at identifying limitations and difficulties related to the characteristics of either the material or the equipment/protocol. To this end, the study compares four NDT methods, established for on-site qualitative and quantitative assessment of soft materials, when used to characterise earth-based mortars in masonry joints. This is, to the authors' knowledge, not only the first application of its kind to earth-based mortars, but it is also a comprehensive application of NDT tools not available in literature for more traditional mortars. The selected methods include the penetrometer test, the Schmidt hammer test, the pendulum rebound hammer test and the scratch test. On this regard, the tests were applied to seven different earth-based mortars identified by visual inspection, based on colours, aggregates, and texture at the Wupatki Pueblo, an open-air archaeological site, in Arizona (US), within the scope of the "Integrated Site Conservation and Management Plan and Training for Wupatki National Monument, Arizona" project, supported by the J. Paul Getty Trust.

First, the testing methods adopted are described by detailing the operating principles of the equipment and the testing protocols. Then, the case study is contextualised and the experimental programme is presented. Subsequently, the main outcomes are discussed, in terms of quantitative and qualitative assessment of the different types of mortar, and advantages and disadvantages of the distinct testing methods are highlighted. Finally, the main conclusions of the work are drawn and complemented with relevant future needs.

2. *In-situ* non-destructive testing methods

The approach of this work consists in analysing and comparing four different NDT methods to estimate on-site the strength and durability of earth-based mortars in masonry joints. The selected methods include the penetrometer, the Schmidt hammer, the pendulum rebound hammer (strength analysis) and the scratch tests (durability analysis). As stated, these methods were not specifically developed for earthen materials, but for other soft materials, such as lime-based or cement-based mortars, renders or plasters, even if the methods remain not widely disseminated and known in the research and professional masonry community. The capacity of these tests to be applied to soft materials, which earthen materials resemble to, was in fact the main reason to select them for this study. Nevertheless, other reasons for the selection can be highlighted, such as the worldwide commercialisation of the testing devices and their easy application without requiring electrical power, which facilitates the investigation of sites in remote places. In order to ensure the preservation of the site's historical and cultural value and adhere to the current conservation policy, the invasiveness and potential damage caused by different methods were also evaluated. As a result, invasive techniques such as the hole-drilling test were avoided to prevent any unnecessary damage. In addition, logistical constraints, such as transport and available budget, were taken into consideration during the selection process, which led to the exclusion of the hole-drilling and helix pull-out tests. The adopted testing procedures were defined according to the instructions provided by the manufacturers, while considering adaptations required by the specificities of the investigated materials and structural elements, as further described in the following sections. It should be also noted that standards are followed whenever they are recommended by manufacturers.

2.1. *Penetrometer test*

The penetrometer test is carried out by measuring the response of the investigated material to the penetration of a needle and correlating it to the compressive strength. The penetrometer used is the RSM-15 model produced by DRC Srl (Fig. 1a). The device consists of a hammer, connected to a manually-loaded spring, that hits a striker in which a steel needle is located. The tip of the needle penetrates the mortar subjected

Fig. 1. Penetrometer test: (a) equipment; (b) in operation.

to dynamic blows with constant impact energy (Fig. 1b). In accordance with the manufacturer's instructions, the test is carried out by applying ten blows and then measuring the unpenetrated length of the needle L_1 with a comparator. The absolute penetration depth of the needle is finally calculated as the difference between the initial length of the needle L_0, equal to 80 mm, and L_1.

The *in-situ* penetration test can be affected by several uncertainty factors, mainly related to the possible heterogeneity of the mortar along the depth. For this reason, at least five acquisitions of ten blows each are recorded for each test and an average value of penetration depth is calculated. Finally, the following equation provided by the manufacturer is used to correlate the penetration depth d [mm] to the compressive strength f_m [MPa]:

$$d = 1.585{f_m}^2 - 11.944f_m + 25.899 \quad (1)$$

Based on Equation (1), the correlation curve in Fig. 2 is provided and the compressive strength f_m is estimated according to the measured penetration depth d:

$$f_m = \frac{5.97E03 - \sqrt{1.58E06 \times d - 5.3E06}}{1.58E03} \quad (2)$$

It is worth noting that the correlation is only possible in the range of penetration depth between about 3 and 22 mm, corresponding to a compressive strength of 3.7 and 0.4 MPa, respectively.

The penetrometer test has already been used *in-situ* to evaluate the strength of mortars in masonry joints [20], but so far mainly lime [11]

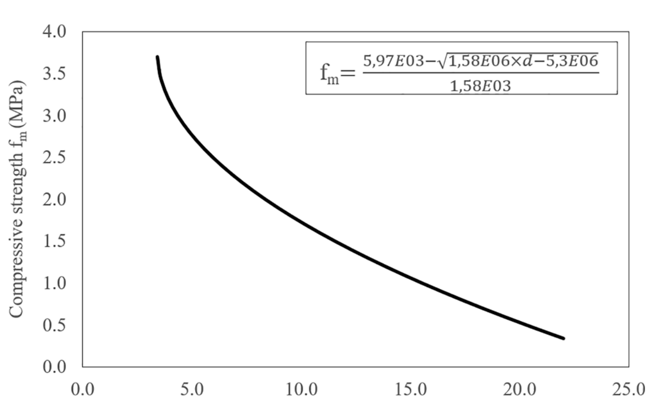

Fig. 2. Correlation curve between penetration depth (after 10 S) and compressive strength.

and gypsum mortars [21] have been successfully tested.

2.2. Schmidt hammer test

The rebound hammer used in the experimental program is the model PASI Srl Rebound hammer type M (Fig. 3a). This model was selected among the manufacturer's products as it was specifically designed for testing mortars. The objective of this non-destructive method is the estimation of the mechanical properties of mortars through the measurement of the rebound of a spring-controlled mass that, once released, strikes a plunger that is in contact with the investigated surface (Fig. 3b). The rebound value, displayed on the graduated scale of the device, provides an assessment of the hardness of the mortar. Indeed, higher rebound values are obtained for harder mortars. A correlation table between the rebound of the metal mass and the compressive strength is provided by the manufacturer of the equipment.

The manufacturer also specifies the testing protocol, where, for each measurement, twelve acquisitions are obtained at different points spaced, at least, 20 mm apart. At each point, three blows are applied, ignoring the values of the first two and recording only the third one. Out of the twelve acquisitions, the minimum and maximum values are discarded and the remaining ten measurements are used to calculate the average value of rebound, R_m. Finally, the conversion curve (Fig. 4), derived from the data provided by the manufacturer, allows the estimation of the compressive strength f_m [MPa] of the analysed mortar as a function of the rebound value R_m. According to the conversion table, the following expression was derived:

$$f_m = 9E05 \times {R_m}^{3.5652} \quad (3)$$

It is worth noting that the correlation is possible only in the range between 1.4 and 25.0 MPa and starting from a rebound value of 15.

The Schmidt hammer method has been used mainly in concrete structures [22–24], for which instructions and standards have also been developed [25,26]. Its use for masonry structures is much less common. Limited applications exist for stone [27] and brick walls [28,29]. Schmidt hammer tests on mortars in masonry joints are even rarer than those on masonry units [30]. For instance, in [31] tests were performed both on joints and units only for qualitative and comparative evaluation.

2.3. Pendulum rebound hammer test

The pendulum rebound hammer used in the experimental program is the Schmidt OS-120PM hammer (Fig. 5a), manufactured by Proceq for mortar testing. The objective of this non-destructive method is the

(a) (b)

Fig. 3. Schmidt hammer test: (a) equipment; (b) in operation.

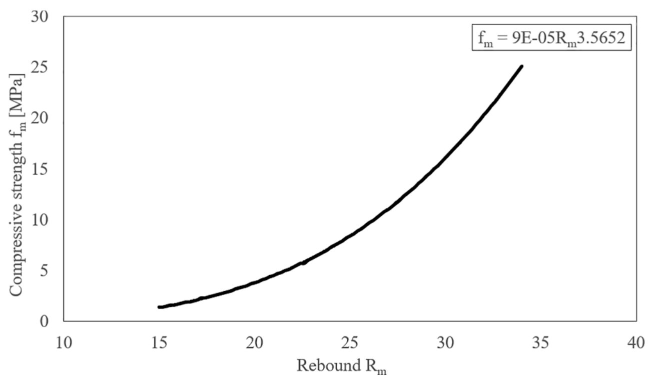

Fig. 4. Correlation curve between rebound value and compressive strength.

estimation of the mechanical properties of an inspected soft material, such as mortars [29] or renders [23,32], through the measurement of the pendulum rebound of a mass after its controlled impact against the surface of the specimen (Fig. 5b). The rebound value provides a qualitative assessment of the hardness of the mortar. Although the operating principle of the Schmidt hammer and the pendulum rebound hammers is therefore the same, the latter was chosen for its lower impact energy, which might be more suitable for testing earthen mortars.

In this case, the testing protocol recommended by the manufacturer is the one in standard EN 12504-2 [25], which was developed originally for concrete, but has been also adopted for mortars. The rebound value is obtained by computing the median of nine rebounds. It should be noted that the standard requires defining a regular grid of measurement points spaced 25 or 50 mm apart, which is hardly applicable in case of testing of bed-joint mortar, due to the irregularity of the masonry (and the uneven distribution of mortars over the walls in the present case study). To overcome this, a minimum number of nine random points, at least 25 mm apart, are defined and tested for a given section of the masonry. According to the manufacturer's rating table, the mortar is then classified as "poor", "average", "reasonable", "good", "very good", and "excellent" depending on the rebound value.

2.4. Scratch test

A mortar scratch test requires using a specific equipment designated as MortarCheck II, manufactured by Enertren Pty Ltd. (Fig. 6a). The test consists in the application, by means of a spring, of a fixed rotational force to a probe with an abrasive tip placed in contact with the surface of the soft material to be investigated (Fig. 6b). The axial force is held constant as, at the commencement of the test, a spencer is removed to allow a 10 mm spring compression of the probe against the joint. After five full turns, the indentation of the probe into the surface is measured. It should be noted that the rotation speed is not specified by the testing protocol, meaning that it depends on the operator. The action of the tip simulates accelerated physical forces that lead to degradation.

The testing protocol recommended by the manufacturer follows the Australian standard AS 3700 [33]. In each test, five individual

(a) (b)

Fig. 5. Pendulum rebound hammer test: (a) equipment; (b) in operation.

(a) (b)

Fig. 6. Scratch test: (a) equipment; (b) in operation.

measurements, spaced at least 10 mm apart, are recorded. Finally, the scratch index is calculated as the average of the individual measurements. It is worth noting that the standard recommends the use of the scratch test to determine compliance with the durability requirements for new mortars. The scratch index is related to one of the mortar durability classes defined by the Australian standard, namely M2, M3, or M4. Therefore, it should be noted that the purpose of the scratch test is significantly different from that of the previous testing methods, thus the procedure for interpreting the results reported in the AS 3700 standard can only be used as a reference. Here, the mortar classes M2, M3, and M4 are associated with a qualitative grade of durability equal to low, intermediate, and high, respectively.

Scratch tests with a different setup have also been performed in a laboratory environment on cement and hydraulic lime mortar cores [34,35], with the aim of determining compressive strength rather than durability performance. Similarly, the NZSEE standard recommends the use of the scratch test to evaluate on-site the mechanical properties, rather than the durability, of clay bricks and cement/lime mortars, using various tools for the scratching process [36,37]. As the present study focuses on the application of standardised commercial devices, such an approach has not been included, nonetheless, investigating the application of these simple tools on earth mortars is a compelling avenue to explore in future research.

3. Description of the Wupatki Pueblo case study

3.1. Historical context

The Wupatki Pueblo is the largest archaeological complex within the Wupatki National Monument (WUPA), a vast area of approximately 143 km^2, where more than 2,500 sites belonging to the Sinagua culture have been found so far. The Wupatki was probably the richest and most influential pueblo in the WUPA area from A.D. 1150 to 1250. It is argued that it was built and inhabited by people belonging also to other cultures [38]. The site, approximately 56 km to northeast of the city of Flagstaff, within the Coconino County, is built on a narrow sandstone ridge and includes two compact blocks of rooms, the South and North units (Fig. 7). A Ballcourt and a Community Room are also located in the area immediately surrounding the Pueblo (Fig. 8). During its highest occupation, the entire site is estimated to have counted about 100 rooms, 80 of which have been excavated to date. Archaeological excavations began in the 1930s but were initially conducted without documenting the operations. Moreover, besides consolidation works, demolition and reconstruction operations were carried out to recreate the Pueblo as it was believed to have been during its heyday [38]. Later on, the intervention policy has changed and the archaeological site has been restored to its probable original state, eliminating the most invasive interventions and the most obvious reconstructions. Currently, conservation policies prohibit any invasive actions or interventions, such as core drilling, which may damage the site and compromise its heritage value and significance. Annual maintenance work mainly consists of repointing mortar and placing capstones, and is carried out by the indigenous individuals. Their profound sense of belonging to the site demonstrates its crucial social relevance.

The masonry walls of the rooms are made of Moenkopi sandstone units, which is the main building material, with earth-based mortar joints. The stones are irregular in shape and extremely variable in size. Basalt pebbles, from the nearby volcanic formations, are included in a few places as decorative bands. Although there is a lack of precise information on the cross-section of the walls, based on the inspection of the collapsed areas, it is assumed that they consist of a single leaf, without an inner core, and with a few stones passing through the entire

Fig. 7. The Wupatki Pueblo: South Unit at the left and North Unit at the right.

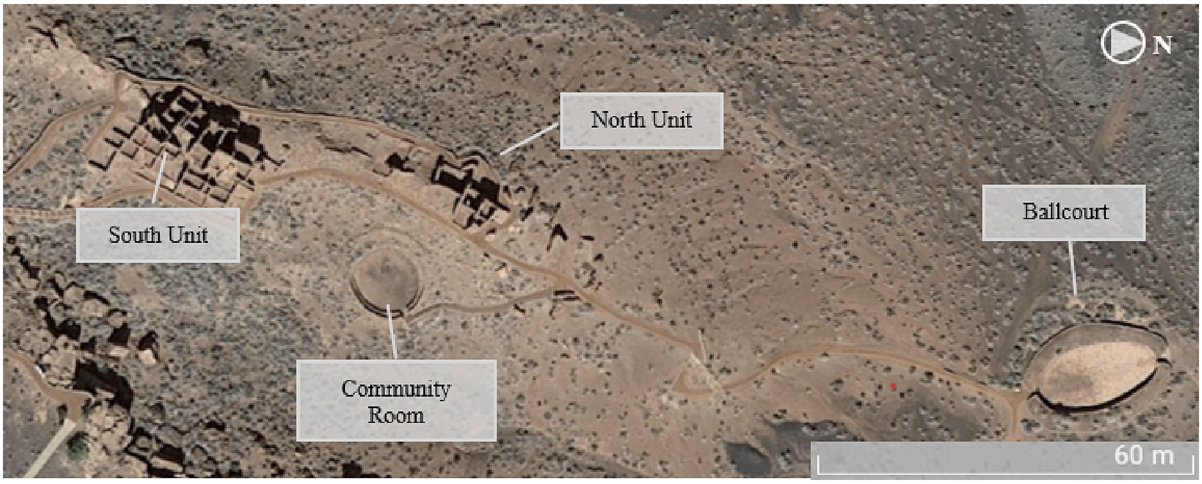

Fig. 8. Satellite view from Google Earth of the Wupatki Pueblo (South and North Units, Community Room and ballcourt).

thickness. Most of the mortar joints have been repointed over time. Recently, earth-based mortars, amended and stabilised with an acrylic-emulsion polymer, Rhoplex E-330, have been employed. The objective is to increase their strength and durability [39], covering past interventions and the original earthen mortar [38]. Cement-based mortars were also used in past interventions, between the 1930s and the 1980s, probably to fill the joints and to rebuild portions of the walls. Due to these numerous repointing interventions, it is nowadays very hard to identify original mortar samples on site. In most cases, there is no evidence of special devices or quoins for corner connections between orthogonal walls. Foundations seem absent with the walls built directly on the soil or on the boulders. Finally, horizontal elements, such as floors and roofs, no longer exist in the ruins.

3.2. Environmental conditions

The remains of the Wupatki Pueblo, buried until a very recent past, are now mostly excavated and threatened by exposure to weathering. The geographical area of the site is characterised by hot and wet summers with a maximum average temperature of 35 °C. The average annual temperature is 14.4 °C. Although the climate is generally warm, there are about 100 days per year, during the winter, in which the temperature drops below 0 °C [40]. In addition, temperature fluctuations during the winter months are likely to cause freeze–thaw cycles. The preservation of the site has been pursued by the archaeologists responsible for regular maintenance. However, degradation phenomena, mostly associated with water run-off and accumulation of water or snow, affect both masonry walls and boulders. Signs of material decay and damage due to salt crystallisation are also present. The recent occurrence of extreme events, such as high-intensity rainfall [41], and future climate change scenarios raise additional concerns. Thus, further actions are deemed necessary to maintain the integrity of the site and to prevent its decay in the long-term. Assessing the current condition of the site is of utmost importance to support associated decisions, justifying the need of conducting investigation studies as those presented here.

4. Experimental investigation

The aforementioned degradation of the earth-based mortars, due to the aggressive environmental conditions, motivated the need for a detailed investigation of the performance of the bed-joint mortars of Wupatki Pueblo. On this regard, seven types of mortars were identified by visual inspection, while considering colour, texture, and characteristics of the aggregates. According to the existing documentation, these mortars were likely used in distinct interventions, thus they have different age and compositions. Among them, six types are earth-based mortars, identified and labelled as EM plus a number (e.g., EM1, EM2, etc.), and one is a cement mortar, labelled as CM (Fig. 9). Their location is shown in Fig. 10. The earth-based mortars were employed during the repointing interventions of the joints, dating from the 1990s to the present day. Although the raw materials and their proportions have changed over time, all these mortars are stabilised with the Rhoplex E-330. These repointing mortars play a key role for the actual and future safety and conservation of the site. Therefore, it is deemed important to examine the evolution of their performance over time to ensure their continued effectiveness. On the other hand, the cement mortar, dating back to the reconstruction years, is extensively present at the site, and it likely constitutes the substrate of many repointed joints. The main purpose of performing cement mortar tests is to provide a benchmark for comparative purposes. Moreover, given its widespread presence, it was deemed appropriate to investigate it to provide a preliminary characterisation of the mortars on site, even though it is no longer in use.

The four testing methods were used for each type of mortar, performing one or more acquisitions. The selection of points for testing was primarily based on the regularity of masonry, wherever possible, taking into account joint thickness and alignments. Other selection criteria included the location of the different types of mortars and visible conservation conditions. All measurements are labelled and numbered using a test identification code (Table 1). For the penetrometer test, a total of nine acquisitions, labelled as P plus the type of mortar (e.g. PEM1, PEM2, etc.), were made, namely one measurement for each type of mortar and three repetitions for EM1 in different areas. For the rebound hammer test, ten acquisitions, labelled as S plus the type of mortar (e.g., SEM1, etc.), were made, namely one per each amended mortar and three for the cement one. For the pendulum hammer, eight tests, labelled as Pe plus the type of mortar (e.g., PeEM1, etc.), were performed, namely one measurement for each type of earthen mortar with three repetitions for EM1. The pendulum hammer test was not conducted on cement mortar due to operational limitations of the instrument and morphological characteristics of the site, which made it impossible to obtain the minimum number of required acquisitions in a single tested area. Finally, for the scratch test, seven measurements, labelled as C plus the type of mortar (e.g., CEM1, etc.), were made, namely one for each of the seven mortar types.

4.1. Penetrometer test

Fig. 11 shows the five penetration depth values measured in each acquisition using filled circles. The average penetration depth and the standard deviation were also calculated in order to evaluate the

(a) (b) (c) (d) (e) (f) (g)

Fig. 9. Types of mortar identified on-site: (a) EM1; (b) EM2; (c) EM3; (d) EM4; (e) EM5; (f) EM6; (g) CM.

consistency of the results. Most of the tests show penetration depth values outside the range between the average and plus/minus the standard deviation. In addition, to the usual scatter, this may be due to different degradation of the investigated mortars and quality of the interface between the repointing and its underlying layers. The large dispersion of results obtained from the penetrometer is therefore noteworthy, as it indicates the instrument's considerable sensitivity to the stratigraphy of the materials, which would not have been discernible through visual inspection alone. In some cases, during the test, the needle of the penetrometer reached a few centimetres of depth and, in some points, passed through more than one layer of mortar with potentially different composition, altering the measurements. Due to the highly irregular thickness of the repointing mortars, which varies from point to point, an overall evaluation of layer thickness was unfeasible. If poor bonding was identified or the detachment of the superficial layer occurred during testing, the reading was discarded and repeated in another location with the same mortar type. It is important to note that the observed damage cannot be attributed to the testing method, but rather to a pre-existing, not-visible condition that was revealed during testing.

The mortar EM2 (test PEM2) presents the largest variability, which is a consequence of a value with significantly poor performance. A similar behaviour, with a single higher penetration value that alters the average, emerges for mortar EM4 (test PEM4), although, in this case, the variability is smaller. For the other cases, a possible abnormal value does not seem to modify the outcomes excessively. It is noted that the penetration values measured for the cement mortar CM (test PCM) and the earth-based mortar EM5 (test PEM5) are very consistent. It is also worth noting that the different tests conducted on mortar EM1, namely PEM1a, PEM1b and PEM1c, show penetration depth measurements values quite similar.

Table 2 presents further details on the conducted tests, namely the location (room number), orientation and type (interior or exterior) of the wall, as well as the compressive strength of the mortars estimated from the average penetration values and the correlation curve of the equipment. It should be noted that the estimated compressive strength is

Fig. 10. Room numbering, location of tests and selected mortars: (a) South Unit, (b) North Unit.

Table 1
Identification of the different tests conducted for each type of mortar.

Mortar	Testing method									
	Penetrometer (P)			Schmidt hammer (S)			Pendulum (Pe)			Scratch (C)
EM1	PEM1a	PEM1b	PEM1c	SEM1	–	–	PeEM1a	PeEM1b	PeEM1c	CEM1
EM2	PEM2	–	–	SEM2	–	–	PeEM2	–	–	CEM2
EM3	PEM3	–	–	SEM3	–	–	PeEM3	–	–	CEM3
EM4	PEM4	–	–	SEM4	–	–	PeEM4	–	–	CEM4
EM5	PEM5	–	–	SEM5	–	–	PeEM5	–	–	CEM5
EM6	PEM6	–	–	SEM6	–	–	PeEM6	–	–	CEM6
CM	PCM	–	–	SCMa	SCMb	SCMc	–	–	–	CCM

limited by the lower bound of the correlation curve, which is equal to 22 mm of penetration (0.4 MPa). However, it was deemed appropriate not to extend the correlation curve beyond the manufacturer's recommended range and to identify out-of-range values as below the stated bound. This value of penetration is exceeded for mortars EM2 (PEM2) and EM4 (PEM4), meaning that their estimated strength is lower than 0.4 MPa. Mortars EM3 (PEM3) and EM6 (PEM6) also show low values of compressive strength, namely of about 0.7 MPa and 0.6 MPa, respectively, whereas the average of the three values estimated for mortar EM1 (PEM1a, PEM1b and PEM1c) is about 1.0 MPa. The highest compressive strength among the earth-based mortars was estimated for EM5 (PEM5), namely 2.0 MPa. Finally, the CM mortar (PCM) has the highest overall value, equal to 2.8 MPa. Although this result was expected, it is worth noting that this value is rather low for a cement-based mortar. Additionally, a correlation can be observed between the dispersion of outcomes and the compressive strength, indicating that mortars with higher compressive strength typically exhibit less dispersion of results.

4.2. Schmidt hammer test

Fig. 12 shows ten out of the twelve measured rebound values (maximum and minimum were discarded), the average and the standard deviation for each of the nine tests. It is worth noting that the tests performed on earth-based amended mortars are characterised by quite similar rebound values. Values outside the range between the average and more or less the standard deviation are observed but they are located evenly on both tails of the distributions. On the other hand, the tests on the cement mortars (SCMa, SCMb and SCMc) show a greater dispersion of the rebound, affected by values of significantly better performance. Multiple repetitions were conducted to address this dispersion, which could have been caused by factors such as differences in age, curing conditions or inadequate conservation. Furthermore, it is

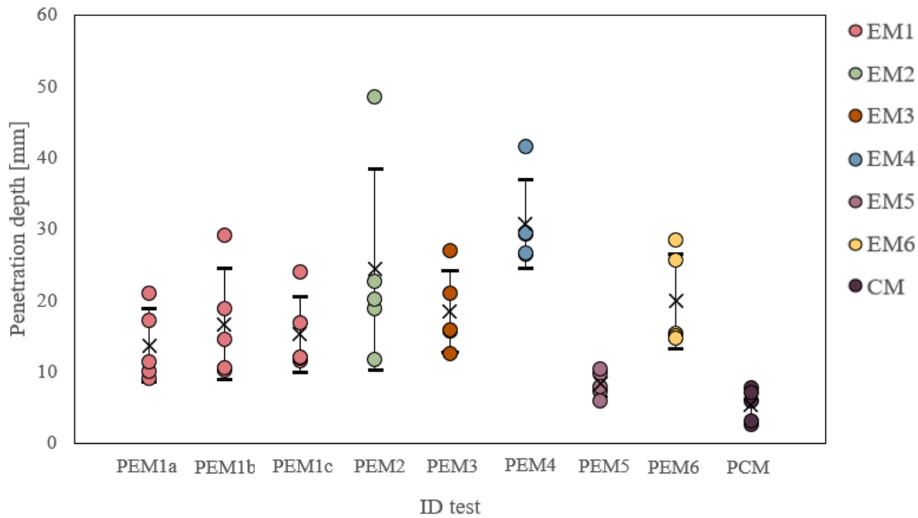

Fig. 11. Results of the penetrometer tests: penetration depth values, average (x) and standard deviation limits (—).

Table 2
Average results of the penetrometer tests and estimation of the compressive strength of the mortars.

ID	Location	Mortar	Av. penetration depth [mm]	Coef. of variation [%]	Comp. strength f_m [MPa]
PEM1a	Room 41 – North (int)	EM1	13.7	37.7	1.2
PEM1b	Room 41 – North (int)	EM1	16.6	47.0	0.9
PEM1c	Room 41 – East (int)	EM1	15.2	34.9	1.0
PEM2	Room 41 – South/East (int)	EM2	24.4	57.9	< 0.4
PEM3	Room 35 – South (int)	EM3	18.4	30.8	0.7
PEM4	Room 35 – South (int)	EM4	30.7	20.4	< 0.4
PEM5	Room 8 – South (int)	EM5	8.2	22.1	2.0
PEM6	Room 1 – North (ext)	EM6	19.8	33.5	0.6
PCM	Room 41 – North (int)	CM	5.3	44.8	2.8

worth noting that such dispersion resulted in some readings, especially for SCMb, being lower than the results for the earth-based mortars, likely due to poor bonding and/or to the presence of softer layers below the cement one, used for repointing. Nonetheless, as expected, cement mortars present higher average rebound values than the earth-based ones.

Similarly to the penetrometer tests, the range of the calibrated conversion table for the Schmidt hammer limits the interpretation of the results for the weakest mortars. Results falling below the recommended range are therefore reported as below the defined threshold, without extending the calibration. In this case, the lower bound, equal to 15, is particularly high for earth-based mortars. Indeed, mortars EM2, EM3, EM4 and EM6 obtained rebound values inferior to 15, meaning that their estimated compressive strength is lower than 1.4 MPa, whereas for mortar EM1 the estimated compressive strength is about 1.4 MPa (see Table 3). For mortar EM5 a higher value of 1.7 MPa is obtained. In the case of the cement mortar CM, considerably higher values of compressive strength are estimated, yet high variations are observed between the three tests conducted, with average values of 9.6, 2.3 and 6.2 MPa obtained in SCMa, SCMb and SCMc, respectively.

4.3. Pendulum rebound hammer test

As shown in Fig. 13, the dispersion in pendulum rebound values is large within all the tests, and also produces a scatter between the average values for the different earth-based mortars. The lower scatter in measured values is achieved in tests PeEM1a and PeEM5 for mortars EM1 and EM5, respectively. It is worth noting that the characteristics of the device prevent its correct use when the recess of the mortar joint with respect to the surface of the stone units does not allow the plunger to reach the surface of the mortar. Therefore, the correctness of the operation was verified at each location and the reading was discarded otherwise.

Based on the correlation provided by the manufacturer, most of the earth-based mortars are classified as "average" (Fig. 14), given the median rebound value between 20 and 30. Nevertheless, mortar EM3 outperforms the other ones, being classified as "reasonable". Mortar EM1 was tested three times, yet the outcomes were not consistent, as they ranged from "poor" (PeEM1c) to "average" category (PeEM1a and PeEM1b).

4.4. Scratch test

As shown in Fig. 15, the scratch test also produced a large dispersion of the results. The lower scatter was found for the cement mortar CM (CCM) and earth-based mortar EM6 (CEM6). On the other hand, mortars EM3 (CEM3) and EM4 (CEM4) present the largest dispersion in the results, as well as the worst performance in terms of indentation values (higher values). This variability may be the consequence of an uneven contact between the device tip and the mortar surface. During the test, the probe must be held against the investigated surface, yet such procedure is not easily applied or controlled, particularly in the case of uneven wall faces as the ones found in the site. The test was influenced by the arrangement of the stone masonry (e.g. lack of vertical alignment of the surface of the units, recess of the joints, etc.) and it required the collaboration of two operators, one holding the device and one applying the rotational force, which none of the other tests did.

Most of the investigated mortar types are classified as M3, to which corresponds an intermediate durability (Table 4). Mortar EM4 presents a higher scratch index value, belonging to class M2 or low durability. Regarding mortar EM3, it presents the highest value of scratch index, which is non-compliant with the range provided by standard AS 3700 [33]. Thus, the durability is classified as very low.

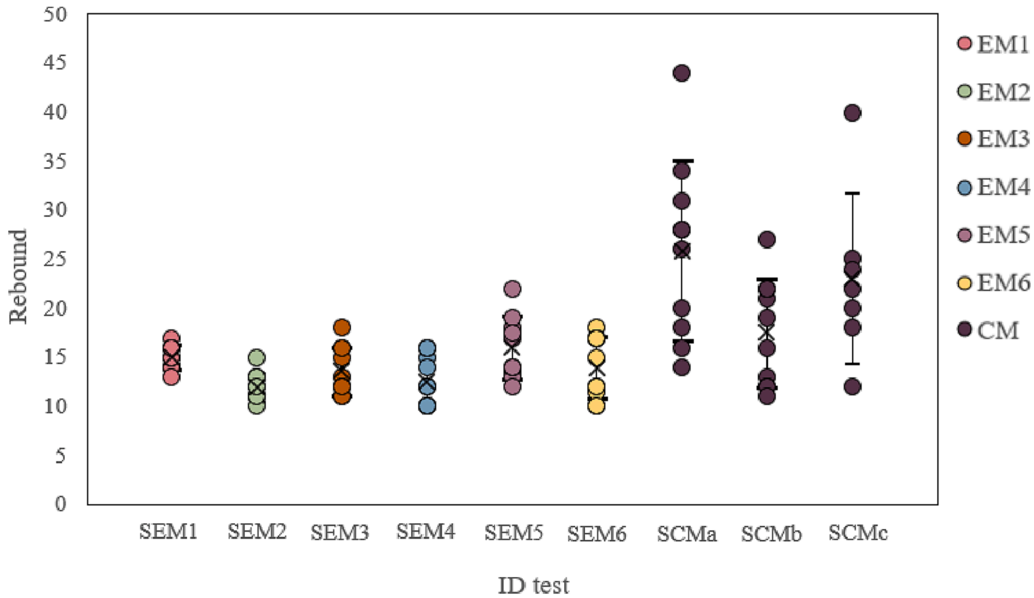

Fig. 12. Results of the Schmidt hammer tests: rebound values, average (x) and standard deviation limits (—).

Table 3
Average results of the Schmidt hammer tests and estimation of the compressive strength of the mortars.

ID	Location	Mortar	Av. rebound value	Coef. of variation [%]	Comp. strength f_m [MPa]
SEM1	Room 41 – North (int)	EM1	15.0	8.3	1.4
SEM2	Room 41 – South (int)	EM2	11.9	12.2	<1.4
SEM3	Room 35 – South (int)	EM3	13.6	18.1	<1.4
SEM4	Room 35 – South (int)	EM4	12.5	20.4	<1.4
SEM5	Room 8 – South (int)	EM5	16.0	19.9	1.7
SEM6	Room 1 – North (ext)	EM6	13.9	22.7	<1.4
SCMa	Room 35 – West (int)	CM	25.9	35.6	9.6
SCMb	Room 41 – North (int)	CM	17.5	31.3	2.3
SCMc	Room 55 – North (int)	CM	23.0	37.6	6.2

5. Discussion

As stated, the investigated mortars were used in past repointing interventions and are characterised by reduced thickness, ranging from a few millimetres to the expected minimum depth of 10–20 mm. The presence of multiple mortar layers complicates the experimental assessment. This is particularly evident for the penetrometer test, which in some cases reached a depth of almost 50 mm. Multiple acquisitions at different testing locations were made to detect and discard anomalous results due to localised defects (e.g., detachment of the mortar, superficial repointing, etc.).

5.1. Mechanical and durability performance

Table 5 shows the comparison between the results obtained for each type of mortar analysed. The quantitative estimations of the compressive strength through the penetrometer and Schmidt hammer tests can be directly compared, whereas the pendulum rebound hammer and scratch tests are complementary to the former, and provide a qualitative assessment of the mortar performance.

Based on the pendulum hammer test, mortar EM3 is the best performing, while the worst one is EM1. Both Schmidt hammer and penetrometer tests, despite a significant variation in estimating the compressive strength, provide a higher rating for EM1, outperformed, among the amended earth-based mortars, only by EM5. It is noted that the results from the penetrometer and Schmidt hammer tests are consistent for all the types of mortar investigated. The compressive strength values are lower than those reported in the literature for earth-based mortars (about 2–3 MPa [4,42]). As expected, in all tests, the highest compressive strength values and the highest performance were obtained for the cement mortar.

5.2. Evaluation of the adopted non-destructive techniques

Upon the aforementioned extensive experimental programme, relevant conclusions regarding the feasibility of these rather simple-to-use field-testing methods can be drawn. Despite the difficulties and limitations encountered, they proved to be promising in the characterisation of earth-based mortars. As shown in Table 6, the tests are rated as good, average or poor in terms of ease-of-use, consistency of results, range and granularity of results, depth of investigation below the visible surface, respect towards cultural value by limiting loss of original material, and versatility in the application. These concepts are subsequently detailed.

The ease-of-use parameter considers factors such as the ergonomics of the device, its weight, the ease of reading the results and the time required for each acquisition. The MortarCheck II, used in the scratch tests, presents the most complicated operation as it requires two operators to hold it steady in place during measurements. However, the device's digital screen makes it easy to read the results. The penetrometer is classified as average in user-friendliness since, despite a non-excessive weight (2.1 kg), the recoil after the initial blows may invalidate the reading and the measurement requires a longer time (approximately 30 s). The Schmidt and pendulum hammers, on the other hand, are easy to use, considering the quick measurements (a few seconds), the fairly low weight of the devices (1.0 kg and 3.2 kg, respectively) and the graduated scale for reading the rebound values. Although the Schmidt hammer, according to the recommended protocol, requires more repetitions, it is lighter and more manoeuvrable, thus, overall, the ease-of-use of the two devices is considered comparable.

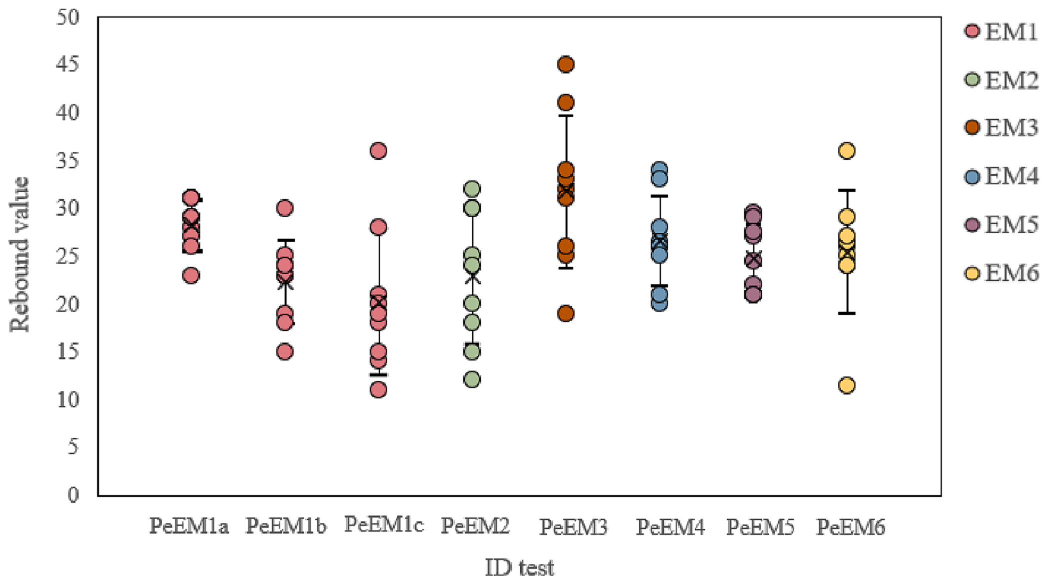

Fig. 13. Results of the pendulum rebound hammer tests: rebound values, average (x) and standard deviation limits (—).

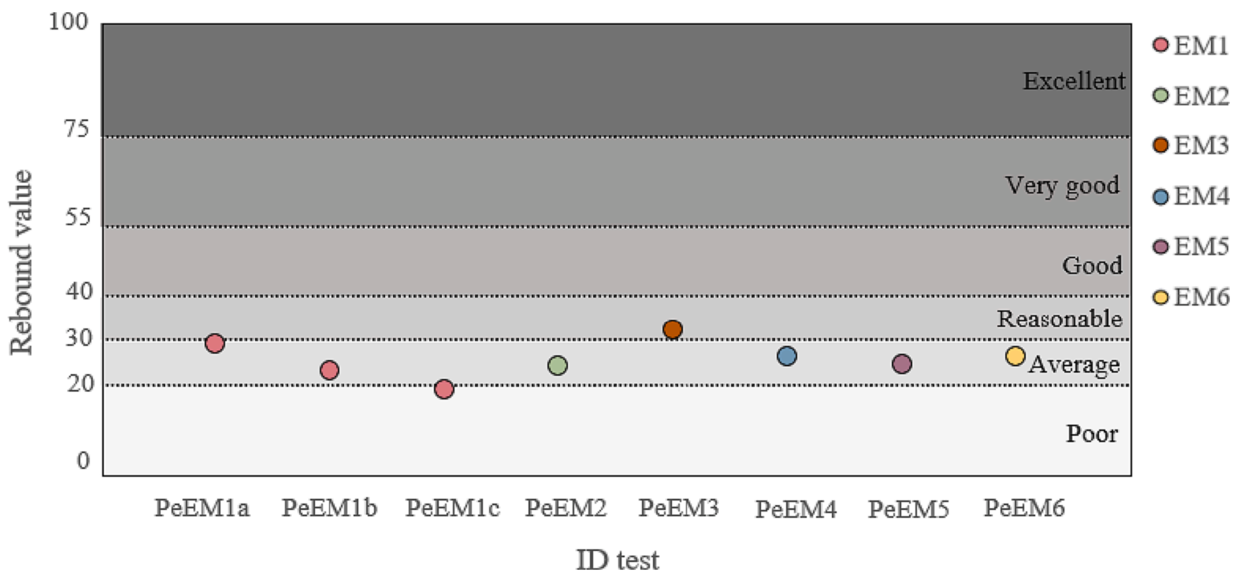

Fig. 14. Classification of the mortars according to the performed pendulum hammer tests.

In all tests, a significant variability in measurements was detected, likely due to specific and localised mortar defects but also, possibly, due to the functioning of the devices. For instance, the uneven pressure between the MortarCheck II probe and the mortar surface may alter the measurements. An increase in rebound values can be also recorded during the repetitions in the Schmidt hammer test, due to an increasing mortar compaction after each stroke. Despite the presence of multiple layers of mortar, the penetrometer showed, instead, a better consistency in the results.

Among the devices, the penetrometer also offers a larger range and granularity of the information, allowing the determination of the compressive strength values below 0.4 MPa. While, for the other devices, most of the mortars fall in the same class, preventing a further distinction. In the case of the Schmidt hammer test, this was due to the lower bound of the calibrated range that was above the rebound values for some tested mortars. This means that the Schmidt Type M hammer may have an excessively high impact energy for the soft and low-strength earth-based mortars, with high energy absorption capacity. In some cases, the impact tip sank into the surface, and the device was unable to record any rebound. As a result, the impact energy has been identified as a limiting factor for the Schmidt hammer's performance compared to the pendulum hammer.

Although the four tests are considered non-destructive, the use of the penetrometer causes a small, but visible, damage on the mortar surface, which may be easily repaired, so that no penalisation is given. For the Schmidt Type M hammer, minor damage, such as small depressions, can also be observed.

However, the penetrometer allows a deeper investigation of the mortar (several centimetres), while the Schmidt and the pendulum rebound hammer tests are limited to the surface mortar, arguably down to approximately 3 cm [25]. This superficial mortar may be compromised by environmental factors and not be representative of the real mechanical properties. The scratch test is rather superficial (less than 1 mm), which aggravates this phenomenon.

The versatility in application is an indicator of the adaptability of the devices to different site specificities. On this regard, the pendulum

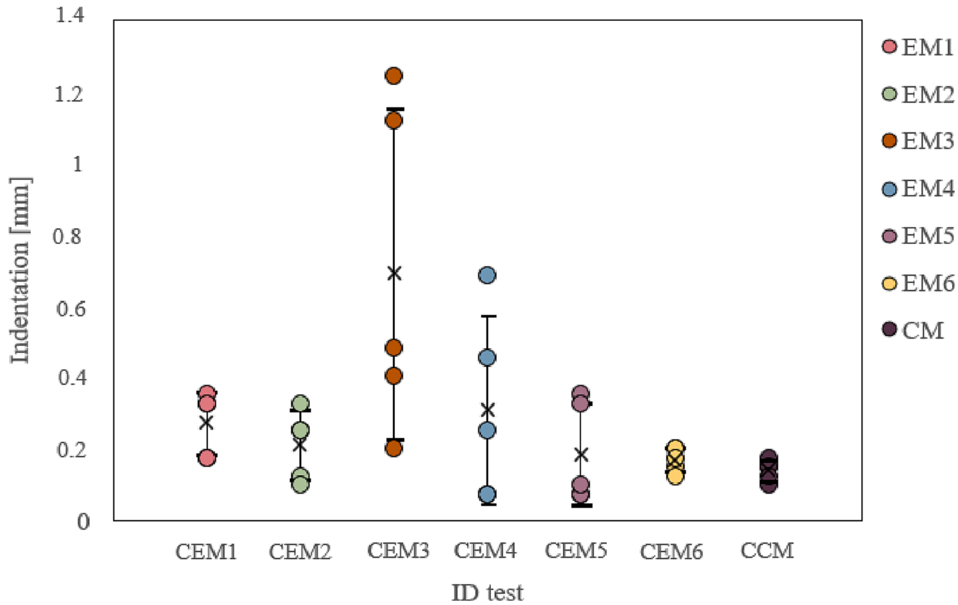

Fig. 15. Results of the scratch tests: indentation values, average (x) and standard deviation limits (−).

Table 4
Average indentation values obtained from the scratch tests and corresponding classification of the mortars.

ID	Location	Mortar	Av. indentation [mm]	Coef. of variation [%]	Mortar class	Durability grade
CEM1	Room 41 – North (int)	**EM1**	0.274	32.3	M3	Intermediate
CEM2	Room 41 – South (int)	**EM2**	0.213	44.9	M3	Intermediate
CEM3	Room 35 – South (int)	**EM3**	0.691	66.8	Not compliant	Very poor
CEM4	Room 35 – South (int)	**EM4**	0.310	84.7	M2	Poor
CEM5	Room 8 – South (int)	**EM5**	0.188	75.6	M3	Intermediate
CEM6	Room 1 – North (ext)	**EM6**	0.173	19.2	M3	Intermediate
CCM	Room 41 – North (int)	**CM**	0.142	20.3	M3	Intermediate

Table 5
Comparison of the properties estimated for the tested mortars according to the conducted tests.

Mortar	Penetrometer	Schmidt hammer	Pendulum hammer	Scratch
	Compressive strength [MPa]		Classification	Durability
EM1	1.0	1.4	Poor/average	Intermediate
EM2	<0.4	<1.4	Average	Intermediate
EM3	0.7	<1.4	Reasonable	Very poor
EM4	<0.4	<1.4	Average	Poor
EM5	2.0	1.7	Average	Intermediate
EM6	0.6	<1.4	Average	Intermediate
CM	2.8	6.0	–	Intermediate

Table 6
Suitability of the equipments to test earth-based mortars in masonry joints (Good +, Average +/−, Poor − performance).

Qualitative indicators	Tests			
	Penetrometer	Schmidt hammer	Pendulum hammer	Scratch
Ease-of-use	+/−	+	+	−
Consistency of results	+	+	+/−	−
Range and granularity of results	+	−	+/−	+/−
Respect towards cultural value	+/−	+/−	+	+
Depth of investigation under the visible surface	+	+/−	+/−	−
Versatility in application	+	+	−	−

hammer and the MortarCheck II are the least performing. For instance, in irregular masonry, the units may be not aligned and have different projections, which can make it difficult for the pendulum hammer to stand vertically. Indeed, small inclinations of the device may alter the rebound values. In addition, if the joint indentation is greater than approximately 5 mm, it may not be possible for the pendulum to make contact with the surface being tested. On the other hand, the use of the MortarCheck II requires a fairly even surface in order to support the device and to guarantee an appropriate contact between the probe and the mortar.

In conclusion, among the analysed NDTs, the penetrometer can be considered the best tool to characterise the mechanical performance of earth-based mortars in masonry joints. Although it causes more damage to the material than the other devices, the invasiveness is still minimal and the damage is easily repairable. On the other hand, the scratch test is likely the least feasible for this specific goal, being mainly concerned with durability and exploring only the very superficial layer, possibly less relevant for ancient mortars. Still, given this characteristic, the scratch test may be capable of measuring the existing deterioration and its progress, if used repeatedly over time. However, the difficulty in use, the lack of consistency in the results and low versatility in the application make the scratch test underperforming.

6. Conclusions

Four non-destructive testing methods used to assess *in-situ*, qualitatively or quantitatively, the strength and durability performance of soft materials have been applied to earth-based mortar joints. The aim was to assess their viability to test this type of materials and to identify limitations and difficulties related to the specific characteristics of either the tested material or the equipment/protocol. The four methods, namely penetrometer, Schmidt hammer, pendulum rebound hammer, and scratch test, were adopted to assess six different types of earth-based mortar and a cement-based mortar identified by visual inspection of the masonry joints at the archaeological site of the Wupatki Pueblo, Arizona (US).

The following considerations emerged from the conducted experimental programme:

- The penetrometer and Schmidt hammer tests allow a quantitative estimation of the compressive strength through correlation curves. However, these quantitative relations have been developed for different materials;
- The pendulum rebound hammer and scratch tests allow only a qualitative assessment of performance and durability of earth-based mortars;
- Although specific correlation curves or grades for earth-based materials are not available, the combination and comparison of different techniques allowed to improve the reliability of the preliminary assessment made;
- Despite generating minor damage, the penetrometer proved to be the best tool for characterising the mechanical properties of earth-based mortars in masonry joints. It showed good consistency and granularity of the results and allowed a deeper investigation of the mortars below the visible surface;
- The Schmidt hammer type M was easy-to-use, although its relatively high impact energy seems inadequate for testing low-strength earthen mortars and most of the results obtained were below the lower bounds of the existing correlation curve;
- The pendulum hammer test was easy-to-use and caused no damage, however some limitations in the use, depending on the morphology of the surface, were found and a wide scatter in the results was found;
- Among the analysed NDTs, the scratch test was the least adequate due to difficulties in use, investigation limited to the very superficial layer of the mortar, dispersion of the results and limited adaptability to the condition found in irregular masonry.

As a final note, these procedures should be adapted to the peculiarities of the earth-based materials, by developing, through destructive testing on laboratory specimens, curves tailored to earth-based mortars. This aims to correlate the quantities measured directly by the devices with the compressive strength. Moreover, effective strategies to assess the superficial deterioration rate by non-destructive tests repeated over time would be valuable. This may be addressed by calibrating the NDTs on specimens subjected to controlled ageing in laboratory conditions.

CRediT authorship contribution statement

Laura Gambilongo: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Alberto Barontini:** . **Rui A. Silva:** Methodology, Resources, Writing – review & editing. **Paulo B. Lourenço:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Paulo B. Lourenco reports financial support was provided by Getty Foundation. Laura Gambilongo reports financial support was provided by Foundation for Science and Technology. ISISE-UM Institute for sustainability and Innovation in Structural Engineering reports financial support was provided by Foundation for Science and Technology.

Data availability

Data will be made available on request.

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