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COMBINED IN-SITU AND LABORATORY MINOR DESTRUCTIVE TESTING OF HISTORICAL MORTARS

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Abstract – Mortar is of all masonry components the most difficult to be experimentally characterised in heritage buildings. This paper investigates the possibility of combining different in-situ and laboratory minor destructive testing (MDT) techniques to assess the strength of mortar in historical brickwork. Lime mortar and clay brick walls were built in the laboratory and then tested in order to derive empirical correlation rules among three different MDT techniques: double punch test (DPT), helix pull-out test (HPT) and pin penetration test (PPT). The outcomes of this activity were used eventually to assess the mortar properties of an important historical heritage structure, Casa Puig i Cadafalch, located near Barcelona. The research is intended to promote the use of MDT in studies and conservation works on built cultural heritage by providing criteria for the evaluation of the strength of existing mortar with respectful sampling and testing techniques.

Keywords: Masonry, Lime Mortar, Minor Destructive Testing (MDT), Double Punch Test (DPT), Helix Pull-out Test (HPT), Pin Penetration Test (PPT), On-site Testing, Compressive Strength, Modernist Architecture, Puig i Cadafalch.

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1. Introduction

The conservation of the structures of the built cultural heritage requires the execution of adequate inspection techniques able to evaluate the mechanical properties of the existing materials. Experimental approaches are highly necessary in order to understand the current condition of the historical structure and plan optimal restoration measures. The experimental activities on historical construction are aimed at increasing the level of knowledge about the characteristics of the existing materials and the structural members (ISCARSAH 2003; Circolare 2 febbraio 2009). This knowledge is necessary to ascertain that the expected structural performance is attained by means of truly indispensable and minimal interventions. The inspection activities must respect the outstanding value of the historical structures and cause a minimum impact on the existing members and materials, as required by the administrators and owners of the built cultural heritage.

The research in the field of the inspection has evolved remarkably during the last years, with the development of several experimental techniques for a respectful characterisation of traditional materials. In the specific case of masonry materials, several testing options are possible (Binda et al. 2000; Bosiljkov et al. 2010). In-situ non-destructive testing (NDT) presents almost null invasiveness. The use of NDT benefits from correlation rules to estimate the physical properties of the materials from the non-destructive evaluation data (Cantini 2012). Minor Destructive Testing (MDT) is extensively used when the evaluation of the strength capacity of the historical materials is required. The growing interest in MDT techniques is due to the possibility of a direct evaluation of the material properties by only causing negligible damage to small or superficial portions of the historical structural member. In this way, repair interventions after MDT are usually minor or even unnecessary. MDT offers also the advantage of reduced costs in terms of instrumentation and time, both for tests on small samples in the laboratory and for in-situ experiments. A possible limitation of MDT could be the local representativeness of the test, since the investigated area is usually very small while the existing constructions often present significant spatial variability and heterogeneity in the material properties. However, this restriction can be overcome by the possibility of repeating easily the MDT on different portions of the existing building.

Reliable techniques are still necessary for the evaluation of the mechanical properties of historical mortars. Sampling and subsequent testing of existing mortar is definitely more challenging than executing the relevant activities on units (brick or stone blocks) due to the difficulties found in extracting non-disturbed specimens of mortar. Difficulties in mortar characterisation are also due to the small thickness of mortar joints, which makes impossible the extraction and testing of the normalized prismatic samples proposed by the standards for new construction (CEN 2007; Drdácký 2011). The MDT techniques at the conservators' disposal can be subdivided into two categories: i) laboratory experiments on small samples extracted on site and ii) in-situ experiments executed directly on the structural components.

As for the historical mortars, recent works about the first category of MDT have proposed the use of the Brazilian tests on small core samples obtained from existing brickwork in combination with the Double Punch Test (DPT) of on-site extracted mortar joints (Pelà et al. 2017, 2016a, 2012; Marastoni et al. 2016a). The DPT is actually a destructive experiment carried out in the laboratory. However, it can be considered as MDT given the small size of the tested mortar joint samples. The DPT is a direct method that becomes feasible whenever it is possible to disassemble some small portions of the existing brickwork or extract some small samples of mortar from hidden parts of the existing masonry, without damaging excessively the structure. Undamaged mortar slabs for DPT can be extracted from cylindrical core samples, drilled from the existing masonry. The core samples can be extracted so that they include a diametric mortar joint confined by two cylindrical segments of brick. The strength values obtained from DPT on joints are usually higher than the actual uniaxial compressive strength of mortar due to the flatness of the specimens and the consequent confinement exerted by the loading punches. The total area of the specimens is typically 50 × 50 mm^2, whereas the loading area is determined by the 20 mm diameter loading punches normally utilized (Henzel and Karl 1987; DIN 18555-9:1999; International Union of Railways 2011).

The second category of MDT techniques for the evaluation of historical mortars includes in-situ experiments executed with portable instruments. These tests can be easily carried out on the site of the construction, are minimally invasive and induce negligible damage to the investigated structure. They offer an interesting option due to the limited cost and the easy repetitiveness of the measurements for a reliable statistical evaluation. The in-situ devices can consists of penetrometers measuring indirectly the compressive strength of the material through empirical correlations with physical magnitudes, such as the ultimate torque necessary to rotate a toothed nail hammered into the mortar joint (Christiansen 2011; Marastoni et al. 2016b), the rebound height of a calibrated mass hitting the investigated material surface (Van Der Klugt 1991), the energy spent to make a standard hole of prescribed dimensions and depth (Gucci and Barsotti 1995, 1997; de

Vekey and Sassu 1997). Several available in-situ tests for historical mortars are conceptually similar to those used for soil investigation and actually constitute ad-hoc readjustments of the dynamic penetration test (Felicetti and Gattesco 1998; Liberatore et al. 2001), the static penetration test (Liberatore et al. 2016), and the vane test (Christiansen 2011; Marastoni et al. 2016b). These improved versions of available geotechnical experiments offer also the possibility of overcoming a common problem of in-situ MDT devices, i.e. the superficial evaluation of mortar properties. In fact, they can provide measurements of mortar characteristics within deeper portions of the masonry structural member.

Two available penetrometric MDT techniques have presented limited application to historical mortars so far, probably due to the lack of reference calibration studies for low strength materials. The Helix Pull-out Test (HPT) is a technique based on the measurement of the force required to extract a helical device stuck into the material with a prescribed depth. The 6 mm diameter helical tie is hammered into a prepared hole and then extracted using a screwed gripper and a proof loading device (de Vekey 1991; de Vekey and Sassu 1997; Ferguson and Skandamoorthy 1994; Binda et al. 1997). The Pin Penetrometer Test (PPT) is commercially known as Windsor probe. It estimates the strength from the depth of penetration of a 3 mm diameter metal rod driven by a sudden charge of powder in case of cement based materials. In case of mortar, the use of a spring-loaded device is sufficient to drive a steel pin into the material. The pin strikes the test material and leaves an indentation. A depth gauge (micrometer) measures the depth of penetration, which is inversely proportional to the mortar compressive strength.

This paper presents the results of two experimental programs based on the combination of different MDT techniques for the evaluation of the strength properties of historical mortars.

The first experimental program was carried out at the Laboratory of Technology of Structures and Construction Materials of the Technical University of Catalonia (UPC-BarcelonaTech). Masonry walls were built using clay bricks and two different types of natural hydraulic lime mortar. These components were chosen on purpose to investigate the material traditionally used in the historical construction. The mortar properties in the two series of walls were evaluated by considering DPT, HPT and PPT for different ages of hardening of lime mortar, in order to investigate different strengths of the material. The experimental results were critically compared in order to derive experimental correlations among the investigated MDT techniques for the typical ranges of strength of historical mortars.

The second experimental program was carried out on a real case study consisting of a Modernist building, Casa Puig i Cadafalch, located in Argentona, near Barcelona, Spain. The results derived from the previous calibration experiments were considered to evaluate the strength of the different types of mortar used in the construction of the building. The combined use of different MDT techniques, such as in-situ HPT and PPT and DPT on small mortar samples extracted on site, showed the potential of the investigated MDT techniques and the possibilities for their improvement and further calibration. The three methods provided a good compromise between limited invasiveness and statistically acceptable experimental measurements. The results of the research could be useful for the studies on diagnosis, preventive conservation and maintenance of historical masonry structures. In fact, the correlation of the results of slightly destructive tests could be used for the evaluation of the quality and decay of existing mortars, but also for the control of new repointing mortars.

The paper is organized as follows. After the Introduction, Section 2 presents the experimental program carried out in the laboratory with details on the materials used, the construction of the reference specimens, the results from the DPT, the PPT and HPT techniques and the obtained empirical correlation rules. Section 3 presents the application of the DPT, the PPT and HPT within the inspection activities of Casa Puig i Cadafalch. Section 4 presents the critical discussion of the experimental results derived from the two campaigns. Finally, some conclusions are presented about the applicability of the investigated MDT methods.

2. Experimental Program in the Laboratory

The experimental investigation was carried out at the Laboratory of Structural Technology and Building Materials of the Technical University of Catalonia (UPC-BarcelonaTech). This section presents the construction of the wall specimens and the experimental setups. A comparison of the results obtained for both standard and MDT tests is also presented.

2.1 Construction of specimens

Two series of small walls were built in stretcher bond with dimensions (width × height × depth) 0.69 × 0.42 × 0.145 m^3 (Figure 1a). Each wall was composed of seven courses and was two brick wide. All the walls were built with handmade fired-clay solid bricks with nominal dimensions of 305 × 145 × 45 mm^3. The thickness of the joints was variable around 15 mm, due to the irregular exterior faces of the handmade bricks. Each of the two series of walls had a different type of mortar in the joints. The first mortar type, denoted by the abbreviation KK, was premixed by the manufacturer by using pure natural hydraulic lime and aggregates with granulometry 0 ÷ 2.5 mm. The second mortar type, denoted as CT mortar, was mixed in the laboratory using the raw components, i.e. natural hydrated lime powder and river sand with granulometry 0 ÷ 2 mm. Both KK and CT mortars were natural hydraulic lime mortars (NHL), classified as NHL 3.5 according to the criteria established by EN 459-1:2010 (CEN 2010). These two materials were employed in the construction of the samples in order to obtain a realistic representation of a historical masonry with low-strength properties. The volume ratio of binder to aggregate was 1:3 in both mortars, since this is a rather typical mix in historical brickwork.

The mortars were tested at different ages of hardening in order to investigate different strength values during the setting of the material in the laboratory. Four walls with mortar KK were tested respectively at about 6, 13, 23 and 35 days from their construction, whereas three walls with mortar CT were tested respectively at about 14, 28 and 61 days from their construction.

2.2 Compression and Flexure Tests on Standard Prismatic Specimens

The strength properties of the two mortars were characterised in a first stage by using the standards for new construction. Prismatic mortar specimens were prepared with metal moulds during the construction of the two series of walls (Figure 1b). Standard flexure and compression tests were carried out on this kind of specimens according to EN 1015-11:2007 (CEN 2007). Three prisms with dimensions 40 × 40 × 160 mm^3 were tested at different hardening ages to obtain the flexural strength f_f of mortar CT and KK (Figure 2a). The compressive strength f_c of each type of mortar was determined by loading the six fragments produced by the flexure tests, measuring roughly 40 × 40 × 80 mm^3, with steel loading platens of 40 × 40 mm^2 (Figure 2b). Both the flexure and compression tests were conducted under load control with a compression machine with a loading cell of 10 kN.

The experimental results on prismatic specimens of KK and CT mortars are summarized in Table 1 in terms of average values and coefficients of variation (CV). Figure 3 shows the graphs with the time evolutions of the average values of flexural and compressive strengths. Both strength evolutions look consistent throughout the time, i.e. an increase/decrease of the compressive strength corresponds to an equivalent trend for the flexural strength. Mortar KK presents a faster increase of strength than mortar CT, since the former is a premixed mortar for restoration with fast hardening and the second is a standard lime mortar obtained from raw materials and thus requiring longer time for curing (Pelà et al. 2017, 2016b; Baronio et al. 1999, 1995). At the age of 23 days, the specimens of mortar KK exhibited local peak values of compressive and flexural strengths that then decreased at 35 days. On the other hand, mortar CT showed a slow and monotonic increase of the compressive and flexural strengths for the different investigated ages.

2.3 Double Punch Tests on Joints Samples Extracted from the Walls

Some courses of the walls were disassembled with the help of a chisel to extract mortar joints for the execution of the DPT at different ages of hardening (Figure 4a). The mortar layers between the units were cut into 50 × 50 mm^2 joint specimens (Figure 4b) having variable thickness around 15 mm. The tests were performed under load control using a compression machine with a loading cell of 10 kN and with loading punches of 20 mm diameter (Figure 4c).

Older references about the DPT (Henzel and Karl 1987; International Union of Railways 2011; DIN 18555-9:1999) suggest to level the surfaces of the mortar sample with 1 mm thick gypsum plaster in contact with the loading punches. This approach was not followed in this research since previous works by the authors showed that this regularisation technique could produce a considerable increase of the strength measured for low-strength mortar samples (Pelà et al. 2016c). In any case, the mortar joints were tested in this research making sure that their loaded surfaces were plane and parallel with intact edges (Marastoni et al. 2016a). After the DPT, the samples showed a crushed central part in-between the loading punches as well as radial cracks towards the exterior perimeter (Figure 4d).

Table 2 shows the strength values from DPT in terms of average values and coefficients of variation (CV) for the two types of mortar. As expected, the DPT strengths resulted higher than the compressive strengths from standard prismatic samples, due to the different sizes and different setting conditions of the mortar samples in the two tests.

It must be remarked that, in fact, the setting conditions of the prismatic mortar samples are very different to those of the mortar joints in masonry walls. After being extracted from the metal moulds, the first are exposed to the laboratory interior environment during the rest of the hardening time. The second remain embedded in the masonry joints and are therefore in contact with porous clay bricks, with very little surface directly exposed to the environment. In the case of lime mortars, these different setting conditions produce, in fact, two distinct mortar types with differentiated mechanical properties. Therefore, the normalized test on prismatic samples can hardly be used to characterize in a reliable way the mechanical properties of the mortars extracted from mortar joints. Because of it, the DPT is regarded as a more appropriate way of determining a representative compression strength for the mortar masonry mortar joints.

Figure 5 shows the graphs with the time evolutions of the average values of the DPT strengths. Both mortar KK and CT show a monotonic increase of the strengths for the different investigated ages, even though the former presents a higher rate and the latter a much slower one. DPT strengths of mortar KK did not show any anomalous peak, as opposite to what was observed for the compressive and flexural strengths in standard prismatic specimens (Figure 3).

2.4 Screw (Helix) Pull-out Tests on Mortar Joints

The HPT was carried out on the bed joints of some walls. The tests were executed at the same ages of the DPT for both the two series of walls with mortars CT and KK. Both the provider of the apparatus and available studies (de Vekey 1991; de Vekey and Sassu 1997; Ferguson and Skandamoorthy 1994; Binda et al. 1997) suggest, prior to executing the test, to drill a pilot hole of 4 ÷ 4.5 mm diameter in the middle of the thickness of the mortar bed joint. A smaller diameter pilot hole of 3 mm was considered in this research since previous studies by the authors showed that a 4 mm diameter pilot hole could reduce considerably the magnitude of HPT readings and also the sensitivity of the instrument to low variations of resistance in low strength mortars (Pelà et al. 2016c). The choice of a 3 mm pilot hole diameter provided unbiased experimental results, at least for the case of pure lime mortar without cement.

The test procedure utilized in this research is as follows. A high-strength steel helical tie with a diameter of 6 mm is mounted into a driving tool. Holding the sleeve of the tool horizontal, the exposed end of the tie is pushed into the pilot hole to a depth of 30 mm. Using the sleeved driving tool, the helical tie is hammered carefully into the pilot hole so that the specified length of its thread is embedded in the mortar. This procedure allows the tie to rotate and cut a thread in the mortar during insertion. After installation, a gripper is then screwed onto the end of the tie. This holds the tie fixed during the test, restraining it from rotating, ensuring a shear failure in the tested material. The loading device is then attached to the gripper and the assembly was rotated to screw down the tie and take up any slack. The reaction frame, constituted by a steel ring, provides the contact with the material's surface. The load applied to the tie is increased steadily until failure. The peak load reached during each test is recorded as the pull-out force. Figure 6 shows the test arrangement as well as the sequence of the operations followed during the HPT.

Table 3 reports the average values of pull-out forces measured on CT and KK mortar bed joints at the different investigated ages. Figure 7a shows graphically the time evolution of the HPT pull-out forces. KK mortar shows an increasing trend of HPT results in agreement with that of DPT strength observed in Figure 5. CT mortar presents lightly increasing values of HPT pull-out forces for the investigated ages, similarly to the very slow rate of increase of DPT strengths. Figure 7b shows the empirical relationships between DPT and HPT measurements for the two types of mortar. These curves show the capability of the HPT to represent the monotonically increase of the DPT strength of the mortars in the bed joints.

2.5 Windsor Pin Penetration Tests on Mortar Joints

The PPT was executed only on the series of walls built with KK mortar. Figure 8 shows the sequence of operations followed during the development of the experimental tests. In the PPT test utilized, a 3 mm diameter and 30.5 mm long pin is inserted into the chuck. The loading nut is tightened, until the trigger mechanism latch closes to hold the spring in place, and then it is completely slackened to the top of the load screw before pulling the trigger. The instrument is placed perpendicularly to a smooth flat surface of the bed joint to be tested (Figure 8a). The trigger is pulled, holding the instrument firmly against the mortar surface (Figure 8b). Once the instrument is removed, a rubber bulb-type blower is used to clean out the small hole made by the pin on the material surface (Figure 8c). A micrometer is then inserted into the indentation left by the pin, making sure that the reference surface of the micrometer for the measurement is flat on the surrounding material (Figure 8d). The micrometer reading is noted. The penetration is obtained by subtracting the reading from one inch (25.4 mm).

Table 4 reports a summary of the experimental results from PPT in terms of average values of pin penetration depths and coefficients of variation obtained at the different ages. The depth of penetration decreases as the mortar hardens and its strength increases (Figure 9a). Figure 9b shows the empirical relationship between PPT readings and DPT strengths at the investigated ages of mortar KK. The MDT technique provides clear and distinct measurements corresponding to the different investigated DPT strengths.

3. Case Study: Casa Puig i Cadafalch (Argentona, Barcelona)

The comparisons obtained in Section 2 between the mortar strength values obtained by DPT and the MDT measurements were considered as reference results in the study of an important Modernist heritage building.

Casa Puig i Cadafalch is located in Argentona, near Barcelona. It was built as the summer house of the architect Josep Puig i Cadafalch (1867-1956), one of the most important representatives of the Modernist architecture in Catalonia. He built the house between 1897 and 1905 as a remodeling of an existing complex composed of three different buildings. With a labyrinthine interior and a style of medieval influence, its rooms and exterior façades are decorated with Modernist architectural elements (Figures 10a-c). It was included in the national cultural heritage list in 1993.

The building is currently under restoration due to the deterioration problems experienced during the last years. Different concerning problems had occurred, such as the collapse of the pavilion of the perimeter walls and of several merlons of the roof parapet (Figure 10b). The planning of the necessary restoration and retrofit interventions required a previous experimental activity with field tests in order to assess the mechanical properties of the existing materials. A particular attention was devoted to the assessment of the strength of the existing mortar. This assessment was of special importance in order to understand the residual capacity to wind actions of the merlons and other decorative elements. The assessment of the mortar strength was also important in order to evaluate the load bearing capacity of the masonry walls. Due to the heritage value of the building, different MDT techniques were applied in order to limit as much as possible the damage on the existing structural members.

Several merlons had fallen down due to the considerable wind actions and the heavy deterioration of the lime mortar in the joints. Some others were disassembled to avoid possible collapse, whereas those showing excessive deformation required urgent propping (Figure 10d). MDT was applied on some merlons that were disassembled, stored and intended to be reconstructed during the restoration works of the house.

DPT was executed on bed joint samples brought to the laboratory (Figure 11a). Due to the irregular faces on the extracted mortar joints, gypsum powder was used for surface regularization. This novel approach was adopted as an alternative to gypsum plaster which had showed to be inappropriate for lower strength mortars, as already commented in Section 2.3. HPT was carried out directly on the mortar joints of the merlons (Figure 11b). Table 5 shows a summary of the DPT and HPT results. Two different types of mortar were detected in the merlons, differing in colour, i.e light grey and dark grey. This basic distinction of the two types of mortar, based on different visual appearances and colours, was later confirmed by the subsequent experimental tests. The light grey mortar provided a DPT average strength of 1.70 MPa, whereas the dark grey mortar gave higher values of 5.45 MPa, see Table 5. The HPT provided average pull-out forces of 248 N for light grey mortar and of 858 N for dark grey mortar. The comparison of these values with the DPT vs. HPT relationships of Figure 7b, referring to the laboratory experimental program presented in Section 2, shows very good agreement.

Without the permission of extracting mortar samples from the interior walls, only in-situ HPT and PPT were executed on bed joints. Four small "windows" were opened in few interior walls by removing just the superficial plaster, in order to induce negligible damage to the existing structural members (Figures 11c-d). Being the Casa Puig i Cadafalch the result of the transformation of three pre-existing buildings, the testing points were selected in order to investigate the different parts of the complex and to understand the corresponding properties of the different mortar materials. The mortar exhibited a brownish colour at the ground floor and at the first floor (Figure 11d), whereas in another position at the first floor and at the second floor the mortar was light grey. Table 6 presents a summary of the HPT and PPT results at the different locations. The HPT provided average measures between 275 N and 654 N, whereas the PPT provided average measures between 13.6 mm and 10.7 mm. A tentative extrapolation of the equivalent DPT strength of mortars in the interior walls could be done by comparing these ranges of values with the DPT vs. HPT and DPT vs. PPT relationships of Figure 7b and Figure 9b. As for the HPT values, the empirical correlations of Figure 7b would suggest DPT strengths ranging between 1.1 MPa and around 4 MPa. As for the PPT values, the obtained measurements fall outside the correlation shown in Figure 9b. However, this correlation can be considered to conclude that the range of obtained mortar DPT strengths is in any case lower than 4 MPa.

4. Discussion of the results from laboratory and in-situ MDT

The laboratory experimental program presented in Section 2 provided useful correlations between different MDT methods for two different types of mortar. The execution of flexural and compressive tests on prismatic samples is the standard technique commonly adopted for the new construction. However, these type of specimens can rarely be tested for the evaluation of the existing properties of historical mortar in real structures. For this reason, DPT was also carried out on mortar joints obtained from the disassembly of the walls previously built in the laboratory. The time evolutions of compressive strengths of prismatic mortar specimens and DPT strengths of mortar joints resulted different due to several reasons. First, both the ambient exposed surfaces of the specimens and the materials in contact with mortar were different during the setting. In specific, the materials in contact with mortar were the steel walls of the moulds for the prismatic specimens and brick faces for the joint samples. Second, the water content of mortar material into the steel moulds was different to that of the same mortar in-between wet bricks during the construction of the wall. Third, the experimental strength values from compressive tests on prismatic samples and from DPT were also different due to the different slenderness of the specimens, resulting in a different confinement exerted by the loading platens. Due to the aforementioned issues, the experimental strengths from compressive tests on prismatic samples and from DPT are hardly comparable. It must be emphasized that, due to the very different curing and water content conditions, conventional samples produced by means of steel moulds cannot be used reliably to determine the actual mechanical properties of lime mortar in the masonry mortar joints. The DPT test was deemed as more reliable for that purpose. The disagreement between both test types should be further investigated by considering additional mortar types and mortar curing conditions.

The DPT exhibited a monotonic increase of the strength with time in the two mortar series, providing a clear representation of the evolving properties of the material in the joints. In this way, it was possible to compare different DPT strengths with the corresponding readings of two different MDT techniques based on a penetrometric system. Both the HPT and PPT showed to be capable of capturing the variations of strength in the two series of mortar at the different investigated ages. The measurements, pull-out force for HPT and penetration depth for PPT, were clearly distinguishable and well correlated to the gradual increase of the mortar strength. The present research considered a 3 mm diameter pilot hole in the HPT since previous works demonstrated that higher diameters of the pilot hole are excessive for low-strength mortars (Pelà et al. 2016c). The PPT showed to be sufficiently reliable in the format proposed by the provider without requiring any substantial improvement.

The experimental program in the laboratory provided helpful empirical relationships among DPT, HPT and PPT, but the obtained correlations did not cover directly the ranges of DPT strengths between 1.2 MPa and 4 MPa, and beyond 7 MPa. For this reason, future research is necessary to extend the experimental database and cover a greater range of strengths allowing more reliable calibration curves. However, the results obtained in this research can be considered as possible reference. Intermediate ranges of strength not directly investigated could be indirectly extrapolated based on the obtained results.

The experimental program carried out in the Casa Puig i Cadafalch (Section 3) provided a clear picture of a possible application of different MDT techniques to a real case study. DPT was carried out on mortar joints extracted from the merlons of the roof parapet. Due to the damage shown by the merlons, they were intended to be disassembled and then reconstructed. The irregularities of the mortar samples required a special treatment prior to the DPT test. This research proposed the use of gypsum powder for the surface regularization of the mortar joints for DPT, as an alternative to the gypsum plaster regularization suggested in previous works (Henzel and Karl 1987; International Union of Railways 2011; DIN 18555-9:1999) that showed to be inappropriate for lower strength mortars (Pelà et al. 2016c). HPT on the bed joints of the merlons provided values of pull-out forces fairly consistent with the measurements obtained in the laboratory program presented in Section 2 with similar mortar strengths. The HPT technique was able to recognize the difference in strengths of the two types of mortar found in the merlons. The same capability was demonstrated by both HPT and PPT in the experiments conducted on the different types of mortar found in the interior walls of the building. The measurements with the two different instruments showed to be always consistent since a higher value of the pull-out force of the helix always corresponded to a lower penetration depth of the pin.

Figure 12 shows a summary of all the HPT and PPT measurements obtained from this combined laboratory and in-situ experimental research. The graph of pull-out force vs. penetration depth shows that there exists an intrinsic relationship between the two different testing systems. This result shows that their combined use in the evaluation of existing mortars allows a mutual control of the quality of the experimental results.

The correlation of the different results of slightly destructive tests for the evaluation of the mortar quality can be useful in the diagnosis of existing building. The obtained information can be used for the evaluation of the mortar characteristic and decay, but also for the control of new repointing mortars. A further aim of the in-situ testing of mortar could be related to the evaluation of the strength of masonry, theoretically possible by applying empirical equations (Lourenço and Pina-Henriques 2006; Drougkas et al. 2015; Pelà et al. 2016b) once quantitative data on constituent materials (mortar and unit strengths) are available. Actually, reliable relationships for historical masonry are still under investigation.

A possible limitation of the investigated MDT techniques can be found in the fact that they only allow a superficial evaluation of the properties of mortar joints. This problem is more important for HPT and PPT in-situ techniques, whereas for DPT it can be overcome by extracting the joint from masonry core samples drilled deeply into the structural members (Pelà et al. 2017, 2016a, 2016b; Marastoni et al. 2016a). Natural environment processes cause decay mostly at the more exterior (superficial) portion of the mortar joints. Moreover, the superficial portion of mortar joints is often repointed as a sort of maintenance intervention. Due to these problems, testing the outer portion of the joint may not give, in some cases, a correct indication of the quality of the mortar existing inside the mortar joint. However, the load bearing capacity of the structural member is mostly determined by the mortar located in the interior of the mortar joint. This important limitation should certainly be taken into account when correlations are used to estimate the mortar strength from MDT results on the exterior portion of mortars. In some cases, removing the superficial mortar thickness and carrying out the MDT on a more interior portion may be feasible. In any case, a previous chemical analysis on the condition and nature of the superficial mortar may help to characterize its conditions and representativeness.

Another possible limitation of the investigated MDT techniques may be the high scatter of the experimental results. In the analysis of Casa Puig i Cadafalch, for instance, a very high coefficient of variation of HPT for light grey mortar was obtained (47.8%, see Table 5). This result may be due to the intrinsic scattering of this type of mortar, along with possible superficial deterioration. It must be noted that the merlons where the mortar was found had been damaged by the environmental actions. The comparison with DPT on mortar slabs extracted from the interior of the joint could help in improving the quality and reliability of the experiments. This experience shows the importance of conducting a step-by-step experimental procedure including several techniques, in which preliminary in-situ MDT evaluations can be conveniently integrated with more direct experiments whenever they do not exhibit acceptable reliability. In case of excessive scattering of MDT data, and without the possibility of cross-relating experimental data from different tests, it is however advisable to avoid using the few scattered results to feed the predictive equations of the masonry strength to assess the safety of an existing building.

5. Conclusions

This paper has presented two experimental programs aimed at investigating the applicability of three different MDT techniques for the evaluation of the strength of historical mortars. The DPT is a destructive method executed in the laboratory on small mortar joint samples, whereas HPT and PPT are based on penetrometric systems and can be carried out on the site of the existing building. The results obtained with the three techniques have been compared in order to obtain tentative correlations allowing the estimation of the mortar compressive strength. However, additional research on a wider variety of mortar types and qualities would be necessary to obtain more general empirical correlations fully applicable to historical mortars.

The research was subdivided into two stages. The first one consisted in carrying out the different tests on small walls built in the laboratory by using hand-molded solid clay bricks and hydraulic lime mortar without cement. This material combination was purposely chosen in order to replicate a possible historical masonry in the laboratory. The DPT, HPT and PPT were executed at different hardening ages of two types of mortar in order to obtain representative results for different strength values. The comparison of the test results allowed the derivation of experimental correlations between the three different tests.

It has been observed that the MDT results are not directly comparable with those provided by standard compression tests on normalized prismatic samples. The main reason for the disagreement between both is attributed to the different setting conditions and moisture content experienced by the prismatic samples in comparison with the mortar joints embedded in masonry walls. After being removed from the metal moulds, and during the setting period, the first expose a much larger surface to the laboratory ambient conditions compared to the second. This specific issue certainly deserves further investigation oriented to better characterize the influencing factors and to improve the laboratory protocols for the preparation, storage and testing of the specimens.

The second stage of the research consisted in the application of the MDT techniques to a real case study consisting of a Modernist heritage building, namely Casa Puig i Cadafalch located in Argentona, near Barcelona. The three MDT techniques provided experimental measurements in good agreement with those previously obtained in the first stage calibration experiments with mortars of similar strength properties. The combined use of different MDT methods constituted a suitable experimental framework in which different types of results could be mutually compared in order to control the correctness of the results. DPT revealed to be an appropriate direct method to assess the mortar strength when there is the possibility of disassembling small members or extracting small samples from the existing building. HPT and PPT, despite their so far limited application to masonry structures, probably due to lack of reference studies, showed to be simple but effective tools for the quick in-situ evaluation of the existing mortar when only negligible damage is allowed in the structure during the inspection. Both the HPT and PPT were able to distinguish different types of mortar by capturing on-site the spatial variability of the mortar strength properties. This feature is extremely important in heritage masonry buildings since they often include additions from different construction stages using different combinations of materials.

The investigated MDT techniques are simple, rather cheap and of quick execution either in the laboratory (DPT) or in-situ (HPT and PPT). These characteristics make them suitable to obtain statistically acceptable experimental datasets involving a sufficient number of measurements.

The results presented in this paper could be easily extended in the future with further calibration data covering a greater range of mortar strengths.

6. Acknowledgments

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Tables

Table 1 – Average flexural and compressive strengths of standard prismatic specimens of mortar.

Standard tests	Mortar CT			Mortar KK			
Age (days)	14	28	61	6	13	23	35
Average f_f (MPa)	0.28	0.47	0.61	0.86	1.25	1.88	1.54
CV %	10.3	6.7	13.7	5.7	16.8	5.3	1.7
Average f_c (MPa)	0.61	0.97	1.10	1.71	2.99	3.91	3.07
CV %	6.5	13.8	4.4	7.9	8.8	10.7	11.0

Table 2 – Average strength values obtained from double punch test on mortar joints.

DPT	Mortar CT			Mortar KK			
Age (days)	14	28	61	6	13	23	35
Average f_f (MPa)	0.96	1.12	1.22	3.97	5.25	5.85	6.97
CV %	23.3	31.0	42.2	23.3	22.2	23.0	24.6

Table 3 – Average values of helix pull-out forces.

HPT	Mortar CT			Mortar KK			
Age (days)	15	30	63	6	13	23	35
Average F (N)	264	277	279	544	800	992	1050
CV %	33.3	20.3	30.5	21.3	13.7	9.2	19.2

Table 4 – Average pin penetration depths obtained by Windsor system.

PPT	Mortar KK			
Age (days)	6	13	23	35
Average d (mm)	10.2	8.6	7.3	6.7
CV %	11.7	13.1	11.7	14.4

Table 5 – Casa Puig i Cadafalch: results from minor destructive testing of the merlons.

MDT	Measurements	Light grey mortar	Dark grey mortar
DPT	Average f (MPa)	1.70	5.45
	CV %	17.0	29.0
HPT	Average F (N)	248	858
	CV %	47.8	15.8

Table 6 – Casa Puig i Cadafalch: results from minor destructive testing of the interior walls.

MDT	Measurements	Ground floor	First floor-a	First floor-b	Second floor
HPT	Average *F* (N)	275	506	438	654
	CV %	19.4	30.9	32.2	21.1
PPT	Average *d* (mm)	13.6	12.1	12.7	10.7
	CV %	3.1	5.4	6.2	6.3

Figures

Figure 1 – Construction of walls for the experimental program in the laboratory (a) and preparation of standard prismatic specimens of mortar in steel moulds (b).

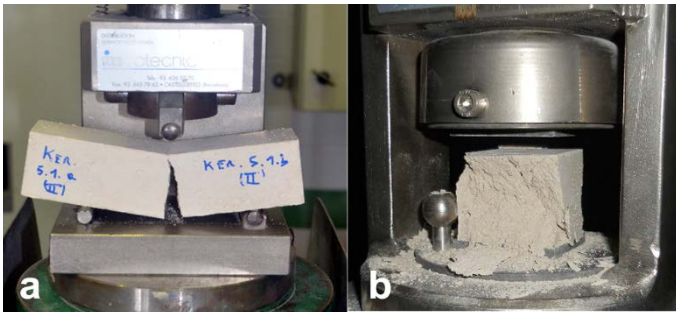

Figure 2 – Flexure (a) and compression (b) tests on standard prismatic specimens of mortar.

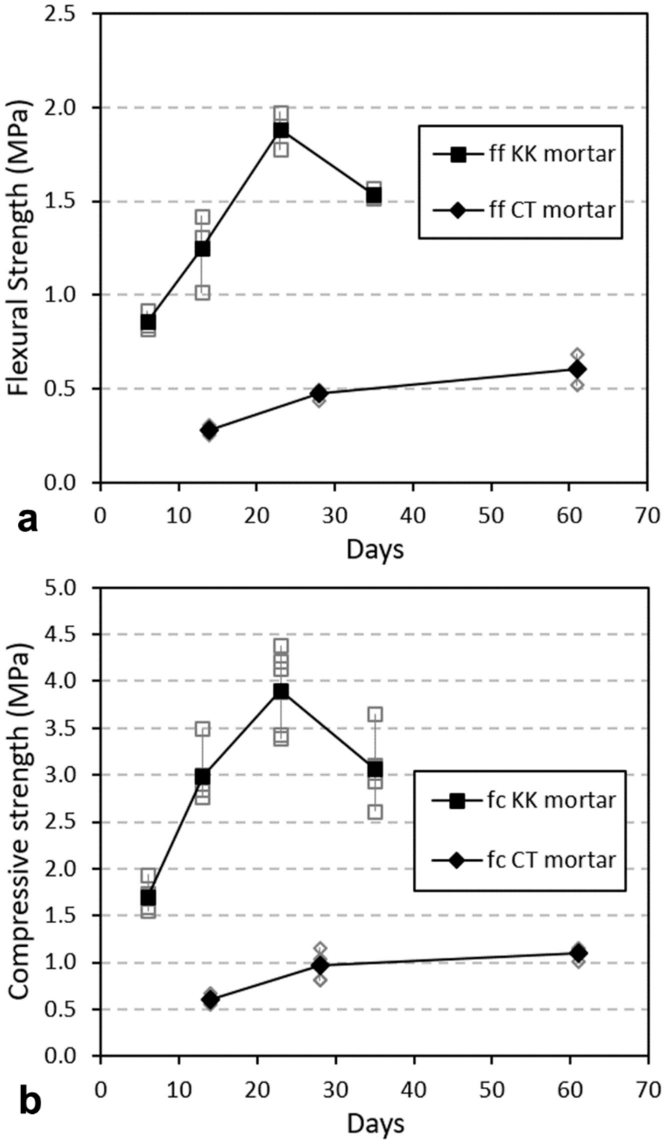

Figure 3 – Time evolution of average flexural strengths (a) and compressive strengths (b) of standard prismatic specimens of mortar.

Figure 4 – Extraction of mortar layers from the walls (a), cutting of joint specimens for double punch test (b), experimental setup (c) and typical failure after the test (d).

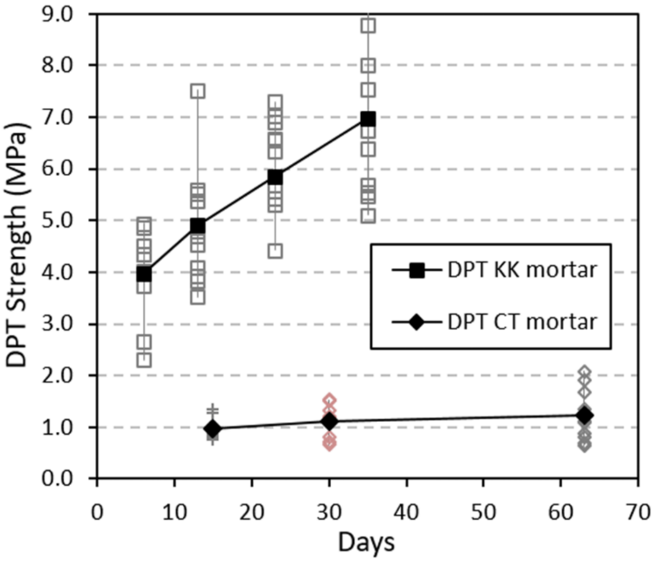

Figure 5 – Time evolution of double punch test strengths of mortar joint samples extracted from the walls.

Figure 6 – Operation of the screw (helix) pull-out test: drilling the pilot hole (a), insertion of the helix into the bed joint using the sleeved driving tool (b), helical ties ready for extraction (c) and pull-out with the loading device (d).

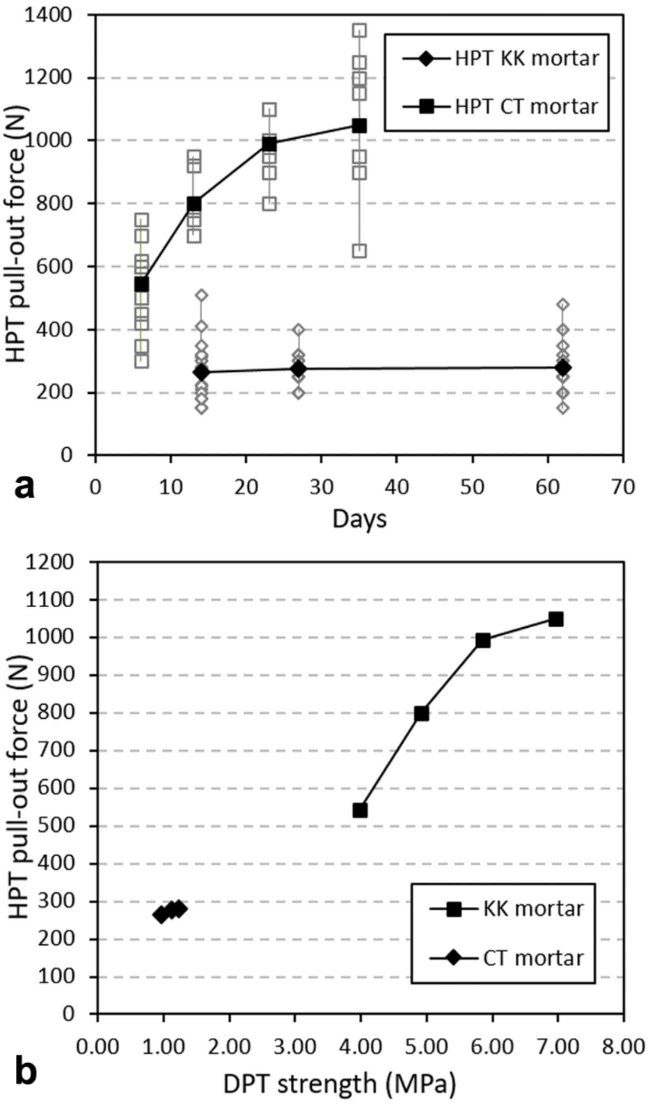

Figure 7 – Time evolution of helix pull-out forces (a) and empirical relationships between double punch test strengths and helix pull-out forces (b).

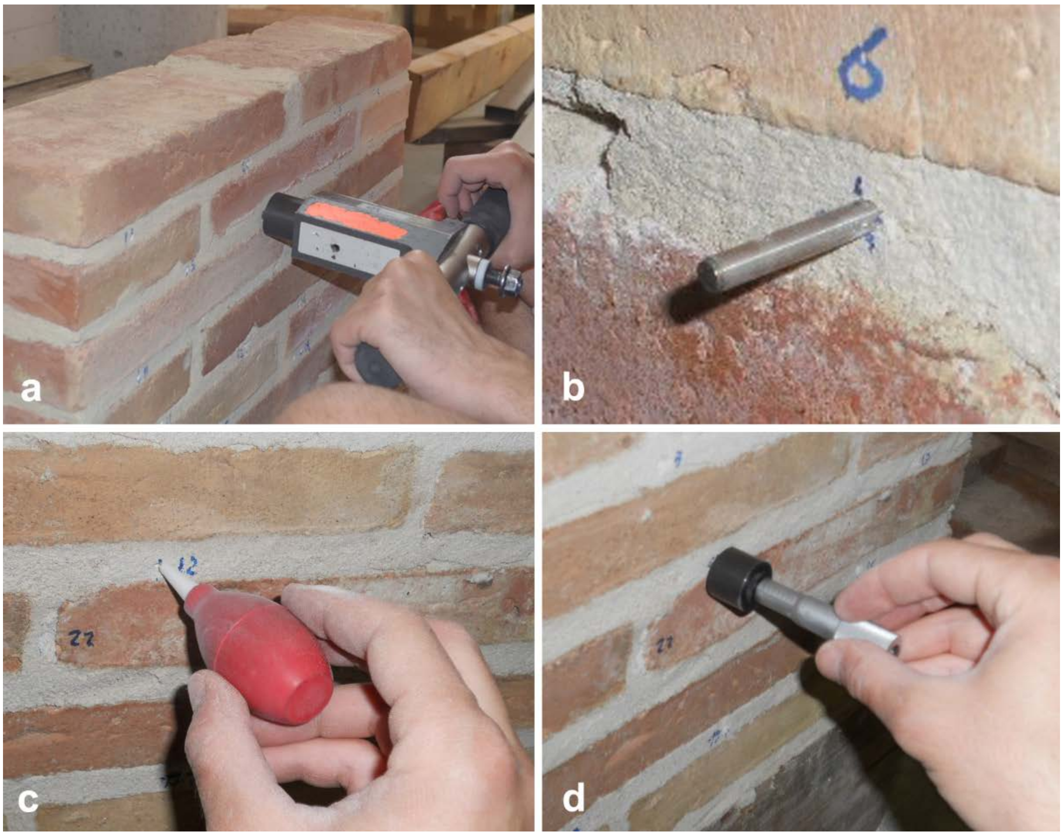

Figure 8 – Operation of the Windsor pin penetration test: instrument for pin insertion (a), pin penetrated into the mortar joint (b), cleaning of the indentation produced by the pin (c) and micrometer for depth measurement (d).

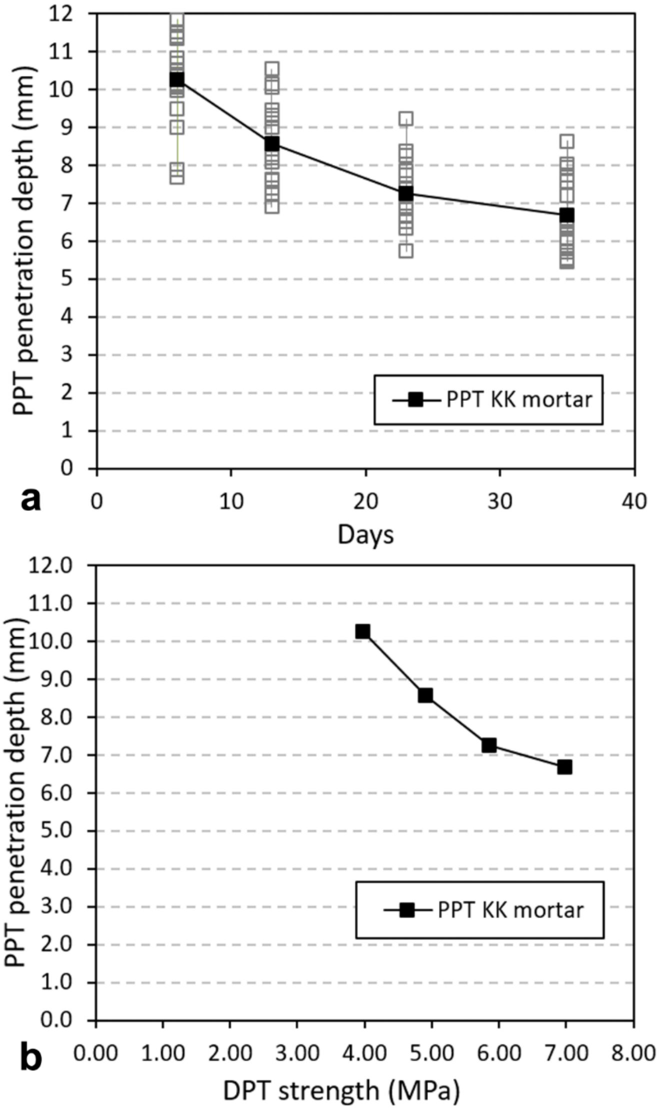

Figure 9 – Time evolution of the penetration depths obtained from the Windsor pin penetrometer (a) and empirical relationships between double punch test strengths and pin penetration depths (b).

Figure 10 – Casa Puig i Cadafalch in Argentona, Barcelona: exterior view before (a, copyright ArteHistoria) and after the collapse of the pavilion and the merlons (b), view of the interior (c) and emergency propping of deformed merlons (d).

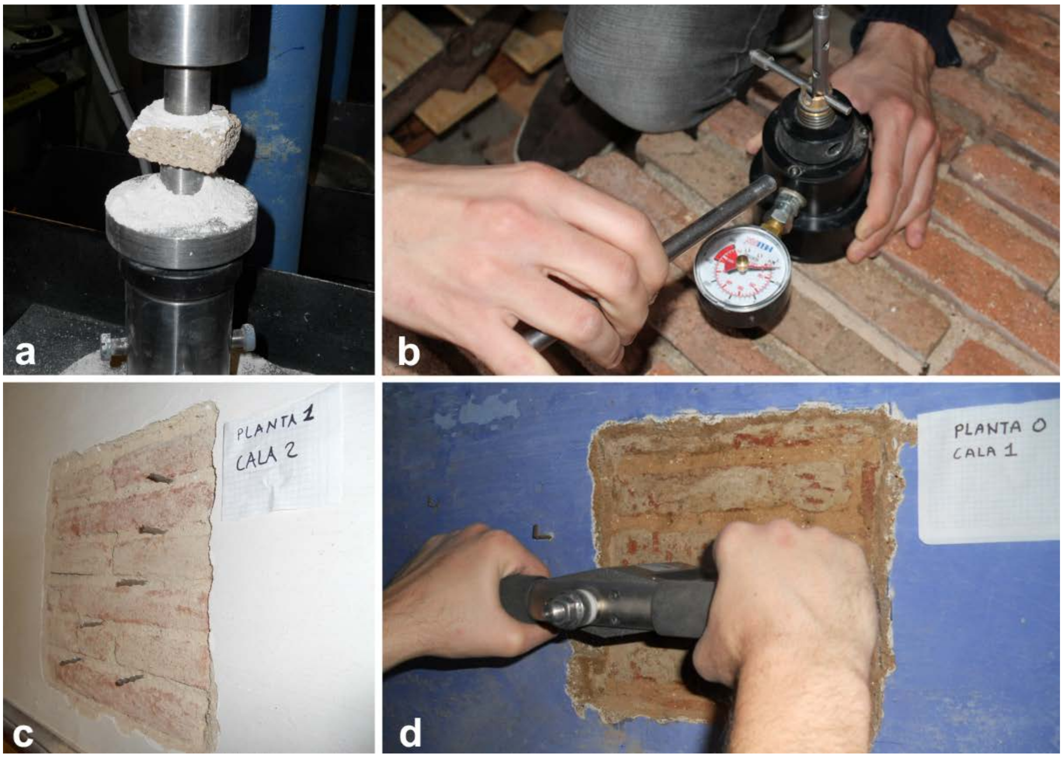

Figure 11 – Minor destructive testing of historical mortars in Casa Puig i Cadafalch: double punch test on mortar joints extracted from the merlons (a), helix pull-out test on the joints of the disassembled merlons (b), helix pull-out test (c) and pin penetration test on joints of the interior walls (d).

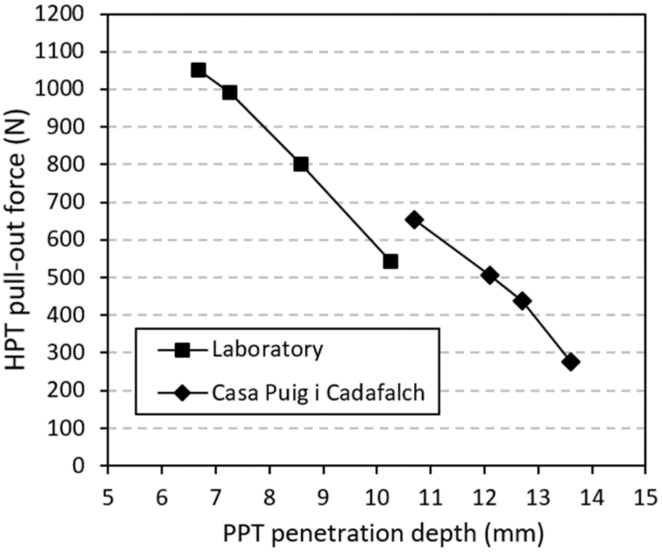

Figure 12 – Helifix pull-out force vs. Windsor Pin penetration depth: correlation obtained from the experimental programs in the laboratory and in Casa Puig i Cadafalch.