Characterization of Mortars Using DRMS: Tests on Field Panels Samples

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Abstract Non-destructive or micro-destructive *in situ* tests are very relevant to the physical characterization of materials used in historical buildings. "Controlled penetration," "sphere shock," and "sonic methods" can be used to evaluate the mechanical resistance of mortars and renders or to monitor the evolution of the surfaces after their application. Used to evaluate surface hardness, *micro-drilling* (DRMS) is a very sensitive technique, and its use in this field is expected to contribute more precise results. The diversity of the composition of the mortars and the systematic presence of abrasive components are limiting factors for the use of this method in this field. In this study, several mortars with different composition and hardness are compared, using drilling resistance as the comparative parameter. The mortars were applied on-site, aiming at their use in real situations, and some samples were tested in the laboratory using conventional techniques that were complemented by additional methods currently used for on-site characterization of materials. The results also highlight the need for an integrated perspective of laboratory and on-site information.

1 *In situ* testing of mortars and renders. General aspects

The conservation of old renders and mortars requires a full characterization of the old materials as well as a very good knowledge of the new ones considered as the most adequate solutions for their replacement. In general, both laboratory and on-site characterizations are considered necessary, and the integration of these two types of information is required for a correct diagnosis and to reach the best solution during conservation or restoration.

Studies performed in laboratory conditions involving mortars and renders usually consider several parameters and are very well documented in the vast literature published in this domain [1, 2, 3, 4]. Although the characterization of the materials applied on-site is considered necessary, the few techniques are available and are considered inaccurate. The LNEC team has been using several methods to characterize old mortars on-site to evaluate the decay state and the properties of the old materials where they are still well-preserved. In some cases, to complement laboratory studies, experimental panels of new formulations have been prepared in order to predict their behaviour, to allow a better selection for the specific case [5, 6, 7], and to evaluate the compatibility with locally preserved old materials.

Quite often, the methods used *in situ* to determine specific parameters that are considered very relevant for a good performance. Such parameters include "the adhesion to background" and "degree of carbonation" (applicable to control the evolution of new formulations in time), as well as water properties, such as "water content" and "water permeability under low pressure." *In situ* techniques also can provide specific information about the type of salts present that can explain decay, and they can help control the expected behaviour of new formulations. Regarding the mechanical characterization, some relevant tests also can be done in order to indirectly evaluate the strength of the render, including 1) *"sphere impact"* and 2)*"controlled penetration,"* two tests that are able to evaluate a kind of resistance offered by the material when a physical object hits the surface. A sonic method, namely 3) *"Pulse wave velocity,"* is a very interesting non-destructive technique; when it is used to characterize a surface, the "indirect array" must be used, although, in this case, additional difficulties related to the interpretation of the results are introduced. "*Schmidt hammer test*" also could be used to evaluate rebound hardness [8], but its use on mortars is limited compared to its use in objects made of concrete. Actually, the integration of all the information provided by multiple tests is generally accepted as the best philosophy.

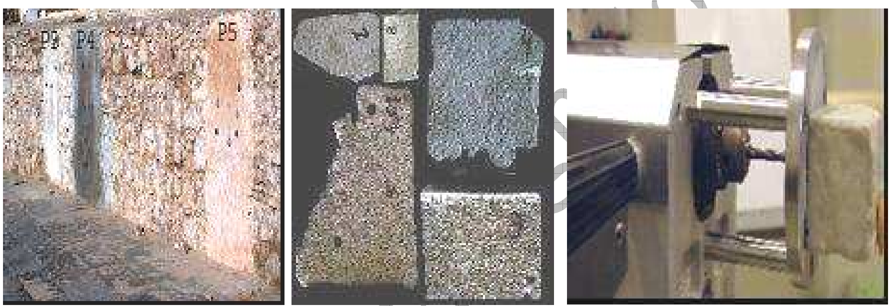
In addition to mortars and renders, on-site characterization of other types of materials and their decay state is a universal demand. *Non-destructive* or at least *micro-destructive* tests have been developed in the last years for better characterization of stone materials used in historical buildings. For example, the 4) "*micro-drilling technique (DRMS)*" was developed for stone characterization, not only in the laboratory but mainly for *in situ* analysis [9]. When applied to mortars, this technique needs to be properly evaluated, given the peculiar nature of these materials, specifically their high quartz content and high heterogeneity. A new instrument has been available and has been successively updated since about 2000 (SINT Technology, Italy), but its use for the characterization of mortars is still very limited.

This paper presents the results of drilling tests performed on samples collected from experimental panels prepared with several lime based mortars, applied in a fortress near Lisbon ("Forte dos Oitavos"). The original compositions of the old lime mortars present and compatibility criteria [7] were taken into account during sample selection.

2 Materials and methods

2.1 Samples

In this study, several compositions of mortars were considered. They include several binders: lime, hydraulic lime, natural pozzolan (from Cabo Verde), silica fume, metakaolin, and white cement. The panels were prepared according to a specific protocol [9], and the mortars were applied in two layers with different compositions, as is usually the case in traditional renders. The panels' compositions are described in Table 1. Fig.1 illustrates three zones of those experimental panels on the Fortress walls (a), the macroscopic aspect of the mortars (b), and the drilling equipment used (c).



a) b) c)

Fig. 1 The experimental panels (a), the macroscopic aspect of the mortars (b), and the DRMS front (c)

After *in situ* characterization, some samples were removed from the panels for laboratory testing (Fig. 1b). These samples are more heterogeneous than conventional laboratory specimens because they are composed of two different layers. Furthermore, they have been exposed to complex conditions, namely, submitted to suction of the substrate in fresh state, variable climatic conditions during the hardening period, and exposure to air over much of the surface. These external conditions produce changes in the mortars' microstructure not expected in the laboratory samples.

Table 1 Composition of mortars tested on the experimental panels

Main constituents	P1 Lime/Hydraulic lime	P2 Lime/White cement	P3 Lime/Pozzolan	P4 Lime/Silica fume	P5 Lime/Metakaolin
Volumetric dosage	1:1:6 (1st)	1:1:6 (1st)	1:0.5:2.5 (1st)	1:0.25:2.5 (1st)	1:0.5:2.5 (1st)
(*air lime: other binder :sand*)	1:2:9 (2nd)	1:2:9 (2nd)	1:0.5:3 (2nd)	1:0.25:3 (2nd)	1:0.5:3 (2nd)

(1st) – first layer; (2nd) – second layer

2.2 Methods

This study will focus on the drilling test results obtained on samples indicated above. In addition to the DRMS data, ultrasonic and compressive strength results are used for comparative purposes. Other swift techniques used to characterize mortars on-site are also taken into account.

2.2.1 Micro-drilling technique (DRMS)

The test consists of drilling a hole and continuously measuring the penetration force with a load cell. During the test, the rotational speed and the penetration rate are kept constant. “Drilling resistance” or “surface hardness determined by drilling” are terms also used to express the value measured.

Several types of drill bits can be used; in this case a 5 ϕ mm of Fischer Extra produced by BOSCH was used. The initial conditions of testing were selected taking into account the expected low resistance of these lime-based materials. The rotation speed of 100 revolutions per minute and the penetration rate of 10 mm/min were selected (“100/10”). Moreover, higher values of rotation speed (until 1200 rpm) were also used in order to test the harder samples. This paper only presents results obtained with “400/10.” To compare and control the wear effect of the drill bits, a very soft, non-abrasive, and homogeneous limestone (Ancã stone) was used.

The experience gathered by utilizing this method on several rock materials allowed us to take several aspects into account when interpreting the drilling data. The “packing effect” due to difficult removal of cuttings and the “abrasiveness” of the material on the drill bit are two examples of effects that can increase the measured values [11, 12].

2.2.2 Other techniques

The *Ultrasonic pulse velocity* (UPV) is calculated as the travel time of the longitudinal wave between two points located at a known distance in the material. An electro-acoustical transducer held in contact with the surface produces a pulse of longitudinal vibrations. After traversing the material, the pulse of vibrations is re-converted into an electrical signal by a second transducer placed at a known distance. Electronic timing circuits enable the transit time of the pulse to be measured. In laboratory conditions, the UPV was determined following the *direct mode* (transmission), by using exponential transducers of 45 kHz. In the field, the *indirect mode* (refraction) can also be used, although it usually leads to less accurate results.

The *Sphere impact test* consists of impacting a hard body with the energy of 3 joules, produced with a steel sphere of 50 mm in diameter. The impact resistance evaluated through the diameter of the concussion made by the sphere and the type of resulting damage allow the assessment of the mortar’s deformability.

The *Controlled penetration test* consists of the penetration of a steel nail, guided by a device fixed to a Martinet Baronnie apparatus to guarantee that the stroke is perpendicular to the surface. Several impacts (typically, three impacts) with constant energy are produced and the respective penetration depths are registered. This test gives information on the mechanical resistance of the internal render coats, permitting the assessment of their performance [6, 7].

3 Results

3.1 Drilling tests

Drilling tests performed on mortars show very different characteristics in comparison with typical graphs obtained in homogeneous rocks such as Ançã (as it is shown on Fig.2, blue line in P2, on the left). Mortars are very heterogeneous materials, and the presence of quartz grains justifies the large variations of the registered forces.

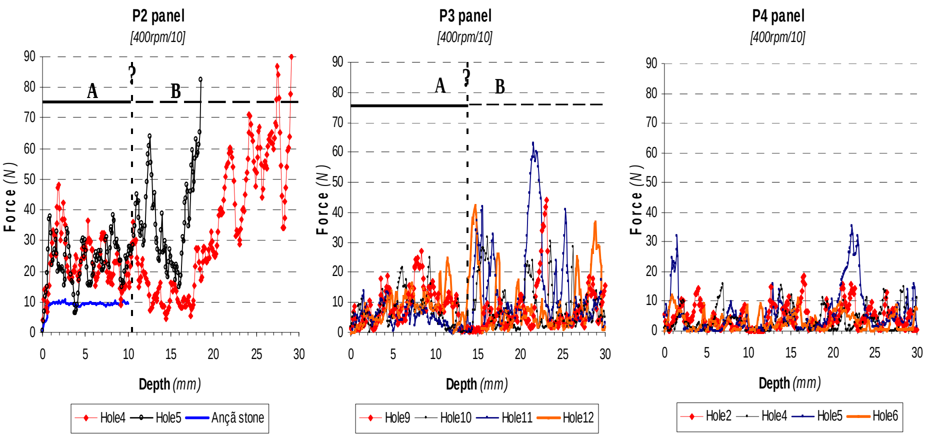


Fig. 2 Drilling graphs of panel samples. Note: A-"external layer", B-"internal layer"

Despite being so diverse and heterogeneous, the materials tested are clearly distinct. For instance, sample P4 shows lower values of drilling forces when compared to P3 and P2. P2 is the hardest of the tested materials. In two cases (P2 and P3), the graphs indicate the presence of two zones with different characteristics; the external layer (10-15 mm) is softer than the internal one, in which the values of forces are higher. This is explained by the application in two layers, with the internal layer designed to be harder than the external one. In the case of P2, the drilling of the "second layer" reaches the maximum limit imposed by the load cell (100N), and even under extreme conditions (1200 rpm) it was not possible to drill this part of the sample. In this particular case, this is due to the presence of different layers in this sample, but without any information about the characteristics of the material, this effect could be misunderstood or attributed to the well known “packing effect” that results from dust accumulation inside the hole. In P3, the existence of two layers is also identified, but in this case the two zones are much more similar. On the contrary, the results for sample P4 do not differentiate the two layers as established in the preparation protocol.

A second handicap must be noted when the drilling technique is used to characterize mortars. In very weak materials, the resistance offered by the material is low. Fissures develop and propagate during the process, producing drill holes with irregular borders and increasing the variation of forces measured during the test. The indentation phase, well-recognized on a typical drilling graph, is not evident in the graphs obtained on mortars, as clearly seen on the examples. For all these reasons, the distributions of drilling forces obtained on heterogeneous materials have a pronounced range of values; the standard deviation is of the order of magnitude of the average values, and in these circumstances the results and conclusions must be taken with care. Even so, the method can also be used in these particular cases, especially if this information is properly integrated.

In this particular case, an evaluation of the mortars abrasiveness was taken into account when the drilling tests were planned. The results indicate that all the materials tested were able to wear the drill bit. In this context and for comparative purposes, the raw data without any correction are considered valid, and the discussion of this topic will be made in a future publication.

Table 2 presents the global average results of the drilling tests; in this context, these values include both layers, even when drilling tests can discriminate their presence.

Table 2 Drilling resistance measurements of mortars (average global values)

Panel Samples	P1 Lime/Hydraulic lime	P2 Lime/White cement	P3 Lime/Pozzolan	P4 Lime/Silica fume	P5 Lime/Metakaolin
Force (N) *[400rpm/10]*	11.9	31.5	9.7	4.4	6.4

Each sample was tested with a different drill bit and about ten holes were drilled. The results are expressed as the mean value of the drilling forces along the total hole length. Of special note are the effect of the white cement in the resistance increase and the advantage of the addition of natural pozzolan in comparison with metakaolin or silica fume, which produces values similar to those obtained in a mixed formulation with hydraulic lime (P1).

The distribution of values is also meaningful and diagnostic, as evident in the histogram presented in Fig.3. P4 and P5 are considered “weak” mortars, identified by A in the graph. They are completely distinct from “strong“ mortars identified as C, which in this particular case are characterized by a very wide range of values, represented in this group by P2. B group represents intermediate characteristics of hardness and includes P1 and P3.

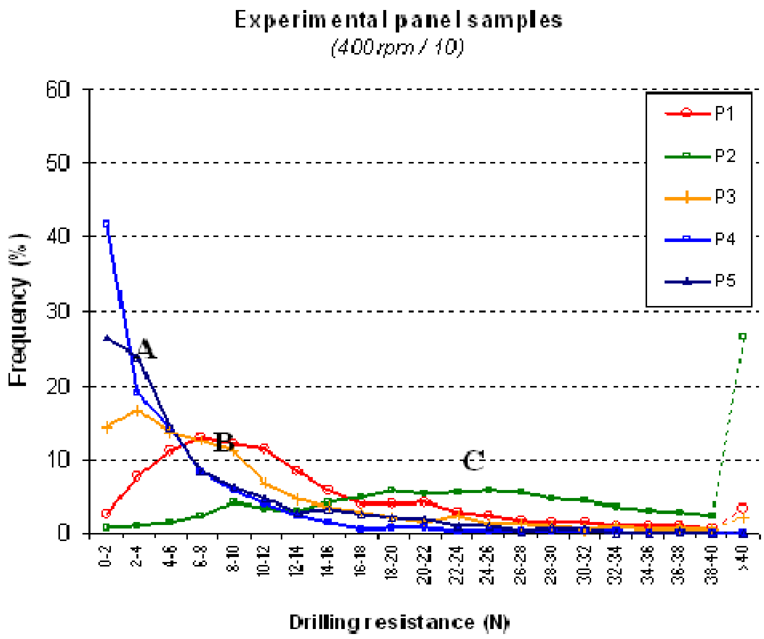


Fig. 3 Frequency distributions of drilling forces on mortar samples

3.2 Other resistance measurements

In different phases of the study, several data were obtained on the experimental panels; during the curing process, *sphere impact* and *controlled penetration* tests were performed. Later, samples were extracted and tested in the laboratory in different steps, the last one corresponding to the drilling and ultrasonic tests. For comparison, all data are presented in Table 3, and the graphs of Fig. 4 represent the most significant correlations.

Table 3 Drilling forces and other resistance measurements

Samples	P1 Lime/ Hydraulic lime	P2 Lime/ White cement	P3 Lime/ Pozzolan	P4 Lime/ Silica fume	P5 Lime/ Metakaolin
DR-Force (N) *[400rpm/10]*	11.9	31.5	9.7	4.4	6.4
Ultrasonic velocity (m/s)	1700	2900	1090	950	1530
Compressive strength (N/mm^2)	1.2	3.8	1.5	0.7	0.8

Sphere impact (ϕ, mm) *	15	12	11	15	11
Controlled penetration (mm)*[a]	11.7	7	6.6	10	9.7

[a] Σ three penetrations * Determined directly on panels after 14 weeks app.

Measured on-site, sphere impact and controlled penetration gave information about the evolution of the resistance in time, and the latter was able to discriminate the different mortar formulations. Nevertheless, as indicators of the final resistance of the surface, the interpretation must be considered with care.

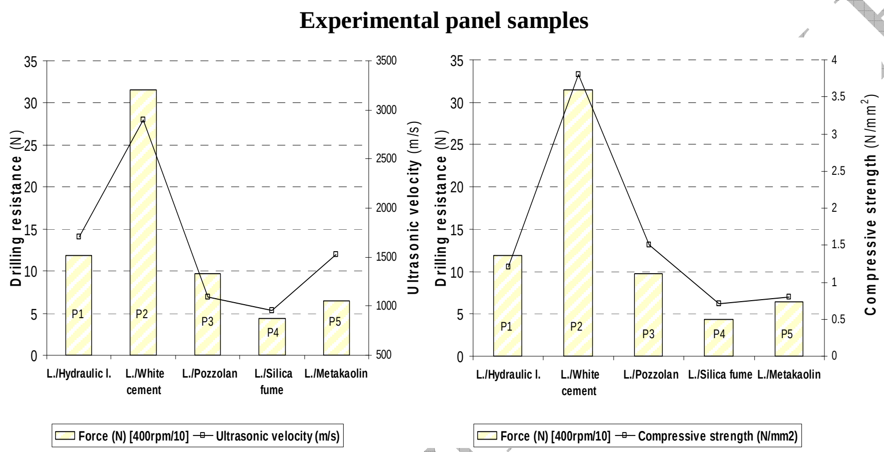


Fig. 4 "Drilling resistance" results versus "Ultrasonic velocity"/"Compressive strength"

The ultrasonic velocity is in good agreement with drilling results, although expressed by the average values of the distributions with great variations.

For hardness characterization, the drilling test should be performed on quite homogeneous samples, but these in situ samples are much more complex due to the application process by layers. In spite of this fact, the classic correlation of compressive strength to drilling hardness indicate the same behaviour, as is clear from the graphs presented here.

4 Conclusions

In this paper, non-destructive and micro-destructive techniques were used in the laboratory to characterize the mechanical resistance of mortars applied on experimental panels simulating real applications.

The ultrasonic velocity, measured in direct mode, is in good agreement with the drilling results. For hardness characterization purposes, drilling tests performed on very heterogeneous materials were able to discriminate different formulations of mortars, confirming the tendency indicated by the non-destructive method. The classic correlation of compressive strength to drilling hardness indicates a strong correlation coefficient and must be considered an encouraging finding, but the low number of samples indicates a need for further research in this domain.

Further investigations should be conducted comparing laboratory samples with similar formulations prepared according to regular procedures used for laboratory testing. On-site characterization of mortars with similar formulations is also needed, not only because the methods must be applied in different conditions (as is the case of the sonic method), but also because the variability of local parameters can influence the final results obtained through on-site measurements.

5 References

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