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Assessing mechanical behavior and heterogeneity of low-strength mortars by the drilling resistance method

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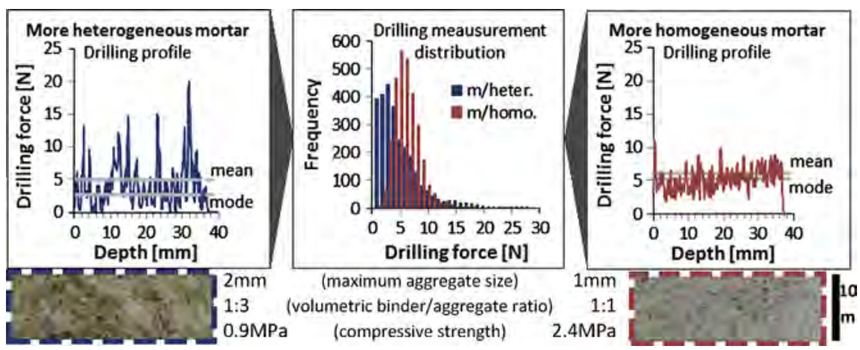
HIGHLIGHTS

- Viability of the method for low-strength mortar characterization.
- Assessment of mortars heterogeneity through the drilling measurements distribution.
- Appraisal of the paste–aggregates bond and relative size of the aggregates.
- Drilling resistance is evaluated by mode instead of mean value.
- Relationships with compressive strength and dynamic modulus of elasticity.

GRAPHICAL ABSTRACT



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ABSTRACT

The drilling resistance method provides the material strength profile in depth. Its use is widespread for soft homogeneous materials, like carbonate stones. The application in heterogeneous materials, like low-strength mortars, is not so well established due to the irregularity of the drilling profiles yielded. This paper demonstrates the viability of the method for low-strength mortar characterization. To achieve this purpose, 19 mortar mixtures with different heterogeneity and strength characteristics were tested. Based on the analysis of the drilling measurements distribution it was concluded that the reported high variability provides valuable information on the heterogeneity characteristics of the mortars. Furthermore, the mode value of the drilling measurements is proposed as a more accurate predictor of the mortar strength than the mean value. Relationships between drilling resistance and other conventional material properties were analyzed and a better understanding of the important factors influencing drilling resistance was achieved.

1. Introduction

Mortar is widely used in construction with different purposes: pointing or bedding for masonry, plasters or renderings for wall coatings, wall paintings and other decorative elements [1]. The availability of an effective *in situ* characterization method is essential for diagnosing decayed mortars, assessing interventions results, such as the improvement of the properties and durability or, simply, collecting data on ancient mortars in order to improve the heritage knowledge.

The drilling resistance is a characterization method that provides strength assessment in depth, with little intrusion (small holes with the size of the adopted drill bit) [2,3]. This unique feature is an advantage for *in situ* applications, since other *in situ* methods, such as the pulse velocity test or the rebound hardness test, only manage to assess a superficial layer [2,4]. This method

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is also an important tool for laboratory characterization, as it provides valuable information with less material destruction than conventional compressive tests.

The drilling test has been used to obtain information concerning mechanical properties of stone and to evaluate performance of applied consolidant treatments [2,3]. The drilling resistance method is widely used on homogeneous stones, mainly carbonate stones which are softer. Good correlations between drilling resistance and uniaxial compressive strength were obtained [5,6]. Some attempts of similar characterization have been developed in heterogeneous stones, such as sandstone. In these cases, drilling and compressive strength did not correlate so well, suggesting different factors affecting these properties [2]. The method was standardized by Rilem TC 177-MDT (Masonry durability and on-site testing) for the assessment of hydraulic cement mortars [7]. The drilling equipment was then one of the first portable tools for evaluating mortar on-site. This device was equipped with an electrical energy meter and the drilling resistance was measured by the consumption of the electricity necessary to make the drill hole [7,8]. The system was not able to provide quite reliable measurements for research work and statistical analysis. Yet it enabled to estimate strength properties, provided the hardness and size of the aggregates were kept above certain values [7]. These factors enhance the variability of measurements. In low-strength mortars, the high variability of the drilling results is considered a limitation to a wider application [8–11].

Mortar is a heterogeneous material, composed of aggregates dispersed in a porous binding system. Hence, like concrete, mortar can be simply understood as a three-phase composite material composed of aggregates (usually harder than the paste), paste (which includes binder crystals and voids) and the interface between aggregates and paste, usually called the interfacial transition zone, ITZ [12,13]. This heterogeneity is determined by the ratio between volume, strength and stiffness of grains and matrix, grain size and bond between grains and matrix [14–17]. Hence, low-strength mortars, such as some ancient or lime mortars, are very heterogeneous materials due to the huge differences between the matrix and hard grains (frequently siliceous). These mortars yield very irregular drilling profiles [8–11].

In this work, the majority of the mortars designed is of low-strength (compressive strength comprised between 1 and 5 MPa) and composed by lime pastes and siliceous aggregates. Diverse water–binder and binder–aggregate ratios were used to produce different mortars. To obtain mortars with a higher paste and ITZ strength, hydraulic binders were adopted. The most resistant one reached a compressive strength of 11 MPa. Siliceous and carbonate aggregates were used to ensure ITZ and hard grains with different strength and stiffness/hardness. Additionally, aggregates with different maximum grain size, D, were adopted to obtain microstructures with different textures. Fig. 1 shows examples of the irregular drilling profiles obtained.

This paper demonstrates the viability of the drilling resistance method for characterization of low-strength heterogeneous materials and, particularly, ancient mortars. To achieve this purpose, 19 mortar mixtures with different heterogeneity and strength characteristics were tested. Based on the analysis of the drilling measurements distribution it was concluded that the reported high variability provides valuable information on the heterogeneity characteristics of the mortars, namely the bond efficiency between the paste and aggregates, and the relative size of the aggregates. Furthermore, the mode value of the drilling measurements is proposed as a more accurate predictor of the mortars strength than the mean value. Interesting indications concerning the interaction of the failure mechanisms are also provided. Relationships between drilling resistance and both compressive strength and dynamic modulus of elasticity were analyzed and a better understanding of the important factors influencing drilling resistance was achieved.

2. Background knowledge

Drilling resistance method provides drilling force measurements, F_d (N), which correspond to the weight-on-bit or thrust to be exerted on the drill to drive the bit at a constant penetration rate, v (mm/min), and revolution speed, ω (rpm). Additionally, it is possible to obtain the resistant cutting torque at constant penetration and revolution rates, if the system is provided with that functionality. The drilling device is shown in Fig. 2.

The cutting depth per revolution, δ (mm), is defined by the expression $\delta = 2\pi \cdot v/\omega$ and characterizes the cutting depth yielding from the indentation process of the bit into the material. The drilling specific strength, J (N/mm^2), was established in previous works by drilling force per cutting area, yielding from the indentation process, according to the penetration law $J = F_d/(a \cdot \delta)$, where a is the bit radius [5,18].

Drilling strength, J, depends on the testing material and both the type and geometry of the drill bit. Since J is a function of δ, it would be possible to compare drilling strength values obtained by different drilling parameters, (v/ω). This assumption was confirmed for two stones [5]. However, this postulation has not been verified for more heterogeneous materials such as mortar or concrete, where more complex failure mechanisms coexist, eventually causing interference in the linear relationship between F_d and δ.

Focusing on the drilling process driven by the drill bit, the interaction between the bit and material is characterized by the coexistence of material cutting and frictional contact [18]. In ductile materials, the failure mechanism that occurs during the drilling process is plastic cutting, which is driven by considerable shearing strains without crack propagation (continuous chipping). On the contrary, in the case of quasi-brittle materials, the failure is determined by significant compressive stresses developed ahead of the tool's tip. This failure mechanism is caused by a blunt drill bit tip,

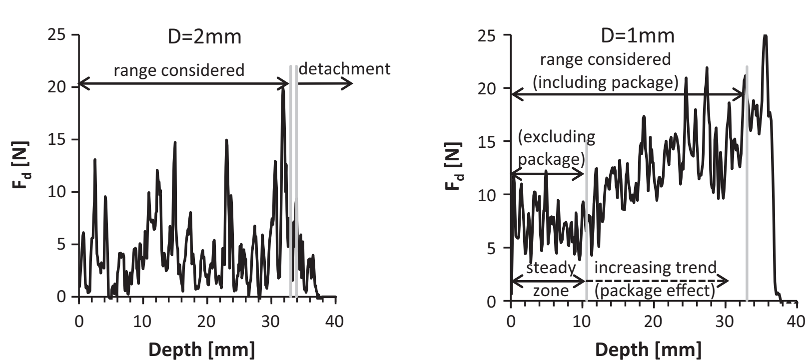

Fig. 1. Drilling profiles of two lime mortar mixtures with different maximum aggregate sizes, D.

Fig. 2. Drilling device.

which had revealed to be more energy efficient [16]. This cutting process is described as being divided into two stages: a growing and a decreasing force stage (Fig. 3). In the first one, fine fragmentation occurs in a narrow band ahead of the bit (plastic crushing) and a pattern of tensile cracks appears in the base material. The second stage is characterized by a discontinuous separation and removal of large fragments (discontinuous chipping). This stepwise chipping formation corresponds to the so-called brittle chipping failure mechanism [16,19–21].

According to this model, when drilling quasi-brittle materials, two main failure mechanisms occur: plastic crushing and brittle chipping. Their relative contribution depends on the strength, stiffness and heterogeneity of the material. Plastic crushing prevails in more resistant, stiff and homogeneous materials because crack propagation is restricted to a limited zone around the bit. In this case, the internal friction between the fragments (milling) ensuing from the crushing becomes crucial. In heterogeneous quasi-brittle materials, microstructural disorder plays an important role because the damage is extended to a wide diffused zone around the main cracks, which provides a certain degree of "ductility". Thus, in the case of heterogeneous quasi-brittle microstructures, there is a considerable amount of energy dissipated all over the extended damaged zone, keeping at low levels the F_d required to drive the drill bit. In the case of more resistant, stiff and homogeneous materials, fragment accumulation is restricted to a narrow damaged zone, causing F_d to increase as it becomes more difficult to drive the drill bit, keeping constant the drilling parameters [16,22].

For these reasons, the results provided by the drilling resistance method are strongly influenced by the prevailing failure

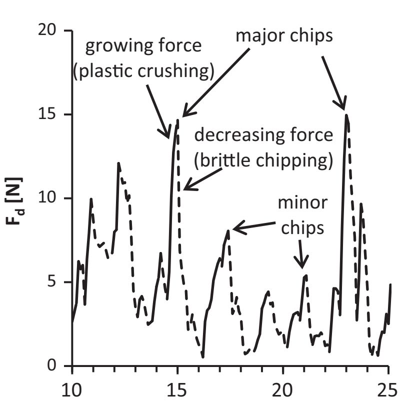

Fig. 3. Drilling process in quasi-brittle materials: plastic crushing (fine fragmentation and tensile crack propagation) and brittle chipping (chip removal) [16]. Depth range (10–25 mm) of the drilling profile shown in Fig. 1-left.

mechanism. The prevalence of the brittle chipping reduces F_d due to the ability of the extended damaged zone to dissipate the drilling process energy. When plastic crushing is the prevailing failure mechanism, F_d rises due to the fragments accumulation in a restricted damaged zone, increasing internal friction. Consequently, strength, stiffness and heterogeneity of the phases, being the most influential properties of failure mechanisms, must be considered when analyzing results provided by the drilling resistance method.

In low-strength mortars, the brittle chipping mechanism is enhanced as the cracks tend to spread along the space between the aggregates. The weak interfaces between grains and matrix play a dominant role in the damage process. Fig. 4 shows specimens of two tested mortars with different heterogeneity characteristics. The bigger holes and the presence of some cracks in the coarser mortar may be related to a more extended damaged zone than in the case of the finer microstructure mortar. The fragments size is also higher in the first case.

In higher strength mortars, the damaged zone becomes more restricted as the matrix strength increases, and the internal friction between the fragments leads to increasing F_d values. This effect is intensified with the drilling depth and may be noticed when the drilling profiles show an increasing trend, when it should theoretically show, on average, a nil slope (Fig. 1-right). This F_d increasing trend in depth corresponds to the so-called package effect [22,23]. The drilling profiles steady zone may be used to calculate the F_d average value, excluding the distortion caused by package [23]. Since this effect is a consequence of internal friction, it is more likely to occur when testing materials in which plastic crushing prevails over brittle chipping.

3. Experimental program

3.1. Materials

A set of 19 mortar mixtures was produced in order to perform the drilling tests (Table 1).

The mortars were designed in order to be similar to the ones found in renderings of ancient buildings (A) or, eventually, suitable to replace ancient mortars (H), according to the following description. Generally, ancient renderings are composed of more than one layer, with different components and thicknesses. AS1 mortars have a binder–aggregate volumetric ratio, B/A, of 1:1 and a maximum aggregate size, D, of 1 mm, to be similar to the finishing coats of ancient renderings. AS2 mortars have B/A = 1:3 and D = 2 mm, to be similar to the base coats of ancient renderings [1,24]. The binder adopted is a non-hydraulic lime, CL90 [EN459-1:2002] and within each group (AS1 and AS2) various water–binder ratios were used to obtain distinct porosities and mechanical properties. The consistency was determined by the flow table test [EN1015-3:1999]. The aggregates used in AS mortars are mixtures of commercial natural sands of siliceous nature. Quartz is the main (50–90% of α-Quartz (SiO_2) content) but quartzite and feldspar may also be present. These sands have controlled chemical and mineralogical composition and are suitable for concrete production [EN12620:2004]. In order to improve the ITZ quality [25–27], four carbonate aggregate mortars (AC11, AC13, AC21, AC26) were produced with the same design parameters of AS11, AS13, AS21 and AS26 mortars, respectively (Table 1). Commercial sands originated in crushed limestone (97% of $CaCO_3$ content) were acquired and separated into each granulometric fraction. Subsequently, the various granulometric fractions of the carbonate aggregates were mixed in such a proportion that the final grain size distribution of carbonate and siliceous aggregates is very similar (Fig. 5).

In order to obtain higher strength microstructures, the H21–H24 blended hydraulic mortars were produced combining three binders – non-hydraulic lime, CL90, natural hydraulic lime, NHL5 [EN459-1:2002] and Portland cement, CEM II/B – L 32.5 [EN197-1:2002]. The siliceous aggregate with D = 2 mm was used in these mortars.

Mortar specimens with 16 × 4×4 cm were produced in accordance with EN1015-2:1998 recommendations and were left to age until properties evolution became minimal. Mortars were tested after, at least 14 months.

3.2. Characterization methods

Besides drilling resistance tests, other characterization methods, such as compressive strength, ultrasonic pulse velocity, dynamic modulus of elasticity and porosity, were performed in order to support results interpretation.

Fig. 4. Specimens of two lime mortars with different maximum aggregate sizes (D = 2 mm above and D = 1 mm below).

Table 1
Mortar mixtures and main physical and mechanical properties.

Mortar	Group	Binder	Aggregate type	D[a] (mm)	B/A[b]	W/B[c]	Flow[d] (mm)	f_c[e] (MPa)	UPV[f] (m/s)	E_d[g] (GPa)	Porosity (%)
AS21	AS2	CL90	Siliceous	2	1:3	1.6	220	0.9	1470	2.91	26.8
AS22						1.5	207	1.1	1640	ND	26.4
AS23						1.4	192	1.3	1690	ND	25.1
AS24						1.3	171	1.6	1760	ND	24.5
AS25						1.28	165	1.7	1820	ND	24.6
AS26						1.2	142	2.1	1880	3.62	23.8
AS27						1.1	122	2.3	1940	ND	22.7
AS11	AS1	CL90	Siliceous	1	1:1	1	222	2.4	1730	4.30	34.5
AS12						0.9	194	2.9	1880	ND	33.1
AS13						0.85	172	3.4	1960	4.47	32.1
AS14						0.8	159	3.9	1910	ND	30.9
AC21	AC2	CL90	Carbonate	2	1:3	1.6	220	1.8	1590	4.81	25.8
AC26						1.2	124	3.4	1900	6.44	22.2
AC11	AC1	CL90	Carbonate	1	1:1	1	211	3.6	1850	5.96	33.6
AC13						0.85	151	4.2	1900	6.73	31.4
HS21	HS	50%CL90 + 50%NHL5[h]	Siliceous	2	1:3	0.9	144	4.2	2130	4.78	27.1
HS22		NHL5				0.9	169	5.9	2200	5.95	26.7
HS23		90%NHL5 + 10%CEM[h]				0.81	164	8.6	2560	10.77	22.6
HS24		50%CL90 + 50%CEM[h]				0.9	154	10.6	2590	10.64	25.8

[a] Maximum aggregate size.
[b] Binder/aggregate volumetric ratio.
[c] Water/binder ratio by weight.
[d] Consistency given by the flow table test.
[e] Compressive strength.
[f] Ultrasonic pulse velocity.
[g] Dynamic modulus of elasticity.
[h] Mixture by weight.

Drilling tests were performed with the drilling device developed by Sint Tecnology (Italy), model DRMS Cordless. Tests were carried out on 19 types of mortars (Table 1), from the rectangular bottom face of the prism specimens, and nine tests were performed on three specimens per mortar.

To obtain comparable results, the tests were performed with the same drilling parameters [3]. Testing 19 mortars belonging to a wide strength range (f_c ranging between 1 MPa and 11 MPa) with the same drilling parameters may bring cell overload or inaccuracy risks to the higher and lower strength mortars, respectively. To avoid these risks, a previous campaign where four v/ω combinations were tested was developed, leading to the choice of the drilling parameters combination v/ω = 40/100 mm/min/rpm.

A drill bit of 5 mm diameter was used. It was decided to use special flat-tip diamond drill bits due to the expected great variability of the measurements. These drill bits ensure lower F_d values and lower random force oscillation (noise) [22]. The drill bit wearing state was assessed at short regular periods to obtain homogeneous and comparable results [28]. The drill bit wearing was found to be almost

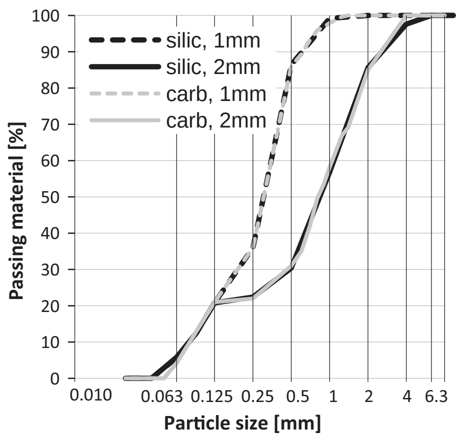

Fig. 5. Grain size distributions of the aggregates.

negligible for lime mortars, probably because the more pronounced failure mechanism is brittle chipping. The wearing of the drill bit is intensified when there is a high internal friction which is associated with plastic crushing failure mechanism.

Drilling tests were performed in the entire thickness of the sample (40 mm). The results considered in the study correspond to the range 0–33 mm (Fig. 1). The upper limit was defined because, for all mortars, F_d goes through a decreasing trend before the end of the sample, which is due to the detachment of the outer layer that remains ahead of the drill bit. The lowest depth found in all cases was 33 mm.

The compression strength tests performed were based on EN1015-11:1999 and carried out using a Form test – Sneider universal machine, model D-7940. The ultrasonic pulse velocity measurements were carried out by using PUNDIT Lab equipment from Proceq, comprising an ultrasonic pulse generating unit and two cylindrical transducers of 5 cm diameter with a frequency of 54 kHz. The ultrasound velocity measurements were performed under direct transmission mode on prismatic specimens. The dynamic modulus of elasticity was assessed by the resonant frequency method, in accordance with ASTM E 1876-01, using Grindosonic E-modulus measurement equipment. The porosity was assessed by samples vacuum immersion, following Rilem I.1 recommendations. Means of six measurements are presented in Table 1.

4. Results and discussion

4.1. Properties of mortars

Compressive strength, ultrasonic pulse velocity and porosity are conventional laboratory tests that provide data on mechanical and physical properties of the materials, but valuable information concerning microstructure and heterogeneity characteristics may also be provided.

In order to understand the differences between the studied mortars, the results provided by these tests are discussed prior to the drilling results analysis.

Mortar, like concrete and many stones, is a heterogeneous material (ratios between volume, strength and stiffness of phases and inhomogeneity occurrences) and this plays a fundamental role in the fracture process [14–16]. In mortar and concrete, the interface between aggregates and the matrix is the weakest zone, due to the presence of bigger pores and higher probability of yielding micro-cracks and the growth of binder crystals of different size [13,25,29]. The huge difference between strength and stiffness of phases causes a stress transfer, mainly through the harder grains (aggregates) and intermediate layers of paste, originating phase separation through the ITZ. Moreover, in brittle or quasi-brittle materials, the crack pattern tends to propagate through the existing inhomogeneities (voids, pores, microcracks), enhancing the role of these discontinuities in the material failure. For more homogeneous materials, a better elastic compatibility arises and the crack pattern tends to grow through the hard grains rather than around them [14,15].

Therefore, ITZ quality is one of the most important factors governing mortars heterogeneity and it was considered, in this work, to help understanding the heterogeneity influence on drilling results. Compressive strength results, as other mechanical tests where failure occurs, are largely influenced by the weakest phase characteristics. Consequently, in this work, f_c is assumed as an indicator of the ITZ quality and, hence, of the mortars heterogeneity.

Fig. 6 shows a regular increasing f_c with the decreasing W/B ratio. Even though the seven higher W/B mortars (AS2) have higher maximum aggregate size ($D = 2$ mm) and lower paste content (B/A = 1:3) than AS1 mortars, these differences are not enhanced in Fig. 6. This behavior may be explained by the huge relevance of the ITZ in the material failure under compressive stress. This behavior is more evident when the quality of this phase is very poor, which is the case of weak binder mortars. Hence, the increasing value of f_c shown in Fig. 6 is due to the increasing paste strength and, hence, ITZ quality, as expected.

The ultrasonic pulse test consists of submitting the material to a transient pulse, causing the propagation of stress waves through it. The pulse velocity of compressive waves in a solid depends on the density and elastic properties of the material. Since no failure occurs, the weakest phase does not prevail and each phase that comprises the material contributes to the final UPV proportionally to its own UPV and volume [30]. This important feature differentiates this method from others where material failure occurs (like compressive, flexural, drilling) and must surely be taken into account when analyzing results.

As in other works, the relationship between f_c and UPV for the studied mortars is exponential (Fig. 7) [31]. Contrarily to what happens with f_c, UPV does not tell AS1 and AS2 mortars apart. As previously stated, UPV considers each phase in the direct proportion of its own UPV and volume, while f_c emphasizes very much the importance of ITZ poor quality. In this situation, UPV values taken by AS1 mortars may have two contradictory contributions which prevent the increase shown by f_c: on the one hand, UPV is expected to increase due to the lower W/B ratio; on the other hand, the lower aggregate content (the stiffer phase) in AS1 (B/A = 1:1) mortars is a negative contribution to the final UPV value [32].

Thus, AS1 and AS2 mortars may be briefly described as a finer and a coarser microstructure respectively, composed of hard grains disseminated in a weak paste matrix and poor quality ITZ, with a slightly increasing strength with W/B from AS21 to AS14 (Fig. 6). A slight heterogeneity decrease is expected in the same order.

Additionally to AS1 and AS2, six more mortars were produced with the purpose of obtaining a decrease in the heterogeneity of the microstructures. Considering the relevance of the ITZ in the mortars heterogeneity, this purpose was pursued by increasing

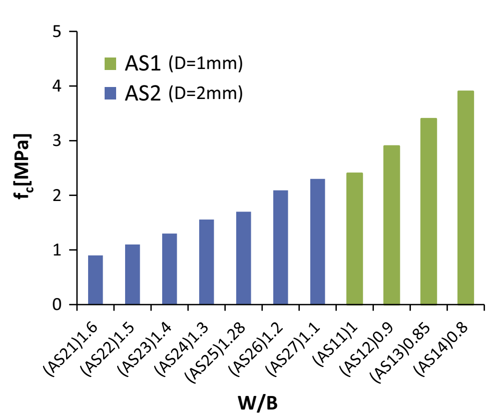

Fig. 6. f_c vs. W/B for AS1 and AS2 mortars. ITZ quality grows and heterogeneity decreases from left to right.

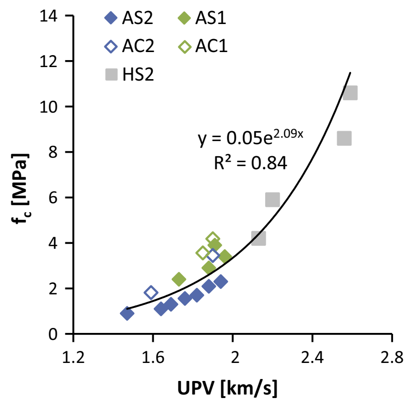

Fig. 7. Relationship between f_c and UPV.

the quality of that phase in two ways: changing the nature of the aggregate from siliceous to carbonate [25,26,29] (AC mortars) and adopting more resistant binders (HS mortars). These changes enabled more homogeneous mortars with different mechanical resistance.

Changing the aggregate nature from siliceous to carbonate caused a f_c average increase of 83% in the coarser microstructure (AS21 vs. AC21 and AS26 vs. AC26) and of 36% in the finer microstructure (AS11 vs. AC11 and AS13 vs. AC13). Ultrasonic pulse velocity exhibits an 8% increase for the more porous mortars (AS21 vs. AC21 and AS11 vs. AC11) and nearly no change for the less porous ones (AS26 vs. AC26 and AS13 vs. AC13) (Fig. 7 and Table 1).

As the composition of the paste is the same in each pair of comparing mortars, f_c is expected to increase due to the increasing ITZ quality, which is provided by the similar structure of the calcitic binder matrix and limestone aggregate. This similarity leads to two events: (i) the chemical continuity decreases the presence of special microstructures which are inhomogeneities [25,33]; (ii) the calcite of the aggregates may provide nucleating sites for crystals to grow during portlandite carbonation of the binder [25,34]. The decrease of the porosity in carbonate aggregate mortars (Table 1) is consistent with this consideration.

There are hardly any changes in UPV results, particularly in the least porous mortars. The positive contribution given by the ITZ quality increase in carbonate aggregate mortars is restricted to the minor proportion of the volume of this phase. A higher expression of this positive contribution is revealed by the most porous mortars, probably due to the better carbonation conditions of the portlandite that occur in this case [25,35]. This different behavior of UPV vs. f_c is particular important to make evident the carbonate aggregate role in the mortars heterogeneity decrease.

Considering HS mortars, the f_c and UPV increment is evident in Fig. 7, and is associated to the paste strength increase and, hence, ITZ quality improvement.

Therefore, this second set of less heterogeneous mortars is composed by mortars with hard grains disseminated in a lower resistant paste (AC) and in a higher resistant paste (HS). The ITZ quality varies within the mortars of this set and is higher than in the first set (AS1 and AS2 mortars).

4.2. Distribution of the drilling force measurements

The interpretation of the drilling resistance results is usually based on the arithmetic mean determination of the F_d measurements obtained inside a given depth range and provided by a given number of tests.

When dealing with heterogeneous materials, where plastic crushing and brittle chipping coexist, the depth range to be considered for analysis must be carefully selected. The plastic crushing mechanism is a growing stress stage, with a considerable accumulation of elastic energy. In a drilling test profile, like the one shown in Fig. 3, this stage is associated with an increasing F_d trend that finally culminates in a load peak. The F_d peaks correspond to the chip formation. The force decrease that follows is due to the chip removal [16]. These discontinuous chip formation and removal is one important cause of the high irregularity of the heterogeneous materials drilling profiles reported. Additionally, the value and frequency of the peak loads are also influenced by both the differential contribution of each failure mechanism and the characteristics of the material positioned on the tip of the drill-bit, whether it is a hard big grain, a hard small grain or a softer matrix.

For this reason, in heterogeneous materials, the depth range of analysis has to be carefully selected in order to include a significant number of representative measurements. The distribution of these measurements (histogram) provides information about the relative importance of each component of the composite material.

Histograms were determined for all mortars. Each one comprises 2970 measurements collected within the 0–33 mm range (10 records acquired for every 1 mm in 9 drilling tests). Fig. 8 shows histograms determined for the AS11 and AS21 mortars. Drilling profiles of individual tests and specimen cross sections are also shown.

The correspondence between drilling profiles and histograms is evident in the histogram tail size which returns the value and the frequency of the peak loads and in the histogram concavity that corresponds to the major concentration of F_d values.

The corresponding boxplot is also shown below the histogram. Boxplots are condensed and convenient ways of graphically depict the relevant data provided by histograms, hence, in the following chapters, the former will be used instead. Mode and mean values are represented inside both boxplots and drilling profiles.

The same information regarding AC11 and AC21 mortars is shown in Fig. 9.

Skewness (or 3rd standardized moment) is a statistical parameter that provides information concerning the distortion of the values assumed by a given variable [36]. In the examples shown in Figs. 8 and 9, SK_{Fd} always takes positive values, which means that histograms tend to be asymmetric, with longer tails on the right side of the distribution and the majority of the F_d values concentrated on the left side. In this work, this trend was observed in the lowest strength mortars and the same behavior is shown by lime and hydraulic lime mortars tested by Del Monte and Vignoli [9], meaning that this positive SK_{Fd} may be related to material heterogeneity.

SK_{Fd} takes higher values for AS than AC mortars. Taking into account that AS11 and AC11 mortars have the same composition and so do the AS21 and AC21 mortars, except for the aggregate nature, it is possible to deduce that a higher SK_{Fd} may be due to the aggregate siliceous nature. Conversely, carbonate aggregate mortars tend to have more symmetric histograms, with a shorter tail on the right side of the distribution.

Assuming that using carbonate instead of siliceous aggregates improves the ITZ quality between grains and matrix, AS mortars are more heterogeneous than AC. Therefore, the longer tail on the right side of AS mortars histograms may result from the higher values and frequency of load peaks associated with the chip formations (Fig. 8). The huge concentration of values in the left side of the histogram, i.e. the considerable amount of low F_d values measured, may be a consequence of the wider extent of the damaged zone that takes place in low-strength heterogeneous materials. In these cases, the mean tends to be higher than the mode.

AC mortars, being more homogeneous, return drilling profiles with less load peaks and with the majority of F_d values concentrated in the middle of the histogram, resulting in a more symmetric histogram and closer mode and mean values.

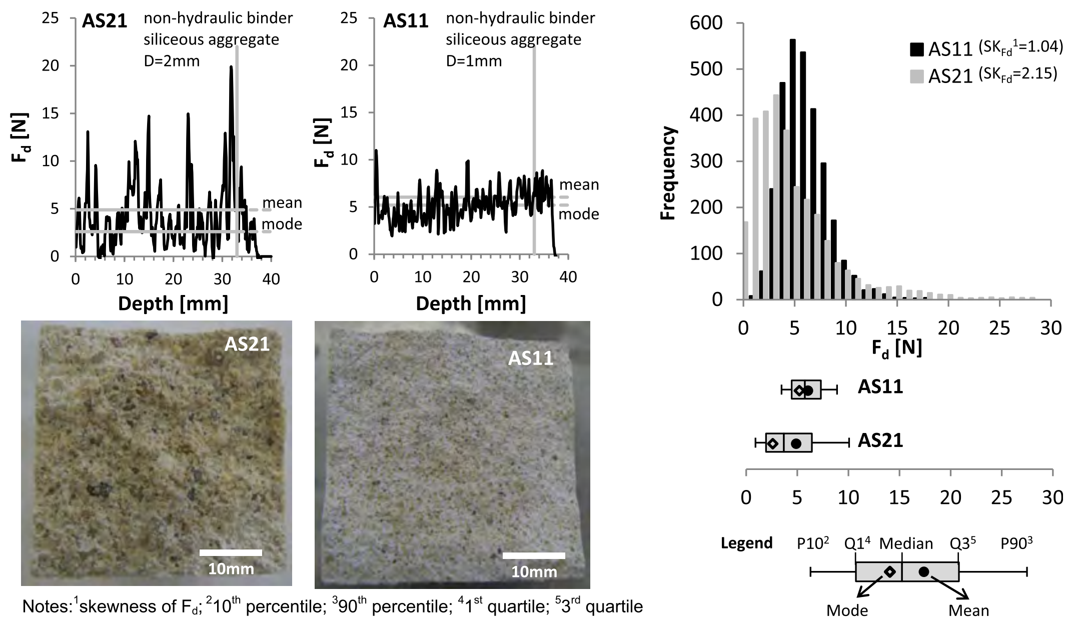

Fig. 8. Histograms, drilling profiles and specimens cross sections of AS11 and AS21 mortars (v/ω = 40/100).

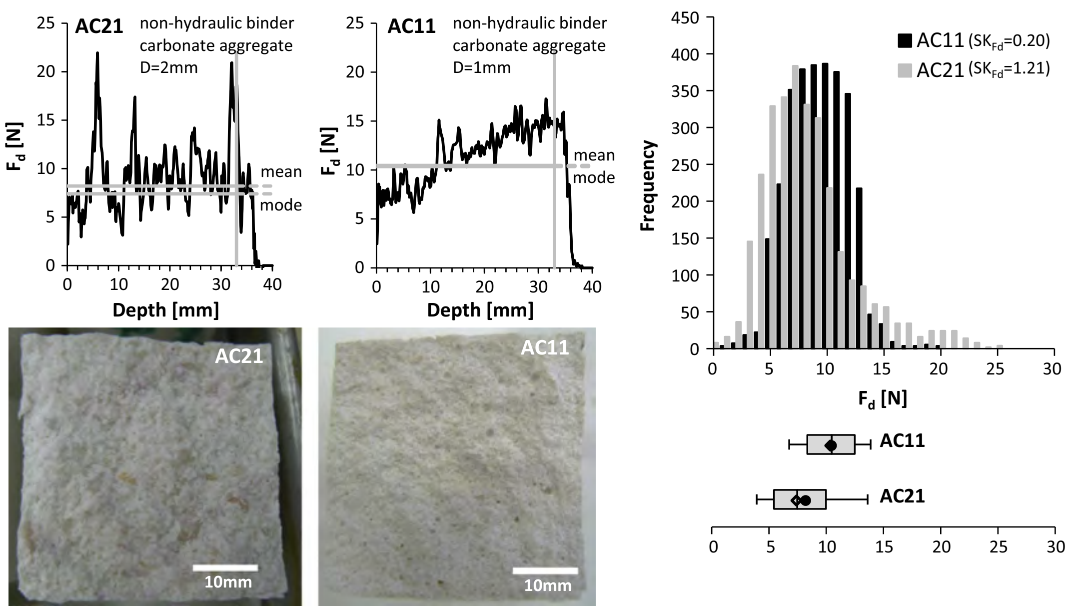

Fig. 9. Histograms, drilling profiles and specimens cross sections of AC11 and AC21 mortars (v/ω = 40/100).

Fig. 10 shows HS21 and HS22 histograms, drilling profiles and specimen cross sections. HS21 and HS22 show more symmetric histograms than AS and AC21 lime mortars, with lower SK_{Fd} values. Since these are siliceous aggregate mortars, this situation should be due to the more resistant binders, which improve the paste strength and, hence, ITZ quality.

These observations point out that SK_{Fd} can be an indicator of the ITZ quality and, consequently, of the material heterogeneity. In this case, higher SK_{Fd} values indicate more heterogeneity. In the following, the skewness of the F_d measurements obtained for the various mortars is analyzed in order to understand if the previous considerations may be generalized, i.e., if there is a significant relationship between this statistical parameter and relevant mortars heterogeneity characteristics.

4.3. Drilling resistance in low ITZ quality mortars

AS1 and AS2 are low-strength paste and ITZ mortars, AS2 with a coarser microstructure. Fig. 11 shows boxplot analysis and Fig. 12 shows relationships between f_c and both SK_{Fd} and coefficient of variation, CV_{Fd} (ratio between F_d standard deviation and the mean value).

As expected, longer boxplots were obtained for AS2 mortars. The wider range of F_d values is due to the higher heterogeneity and the aggregate bigger size leads to higher peak values (Fig. 8) for the coarser mortars. Consistently, AS2 mortars have higher CV_{Fd} than AS1 mortars (Fig. 12). The high CV_{Fd} value associated to a positive SK_{Fd} is the cause of an F_d mean higher than mode, particularly for AS2 mortars (Fig. 11). In Fig. 13, relationships between F_d

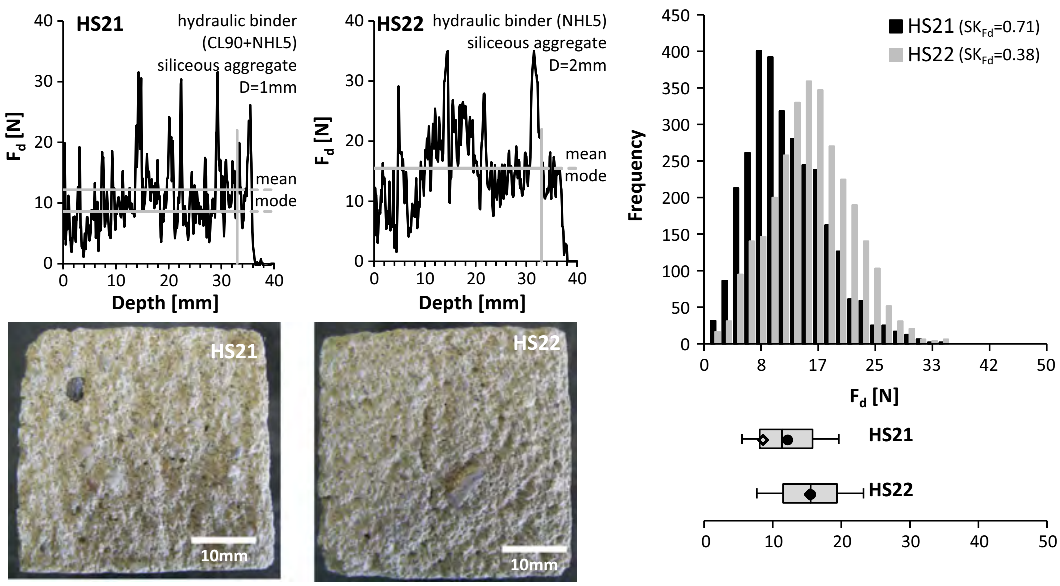

Fig. 10. Histograms, drilling profiles and specimens cross sections of HS21 and HS22 mortars (v/ω = 40/100).

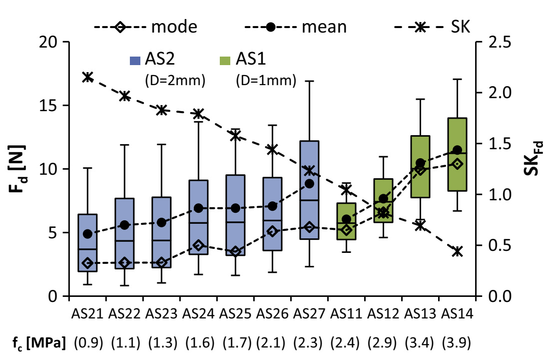

Fig. 11. Boxplots of AS2 and AS1 mortars. F_d and SK_{Fd} in terms of f_c.

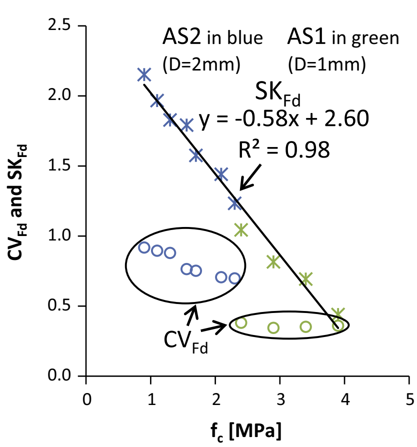

Fig. 12. SK_{Fd} and CV_{Fd} in terms of f_c for AS2 and AS1 mortars.

mean and mode values and f_c are plotted, and the higher difference between these parameters is evident for AS2 mortars.

The relationship between compressive strength and drilling resistance is an important result referred in many publications, since the compressive test is a very well established and accepted characterization method to assess mechanical resistance [2–6]. In the published works, the drilling resistance result was determined as the mean of the measurements. However, in the case of distributions with a configuration other than the normal function, other measures of the distribution central tendency, such as mode or median, have to be considered as alternative ways to assess material strength.

In Fig. 13, it is possible to consider all the 11 mortars in the same relationship only for the mode values. Hence, in drilling tests, mode seems to be a better indicator of f_c, especially when comparing mortars with different aggregate sizes.

SK_{Fd} correlates well with f_c (Fig. 12), and this parameter does not seem to be significantly affected by the different aggregate size of the mortars. Considering the increasing ITZ quality shown by the f_c improvement, here, once again, the SK_{Fd} decrease appears as a good indicator of the heterogeneity reduction. On the contrary, no relationship was found between CV_{Fd} and f_c, but CV_{Fd} seems to be a very good indicator of the aggregate maximum size.

4.4. Drilling resistance for higher ITZ quality mortars

AC and HS are higher ITZ quality mortars than AS1 and AS2, due to the replacement of siliceous by carbonate aggregates (AC) and to the adoption of hydraulic binders (HS).

Boxplots determined for these mortars (Fig. 14) indicate more symmetric distributions than for AS mortars. In this set, AC21 and HS21 mortars show the most asymmetric distributions. In

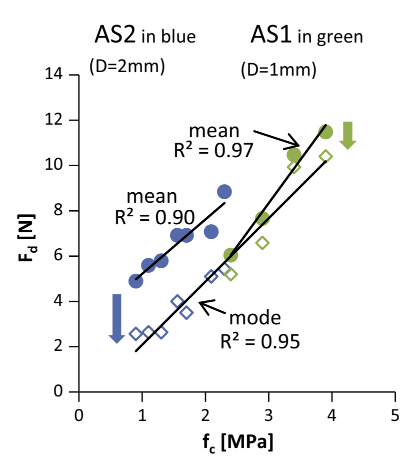

Fig. 13. Relationships between F_d mean and mode and f_c for AS1 and AS2 mortars.

order to assess the expected relationship between SK_{Fd} and heterogeneity, relationships between SK_{Fd} and f_c were plotted for all the studied mortars (Fig. 15).

R1 relationship is the same shown in Fig. 12. HS mortars clearly stand out of relationship R1, but when considering these mortars together with AS2, it is possible to obtain a cubic relationship (R2, Fig. 15) in which SK_{Fd} tends to zero for higher values of f_c. The AC2 mortars markers stay very close to relationship R1, but slightly to the left.

For AS2 and AS1 mortars (R1 relationship) the ITZ poor quality governs failure both in drilling and in compression. For this reason SK_{Fd} and f_c were both considered as heterogeneity indicators. The arising of different relations between SK_{Fd} and f_c, when higher ITZ quality mortars are considered, indicates that these parameters may be affected by additional factors in a different way. HS mortars return, on average, higher f_c values than AC mortars. However, it does not seem reasonable to infer that HS mortars are more homogeneous than AC mortars. The hydraulic binders adopted in HS mortars are expected to strongly influence the f_c increment. Conversely, the lower strength/stiffness of the paste, ITZ and aggregates of AC mortars surely accounts for their lower f_c values. Hence, besides heterogeneity, also strength/stiffness of the components should be considered as an additional factor governing f_c. Carrying out similar analysis for SK_{Fd}, this indicator appears to be more related to homogeneity than f_c, since a consistent tendency of SK_{Fd} reduction is observed for AC and HS mortars: excluding AC21 and HS21 mortars, SK_{Fd} takes values below 0.20, whilst f_c varies between 3.4 MPa and 10.6 MPa. Yet the hypothesis of strength/stiffness of components can also affect SK_{Fd} (although in a lower proportion than f_c) may not be discharged. In fact, the consideration of this factor may explain why microstructures with an apparently different homogeneity show similar SK_{Fd} values, like happens between AC11 and HS22 ($SK_{Fd} = 0.20$ and $SK_{Fd} = 0.18$, respectively) or between AC13 and HS23/HS24 ($SK_{Fd} = 0.06$ and $SK_{Fd} = -0.02$, respectively). Furthermore, the failure mechanisms of drilling, somewhat described by SK_{Fd}, are expected to be affected by these both factors – homogeneity and strength/stiffness of the materials. In this case, SK_{Fd} takes higher values for more heterogeneous and weaker materials (where brittle chipping prevails) and, conversely, lower values for more homogeneous and/or stronger materials (where plastic crushing prevails).

Therefore, the relationships shown in Fig. 15 are due to both heterogeneity and strength/stiffness differences of the materials. These differences are consequence of 3 aspects: (i) paste strength (higher for more resistant binders and lower water–binder ratio); (ii) ITZ quality (better for higher paste strength, more chemically compatible type of aggregate, finer microstructure); (iii) strength and stiffness of the aggregates. When the ITZ quality is high enough, the cracks ensuing from the failure tend to go through the hard grains rather than around them [14,15]. Furthermore, the grains hardness is also relevant to the interaction between drill-bit and material [20]. Hence, failure is affected not only by the properties of the paste and ITZ, but also by the properties of the aggregates. In this case, the total F_d value is the sum of the contributions due to each phase (paste, ITZ and aggregates). Strength and stiffness/hardness of the grains have a higher influence on the results than when the grains are not broken [10].

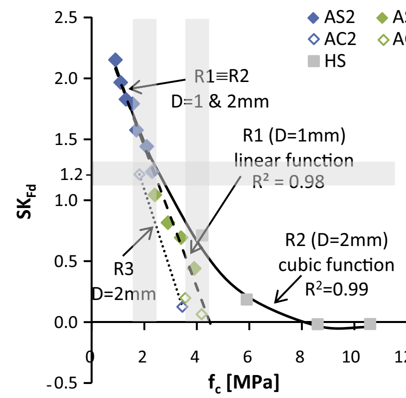

Fig. 15. Relationships between SK_{Fd} and f_c.

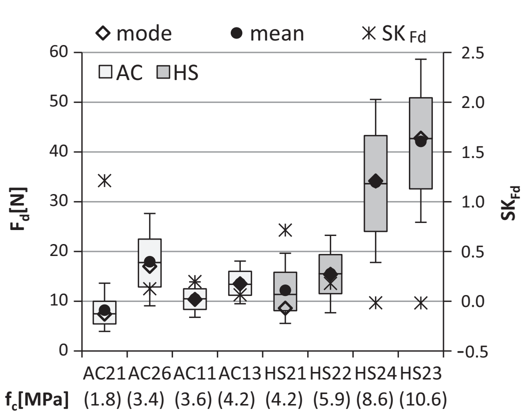

Fig. 14. Boxplots and SK_{Fd} for AC and HS mortars in terms of f_c.

The studied mortars enabled the establishment of three behavior trends between SK_{Fd} and f_c: (i) a linear relationship, R1, which includes low-strength mortars with the finer microstructure (AS1). AS2 mortars may also be included in this relationship, in spite of the coarser microstructure. This is possible because for low-strength mortars, the failure is conditioned by the weakness of the ITZ and the aggregate differences do not disturb the relationship. (ii) R2 relationship that includes coarser mortars (AS2 and HS2). The inhomogeneity occurrences of the ITZ are more pronounced than in finer microstructures or for carbonate aggregate mortars. As a consequence, more brittle chipping is expected for the same f_c and SK_{Fd} decrease with f_c is slower than in R1 and R3 mortars. iii) R3 relationship includes AC2 mortars, where aggregates are more active in the failure process, being eventually broken. This is due to the higher ITZ quality and the lower hardness of the carbonate aggregates [20]. AC1 mortars are positioned at the bottom of the chart between the R3 and R1 relationships, suggesting an intermediate behavior. This is explained by the ITZ quality, which is better in AC1 than AS1 mortars due to the carbonate aggregates, and by the carbonate aggregates content and size, which is lower in AC1 than in AC2.

4.5. Important factors influencing drilling resistance

Different behavior trends between SK_{Fd} and f_c become evident for mortars with f_c higher than a certain value of around 2 MPa in this work (Fig. 15). For mortars with f_c lower than this value, the failure is governed by the ITZ due to its poor quality. This is valid for both the finer and coarser microstructures of siliceous aggregates. The low number of the tested coarser mortars with carbonate aggregates does not allow a similar conclusion, but the same behavior is expected since aggregates are only able to influence failure for high enough paste and ITZ strength. Hence, for lower strength mortars (f_c under around 2 MPa in this work), ITZ strength is the main factor that affects the results. The heterogeneity and low-strength of these mortars lead to brittle chipping prevail (causing SK_{Fd} to take high values, above around 1.2), regardless of the hardness and size of the aggregates.

For higher strength mortars (f_c above around 2 MPa in this work) the aggregates start contributing to the failure in drilling tests, as paste and ITZ strength enables that possibility. Consequently, plastic crushing becomes more relevant. Consistently, SK_{Fd} takes lower values, below around 1.2. For R3 and R1 mortars, F_d grows more due to increase in homogeneity (in particular R3 mortars) than in strength. These mortars are weaker than R2, with f_c values below 4 MPa. For R2 mortars, F_d grows more due to increase in strength than in homogeneity, with f_c values between around 4 MPa and 11 MPa in this work. The mortar strength value above which aggregates are broken should be lower for mortars belonging to R3 relationship, higher for R1 mortars and the highest for R2 mortars (Fig. 15).

Figs. 16 and 17 show, respectively, SK_{Fd} in terms of F_d and F_d in terms of f_c, for the 19 tested mortars. The analysis is performed considering F_d mode values as this average parameter proved to be the most accurate indicator of the mortars mechanical resistance. F_d values were determined excluding the package effect range, whenever it occurred.

A linear relationship between SK_{Fd} and F_d ($R^2 = 0.81$) was obtained for all mortars, with the exception of HS23 and HS24 (Fig. 16). As expected, F_d is very strongly influenced by SK_{Fd} and, hence, by the failure mechanisms. SK_{Fd} tends to stabilize for values around zero, which happens for F_d higher than around 15 N (Figs. 16 and 17). The distribution of F_d measurements is an asymmetric function, with the majority of the values on the left side, for lower strength mortars, and evolves to an essentially symmetric function, for higher strength and homogeneous mortars. This is the case of AC13, AC26, HS22, HS23 and HS24 mortars, despite the different F_d. Hence, for F_d higher than a certain value (around 15 N in this work), this feature is no longer able to detect the material heterogeneity. This ability may return by performing tests with different drilling parameters, corresponding to a lower δ.

A linear relationship with a good coefficient of determination ($R^2 = 0.98$) was obtained between F_d and f_c for AS2, AS1, AC11, HS21 and HS22 mortars (T1, Fig. 17). The siliceous aggregates cause heterogeneity and the strength increase is mainly caused by ITZ and paste contribution. As a consequence, failure is governed by ITZ and both f_c and F_d increase with ITZ quality. Plastic crushing also increases, more due to the increase in strength than in homogeneity. The remaining mortars markers (AC21, AC26 and AC13) are positioned above T1 relationship, meaning that, for the same F_d, f_c is lower. Contrarily to T1 mortars, in these cases the plastic crushing increase is more due to the homogeneity improvement, ensuing from the carbonate aggregates. The F_d rise is particularly high for AC26 mortar, probably due to the higher ITZ quality

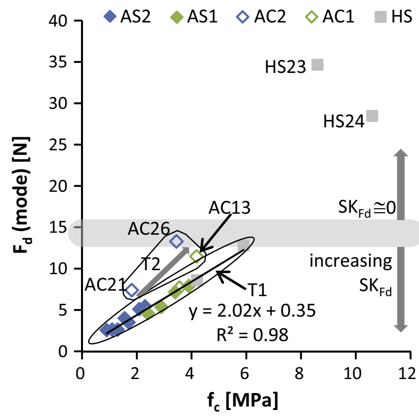

Fig. 17. Relationship between F_d and f_c.

than AC21 and due to the higher aggregate content and size than in AC13. Hence, for more homogeneous mortars, the F_d increase with f_c is higher and this may be observed comparing the T2 slope (represented by the arrow near AC21, AC26 and AC13 mortars) higher than the T1 slope.

Plastic crushing prevails in stiffer and more homogeneous materials since they have not the necessary "ductility" to dissipate the elastic energy accumulated during the test. This consideration points out to a possible relationship between drilling resistance and modulus of elasticity. Considering that f_c is also regarded in the literature as being related to the dynamic modulus of elasticity, E_d, [14] relationships between E_d and both F_d and f_c were determined for 12 mortars (Figs. 18 and 19). The coefficient of determination is slightly higher for the relationship with F_d ($R^2 = 0.94$) than with f_c ($R^2 = 0.87$). However, in the first relationship only AC1 mortars do not fit so well (R^2 increases from 0.94 to 0.97 when they are removed), while for the second relationship, six mortars (all the four carbonate aggregate mortars, HS23 and HS24) could be included in a different relationship from the remaining six.

F_d seems to have a more similar behavior to E_d than to f_c (Fig. 17). The huge relevance of the plastic crushing mechanism in AC, HS23 and HS24 mortars may be the reason for this. The drilling force is very sensitive to the plastic crushing mechanism and this causes a dependence reduction on this feature with the ITZ quality. On the contrary, f_c is very conditioned by the ITZ quality. E_d is assessed without material failure and considers equally all the contributions of the phases present in the composite material [37,38]. Hence, the ITZ quality is not so relevant.

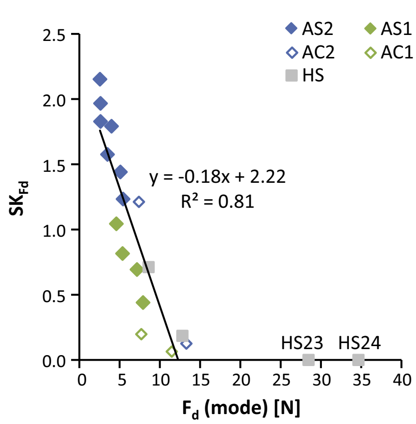

Fig. 16. Relationship between SK_{Fd} and F_d.

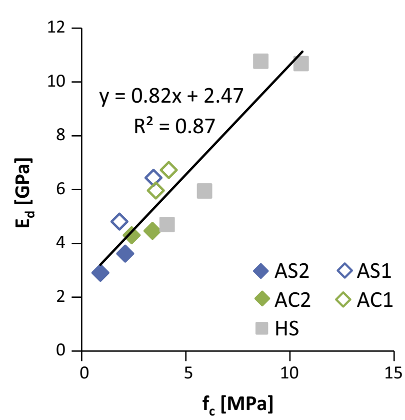

Fig. 18. Relationship between E_d and f_c.

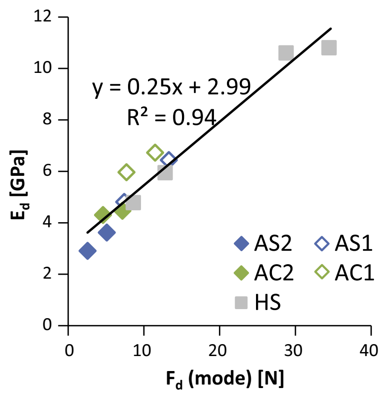

Fig. 19. Relationship between E_d and F_d.

5. Conclusions and further work

The most remarkable result of this paper is the awareness that the skewness of the drilling force measurements provides valuable information concerning the material heterogeneity and drilling failure mechanisms. As a consequence, a better understanding of the drilling results provided by low-strength heterogeneous mortars was achieved.

Low-strength mortars are weak heterogeneous materials, where the poor quality of the ITZ governs material failure. This happens both in drilling and in compressive strength tests and, hence, these two features show similar behavior. In the drilling process, brittle chipping is the prevailing failure mechanism and, hence, drilling force values are kept in a low level. Slight variations that occur are due to the increasing quality of ITZ and paste and result, mainly, from the additional energy needed to break the links between the particles. Aggregates are removed without being cut through. In these situations, skewness values are expected to take values above around 1.2, with an increasing trend with the strength reduction.

For mortars with paste and ITZ strength higher than a certain value, the plastic crushing mechanism is more pronounced, there is less chips formation and removal, a major volume of material is cut by plastic crushing and frictional contact becomes crucial. Aggregates may participate in the failure process, by being broken, if paste and ITZ strength is high enough. These additional factors (plastic crushing and frictional contact) cause a drilling force increase beyond the contribution of the mechanical resistance. In these situations the decrease of the skewness with compressive strength is differently affected, depending on the mortars composition (strength, stiffness/hardness and volume of the phases and the size of the aggregates). Skewness values below 1.2 are expected for this type of mortars.

This knowledge will be really useful when applying the drilling technique to real masonry mortars of unknown composition, providing richer information and more conclusive results. The skewness of the drilling force enables a qualitative evaluation of the bond between paste and aggregates. Higher skewness values indicate more heterogeneous and weak mortars. This is the case of many ancient mortars with a composition based on lime and on siliceous sands. Skewness values above 1.2 are likely to correspond to this type of mortars. In this case, the compressive strength may be estimated from the relationships between drilling resistance and compressive strength established in this paper. A compressive strength below around 2 MPa is expected. Also the maximum aggregate size may be estimated from the coefficient of variation of the drilling force. Additionally, the drilling resistance may be used to estimate the dynamic modulus of elasticity, as a good relationship between these features was established for the mortars studied in this work.

Conversely, if skewness values below around 1.2 are obtained in drilling tests and the mortar composition is unknown, two hypotheses may be considered: (i) it is a more homogeneous and weaker mortar (compressive strength shall not exceed around 4 MPa) or; (ii) it is a more heterogeneous and stronger mortar (compressive strength above around 4 MPa is expected). This happens because skewness is affected by both homogeneity and strength/stiffness of materials. Hence, further research is required to understand how drilling results may be used to take apart these mortars. Testing mortars with different heterogeneous characteristics, where drilling results are not so affected by the poor quality of the ITZ, will allow understanding the influence of each composition parameter (aggregate nature and size, B/A ratio, binder type, W/B ratio). In the meanwhile, complementary characterization techniques may be conducted to assess the aggregate mineralogy, grain size and the type of binder. This information enables to choose the most appropriate correlation between compressive strength and drilling force, through the analogy between the characteristics of the unknown mortar composition and the mortars studied in this paper.

The studied mortars were designed to enable a better understanding of the drilling results provided by low-strength heterogeneous mortars, like ancient mortars, and this purpose was achieved. However, further research is required to enhance the quality of the provided information by the drilling technique, especially if applied to real masonry mortars. The results were obtained from prismatic samples; hence, further tests on renderings are important to understand the influence of the different sample shape. Additionally, skewness and mode are statistical parameters which require a huge number of measurements to obtain accurate values. However, in some situations the number of measurements available is small (like usually happens in the field). Further research is important to find the minimum number of measurements required to keep the accuracy of the results. A critical appraisal of the mean value could be an alternative to the mode. The mean value of the drilling force is highly influenced by the peak loads that occur for materials with bigger hard grains. However, the coefficient of variation is a good indicator of the maximum aggregate size in heterogeneous low-strength mortars, giving information about the accuracy of the mean.

Finally, changing operational features, such as the drilling parameters or the rate of records acquisition, are expected to affect the results. Further research is required to quantify their influence. In particular, drilling parameters affect the prevailing failure mechanism. Being the skewness an indicator of the ratio between failure mechanisms, it enables the estimation of each mechanism contribution to the total drilling force. This will provide interesting indications to improve the characterization models used to simulate the drilling process and to create the possibility of comparing drilling strength, *J*, obtained by different drilling parameters.

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