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

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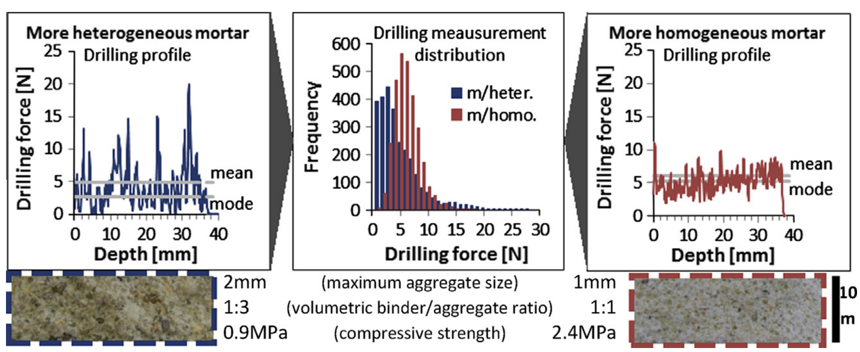
HIGHLIGHTS

- 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.

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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,

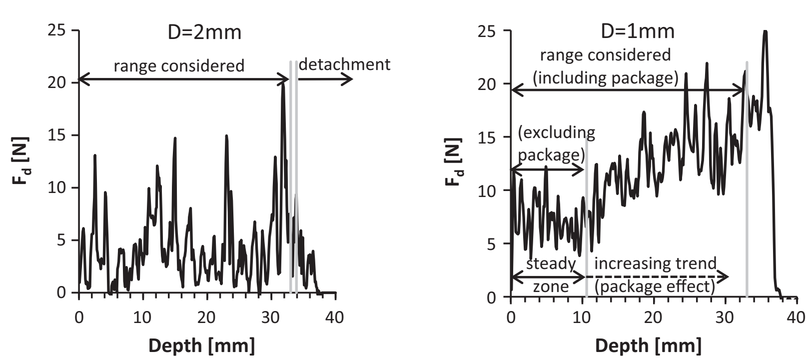

Fig. 1. Drilling profiles of two lime mortar mixtures with different maximum aggregate sizes, *D*.

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