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Torque Penetrometric Test for the in-situ characterisation of historical mortars: fracture mechanics interpretation and experimental validation

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HIGHLIGHTS

- Novel torque penetrometer for the in-situ mechanical characterisation of mortar.
- Toothed nail inserted into the mortar and twisted with a torque-meter until failure.
- Proposal of an interpretation theory based on fracture mechanics.
- Interpretation theory validated using new and available experimental campaigns.
- In-situ applications prove the reliability of the instrument for historical mortars.

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ABSTRACT

The assessment of historical structures requires appropriate knowledge of the behaviour of the investigated materials. Concerning masonry, its mechanical characterisation is a challenging task, since its composite nature requires the careful evaluation of the behaviour of its material components. In particular, the experimental assessment of the strength of existing mortar in historical structures still encounters several difficulties. This study investigates a novel Minor Destructive Testing (MDT) technique virtually equivalent to the vane test used for soils. The instrumentation, called herein Torque Penetrometric Test (TPT), is composed of a steel nail with four protruding teeth and a torque wrench. The test consists in inserting the toothed nail into a mortar joint and then applying a torque by means of a dynamometric key, until reaching the failure of the material. This work presents a novel interpretation theory based on basic concepts of fracture mechanics and applied to the micro-mechanical analysis of the stress state induced by the instrument on the investigated mortar. The proposed interpretative theory is validated through the execution of experimental tests in the laboratory and in a historical masonry building. The test proves to be effective for a quick in-situ MDT evaluation of the strength of existing mortars.

1. Introduction

The structural assessment of historical buildings has become a fundamental topic in the conservation of the built cultural heritage, especially in the last decades where significant catastrophic events have threatened many important constructions [1,2]. Concerning monuments, the evaluation of the structural health and the identification of possible vulnerabilities can help to preserve their original cultural value.

The conservation and protection of historical structures require a multidisciplinary approach involving a variety of professional skills. For this reason, the ICOMOS produced relevant recommendations in 2003 [3] in order to assist and advise the professionals involved in the assessment of historical masonry buildings. The proposed approach, called "Knowledge-Based Assessment", is based on the careful analysis of the information about the original structural conception, the construction techniques, the existing damage and the modifications occurred in the building's life. Both qualitative and quantitative approaches can be adopted in the

Abbreviations: DFJ, Double Flat Jack; DPT, Double Punch Test; DRMS, Drilling Resistance Measurement System; MDT, Minor Destructive Testing; NDT, Non Destructive Testing; TPT, Torque Penetrometric Test.

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diagnosis. The importance of the qualitative approach is based on a direct recognition of the monument, whereas the quantitative approach is fundamental in establishing the mechanical data necessary for the analysis phase. In this context, it is convenient to organise different levels of experimental activities. The inspection can start with simpler and less invasive tests, and proceed afterwards to more sophisticated and destructive tests to be executed only in few specific positions.

The experimental characterisation of masonry requires the evaluation of the properties of the constituent materials, i.e. units (stone or brick) and mortar (cement, lime, etc.). With the development of new technologies for the experimental testing of masonry constructions, several Non Destructive Testing (NDT) techniques were proposed to obtain information on the structure without damaging it. Most of NDT methods are based on the transmission of sonic or electromagnetic waves through the material. The sonic test [4] has shown its suitability in the estimation of the elastic properties of the materials, also allowing the determination of internal defects or discontinuities. The Ground Penetrating Radar (GPR) can detect the presence of voids, structural irregularities, different materials or moisture inside the existing masonry. The complementary use of these investigation techniques is a common practice in order to improve the reliability of the NDT results.

Several standards and recommendations for the assessment of historical structures [5] suggest to combine NDT and laboratory testing to improve the level of knowledge of the materials' properties. This approach is usually considered in works dealing with the assessment of historical masonry buildings [6].

Fully destructive tests are not possible in historical structures since all the experimental activities must respect the intrinsic heritage value of the buildings. For this reason, recent research is addressing the development of efficient Minor Destructive Testing (MDT), based either on penetrometric techniques or extraction of small samples of masonry to be tested in the laboratory [7–16].

Penetrometric techniques can be classified either as MDT or NDT [7], since the entity of damage induced to the structure is minimal. These tests are performed directly on the material to be investigated, requiring the removal of plaster or coating surfaces. The penetrometric tests for masonry are usually modified versions of micro-destructive techniques available for other materials (mainly concrete).

The Pin Penetration Test, also known as Windsor Probe, was initially designed for the investigation of hardened concrete according to the US standards [17]. The system uses a metal pin driven into the material since the recorded depth of penetration can be easily correlated to the material's compressive strength. Recent works about the application of such technique to low-strength mortars can be found in [12,18].

The Schmidt Hammer test is also well-known as NDT for concrete [19]. In this case, the compressive strength of the material is correlated to its superficial hardness. Using this principle, Van Der Klugt [20] proposed a pendulum hammer for the quality assessment of masonry joints.

The DRMS (Drilling Resistance Measurement System) method investigates the mortar strength [21] by measuring the force necessary to penetrate a compact material. Other researchers have developed different types of penetrometers [22,23], using the basic principles of the Standard Penetration Test (SPT) used in soil characterisation.

Recently, Christiansen proposed a torque penetrometer called X-Drill [24] consisting of a four-teeth nail made of stainless steel. A 6 mm diameter pilot hole is executed in order to drive the instrument into the mortar joint. The test is carried out by using a torque-meter that measures the maximum torque M_v resisted by the material. The author presented experimental relationships between the laboratory compressive strengths of some types of mortars and the corresponding values of torque obtained with the X-Drill.

This paper presents a MDT penetrometric technique called Torque Penetrometric Tests (TPT). This apparatus for in-situ testing is based on the procedures of both the geotechnical vane test and the X-Drill technique, but it provides important conceptual improvements in order to obtain more reliable experimental results [25]. This study presents a new mechanical interpretation theory of the TPT based on fracture mechanics. The proposed approach provides a simple analytical expression for the evaluation of the compressive strength of existing mortars. All the parameters of the proposed model are calibrated by means of experimental data available in the existing literature for several types of mortar.

The TPT technique and its interpretation theory were calibrated by considering a representative set of mortar specimens built in the laboratory with different compositions, corresponding to a rather wide range of compressive strengths. The comparison between the TPT measurements and the standard laboratory compression tests on the set of specimens provided the basic results for the interpretation of the TPT response [25]. Additional calibration data were gathered from experiments available in the literature [24]. Finally, the paper presents the results of real applications on a masonry wall built in the laboratory with historical-like materials [9,10], as well as on the existing masonry walls of a historical building struck by the 2012 Emilia-Romagna earthquake.

2. Description of the apparatus

The apparatus proposed in this research for MDT of historical mortars is called Torque Penetrometric Tests (TPT) [25]. It is composed of a nail with four teeth and a torque wrench. The nail is obtained by shaping a class 8.8 steel screw (characteristic tensile and yield strengths: 800 MPa and 640 MPa) with a lathe, and then manufacturing the teeth with a mill (Fig. 1). This material was chosen for its high performance, reducing the risk of torque failure of the nail during the test. The cost of the device is limited due to the large availability of the material and the easy manufacturing.

The geometry of the novel instrument was studied in order to reduce the sources of uncertainties of the testing technique, as well as the drawbacks detected in previous studies. Christiansen's X-Drill [24] was characterised by a fully toothed shank with an external diameter of 10 mm and an internal diameter of 6.5 mm. The X-Drill method required the measurement of the depth of investigation L_w at each test, set in the range between 15 mm and 20 mm [24]. This operation introduced L_w as a further uncertainty in the problem (see Fig. 2a), since the errors related to the estimation of the variable L_w affected also the evaluation of the ultimate normalised torque $m_v = M_v/L_w$ to be related with the material's compressive strength. Furthermore, the fully toothed shank of the X-Drill allowed the investigation of the sole external

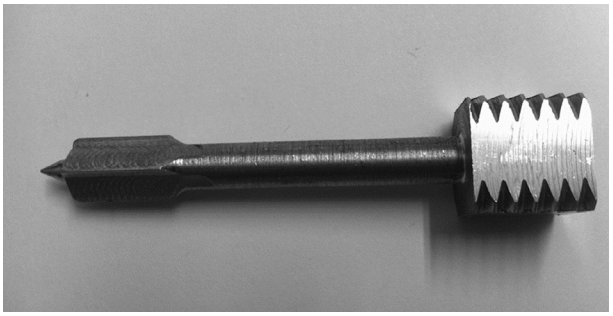

Fig. 1. Novel nail proposed for the Torque Penetrometric Test of historical mortars [25].