In lab and in situ assessment of masonry stones’ mechanical properties through the micro-drilling technique

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Abstract

Prevention and rehabilitation procedures on historical masonries can be successfully accomplished, only if a reliable characterization of masonry constituents’ properties has been formerly performed. During recent years several destructive and non-destructive techniques have been implemented for assessing the strength properties of masonry structural components (stones, bricks, mortars). The aim of this work is to demonstrate the capability of a micro-drilling technique to characterize in situ and quasi-non-destructively the strength properties of masonry stones.

1 Introduction

The European Cultural Heritage deals with a great variety of structures of high intrinsic value. Among these are the Natural Building (NB) Stones (or NBS), the key elements of our historical monuments. The NB stones, which have been used in the past in historical monuments in Europe, are various types of metamorphic, sedimentary and igneous rocks. NB stones are inhomogeneous as they consist of
grains of various minerals, they contain defects, such as pores and cracks, and frequently they are highly anisotropic. Historical monuments usually have been subjected through time to mechanical loads, and to various types of weathering (i.e. temperature variations, atmospheric pollution, freeze and thaw, moisture transport etc.), which affect their quality and impose damage of certain type and degree. The induced damage on NB stones due to aggressive urban environment may lead to significant losses of the elasticity and strength properties of the outermost layers of stone and result in erosion features, cohesionless appearance and disintegration. Damage/crack diagnosis of NB stones is the first stage in the planning of the remedial steps to which the success of the restoration will be entrusted. An erroneous diagnosis may be very harmful to the cultural, structural and economic outcome of the operation.

Up-to-now the classical processes for measuring either the mechanical properties and effectiveness of consolidation treatments or the surface damage of stones are observational, empirical or destructive. In the second method we may mention the rebound hardness Schmidt hammer technique with subsequent empirical correlation of the rebound index with the Uniaxial Compressive Strength (UCS). According to the last method a sample is taken from the structure – if it is permitted – it is cut and then standard rock mechanical tests are performed on it. However, the knowledge of the mechanical properties and damage must result from non-destructive tests if we want to use the structure thereafter. Up-to-now there is not available in the market a valid “stone-friendly” technology (i.e. non-destructive), procedure or apparatus for the in situ assessment of damage and effectiveness of consolidation treatments of stones.

2 A new drilling force and torque measurement system (DFTMS)

The determination of the strength parameters of stones is based on the interpretation of thrust (in N) and torque (in N x mm) with penetration depth measurements, necessary to perform a drillhole of depth 1-5cm and diameter 3-9mm, with specific drilling operative conditions, by using a special portable and automated microdrilling DFTMS prototype device. The prototype and six DFTMS devices have been developed within the Hardrock Project (SMT4 - CT96 -206), funded by the EC and built by SINT (Italy). The DFTMS, that is illustrated in Figure 1, consists of:

- Mechanical Device: equipped with motors for positioning and drilling (DD in the Figure 1a).
- Electronic Unit: power unit, motor control board for dc motor; motor control board for stepper motor; conditioning amplifier for the load cell signal; graphic display; Keyboard (EU in Figure 1a).
- Tripod: It can be adjusted in height from 830 to 1600 mm with its legs standing on a plane larger no more than 900 mm in drilling direction. The tripod feet could be fixed to the floor using screws or nails. Its head allows 3D movements in order to correctly positioning the drilling unit (T in the Figure 1a).
• Accessories: 2 steel plates with 3 threaded bars and lock nuts to hold a stone specimen (SH in the figure); power line (220 V) and connection cables (serial interface RS232; external power 24 V DC /3 A max.); PC's dedicated software for data elaboration and printing.

The rotation speed of the drill can be set by the user from 0 to 1200 rpm and is controlled by the electronic device (PWM with tacho feedback) (RS in Figure 1b) in order to have a constant speed during the entire drilling work. The displacement of the drill is controlled with a stepper motor to give constant speed of movement with resolution of 0.0025 mm/step. The position of the drill referred to the surface of the stone (starting point) is always known because it is controlled directly by the software through the dedicated electronics. The evaluation of the stone strength parameters are related to the drill penetration force and drilling torque measured by a pair of load cells (LC in Figure 1b), during drilling. The system measures continuously the penetration force and torque, as well as the actual drill position.

Figure 1: Photos of the current microdrilling device: (a) Drilling Force Measurement System (DFTMS) components: EU=electronic control unit, DD=drilling device, SH=sample holder, T=tripod with three-dimensional moving head; (b) LC=load cell, RS=rotational speed sensors, DB=drill bit.

The drill bits that may be used are coming from the normal masonry practice and are made either from hard steel (Fischer SDD or FSDD) or by soldering a tip of polycrystalline diamond (PCD) as it is illustrated in Figure 2. The drill bit diameter (Figure 2a) may range from 3 mm to 9 mm.

Finally, all logged data (thrust, torque and drill position) and test data settings are memorized on a Flash EEPROM (non volatile but erasable memory) or transmitted directly to a laptop PC through a standard serial communication port.
Figure 2: (a) Small diameter bit design, and (b) photograph of the PCD drill-bit used in the experiments (PCD insert of a length of 5 mm soldered at the tip of a normal steel drill bit (2a=4.8 mm).

3 The micro-drilling method for non-destructive characterization of stones

Micro-drilling is performed by the new portable Drilling Force and Torque Measurement System [1] (DFTMS). The stone is drilled (hole-diameter 3\(\pm\)5 mm, hole-depth 1\(\pm\)5 cm) under specific operative conditions (drilling depth, rotational and penetration rate, type of drill-bit), whereas the applied thrust force and torque are simultaneously measured.

As it is illustrated in Figure 3, it is proposed in this work to smooth the thrust force (WOB) and torque versus penetration depth data by fitting negative exponential curves.

Figure 3: Example of smoothing of (a) WOB vs. depth data and (b) torque vs. depth data during a microdrilling test on Wustenzeller sandstone.
In order to demonstrate the applicability of DFTMS for the detection of cracks in stones a series of experiments were carried out in Goia (Carrara) marble with an artificial crack. Figure 4 shows the detection of crack position by means of the DFTMS.

![Gola marble sample with artificial crack](image)

**Figure 4:** Microdrilling test on marble specimen with artificial crack.

A database, consisted of ‘in lab’ and ‘in situ’ drilling measurements, for various masonry stone types, was generated. For the same stone types, uniaxial and triaxial compression tests were performed in order to assess the validity of the method.

The phenomenological model of Exadaktylos et al [2] and Exadaktylos and Stavropoulou [3] was implemented to correlate the drilling data \((T, W, v, a, \delta)\) with the strength properties of each stone type. The general expression of the model has as follows

\[
\frac{T}{f_c \delta a^2} = T \left( \frac{W}{f_c \delta a}, \frac{v}{a \delta}, \mu, \gamma \right)
\]

in which:
- \(W\) = axial thrust force or weight-on-bit,
- \(T\) = torque,
- \(a\) = drillhole radius,
- \(\delta\) = penetration depth per revolution,
- \(v\) = penetration rate,
- \(\gamma\) = dimensionless constant that accounts for the bit geometry,
- \(f_c\) = UCS of the rock and
- \(\mu\) = friction coefficient of the rock.
The model was suitably calibrated on the drilling data obtained from four stone types, resulting in accurate and reliable predictions of the UCS ($f_c$) as well as the internal friction angle ($\varphi$) of each stone. Figure 5 illustrates the very good comparability of triaxial compressive strength data (point-symbols) obeying the constitutive relation below with the microdrilling data (continuous lines) for all stones.

$$\sigma_1 - m\sigma_3 = f_c, \quad m = \frac{1 + \sin \varphi}{1 - \sin \varphi}$$

wherein $\sigma_1$ denotes the greater axial stress and $\sigma_3$ denotes the lower lateral stress that remains constant during the test on axisymmetric cylindrical specimens.

![Comparison with triaxial compression tests](image)

Figure 5: Comparison of triaxial strength data for the four stone types.

4 In situ micro-drilling tests

An extensive programme of in situ micro-drilling tests was realized at the SPAP building, located at the area of Ancient Olympia in Peloponese (Figure 6). SPAP building is a typical two-storey masonry structure, erected at the end of 19th century and initially owned by the Peloponese Railways Association. The Greek Ministry of Culture, which is the present owner, has elaborated a detailed rehabilitation programme for the building, in order to accommodate the needs of the 7th Ephorate of Prehistorical and Classical Antiquities.
In parallel with the in situ micro-drilling tests, a set of laboratory tests was performed on stone cores, sampled from various locations of the structure. The main stone type (according to the results of the petrographic analysis on thin sections) is a gray-whitish coloured limestone, with small percentages of quartz and albite, usually characterized as ‘beach rock’. The laboratory test results are summarized in Table 1.

Table 1. Physico-chemical characteristics of structure’s main stone type [4]

<table>
<thead>
<tr>
<th>X-ray diffraction analysis [xxx: much, xx: enough, x: little]</th>
<th>Apparent density (gr/cm³)</th>
<th>Apparent porosity (%)</th>
<th>Uniaxial compression strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcite     Quartz    Albite    Microcline</td>
<td>2,53</td>
<td>9,13</td>
<td>65,1</td>
</tr>
<tr>
<td>xxx         x          x          traces</td>
<td></td>
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Micro-drilling tests were performed on the structure’s main stone type (gray-whitish coloured limestone) at fourteen (14) locations (Figure 6), for two penetration rates (5 and 10 mm/min) and various rotational speeds (varying between 300 rpm and 900 rpm).
Typical diagrams of the drilling force (WOB) versus penetration depth and torque moment versus penetration depth are given in Figure 7.

Smoothened drilling data (fitted with a negative exponential curve) are implemented in the phenomenological model of Exadaktylos et al [2] and Exadaktylos and Stavropoulou [3], in order to evaluate the UCS ($f_c$), as well as the internal friction angle ($\phi$), of the in situ examined stone (Figure 8).
The accurate prediction of the UCS value (63.6 MPa) in comparison with the respective laboratory test value (65.1 MPa), validates the credibility of the method and the reliability of the model.

5 Conclusions

A novel quasi-nondestructive method for in lab and in situ evaluation of stone strength parameters has been presented. This method is based on the micro-drilling technique and on an appropriate theoretical model for drilling of rock. Laboratory test data have demonstrated that this method may be used for the estimation of rock strength in triaxial compression. Hence, expensive, destructive and time-consuming triaxial tests on geomaterials may be avoided. However, this remains to be further confirmed by means of more lab tests. In situ micro-drilling tests at SPAP building have also demonstrated the reliability of the proposed methodology. It is worth mentioning here that no other available method today in the market (i.e. Schmidt rebound hammer, ultrasonics etc.) can be used for the same job as the above, that is for the in situ, non-destructive estimation of stone strength parameters, that are essential for restoration design.

Acknowledgements

The partial financial support of this study by the European Union DGXII MCDUR Project with Contract G6RD-CT2000-00266, as well as by DIAS "Integrated tool for in situ characterization of effectiveness and durability of conservation techniques in historical structures (DIAS)", Proposal No. DIAS-EVK4-2001-00141, is kindly acknowledged here.
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