ON-SITE DETERMINATION OF COMPRESSIVE STRENGTH FOR HISTORICAL MORTARS WITH THE SCRATCHING TEST : METHOD AND PRELIMINARY RESULTS

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ABSTRACT

Since the civil authorities have understood the necessity to preserve old heritage buildings, important budgets have been allocated to finance restoration campaigns. For historical masonry buildings affected by structural pathologies, the restoration campaigns have to be preceded by stabilisation works. In order to understand precisely the structural behaviour of such constructions and to propose effective solutions for the future, engineers need correct knowledge of the constitutive materials (stone, mortar, ...) Several on-site determination techniques exist, each having advantages and disadvantages.

This paper presents a scratching device, used daily by the petroleum industry for the measurement of the mechanical properties of rock materials. The scratching test has already shown its suitability in that field [1, 2, 3] and the paper proposes to extend it for on-site determination, from a small piece of mortar, of the uniaxial compressive strength - UCS. First, the method is presented. The data recorded during a scratching test are then interpreted with a phenomenological model in order to compute the intrinsic specific energy - ε - of the material, which is correlated with the UCS. The results of a preliminary calibration campaign performed on lab mortars in order to determine the relation between ε and the UCS are presented. Finally, application of the technique in the framework of the stabilisation works on the Our-Lady cathedral of Tournai (UNESCO World Heritage) is described. The preliminary results are encouraging and further research is in progress.

KEYWORDS: mortars, compressive strength, less-destructive method, on-site determination

INTRODUCTION

Several papers [4, 5, 6, 7] have presented strong experimental evidence that, for rock materials, strength properties can be assessed from scratching tests. A first, portable device was developed during the 90's at the University of Minnesota (USA) in order to conduct quick and precise tests. Subsequently, the apparatus has been improved and the experimental procedure has been optimised [8]. Numerous tests have been successfully conducted on numerous materials: rocks but also some construction materials [3].

SCRATCHING TEST: PRINCIPLE AND TESTING DEVICE

The scratching test consists of tracing a groove at constant shallow depth d, at the surface of a rock sample, with a rectangular PDC cutter of width w (see Figure 1). The cutter is inclined at an angle θ and is displaced at constant horizontal velocity v. The magnitude and inclination of the force F acting on the cutter are accurately measured and recorded during the test. The main characteristics of the experimental setup are summarised in Table 1.

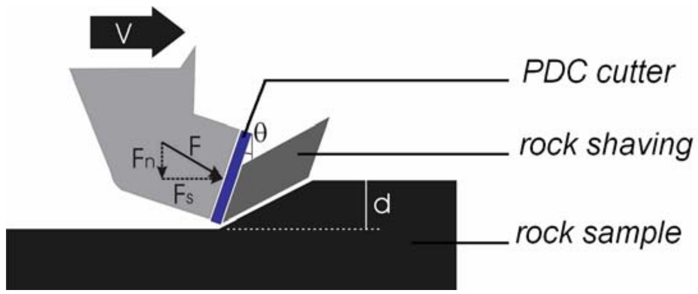

Figure 1 - Scratching test setup

Table 1 - Characteristics of the scratching test setup

θ	w (mm)	v (mm/s)	d (mm)	F_s,F_n (N)
15	10	4 - 10	0.1 - 1	0 - 4000

The main components of the testing device used for rock materials are presented in Figure 2. The device consists of a fixed sample holder of length L and a moving cart housing the vertical positioning system, the load cell and the cutting element holder. The horizontal movement of the cart is operated by a computer controlled stepper-motor driving a horizontal motion Archimedes screw via a gearbox. A micrometer indicates the depth of cut, manually adjusted with the positioning system. The vertical travelling mechanism can be locked in order to maintain a constant depth of cut while cutting. The load sensor measures the horizontal F_s and vertical F_n components of the force F acting on the cutter. The load sensor has been fully calibrated by the manufacturer with the cutter holder mounted on it and the force applied at the tip of the cutter. The complete acquisition line achieves 0.5 % cross-talk and about 0.5 N of precision over the entire measurement range. The scanning rate is typically set at 25 samples per millimetre.

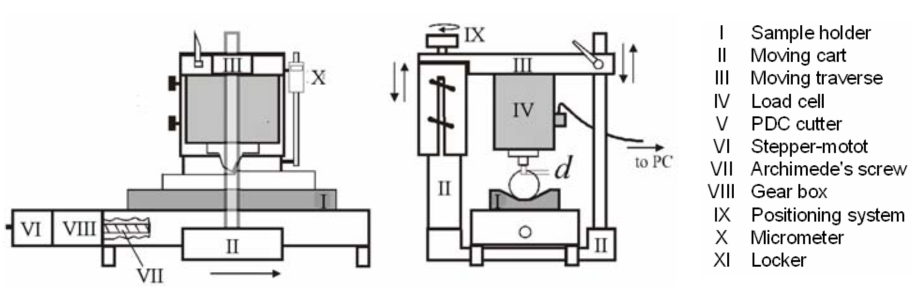

Figure 2 - Conceptual sketch of the testing device

THEORETICAL BACKGROUND AND VALIDATION ON ROCK MATERIALS

Rock cutting is associated with a "ductile" or a "brittle" mode of failure depending on the depth of cut [7]. The ductile mode takes place at shallow depth of cut and is associated with plastic flow, while the brittle mode occurs above a threshold depth of cut and is characterised by the propagation of tensile crack.

It was shown that within the ductile regime, the magnitude of the force (averaged over a length *s* many times the depth of cut, $s \sim 5\text{-}10$ mm) acting on a sharp cutter increases linearly with the cross-section area of the groove being traced (i.e. with the depth of cut for rectangular cutter). This can be seen in Figure 3.

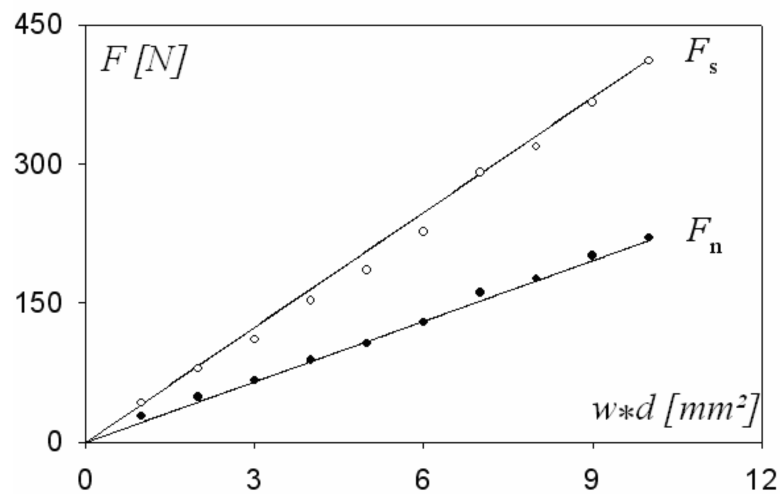

Figure 3 - Evolution of F_s and F_n with w∗d *[after (3): w = 10mm, Lens limestone]*

The two measured components of the force can be written [9] as presented in Equations 1 and 2.

$$F_{cs} = \varepsilon * w * d \qquad \text{Equation 1}$$

$$F_{cn} = \zeta * \varepsilon * w * d \qquad \text{Equation 2}$$

where ζ characterises the inclination of the force vector and ε is the intrinsic specific energy. The adjective "intrinsic" refers to the pure cutting process (subscript *c*) obtained with a sharp cutter, not accounting for energy dissipated (frictional force) along the wear surface of an eventual blunt cutter. During the test, the ratio ρ of the normal to the tangential component of the force can be used to monitor the sharpness of the cutter: in fact, ρ is ζ for a sharp cutter and bluntness causes ρ to increase. The intrinsic specific energy varies from one type of rock material to another, as presented in Figure 4.

Experimental results show that ε varies with the material strength. These results were the motivation to establish a correlation between the intrinsic specific energy and a standard material strength property, such as the uniaxial compressive strength *q*.

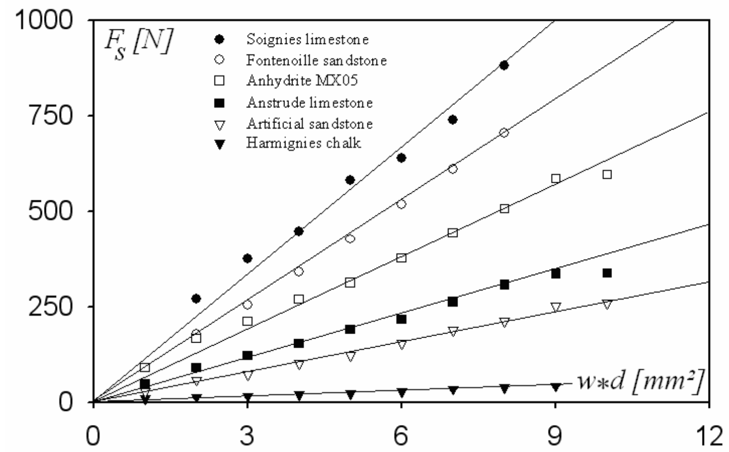

Figure 4 - Evolution of F_s with w∗d ***[after [3]: w = 10mm, 6 different rock materials]***

Numerous scratching tests were conducted in three different laboratories (University of Minnesota, Geo Mechanics Department, USA ; Polytechnic Faculty of Mons, Mining Engineering Department, Belgium and Total oil company, Rock Mechanics Department, France) on 252 rock materials divided into 92 sandstones, 86 limestones, 19 shales, 6 dolomites, 4 chalks, 3 granites or granodiorites, 2 coals, 2 anhydrites, 17 construction materials (clay, cement, plaster …) and 3 refractories. Tests were conducted with sharp cutters at depths of cut ranging from 0.1 to 1 mm. Particular attention was given to avoiding chipping and to control the state of sharpness of the cutter. In parallel, uniaxial compression tests were conducted on the same rock materials. As much as possible, the tests were performed on the same rock samples (typically plugs of 25 mm diameter and 50 mm length). It was found that a minimum of three cuts (at different depths of cut) must be conducted to provide a precise estimation of the material strength. The intrinsic specific energy was identified with the slope of the best linear fit conducted on data points in the $F_s - w{*}d$ diagram.

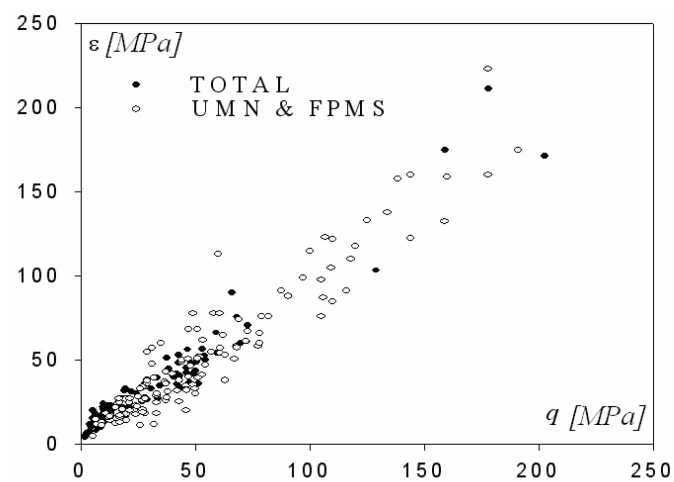

Figure 5 - Correlation between ε and q ***[after [3]: for 252 different rock materials]***

The strong correlation between the intrinsic specific energy and the uniaxial compressive strength (illustrated in Figure 5 and best linear fit as Equation 3) shows that the scratching test is efficient for a great range of homogeneous and cohesive rock materials. The encouraging results obtained on chalks and other sedimentary rocks with poor compressive strength led to the study of possible transposition of the technique to the testing of cohesive and homogeneous mortars, the advantage being the possibility of collecting information from a rather small piece of mortar.

$$\varepsilon = 0.97 * q + 0.06 \qquad \text{Equation 3}$$

REQUIREMENTS AND PRELIMINARY CALIBRATION FOR MORTAR TESTING

The first part of the research concerned the adaptation of the test device and the experimental procedure to mortars. Numerous tests have been performed on two "limiting" mortars: one of low compressive strength (~0.4 MPa) and one of high compressive strength (~30 MPa). These tests allowed the modifications needed to make the scratching test efficient for mortars to be determined. The main modifications are:

- adaptation of the load cell to the specific force range encountered;
- specific training to develop particular skills of the operator;
- implementation of new software.

The second part of the research concerned the calibration of the technique. This is necessary for further use as a means of on-site determination of the uniaxial compressive strength. This paper presents the results of the preliminary calibration tests. These tests were performed on 9 different mortars prepared with natural hydraulic lime, hydrated lime and/or cement. The compositions, summarised in Table 2, were chosen to provide mortars showing different compressive strengths mostly located in a convenient range (from 0.5 MPa up to 15 MPa).

Table 2 - Lab mortars used for preliminary calibration (composition in volume)

Mortar #	Mine Sand	River Sand	Portland Cement	N Hydraulic Lime	Hydrated Lime
1	0	24	3	0	7.5
2	0	24	6	0	0
3	6	18	0	9	0
4	24	0	9	0	0
5	24	0	0	6	0
6	Manufactured mortar				
7	Manufactured mortar				
8	0	21	5	0	8
9	0	24	0	12	0

On each lab mortar, several types of test were performed :

- UCS determination according to European standard EN 1015-11. This test is based on the compression of prisms of 40 x 40 x 75 mm^3 between two steel platens of 40 x 40 mm^2. The value of q_{EN} presented in Table 3 is the mean value from 10 measures for the first set of mortars (# 1 to # 5) and from 60 measures for the second set (# 6 to # 9).

- UCS determination according to the International Society for Rock Mechanics (ISRM). This test is based on the compression of cylindrical samples (diameter 40 mm and height 80 mm) between two steel platens. The value of q_{ISRM} in Table 3 is the mean value from 15 measures (mortars # 1 to # 9).

- Intrinsic specific energy determination using the adapted scratching test device: the value of ε presented in Table 3 is computed from tests performed at 10 depths of cutting with a nominally sharp cutter (mortars # 1 to # 9).

Table 3 - Results of the tests performed durig the preliminary calibration campaign

Mortar #	q_{EN} **[MPa]**	q_{ISRM} **[MPa]**	ε_{10} **[MPa]**
1	3.12	2.9	5.9
2	12.06	10.8	17.5
3	2.76	2.1	4.3
4	31.9	25.3	42.4
5	0.38	0.36	0.8
6	6.62	6.6	10.7
7	4.77	4.3	8.2
8	12.19	9.1	18.2
9	4.66	4.4	9.0

The results obtained during the preliminary calibration programme are shown on Figure 6. There is a strong correlation (R^2~0.99) between ε and the conventional values of the UCS. Best linear fits are presented as Equation 4 (for UCS-EN) and Equation 5 (for UCS-ISRM). However these fits are only based on 9 mortars (more data should be completed in order to improve the relation). Nevertheless, this abacus can be used for quick on-site interpretation.

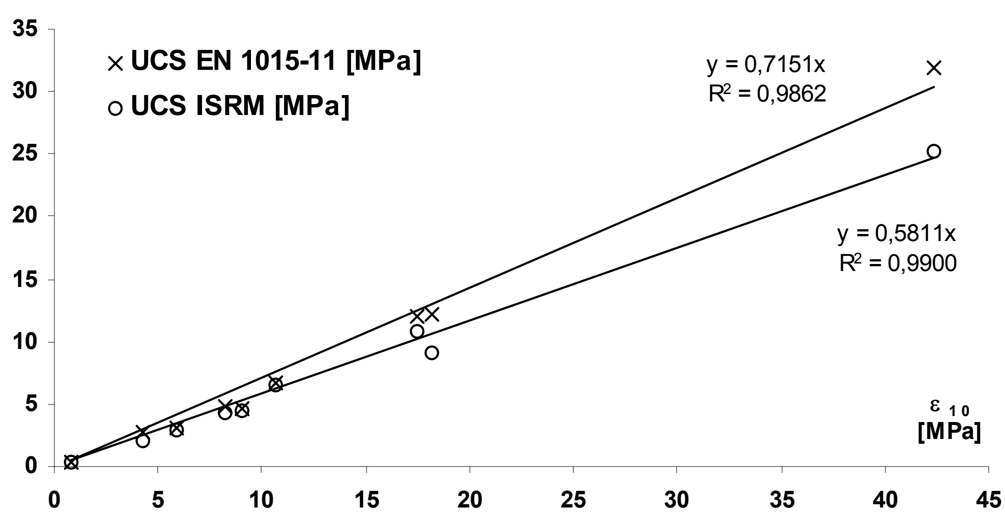

Figure 6 - Correlation between ε and UCS (EN & ISRM) for mortars

$q_{EN} = 0.7151 * \varepsilon$ Equation 4

$q_{ISRM} = 0.5811 * \varepsilon$ Equation 5

PRACTICAL APPLICATION ON A HERITAGE BUILDING

The Our-Lady cathedral of Tournai (B) was built during the 12th and 13th centuries and has suffered several structural pathologies for a very long time caused by underground phenomena. The use of a powerful stabilisation technique (called "Jet Grouting") needs precise quality assessment of the masonry foundations, which are composed of massive calcar stones and thick layers (~50 mm) of a medieval cohesive and homogeneous mortar.

Figure 7 - The Our Lady cathedral of Tournai

An important test programme has been carried out, using a traditional approach: from cores (see Figure 8-left) removed out of the masonry, cylindrical samples are realised and tested according to ISRM. The technique is efficient for stones but problems often occur with mortars. It is not easy to find masonry cores with enough mortar to prepare samples of sufficient size. While the information obtained about stones is sufficient, information about the mortars is often incomplete. The main UCS values of the mortars tested ranged from 5 to 15 MPa for cores coming from different parts of the church.

Figure 8 - Cores removed out of the foundation - normal (left) and small diameter (right)

A complementary scratching test campaign (to determine the intrinsic specific energy) was carried out. From the measured values of ε, the corresponding values of q_{EN} and q_{ISRM} were computed on the basis of the preliminary calibration abacus (Figure 6). The values obtained from the different mortars tested are within the range of the UCS obtained from the traditional test programme. Moreover, the information obtained with the scratching test was more plentiful:

- The surface character allows testing of "poor cores" where insufficient mortar was present to realise large enough samples. It is important to note that the measurement was started after several passes at the same location in order to test mortar not debonded by the drilling operations. In this way, most of the cores removed from the foundation could be analysed successfully.
- The less-destructive character allows several tests to be performed on the same sample. That is obviously favourable from a statistical point of view. This way, the results can be controlled.
- The possibility of using small diameter cores (see Figure 8 - right) allows cores to be taken from a greater number of zones by removing the same total quantity from the walls. In this way, the results of the tests become more representative of all the masonry.

It is important to note that the local approach of the scratching test needs to be involved in an extensive test programme (enough tests to ensure the results are representative) or to be coupled with non-destructive techniques working at a global level.

Table 4 - Results of scratching tests performed in the Our Lady cathedral of Tournai

Localization of the mortar sample	**ε_{10} [MPa]** **Measured value**	**q_{EN} [MPa]** **Computed value**	**q_{ISRM} [MPa]** **Computed value**
Mantille	13.7	9.8	8
Absydium	34.6	24.7	20.1
Brunin	13.3	9.5	7.7
Lanterne #1	17.7	12.7	10.3
Lanterne #2	24.6	17.6	14.3
Nave	8.5	6.1	4.9

CONCLUSIONS

This paper presents the scratching test, its applications on rocks and some very preliminary investigations (~390 measurements) concerning its extension to the field of historical mortars.

The results show that with small modifications, the device used for rocks can also be used for mortars. The test appears to be an efficient way for on-site determination of the compressive strength of homogeneous and cohesive mortars. The technique does not seem to be applicable to mortars presenting severe inhomogeneity (grains of great size,...) or very poor cohesion.

Our experience is limited and it is not possible to propose strong conclusions about the accuracy of the solution, but the preliminary results are encouraging. An extensive research campaign should be initiated to confirm our first results. This campaign should include a greater number of lab tests to provide a robust database and several comparative studies performed on heritage masonry buildings in order to validate the method.

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