THE RECOURSE TO CUTTING-BASED TOMOGRAPHY FOR QUANTIFYING THE SURFACE STRENGTHENING OF ALTERED STONES

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ABSTRACT

Several causes may be responsible for physical or chemical degradations affecting materials used in stone masonry structures. In most of the cases, a treatment with specific products may be prescribed, targeting a surface strengthening effect. In prevision of such interventions, a fundamental key point consists in quantifying the initial alteration of the material in order to opt for the most appropriate solution and, later, in estimating to what an extent the treatment will have brought an effectively beneficial effect. Transposed from a daily usage in the petroleum industry, the little destructive cutting test is here proposed in combination with a tomographical tool that allows visualizing the strength state inside sample stones before and after that a treatment has been applied.

KEYWORDS: retrofitting, masonry, stone, alteration, degradation, strengthening, quantification, cutting test, tomography, ethyl silicate, lime water

1 INTRODUCTION

Masonry constitutes a building material that has been widely used along the centuries and in most of places around the world. Therefore, it usually constitutes a key element of contemporary rehabilitation projects and the importance of related aspects keeps increasing as many chemical or physical phenomena with either a natural or an anthropic origin are likely to affect the state of conservation of the constitutive elements like stone blocks, clay bricks or mortar joints. As a consequence of such various alteration phenomena, local or global degradations may appear and the rehabilitation interventions on affected masonries will imply the recourse to specific treatments in order to bring better characteristics back.

Several types of treatment are commercially available, acknowledged to be more (lime-based solutions) or less (ethyl silicate or resin-based solutions) durable. The fundamental difficulty concerns the possibility to determine whether a treatment is required (**prescription aspects**) and, once it is the case, to control to what an extent the proposed treatment has provided the expected effects (**control aspects**). The present paper describes a technical approach based on a quantitative little destructive testing device that allows a sharp visualization of the local strength state. The first part of the paper deals with classically encountered stone alteration problems, insisting on strengthening treatments likely to improve the durability of impacted structures. The particular problem associated with the prescription and control of interventions is discussed as it constitutes a key aspect associated with such financial investments. Then, the second part of the paper concerns the cutting test: it enounces the main concepts and presents interesting clues of validity justifying a daily usage for indirect strength measurement in the petroleum industry. Based on this technology, a tomographical approach coupling specific software facilities with a hardware lab device is presented. Finally, the third part of the paper proposes a case study were both the aspects are synthesized concerning the preservations of several heritage building located in a same area in the centre of Belgium and erected with soft stony materials, outlining problems that are representative of the ones often encountered in northern Europe.

2 ALTERATION AND STRENGTHENING OF STONES

2.1 STONE ALTERATION

Investigation campaigns carried out under the direction of the International Council on Monuments and Sites – ICOMOS – on various buildings around the world have allowed listing several kinds of alteration or degradation that are likely to affect stone masonry materials. Most of them can be visible to the naked eye and 5 main families may be outlined. Due to the rather artificial character of the proposed classification, real cases will sometimes appear as a combination of several aspects. In practice, ICOMOS recommends that a preliminary study should systematically be carried out before the alteration may be treated and/or eliminated.

The first family concerns **unfixing** (cleavage, burst, blister…), that occurs as aggregates, flakes or leaves become removed, progressively exposing the internal surface of stones. The alteration can be evolving and then lead to structural problems. It can have a wide range of causes, like action of salts, heterogeneity of stone properties, thermal strengths or overloads. The second family gathers alterations associated with **loss of matter** leading to the appearance of cavities to the stone surface, altering roughness, texture and sometime blocks outlines. The cavities size can vary from a few millimeters to a few centimeters. Generally, they affect only the surface of materials and they do not progress in the depths of the matter. The main causes are frequently anthropic or atmospheric factors. **Cracking** constitutes the third family of listed alterations, classified in two categories (micro-cracks and macro-cracks). Such a problem is often serious as it announces a possible rupture of a building part. Moreover it permits to potentially aggressive agents like water to migrate in depth and accelerate the phenomena, e.g. by the action of frost/defrost cycles.

Figure 1: unfixing (left), loss of matter (centre) and cracking (right) [after 5]

Both the latter types of alterations are **chromatic alteration** and **biologic colonization**. Rather far from strength considerations, these aspects will not be detailed in the present paper.

2.2 STRENGTHENING POSSIBILITIES

Relying on family of alteration for proposing an adequate treatment is not simple. Usually, the treatment will better be prescribed with regard to the intrinsic nature of the material, the environment and/or other parameters. Although organic as well as mineral hardeners are available, the late category is mainly used, especially ethyl-silicate and lime water.

Ethyl-silicate is often used for the treatment of altered façades where it is applied using a brush. The reaction is articulated around a first hydrolysis reaction done in the presence of water where the alkoxy groups (Si-OR) ($R=CH_2CH_3$) are converted in silanol groups (Si-OH), later followed by a condensation reaction establishing a siloxane bridge (Si-O-Si).

$$SiO_4(C_2H_5)_4 + n\ H_2O \rightarrow SiO_2\ .\ n\ H_2O + 4\ C_2H_5OH$$

The silica gel that is produced hardens in a third time during the drying and the effectiveness of this strengthening treatment is noticed after 2 or 3 weeks. This product needs an immediate application of a damp-proofing.

The employment of **lime water** happens generally within the framework of classified monuments. The lime water is a saturated solution of calcium hydroxide ($Ca(OH)_2$) produced by the mixing of lime and water. Lime powder is easily obtained by heating chalk. The reaction that it produces is the disintegration of limestone to quicklime and carbon dioxide. Then, quicklime is diluted in water to obtain slaked lime and calcium hydroxide. The global reaction is made as follow:

$$CaCO_3 \rightarrow CaO + CO_2 \qquad\qquad CaO + H_2O \rightarrow Ca(OH)_2$$

Some products composed of potassium (or sodium) silicate have been investigated. They may react with the carbon dioxide to form silicon dioxide and potassium (sodium) carbonate, replacing the lost material binder. Unfortunately, the surface being little permeable to water gas, damages may appear as a consequence of the treatment. Some impregnation techniques using polyester dissolved in styrene are also available with a polymerization achieved by using gamma-ray. Nevertheless, the treatment making the surface to become too much hardened, cleavages often occur, again posing the problem in terms of durability.

2.3 QUANTIFICATION AS KEY FOR PRESCRIPTION & CONTROL

Facing a stone alteration problem, the practitioner of rehabilitation appears in the role of a medicine man. Following an anamnesis phase where the material should be interrogated, he will attempt to prescribe a treatment but he would later have to verify the effectiveness of the solution he prescribed.

In this framework, several parameters should be monitored, among which mechanical capabilities appear as preponderant although physical (density, porosity, permeability) or aesthetical considerations (chromaticity, texture) may sometimes reveal complementarily interesting.

In most of the cases, classical lab determination tests may hardly be used: such conventional approaches rely on samples that should present a given size and/or morphology and be available in a sufficient number of pieces. Further than the practical possibility to collect such samples, the **integrity preservation of the structure to be rehabilitated** appears as critical. In this framework, several little destructive testing techniques have been developed that will not be exhaustively detailed in the present paper. In most of the cases, the field measurement of a parameter is proposed that will later be correlated with the expected property. Unfortunately, only few techniques are likely to provide measurements intervening at a very local level. Moreover, most of the even available ones are associated with a qualitative determination approach instead of a quantitative one, required for convenient usage in prescription or control of strengthening treatments.

3 CUTTING TEST COMBINED WITH TOMOGRAPHY

The local quantitative estimation of the compressive strength based on limited size samples constitutes the core business associated with the translational cutting test. In deep conjunction with a tomography tool developed inside the MATLAB environment, it brings the opportunity to penetrate further than the surface of stones, towards the invisibleness of altered zones with either lab or field tests.

As the method has widely been discussed elsewhere[1], the present paper will essentially focus on aspects important for the purpose of our study.

3.1 CUTTING TEST PRINCIPLE

The cutting test consists in creating a deep groove at the surface of a sample by removing successively thin layers of material with a rectangular PDC cutter of width w, a groove at constant shallow depth d. The cutter is inclined by 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.

θ	$[°]$	15
W	$[mm]$	10
v	$[mm/s]$	**0 → 200**
d	$[mm/s]$	$0.1 \to 1$
F_s	$[N]$	$0 \to 4000$
F_n	$[N]$	$0 \to 4000$

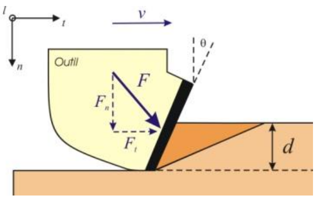


Figure 2: scratching test setup

The testing device is composed of a fixed sample holder of length L and a moving frame (horizontal motion) equipped with a moving beam (vertical motion). The horizontal movement of the frame is operated by a computer controlled stepper-motor driving a motion screw via a gearbox. The vertical movement of the beam is manually adjusted with the positioning system. It can be locked, in order to maintain a constant depth of cut while cutting. A micrometer indicates the value of depth of cut. The load sensor fixed on the moving beam measures the horizontal F_s and vertical F_n components of the force F acting on the cutter holder.

[1] Experimental evidences presented in [3], [4] and [8] outline that data recorded during a translational cutting test could be interpreted for computing the intrinsic specific energy ε of a geomaterial. The improvement of the procedure as well as correlations between ε and the compressive strength has later been widely discussed in [7] and [1].

3.2 CONCEPTS VALIDATION

Stone cutting is associated with a "ductile" or a "brittle" mode of failure depending on the depth of cut. The ductile mode takes place at shallow depth of cut and is associated with a plastic flow, while the brittle mode occurs above a threshold depth of cut and is characterized by the propagation of a tensile crack. It was shown that, within the ductile regime, the magnitude of the force acting on a sharp cutter, averaged over a length s many times the depth of cut (s ~ 5 to 10 mm) is found to increase linearly with the cross-section area of the groove being traced, what is expressed through the equation 1.

$$F_{cs} = \epsilon \cdot w \cdot d \tag{1}$$

where ε is the intrinsic specific energy.

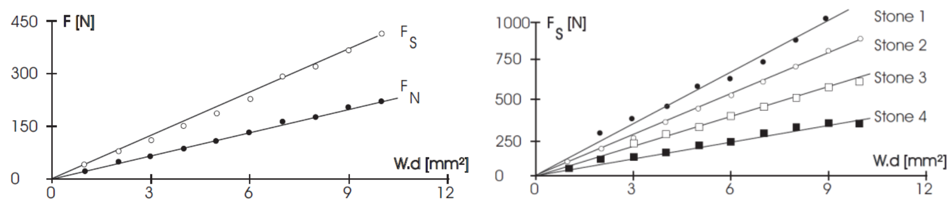


Figure 3: one stone $F_{s,n}= F_{s,n}$ (w.d) – Several stones $F_s= F_s$ (w.d)

The adjective "intrinsic" refers to the pure cutting process (subscript c) obtained with a sharp cutter, not accounting for energy dissipated by frictional forces along the wear surface of an eventual blunt cutter. During the test, the ratio r of the normal to the tangential component of the force can be used to monitor the cutter sharpness. The intrinsic specific energy varies from one type of geomaterial to another and experiments show that the intrinsic specific energy varies with the material strength.

Numerous scratching tests were conducted at the University of Mons on several types of geomaterials (stones, clays, mortars). For each of them, the tests were conducted with sharp cutters at depth of cut ranging from 0.1 to 1 mm. Particular attention was given to avoid the occurrence of chipping and to control the cutter state of sharpness. In parallel, compression tests were conducted on the same rock materials; as much as possible the tests were performed on the same samples (cylinders of 25 mm diameter and 50 mm length). It was found that a minimum of three grooves (at different depth of cut) must be traced 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 $F_s= F_s$(w.d) diagram.

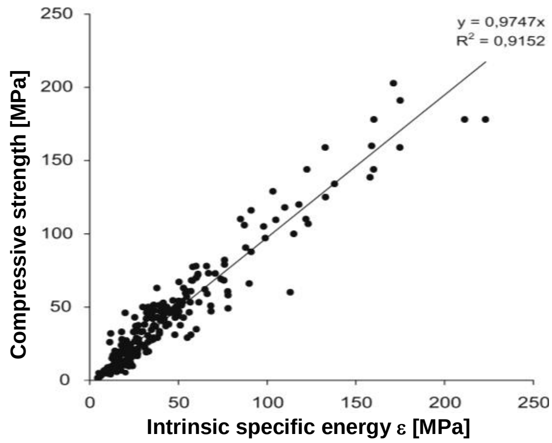


Figure 4: correlation between ε and q for geomaterials & building materials

This strong correlation shows that the translational cutting test is efficient on a great range of homogeneous materials, even for poor value of compressive strength. The transpositions to altered materials essentially concern the adaptation of the load cell to the specific range of cutting forces and some software implementations.

3.3 CUTTING-BASED TOMOGRAPHY

Disposing of a technique likely to provide a local value of material strength, the main problem will now concern the data management. In fact, a low value for the cutting depth d (~125 µm) and the velocity v (~100 mm/sec) combined with a high frequency (~ 800 Hz) and a number of cuts per groove (~150) leads to collect one value of strength at around each 100 µm of spatial interval. Further than the analysis of impressive data matrix, the authors proposed to rely on some kind of data mapping: the recorded strength values will be used as the basis for a spatial interpolation that will later become coupled with classical visualization facilities (color code associated with the measured value of the strength). In practice, a basic implementation of this concept may be implemented inside the MATLAB environment under the shape of stand-alone routines.

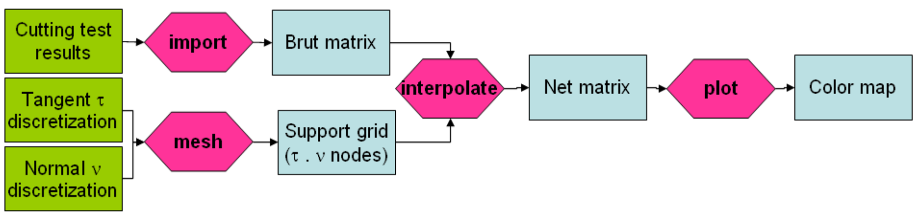


Figure 5: algorithm for simplified establishment of a color map

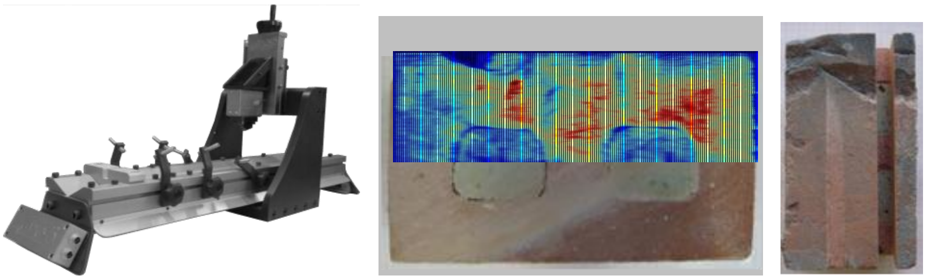
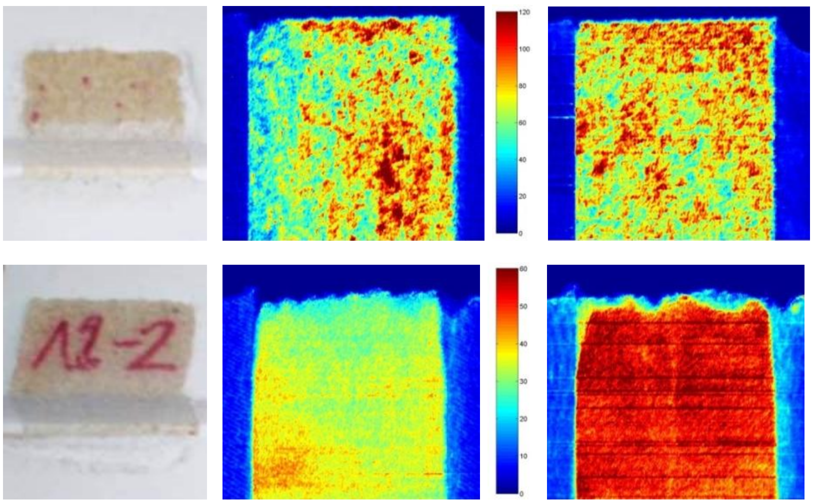


Figure 6: commercial device (left), mapping (centre) and top groove (right)

3.4 ILLUSTRATION OF TREATEMENT (IN) EFFECTIVENESS

The combination of the presented technologies may then be used for illustrating in what manner the specificities of a stone type may influence the effectiveness of an eventual strengthening treatment. The illustration concerns two types of stones: respectively a calcarenite and a massive chalk, both of them being affected by salt weathering. The stone samples have been tested before any treatment for establishing a reference map. Then, three applications of ethyl-silicate are performed with each time 48 ours delay. The stone samples are then tested again 7, 14 and 21 days after the last ethyl-silicate application. The color maps show that the strengthening effect may be clearly observed on the massive chalk that was characterized by its very low initial characteristics although it remains less impressive on the calcarenite.



calcarenite

chalk

Figure 7: stone sample (left), map before and 21 days after treatment (right)

4 CASE STUDY CONCERNING LINCENT AREA IN BELGIUM

The case study concerns the Saint-Christophe stone masonry church located in Racourt (Belgium) and is representative for a great number of civil or cultural buildings erected since the Roman period in an important area located between Brussel and Liege. The considered monument has been erected during the XIVth and XVth centuries, according to a combination of Romanesque and Gothic styles. It has been partly erected using a stone called “Tuffeau de Lincent” that was locally extracted and used for building despite the fact it later revealed as highly sensitive to alteration or degradation phenomena. The studied church suffers various degradations like unfixing or loss of matter affecting a great number of structural members (walls, buttresses) playing a strategic role in the stability. In practice, the serious state of degradation led to initiate a great restoration campaign, financially supported by the civil authorities. Facing the alteration problem, the situation appeared as delicate and justified a sharp approach of the problems.

Figure 8: church view (left), altered wall (centre) and buttress (right)

In the classical approach, a hybrid rehabilitation intervention would have been prescribed. A treatment with ethyl-silicate would have been proposed for strengthening the “Lincent” parts that will be conserved and, local replacements for too much altered stones would have been proposed. As no extraction site is available for “Lincent” anymore, the recourse to an aesthetically similar stone like the “Tuffeau de Maastricht” would have been proposed. Due to the lower mechanical characteristics exhibited by the replacement stone, a preventive strengthening treatment with lime-base solutions would have been proposed. Disposing of the tools we developed, it is possible to analyze the pertinence of such a classical approach. In practice, both the “Lincent” and “Maastricht” stones are sufficiently weak or weakened for justifying the recourse to a strengthening treatment. A first study was carried out on the “Tuffeau de Maastricht”, the effectiveness of both the treatments those are currently authorized and/or recommended by the Heritage Administration in Belgium for improving the quality of altered materials (lime water and ethyl silicate solution) has been studied. For each product, two kinds of practical processes have been investigated: brush application and capillary aspiration. For each solution, the evolution of strength levels as well as the progression of the strengthened zone with the time has been carefully studied with the help of the cutting-based tomography. In this framework, the short term effectiveness of ethyl silicate has definitely been outlined while lime water treatments have illustrated their limitations. Then, the treatment of the "Tuffeau de Lincent" has also been investigated, only with ethyl-silicate and only a limited surface strengthening effect has been noticed.

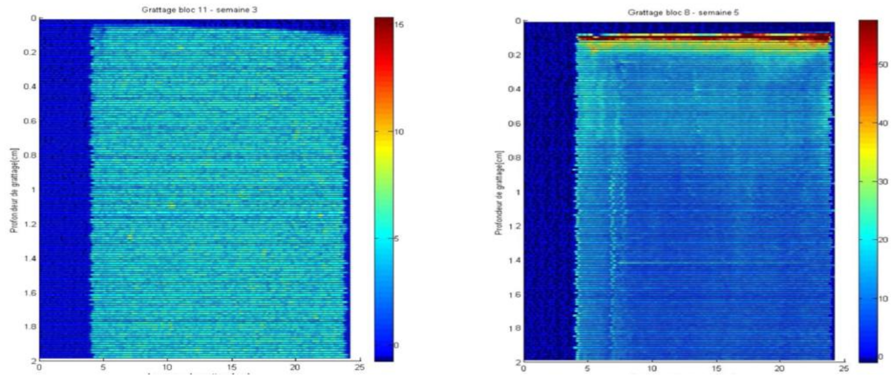


Figure 9: treatment with lime water (left) and ethyl-silicate (right)

The data collected through both the requested tomographical analysis allowed reconsidering the classical approach that was initially proposed for the rehabilitation of the Saint-Christophe church. At this time, the authors have illustrated to what an extent the initial proposition would have been associated to money waste due to the relative ineffectiveness of the proposed solutions, leading the technical committee to engaged itself in other ways for achieving a performing and durable rehabilitation of the site.

5 CONCLUSIONS

In the continuation of a discussion concerning the main causes of alteration that may be encountered on stones, the paper describes some strengthening solutions and insists on the interest for disposing of sharp measurement devices for prescription and control purposes. An innovative usage of cutting test in combination with a visualization tool is presented, allowing tomographical views to be established. Such a combined tool is then used for carrying out a mechanical study on a restoration site where it allowed improving the relevance of the intervention in terms of durability.

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