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Short communication

Evaluation of small core-based specimens for characterization of stone deterioration

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1. Introduction

The failure of rock material involves crack initiation and crack propagation (Fig. 1). Most of the time, decay processes observed in stone heritage can be related to the process of crack propagation due to a specific environmental stress. Depending on the applied stress at this crack tip, three failure modes and mixed-mode conditions may be induced [1]. This research focuses on the evaluation and adaptation of small core-based specimens for the purpose of stone conservation and only mode I loading configuration is considered. To understand decay phenomena, several methods are considered to measure the mode I fracture toughness K_{IC}, required for the crack initiation and considered as an intrinsic property of a material.

As a matter of fact, damage and crack initiation can be induced within stone by several environmental changes. Thus, their impacts on intrinsic parameters and properties have to be considered to evaluate and understand the fracture mechanisms, leading to stone decay. Indeed, stresses and damage may be the results of complex processes. They may be due to the crystallization of soluble salts causing a confined pressure, inducing stresses that may be sufficient to initiate a crack from the crystallized inclusion. Damage can also result from a freezing of water on the pore network, creating stresses and the propagation of microcracks. Hygroscopic swelling phenomenon is also observed within the clay-bearing stones when subjected to high natural variations of relative humidity and temperature. Indeed, clay minerals are especially reactive to these hygric wetting/drying cycles. The swelling of the clay matrix creates localized deformation and induces stresses. Such repeated solicitations can initiate cracking and deterioration, as scaling or desquamation, can appear. Evaluating crack propagation and fracture mechanics properties is necessary to a better understanding of decay phenomena and processes involved in deterioration. Toughness measurement and development of methodologies adapted to follow and understand these mechanisms have to be considered to evaluate the stone decay and its durability.

Several fracture mechanics tests have been proposed and developed over the past few years. For each method, a pre-existing notch is required within the sample and the stress intensity factor K_I is expressed as a function of the applied stress σ, the length a of the initial notch and a Y factor, depending on the sample geometry, and provided by numerical analyses [2–5]:

$$K_I = \sigma\sqrt{\pi a}\ Y \tag{1}$$

Single Edge Notched Bending (SENB) geometry is a standard fracture testing specimen used to measure toughness [6,7]. However, as a regular notched beam sample, this geometry is not preferred for stone conservation research since cores are collected. The International Society for Rock Mechanics (ISRM) suggested a few

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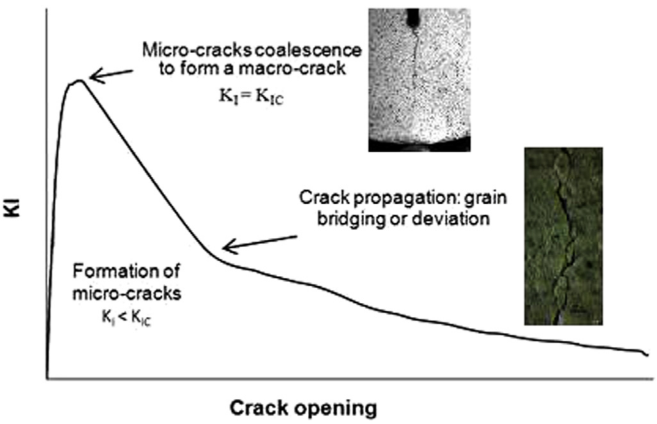

Fig. 1. Crack propagation into a porous substrate from microracks formation and their coalescence into a main crack, and its propagation until failure of the specimen.

methods to measure the fracture toughness of a rock, using core-based specimen [8] and several studies using core specimen have covered a large number of parameters [9,10]. Fracture behavior has been studied with Cracked Straight Trough Brazilian Disc (CSTBD) [11] followed by Cracked Chevron Notched Brazilian Disc (CCNBD) [12]. Parameters influencing the results of these tests have been reviewed and corrected by Wang [4] and size effects on fracture toughness using such samples have been evaluated by Ayatollahi and Akbardoost [13]. However, these two samples are loaded in diametral compression. Fracture tests applying a three-point bending loading would be more convenient to induce a pure mode I tensile fracture. Thus, Straight Notched Disc Bending (SNDB) and Semi-Circular Bending (SCB), using respectively circular and semi-circular specimens, seem to be more useful methods for stone mode I fracture toughness measurement [5,14]. These two specimens are straight notched and loaded under three-point bending. These core-based specimens have been developed for geomaterials, and the samples are prepared from core and are usually 60 to 100 mm in diameter [15–17].

However, in order to study stone as a building material, cores collected on a monument have to be less than 45 mm in diameter. As a matter of fact, to provide such mechanical testing, stone cores must be sampled from monuments showing decay. Preservation of the sites involves the smallest sampling on monuments, and stone cores collected do not exceed 45 mm in diameter. Thus this research first aims to verify the feasibility of applying such usual mechanical tests for small diameter samples and to find suitable testing. Methods and loading configuration as well as size effects – thickness and notch length – on toughness are investigated to propose suitable parameters for stone heritage samples. Characterization of several stones showing deterioration and cracking is then proposed using the selected methodologies.

2. Materials and testing

2.1. Rock properties

For this research the effects of method and sample geometry are considered by testing Tuffeau limestone. Mineralogical and structural properties of this stone, used for the château de Chambord as well as for many monuments on the val de Loire, have been thoroughly investigated over the past few years [18,19]. However, few studies have focused on the mechanical properties, especially the toughness, of this porous limestone (total porosity measured as 46%). Using this brittle rock, fracture mechanics methods are compared, and the most favorable one for stone conservation is proposed.

To evaluate the effects of geometrical parameters on toughness for the Tuffeau, and to validate the proposed methodologies, three other stones have been selected. Saint-Maximin limestone, with a total porosity of 39% and lower than Tuffeau, Thuringer sandstone, with a total porosity of 12%, and a granite, with a total porosity of 2%, were selected. Their fracture toughness was measured under the configuration proposed after investigated the Tuffeau. For all sedimentary stones used in this research, stone cores have been collected in the direction perpendicular to the natural bedding.

2.2. Testing

For all tests the samples are quasistatistatically loaded in an Instron testing machine at a displacement rate of 0.2 mm min^{-1} to avoid dynamic effect. Crack opening measurement is performed using a linear variable displacement transducer (LVDT) Solartron with a measuring range of 2 mm and 0.1 μm accuracy, affixed at the tip of the initial notch. It was used for all tests, except for the SNDB specimen because of the circular geometry of the sample. A camera Jai TM-1327-GE, acquiring 90 images per second is also used to monitor the initiation and the propagation of the crack.

Investigations of surface roughness have been conducted using a SurPhase™ system with a z resolution of 22 μm. To illustrate the difference on fracture surfaces, the Root Mean Square (RMS) roughness R_q of the real surface compared to the average roughness R_a is studied for CSTBD and SCB samples [20].

3. Experimental fracture mechanics methods and parameters

For the selected methods the only required data to measure toughness is the critical fracture load [21,22]. Thus, this review is based on the measurement of the mode I fracture toughness K_{IC} knowing the maximum applied stress σ_{max}, the geometrical parameters and the numerically calculated factors Y [2–5]. Because of the relatively small samples that may be collected on a monument, the radius R of the core for circular specimens is fixed at 22.5 mm. The influence of parameters as the thickness t and the length of the initial notch a on K_{IC} is considered. By choosing appropriate parameters, it is expected that fracture toughness will tend towards the SENB reference value $K_{IC(\mathrm{SENB})}$. For each configuration, eight samples have been tested.

3.1. SENB specimen

The SENB specimen is a normed $160 \times 40 \times 40$ mm^3 beam collected from the Tuffeau block. The influence of the initial straight notch length a on toughness was estimated by varying the ratio a/w. Several 1 mm width notch length a were prepared so that $a/w=0.1$, 0.2, and 0.4. The distance between the supports rollers 2 $S/L=0.6$ is selected for the three-point loading.

3.2. CSTBD specimen

The core was sliced into disks of two thicknesses, $b=5$ and 10 mm. CSTBD specimens also require a straight slot of $2a$ machined using a 1 mm drill in the center of the disc (Table 1) so that $a/R=0.2$. The initial notch is aligned in the diametral-compression axis for a pure mode I loading.

3.3. SNDB and SCB specimens

The SNDB and SCB tests are carried out on circular specimens with a radius of $R=22.5$ mm, prepared by slicing the core at the