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Microcracking based rock classification using ultrasonic and porosity parameters and multivariate analysis methods

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ABSTRACT

This work aims at presenting a new methodology, based on NDT ultrasonic techniques and water porosity measurements, to characterize the microcracking state of rocks and classify them in microcracking based equivalent groups. The measurements of ultrasonic pulse velocity, the attenuation coefficient and the porosity by water saturation under vacuum conditions make it possible to compare and validate all these techniques as good practices to classify aggregates and ornamental stones with regard to their rock matrix compactness.
Beyond the fact that these developments give new approaches to assess the rock microcracking, it was shown that these parameters have a direct relationship. Indeed, the classification methodology was applied to a database containing 56 cores coming from blocks sampled in an aggregate production quarry. For these cores, ultrasonic parameters (wave velocity, attenuation and anisotropy coefficients) and porosity parameters (total water, crack and pore porosities) were measured. Two multivariate statistical methods (Principal Component Analysis and Cluster Analysis) were applied on this database to assess the relationship between all these parameters and to classify the cores into micro-structurally similar groups.
The application of the setup methodology on the core database allows us to study the main correlations between the measured microcracking rock properties. On the other hand, it was shown that the method can be used as an effective way to characterize the differences in terms of microstructure between rock samples.

1. Introduction

It is now agreed that grain fabric and microstructure play an essential role in predicting building stone and concrete durability (Koch and Siegesmund, 2004; Åkesson et al., 2006; Cantisani et al., 2009; Sáez-Pérez and Rodríguez-Gordillo, 2009; Luque et al., 2010). In particular, the microcracking within one aggregate is the result of three types of processes. First, the natural process, resulting from the rock genesis and tectonic history, is an intrinsic microcracking which is both uncontrollable and unavoidable. Then, blast-induced microcracks which are the result of the dynamic loads were induced by the detonating explosive. Several works have been previously published on the estimation of the total blast-induced crack areas with muckpile blocks (Hamdi et al., 2003, 2008, 2011). Finally, the cracks were induced by the crushing process.

Thus, the evaluation of existing microcracks within the final aggregate is an important task in all subsequent civil uses dealing with mechanical performances (concrete civil structure, retaining structures, drainage of fluid, roads, …). Until now, researchers have evaluated the mechanical performance of aggregates with common conventional tests (Los Angeles, Deval, Micro-deval, …) without focusing on the petrographic characteristics and microstructure anisotropy (grain size, shape and orientation) of the aggregate. Despite that a number of NDT acoustic techniques were applied to manufactured concrete or mortar or even rock material, they didn't generally deal with final quarry produced aggregate quality. For instance, Lafhaj et al. (2006) determined the correlations between ultrasonic pulse velocity (UPV), porosity and permeability based on the investigation of seven mortar mixtures with water/cement ratio varying from 0.3 to 0.6. Goueygou et al. (2009) investigated the relationship between Rayleigh wave velocity at ultrasonic frequencies and porosity in dry and fully saturated mortar. These studies and others assessed the potential of the ultrasonic techniques to non-destructively estimate porosity, permeability and elastic moduli (Hernández et al., 2000; Assefa et al., 2003; Punurai et al., 2006).

For rock fabric characterization, the parameter most commonly measured is the ultrasonic pulse velocity (UPV) as it is the most sensitive parameter to variation in material properties (heterogeneity, anisotropy, …). Ultrasonic attenuation (UA) is less frequently used (Hernandez et al., 2000; Goueygou et al., 2002). Martínez-Martínez et al. (2011) recently proposed a novel ultrasonic estimator based on wave energy: spatial attenuation and showed that it is highly sensitive to the petrographic characteristics of rocks as well as to the presence of individual defects (fractures, vugs or disintegrated areas). Sarout

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and Guéguen (2008) used an experimental setup to determine the elastic wave velocities in transversely isotropic shales with horizontal bedding plane. Sarout et al. (2009) presented a semi-automatic processing technique which is based on ultrasonic signal analysis by a wavelet transform and an onset-time picking procedure. Porosity is selected because it is considered as a key parameter which indicates the material durability (Lafhaj et al., 2006).

Other NDT acoustic techniques like X-rays, radar and thermography were used in order to produce 2D/3D "tomograms" of the structure (Ito et al., 2001; Diamanti et al., 2008; Ohtsu and Alver, 2009). Chai et al. (2011) conducted ultrasonic measurements of cubic specimens and numerical simulations of wave propagation to show the potential of attenuation tomography as a complementary method to the travel time tomography. These methods have been shown to be time-consuming.

Those studies which aimed at rock fabric characterization are generally conducted at a sample scale (few centimeters) with a regular geometrical shape. Natural aggregates, produced by a quarry, neither have a regular shape nor the requested size.

The objective of the paper is to present a new experimental methodology to assess rock microcracking, which is based on the measurement of ultrasonic parameters (pulse velocity and attenuation) and water porosity. Moreover, another objective of the paper is to present the results of the application of the Principal Component and Cluster Analysis statistical methods to the data gathered in order to assess the relative influence between the ultrasonic and porosity parameters as real microcracking indicators and to classify the investigated rock samples in microcracking based equivalent groups. Finally, the analysis of the main results is detailed.

2. Experimental methodology description

2.1. Experimental device description

The general procedure of the experimental device is based on the measurement of ultrasonic pulse velocity using a couple of transducers, one generating an ultrasonic pulse and the other capturing the received wave. Fig. 1 shows an example of the input and output signals. A silicone gel is used as coupling agent at the emitter/sample and the sample/receiver interfaces. The emitter is an ultrasonic square signal pulse whereas the received signal is digitized at 20 MHz and recorded using an automatic acquisition system.

Moreover, the generated and received signals were saved in order to be processed by a MATLAB based program that computes the ultrasonic parameters presented hereafter.

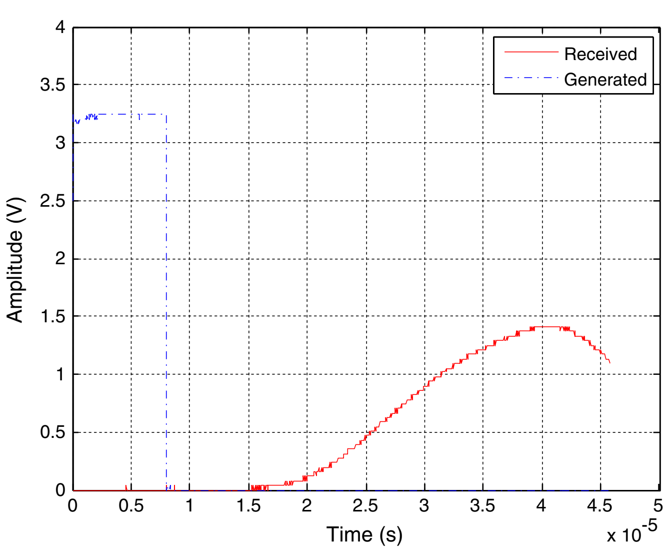

Fig. 1. Generated and received signals.

It is worth noticing that to characterize the anisotropy of the investigated cores, which is a key parameter; three measures were done for each core, one in the longitudinal direction and 2 in the transversal direction as shown in Fig. 2. When possible, these directions were related to the bedding planes. Then, the core axis was orientated and noticed as parallel in relation with these planes, making it possible to test the anisotropy of the rock matrix.

2.2. P wave velocity

Knowing the distance L between the two transducers (length of the sample for measure 1 and sample diameter for measures 2 and 3), one can deduce the ultrasonic pulse velocity as:

$$V_P = \frac{L}{\Delta t}(m/s)$$

where Δt is the transit time of the pulse (as indicated in Figure 1).

2.3. Anisotropy coefficients

Among all petrographic characteristics, anisotropy is probably the most influencing parameter in wave transmission within rock material. It is highly sensitive to the presence of individual defects (fractures, vugs or disintegrated areas) and to their characteristics (grain size, shape and orientation). In order to estimate the anisotropy of P wave velocities, two parameters were computed for each core:

- the coefficient of anisotropy k_1, which was defined by Birch (1961) as:

$$k_1 = \frac{V_{P\,max} - V_{P\,min}}{(V_{P\,max} + V_{P\,min})/2} \times 100\% \quad (1)$$

where V_{Pmax} is the maximum ultrasonic velocity and V_{Pmin} is the minimum ultrasonic velocity among the three velocities measured.

- the coefficient of anisotropy k_2 defined as:

$$k_2 = \frac{\left|V_{//} - \overline{V_\perp}\right|}{\overline{V_\perp}} \times 100\% \quad (2)$$

where $V_{//}$ is the velocity measured in the direction of the core axis, $\overline{V_\perp}$ is the mean of the velocities measured perpendicularly to the core axis and | | is the absolute value sign.

These two anisotropy parameters will be shown by the present work to be directly linked (Section 5.1).

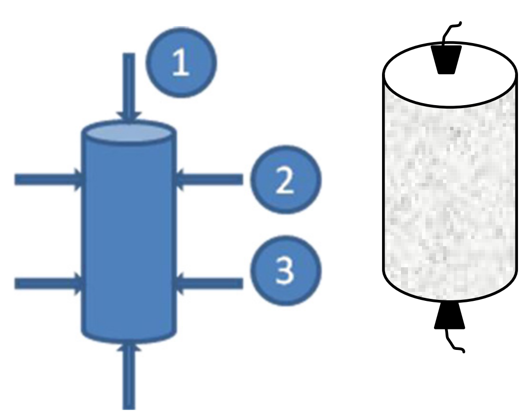

Fig. 2. P wave ultrasonic measurements: one longitudinal and two transversal measures were performed.