International Journal of Rock Mechanics & Mining Sciences 83 (2016) 73–85

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Characterization of rock cracking patterns in diametral compression tests by acoustic emission and petrographic analysis

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ARTICLE INFO

Article history:
Received 15 April 2015
Received in revised form
18 November 2015
Accepted 30 December 2015
Available online 7 January 2016

Keywords:
Acoustic emission
Cracking process
Cracking pattern
Three-dimensional localization
Petrography
Diametral compression test

ABSTRACT

Pre-existing microscopic flaws in brittle rocks act as local stress concentrators and cause the nucleation and propagation of microcracks, resulting in a decrease of stiffness. The propagation of microcracks causes a sudden release of energy in the form of elastic waves, known as acoustic emission (AE), detected by sensors, enabling the non-destructive monitoring of cracking.

Marble and monzogranite specimens were subjected to displacement-controlled diametral compression tests for the characterization of the cracking pattern according to AE parameters, three-dimensional localization of the AE sources and petrographic analysis. The tests included unload–reload cycles after peak. Microcracking in monzogranite and marble was initiated at approximately 90% and 60% of the peak load, respectively. Before peak load, both rocks showed the development of microcracks uniformly distributed on the plane containing the loading edges. At the post-peak stage, new microcracks were first concentrated on one of the faces at the center of the specimen along the loading axis and then spread through its thickness all the way to the other face. The main portion of the microcracking in marble was concentrated just after peak, while in monzogranite it extended through to the end of the test. The microcracking process in monzogranite was initiated and propagated mainly through quartz crystals, not along visible weakness planes and it released high-level energy, while in marble it followed the cleavage planes and released low-level energy.

1. Introduction

Although compression is more often present in practical applications of rock mechanics, tensile stresses are also observed, e.g. around openings, during crushing, drilling, in hydraulic fracturing, in load bearing capacity problems, caving, etc. On a microscopic scale, tensile stresses are also present even under compressive loads. Experimental studies on different types of rock under tension are therefore essential for understanding their failure process. Diametral compression tests have been widely used to estimate the tensile strength of quasi-brittle materials[1] because they enable the study of the behavior of rock subjected to tension without the difficulties of direct tension tests. Furthermore, the predictable location of the damage zone of a specimen allows a simpler test setup as well as a comparison with AE monitoring.

Several attempts have been made to use fracture mechanics concepts in order to explain the crack propagation process in rocks[2–7]; however, the problem of defining the role of each microcrack and its contribution to overall behavior after coalescence is not easy to model.

Several numerical simulations have been reported for the study of the progressive cracking process that leads to the failure of rocks and rocklike materials under diametral compression tests.[1,8–14] Such numerical models require a spatial distribution of the mechanical properties of the material at the level of specimen scale. None of the studies above used experimental results as the input for such distributions. The results presented here are intended to throw some light on the procedures used to obtain distributions of properties needed for realistic modeling of the rock cracking process.

Conventional diametral compression tests enable the assessment of the behavior of rocks on a macroscopic scale and provide general information, such as load and deformation at failure. Nevertheless, realistic insights of the progression of damage, from microscopic to macroscopic cracking, can be evaluated only with experimental data, such as those reported in this paper.

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http://dx.doi.org/10.1016/j.ijrmms.2015.12.017
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Since the cracking process is generated inside specimens under increasing load, monitoring the location and the intensity of cracking events is fundamental for a quantitative understanding of the process. The propagation of microcracks in quasi-brittle materials releases energy as transient elastic waves known as acoustic emissions, AE.[15] Such waves can be collected by sensors distributed on the surface of the specimen.

The AE monitoring technique has been applied to qualitative assessment of the relationship between the microcracking process and AE parameters, such as wave amplitude, AE energy, AE counts, duration, rise time and AE average frequency.[16–23] Quantitative analyses of the cracking process based on the three-dimensional localization of AE sources have been applied to uniaxial, biaxial, triaxial, bending and diametral compression laboratory tests as well as underground excavations[15,24–36]; however, these descriptions are usually focused on either AE parameters or the localization of the AE sources, and do not analyze such aspects together.

Some research involving both AE parameters and localization of AE sources has been carried out.[37–41] In order to improve the characterization of microcracking of rocks, petrography has been combined with the analysis of AE parameters,[9,42] including petrographic analyses at peak and pre-peak loading stage.[43] Only a few studies including AE parameters, localization of AE sources and petrography have been published.[10,44–47] These analyses suffer from at least one of the following limitations: concentrated on a portion of signals collected at specific stages of the loading process; focused on the pre-peak and peak stages; the number of AE sensors used for monitoring does not allow three-dimensional localization of AE sources; petrographic characterization of the intact and failed specimens only (before loading and at the end on the test), which hinders the comprehensive characterization of the generation and coalescence of damage to rock under static load. Those techniques have not been applied together for the analysis of the cracking process in displacement-controlled diametral compression tests on solid discs.

Acoustic emission has been applied to monitoring diametral compression tests.[10,15,48] Falls et al.[48] report two-dimensional localization of AE sources in granite specimens and Labuz et al.[15] carried out three-dimensional localization of AE sources in concrete specimens. Both studies focused on the cracking pattern of specimens prior to and around the peak strength. Van de Steen et al.[10] carried out linear localization of AE sources in crinoidal limestone specimens subjected to diametral compression test. They[10] used specimens with a hole and combined AE monitoring with petrographic analyses at the peak load. However, neither the complete characterization of the damage process during the stages of the test, including the post-peak stage, nor the characterization of the cracking pattern along the thickness of the specimen were carried out. The use of AE energy density that enables the visualization of the most important areas of microcracking and the use of petrographic analyses to follow the cracking process of rock under loading (not only at the peak) have not been previously adopted in diametral compression tests.

The present paper reports on the characterization of the cracking process and the cracking patterns of both a metamorphic and an igneous rock subjected to displacement-controlled cyclic diametral compression tests. The descriptions of the failure of rock specimens on a scale ranging from microscopic to macroscopic cracking were based on the complementary analysis of AE parameters (AE counts and AE energy), three-dimensional localization of AE sources and petrographic analysis of specimens subjected to different stages of loading (intact specimens, pre-peak and post-peak stages). Such aspects were incorporated in order to obtain the overall characterization of the progressive damage process throughout the tests, which includes the pre-peak, peak and post-peak stages of loading, as well as an assessment of the progression of the cracking pattern through the thickness of the disc specimens. The three-dimensional localization was improved by the inclusion of the AE energy density as a parameter so that the main cracking zones inside the specimen volume and their progression during the test could be visualized.

2. Experimental procedure

2.1. Description of rock specimens

The first rock selected is a marble from the Italva Group, collected in Cachoeiro de Itapemirim, ES, Brazil. The second is a monzogranite from the Cantareira Batholith, collected in São Paulo, SP, Brazil. Both date from the Neoproterozoic period-790–600 Ma. for the marble[49] and 590–563 Ma. for the monzogranite,[50] and were selected due to their differences in geological genesis and mechanical properties, including their natural microcracking density. Geologically, monzogranite is an igneous rock formed by different minerals in an imbricated configuration (mainly quartz and microcline/plagioclase) while marble is practically a monomineralic (calcite) metamorphic rock. At the microscopic level, the monomineralic or polymineralic structure of the rocks, as well as the presence or absence of cleavage planes and the previous existence of intra-mineral microcracks, are the main features that influence the behavior of these rock specimens in diametral compression tests. Mechanically, monzogranite is more brittle and has higher compressive and tensile strengths than marble.

2.2. AE monitoring description

The AE equipment employed in the tests consisted of six wide band piezoelectric sensors, six amplifiers and an eight-channel system developed by Physical Acoustics South America (PASA). For the purpose of this study, two relevant AE parameters were recorded for each signal: AE counts and AE energy (see Ref. 51). AE energy is represented by the area under the curve of voltage versus time, adjusted by constant factors so that it is compatible with the values determined by previous analogic systems from PASA systems. Voltage was converted to samples at an acquisition rate of 100 kHz/mV, with a pattern gain of 20 dB, called energy reference gain (*ERG*). As a result, the AE energy is a dimensionless value[52] calculated by:

$$\text{AE energy} = 10^{\left(\frac{ERG-20}{20}\right)} \bullet 100\frac{\text{kHz}}{\text{mV}} \bullet \int_0^{t_d} V(t)\,\text{d}t \tag{1}$$

where the t_d parameter is the duration of the signal. Whenever another acquisition rate is used, the values must be adjusted. AE energy and AE counts are dimensionless parameters that will be used in the following graphs and figures for interpretation of the damage process.

The signals and their AE parameters were recorded using AEwin® software from PASA and the gain was set to 40 dB. The time parameters for the AE signals definition, called Peak Definition Time (*PDT*), Hit Definition Time (*HDT*) and Hit Lockout Time (*HLT*), were set to 50, 100 and 100 μs, respectively, and the acquisition rate was adjusted to 1 MHz. The value for PDT should allow for the correct identification of the signal peak. An adequate value for HDT should enable AE signals to be recorded as single hits. An appropriate value for HLT should avoid signal reflection problems. In order to collect proper signals for the analysis, those time parameters should be adjusted by trial and error until such conditions are satisfied.[53–55] The values obtained by this process were very similar to those presented by Chang and Lee,[33] who implemented AE monitoring and three-dimensional localization in