Mode I fracture toughness determination of granite specimens using *p*seudo-compact tension method

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ABSTRACT

Mode I fracture toughness (K_{IC}) is one of the most important parameters in fracture mechanics of brittle material. Several laboratory methods have been suggested to determine the mode I fracture toughness. However, many of these methods are dealing with the lengthy sample preparation procedure, premature failure of samples, and difficulties in obtaining the precise value of the fracture toughness property. In this paper, recently proposed *p*seudo-compact tension method is used to evaluate mode I fracture toughness of a middle-grain granite benefiting the advantages of this method including; simplicity of the test, high level of test control and high accuracy of the K_{IC} value. For this purpose, granite samples in four different diameters and with six test repeats per diameter have been prepared and tested using the *p*seudo-compact tension method. For each sample, in addition to recording the load and displacement data, the acoustic events during the loading process were also recorded simultaneously by an acoustic emission equipment. First, the resulted fracture toughness value for each sample have been determined, then the size effect has been evaluated and analyzed. Finally, results of the acoustic emission method, as the monitoring tool in the fracturing process of tested samples, have been analyzed. The qualitative evolution of acoustic emission parameters well illustrates the mechanical process occurring in the tested samples with well-matched coinciding with the mechanical transitions observed in samples during loading process. Experimental results show that mode I fracture toughness is positively related to the specimen size and there is a noticeable size effect in K_{IC} value up to a certain diameter.

KEYWORDS

Mode I fracture toughness, pseudo-compact tension test, acoustic emission method, brittle rock fracturing process, scale effect.

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1. Introduction

Fracture toughness have paramount importance in engineering projects involving rock materials, in which cracks are omnipresent [1, 2]. Since the tensile strength of a rock material is comparatively lower than its compressive and shearing stresses, the mode I fracture toughness (K_{IC}) arises as the most relevant and studied parameter in rock fracture mechanics. In order to measure the mode I fracture toughness of rock material, the International Society for Rock Mechanics (ISRM) endorses four suggested methods, namely the short rod (SR), chevron bend (CB), cracked chevron notched Brazilian disc (CCNBD), and semi-circular bend (SCB) methods [3-5]. Some of these methods may be difficult to apply on a routine basis due to a number of issues, such as: a) the small failure initiation and propagation loads require excellent test control; b) a relatively large sample volume is needed (CB); c) cumbersome or difficult sample preparation (SR, CB, and CCNBD); d) imprecisions in the computation of the stress intensity factor (CCNBD); e) the indirect generation of tensile loads via sample compression (especially in SCB and CCNBD). To overcome some of these limitations, in this contribution we present an alternate simple approach, referred to as *p*seudo-compact tension (*p*CT), to measure K_{IC} in rocks using cylindrical single edge-notched specimens loaded in pure tension.

2. Methodology

Granite specimens originated from Spain were used to assess the specimen size effect on the corresponding K_{IC} obtained by the recently developed *p*seudo-compact tension (*p*CT) approach. The *p*seudo-compact tension test [6] cell is based on a modification of the compact tension (CT) specimen described in ASTM standard methods [7] for testing metallic materials. The specimen geometry of the test is outlined in Figure 1.

This study investigates the effect of specimen size (diameter) on the corresponding K_{IC} of a crystalline rock. For this purpose four different diameter sizes were chosen including specimens of 30 mm, 37 mm, 40 mm, and 54 mm diameter. For each one of the diameter sizes 6 replicate tests were considered and a total of 24 tests were performed. The test specimens were equipped with two wide-band acoustic emission (AE) sensors (Vallen VS700-D; frequency range: 150-800 kHz; peak frequency: 600-800 kHz) attached on both lateral sides of the specimen. The *p*CT specimens were loaded under pure tensile conditions using a specially designed testing device equipped with a 50 kN load cell [6].

Mode I fracture toughness for *p*CT specimens (K_{IC}) is computed using equation (1):

$$K_{IC} = Y'_{pCT}\frac{P_{max}}{bB}\sqrt{\pi a} \qquad (1)$$

, where, P_{max} is the peak load (N); b is the distance from the base of the groove to the bottom of the specimen (m); B is the specimen thickness (m); a is the length of the straight notch (m); and Y'_{pCT} is the dimensionless intensity factor.

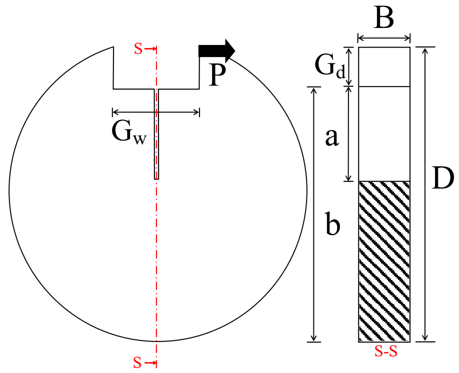

Figure 1: Identification of the main geometric dimensions of the *p*CT specimen (modified after [6]), D: diameter; B: thickness; a: notch length; G_d: depth of U shaped groove; G_w: width of the U-shaped groove; b: distance from the base of the groove to the bottom of the specimen. The values of a/b, G_d, and G_w are fixed in this study and equal to 0.25, 5, and 10 mm, respectively.

3. Results and Discussion

Fracture toughness test results were considered valid in specimens in which the crack propagates vertically from the edge of the notch to the lower edge of the specimen. In the valid tests, the K_{IC} value was measured using equation (1). Figure 2 shows the obtained values of K_{IC} using the *p*CT method, in which the K_{IC} increases as the specimen size increases. In fact, there is a clear size effect which is likely related to the presence of heterogeneities in the tested rock.

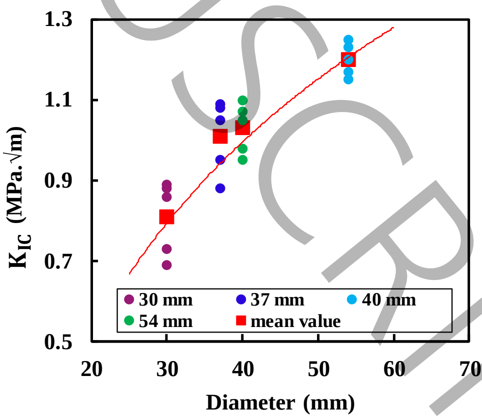

Figure 2. Mode (I) fracture toughness variations as a function of specimen diameter.

In terms of fracture behavior, the *p*CT method provides a good control on the specimen during the experiments even beyond maximum load. This is proved by the load-displacement curves obtained during the tests, which can be found in the full manuscript of this study.

In this study an assessment of cracking process is carried on for each specimen according to the general model of Martin and Chandler (1994), about the progressive failure of brittle rocks, and with respect to the changes of acoustic emission activity distinguished by AE counts and energy characteristics. Accordingly, the failure process of each specimen is divided to five stages (shown in varying shades of green in Fig. 3).

Stage I: Closure of pre-existing flaws and microcracks; Stage II: Development of the material's elastic component, marked by a linear stress-strain relationship; Stage III: Microcracks evolve into mesocracks, leading to accelerated damage and the formation of macrocracks once the load reaches the critical K_{IC} value; Stage IV: Initiated at peak load, the material retains some cohesion but gradually loses strength; Stage V: Advanced interactions between cracks cause the specimen to split.

This five-stage model aligns with AE data. Initially, E_{AE} is minimal, rising slowly during the linear phase as microcracks form. It accelerates significantly during stable crack growth, and peaking at the maximum load.

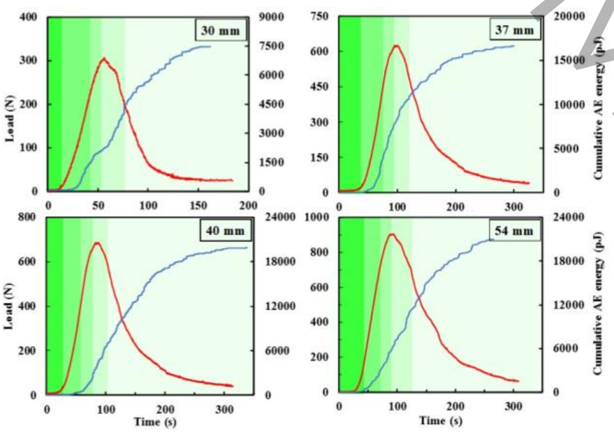

Figure 3. Load- time and cumulative AE energy- time curves obtained from AE monitoring of *p*CT method for specimens of 30 mm (up- left), 37 mm (up- right), 40 mm (down- left) and 54 mm (down- right) diameter; (Background colors indicate each stages of failure).

4. Conclusions

In this study, the effect of the specimen size on the fracture toughness of Mode I in a crystalline rock was investigated using the *p*CT method and the AE technique. The results obtained from the fracture toughness test using the *p*CT method indicate that the fracture toughness is a function of specimen size (up to a specific diameter) and increases with an increase in specimen size. The mechanical behavior of during the tests show that the *p*CT method provides a good control on the specimen during the experiments even beyond the maximum load and proves the suitability of the *p*CT method for evaluating the Mode I fracture toughness of brittle materials. Additionally, this method allows for a complete characterization of fracture behavior, enabling the study of rock behavior at various stages of rock failure using real-time AE monitoring tool during the fracture process.

5. References

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