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Correlation between Inelastic Volumetric Strain and Acoustic Emission Wave for Damage Assessment

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ABSTRACT

A comparative evaluation between a mechanically measured stress-strain relation and an acoustic emission technique was presented for a quantitative assessment of progressive damage evolution in KURT granite. In this study, it was attempted to correlate the inelastic volumetric strain, called crack volumetric strain and acoustic emission energy to the degree of damage in granite. From the results, it was suggested that the damage estimation from the AE energy method is closely related to that from crack volumetric strain and is preferred from the perspective of its practical field applicability.

1. INTRODUCTION

Acoustic emission (AE) is elastic wave emitted by microcracks or fractures within the material as they are newly created or propagated. The AE technique is considered one of the most promising techniques for real-time monitoring of the in-situ performance of near-field rock masses (SKB 2005). Since acoustic emissions are very sensitive to the initiation and growth of cracks in materials, they have been widely used to evaluate the cracking processes in structure health monitoring. However, it has been usually directed in a qualitative analysis such as detecting the onset of crack generation or crack source location.

The aim of this study is to identify the correlation between mechanically measured stress-strain data and physically detected AE data for the quantitative damage evolution in granite. In this study, it was attempted to correlate the inelastic volumetric strain, called crack volumetric strain and acoustic emission energy to the degree of damage in granite. Additionally, the stress levels for the stages of crack development of KURT granite were investigated from the laboratory tests.

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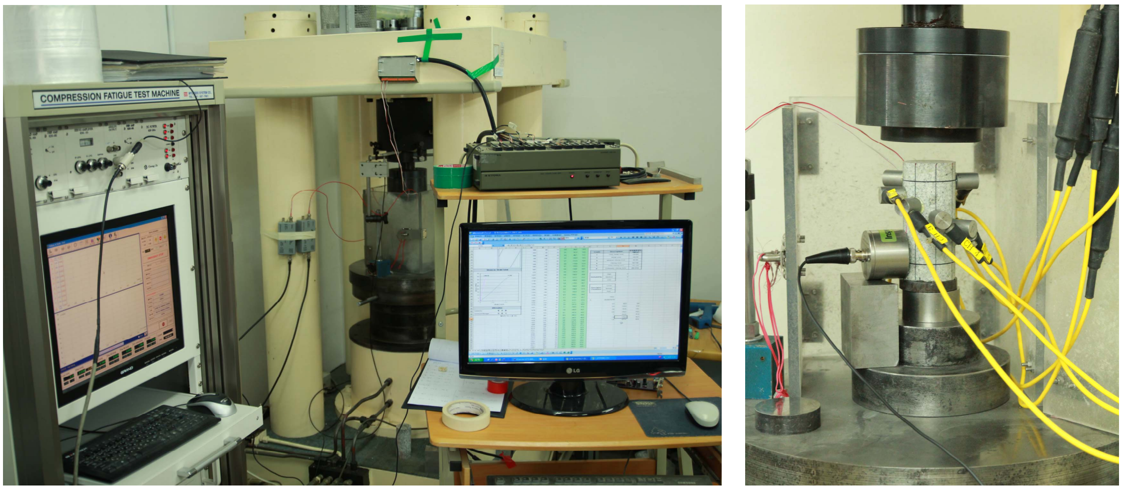
2. MATERIAL AND TEST METHODS

The uniaxial compression tests were executed based on ISRM (1979). At the same time, both the strain-stress and AE activity were recorded simultaneously (Fig. 1). The AE sensor (AE603SW-GA: Φ20x20H mm) had a resonance frequency of 60±20% (kHz) and a sensitivity of 115 dB. To enhance the detection efficiency of the transducers for recording, the output voltage of the AE sensor was amplified to 60dB in total by both a pre-amplifier and the main-amplifier.



(a) (b)

Fig. 1. Experimental set-up: (a) data acquisition system for the measurements of both stress-strain and AE count, and (b) an AE sensor array.

3. DAMAGE LEVEL FOR DEVELOPMENT

The failure process of brittle rock can be divided into several stages characterized by changes in the values of axial and lateral strains or AE data recorded during a uniaxial compression test (Fig. 2). As suggested by Martin (2001), crack closure (σ_{cc}) occurs during the initial stage of loading when existing cracks close and can be determined as the point where the axial stiffness curve changes from non-linear to linear or, where the crack volumetric strain approaches zero. The crack initiation stress threshold (σ_{ci}) is defined by the onset of stable crack growth, and indicated as the point where the crack volumetric strain deviates from zero. Thus, the stress region between crack closure and crack initiation is regarded as the zone showing elastic behavior. While, the crack damage stress threshold (σ_{cd}) is characterized by unstable crack growth, which has been associated with the point of reversal in the total volumetric strain. The point where large irregularity in volumetric stiffness occurs, is also referred to as crack coalescence (σ_{cs}).

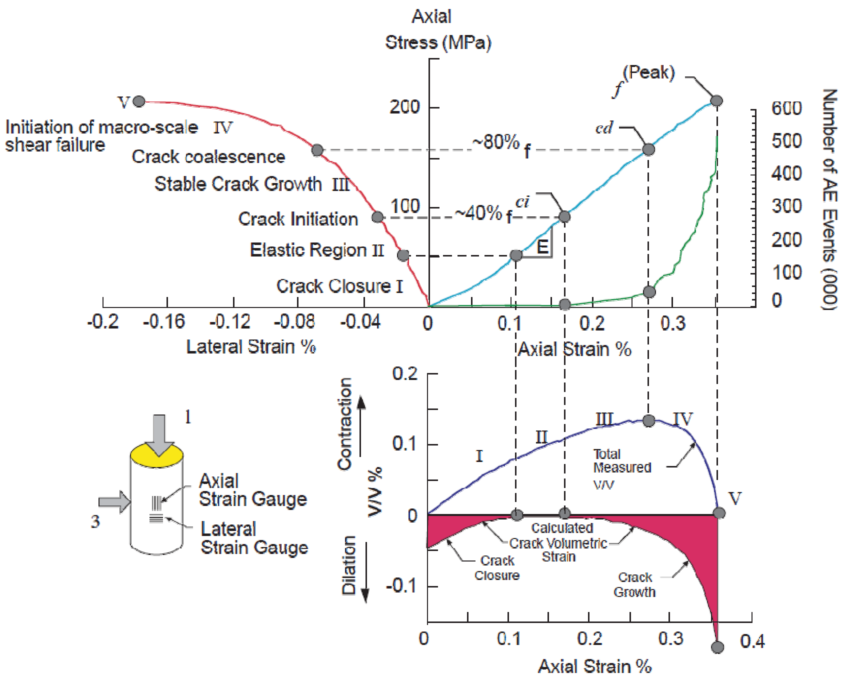


Fig. 2. Stress-strain relation representing the stages of crack development (Martin et al., 2001)

4. RESULTS AND DISCUSSION

4.1 Damage estimation from stress-strain relation

For a cylindrical sample loaded uniaxially, the inelastic volumetric strain is determined by substracting the linear elastic component of the volumetric strain as follows:

$$\varepsilon^{ie}{}_{v} = \varepsilon_{v} - \frac{1-2\upsilon}{E} \cdot (\sigma_{axial}) \qquad (1)$$

where $\varepsilon^{ie}{}_{\upsilon}$ is the inelastic volumetric strain, ε_{υ} is the total volumetric strain, $\varepsilon^{e}{}_{\upsilon}$ is the elastic component in the total volumetric strain, E and υ are the elastic constant, and σ_{axial} is the axial stress level. Martin (1994) defined inelastic volumetric strain as crack volumetric strain, which is attributed to axial cracking. Based on the measured stress-strain data, the variation of volumetric strain and stiffness were calculated and the crack volumetric strain was derived as shown in Fig. 3. It was found that the crack closure was determined to be $0.39\sigma_c$, the crack initiation $0.49\sigma_c$, the crack coalescence $0.57\sigma_c$, and the crack damage $0.71\sigma_c$ from Fig. 3.

Because the generation of cracks is inevitably followed by an increase in the volume of granite, leaving some permanent plastic deformation, it can be assumed that the volume change is proportional to the damage. Thus we further attempted to correlate the accumulated inelastic volumetric strain to the quantitative degree of damage in this study. The calculated crack volumetric strain at each stress level was normalized by the total accumulated inelastic volumetric strain. Therefore normalized accumulated inelastic volumetric strain can be considered as the relative degree of damage (D) in this study. Figure 4 derived from Fig. 3, shows the progressive damage evolution of KURT granite with regard to the stress level.

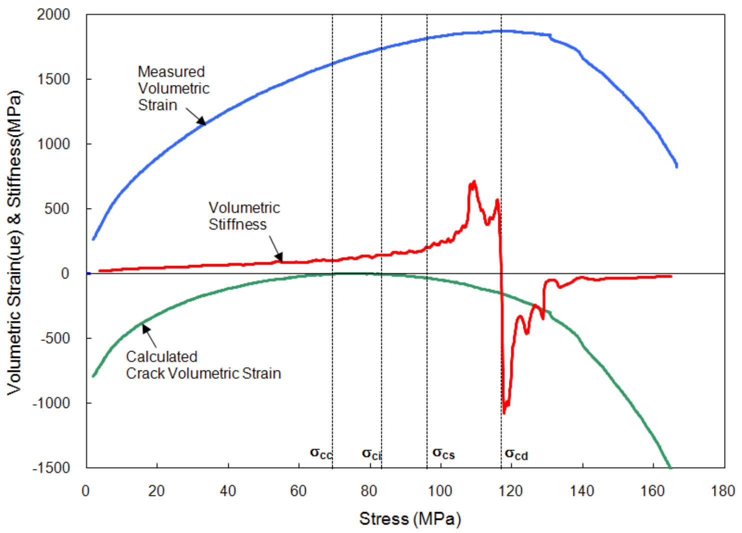


Fig. 3. Variation of volumetric strain and stiffness according to stress.

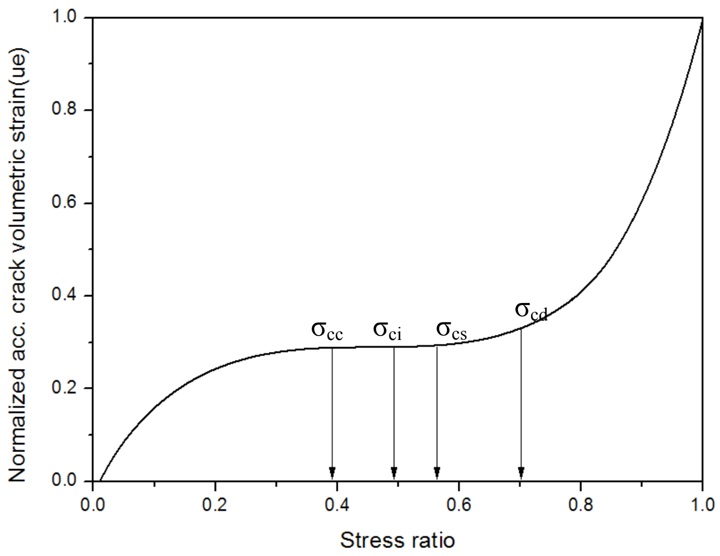


Fig. 4. Normalized cumulative crack volumetric strain (damage evolution)

4.2 Damage estimation based on AE data

The degree of damage caused from crack growth in a progressive failure of a rock specimen can be closely related to the energy content of the AE signal and corresponds to the total elastic energy released by an AE event. With regard to the AE energy, relative degree of damage (damage parameter D) in the rock specimen can be inferred from the normalization of cumulative AE energy up to each stress level by the total cumulative AE energy until failure. If we assume that the matrix material is linearly elastic, then the effect of the cracks, that is, damage can be accounted for by changes in the effective modulus of the material as follows (Atkinson 1987):

$$E = E_0(1-D) \tag{2}$$

where E_0 indicates the elastic modulus of a virgin material, E is the elastic modulus of a damaged material, and D is a damage parameter. Therefore rock deformation between fracture initiation and failure can be described by the continuous accumulation of stress-induced fracture damage. In this study, (1-D) in Eq. (2) is assumed as the integrity of the rock specimen. Although the damage evolution profiles of normalized inelastic volumetric strain and accumulated AE energy show similar patterns and shape, their amount of integrities are somewhat different. This is mainly caused from the initial flurry of acoustic activity in the early stages of the test related to the end effect of seating, crack closure and other system effects.

For the purpose of a systematic comparison of damage evolution with a stress increase, it was assumed that damage accumulation doesn’t occur below the crack initiation stress threshold. This is reasonable because theoretically no damage is accumulated in an elastic region of the material, that is, between crack closure and crack initiation. Fig. 5 shows a modified integrity profile by considering that damage starts to be accumulated only beyond the crack initiation threshold level, and that all integrities are values normalized by them of the elastic region.

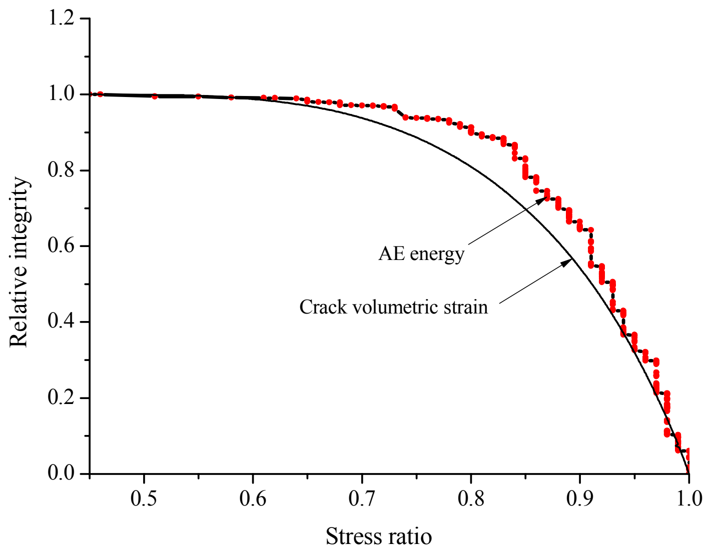


Fig. 5. Normalized integrity beyond the crack initiation stress

5. CONCLUSION

The relative integrity profile derived from the damage parameter between stress-strain relation (inelastic volumetric strain) and AE method (signal energy) shows a similar pattern although the basic mechanisms in derivation of each degradation are different. The damage parameters of KURT granite derived from the mechanically measured stress-strain relation could be successfully correlated and compared to those from physically detected acoustic emission waves, provided that effects such as an initial flurry of acoustic activity in the early stages of the test were taken into account. Because it is generally difficult to measure the stress-strain relation of rock mass in a field, the field application of the AE method rather than crack volumetric strain seems to be more practical.

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