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Energy evolution characteristics of hard rock during triaxial failure with different loading and unloading paths

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A B S T R A C T

Triaxial compression tests were conducted on fine-to-medium–grained granite specimens, with initial confining pressures of 10, 20, 40, and 60 MPa, under various loading and unloading stress paths. The energy evolution characteristics of granite specimens from a quarry in Miluo city (China) were studied in the triaxial deformation and failure process of the rocks. The results show that the time history curves of the total strain energy, elastic strain energy, and dissipative strain energy exhibit significant stage features. In particular, the ratio of the dissipative strain energy to the total strain energy can be used to describe the deformation and degree of damage to rock specimens during the triaxial loading and unloading processes. Under the same initial confining pressure, the maximum values of the total strain energy, elastic strain energy, and dissipative strain energy occur in the conventional triaxial compressive testing of group I, and the minimum values occur in test group II with constant axial stress and decreasing confining pressure. The total strain energy, elastic strain energy, and circumferential strain energy all increase as the initial confining pressure increases, whereas the dissipative strain energy does not. During the process of unloading the confining pressure, the increase of the circumferential strain is considerably larger than that of the axial strain. Under unloading conditions, rock bursts may occur more easily for hard rocks than under conventional triaxial loading conditions, especially under the conditions of test group III with increasing axial stress and decreasing confining pressure. The micro-difference in the granite micro-cracks was identified using a scanning electron microscope (SEM) combined with an energy dispersive spectrometer (EDS). Shear failure characteristics were observed in a conventional triaxial test, and the combined tension and shear failure was identified through unloading confining pressure tests. The tensile failure characteristics of the granite in group III are more pronounced than those of group II. This indicates that the triaxial failure of rock results from the development of micro-extension cracks and volumetric expansion in the granite specimen under unloading confining pressure tests.

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List of symbols

U	Total strain energy
U_e	Elastic strain energy
U_d	Dissipative strain energy
U_1	Axial strain energy
U_3	Circumferential strain energy
U_d/U	The ratio of the dissipative strain energy to the total strain energy
ε_1	Axial strain
ε_3	Circumferential strain
σ_1	Axial stress or the major principal stress
σ_3	Confining pressure
${\sigma_3}^0$	Initial confining pressure
${\sigma_3}^f$	Confining pressure of rock failure
E	Young's modulus
ν	Poisson's ratio

1. Introduction

The relationships between stress, strain, acoustic or seismic emissions, and seismic energy releases are highly important for understanding the mechanical behavior of rock and rock masses, particularly for deep rock mechanics with high in-situ stresses. Engineering activities, such as blasting by mining and tunneling in highly-stressed areas, can induce severe damage and instability in rock masses, due to the release and transfer of energy in the surrounding rocks (Sanchidrian et al., 2007; He et al., 2015). The stress-strain relationship and the strength and deformation properties of rocks have been well studied under triaxial compression (Li et al., 2012; Yang, 2016). The Mohr-Coulomb and Hoek-Brown criteria can also be used to evaluate the relationships between principal stresses during triaxial failure (Li et al., 2012). However, the stress-strain relationship cannot fully describe the failure processes of rocks. The stress-strain curves of rocks may be roughly the same, but exhibit different failure modes with different characteristics of energy release. Therefore, it would be better to describe the deformation and failure of rocks from the viewpoint of energy (Xie et al., 2009). Indeed, the failure process of rock is driven by energy activities, including absorption, evolution, and the release and dissipation of strain energy (Nishiyama et al., 2002; McSaveney and Davies, 2009; Tao et al., 2013; Wasantha et al., 2014).

Some researchers have carried out experimental studies and numerical simulations on the variation rule of energy in the failure process of rock. Based on numerical simulations, Fialko and Rubin (1997) discovered that the tensile fracture energy depends in general on the crack size and the distribution of loads within it, as well as the ambient stress. Bagde and Petroš (2009) found that the energy required to cause fractures increased rapidly with an increasing amplitude and frequency in dynamic cyclic loading. Peng et al. (2015) experimentally studied the energy dissipation and release during coal failure under conventional triaxial compression, and proposed two parameters (failure energy ratio and stress drop coefficient) to describe the failure mode of coal under different confining pressures. The effects of various strain rates on the fracture toughness and the energy-release rate of gas shales have also been investigated, and the experimental results indicate that the fracture toughness and energy-release rate are functions of the strain rate (Mahanta et al., 2017). The distortional strain energy at dilation and at failure from various loading rates varies linearly with the mean normal stress in a triaxial test, and it has been proven that the strain energy criterion considering both distortional and mean stress–strains at dilation tends to produce conservative results (Fuenkajorn et al., 2012). It has been shown that the energy evolution can reflect the deformation and failure processes of rock. The energy dissipation associated with the

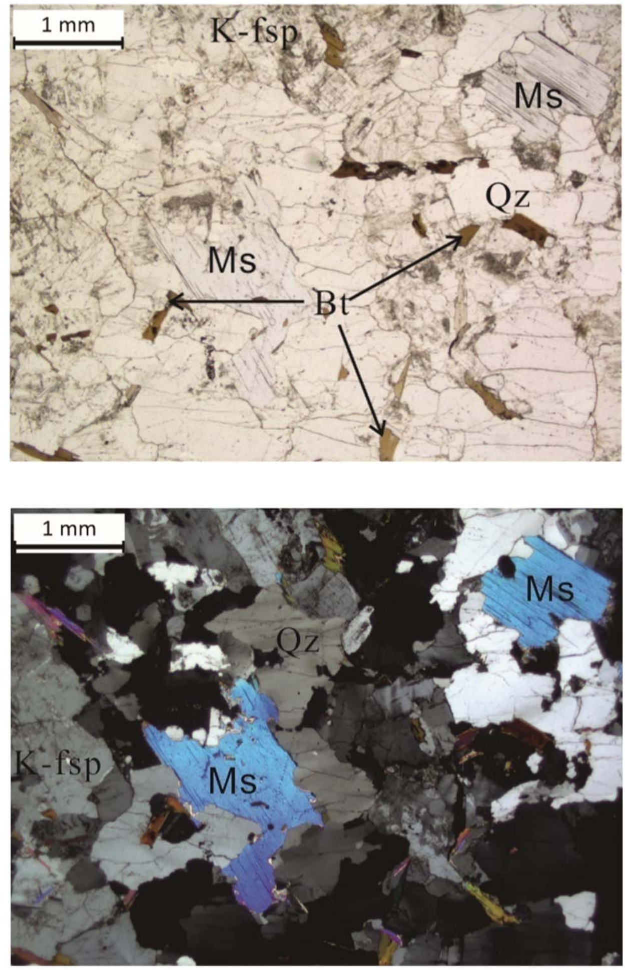

Fig. 1. Polarized light micrographs of granite specimen: (a). PPL; (b). CPL. (The letters Qz, K-fsp, Ms and Bt represent quartz, potassium feldspar, muscovite and biotite, respectively).

Table 1
Mineral composition and grain size distribution of the granite specimen.

Mineral composition	Grain size (mm)	Content (%)
Quartz	0.2–5	56
Potassium feldspar	0.5 × 1–3.2 × 5.5	30
Muscovite	0.02 × 0.05–1.5 × 2.2	7
Biotite	0.03 × 0.06–1.2 × 3.2	5
Apatite	0.01–0.2	1
Others	0.01–0.2	1

creation of new surfaces and the redistribution of stored strain energy leads to weaknesses in material strength (Li, 2001). The ratio of the dissipative strain energy to the total strain energy has been proposed for appraising the energy dissipation and damage accumulation degree during the four deformation stages, and the total input energy and dissipated energy have been adopted to describe the freeze-thaw mechanical coupling damage evolution properties during the deformation and failure process of red-sandstone (Wang et al., 2017). Recently, the effects of loading and unloading processes on the fracturing and failure of rock under triaxial compression conditions have attracted the attention of researchers (He et al., 2010; Yin et al., 2012; Huang and Li, 2014; Li et al., 2014; Du et al., 2015). Some conventional triaxial tests (Huang and Li, 2014; Zhao et al., 2015) and true triaxial tests (He et al., 2010; Li et al., 2015) with different loading and unloading stress paths have been performed to study the failure process of rock, and the corresponding energy conversion in rock has also been discussed. The