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Mechanical and damage evolution properties of sandstone under triaxial compression

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ABSTRACT

To study the mechanical and damage evolution properties of sandstone under triaxial compression, we analyzed the stress strain curve characteristics, deformation and strength properties, and failure process and characteristics of sandstone samples under different stress states. The experimental results reveal that peak strength, residual strength, elasticity modulus and deformation modulus increase linearly with confining pressure, and failure models transform from fragile failure under low confining pressure to ductility failure under high confining pressure. Macroscopic failure forms of samples under uniaxial compression were split failure parallel to the axis of samples, while macroscopic failure forms under uniaxial compression were shear failure, the shear failure angle of which decreased linearly with confining pressure. There were significant volume dilatation properties in the loading process of sandstone under different confining pressures, and we analyzed the damage evolution properties of samples based on acoustic emission damage and volumetric dilatation damage, and established damage constitutive model, realizing the real-time quantitative evaluation of samples damage state in loading process.

1. Introduction

Due to the constant movement and development of the crust, there are inevitably a large number of initial defects such as micropores, joints and cracks in the rock mass. The deformation and damage of the rock mass, along with the propagation, development and connection of original cracks, is strongly affected and restricted by internal initial defects, especially structural planes with joints scale [1,2]. Therefore, research on fracture damage evolution progress and the characteristics of rock under the condition of triaxial compression is of great significance to mining engineering, tunnel engineering and geotechnical engineering.

Damage is a phenomenon whereby micro defects in a material under monotonic loading or reloading leads to a progressive decrease in the cohesion and damage of volume units. Many scholars at home and abroad have carried out systematic research into the damage evolution characteristics and constitutive models of rock, and have achieved some remarkable results in this field. Lu et al. [3] studied the complete stress–strain curve characteristics of marble under triaxial compression, and established the bilinear elastic-linear strain-softening residual ideal plastic damage constitutive model. Ren [4] studied the damage evolution laws of coal and the rock mass using a computerized tomography triaxial loading system, realizing the quantitative evaluation of the damage state. Jin et al. [5] studied damage evolution of rock under uniaxial compression and built the coal-rock damage evolution model which considered residual strength based on electromagnetic radiation characteristics. Zhang et al. [6] studied the deformation and failure mechanism of strong weathered sandstone by triaxial compression testing, and analyzed the damage evolution processes and established damage evolution equations based on the density method. Li et al. [7] studied the microscopic damage characteristics of siltstone under triaxial compression by scanning electron microscopy and digital image technology, and analyzed the statistical distribution characteristics of azimuth angle, length and width of cracks. Zhou et al. [8] studied the strength, deformation and fracture damage characteristics of sandstone by uniaxial cyclic loading and unloading tests, and defined a damage variable based on linear damage mechanics theory and acoustic emission (AE). Cao et al. [9] established a new damage model and a statistical damage constitutive model of rock under specific confining pressure according to the force of the damaged and undamaged parts in rock on the base of statistical damage theory. Li et al. [10] studied the damage evolution characteristics in the whole uniaxial compression

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process of sandstone by electrical resistivity and AE, and proposed a status qualitative criterion for rock damage. The indicators such as AE, CT values, density, electrical resistivity and crack length were adopted to evaluate the degree of damage and to study the damage evolution laws of rock in related research. However, research on the damage evolution process of rock on the basis of the dilatation properties is less well developed.

Therefore, in this paper, the deformation and failure process, mechanical properties and evolution laws of sandstone under different stress states by uniaxial and triaxial compression tests are described, damage evolution based on AE and dilatation properties is analyzed, and a damage constitutive model, realizing real-time and quantitative evaluation of the damage state in the whole compression process, is established.

2. Experimental

2.1. Equipment and sample preparation

Uniaxial and triaxial compression tests of sandstone were carried out on a TAW-2000 rock mechanics electro-hydraulic servo testing system, having a maximum axial force of 2000 kN, maximum confining pressure of 60 MPa, axial deformation measurement range from 0 to 10 mm, and radial deformation measurement range from 0 to 5 mm, and which can be used for uniaxial compression tests, uniaxial compression creep tests, triaxial compression tests and triaxial compression creep tests.

Red sandstone, taken from Linyi of Shandong province, has a fine, blocky structure, good homogeneity, with a main mineral composition of quartz 17%, feldspar 42%, andesitic debris 25%, cements 15% and zircons 1%. The diameter distribution of the sandstone is: 0.10–0.25 mm 60%, 0.25–0.50 mm 35% and 0.50–1.00 mm 5%. The cementing type of the sandstone is pore cementation with grain point-line contact.

Saturated red sandstone was processed into standard samples with diameters of 50 mm and height of 100 mm according to the standard testing method of *Methods for Determining the Physical and Mechanical Properties of Coal and Rock* (GB/T23561.1-2009) and ISRM. Sample specifications are shown in Table 1.

2.2. Schemes and process

The confining pressure of triaxial compression tests were 5, 10, 15, 20 and 30 MPa respectively. The experimental process was as follows.

The confining pressure was loaded to the set value at a rate of 0.05 MPa/s after the installation of samples. With a constant confining pressure, axial pressure was increased by the displacement control method at a loading rate of 0.002 mm/s until failure of the sample occurred. The axial pressure loading rate of the T-6 sample after peak strength was reached was 0.001 mm/s. The loading control methods of samples are shown in Table 1.

Table 1
Sample specification and loading control methods.

Sample No.	Diameter (mm)	Height (mm)	Test type	Loading rate (mm/s)
U-1	49.92	100.38	Uniaxial compression	0.002
U-2	49.72	100.62		
U-3	49.58	100.12		
T-1	49.62	100.28	Triaxial compression	0.002
T-2	49.72	99.98		
T-3	49.72	99.94		
T-4	49.62	100.40		
T-5	49.60	101.48		
T-6	49.72	100.80		Pre-peak 0.002 Post-peak 0.001

3. Results and discussion

Fig. 1 shows the complete stress–strain curves of sandstone samples under uniaxial and triaxial compression; experimental results are shown in Table 2.

3.1. Characteristics of complete stress–strain curves

As shown in Fig. 1, complete stress–strain curves of sandstone samples under uniaxial compression can be divided into five stages, including fissure compression, elastic deformation, steady crack propagation, unsteady fracture propagation and a strain-softening stage. The residual deformation stage is not included. Fig. 1 shows good elastic property in the pre-peak stage of the stress–strain curves, and the peak point and strain-softening stage can only hold for a remarkably short time, presenting the characteristics of brittleness failure.

There is no obvious fissure compression stage in the complete stress–strain curves of the sandstone samples under triaxial compression. Deviatoric stress increases linearly with increasing axial strain, radial strain and volumetric strain in the stress–strain curves up to the yield point, and the slope of the curves increases with increasing confining pressure. After the yield point, with increasing axial stress, new cracks gradually initiate in the samples with increasing axial stress, with further propagation of the original cracks and energy dissipation; this leads to the up-convex morphology of the stress–strain curves, a decrease in the stress–strain curve slope and an increase in plastic deformation. When the deviatoric stress reaches the failure strength, new macroscopic cracks initiate in the samples leading to failure of the samples, which shows the characteristics of a sharp increase in axial strain, radial strain and volumetric strain, and a decrease in sample strength. With increasing confining pressure, the slopes of the stress–strain curves, peak strength and residual strength have a great improvement, the samples at the strain-softening stages have smoother stress–strain curves, showing certain behavior of plastic deformation.

The residual strength of the samples under a confining pressure of 30 MPa and a loading rate of 0.001 mm/s is higher, and the slopes of the stress–strain curves are becoming smaller at the strain-softening stage, showing clear behavior of plastic deforma-

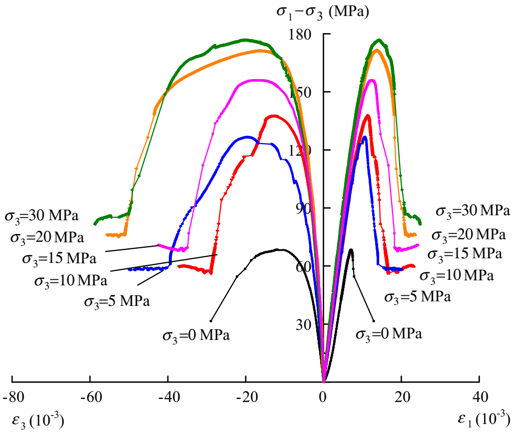

Fig. 1. Complete stress–strain curves of sandstone samples in uniaxial and triaxial compression tests.