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Mechanical properties and failure characteristics of fractured sandstone with grouting and anchorage

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ABSTRACT

Based on uniaxial compression experimental results on fractured sandstone with grouting and anchorage, we studied the strength and deformation properties, the failure model, crack formation and evolution laws of fractured sandstone under different conditions of anchorage. The experimental results show that the strength and elastic modulus of fractured sandstone with different fracture angles are significantly lower than those of intact sandstone. Compared with the fractured samples without anchorage, the peak strength, residual strength, peak and ultimate axial strain of fractured sandstone under different anchorage increase by 64.5–320.0%, 62.8–493.0%, and 31.6–181.4%, respectively. The number of bolts and degree of pre-stress has certain effects on the peak strength and failure model of fractured sandstone. The peak strength of fractured sandstone under different anchorage increases to some extent, and the failure model of fractured sandstone also transforms from tensile failure to tensile–shear mixed failure with the number of bolts. The pre-stress can restrain the formation and evolution process of tensile cracks, delay the failure process of fractured sandstone under anchorage and impel the transformation of failure model from brittle failure to plastic failure.

1. Introduction

A rock mass is a geologic body which was formed in certain geological environments from deformation and destructive geological processes, and has a specific composition and structure. Due to the constant movement and development of the Earth's crust, the rock mass, in which there are many discontinuous surfaces such as joints and cracks, takes on a significant discontinuity. The mechanical properties of the rock mass can be greatly influenced by joints and cracks, resulting in a reduction in the deformation modulus and strength and obvious anisotropy of the rock mass, which seriously affects the engineering stability of the rock mass [1,2]. The propagation of original cracks and the initiation, propagation and connection of new cracks at the crack tip will lead to instability and failure of the rock mass and supporting structure. This is due to the influence of excavation unloading, seepage, mining and additional load during geotechnical engineering construction and long-term operation [3,4]. Measures such as grouting and anchoring should be applied to guarantee the stability of the fractured rock mass. Grouting and anchoring, the most commonly used techniques in geotechnical engineering support and reinforcement, can improve the structure and performance of the surrounding rock, make full use of its bearing capacity, and provide a foundation for the long-term stability of the surrounding rock. The mechanism of grouting and anchoring reinforcement is not fully clear. Therefore, a study of the mechanical properties of a fractured rock mass with grouting and anchorage has an important theoretical value and practical significance to guarantee the stability and security of a fractured rock mass under complex conditions [5].

Experts and scholars throughout the world have gained many achievements in research of fractured rock mass reinforcement properties by theoretical analysis, similarity model testing and numerical simulation [6–12]. Ge et al. studied the effects of bolting on the joint surface shear behavior using similarity model tests in the laboratory combined with theoretical analysis [13]. Zhang et al. simulated the support effects of bolting in a discontinuous jointed rock mass by creating a model of cylindrical damage in rock bolts using an element model [14]. Han et al. studied the mechanical characteristics of a cracked rock mass reinforced by bolting and grouting using numerical simulation and similarity model tests, and verified the stress strengthening characteristics in the carrying process [15,16]. Song researched the effects of bolts, fractures and adhesive materials on the failure mode and integral mechanical

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properties of a fractured rock mass using similarity model tests and uniaxial and triaxial compression tests [17]. Zhang et al. studied the strength and deformation properties, failure mode and crack propagation characteristics of anchored fractured rock under uniaxial tension through similarity model testing [18]. Xu et al. researched the influence of anchorage parameters such as length, diameter and anchorage distance on the failure behaviors of a rock slope by similarity model tests [19]. Although the achievements mentioned above have played an important role in promoting the development of fractured rock mass reinforcement theory and technology, there are some deficiencies such as abstract and simplified theoretical model and homogeneous similarity materials in tests.

In this paper, persistent fissures with different angles were cut in red sandstone to get fractured samples. Uniaxial compression experiments of fractured samples under different anchorages were carried out using a rock mechanics rigidity testing system. The strength and deformation properties, failure model, crack propagation and evolution laws of fractured samples under different anchorages under uniaxial compression were studied and grouting and anchorage mechanisms of fractured rock mass were revealed further.

2. Experimental

2.1. Equipments and methods

Uniaxial compression experiments of fractured samples under different anchorages were carried out on a TATW-2000 rock mechanics electro-hydraulic servo testing system using the displacement control method with a loading rate of 0.005 mm/s. The system comprises of an axial loading system, servo oil-source system, confining pressure loading system, monitoring and control systems as well as other components. Data on stress, strain and displacement can be collected automatically, and the corresponding curve can be drawn and outputted as well. The maximum axial force of the test system is 2000 kN with force and displacement measurement accuracy less than 1%.

2.2. Sample preparation

Red sandstone, taken from Jinan city, Shandong province, has a fine, blocky structure and good homogeneity. The main mineral composition is: 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 0.5–1.0 mm 5%. The cementing type of the sandstone is pore cementation with grain point-line contact.

The sample preparation process was as follows: first, standard samples 150 mm × 150 mm × 150 mm were prepared from irregular pieces of rock. Then, pre-existing persistent fissures with 30°, 45° and 60° angles were prepared by cutting (Fig. 1). The sample, was then placed vertically into a prefabricated wooden template and fixed. Finally, cement paste was poured into the persistent fissure in the sample, which was then cured under standard conditions for 28 days. The thickness of pre-existing fissures was about 8.0 mm. The cement paste was made of 42.5 common Portland cement, with a water/cement ratio of 0.75.

A hole was drilled in the center of the sample with a 16 mm diameter drill, and a 16 mm diameter rebar having a yield strength of 465 MPa, a tensile strength of 650 MPa and an elongation of 23.5%, was then inserted to simulate the anchorage of the bolt. Two steel plates with a thickness of 5.0 mm were installed on the opposite sides of the sample to simulate bolt plates. The bolt was pre-stressed to approximately 500 N using a torque wrench. Uniaxial compression experiments were carried out on fractured samples with pre-existing fissures at all orientations under 5 different anchorage arrangements: non-anchorage (NA), non-pre-stressed single anchorage (NPSA), pre-stressed single anchorage (PSA), non-pre-stressed double anchorage (NPDA) and pre-stressed double anchorage (PDA).

3. Results and discussion

Fig. 2 shows the axial stress–strain curves of fractured samples with different fissure angles under NA, and Fig. 3 shows the axial stress–strain curves under different anchorage arrangements. Table 1 lists the mechanical parameters of fractured samples under different anchorages.

3.1. Stress–strain relationship

As shown in Fig. 2, intact sandstone samples take on brittle failure characteristics. Elastic behavior is demonstrated in the pre-peak region of the stress–strain curve, and the strain-softening phase only persists for a remarkably short time. The stress–strain curve declines to the residual strength stage due to the instantaneous instability failure of the sample after the peak point. The stress–strain curves of fractured samples under different anchorage show obvious compression of fissures and an elastic deformation stage (Fig. 3). With increasing load, cracks initiate and propagate in the stress concentration regions near the pre-existing fissures of fractured samples, which are demonstrated by the reductions in slope in the stress–strain curve.

3.2. Strength and deformation characteristics

From Table 1, it can be seen that the pre-existing fissures have a great effect on the strength of fractured samples. The peak strength of fractured samples with 30°, 45° and 60° pre-existing fissure angle are respectively: 20.01, 8.29 and 14.18 MPa, which decrease by 60.86%, 83.79% and 72.27% compared with intact samples, as well as a reduction in elastic modulus of 59.29% 50.51% and 59.29% correspondingly. The influence laws of fissure inclination angle on

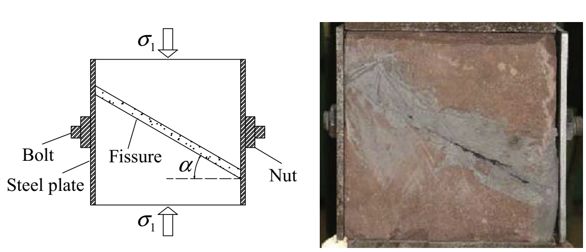

Fig. 1. Fractured sandstone sample with grouting and anchorage.

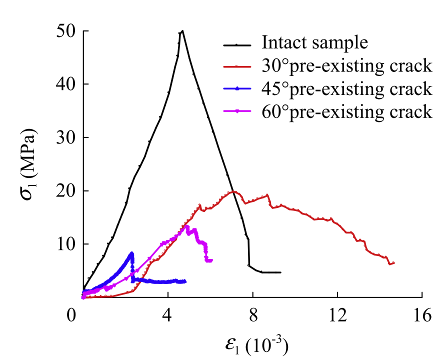

Fig. 2. Stress–strain curves of fractured samples with different fissure angles.