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Experimental investigation on dilatancy behavior of water-saturated sandstone

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ABSTRACT

It is important to study the dilatancy property of water-saturated rock for understanding the engineering behavior of loaded rock mass. This study carried out the uniaxial and triaxial compressive experiments on the water-saturated red sandstone, analyzed the influences of confining pressure and pore pressure on dilatancy property of water-saturated rock, and discussed the reasonable basis of the stress of dilatancy onset as a strength design parameter of rock engineering, finally established the prediction model of the stress of dilatancy onset under the impacts of confining pressure and pore pressure. The results show that the strength parameters (the stress of dilatancy onset and peak strength) and deformation parameters (axial strain and circumferential strain) of water-saturated sandstone increase with the confining pressure, and the relations can be fitted with a positive linear function. The cohesion and internal friction angle obtained from the stress of dilatancy onset decrease by 11.57% and 7.33%, respectively, when compared with those obtained from the peak strength. The strength parameters and deformation parameters of water-saturated sandstone decrease basically with the increase of pore pressure, in which the relations between strength parameters or axial strain and pore pressure can be fitted with a negative linear function. However, the relation between the peak circumferential strain and the pore pressure should be characterized by a negative exponential function, and the circumferential strain at dilatancy onset isn't affected by the pore pressure.

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1. Introduction

The transition from compression to dilatancy of rock mass in the deformation process under loading causes the full development of structural defects such as original fissures, pores and new cracks, which results in the irreversible damage in rock. Consequently, the failure of rock mass and the safety problem in engineering easily occur [1–4]. For example, during the construction of tunnel in the mountainous areas with the red sandstone including Hunan, Hubei, and Jiangxi provinces, the dilatancy of rock frequently caused the failure of fissure structure in rock mass under the effects of excavation, geological structure and erosion of long-term rainwater, which resulted in the geological hazards such as collapse and water inrush [5,6]. In coal mining, the dilatancy displacement increased sharply under the impacts of mining and groundwater, and then the fissures in rock mass fully developed to form the underground watercourses, which causes the water bursting disaster [7,8]. Therefore, it is important to study the dilatancy property of water-saturated rock for understanding the engineering behavior of loaded rock mass.

Abundant studies including experiment and numerical simulation have been performed to investigate the dilatancy behavior of rock under loading. For example, some scholars discussed the variations of porosity and permeability of rock in the stage of dilatancy, and the full development of microcracks among rock grain was confirmed by the microstructure observation. Even if the deformation is extremely small, the permeability increases with magnitude because of the expansion and propagation of cracks in rock [9,10]. Because the engineering rock mass in some areas is under the condition of high pore pressure, Alkan et al. studied the effect of pore pressure on the stress of dilatancy onset through the conventional triaxial experiment of rock [11]. In order to obtain the influence of rock dilatancy on the stability of tunnel, Tan and Alejano et al. calculated the dilatancy region of tunnel by constructing the constitutive equation of dilatancy [12–14]. The deep rock mass is usually

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under three-directional compression, so lots of researches about the relations between confining pressure and dilatancy parameters were carried out [15–18]. And some scholars investigated the dilatancy property of different rocks under creep deformation for understanding the dilatancy behavior of rock mass under long-term loading [19–21]. Due to the cracks, microcracks, joints and other defects are widely distributed in the engineering rock mass, Yang and Trivedi et al. analyzed the impact of pre-existing fissures on dilatancy parameters of rock [22,23]. In addition, the effect of dilatancy property on mechanisms of crustal fault, floor heave deformation of roadway, rock burst and precursor information of earthquake was discussed [24,25].

There are many factors that affect the dilatancy property of rock. However, due to the different external loads, the dilatancy parameters of rock are difficult to quantify, and it is difficult to give the optimal parameter selection in engineering design. For this purpose, Martin and Chandler suggested that the 50% uniaxial compressive strength (UCS) can be used as the strength design parameter of rock material to reduce the occurrence of safety accident in engineering [26]. However, this is only an empirical criterion, and its mechanism isn't revealed clearly. Consequently, the uniaxial and triaxial compressive experiments of water-saturated red sandstone under different confining pressures and pore pressures were carried out, the influences of confining pressure and pore pressure on dilatancy property of water-saturated rock were analyzed, the rationality of the stress of dilatancy onset as a strength design parameter of rock engineering was discussed, and the prediction model of the stress of dilatancy onset under the impacts of confining pressure and pore pressure was established.

2. Experimental materials and method

In this test, the red sandstone specimens were obtained from Hongyang Mine in Shandong, China. The average density is about 2.43 g/cm^3, and the X-ray diffraction (XRD) spectrum is shown in Fig. 1. According to the test method proposed by the International Society for Rock Mechanics (ISRM), the rock specimens were processed into cylinders of ϕ50 mm $\times$ 100 mm, which two ends were polished, and the non-parallelism and non-perpendicularity were controlled within ±0.02 mm [27]. Then the processed rock specimens were soaked with distilled water for more than 96 h until the qualities of specimens weren't increased to ensure that it reached saturation. The average moisture content is about 2.51% under the condition of saturation [28,29].

This study uses MTS815 rock mechanics test system for experiment, as shown in Fig. 2. The Vaseline was applied between the both ends of specimen and the indenter to eliminate the effect of the indenter loading on acoustic emission (AE) signals. The MTS815 system was controlled to load rock specimen at axial loading rate of 0.002 mm/s, and the initial prestress is 0.5 kN [30,31]. The confining pressure levels were set respectively at 0, 5, 10, 15 and 20 MPa in triaxial compressive experiment at a rate of 0.04 MPa/s, after the confining pressure loaded to the specified value, the axial displacement of 0.002 mm/s was conducted with the constant confining pressure. And the pore pressure levels were set respectively at 0, 3, 5 and 8 MPa at a rate of 0.02 MPa/s in compressive experiment. After the pore pressure loaded to the specified value, the axial displacement of 0.002 mm/s was conducted with the constant pore pressure. In this paper, the symbol of σ_3 is the confining pressure and the symbol of σ_u is the pore pressure.

Fig. 2. MTS 815 system.

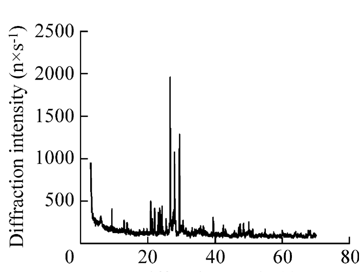

Fig. 1. XRD spectrum of red sandstone.

3. Experimental results

In order to test the difference among the sandstone specimens, a group of specimens were randomly selected for the uniaxial compressive experiment as shown in Fig. 3. The results show that the UCS of the four rock specimens are 113.74, 107.38, 104.36 and 101.28 MPa, the average value is 106.67 MPa, and the coefficient of variation only is 6.63%. It can be seen that the discrepancy among the different specimens processed by the same rock mass is small and can be used for the comparative test.

According to the literatures, the initial point of $\varepsilon_1 < |\varepsilon_2 + \varepsilon_3|$ (or the end point of $\varepsilon_1 \geq |\varepsilon_2 + \varepsilon_3|$) during the load process can be defined as the cd point of dilatancy onset [32,33]. Fig. 4 presents the mechanical behavior of water-saturated red sandstone to denote the dilatancy characteristic, which shows that the load process of red sandstone specimens can be divided five stages, including o-cc stage of pore compaction, cc-ci stage of elastic deformation, ci-cd stage of initiation and stability expansion of crack, cd-c stage of damage and unstable propagation of crack and failure stage. The characteristics of each stage are described in detail below:

(1) o-cc stage of pore compaction: The existences of the original cracks and pores in rock specimen compact with the increase of axial stress, which causes the stress-strain to present nonlinearity. The AE signals are weak in this stage. However, the circumferential strain remains the same on

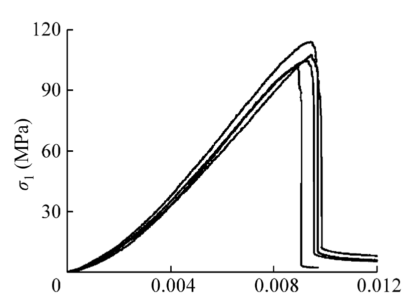

Fig. 3. Axial stress-axial strain curves of water-saturated sandstone under uniaxial compression.

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