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Experimental investigation on the energy evolution of dry and water-saturated red sandstones

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ABSTRACT

In order to investigate the effect of water content on the energy evolution of red sandstone, the axial loading–unloading experiments on dry and water-saturated sandstone samples were conducted, and the distribution and evolution of elastic energy and dissipated energy within the rock were measured. The results show that the saturation process from dry to fully-saturated states reduces the strength, rigidity and brittleness of the rock by 30.2%, 25.5% and 16.7%, respectively. The water-saturated sample has larger irreversible deformation in the pre-peak stage and smaller stress drop in the post-peak stage. The saturation process decreases the accumulation energy limit by 38.9%, but increases the dissipated energy and residual elastic energy density, thus greatly reducing the magnitude and rate of energy release. The water-saturated sample has lower conversion efficiency to elastic energy by 3% in the pre-peak region; moreover, the elastic energy ratio falls with a smaller range in the post-peak stage. Therefore, saturation process can greatly reduce the risk of dynamic disaster, and heterogeneous water content can lead to dynamic disaster possibly on the other hand.

1. Introduction

Rock mass in mine engineering, hydraulic project and underground space development often undergoes water environment [1]. Water content affects physical and mechanical properties of the rock greatly, and determines its engineering properties to some extent. Water content has two effects on the engineering properties of rock mass. On one hand, water makes rock mass fail and become instable, which induces relevant disasters such as water inrush and surrounding rock deformation in water-rich tunnel [2,3]. On the other hand, water may modify the rock structure and change its mechanical property. Based on this modification, some new techniques have been developed such as water-injection method for rock burst control and hydraulic cutting seam for methane extraction [4,5].

In order to prevent and manage potential engineering hazards under water environment effectively, and change the rock structure and mechanical property through water, it is necessary to investigate the energy evolution of the rock mass under different water contents.

The effects of water on the mechanical properties of rock mass have been widely investigated. These investigations can be divided into the following two groups.

The first one is to investigate the effect of water on mechanical properties of rock. For example, Chen et al. carried out uniaxial compression tests on sandstone, limestone and marble samples with different moisture contents by using MTS electro-hydraulic servo system [6]. Their results show that both peak strength and elasticity modulus of rock decrease rapidly with the increase of moisture content. Hadizadeh analyzed the water softening based on the variation of strength under different confining pressure and strain rate [7]. Men et al. regarded water as one of the primary factors which can determine the mechanical properties of rock mass [8]. They found that rock performs brittle and shear failure when the moisture content is low, while it is plastic failure when the moisture content is high. Zhou et al. tested the variation of uniaxial compressive strength, splitting tensile strength, and shear strength with saturation period [9]. Their results showed that the three strength parameters decrease exponentially with saturation period. Yang et al. studied the microstructure and mechanical properties of water-weakening slates [10]. It is observed that the compressive strength declines with the absorption time and increased in minus logarithm law, and the elastic modulus also has decreasing trend. Yang et al. carried out triaxial creep

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experiments on shale samples with different water contents [11]. They discovered that the ultimate creep deformation and creep rate increase significantly as the water content increases; simultaneously, the ultimate creep deformation modulus and viscosity coefficient drop obviously. Peng et al. scanned the surface topography of hydrous rock samples using 3D laser surface profilometer [12]. It is found that the discreteness and roughness of surface elevation become greater for higher water content. Ji et al. investigated the relationship between expansion strain and moisture content along with water soaking time [13]. Mao and Qi et al. discussed the effect of water content on rock burst index, which shows that the rock burst index of coal seam varies inversely to its moisture content, and this relationship is the most sensitive at initial state [14,15].

The other one is to study the effect of water on geophysical responses during rock deformation and failure. Zhu et al. tested the acoustic parameters of rock samples under dry and water-saturated conditions with ultrasonic method [16]. Their observations showed that the dominant frequency of P waves becomes lower, but the P wave velocity is hardly affected. Rong et al. analyzed the difference of electromagnetic radiation spectrum among water-saturated, natural and dry samples, and found that water makes the intensity become lower [17]. Qin et al. carried out acoustic emission testing under uniaxial compression on coal specimen with different moisture contents [18]. They observed that the accumulated acoustic emission counts decrease with the increase of moisture content, meanwhile evident time delay exits. Chen et al. conducted P wave transmission test on three rocks, i.e., red sandstone, marble, and granite under dry and water-saturated conditions using intelligent sonograph, and their results showed that the P wave velocity of water-saturated sample is larger, and the wave energy concentrates on lower frequency period, and energy weakens more rapidly [19].

Those studies fully indicate that water content has a significant impact on the microstructure and physical–mechanical properties of rock. The saturation process affects the energy evolution during rock deformation and failure. Because the energy behavior of rock relates its failure mode directly and stands for much closer to physical essence of material damage and failure, it is necessary to investigate the effect of water content on rock energy evolution [20–22]. In this paper, the axial loading–unloading tests on dry and water-saturated red sandstone samples were conducted to reveal the effect of water content on rock energy evolution. It further explored its enlightenment to dynamic disaster control of rock mass. The results can deepen the understanding of water–rock interaction, and are helpful for associated engineering practice.

2. Calculation methods of rock energy

The energy evolution of rocks can be roughly divided into four processes: energy input, energy accumulation, energy dissipation and energy release. Rock energy has many types, so it is difficult to monitor and measure each type in laboratory tests [20]. Considering the non-reversibility of dissipated energy and reversibility of elastic energy, and their roles in rock fragmentation degree and broken intensity respectively, only the dissipated energy and the elastic energy are discussed here [20]. The energy conservation law can be expressed as

$$W = E_e + E_d \tag{1}$$

where W is the input energy or the work that external forces do on rock, J; E_e the accumulated elastic energy in rock, J; and E_d the dissipated energy during loading process, which is related to damage and plastic deformation, J.

In view of the reversibility of elastic energy, the elastic energy and the dissipated energy can be calculated using loading–unloading stress–strain curve of rock. The elastic energy at a certain stress level can be taken as energy release after unloading at this point. Similarly, the dissipated energy is the difference between the input energy and accumulated elastic energy [22]. As shown in Fig. 1, it is the loading–unloading stress–strain curve of rock sample on direction i. When the stress level is σ', the elastic energy density is u_{ie}, which is equal to the area between unloading curve and strain axis. The dissipated energy density u_{id} is determined by the area between loading curve and unloading curve.

$$u_{\mathrm{id}} = \int_0^{\varepsilon'} \sigma_i \mathrm{d}\varepsilon_i - \int_{\varepsilon''}^{\varepsilon'} \sigma_i \mathrm{d}\varepsilon_i \tag{2}$$

$$u_{\mathrm{ie}} = \int_{\varepsilon''}^{\varepsilon'} \sigma_i \mathrm{d}\varepsilon_i \tag{3}$$

where ε' is the corresponding strain of σ'; and ε' is the remnant strain after stress unloading from σ' to zero.

3. Experimental

3.1. Specimen preparation

The rock samples used in this test were taken from Hanwang stone pit in the south of Xuzhou, Jiangsu Province, China. The rock material is maroon, and has fine grained texture. Its P wave velocity is about 4300 m/s, which indicates that it has good integrality and homogeneity. Its average density is 2.71 g/cm^3. The main components are feldspar (about 45%), quartz (about 13.5%) and chippings (about 31.5%). All samples were prepared in accordance with ISRM suggested shape and size, and were processed into cylinders with a diameter of 50 mm, and a length of 100 mm. The photograph and X-ray diffraction pattern of the samples are seen in Fig. 2.

Stoving tests indicate that the initial moisture content of these rock samples is about zero because of long-term air seasoning. The mass and moisture content of rock sample vary with the water soaking time, as shown in Fig. 3. It is observed that the mass of rock sample grows in a power function when the time soaking is less than 18 h, and nearly remains unchanged when more than 18 h. The growth rate is high before 10 h and then decreases gradually. The state of mass unchanged is regarded as the water-saturated state which has the moisture content of 2.25%.

In-situ rock mass is usually water-saturated. On the other hand, rock samples with different moisture contents are obtained by water soaking in different times in laboratory test, but uneven moisture content (larger near the surface, small inside) is observed due to short soaking time, so the effect of moisture content is unable to be revealed truly. For those two reasons, just dry and water-saturated samples are investigated in this study. Three

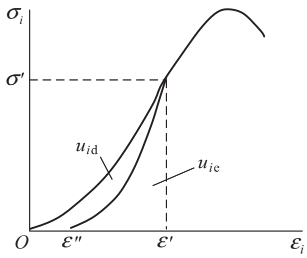

Fig. 1. Loading and unloading stress–strain curves of rock at stress of σ' on direction i.