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Effect of the layer orientation on mechanics and energy evolution characteristics of shales under uniaxial loading

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ABSTRACT

The uniaxial compression tests were conducted on the cylindrical shale specimens with bedding plane inclined at 0° and 90° to the axial loading direction, respectively. Effect of the bedding orientation on the mechanical property and energy evolution characteristics of shales was revealed. The failure mechanisms of the specimens with layers in 0° orientation showed splitting failure along weak bedding, while the specimens with layers in 90° orientation were failed by shearing sliding. The values of compressive strength, elastic modulus and shear modulus of samples at 0° were higher than those of samples at 90° and there was little difference of Poisson's ratio between samples at 0° and 90°. The analysis of the stress–strain energy and acoustic emission (AE) energy indicated that the growth rate of absorbed energy density and elastic energy density at 0° was significantly faster than that at 90°, hence their final values at 0° were relatively larger than the latter. Moreover, higher energy release was observed for specimens at 0°. The energy release and rapid growth of energy dissipation also appeared more early at 0°. The stress ratio 63% was a critical point of energy distribution at which differences started to arise between samples at 0° and 90°. These results indicated that the failure of shale at 0° was more violent and devastative than the failure of shale at 90°.

1. Introduction

Rock is a heterogeneous composite material, resulting in significant anisotropy, especially for bedding rock. Therefore, the process of deformation and failure for rock shows a strong complex miscellaneous due to the presence of bedding plane [1,2]. In most cases, oil, natural gas and nuclear waste are often stored in the bedding rock, so mechanical behavior of bedding rock receives more attention in energy shortage condition. For this reason, many studies about effect of bedding plane direction on rock mechanics have been highlighted in the literature [3–13]. However, the traditional stress–strain relationship cannot reveal the essence of the deformation and failure of rock effectively. Besides, it provides the limited information about the mechanical response of rock. A better picture of bedding rock behavior can be obtained by considering the energy evolution during rock deformation [14]. In fact, energy dissipation, energy accumulation and energy release occur evidently during the process of rock deformation and failure [15,16]. The essence of rock failure is a state of instability phenomenon driven by energy [17]. Thus, studying the energy evolution of bedding rock can provide important information about rock mechanical behavior, which is expected to truly reflect the bedding rock damage law and contributes to solve the relevant engineering problems accurately.

Currently, few studies in the literature describe mechanical behavior of bedding rock by energy-related characterizations. Xie et al. proposed a failure criterion of layered rock mass based on the analysis of distortion energy and general potential energy of volume, and the failure criterion is well accordant with the result of biaxial compressive test on layered rock [18]. Wasantha et al. investigated the energy releasing characteristics of bedded-sandstone with bedding layers in different orientations under uniaxial compression by analyzing the acoustic emission (AE) energy [14]. Zhang et al. also used AE energy to study the effect of coal's bedding plane direction on characteristics of the energy release [19]. Tavallali and Vervoort carried out the Brazilian tensile test on layered sandstone to examine the variation in the applied energy as a function of the inclination angle between the layer plane and the loading direction [13]. After the above literature review, it is clear that these studies only focused on released AE energy or total energy prior to stress peak value, and did not

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consider the variation of energy in real time during the whole failure process. Moreover, the energy allocation pattern that is the relationship among the absorbed energy, elastic energy and dissipated energy was not analyzed.

In this paper, the uniaxial compression tests were conducted on the cylindrical shale specimens with bedding plane inclined at 0° and 90° to the axial loading direction, respectively. At the same time, an acoustic emission system was used to monitor the released energy of shale in experiment process. Besides, this study discussed the influences of the orientation of layers on mechanical property, failure mechanisms, and energy evolution. The results of study can provide guidance in hydraulic fracturing of shale and stability of shale wellbore.

2. Energy calculation during shale deformation

The deformation and failure of shale is relevant to its internal energy conversion, including energy accumulation, release and dissipation, that is, assuming that there is no heat exchange between the physical process and the external, the energy accumulation will be self-organized by elastic energy release and energy dissipation [16,20,21]:

$$u = u^e + u^d \tag{1}$$

where u is the external power; u^e the elastic strain energy; and u^d the dissipated energy.

The stress–strain curve of rock is shown in Fig. 1. From the view of thermodynamics, the energy dissipation is unidirectional and irreversible, while the energy release is a two-way process, which is reversible under some specific conditions [16]. Thus, the elastic strain energy density u^e can be determined by the area between unloading curve and horizontal axis, and dissipated energy u^d is obtained through the area between loading and unloading curve [15].

$$u = \int_0^{\varepsilon_i} \sigma \, d\varepsilon \tag{2}$$

$$u^e = \frac{1}{2}\sigma_i \varepsilon_i^e = \frac{1}{2}\frac{\sigma_i^2}{E_u} \tag{3}$$

$$u^d = u - u^e \tag{4}$$

While the peak-strength of the rock under cyclic loading and unloading conditions is less than the uniaxial compressive strength, especially for the brittle rock because low stress failure of rock under cyclic loading and unloading conditions is most likely to occur [22]. Thus, there is often a deviation compared with practical engineering. In this study, the unloading process of the test is not done. Taking the initial elastic modulus E_0 in place of unloading elastic modulus E_u, Eq. (3) can be rewritten as follows [16,23–25]:

$$u^e = \frac{1}{2}\frac{\sigma_i^2}{E_0} \tag{5}$$

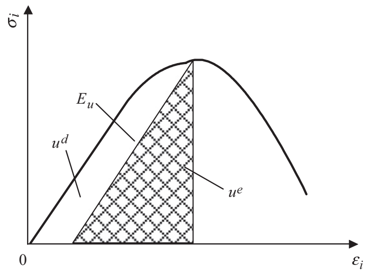

Fig. 1. Quantitative relationship of elastic strain energy release and dissipated energy.

In order to verify the rationality of this substitution, this study compared the energy evolution of the brittle red sandstone between uniaxial cyclic loading tests (sample numbers: CU-1, CU-2, CU-3 and CU-4) and conventional uniaxial tests (sample numbers: U-1, U-2, U-3 and U-4). It can be obtained from Fig. 2 that three kinds of energy density have the similar change trend in two different loading types, and the deviation about the three kinds of energy density in two loading types is less than 15%. It should be noted that the deviation also contains the influence of the internal structure of rock specimens even from the same block of rock. Therefore, it is feasible for brittle rock to take the initial elastic modulus in place of unloading modulus elastic in strain energy calculation, which reduces the workload of test and is helpful for calculation.

3. Experimental procedure

3.1. Specimen preparation

The shale mass which is taken from Pengshui block in Chongqing, China, belongs to southern marine Longmaxi Silurian black shale. This shale mainly consists of quartz, feldspar, pyrite, albite and calcite, and clay mineral content is less. Fig. 3 shows clear layer. The flakes of clay minerals and mica are aligned parallel to the bedding. The layer and the mineral alignment affect the mechanical properties as a function of the inclination angle [26]. To investigate the effect of bedding plane direction on energy evolution during deformation, cylindrical specimens with the diameter of 50 mm cored from the original shale blocks along vertical and parallel the bedding using a core drilling, separately. Then, specimens with a height of 100 mm were cut using a cutting machine. A grinding machine was used finally to ensure that the two ends of the specimens were flat and parallel.

3.2. Experimental instrument and method

The uniaxial compression tests were performed on the MTS815.02 electro-hydraulic servo-controlled rock mechanic testing system with a load capacity of 4600 kN. The system consists of the loading system, triaxial cell, confining pressure intensifier, pore pressure intensifier, controller, hydraulic power supply and computer system. The strain and load data were acquired and stored in the computer. The PCI-2 AE system manufactured by physical acoustics corporation was employed to monitor released energy of shale during all the tests.

In the uniaxial compression tests, four specimens were investigated and were divided into two groups. Two samples (sample numbers: 0°-1, 0°-2) were loaded with axis parallel to the bedding (0°), and two specimens (sample numbers: 90°-1, 90°-2) were prepared to load with axis vertical to the bedding (90°). After lateral displacement of the extensometer was installed on the specimen surface and the AE sensor was glued to the specimen surface, the samples were installed on the machine base. The loading schematic and testing arrangement are shown in Fig. 4. During the experiments, the loading rate was controlled at 0.1 mm/min by the displacement. The pieces of failed rock were collected to investigate the relationship between the original bedding plane and the failure plane after the failure of each specimen.

4. Rock mechanical properties and failure mechanisms

4.1. Failure patterns

Fig. 5 shows the failure pattern of all specimens. The failure pattern of shale specimens with the angle of 0° are given priority to

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