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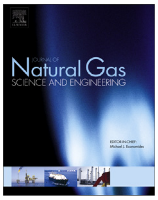

Effect of saturated fluid on the failure mode of brittle gas shale

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ABSTRACT

To understand the influence of fluid saturation on the failure mode of gas shale, a series of triaxial compression tests under the quasi-static loading conditions were conducted using the GCTS (Geotechnical Consulting and Testing System) under different conditions (dry, water saturation, and slickwater saturation). The results showed that the rupture of dry shale samples was accompanied by a transient release of energy, which formed into the main splitting crack. Simultaneously, high-energy tension-type acoustic emission (AE) events were detected around the peak stress. Shale saturated with fluid decreased the strength and increased deformation. The presence of a "step" disturbance was clear in the expansion stage before rupture, and low-energy shear rupture events were detected repeatedly. This indicates that there were internal microslips and distributed micro-cracks to form, which maintained the overall integrity of the cores. Based on the analysis above, two failure modes were discovered: transient main crack failure mode for dry shale and distributed micro-failure mode for shale saturated with fluid. The effect of fluid saturation on the failure mode of shale was clear. This effect can increase the pore pressure; reduce fracture-surface energy; enhance the softening effect caused by water-absorbing clay, which reduced the effective stress on crack surfaces; promoted rock shear slip inside the rock; and changed the energy release characteristic and fracture mode of the shale under a stress condition, which were conducive to the formation of a crack network. The experimental results showed that saturated slickwater had a stronger effect on the failure mode of brittleness gas shale than that of saturated water.

1. Introduction

Shale gas is a typical marginal oil and gas resource. To achieve a commercial production rate, it is essential to form a spatial fracture network by hydraulic fracturing (King, 2010). The formation of a crack network is related to the reservoir's brittleness (Guo et al., 2013, 2015; Jin et al., 2014), development degree of the natural fracture (Ren et al., 2014; Mahrer, 1999), magnitude of the horizontal stress difference (Yushi et al., 2016) and the interaction between the fluid and reservoir (Blanton, 1986; Warpinski et al., 2005). Experiments on shale mechanics are essential indicators that reveal the mechanical behavior and are used to analyze the initiation and propagation of the crack network during the shale reservoir development process and evaluate stimulations. The rock failure mode is closely related to the formation of a crack network, which is a self-supporting complex spatial crack network formed by shear slips and is an important objective of gas shale reservoir stimulations.

According to rock deformation after failure theory, the failure mode of a rock can be divided into many forms, such as single shear failure, double shear failure and splitting failure (Paterson and Wong, 2005; Mogi, 2007). The complexity of the fracture morphology of the shale is related to the confining pressure. At a confining pressure of zero, the morphology of axial splitting can be observed. As the confining pressure increases, the failure mode changes from splitting failure to shear failure (Amann et al., 2011). Shale is a typical brittle rock with strong heterogeneity and exhibits significant anisotropy in intensity of failure. Slip on bedding has been found to reduce the cohesion by 10%–70% and reduce the friction angle by 7%–17%. A greater reduction can generally be observed, particularly for low-porosity rocks (Ewy et al., 2010). The anisotropy of shale greatly influences its failure and deformation characteristics. When the angle between the loading direction and the bedding direction is between 0 and 15°, the failure mechanism

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is dominated by tension fractures, and the stress-strain relation curve has a longer compression-dense and strengthening stage, a shorter linearity deformation stage, and a "plastic-elastic-plastic" curve. When the angle is between 30 and 60°, the failure mechanism is dominated by shear fractures. The stress-strain relation curve has a shorter compression-dense stage and a longer linearity deformation stage. The entire stress-strain relation curve is a "plastic-elastic" curve. The failure mechanism is dominated by mixed combination of tension and shear forces for the remaining angle interval (He and Huang, 2003). When the angle is between 75 and 90°, the stress-strain relation curve does not have a compression-dense stage. The entire stress-strain relation curve is an "elastic-plastic" curve (He and Huang, 2003).

The macro-fracture of shale is affected by the fabric characteristic, coring direction, confining pressure et al. Based on microstructure research, the mechanical characteristics, the crack and fracture morphology of shale, Zhong et al. (2015) established the fracture mode of shale, where it was revealed that the microscopic mechanism behind a macro-fracture is the formation of a microscopic fracture. The researchers believe that macro-fractures of the shale are related to pore structure and the micro-cracks propagation where the compressive strength of the samples within parallel to vertical layers is the highest. The Young's Modulus decreases as β increases, where β is the angle between the structured surface and the axis of the cylinder. Cracks form in the soft surface and in the layer near the surface.

The fluid saturation has a great influence on the mechanical properties of rock, particularly for clay-rich rock. Remvik and Skalle (1993) showed that the Young's Modulus of shale was reduced by 20–60%, and the peak strength was reduced by as much as 50% due to the reaction with deionized water. Horsrud et al. (1994) presented data that showed a 28% reduction in peak strength for triaxial-loading silty claystone, which was exposed to fresh water for five days. Amanullah et al. (1994) noted that as the intensity of rock-fluid interactions increased, the brittleness of mud rocks decreased. For rocks in existing apparent bedding, the fluid saturation effect was stronger.

Although domestic and foreign scholars have investigated the mechanical characteristics of shale and its fracture modes, the impact of fluid saturation on the fracture mode of shale has rarely been considered, and the mechanism and understanding of the fracture modes are unclear. The interaction between fluid and shale significantly affects the mechanical characteristics of the shale reservoir, which has a significant influence on the crack initiation and propagation, and subsequently affects the ultimate production rate. Therefore, it is essential to understand the relationship between the fluid and shale when fracturing is performed to improve the production rate. Based on the previous studies, the influence of fluid saturation on the fracture mode of gas shale considering both the macro-fracture morphology and micro-mechanism is investigated in this research. The difference in the fracture morphology of shale before and after being saturated with fluid from the perspective of energy transformation is analyzed. This study provides important knowledge regarding the formation mechanism of a complex fracture network and the optimization of the fracturing fluid.

2. Experimental equipment and methods

2.1. Experimental equipment and sample

The experiment was performed using a GCTS (Geotechnical Consulting and Testing System) RTR-1000 servo testing system with digital feedback (as seen in Fig. 1). The testing system has an independent control system for the axial pressure, confining pressure, pore pressure, acoustic emission, and temperature. The main part of testing machine contains the overall frame structure with a maximum axial pressure of 1000 KN, maximum confining pressure of 140 MPa, maximum pore pressure of 140 MPa and a minimum sampling interval of 1 ms. The system is equipped with an acoustic emission system, which is the PAC (Physical Acoustic Corporation) PCI-2 acoustic emission monitoring system; the external reference displays the pressure value at the same time by dual channels monitoring.

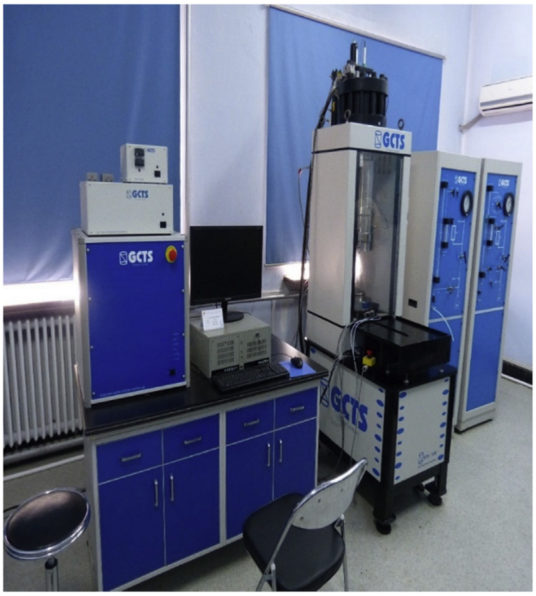

Fig. 1. RTR-1000 high-temperature and high-pressure triaxial servo testing systems.

The test samples were taken from intact rock from the outcrop of the Longmaxi Group in southeast Chongqing (as seen in Fig. 2). The 15 samples were cored successfully, 12 of which were used for mechanical tests. The cores parallelism error was less than 0.05 mm, and there was no obvious weak surface or bedding on the samples. The basic physical parameters of the cores are shown in Table 1.

2.2. Experimental method

First, the samples were divided into three groups: dry shale, shale saturated with water for a week and shale saturated with slickwater for a week. The experiment was performed at a confining pressure of 10 MPa at a fixed strain rate-controlled loading with a loading rate of 2×10^{-6}/s and sampling rate of 1 Hz. The three strain gauges are shown in Fig. 3. Based on the technique of magnetic induction, two axial gauges were used to measure the axial strain of the sample, and radial strain gauge was used to measure the radial stain of the sample. Heat shrink tubing was used to seal the core with the upper and lower pressure head before the experiments, which prevented the hydraulic oil in the pressured chamber from entering and contaminating the samples. During the experiment, the acoustic emission monitoring experiment was performed simultaneously. The signals were recorded using threshold trigger signal acquisition in a two-channel monitoring board PCI-2, PAC with a sampling rate of 10 MHz, which was pre-amplified by 40 dB and used a filter range from 100 KHz to 1 MHz to monitor the entire load process in real time.