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Experimental study of brittleness anisotropy of shale in triaxial compression

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ABSTRACT

Brittleness of rock plays a key role in petroleum related rock mechanics. Compression brittle failure of shale is more relevance to directional wellbore stability. The bedding angle (0°, 30°, 45°, 60°, 90°) dependent brittleness of anisotropic Longmaxi shale samples was studied by conducting triaxial experiments under various confining pressure (15, 25, 40 *MPa*). A servo-controlled loading system was used to keep axial loading strain rate as constant ($8.33 \times 10^{-5}/s$) at room temperature. The stress and strain was synchronously and independently recorded with time. We used five definition of brittleness indices that were based on laboratory stress-strain curves to characterize the anisotropy of brittleness. The results show that for 30°-sample and 45°-sample under relative low confining pressure (15 *MPa*), the stress-strain curves deviate from stress-time relations during instant rupture of post-failure. Under confining pressure of 25 *MPa*, both pre-failure and post-failure indices of brittleness remain highly consistent along bedding angle as a sine curve. When the confining pressure is increased to 40 *MPa*, variation patterns of brittleness indices clearly differentiate into pre-failure or post-failure type. It seems that the unstable recording of servo system during explosive failure of samples can be considered as a relative brittleness indicator. The results indicate that the brittleness of samples in some certain bedding angle don't decrease with increasing confining pressure, instead the post-failure type indices may increase. The brittleness anisotropy of Longmaxi shale samples is bedding angle (structure) dependent, and it decreases with increasing confining pressure.

1. Introduction

Broadly speaking, rock brittleness is the liability of rock failing without large plastic deformation when it is subjected to stress. Brittleness (plasticity) has a strong effect on borehole stability and mud weight window (Fjær et al., 2002). Compared to tensile/sliding failure under hydraulic fracturing, compression shear failure of shale with different orientation of bedding planes is more relevance to directional wellbore stability. The brittleness (the ease of microcracking) in the presence of favorable in situ stress conditions determines the shape of the breakout zone (Hajiabdolmajid, 2002). As we know, shale is anisotropic, often with a pronounced plane of weakness, so brittleness is also likely to be directionally dependent (Holt et al., 2011). Holt et al. (2015) showed that brittleness in anisotropic shale depended on the direction of loading with respect to the symmetry plane (Holt et al., 2015).

However, the principles of brittleness measurement vary from authors to authors, and most recent summary or reviews on definitions of brittleness index were presented by Jin et al. (2015), Zhang et al. (2016) and Rybacki et al. (2016). Geng et al. (2015) classified common brittleness indices into three categories according to application scope and data source available as: laboratory characterization, well logging, and seismic interpretation (Geng et al., 2015). There are dozens of brittleness indices, which result in different values even for the same rock. Yang et al. (2013) used the same triaxial test data to calculate four brittleness indices, which varied considerably, and the different indices do not correlate well with rock strength or elastic properties (Yang et al., 2013).

Laboratory characterization of brittleness mostly bases on mechanical parameters of rock samples. Such parameters include strength (e.g. shear strength, tensile strength, peak strength, and residual strength, etc.), elastic properties (e.g. Young's modulus, Poisson's ratio, etc.), strains (e.g. elastic/plastic strain, residual strain, etc.), hardness, fracture toughness and many other failure

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characteristic parameters (e.g. internal friction angle, energy release rate, etc.). This type of brittleness indices mainly focuses on brittle failure of rock samples in laboratory tests (Andreev, 1995; Hajiabdolmajid et al., 2002). Hucka and Das (1974) and Altindag (2000) discussed the relationship between rock fracture toughness and brittleness. Kahraman and Altindag (2004) estimated fracture toughness by using an empirical relation of brittleness (Kahraman and Altindag, 2004). Tarasov and Potvin (2013) proposed a "universal" brittleness estimation with consideration of two failure modes of rock (Tarasov and Potvin, 2013).

In laboratory tests, the brittleness anisotropy of shale is not only directionally dependent, but is also affected by confining pressure. Rocks are commonly more brittle at low confining pressure and will show a tendency toward ductility when the confining pressure increases (Yang et al., 2013; Jaeger et al., 2009; Paterson and Wong, 2005; Becker, 1892). Holt et al. (2011) demonstrated that brittleness indices calculated from triaxial data (3 different North Sea shales) decreased with increasing confining pressure (Holt et al., 2011). However, the range of confining pressure (2, 7, 12 MPa) in the experiment was limited, and only 3 angles (between the axial stress direction and the normal to the bedding plane - 0°, 37°, 90°) of samples were used for triaxial experiments.

In this paper, we will present the brittleness anisotropy of Longmaxi shale by comparing 5 different brittleness indices (listed in Table 1) defined by stress-strain curves. Triaxial compression tests on shale samples with 5 different bedding angles (between the axial stress direction and the bedding plane - 0°, 30°, 45°, 60°, 90°) were carried out under 3 confining pressure (15, 25, 40 MPa) respectively. We discussed the observation of brittleness indices that belongs to pre-failure and post-failure type. We also discussed the potential laboratory characters of brittleness that would be in favor of fracture initiation and propagation.

2. Experimental methods

2.1. Sample characterization and preparation

The rock samples for triaxial experiment were cored from reservoir outcrop of Lower-Silurian Longmaxi shale. Longmaxi shale is located in Sichuan basin, Southwest China. It's currently the largest commercial shale gas reservoir in China. Lower Silurian Longmaxi Formation has been the most promising target, with an average thickness of 100~120 m (Chengzao et al., 2012), buried depth of 2000~4500 m (Chen et al., 2014). The peak strength of down-hole samples cored parallel to bedding planes was approximately 182 *MPa* (confining pressure = 20 *MPa*). However, samples in multiple bedding angles are required. It's impossible to obtain as many samples as required by using downhole drilling cores, as they're limited by size. In addition, downhole cores widely distribute in large scale of depth, with obvious variation of physical properties. In order to minimize the influence of weathering and heterogeneity, large outcrop (40~50 cm) with uniform texture and bedding planes was selected for our experiment, then it was cut to a smaller cube (25~35 cm, as shown in Fig. 1).

Every 3 cylindrical dry samples (as a group) were cored in 5 bedding angles (0°, 30°, 45°, 60°, 90°) respectively with air cooling from the same outcrop, 15 samples in total. The bedding angle is defined as the angle between symmetric axis of samples and its macro bedding planes. All samples were cylindrical with a diameter of 1 inch and height of 2 inch. The samples were prepared by cutting and polishing the end faces parallel. The dry samples were preserved under the same room temperature and humidity, avoiding the influence of different fluid type and saturation. The XRD analysis result of mineral composition was Quartz-39.9%, Dolomite-22.5%, Clay-18.2%, Hematite-2.5%, Calcite-15.5%, and Others-1.4%. The density of samples was 2.55 g/cm^3. The samples are brittle and hard black shale, with compressive strength ≈ 200 *MPa* (confining pressure $\approx$ 15 *MPa*) and Poisson's ratio $\approx$ 0.15 (Geng et al., 2015; Liang et al., 2014).

2.2. Experimental set up and procedure

Triaxial experiments were performed using an improved GCTS servo testing system in China University of Petroleum, Beijing. Since a reliable and accurate post-peak stress-strain curve is vitally important for rock brittleness determination, we sealed the samples by using shrinkable-tube with rubber belt on both ends,

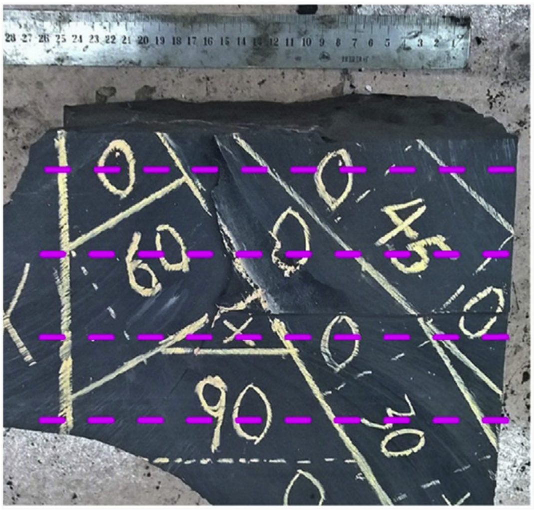

Fig. 1. Natural reservoir outcrop of Longmaxi shale. The pink dash lines denote the occurrence of macro bedding planes.

Table 1
Common Brittleness Indices based on Stress-Strain Curves.

Definition	Description	Reference
$B_1 = \varepsilon_{re}/\varepsilon_{tol}$	ε_{re}- reversible strain, ε_{tol}- total strain at failure	V. Hucka (Hucka and Das, 1974)
$B_2 = W_r/W_t$	W_r - reversible strain energy, W_t - total strain energy	L. Baron (Baron et al., 1962)
$B_3 = (\varepsilon_f^p - \varepsilon_c^p)/\varepsilon_c^p$	ε_f^p - plastic strain (damage) for frictional strengthening, ε_c^p - plastic strain (damage) for cohesion loss	V.Hajiabdolmajid (Hajiabdolmajid, 2002)
$B_4 = (\tau_p - \tau_r)/\tau_p$	τ_p - peak stress; τ_r - residual stress	A. W. Bishop (Bishop, 1967)
$B_5 = \frac{E}{\mu} \cdot D_p \cdot R_s$	*E - elastic modulus,* μ *- Poisson's ratio,* D_p - phenomenological macroscopic damage, R_s - triaxial strength release rate	Z. Geng (Geng et al., 2015)