Mechanical anisotropy and tension-shear characteristics of shale in Pengshui area, Chongqing

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ABSTRACT: As an unconventional energy, shale gas is being developed widely. As one of the core means of development for shale gas, hydraulic fracturing is greatly affected by the mechanical properties of shale, especially its anisotropy and shear characteristics related to the activation of natural structural planes. In this paper, the law of anisotropy characterized by wave velocity and its ratio of shale is summarized through the analysis for the velocity of P-wave and S-wave, the strength characteristics of shale under tension-shear condition is also obtained through the mechanical tests on shale samples in different directions.

Keywords: Shale, mechanical characteristics, anisotropy, tension-shear.

1 INTRODUCTION

Shale gas needs to be developed with horizontal drilling and hydraulic fracturing because of its low porosity and permeability. The horizontal section of shale gas well is generally long, the bedding of the reservoir is aboundunt, the reservoir is mechanically brittle, and structural plane with steep dip angle could be sometimes viewed in the reservoir, which makes the wall of the wells prone to collapse, leakage and so on (Zou et al, 2010). Therefore, the strength characteristics of shale affected by bedding plane is particularly important. Referring to the anisotropy of shale, Hornby et al (1994) developed a theoretical framework to predict the effective elastic properties of shale. Ortega et al (2010) evaluated the influence of clay particles and other factors on shale anisotropy on multi-scale with comprehensive micromechanical theory. Niandou et al (1997) carried out static compression tests and triaxial tests (including unloading process) on Tournemire shale, which revealed the anisotropic mechanical-behavior of shale.

Since the mid-10990s, researchers began to study the mechanical response and failure of rock under the combined action of tension and shearing. The tension-shear tests for rock include direct and indirect tension-shear test. The direct tension-shear test means that the tensile force and shear force are applied to the rock sample independently and meanwhile. The indirect tension-shear test makes the specimen sheared indirectly by applying the tension or shear force indirectly or modifying the conventional cylindrical or cube rock specimen.

In this study, the anisotropy of shale is revealed by analyzing the wave velocity and velocity ratio of shale in three directions and the strength characteristics of shale of shale in tension-shear zone are summarized with the tension-shear tests for shale in different directions.

2 METHODOLOGY

2.1 Measurement for velocity of P-wave and S-wave for shale

The P-wave and S-wave velocities of 17 shale samples from the Silurian Longmaxi formation in Pengshui, Chongqing were measured and the ratio of these two velocities were calculated. In addition, an approach for characterizing anisotropy of shale based on wave-velocity ratio was established. When it comes to the shale samples with the size of 100mm×100mm×100mm in Figure 1, the two directions parallel to the bedding plane are marked as d_1 and d_2 and he direction perpendicular to the bedding plane is marked as d_3. When measuring P-wave velocity, 16 points were measured in each direction and the distance between each two points and the distance between edge point and boundary is 20 mm to explore the distribution of P-wave velocity in the three directions. In S-wave velocity measurement, 4 points in each were measured and the distance between each two points and the distance between edge point and boundary is about 33 mm, as shown in Figure 2.

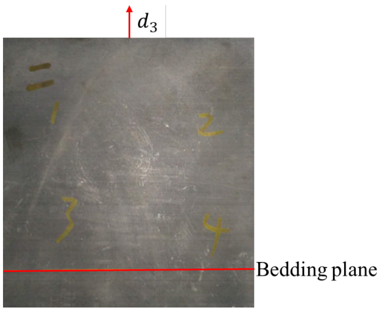

Figure 1. Photo for one of shale samples in the experiments.

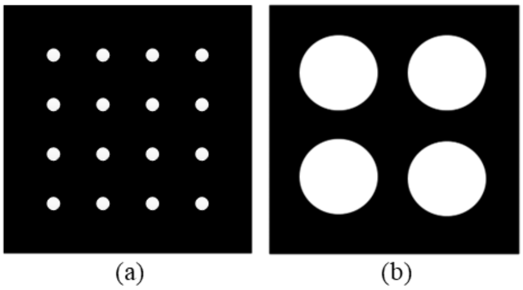

Figure 2. Layout of measuring points for wave-velocity test: (a) layout of measuring points for P-wave; (b) layout of measuring points for S-wave.

2.2 Tension-shear test for shale

In this study, the tension-shear test system for rock developed by Institute of Geology and Geophysics, Chinese Academy of Sciences and the PIC2-Main-34 detection system for acoustic signal by American Physical Acoustics Company (PAC) were used to study the tensile and shear mechanical properties of shale. The tension-shear test system for rock can output normal load of -100kN~1000kN (negative for tensile load) and the shear load of 0~800kN. The detection system for acoustic signal can measure the acoustic signals in the range of 200Hz~700KHz when the confining pressure is up to 50MPa and the temperature is up to 150 °C. In the experiments, the tensile stress was applied to the sample at the speed of 30N/s to the set value, and then the shear stress was also applied at the speed of 30N/s until the sample was failure. After the experiment, the fracture surface of the sample was scanned with three-dimensional laser scanner to calculate the corresponding roughness. The arrangement of the acoustic emission sensors and the implementation for loading is shown in Figure 3.

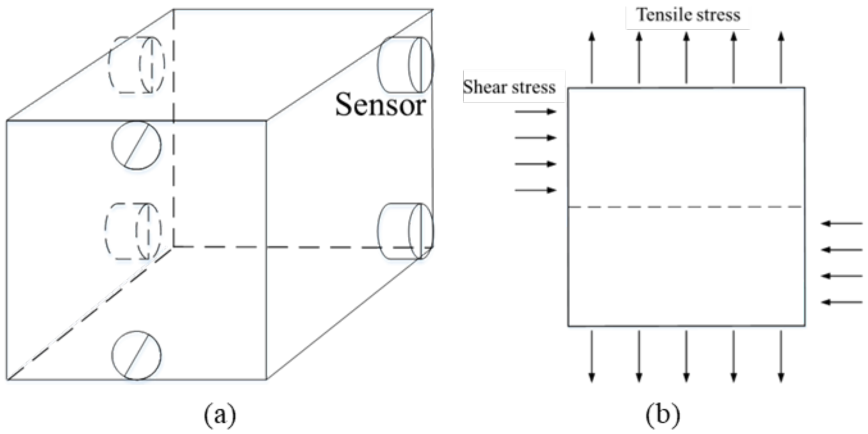

Figure 3. (a) arrangement of sensors for acoustic-emission signal; (b) the mode of application for tensile and shear load.

3 RESULTS

3.1 Mechanical anisotropy of shale characterized by P-wave velocity, S-wave velocity and their ratio

As shown in Figure 4, when P-wave velocity in d_3 direction is about 2800 m/s, the corresponding increment of P-wave velocity in d_1 and d_2 direction is 35%-45%, while when the P-wave velocity in d_3 direction is about 3700 m/s, the corresponding increment of P-wave velocity in d_1 and d_2 direction is reduced to 10%-20%. The S-wave shows the same trend. When the S-wave velocity in d_3 direction is about 2200 m/s, the corresponding increment of S-wave velocity in d_1 and d_2 direction is 30%-40%. When the S-wave velocity in d_3 direction is about 2800 m/s, the corresponding increment of S-wave velocity in d_1 and d_2 direction is reduced to 5%-17%. In a word, with the increase of velocity of P-wave and S-wave in d_3 direction, the increment of wave velocity in d_1 and d_2 direction decreases, and there is a good linear relationship between them, which indicates that the smaller P-wave and S-wave velocity is, the more obvious the anisotropy of wave velocity is in the direction perpendicular to the bedding plane of shale. This may be due to that the filling material could be more compacted under stress than rock matrix and thus the anisotropy is reduced under higher stress when wave velocity is high.

The ratio of velocity of P-wave and S-wave along d_1, d_2, and d_3 were recorded as r_1, r_2, and r_3 respectively. As shown in Figure 5, r_3 of the sample was taken as abscissa and increment of wave-velocity ratio k_{13} and k_{23} was taken as ordinates. With the increase of the wave-velocity ratio in d_3 direction, the relative increment of the wave-velocity ratio parallel to the bedding plane decreases and the correlation index can reach 0.7234 and 0.7548. This indicates that when the wave velocity perpendicular to the bedding plane is low, the wave velocity ratio parallel to the bedding plane of shale is quite different from it, but when the wave velocity perpendicular to the bedding plane is high, the wave-velocity ratio of shale parallel to the bedding plane is little different from it.

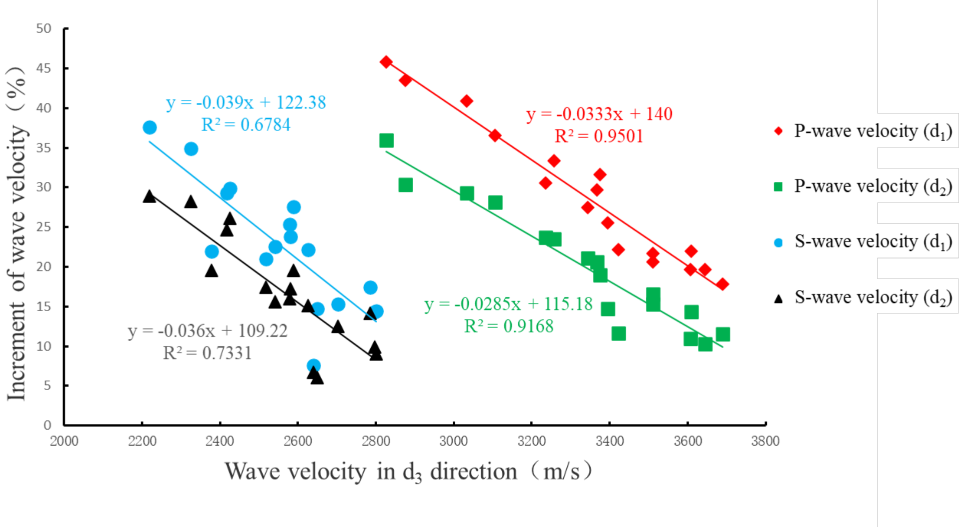

Figure 4. The distribution of the velocity increment of P-wave and S-wave in shale. The wave velocities in d_3 direction are taken as abscissa and the corresponding increments of P-wave and S-wave velocity in d_1 and d_2 direction are taken as ordinates.

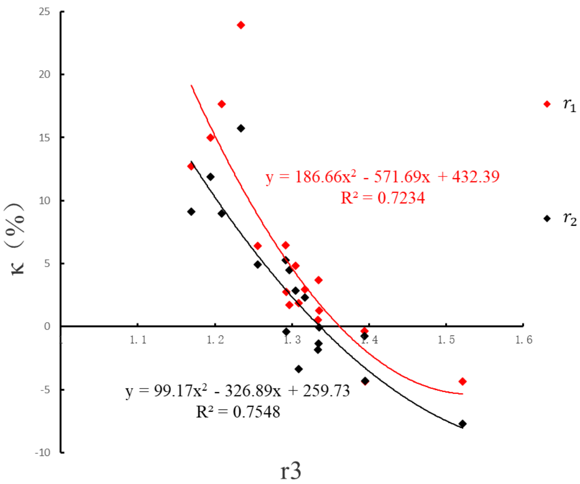

Figure 5. Relationship between k_{13}, k_{23}, and r_3.

3.2 Tension-shear mechanical characteristics of shale

When the direction of tensile load applied in the tension-shear test of the shale sample is parallel to the bedding plane, the relationship between the pre-applied tensile stress, shear stress and shear strain at failure, and roughness of the fracture surface is summarized in Table 1, in which the roughness of the fracture surface means the ratio of the actual fracture surface area to the projected fracture surface area (Aimone-Martin et al. 1997), and the calculation takes the following form:

$$R_m(SRA) = \frac{A_1}{A_0} \tag{1}$$

Where $R_m(SRA)$ is the roughness, A_1 is the area of actual fracture surface, and A_0 is the area of projected fracture-surface.

There is a good linear relationship between the preloaded tensile stress and the roughness of the fracture after failure when the tensile stress is parallel to bedding planes. The lower the preloaded tensile stress, the more dependent the failure of shale is on shear stress. The roughness of the fracture surface produced by shear failure is lower than that of the fracture surface due to tensile failure. Therefore, the competition between shear and tensile stresses could lead to different fracture roughness. That is, the fracture roughness increases with the preloaded tensile stress. Meanwhile, the increasing preloaded tensile stress reduces shear stress at failure, which may be due to the damage by the preloaded tensile stress on the sample before shearing. Therefore, the higher shear stress at failure, the lower the roughness of fracture surface.

Table 1. Results for tension-shear test (the tensile stress is parallel to bedding planes).

Preloaded tensile stress (MPa)	Shear stress at failure (MPa)	Shear strain at failure (%)	Roughness of fracture surface
2	0.8600	0.7330	1.2812
1.5	0.9675	0.5762	1.2163
0.5	5.7492	0.5201	1.1194

When the direction of the tensile load applied in the tension-shear test of shale is perpendicular to the bedding planes, the relationship between the preloaded tensile stress, shear stress at failure, shear strain at failure, and the roughness of fracture surface is summarized in Table 2. It can be seen that when the preloaded tensile stress of shale is perpendicular to the bedding plane, the higher the preloaded tensile stress, the lower the shear stress at failure, and the greater the roughness of the fracture surface. This phenomenon is the same when the preloaded tensile stress is parallel to bedding planes, and their principles are also similar. In addition, the roughness of fracture surface is always lower than that when the direction of the tensile load is parallel to the bedding planes, which may be due to that the failure fractures are actually reactivated bedding planes that are smooth when tensile stress is perpendicular to the bedding planes while the failure fractures are fresh and rough when tensile stress is parallel to the bedding planes.

Table 2. Results for tension-shear test (the tensile stress is perpendicular to bedding planes).

Preloaded tensile stress (MPa)	Shear stress at failure (MPa)	Shear strain at failure (%)	Roughness of fracture surface
0.7	1.3208	0.6402	1.1334
0.5	1.6475	0.6508	1.0205

4 CONCLUSIONS

Based on the analysis for P-wave and S-wave velocity data of shale, this paper confirms the anisotropy of shale, summarizes the relationship between wave velocity, wave-velocity ratio and anisotropy, and conducted tension-shear mechanical tests. The mechanical parameters of shale under tension-shear condition and the relationship between roughness of fracture surface and anisotropy are studied. The main conclusions are as follows:

1. The P-wave and S-wave velocity and velocity ratio of shale indicates anisotropy. The lower the velocity and velocity ratio perpendicular to the bedding planes, the more obvious the anisotropy characterized by wave velocity.
2. Regardless of the direction of the preloaded tensile-stress, in tension-shear experiments, the roughness of fracture surface of shale increases with the increase of the preloaded tensile stress and the roughness of the fracture surface when the tensile stress is perpendicular to bedding planes is generally less than the roughness of the fracture surface when the tensile stress is parallel to bedding planes.

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