Fracability evaluation of shale in the Wufeng-Longmaxi Formation in Changning area, Sichuan Basin

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Abstract: The fracturing technology for shale gas reservoir is the key to the development of shale gas industrialization. It makes much sense to study the mechanical properties and deformation characteristics of shale, due to its close relationship with the fracability of shale gas reservoir. This paper took marine shale in Changning area, southern Sichuan Basin of China as the research object. Based on field profile and hand specimen observation, we analyzed the development of natural fractures and collected samples from Wufeng Formation and Longmaxi Formation. Combined with the indoor experiment, we investigated the macroscopic and microscopic structural feature and the remarkable heterogeneity of shale samples. Then we illustrated the mechanics and deformation characteristics of shale, through uniaxial compression test and direct shear test. The shale has two types of fracture modes, which depending on the angular relation between loading direction and the bedding plane. Besides, Wufeng shale has a higher value of brittleness index, which is calculated from two methods, mechanical parameters and mineral composition, than Longmaxi shale. Given the above results, we proposed a kind of fracability evaluation model for shale gas reservoir using the analytic hierarchy process. Four influence factors, brittleness index, fracture toughness, natural fractures and cohesive force, are considered. Finally, under the control of normalized value and weight coefficient of each influence factor, the calculations results indicate that the fracability index of Wufeng Formation is higher than Longmaxi Formation, in Changning area, southern Sichuan Basin.

Keywords: Sichuan Basin, marine shale, mechanical properties, fracability evaluation, analytic hierarchy process

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1 Introduction

The research about shale gas reservoir, including pore and fracture system, gas bearing property and alteration ability, is one of the most important contents of unconventional oil and gas exploration and development (Zou et al., 2010; Zou Caineng et al., 2012; Chalmers et al., 2012; Liu Dayong et al., 2013; Ju et al., 2014, 2017, 2018; Guo Xusheng, 2014; Wang and Ju, 2015; Cui et al., 2017; Zhang Qian et al., 2018; Fan et al., 2018; Qi et al., 2019; Yu et al., 2019). After long geologic evolution, the structural environment determines the development and distribution of shale formation, providing the material basis for hydrocarbon accumulation. As for whether it can be a valuable industrial gas reservoir, depending on its later structural deformation and artificial modification of pore and permeability system. In other words, fracturing reconstruction technology, which can make massive, interconnected and stable fissure networks for shale gas reservoir, is critical (Miao Wenpei et al., 2014). Moreover, the mechanical test of shale is an important means to reveal its anisotropy and mechanical behavior (Vernik and Nur, 1992; Niandou et al., 1997; Kuila et al., 2011; Lü et al., 2017). It can provide essential mechanical parameters for the establishment of fracturing scheme and evaluation of fracture trend (Joshi et al., 2012).

The rheological behavior is one of the most important mechanical properties of the rock. It means that rock can exhibit the features related to the time of deformation, flow and fracture, under external load, temperature and other conditions (Sun Jun, 2007). For this mechanical behavior, many scholars have carried out relevant studies on limestone, conglomerate, sandstone, andesite and marble (Okubo et al., 1991; Maranini and Brignolli, 1999; Liu Guangting et al., 2004; Li Nan et al., 2012). However, at present, there are few studies on the rheological properties of shale (Ma et al., 2015; Ju et al., 2018; Zhu et al., 2018). The detachment layer of shale can form detachment fold, shear fault break fold and so on, which becomes an important trap type for hydrocarbon accumulation. This kind of macrostructure built by natural rheology of shale is the external manifestation of its microscopic deformation mechanism. Meanwhile, it provides constraint conditions for the deformation mechanism, such as brittle fracture, twin/twist, and dynamic recrystallization.
The term “fracability” can be described as the probability to create a complexity fracture network and large stimulated reservoir volume in shale gas reservoir to obtain high economic benefits under the same condition fracturing technology (Zhao Jinzhou et al., 2015). The evaluation of fracability mainly surrounds some aspects, including brittleness index, mineral composition, fracture toughness, and development of natural fractures (Chong et al., 2010; Breyer et al., 2011; Enderlin et al., 2011; Mullen and Enderlin, 2012; Tang Ying et al., 2012; Yuan Junliang et al., 2013). However, there is no unified standard established to evaluate the fracability of shale gas reservoir. And a quantitative evaluation based on a single factor is difficult to reflect the general characteristics of the fracturing process (Jin et al., 2015).

2 Geological Settings

Located in southwest China, Sichuan basin is one of China’s largest sedimentary basins as well as a significant natural gas producing area. The Early Paleozoic sedimentary rocks of Sichuan Basin are as thick as 1400-3600 m. Four sets of marine black shales have been developed during this geological period, including Upper Sinian Doushantuo Formation, Lower Cambrian Qiongzhusi Formation, Upper Ordovician Wufeng Formation and Lower Silurian Longmaxi Formation (Chen Shangbin et al., 2011; Wei Xiangfeng et al., 2017; Chen et al., 2018). Our research area is within Changning shale gas field, which located at the south side of south Sichuan low steep fold belt. Although the Changning area underwent multiple tectonic movements, they have not significantly damaged the overall tectonic pattern of the Lower Paleozoic.

We collected the shale samples from the Lower Paleozoic Wufeng-Longmaxi Formation, in Shuanghe Town, Changning County. The outcrop, on the north flank of Changning anticline (Fig. 1), consists mainly of black-gray and black carbonaceous shale, which has identified beddings, high carbon content, abundant graptolite fossil and pyrite. The thick shale samples with weak weathering degree used in the mechanics experiments were taken from upper Wufeng Formation and lower Longmaxi Formation. They were less affected by tectonism, showing no visible fracture and other deformable structures. Furthermore, in the process of sample collection and transportation, we took protective measures to avoid disturbance, which may result in fractures. In a word, the whole process ensured the integrity of the sample.

3 Samples and Methods

The diversity of sedimentary patterns, the complexity of diagenesis and the multistage of tectonic evolution, all three factors contribute to the heterogeneity of shale (Yu Bingsong, 2012; Chen Tianyu et al., 2014; Ju et al., 2014). To study the mechanics and deformation characteristics of the shale samples, we conducted the uniaxial compression deformation test and direct shear test. Moreover, to minimize the impact of heterogeneity, the samples used in one type of test were taken from areas that are as close as possible in the shale block.

3.1 Microscopic observation

We used optical microscope in this paper to study the microstructure of shale. For optical microscope observation, samples were cut and polished to the thin section on glass slides, about 0.03 mm thick and a visible region of 5 centimeters square. Then these thin sections were put under the optical microscope, Leica DMLP polarizing microscope with a Leica DFC450C camera system, for imaging and analyses.
3.2 Shale mineralogy

Twelve samples were tested for mineral composition by X-ray diffraction (XRD) analyses using Rigaku TTR III Multifunction X-ray Diffractometer. Crushed samples (180-250 μm) were mixed with ethanol, hand ground in a mortar and pestle, and then smear mounted on glass slides for XRD analyses. A semi-quantitative estimation of the mineral content of samples was determined using Rietveld analyses (Rietveld, 1967), which fits a polynomial curve to the diffractograms (Chalmers et al., 2012).

3.3 Uniaxial compression deformation test

We conducted the test at T type workbench testing machine in mechanical laboratory of Advanced Research Center, Central South University. We used this test to study shale’s deformation characteristics and parameters of rock strength including uniaxial compressive strength, uniaxial compression stress-strain curve, Young’s modulus, and Poisson’s ratio.

According to international practice, we processed the shale samples into standard cylinders as ø25 mm×50 mm and divided them into two groups, the loading direction parallel, and perpendicular to the bedding plane (Table 1). Then, we stuck strain gages on the center of the flank of cylinder specimen. After this operation, we applied the initial load. When the working condition of the testing machine and strain gage was stable, the sample was uniformly loaded with the loading speed of 0.5-1.0 MPa/s until the sample was broken entirely. During the test, we kept the ambient temperature unchanged and measured the temperature and humidity in the laboratory. At the final step, we recorded the damage load value and the phenomena occurred during the loading process, photographed the broken samples as well as described the failure patterns and characteristics after the test.

Table 1 The sample processing information of mechanical tests

<table>
<thead>
<tr>
<th>Test project</th>
<th>Formation</th>
<th>ID</th>
<th>Size/mm</th>
<th>Loading direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wufeng</td>
<td>Uniaxial</td>
<td>W1-1</td>
<td>ø25×50</td>
<td>Perpendicular to bedding plane</td>
</tr>
<tr>
<td></td>
<td>compression test</td>
<td>W1-2</td>
<td></td>
<td>Parallel to bedding plane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W2-1</td>
<td></td>
<td>Perpendicular to bedding plane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W2-2</td>
<td></td>
<td>Parallel to bedding plane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L1-1</td>
<td></td>
<td>Perpendicular to bedding plane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L1-2</td>
<td></td>
<td>Parallel to bedding plane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L2-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>L2-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longmaxi</td>
<td>Direct shear test</td>
<td>W-1</td>
<td></td>
<td>Perpendicular to bedding plane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>W-4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>W-5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>W-6</td>
<td>50×50×50</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>W-9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>L-4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>L-5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>L-6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.4 Direct shear test

We conducted the direct shear test at RYL-600 microcomputer-controlled rock direct shear instrument made by Changchun Chaoyang Company, in mechanical laboratory of Advanced Research Center, Central South University. The instrument is equipped with control software to control the loading mode of the experiment and record the experimental data. Through this test, we can determine the shear strength characteristics of samples.

According to international practice, we processed the shale samples into cubes as 50mm×50mm×50mm (Table 1). And to make the shear direction along the predetermined shear plane, we cut 5% of the length along the shear direction as inducing joint (reserved shear cracks) (Fig. 2a). The inducing joint parallel to the bedding direction means that the shear force is parallel to the bedding and the normal load is perpendicular to the bedding, which was used to prevent the effect of bedding plane on the test.

After the sample processed, we placed it in the mold (Fig. 2b). When the reading of the normal load is stable, shear load was applied in stages every five minutes until the sample was damaged. During the test, we kept the ambient temperature constant, recorded shear displacement of each shear load and the maximum number on the shear pressure gauge at sample damaging time. After calculating the normal stress and shear stress under the normal loads, we drew the relation curves of shear stress, shear strain and normal strain under different normal stress, and determined the shear stress of feature points at each shear stage. Finally, the corresponding shear strength parameters are determined according to the Coulomb equation.
4 Results

4.1 Development characteristics of natural fractures

By observing outcrops and hand specimen, we found that Wufeng shale has obvious massive features with undeveloped bedding or fractures. While the bedding of Longmaxi shale is more developed, along which fractures tend to form. Furthermore, we could see many fractures filled with quartz or pyrite and few tension fractures.

Under the optical microscope, we can see the micro-scale fractures more clearly. Comparatively speaking, denser fractures grow within Longmaxi shale (Fig. 3). Although open fractures are not very common, well-developed filled fractures can become the main contributing factor of weak spots during the fracturing process (Bowker, 2007).
4.2 Mineral composition characteristics

The mineral compositions (mass fraction) of 12 selected samples using powder XRD were shown in Table 2. This parameter has a significant impact on mechanical properties, development of pore and fracture, and fracturing mode. For the brittleness of shale, we can divide the mineral composition into two parts, brittle minerals, and clay minerals. Brittle minerals usually refer to all components except clay minerals, including quartz, feldspar, calcite, and pyrite. As seen from the table, Wufeng shale has a higher value of brittle minerals, especially the quartz content, and lower value of clay minerals than Longmaxi shale.

Table 2 The mineral composition of shale samples

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Quartz (%)</th>
<th>Feldspar (%)</th>
<th>Dolomite (%)</th>
<th>Calcite (%)</th>
<th>Clay (%)</th>
<th>Pyrite (%)</th>
</tr>
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<tr>
<td>W1-1</td>
<td>55.2</td>
<td>13.8</td>
<td>19.2</td>
<td>10.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W2-1</td>
<td>46.4</td>
<td>10.7</td>
<td>16.9</td>
<td>25.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W-2</td>
<td>60.8</td>
<td>3.0</td>
<td>0</td>
<td>36.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W-4</td>
<td>47.3</td>
<td>1.5</td>
<td>19.8</td>
<td>12</td>
<td>19.4</td>
<td>0</td>
</tr>
<tr>
<td>W-6</td>
<td>36.0</td>
<td>3.5</td>
<td>24.1</td>
<td>17.2</td>
<td>16.3</td>
<td>2.9</td>
</tr>
<tr>
<td>L1-1</td>
<td>37.8</td>
<td>3.4</td>
<td>22.9</td>
<td>10.9</td>
<td>19.1</td>
<td>5.9</td>
</tr>
<tr>
<td>L1-2</td>
<td>41.5</td>
<td>3.8</td>
<td>13.2</td>
<td>20.2</td>
<td>18.4</td>
<td>2.9</td>
</tr>
<tr>
<td>L2-1</td>
<td>25.9</td>
<td>9.2</td>
<td>10.0</td>
<td>9.8</td>
<td>43.2</td>
<td>1.9</td>
</tr>
<tr>
<td>L2-2</td>
<td>25.6</td>
<td>9.6</td>
<td>12.8</td>
<td>8.6</td>
<td>41.0</td>
<td>2.4</td>
</tr>
<tr>
<td>L-4</td>
<td>16.3</td>
<td>6.3</td>
<td>10.1</td>
<td>35.8</td>
<td>29.9</td>
<td>1.6</td>
</tr>
<tr>
<td>L-5</td>
<td>19.2</td>
<td>6.1</td>
<td>17.0</td>
<td>30.6</td>
<td>24.5</td>
<td>2.6</td>
</tr>
<tr>
<td>L-6</td>
<td>13.6</td>
<td>4.6</td>
<td>13.2</td>
<td>31.9</td>
<td>35.1</td>
<td>1.6</td>
</tr>
</tbody>
</table>

4.3 Mechanical properties of uniaxial compression

The results of uniaxial compression tests illustrated above were used to calculate some rock mechanical parameters. One of the samples, W1-1, broken too early due to internal fracture development, which led to low rock strength and parameters such as Young’s modulus and Poisson’s ratio cannot be acquired. The results show that the average compressive strength of Wufeng shale samples is 136.6 MPa, the average Young’s modulus is 13.83 GPa. While Longmaxi shale samples have lower values, 62.4 MPa for the average compressive strength, and 7.06 GPa for the average Young’s modulus. Densely developed cracks can be found within Longmaxi shale samples during sample preparation. Combining test result of sample W1-1, we can see that the development of natural cracks in shale reduces the strength of the whole rock dramatically.

From the uniaxial compression deformation stress-strain curve, we found that Wufeng shale samples and Longmaxi shale samples generally have similar mechanical properties. Their stress-strain curves can be divided into four stages, including compaction stage, elastic deformation stage, elastoplastic deformation stage and post-break brittle failure stage. The longer linear part represents significant elastic feature. While after the linear segment, the elastoplastic deformation stage is not apparent. Moreover, when reaching the peak stress, brittle fracture occurs rapidly. The degree of shear strain of all the samples shows significant brittle characteristics.

The failure forms of shale samples differ due to different directions. Under the case of the loading direction perpendicular to the bedding plane, the broken cracks form at an angle from the loading direction (about 30°). In the other case, which loading direction parallel to the bedding, several vertical cracks run through the entire rock when the sample is broken. It indicates that the stratification or heterogeneity of shale has an essential influence on its fracture mode and even the fracturing characteristics. (Xu Tianyang et al., 2018)

4.4 Mechanical properties of direct shear

Because different shapes and sizes of rocks may influence compressive strength (Liu Baochen et al., 1998), we first carried out the uniaxial compression test of Wufeng shale cube samples, W-7 and W-8. The average compressive strength of them is 54.5 MPa. Referencing the result, we took direct shear tests of two samples each group for three groups, with the normal load of 35 MPa, 40 MPa and 45 MPa respectively. The average value of maximum shear stress of Wufeng shale samples under normal load of 35 MPa, 40 MPa, 45 MPa is 38.32 MPa, 44.65 MPa and 44.81 MPa respectively. It demonstrates that the shear strength increases with the normal load. In addition, based on the shear stress-strain curve (Fig. 4), after linear fitting, we can get the internal friction angle of the sample is 33.0°, and the cohesive force is 16.6 MPa. Given the above, the expression of shear strength of Wufeng shale samples is as follows.

$$\tau = 0.65\sigma + 16.6$$ (1)
Fig. 4. The shear stress-strain curve of Wufeng shale samples under different values of normal load.

Direct shear test of Longmaxi shale sample was carried out with the same method. The compressive strength of the cube sample is 26.0 MPa. Therefore, we took direct shear tests for three groups, with the normal load of 10 MPa, 15 MPa and 20 MPa respectively. The maximum shear stress corresponding to each normal load is 26.02 MPa, 27.19 MPa and 38.52 MPa. Similarly, the shear strength of Longmaxi shale sample increases with the normal load. After linear fitting of the shear stress-strain curve (Fig. 5), the internal friction angle of the sample is 50.2°, the cohesive force is 11.3 MPa. Moreover, the expression of shear strength of Longmaxi shale samples is as follows.

\[ \tau = 1.2\sigma + 11.3 \]  

(2)

Fig. 5. The shear stress-strain curve of Longmaxi shale samples under different values of normal load.

Under the shear force, the main fracture developed along the direction of the reserved shear crack (Fig. 6a), also, secondary fractures formed from the main middle fracture through to the top and bottom of the sample (Fig. 6b). The development model of fracture network illustrates that the reserved shear crack of the sample is the key to the shear direction of shale, which is equivalent to the role of sizeable natural shale cracks. Secondary fractures develop based on main fractures, and at an angle with the latter. They generally form along the natural weak surface and micro-fracture of the sample.
5 Discussions

5.1 Shale fracture mode
According to the uniaxial compression test results, we proposed two kinds of fracture modes of shale, single plane shear fracture and split fracture. The bedding planes and natural cracks of shale are its main weak surface. Fractures are more likely to develop, expand and penetrate through the sample, to form split fractures along the bedding and numerous cracks when the loading direction is parallel to the bedding direction. On the other hand, regarding the loading direction normal to the bedding direction, shear fractures occur due to shear stress on the fracture surface exceeding the ultimate strength. The angle between fracture surface and loading direction is $\beta = \pi/4 - \phi/2$ ($\phi$ means internal friction angle of shale) according to Coulomb criterion.

This research was limited to the number of samples. Thus, no compressive strength tests of samples taken at different angles were conducted. However, through the comparison of the test results of vertical and parallel bedding directions, we can find that there exists a significant difference in fracture model rather than mechanical strength. The heterogeneity has an important influence on the mechanical properties of shale.

The samples damaged by direct shear tests showed uneven shear failure surface, on which striation can sometimes be observed. During the test, the internal damage accumulated continuously, and the micro-cracks gradually developed until connection, resulting in shear failure of the sample. The inherent heterogeneity of shale and fracture expansion leads to the unevenness of the fracture surface. And the test data illustrated that the normal load also has significant effects on damage characteristics. With a low normal load, the fracture surface undulated greatly, and the edges were prominent. Under higher normal load, the fracture surface tended to be smooth, with less rough edges, and significant surface striations.

5.2 Influence factors of fracability evaluation

Some scholars only use one index, brittleness index, to evaluate the fracability of shale gas reservoir (Diao Haiyan, 2013). Others attempt to establish the mathematical model of comprehensive influence factors (Chen Jiangzhou et al., 2017). So far, a systematic, comprehensive and quantitative evaluation model of shale fracability has not been formed, as a result of a single evaluation factor or multiple overlapping factors.

In this paper, we have taken brittleness index, fracture toughness, natural fractures and cohesive force as evaluation indexes to develop a mathematical model of fracability evaluation.

5.2.1 Brittleness index
Brittleness index is the core index to evaluate the fracability of shale gas reservoir (Rybacki et al., 2016). We used two kinds of methods to get this value in the paper. Regarding Poisson’s ratio, the lower the value, the more brittle the rock, and as values of Young’s modulus increase, the more brittle the rock will be. According to the previous research results (Rickman et al., 2008), we used the formulas of brittleness index calculated from Poisson’s ratio and Young’s modulus as follows.

\[
YM_{\text{BI}} = ((\text{YMS} - 1)/(8 - 1))^*100 \tag{3}
\]

\[
PR_{\text{BI}} = ((\text{PR} - 0.4)/(0.15 - 0.4))^*100 \tag{4}
\]

\[
BI = (YM_{\text{BI}} + PR_{\text{BI}})/2 \tag{5}
\]

In the above formulas, $YM_{\text{BI}}$ means normalized Young’s modulus, non-dimension; $YMS$ means static Young’s modulus, 10 GPa; $PR_{\text{BI}}$ means normalized Poisson’s ratio, non-dimension; $PR$ means static Poisson’s ratio, non-dimension; $BI$ means brittleness index, non-dimension.

Based on the test data, Wufeng shale samples have average Young’s modulus of 13.83 GPa, and average Poisson's ratio of 0.31. While Longmaxi shale samples have average Young’s modulus of 7.06 GPa, and average Poisson's ratio of 0.35. Substituting them into the above equations, we can get the brittleness index of 20.7% for Wufeng shale, and 7.9% for Longmaxi shale.

In addition to the method of mechanical parameters, the brittleness index can be calculated by using the method of mineral composition (Jarvie et al., 2007).

\[
BI = Q/(Q + C + CL) \tag{6}
\]

In this formula, $BI$ means brittleness index, $Q$ means quartz content, $C$ means carbonate minerals content, and $CL$ means clay minerals content. Shale gas reservoir with high amounts of brittle minerals is more likely to produce natural and induced fractures. Conversely, high clay minerals content would significantly reduce the ability to produce fractures. In addition, hydraulic fracturing process may cause hydrated swell and dispersion of clay minerals, which makes permeability decreasing. Based on the mineral composition data of the sample (Table 2), we can calculate the brittleness index of Wufeng...
shale and Longmaxi shale, 55.9% and 21.0% respectively.

The above two methods both indicate that Wufeng shale samples have a higher degree of brittleness than Longmaxi shale samples, which is better for artificial fracturing that can form complex fracture networks easily.

5.2.2 Fracture toughness

The term fracture toughness reflects the ability of the fracture to extend forward after formation, during the fracturing process (Yuan Junliang et al., 2013). A smaller value of fracture toughness usually means the stronger penetrating capacity of fractures produced by hydraulic fracturing, as well as larger fracturing volume of the reservoir. In materials science, fracture toughness represents the energy absorbed by a material before it breaks. Thus, we used the shaded area, as shown in the stress-strain diagram of uniaxial compression test (Fig. 7), which refers to the amount of energy required to create new fractures in the rock of per unit volume, to indicate indirectly the value of fracture toughness (Li et al., 2015).

![Fig. 7. The stress-strain diagram of the uniaxial compression test (modified after Li et al., 2015). The area of the shaded region can indirectly indicate the value of fracture toughness.](image)

The calculation results show that the average value of the fracture toughness of Longmaxi shale samples is significantly higher than that of Wufeng shale samples. It means that Longmaxi shale could respond better to hydraulic stimulation, considering this influence factor.

5.2.3 Natural fractures

In the original condition of the shale layer, natural fractures are mostly closed or filled with calcite or quartz veins. Nevertheless, they can promote the extension of the fracture network, and increase the conductivity of fracture during the fracturing process. In general, just for artificial fracturing, the more natural fractures develop, the better. The observations above, from different scales, show that the fractures in Longmaxi shale develop better than Wufeng shale.

5.2.4 Cohesive force

Cohesive force and internal friction angle are two parameters of shear strength. Among them, cohesive force refers to the physical and chemical forces between mineral particles in rocks. According to Coulomb’s law, the higher the value of cohesive force, the harder the rock as well as the worse the fracability. Thus, cohesive force is a negative factor for fracability evaluation. From the results of direct shear tests, we can acquire that the mean value of cohesive force of Wufeng shale samples is 16.6MPa, while Longmaxi shale samples, only 11.35MPa.

5.3 Mathematical modeling for fracability evaluation

Summing up the previous studying achievements (Tang Ying et al., 2012; Fu et al., 2015; Sui et al., 2016), we established the mathematical model for fracability evaluation following these steps. First, we determined the influence factors that should be considered, including brittleness index, fracture toughness, natural fractures and cohesive force. Then we normalized the parameters by range transformation or experience method, due to their different scopes and dimensions. For the positive factor,

$$S = \frac{x - x_{min}}{x_{max} - x_{min}}$$  \hspace{1cm} (7)

While for the negative factor,
\[ S = \frac{x_{\text{max}} - x}{x_{\text{max}} - x_{\text{min}}} \]  

(8)

In both of these formulas, \( S \) stands for the normalized value of the parameter; \( X \) stands for the value of the parameter; \( X_{\text{max}} \) stands for the maximum value of the parameter; \( X_{\text{min}} \) stands for the minimum value of the parameter.

From the two methods mentioned above about calculating brittleness index, we choose the mineral composition method. As the secondary important evaluation parameter in this paper, the value of fracture toughness mainly depends on the mechanical properties of samples. To avoid double counting the influence of mechanical parameters such as Young’s modulus and Poisson's ratio, we use brittle mineral content to calculate the brittleness index.

In terms of natural fractures, which are difficult to quantify, we assigned value through experience method, according to the fracture density, developing and filling state, length and width of fractures (Tang Ying et al., 2012). The normalized values of both methods are all between 0 and 1. 0 means the worst value and 1 means the optimal value. All the normalized results are shown in Table 5, among them, we used the value to represent the degree of development of natural fractures, 0.2, 0.5, 0.8 for poor, moderate and good, respectively. Other values mean the developmental levels between the above.

After normalization, we should determine the impact of each influence factor on fracturing ability, because their influence degrees are different. Refer to Fu et al. (2015) and Sui et al. (2016), we used analytic hierarchy process to confirm the weight value of each parameter (Table 3). The method for this is to group the parameters into a hierarchical structure and then use judgment matrix criteria to assign values of the parameters according to their degree of importance.

**Table 3 Judgment matrix criteria and its meaning**

<table>
<thead>
<tr>
<th>( a_{ij} )</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( a_i ) compared with ( a_j ), equal important</td>
</tr>
<tr>
<td>3</td>
<td>( a_i ) compared with ( a_j ), slightly more important</td>
</tr>
<tr>
<td>5</td>
<td>( a_i ) compared with ( a_j ), relatively strong important</td>
</tr>
<tr>
<td>7</td>
<td>( a_i ) compared with ( a_j ), strong important</td>
</tr>
<tr>
<td>9</td>
<td>( a_i ) compared with ( a_j ), absolutely important</td>
</tr>
</tbody>
</table>

2, 4, 6, 8 The intermediate values reflect intermediate position of importance

Properties of judgment matrix: (1) \( a_{ij} > 0 \); (2) \( a_{ii} = 1 / a_{ij} \); (3) \( a_{ij} = 1 \)

Then we constructed the matrix \( (a_{ij}) \) of the influence factor's scales, depending on the relative importance of each factor (Table 4). In this scale matrix, brittleness index is regarded as the most important influence factor, because it has a direct and significant impact on the fracability of shale. Conversely, cohesive force is put at the end of the list, owing to its indirect influence, by affecting the brittleness, on the fracability.

**Table 4 The scale matrix of the four influence factors**

<table>
<thead>
<tr>
<th>( a_{ij} )</th>
<th>Brittleness index</th>
<th>Fracture toughness</th>
<th>Natural fractures</th>
<th>Cohesive force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brittleness index</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Fracture toughness</td>
<td>1/3</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Natural fractures</td>
<td>1/5</td>
<td>1/3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Cohesive force</td>
<td>1/7</td>
<td>1/4</td>
<td>1/2</td>
<td>1</td>
</tr>
</tbody>
</table>

Based on the above matrix, the calculated weight value of each parameter by formula (9) is 0.569, 0.255, 0.110, and 0.066 for brittleness index, fracture toughness, natural fractures and cohesive force, respectively.

\[ W_i = \frac{\sum_{j=1}^{n} a_{ij}}{n} \]  

(9)

Where \( W_i \) stands for the weight value, and the number \( a_{ij} \) scales the significance of factors in the matrix. Finally, we weighted the normalization values with different weight coefficients to obtain the fracability index. The formula is shown below:

\[ \text{FI} = \sum_{i=1}^{n} S_i W_i \]  

(10)

In this formula, FI is fracability index; \( S_i \) is the normalized value of each influence factor of the shale sample; \( W_i \) is the weight coefficient of each influence factor; \( n \) is the number of influence factor. All the parameters are non-dimensional.

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With formula (10), we obtained the fracability index of the target strata, Wufeng shale and Longmaxi shale in Changning area, southern Sichuan Basin (Table 5). The results indicate that the fracability index of Wufeng shale is a little higher than Longmaxi shale, which means it is easier to create a complexity fracture network and large stimulated reservoir volume. However, given its higher resource potential, Longmaxi shale is currently the most significant exploration and development strata in Sichuan Basin. Our research shows that it is feasible to do horizontal drilling and hydraulic fracturing through Wufeng Formation, inducing dense fractures penetrating the overlying Longmaxi Formation, to increase shale gas output.

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Fracability evaluation of Wufeng shale and Longmaxi shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influence factor</td>
<td>Weight coefficient</td>
</tr>
<tr>
<td>Brittleness index</td>
<td>0.569</td>
</tr>
<tr>
<td>Fracture toughness</td>
<td>0.255</td>
</tr>
<tr>
<td>Natural fractures</td>
<td>0.110</td>
</tr>
<tr>
<td>Cohesive force</td>
<td>0.066</td>
</tr>
<tr>
<td>Fracability index</td>
<td></td>
</tr>
</tbody>
</table>

6 Conclusions

By field observation, laboratory microscope analysis and rock mechanical test, we studied multiscale structural features and mechanical characteristics of Wufeng shale and Longmaxi shale in Changning area, southern Sichuan Basin. Also, we analyzed several factors affecting the fracability of shale gas reservoir, including brittleness index, fracture toughness, natural fractures and cohesive force. Finally, we established a multi-factor evaluation system for shale fracability using analytic hierarchy process, and carried out a quantitative comparative analysis of fracability of target shale strata. The main conclusions are as follows:

(1) The shale has two types of fracture modes, single plane shear fracture and split fracture. The former develops when the loading direction is perpendicular to the bedding, while the latter forms when loading direction is parallel to the bedding.

(2) Wufeng shale and Longmaxi shale both show prominent elastic features, though Wufeng shale has little higher uniaxial compressive strength and elastic modulus. Furthermore, Wufeng shale has lower internal friction angle and higher cohesive force than Longmaxi shale, which usually means worse fracability.

(3) Two methods were used to calculate the brittleness index, considering mechanical parameters and mineral composition respectively. The results of both methods show that Wufeng shale has a higher value of brittleness index than Longmaxi shale.

(4) We established a fracability evaluation model using analytic hierarchy process, taking brittleness index, fracture toughness, natural fractures and cohesive force as influence factors. The calculated fracability index of Wufeng shale is higher than Longmaxi shale, which shows greater development potential of fracability.

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References


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