Mechanical characteristics and influencing factors of shallow igneous rocks in Junggar Basin

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Abstract. The mechanical properties of rocks play a pivotal role in hydraulic fracture propagation. In this study, mineral composition experiments, uniaxial and triaxial tests, shear tests, and fracture toughness tests were performed to analyze the rock mechanics characteristics of igneous rocks and their relationship with confining pressure, mineral composition, lithology, and lithofacies. The results show that the confining pressure has a significant influence on the elastic modulus and compressive strength of the igneous rock, but an insignificant effect on Poisson's ratio. The contents of clay minerals and brittle minerals significantly affect the mechanical properties. However, the lithology and lithofacies do not have an evident influence on the rock mechanical properties. In this study, a dimensionless elastic modulus, namely, the ratio of the elastic modulus to the confining pressure is proposed. The average dimensionless elastic modulus under different confining pressures exhibited a good linear correlation with the confining pressure. This parameter can be used to predict the elastic modulus. The results of this study can provide a basis for the hydraulic fracturing design of shallow igneous rock formations in the Junggar Basin in China.

1. Introduction

With the advancement of the exploration and development of oil and gas in China, igneous rock formations have become an important target. Compared with conventional oil and gas reservoirs, igneous rock reservoirs in the Chepazi area have poor matrix permeability and porosity [1], and hydraulic fracturing technology is needed to achieve industrial productivity [2, 3]. Rock mechanical properties are key parameters for reservoir evaluation, hydraulic fracturing design, and stimulation effects [4, 5]. The mechanical characteristics of tight sandstone, shale, and carbonate rocks, with their influencing factors, have been widely investigated in previous studies [6–8]. With regard to igneous
rocks, which have complex lithology and lithofacies [9], the current studies mainly focus on the geological and petrophysical characteristics [10–13]. There are few reports on the mechanical properties, resulting in an unclear understanding of the corresponding fracturing strategies.

In this study, rock mechanics and petrophysical experiments, such as uniaxial and triaxial mechanical tests, tensile and shear strength tests, fracture toughness tests, and mineral composition analysis, were performed using downhole igneous rock cores from the Junggar Basin. The influences of confined pressure, mineral composition, lithology, and lithofacies on rock mechanical properties were analyzed and compared. The correlations between the rock mechanical properties and controlling factors were determined.

2. Lithology, lithofacies, and mineral composition

The cores were taken from a development Well in the Chepaizi embossment in the western uplift of the Junggar Basin, Xinjiang, with a depth of 584.84–1084.41 m. The Chepaizi embossment has developed on a Carboniferous igneous substratum that had been uplifted for a long time since the Late Hercynian. The Yanshan Movement during the Mesozoic period caused several variations in the tectonic structure, and the strata above the top Carboniferous are mainly truncated and overlapped. It generally appears as a monoclinic belt dipping in the southeast. In this area, the lithology includes andesite, volcanic tuff, lava breccia, and granite porphyry, while the lithofacies includes effusion facies, explosion facies, and eruption–sedimentary facies. The lithology, lithofacies, and mineral composition of the samples are summarized in Table 1.

| Well no. | Clay mineral (%) | Quartz (%) | Orthoclase (%) | Plagioclase (%) | Calcite (%) | Dolomite (%) | Lithology          | Lithofacies               |
|---------|------------------|------------|----------------|-----------------|-------------|--------------|--------------------|--------------------------|
| 1       | 24.98            | 11.57      | 2.76           | 50.12           | 7.01        | 2.26         | Volcanic tuff      | Explosion facies         |
| 2       | 27.39            | 21.39      | 3.09           | 39.08           | 4.31        | 4.74         | Andesite           | Effusion facies          |
| 3       | 21.47            | 17.38      | 4.11           | 47.86           | 5.24        | 3.94         | Lava breccia       | Effusion facies          |
| 4       | 36.17            | 34.85      | 2.58           | 14.49           | 8.08        | 3.83         | Lava breccia       | Explosion facies         |
| 5       | 22.05            | 34.13      | 5.02           | 22.75           | 2.01        | 2.43         | Volcanic tuff      | Eruption–sedimentary facies |

The content of brittle minerals (quartz and feldspar) is relatively high, with values ranging from 51.91% to 69.35% and an average content of 62.24%. The clay mineral content ranges from 21.47% to 36.17%, with an average content of 26.41%.

3. Test results and rock mechanical characteristics

3.1 Uniaxial and triaxial rock mechanics test results

The RTR-1000 static (dynamic) triaxial rock mechanics testing system was used to perform uniaxial and triaxial full stress–strain tests. The rock samples were processed to a standard size (length: 50 mm
and diameter: 25 mm). The end faces of the samples were polished to ensure that they were smooth, parallel, and perpendicular to the central axis.

According to the stress–strain curves shown in Figure 1, the cores under uniaxial compression mainly experienced elastic deformation, and the stress–strain curves were nearly straight. The yield stress and strength limit almost overlapped, and the cores failed almost directly after reaching the limit of elastic deformation. As the confining pressure increased, the deformation stage before the rock failure was still approximately straight, and the cores could withstand higher axial stress, as shown in Figure 2. Generally, under uniaxial compression, the shape of the curve after the peak is complicated. When a confining pressure is applied, the failure part exhibits a vertical descending tendency. The rock performance under pressure shows that the failure mode changed from the longitudinal split to shear slip, as shown in Figure 3.

Under different confining pressures, the stress–strain curve of the igneous rocks in this area showed three stages. (1) The first stage is the initial compaction stage, in which the microcracks and pores inside the rock close rapidly. (2) The second stage is the linear elasticity deformation stage, and rocks undergo linear elastic deformation. (3) The third stage is the postpeak strain stage, in which only residual strength remains after the rock rupture.
3.2 Tensile strength and shear strength
An RTR-1000 static (dynamic) triaxial rock mechanics testing system was used to determine the tensile strengths of the cores. The results are listed in Table 2.

Table 2. Tensile strength

| Well no. | Maximum load (kN) | Tensile strength (MPa) | Tensile strength averaged (MPa) |
|----------|-------------------|------------------------|-------------------------------|
| 1        | 1.087             | 1.38                   |                               |
|          | 1.319             | 1.64                   | 1.65                          |
|          | 1.657             | 1.92                   |                               |
|          | 1.693             | 2.38                   |                               |
| 2        | 2.589             | 3.9                    | 3.64                          |
|          | 3.487             | 4.63                   |                               |
|          | 1.387             | 1.81                   |                               |
| 3        | 1.419             | 1.86                   | 1.88                          |
|          | 1.557             | 1.97                   |                               |
|          | 2.08              | 2.76                   |                               |
| 5        | 1.158             | 1.43                   | 2.76                          |
|          | 3.224             | 4.1                    |                               |

A direct shear apparatus was used to obtain the shear strength, cohesion, and internal friction angle, which reflect the friction characteristics and shear strength of the samples. The results are listed in Table 3. The maximum shear strength of the samples from the four wells specified in Table 3 was 32.52 MPa, while the minimum shear strength was 13.25 MPa, and the average shear strength was 21.55 MPa. For cohesion, the maximum, minimum, and average values were 11.56, 5.98, and 9.27 MPa, respectively.

Table 3. Shear strength, cohesion, and internal friction angle

| Well no. | Vertical stress (MPa) | Vertical load (kN) | Maximum load (kN) | Shear strength (MPa) | Cohesion (MPa) | Internal angle (°) |
|----------|-----------------------|-------------------|-------------------|----------------------|---------------|--------------------|
| 1        | 5                     | 2.5               | 8.19              | 21.11                | 8.77          | 54.23              |
|          | 10                    | 5                 | 10.57             | 21.11                |               |                    |
|          | 15                    | 7.6               | 15.29             | 30.36                |               |                    |
|          | 6                     | 3.1               | 9.29              | 18.08                |               |                    |
| 3        | 12                    | 6.1               | 11.86             | 11.56                |               | 45.97              |
|          | 18                    | 9.2               | 15.56             | 30.49                |               |                    |
|          | 6                     | 3                 | 7.51              | 14.89                |               |                    |
| 4        | 12                    | 5.8               | 11.35             | 23.4                 | 5.98          | 55.76              |
|          | 18                    | 8.8               | 15.88             | 32.52                |               |                    |
| 6        | 4                     | 2.1               | 6.82              | 13.25                | 10.75         | 33.13              |
3.3 Fracture toughness

The type I and type II fracture toughness of rocks were measured by using cracked straight through Brazilian disk specimens of cores. The results are summarized in Table 4. The type II fracture toughness of all the samples from the three wells specified in Table 4 was greater than that of type I fracture, indicating that tensile failure, rather than shear failure, was dominant. This phenomenon is consistent with the relative magnitudes of the shear strength and tensile strength specified in Tables 2 and 3.

| Well no. | Diameter (D/mm) | Thickness (B/mm) | Fracture length (2a/mm) | Peak load (P/N) | \( K_{IC} \) (MPa.m\(^{0.5}\)) | \( K_{IIC} \) (MPa.m\(^{0.5}\)) |
|---------|----------------|------------------|-------------------------|----------------|-------------------------------|-----------------------------|
| 1       | 49.71          | 17.45            | 27.8                    | 1947           | 0.446                         | —                           |
|         | 49.73          | 19.1             | 27.47                   | 1705           | —                             | 0.527                       |
| 2       | 49.62          | 19.02            | 28                      | 4571           | 0.971                         | —                           |
|         | 49.66          | 18.97            | 27.19                   | 3777           | —                             | 1.162                       |
| 3       | 49.62          | 18.72            | 27.5                    | 4830           | 1.02                          | —                           |
|         | 49.64          | 19               | 27.48                   | 3992           | —                             | 1.244                       |

4. Analysis and discussion

4.1 Impact of confining pressure

The rock deformation is closely related to the confining pressure. The changes in the elastic modulus, compressive strength, and Poisson’s ratio with confining pressure are shown in Figure 4 (a), (b), and (c), respectively. The Young’s modulus of the rock in the three wells other than Well 3 increased with increase in confining pressure, and the value for Well 2 showed a linear relationship with the confining pressure. Further, the rock compressive strength of the cores from the three wells other than Well 4 exhibited a nonlinear relationship with the confining pressure. For the cores from Well 2, for example, as the confining pressure increased from 5 to 10 MPa, the compressive strength increased by 2.96%, and when the confining pressure increased from 10 to 15 MPa, the compressive strength increased dramatically by 28.43%. The Poisson’s ratios of the rocks in the four wells too experienced some changes.
Figure 4. Elastic modulus (a), compressive strength (b), and Poisson's ratio (c) at different confining pressures.

Under uniaxial compression, the maximum, minimum, and average compressive strengths of rocks were 88.6, 21.7, and 68.56 MPa, respectively. The elastic modulus was in the range 9926.4–17,784.9 MPa, with an average of 14,290.6 MPa. Poisson's ratio varied from 0.122 to 0.279, with an average of
0.190. However, it is unreasonable to focus on only the mechanical parameters because the elastic moduli are related not only to the mechanical properties of the rock samples themselves, but also the confining pressure applied during the experiments. To combine the influences of the two factors, a dimensionless elastic modulus $E_D$ was defined:

$$E_D = \frac{E}{P_c} \quad (1)$$

where $E$ is the elastic modulus [MPa], and $P_c$ is the confining pressure [MPa]. The dimensionless elastic moduli under different confining pressures are shown in Figure 5. The value decreases as the confining pressure increases and reaches a maximum at a confining pressure of 5 MPa. The ratios of the maximum and minimum values of the elastic modulus under a given confining pressure are 1.21 for 5 MPa, 1.10 for 10 MPa, and 1.27 for 15 MPa. Nevertheless, the differences in the dimensionless elastic modulus are small, especially when the confining pressure is less than 10 MPa (as shown in Figure 6). The average dimensionless elastic modulus has an approximately linear relationship with the confining pressure, and the $R^2$ fitted to the linear relationship can reach 0.9. Using this relationship and the confining pressure, the values of the elastic modulus under different confining pressures can be predicted. The average dimensionless elastic modulus has an approximately linear relationship with the confining pressure, and the $R^2$ fitted by the linear relationship can reach 0.9. This relationship can be used effectively to predict the elastic modulus under different confining pressures.

Figure 5. Dimensional elastic modulus of three wells under different confining pressures.
4.2 Impact of mineral composition

Pearson's linear correlation coefficient was used to measure the linear correlation between two variables, $X$ and $Y$, with values between $-1$ and $1$ [14]. The coefficient $r$ is defined as follows:

$$r = \frac{\sum_{i=1}^{n} (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n} (X_i - \bar{X})^2} \sqrt{\sum_{i=1}^{n} (Y_i - \bar{Y})^2}}$$

(2)

where $X_i$ and $Y_i$ are the $i$-th values of variables $X$ and $Y$, respectively, and $\bar{X}$ and $\bar{Y}$ are the averaged values of the two variables, respectively. This parameter is used to characterize the relationship between the mineral composition and mechanical properties (see Table 5). Generally, the correlation is considerable when $|r| \geq 0.6$, but in this study, a Pearson correlation coefficient exceeding 0.9 is regarded as a significant correlation. Under a confining pressure of 5 MPa, as the carbonate mineral content increases, the value of the elastic modulus also increases. Under confining pressures of 10 and 15 MPa, the elastic modulus shows a good linear correlation with the contents of clay and brittle minerals. This means that the mineral composition may not be the controlling factor of the mechanical properties of igneous rock; otherwise, a clear trend would have been observed. The tensile strength has no apparent relevance to the mineral composition, but the shear strength shows a good correlation with calcite and dolomite, and the fracture toughness shows a good relationship with plagioclase.

Table 5. Pearson correlation coefficients between mineral composition and rock mechanics

| Parameters                     | Clay minerals | Quartz | Orthoclase | Plagioclase | Calcite | Dolomite |
|--------------------------------|---------------|--------|------------|-------------|---------|----------|
| Poisson's ratio — uniaxial     | 0.185         | 0.379  | 0.131      | -0.409      | 0.341   | -0.452   |
| Elastic modulus — uniaxial     | -0.700        | -0.736 | 0.142      | 0.784       | -0.388  | -0.254   |
| Compressive strength —        | -0.776        | -0.708 | 0.248      | 0.775       | -0.455  | -0.309   |

Figure 6. Relationship between the average dimensionless elastic modulus and confining pressure.
### 4.3 Impact of lithology and lithofacies

From the data shown in Tables 6 and 7, the Poisson's ratio of andesite is relatively low, and the elastic modulus and compressive strength of the volcanic breccia are relatively low. There are few differences between rocks of different lithologies in terms of the shear strength, cohesion, and internal friction angle of rocks with different lithologies. In terms of fracture toughness, tuff types I and II are larger than those of andesite. The Poisson's ratio of the effusion facies is lower than that of the other two lithofacies, but there are no significant differences in terms of the elastic modulus, tensile strength, shear strength, and internal friction angle. According to the statistical results, the relationship between the lithology, lithofacies, and rock mechanical properties is not significant.

#### Table 6. Relationships between lithology and rock mechanical properties

| Lithology       | Poisson's ratio | Elastic modulus (MPa) | Compressive strength (MPa) | Tensile strength (MPa) | Shear strength (MPa) | Cohesion (MPa) | Internal frictional angle (°) | $K_{IC}$ (MPa.m$^{0.5}$) | $K_{IIC}$ (MPa.m$^{0.5}$) |
|-----------------|-----------------|-----------------------|---------------------------|-----------------------|---------------------|----------------|--------------------------------|--------------------------|--------------------------|
| Tuff            | 0.20            | 15088                 | 73.39                     | 2.21                  | -                   | -              | -                              | 0.971                    | 1.162                    |
| Andesite        | 0.14            | 15334                 | 71.65                     | 2.76                  | 22.65               | 8.77           | 54.23                          | 0.73                     | 0.886                    |
| Volcanic breccia| 0.22            | 11808                 | 41.50                     | -                     | 23.79               | 8.77           | 50.87                          | -                        | -                       |

#### Table 7. Relationships between lithofacies and rock mechanical properties

| Lithofacies     | Poisson's ratio | Elastic modulus (MPa) | Compressive strength (MPa) | Tensile strength (MPa) | Shear strength (MPa) | Cohesion (MPa) | Internal frictional angle (°) | $K_{IC}$ (MPa.m$^{0.5}$) | $K_{IIC}$ (MPa.m$^{0.5}$) |
|-----------------|-----------------|-----------------------|---------------------------|-----------------------|---------------------|----------------|--------------------------------|--------------------------|--------------------------|
|                 |                 |                       |                           |                       |                     |                |                                |                          |                          |
5. Conclusion
The rock mechanical properties and influencing factors of shallow igneous rocks in the Junggar Basin were studied via experiments and analysis. The following conclusions were drawn.
(1) Under uniaxial and triaxial compression conditions, the shallow igneous rocks mainly experienced elastic deformation. The stress–strain curve consists of the initial compaction, elastic deformation, and postpeak strain stages. As the confining pressure increases, the rock failure mode tends to be shear failure.
(2) The tensile strength of rocks in this area is less than their shear strength, and the type I fracture toughness is less than the type II fracture toughness, indicating that the rock is more prone to tensile failure during hydraulic fracturing.
(3) As the confining pressure increases, the rock elastic modulus and compressive strength exhibit a similar variation trend. A dimensionless elastic modulus was defined. Under identical confining pressures, this modulus shows little differences among different wells. The averaged dimensionless elastic modulus presents a linear relationship with the confining pressure, and this relationship can be used to predict the elastic moduli of rocks at different depths in a block.
(4) The relationships between the mineral composition, lithology, lithofacies, and mechanical properties of rocks in this area are not significant, and further investigations are needed.

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7. References
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