

Input Impedance Modeling and Stability Analysis for Virtual Synchronous Generator

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ABSTRACT

With regard to the difficulty in sampling the deep tight carbonate reservoir and the few related studies on the deep tight carbonate reservoir, 28 rock samples buried below 6000m in the Eastern Tarim Basin were taken as the study object. Under the confining pressure of 100MPa, the microcomputer controlled electro-hydraulic servo rock triaxial testing machine was used to conduct an experimental study on the mechanics parameters of the rock sample in laboratory. The experimental results show that the rock of the deep tight carbonate reservoir in the Eastern Tarim Basin has a higher Young modulus, a lower Poisson ratio and a higher compressive strength. According to the experimental data, the correlation between the compressive strength and the Young modulus was studied. The regression fit relationship between the compressive strength and the Young modulus was obtained by analysis and comparison, and the reliability was verified. Moreover, the relationship between the mechanics parameters and the density was clarified by discussing the law between the mechanics parameters and the physical parameters of the rock. The brittleness index of rock samples was calculated by Rickman brittleness evaluation method to establish the rock brittleness index map of the deep tight carbonate reservoir in the Eastern Tarim Basin. An extended computing was made on the fracturing index, to established the fracturing index map for fracturing evaluation. The research results provide an important basis for the fracturing design in the Eastern Tarim Basin, and have important guiding significance for the study of the mechanics parameters of the deep tight carbonate reservoir.

1. INTRODUCTION

Carbonate reservoirs are extensively distributed, and take a higher proportion of 40% in large oil and gas fields on a global scale. Many large and medium-sized carbonate reservoirs have been discovered in China in Bohai Bay, Tarim Basin, Ordos Basin and Sichuan Basin, demonstrating the enormous potential of carbonate rocks. Therefore, it is of great significance to study the carbonate reservoir (Kang, Y. 2008).

The deep tight carbonate reservoir has extremely complex geological conditions, such as large buried depth, strong heterogeneity, development of fractures and karst caves, low porosity and low permeability. The pore space of the reservoir is dominated by matrix and secondary pores.

The reservoir pores include intercrystalline pores, intercrystalline dissolved pores, fracture, and dissolved pores, which makes it difficult to grasp the change rule of the rock mechanics parameters of carbonate reservoirs. Therefore, the study of the law of the rock mechanics parameters in the deep tight carbonate reservoir is of great importance. Scholars at home and abroad have come up with some research results. Ameen et al. studied the relationship between acoustic waves and rock mechanics parameters in carbonate reservoirs, and predicted and analyzed rock mechanics parameters(Ameen, M. et al. 2009); Jarot et al. analyzed the influence law of pressure and temperature on rock mechanics parameters(Iarot S.and Ariffin S. 2009); Xu Guosheng studied the relationship between the acoustic characteristics and the rock mechanics parameters in the carbonate reservoir of the buried hill through laboratory experiments(Xu, G. 2004); Zhou Xingui et al. studied the rock mechanics characteristics of the Tarim Basin through drilling and logging data(Zhou, X. et al. 2002); Guo Yintong studied the mechanics parameter characteristic of the carbonate reservoir in East Sichuan through laboratory experiments(Guo, Y. et al. 2012); Gan Xinxing et al. established the prediction models of mechanics parameters such as Young modulus and Poisson ratio of marine carbonate rocks through a large number of laboratory experiments(Gan, X, at al. 2011); Zhang Qiangyong et al. used the rock samples of the carbonate reservoir in Tahe Oilfield to obtain the mechanics parameter of the ultra-deep carbonate rocks(Zhang, Q. at al. 2015); Li Nianyin et al. calculated the brittleness index of the carbonate reservoir in the Ordos Basin using the Young modulus and Poisson ratio, and evaluated the brittleness of the reservoir(Li, N. et al. 2016); Lin Bin et al. established the nonlinear regression prediction model of the compressive strength and the Young modulus of rocks through a large number of experimental data(Lin, B. and Xu, D. 2017); Zhang Jianhui studied the relationship between rock mechanics parameters and rock physical parameters, and predicted by the fitting formula(Zhang, J. 2017); Ren Yan et al. proposed the fracturing index based on brittleness index, fracture toughness and compressive strength, and predicted the fracturing behavior of the tight carbonate reservoir in Moxi Area of Central Sichuan(Ren, Y. et al 2018).

Due to the difficulty of drilling and sampling deep tight carbonate rocks, few scholars have studied carbonate reservoirs with a burial depth of 6000m. Therefore, the mechanics experiment was carried out in laboratory using the rock samples of the tight carbonate reservoir buried below 6000m in the Eastern Tarim Basin under the confining pressure of 100MPa, to effectively obtain the corresponding mechanics parameters, furthermore, the correlation analysis of mechanics parameters and the fracturing evaluation were carried out in this paper.

2. EXPERIMENTAL METHOD

2.1. Experimental Sample and Apparatus

The experimental cores were taken from the Eastern Tarim Basin, with the sampling depth below 6000m, and the average porosity of 0.618%. The rock, mainly composed of dolomite and calcite, is a typical deep tight carbonate rock. They are standard rock samples with a diameter of 2.5cm and a length of 5.0cm, which meets the requirements of the rock sample for measuring mechanics parameters.

The rock mechanics parameters were tested in accordance with the Standard for Test Methods of Engineering Rock Mass (GB/T 50266-2013). The standard rock samples were placed in a pressure chamber, and sealed with an oil-resistant heat-shrinkable tube, and the parameters are adjusted by manual and computer.

The axial pressure was applied to the rock sample through the computer-controlled operation, the static parameters of the rock were measured, and the data was collected by the servo system. The experimental equipment is shown in Figure 1.

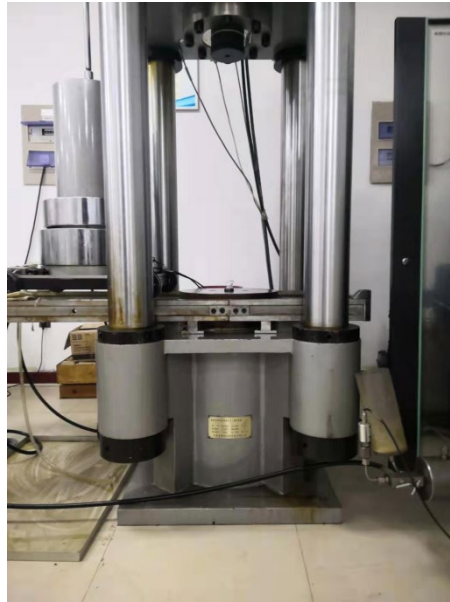


Figure 1 Experimental Equipment

2.2. Calculation Principle

Young modulus and Poisson ratio are two fundamental parameters describing rock deformation characteristics. The Young modulus describes the deformation resistance of the material, and the Poisson ratio reflects the lateral deformation ability of the material (Lin, Z. et al 1998; Zhi, H. 2014). The calculation formula of the static elastic parameter is shown as follows:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon_1} \quad (1)$$

$$E = \frac{\Delta\varepsilon_2}{\Delta\varepsilon_1} \quad (2)$$

where in:

- E - Young modulus, MPa;
- μ - Poisson ratio;
- $\Delta\sigma$ - Axial stress increment, N;
- $\Delta\varepsilon_1$ - Axial strain increment, m²;
- $\Delta\varepsilon_2$ - Radial strain increment, m²;

Compressive strength plays an important role in guiding the mechanics characteristics of rock(Yue, X. et al 2014). The calculation formula of the compressive strength is shown in the formula (3):

$$\sigma = \frac{F}{A} \quad (3)$$

where in:

- σ - Compressive strength, MPa;
- F - Axial load, N;
- A - Sample area, m².

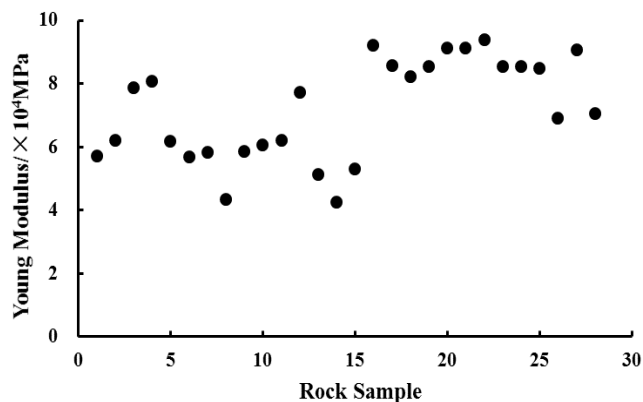
3. EXPERIMENTAL RESULT

The physical parameters of 28 rock samples taken from the deep tight carbonate reservoir in the Eastern Tarim Basin are shown in Table 1. All rock samples were measured for Young modulus, Poisson ratio and compressive strength under the confining pressure of 100MPa, as shown in Figure 2.

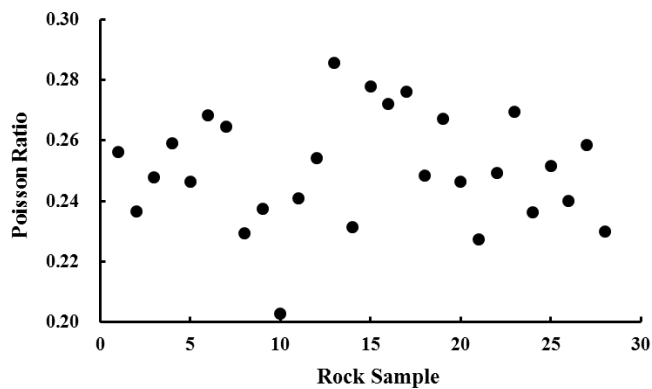
According to the experimental data, the rock sample has a Young modulus between 4×10^4 MPa and 10×10^4 MPa, a Poisson ratio between 0.2 and 0.3, and a compressive strength between 300 MPa and 800 MPa. It is observed that the deep tight carbonate reservoir in the Eastern Tarim Basin has a higher Young modulus, a lower Poisson ratio and a higher compressive strength.

Table 1 Physical Parameters of Rock Samples

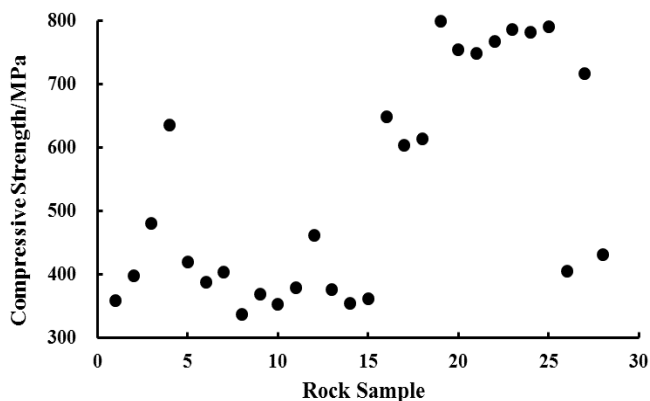
NO.	Density kg/m ³	Porosity %	Confining Pressure MPa	NO.	Density kg/m ³	Porosity %	Confining Pressure MPa
A1	2.642	0.172	100	A15	2.650	0.718	100
A2	2.715	0.204	100	A16	2.811	0.942	100
A3	2.556	1.128	100	A17	2.866	1.117	100
A4	2.823	0.756	100	A18	2.801	1.125	100
A5	2.724	0.204	100	A19	2.826	1.178	100
A6	2.692	0.502	100	A20	2.767	0.375	100
A7	2.686	0.330	100	A21	2.798	0.216	100
A8	2.654	0.573	100	A22	2.827	0.469	100
A9	2.728	0.533	100	A23	2.686	0.367	100
A10	2.720	0.187	100	A24	2.797	0.596	100
A11	2.674	0.460	100	A25	2.710	0.652	100
A12	2.737	0.546	100	A26	2.694	0.800	100
A13	2.688	0.418	100	A27	2.842	0.237	100
A14	2.583	0.633	100	A28	2.609	0.789	100



(a) Young Modulus Test Result



(b) Poisson Ratio Test Result



(c) Compressive Strength Test Result

Figure 2 Measurement Results of Static Mechanics Parameters

4. EXPERIMENTAL ANALYSIS

According to the experimental results, the correlation between mechanics parameters and the laws between mechanics parameters and physical parameters were studied, and the fracturing behavior of the deep tight carbonate reservoir in the Eastern Tarim Basin was evaluated.

4.1 Correlation Analysis of Mechanics Parameters

The compressive strength obtained by the compression test is affected by many factors, and the measured results have some ambiguity. Therefore, it is important to establish the relationship between the compressive strength and other mechanics parameters (Liu, B. et al 1998; Yang, S. et al 2005; You, M. and Su, C. 2006). Two-thirds of the measured data were randomly selected as the sample data for fitting, and the remaining one-third of the data were tested to prove the reliability of the data. According to the measurement results of the deep tight carbonate rock, the overall relationship between the compressive strength and the Young modulus was plotted, as shown in Figure 4, and the regression fit was carried out between the two using linear, quadratic and power functions respectively, to obtain the fitting equation and correlation coefficients, as shown in Table.

Table 2 Fitting Equation of the Compressive Strength and the Young Modulus

Function Relationship	Fitting Equation	Correlation Coefficient
Linear fit	$y = 98.991x - 185.96$	0.7811
Quadratic fit	$y = 19.057x^2 - 176.89x + 743.33$	0.8284
Power fit	$y = 43.709x^{1.2503}$	0.7987

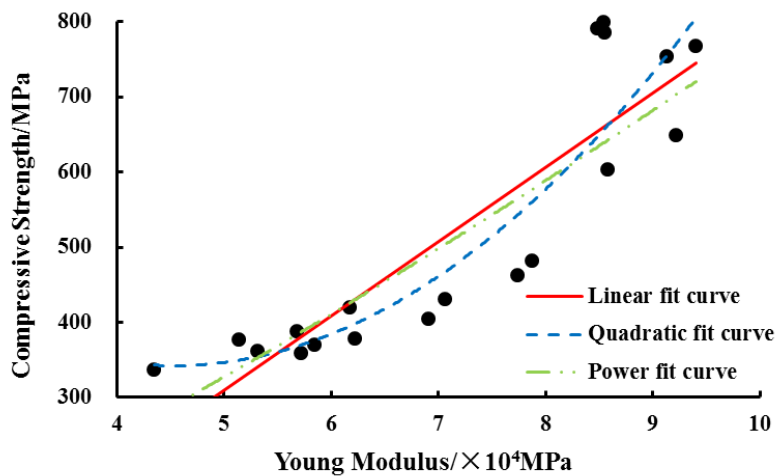


Figure 4 Relationship between the Compressive Strength and the Young Modulus

Apparently, for the deep tight carbonate reservoir, the compressive strength and the Young modulus show a significant positive correlation, that is, for the rock with larger Young modulus, the corresponding compressive strength is greater. By comparing the correlation coefficients of three fitting equations, the quadratic fit model has a good correlation, which can provide a reference for describing the relationship between the compressive strength and the Young modulus. The prediction was performed by applying a fitting formula to the data not involved in the fitting, and the predicted value and the experimental value were plotted as a curve for comparison, as shown in Figure 5.

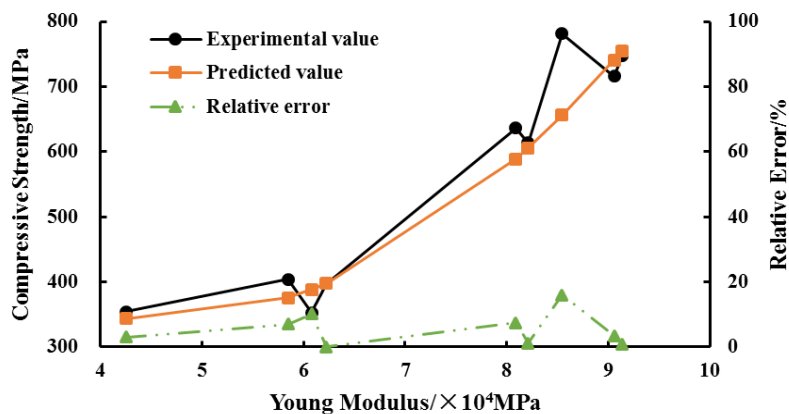
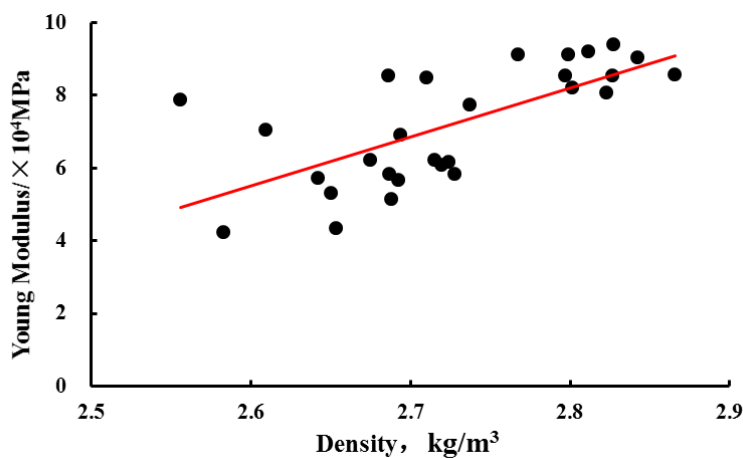


Figure 5 Comparison of the Predicted Value and the Experimental Value of the Compressive Strength

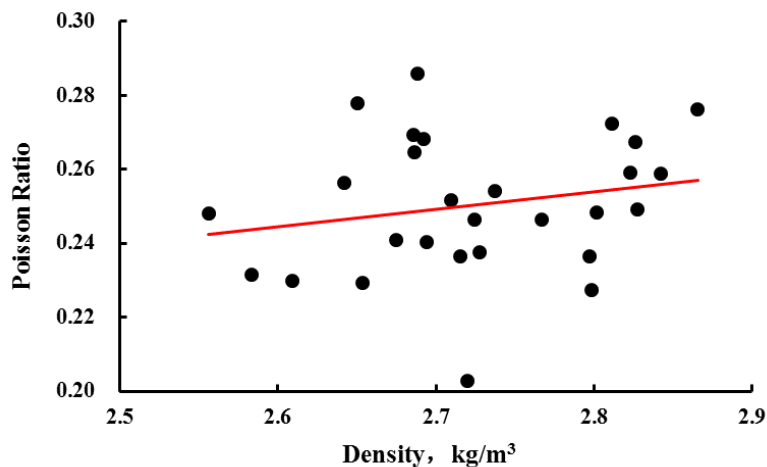
The figure shows that all relative errors are below 20%, and only two rock samples have a relative error of more than 10%. The predicted values of most rock samples are close to the experimental values, with relatively small error, the change trend of the predicted value curve is basically consistent with that of the experimental value curve, indicating that the regression fit model has a higher accuracy. For the deep tight carbonate reservoir, there is a good correlation between the compressive strength and the Young modulus. In the absence of compressive strength data, the corresponding Young modulus can be used.

4.2 Physical Parameter Relationship Analysis

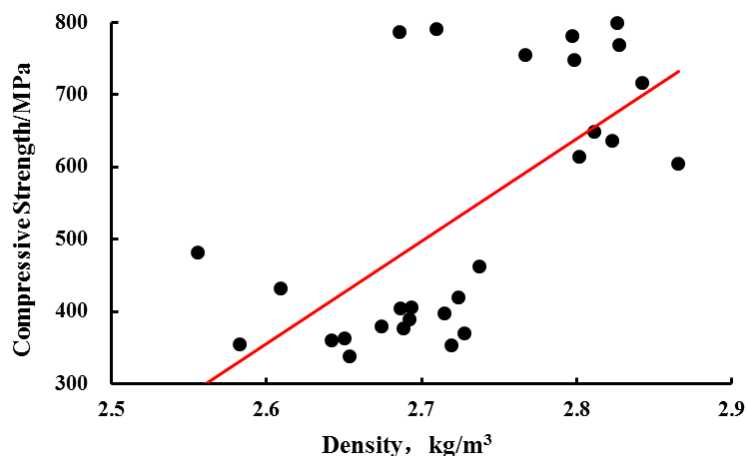
Discussing and analyzing the relationship between rock mechanics parameters and rock physical parameters, and clarifying the correlation between the two, has important practical significance for engineering. Based on the measured data, an in-depth discussion was made for the correlation between the mechanics parameters and the density of the rock sample.



(a) Change Law of Young Modulus with Density



(b) Change Law of Poisson Ratio with Density



(c) Change Law of Compressive Strength with Density

Figure 3 Relationship between Static Mechanics Parameters and Rock Sample Density

The linear fitting is applied, and the fitting formula is shown as follows.

Table 3. Fitting Formula of Mechanics Parameters and Density

Mechanics Parameters	Fitting Equation	Correlation Coefficient
Young modulus	$y = 13.445x - 29.499$	0.472
Poisson ratio	$y = 0.0468x + 0.1229$	0.0419
Compressive strength	$y = 1416.5x - 3327$	0.4359

According to Figure 3 and Table 3, the Poisson ratio presents discrete data with small correlation coefficient, indicating that the Poisson ratio of the rock sample has no significant relationship with the density. The correlation coefficient of the linear fit between the Young modulus and the compressive strength is at a medium level. However, it shows a significant positive correlation between Young modulus, compressive strength and density, that is, the greater the rock density, the greater the Young modulus and compressive strength.

4.3 Rock Fracturing Evaluation and Analysis

No relevant fracturing evaluation criteria have been developed for carbonate reservoirs, so the evaluation method of shale was adopted in this paper for evaluation. Rickman, in summarizing the Barnett shale, proposed a method to evaluate the brittleness of rocks by using Young modulus and Poisson ratio to calculate the brittleness index (Rickman R et al.2008). He also pointed out that when the brittleness index of the rock is greater than 0.4, the rock is brittle, and when the brittleness index is greater than 0.6, the rock has a very strong brittleness. The related calculation formula is shown below:

$$B_I = \frac{E_{BRIT} + \mu_{BRIT}}{2} \quad (4)$$

$$E_{BRIT} = (E_S = E_{min}) / (E_{max} - E_{min}) \quad (5)$$

$$\mu_{BRIT} = (\mu_S - \mu_{max}) / (\mu_{min} - \mu_{max}) \quad (6)$$

where in:

- B_I - Rock brittleness index;
- E_{max} - Maximum Young modulus, MPa;
- E_{min} - Minimum Young modulus, MPa;
- μ_{max} - Maximum Poisson ratio;
- μ_{min} - Minimum Poisson ratio;
- E_{BRIT} - The component of normalized Young modulus to brittleness, dimensionless;
- μ_{BRIT} - The component of normalized Poisson ratio to brittleness, dimensionless.

Using the measured Young modulus and Poisson ratio of the rock, the brittleness index of the rock samples in the deep tight carbonate reservoir was calculated by the formula. The brittleness index of the rock sample was between 0.2 and 0.8, and most of the rock samples were characterized by strong brittleness, as shown in Figure 4.

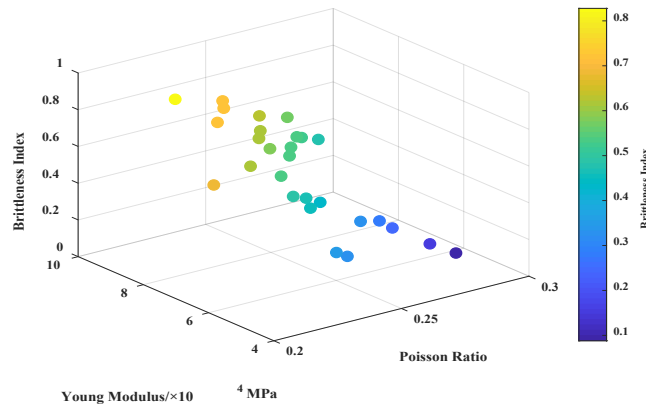


Figure 4 Rock Brittleness Index Map of the Deep Tight Carbonate Reservoir

According to the analysis result of Rickman brittleness evaluation method, the rock of the deep tight carbonate reservoir is mainly brittle rock, showing certain brittle characteristics, and some rocks are strongly brittle and are sensitive to fracturing.

However, it is inaccurate to evaluate the reservoir fracturing using only the brittleness index, which does not consider the influence of fracture toughness. The fracture toughness, as an inherent property of the material, is a quantity that describes the ability of the material to resist macro crack unstable propagation. In this paper, the empirical relationship between fracture toughness and Young modulus (Jin, X. et al 2015) was used to evaluate the fracture toughness values of rocks:

$$K_{IC} = 0.313 + 0.027E \quad (7)$$

Sun Jianmeng et al. believed that only reservoirs with high brittleness index and low fracture toughness have good fracturing behavior (Sun, J. et al. 2015). To overcome this deficiency, the evaluation was made based on a mathematical model of the fracturing index:

$$F_1 = B_{IBRIT} \cdot K_{ICBRIT} \quad (8)$$

$$B_{IBRIT} = \frac{B_I \cdot K_{Imin}}{B_{Imax} - B_{Imin}} \quad (9)$$

$$K_{IC} = \frac{K_{ICmax} - K_{IC}}{K_{ICmax} - K_{ICmin}} \quad (10)$$

where in:

- F_1 - Fracturing index;
- B_{Imax} - Maximum fracturing index, %;
- B_{Imin} - Minimum fracturing index, %;
- K_{ICmax} - Maximum fracture toughness, $\text{MPa} \cdot \text{m}^{1/2}$;
- K_{ICmin} - Minimum fracture toughness, $\text{MPa} \cdot \text{m}^{1/2}$;
- B_{IBRIT} - The component of the normalized brittleness index to the fracturing index, dimensionless;
- K_{ICBRIT} - The component of the normalized fracture toughness to the fracturing index, dimensionless.

The fracturing index was calculated according to the formula (10), and the three-dimensional map was drawn, as shown in Figure 5. The analysis shows that the fracturing index of some rocks is greater than 0.1, with good fracturing behavior; several cores have a fracturing index of less than 0.1, with poor fracturing behavior. Generally, the reservoir has a good fracturing behavior.

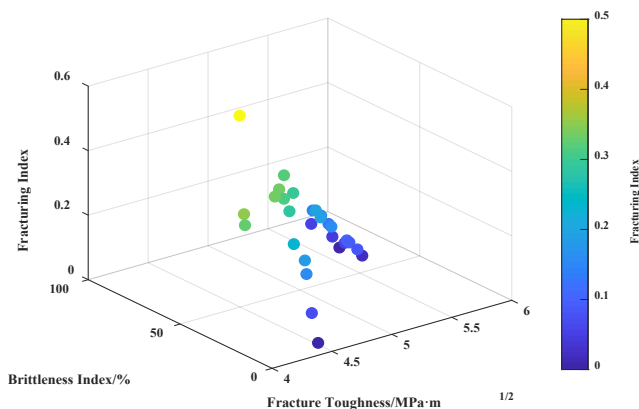


Figure 5 Rock Fracturing Index Map of the Deep Tight Carbonate Reservoir

From the above, the deep tight carbonate reservoir in the Eastern Tarim Basin shows general brittleness characteristics, the rock has a medium fracture toughness and a good fracturing index on the whole, indicating that the reservoir has a good fracturing behavior.

5. CONCLUSIONS

- (1) The Young modulus, Poisson ratio and compressive strength of the rock in the tight carbonate reservoir buried below 6000m in the Eastern Tarim Basin were measured by the laboratory rock mechanics parameter test, which provides data support for the subsequent development of the Eastern Tarim Basin.
- (2) The compressive strength and Young modulus of rock samples show a significant positive correlation, and the linear, quadratic polynomial and power fitting formulas were made for the compressive strength and Young modulus. The comparison shows the optimality of the quadratic fitting formula, with the reliability tested, which provides a guiding significance for the prediction of the compressive strength.
- (3) The relationship between Young modulus, Poisson ratio and compressive strength of rock samples and rock sample density was obtained, showing a relatively discrete relation between Poisson ratio and density, and a significant positive correlation between Young modulus and compressive strength with rock density, which provides a basis for the study of the relationship between the mechanics parameters and physical properties of the deep tight carbonate rock.
- (4) The brittleness index of the rock sample was calculated by Rickman brittleness evaluation method, and the brittleness index prediction map was drawn. The fracture toughness of the rock sample was estimated according to the empirical formula, the fracturing index was further obtained, and the fracturing index map was drawn. It is believed that the deep tight carbonate reservoir in the Eastern Tarim Basin has a good fracturing behavior.

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