ISSN: 2414-1895 DOI: 10.6919/ICJE.202309_9(9).0013

Prediction of Fracture Toughness in Tight Sandstone based on Tensile Strength

Yu Fu, Fuwei Li

Petroleum Engineering School, Southwest Petroleum University, Chengdu, China

Abstract

The fracture toughness of rock plays a crucial role in quantitatively evaluating the fracability of shale reservoirs. In this study, the I-mode (opening mode) and II-mode (shearing mode) fracture toughness of ten samples of tight sandstone from the Sulige area were determined using the Straight Notched Brazilian Disk (SNBD) test. Based on the experimental results and the tensile strength data, a regression analysis was conducted to establish a direct relationship between fracture toughness and tensile strength in tight sandstone. In comparison to previous fracture toughness prediction models based on tensile strength, the proposed model establishes a direct correlation between fracture toughness and tensile strength. The predictive model demonstrates that fracture toughness in tight sandstone is directly proportional to the rock's tensile strength. The results indicate a good correlation between calculated and measured fracture toughness, providing an important theoretical basis for identifying the optimal design parameters in engineering processes.

Keywords

Tight Sandstone; Fracture Toughness; Tensile Strength; Regression Fitting.

1. Introduction

When rocks are subjected to stress beyond a certain threshold, they tend to fracture. Rock strength is an inherent property, and fracture toughness is a critical parameter that effectively characterizes a rock's resistance to fracture. A higher fracture toughness indicates a greater ability to impede crack propagation, making it an important factor in evaluating the ease of hydraulic fracturing in reservoirs. It reflects the ability of fractures to propagate forward after their formation during the fracturing process. Accurate prediction of fracture toughness in tight sandstone is of significant academic and practical importance. Through in-depth research and accurate prediction of fracture toughness, optimization of fracturing designs can be achieved, enhancing reservoir permeability and productivity. Additionally, it enables the prediction of crack propagation behavior, guiding oil and gas migration simulations and reservoir stimulation. Furthermore, it facilitates the assessment of reservoir stability, prevention of potential geological hazards, improvement of engineering structure safety, mitigation of rock fracture and collapse risks, and advancement of sustainable energy development by effectively managing reservoir exploitation processes. These research achievements have vital academic value and practical significance in advancing tight sandstone hydraulic fracturing technology, enhancing energy production, and ensuring engineering safety. However, fracture toughness testing is cumbersome and restricted by core sampling conditions, making it challenging to conduct extensive measurements using conventional testing methods, which are highly stochastic. Currently, fracture toughness calculations primarily rely on empirical formulas established by researchers such as Chen Zhixi. However, their applicability to deep tight sandstone requires further investigation.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202309_9(9).0013

From the perspective of rock fracture mechanics, rocks fracture under external stress, and thus, the ability to resist tensile failure in rocks can be equated to their fracture strength. In fact, the tensile strength of reservoir rocks directly determines their fracture toughness. This paper summarizes and analyzes research findings on the relationship between tensile strength and fracture toughness. As shown in the table, a positive correlation between tensile strength and fracture toughness can be observed across various rock types, with tensile strength being the sole influencing factor in the majority of expressions.

Table 1. A positive correlation between tensile strength and fracture toughness can be observed across various rock types

Formula	Rock Type	Reference
K_{IC}=0.0945σ_t+0.0245	Tight Sandstone	Zhao, N. et al. (2022)
$K_{IC}=0.0043\sigma_t^3+0.123\sigma_t^2+0.417\sigma_t-0.176$	Tight Sandstone	Song, M. et al. (2019)
$K_{IC}=0.107\sigma_t+0.271$	Fractured Sandstone	Zhang, H. et al. (2019)
$K_{IC}=0.1453\sigma_t$	Soft Rock	Zhang (2002)
$K_{IC}=0.2176P_c+0.0059\sigma_t^3+0.0923\sigma_t^2+0.517\sigma_t-0.3322$	Sandstone	Jin, Y. et al. (2001)

On the basis of being able to continuously and quantitatively characterize the tensile strength in the research area, a quantitative characterization model for fracture toughness of reservoirs in the study area can be constructed by combining a small amount of fracture toughness test data. By measuring the tensile strength of rocks and considering other factors that may affect fracture toughness, such as porosity, particle size distribution, and mineral composition, as well as microstructural features, a reliable predictive model can be established to estimate the fracture toughness of rocks.

2. Fracture Toughness Experimental Testing

According to the recommended standard of Part 8 by the American Rock Mechanics Association, the SCB (Semi-circular Bending Test) fracture toughness test was conducted on Type I fracture toughness of tight sandstone samples Su53-58-24H and Su53-58-46H using the GCTS RTR-1500 high-temperature and high-pressure rock comprehensive testing system.

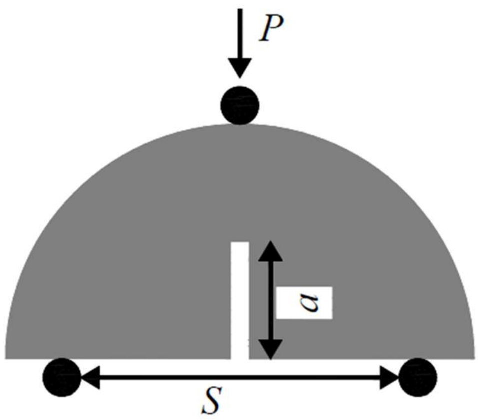

Figure 1. Schematic diagram of the SCB specimen

ISSN: 2414-1895 DOI: 10.6919/ICJE.202309_9(9).0013

The full-diameter downhole cores were processed into semi-circular discs, and artificial slots were machined at the center of the semi-circular discs using a wire cutter. The schematic diagram of the SCB specimen is shown in the figure, where P represents the applied load (N), S represents the distance between the two support ends (mm), and a represents the length of the artificial slot (mm). According to the standards recommended by ISRM (International Society for Rock Mechanics), the dimensions of the notch and the distance between support ends were determined as S/(2R)=0.8 and a/R=0.4, respectively. Thus, S was set to 80 mm and a was set to 20 mm. The width of the artificial slot was approximately 1 mm.

The fracture toughness of the SCB specimen is calculated using the following equation:

$$K_{IC} = \frac{P_{\max}\sqrt{\pi a}}{2RB}Y' \tag{1}$$

$$Y' = -1.297 + 9.516[S/2R] - (0.47 + 16.457[S/2R])\beta + (1.071 + 34.401[S/2R])\beta^2 \tag{2}$$

$$\beta = a/R \tag{3}$$

In the equation:

$P_{\max}$ - represents the load (N) at the sample fracture;

Y' - represents the dimensionless stress intensity factor (without units);

B - represents the sample thickness (mm);

R - represents the sample radius (mm).

A total of 10 test groups were conducted, with 4 groups tested in Well A and 6 groups tested in Well B, using a displacement loading mode of 0.3 mm/min. The test results are shown in the table.

Table 2. Experimental results of fracture toughness testing

Well No	Depth (m)	Thickness (mm)	Diameter (mm)	Notch (mm)	Peak Load (N)	Fracture Toughness (MPa·m$^{1/2}$)
A	3341.12	21.0	97.0	22.5	8083	3.69
		22.5	96.5	20.0	7753	2.82
	3341.49	31.5	95.0	20.0	8598	2.35
	3345.63	24.1	98.5	23.0	8897	3.49
B	3270.4	28.0	97.0	20.0	12063	3.47
		30.8	97.5	20.0	13434	3.45
	3273.34	29.0	97.5	21.0	9041	2.64
		32.2	97.5	26.5	8217	3.22
	3280.09	21.7	98.0	21.0	9196	3.53
	3281.16	38.6	98.0	20.0	12579	2.54

The results show that the fracture toughness of the sampled intervals ranges from 2.35 to 3.69 MPa·m1/2, with an average of 3.12 MPa·m1/2. The fracture toughness of the sampled intervals has small variations, indicating a high resistance to rock fracture.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202309_9(9).0013

3. Fracture Toughness Prediction based on Tensile Strength

When rocks are subjected to stress beyond a certain threshold, they tend to fracture. Rock strength is an inherent property, and fracture toughness is a critical parameter that effectively characterizes the rock's resistance to fracture. A higher fracture toughness value indicates a greater ability to inhibit crack propagation and measures the material's resistance to unstable crack extension. However, fracture toughness testing is cumbersome and limited by coring conditions, making it challenging to determine fracture toughness through conventional testing methods. From the perspective of fracture mechanisms, rocks fracture under external stress, and the ability of rocks to resist tensile failure can be equated to their fracture strength. The tensile strength of reservoir rocks directly determines their fracture toughness. This study summarizes and statistically analyzes the relationship between tensile strength and fracture toughness, as shown in the table. Tensile strength and fracture toughness exhibit a positive correlation across all rock types, with tensile strength being the primary influencing factor in the majority of expressions. Building on the continuous and quantitative characterization of tensile strength in the study area, combined with a limited number of fracture toughness tests, a quantitative representation model for reservoir fracture toughness can be established.

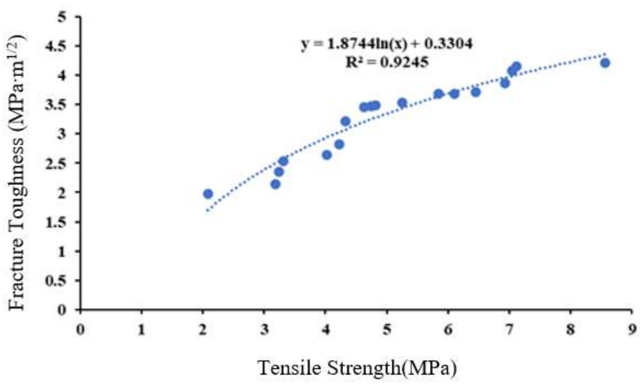

Figure 2. Fitting relationship between tensile strength and fracture toughness

$$\begin{cases} K_{IC} = 1.8744\ln(\sigma_t) + 0.3304 \\ R^2 = 0.9245 \end{cases} \tag{4}$$

4. Conclusion and Outlook

(1) The research findings on the relationship between tensile strength and fracture toughness have been systematically summarized and analyzed. Tensile strength and fracture toughness exhibit a positive correlation across all rock types, with tensile strength being the primary influencing factor in the majority of expressions. Tensile strength and fracture toughness are important parameters for evaluating the potential for significant reservoir volume enhancement.

(2) By combining tensile strength data, the fracture toughness of dense sandstone was regressed, establishing a direct link between fracture toughness and tensile strength. The predicted model shows that the fracture toughness of dense sandstone is directly proportional to the rock's tensile strength, with the best fit achieved through logarithmic regression. The calculated fracture toughness demonstrates good correlation with the measured fracture toughness. The developed model can be used for continuous prediction of fracture toughness in deep sandstone formations, addressing the challenge of the lack of continuous fracture toughness data during hydraulic fracturing operations in tight sandstone reservoirs.

References

[1] Jin, Y., Chen, M., Wang, H., et al. (2008). Method for Predicting Fracture Toughness of Rock Type II Using Logging Data. Journal of Rock Mechanics and Engineering, DOI: JournalArticle/5af290d0c095d718d8f728d1.

[2] Zhang, H., Yin, G., Wang, Z., et al. (2019). Evaluation of Fracturability in Deep Fractured Sandstone Gas Reservoirs in the Kuqa Depression. Xinjiang Petroleum Geology, 40(1), 8. DOI: 10.7657/XJPG20190117.

[3] Song, M., Liu, Z., Zhang, X., et al. (2019). Evaluation of Fracturability of Tight Sandstone Reservoirs Based on an Improved Analytic Hierarchy Process: A Case Study of Jurassic Reservoirs in Well Z109, Junggar Basin. Journal of Geomechanics, 25(4). DOI: 10.12090/j.issn.1006-6616.2019.25.04.049.

[4] Chen, Z., Chen, M., Jin, Y. (1997). Experimental Study on the Correlation between Rock Fracture Toughness and Acoustic Velocity. Petroleum Drilling Techniques, 19(5), 6. DOI: CNKI:SUN:SYZC.0.1997-05-016.

[5] Zhang, B., Tian, G., Shen, W., et al. (2023). Study on Rock Fracture Toughness under Different Stress Conditions. In Proceedings of the 6th National Symposium on Rock Mechanics and Engineering. DOI: ConferenceArticle/5aa6a1aec095d72220f0665a.