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Comparison of Rock Toughness Measurement Methods for Hydraulic Fracturing: A Research Note

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INFORMATION

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ABSTRACT

One important rock property is toughness, which is the ability of a rock to resist further deformation or fracturing. Three modes used to quantify this property are: the opening mode (mode I), the shearing mode (mode II), and the tearing mode (mode III). In order to successfully fracture a rock, an estimation of rock toughness must be calculated for the formation. Three tests developed to quench that need are the scratch test, straight-notched Brazilian disc specimen test, and the semicircular bend test. The objective of this paper is to present the procedure, governing equation, and results for each test. Moreover, analysis of the results obtained from each test produced important correlations between rock toughness and shale properties. A comprehensive comparison is conducted on the tests presenting three primary differences, which are convenience, variables, and accuracy. In all three tests, the method used to induce fractures was a common limitation that restricted their applicability. This indicates the need to conduct more study and research in the field of fracture toughness measurement.

1. Introduction

The role rock toughness plays in the hydraulic fracturing industry is substantial, thus three tests were developed to measure it. The first test conducted is the scratch test, which requires extensive sample preparation from surface smoothing and polishing to three different analyses that attempt to image the microstructure of the shale. The test was implanted on three different shale formations, thus producing several notable results; the notch width increased as the scratching path increased, fracture toughness decreased with increasing depth, and residual grooves are made of both soft and rigid constituents (Zhao et al., 2020).

The second test is the straight-notched Brazilian disk specimen (SNBD) test. The samples were split into two groups of seven samples each. One group was used to measure the opening mode, while the other was used to measure the shearing mode. The results of the SNBD test produced a successful inversion model between the fracture toughness and well-log data presenting three different correlations; fracture toughness is directly pro-portional to rock density and transit time, but it is inversely proportional to shale content (Kramarov et al., 2020).

The last test conducted is the semicircular bend test, which was applied on 21 samples containing calcite-cemented fractures. Its procedure is similar to the SNBD but differs in the notch placement and the angle chosen. The results of this test could be used to predict the path a fracture will travel depending on the initial angle. The test also proved that fracture toughness is lowered as vein thickness increases and that fracturing only occurs within the calcite veins. Three primary differences observed between the tests are convenience, variables, and accuracy. Given that the findings align with the anisotropic characteristics of shale and laminated rocks as stated in the research conducted (Ifrene et al., 2022; Irofti et al., 2023), the scratch test has been determined to be the most precise but also the least convenient method. It is worth noting that the manner in which fractures are induced in all three tests imposes a limitation that hampers their broader application. Consequently, this underscores the necessity for further exploration and investigation in this particular domain. To overcome these limitations, future research efforts should focus on developing alternative techniques that provide a more comprehensive understanding of the behavior of shale and laminated rocks under different conditions. Additionally, exploring innovative methodologies may enhance the accuracy and convenience of fracture testing while widening its scope of applicability.

2. Importance of Hydraulic Fracturing

Energy moves the world. This statement might at first sound like an exaggeration, but under closer inspection, you will notice that it is absolutely true. Thus, to ensure an enduring and continuous energy supply, researchers have been studying methods to extract gas from shale formations through unconventional methods. Even with all the difficulties they present, shale formations swiftly attracted the attention of the oil industry because of their impacts on the economy, and their unlimited potential. Furthermore, the ultralow porosity and permeability of shale gas reservoirs pose significant obstacles to efficient gas extraction. The limited flow pathways within the rock matrix restrict the movement of gas (Aihar et al., 2023), and are composed of multi-scale constituents (Akono and Ulm, 2012).

Two methods developed to deal with this dilemma are horizontal drilling and hydraulic fracturing. Horizontal drilling presents a way to maximize the area coverage of the trapped hydrocarbon which is not possible with vertical drilling. On the other hand, hydraulic fracturing propagates the preexisting natural fractures within shale formations, effectively creating a network of interconnected pathways for fluid flow (Irofti et al., 2022; Ifrene et al., 2023), through the injection of highly pressurized fracturing fluid. That enhances the permeability of the reservoir by allowing access to trapped gas.

To successfully maintain an open crack and produce the gas, the fracturing fluid must be able to exceed the fracture toughness of the reservoir rock. This requires careful selection of fracturing fluids with appropriate viscosity, proppants to prop open the fractures, and additives to control fluid behavior and prevent premature closure of fractures. Striking the right balance between fluid properties and the geomechanical characteristics of the reservoir rock is critical for achieving optimal fracture propagation and sustained gas production (Imani et al., 2022). Thus, it is highly imperative to measure the fracture toughness of a shale formation.

Three methods used to estimate the value of fracture toughness of rocks are the scratch test, the straight-notched Brazilian disk specimen (SNBD) test, and the semicircular bend test. A comparison of the procedures, equations, and results of each test showed three primary differences between them, and one common limitation.

3. Measuring Rock Toughness

Advancements in the field of fracture mechanics highlighted the importance of fracture characterization through rock properties (Ifrene et al., 2023; Irofti et al., 2023; Abes et al., 2021) like fracture toughness. Fracture toughness characterizes a material's capacity to withstand additional fracturing, encompassing three distinct modes: mode I, which involves opening, and mode II, which involves shearing (Abid et al., 2021), and the tearing mode (mode III). Fractures resulting from hydraulic fracturing are categorized as mode I or mode II, or a combination of the two modes (Zijian et al., 2016; Mazhnik and Oganov, 2019).

To accurately assess the fracture toughness of reservoirs, numerous laboratory experiments have been devised. These tests aim to closely mimic the in-situ fracture properties, yielding three commonly employed methods for measuring fracture toughness. By utilizing these tests, engineers and researchers can gain valuable insights into fracture behavior and optimize hydraulic fracturing techniques for enhanced resource extraction.

3.1. The Scratch Test

The scratch test is based on a simple fact; a harder material will scratch a softer one. After scratching, relative hardness can be determined using the Mohs scale. Akono and Kabir (2015) used an adjusted version of this method to carefully study three shale systems, including Toarcian in Paris Basin, France, and Lower and Upper Woodford shale in Oklahoma, US (Akono and Kabir, 2015). What makes Akono and Kabir’s method different from a regular scratch test is the sample preparation all rocks had to go through before the implementation of the test.

3.1.1. Sample Preparation

The sample preparation conducted before the scratch test is essentially made up of three steps. First, the samples have to be carefully polished to eliminate all surface irregularities. Then, the samples have to go through three different analyses to image the microstructure of the shale; the three analyses are an X-ray diffraction, an optical microscopy, and a scanning electron microscopy. The next step is measuring the elastic properties of the shale sections, which are Young’s modulus and Poisson’s ratio, through the application of mini-compression tests and ultrasonic pulse velocity tests [14].. Finally, after all this sample preparation is done, the scratch test is implemented.

3.1.2. Test Procedure

The scratch test is done using a diamond stylus with a known geometry. The diamond stylus is used to apply a linearly increasing vertical load with a constant speed of 6 mm/min covering a scratch path of 3-mm. The resulting penetrated depth is then measured, and the test is repeated four times. After that, an optical microscopy technique is applied to image the residual groove and penetrated depth. Throughout the test, micro-cracking is monitored through acoustic emissions (Akono and Kabir, 2015). The results they got agreed with the known anisotropic nature of shale samples; scratch propagation is parallel to shale bedding plane. The equation used to calculate the fracture toughness for the scratch test is:

$$K_s = F_T / sqrt(2PA(d)) \quad (1)$$

where K_s is fracture toughness, F_T is horizontal force, P is the perimeter of the fracture surface, A is the contact area, and d is the penetrating depth.

3.1.3. Test Results

The scratch test estimated rock toughness on a finer scale through the application of nano-indentation, and its heavy reliance on microstructural analysis, such as optical microscopy and scanning electron microscopy. Its results surprisingly revealed a granular microstructure, including organic matter pockets and micropores, in the shale samples. Moreover, the record of the micro-crack produced a curve of horizontal force that peaks at nano-cracks followed by a sudden drop off (Akono and Kabir, 2015).

Three properties of the sample were also observed from the results of the test. First, the width of the notch increased as the scratching path increased. This could be explained by how increasing linear force develops more micro-cracks in the horizontal direction. Second, the fracture toughness decreased with increasing depth. This property is explained by how all shale samples transition from ductile to brittle as depth increases. Last, the residual grooves are made of both soft and rigid constituents. Mixed stress directions cause crack bridging and crack branching, thus pulling out the softer section of the groove.

3.2. The Stright-notched Brazilian Disk Specimen Test (SNBD)

The concept of applying vertical load to test fracture toughness practiced in the scratch test was also used to conduct another test, which is the straight-notched Brazilian disk specimen Test (SNBD). Zijian et al. (2016) applied the SNBD test on 14 shale samples from a gas reservoir in China with average thickness of 2.5 cm (Zijian et al., 2016). The samples were split into two groups, one used to measure the opening mode (mode I), and the other used to measure the shearing mode (mode II).

3.2.1. Procedure

The test starts out by initiating a central 1.4 cm long crack on all samples. Then a vertical load is applied at a rate of 0.1 mm/min continuously until the rock is fractured. The test of mode I for fracture toughness exerted the vertical load at an angle of 0° with respect to the central notch, while the test for mode II exerted it at an angle of 30° (Zijian et al., 2016). Like during the scratch test, micro-cracks are monitored throughout the test using acoustic emission. Results were then used to create a predictive model of the first two modes of fracture toughness. The equation used to calculate the fracture toughness for the SNBD test mode I and II is:

$$K_I = [P\ sqrt(a) / RB\ sqrt(\pi)]\ N_I \quad (2)$$

$$K_{II} = [P\ sqrt(a) / RB\ sqrt(\pi)]\ N_{II} \quad (3)$$

where K_I, K_{II} are mode I and mode II fracture toughness, respectively. P is radial load, a is the semi-length of the notch, B is the thickness of the radius, and R is the radius of the disc. N_I and N_{II} are constant mode intensity factors.

3.2.2. Test Results

The results of the SNBD test were especially interesting because of how dispersed the values for mode II were between the samples. This implicitly indicates that the values of the shearing mode of fracture toughness depend on sample and location. In comparison, the values calculated for mode I were more uniform indicating the difficulty of inducing tensile fractures in most shale samples (Zijian et al., 2016). Simply put, the difficulty of inducing shearing fractures is variable, while the difficulty of inducing tensile fractures is especially high for shale formations. The results of the SNBD test produced a successful inversion model between the fracture toughness and well-log data with three graphs each presenting a different correlation; fracture toughness is directly proportional to rock density and transit time, but it is inversely proportional to shale content.

3.3. The Semi-Circular Bend Test (SCB)

"Preexisting discontinuities in shale, including natural fractures and bedding, act as planes of weakness that divert fracture propagation" (Lee et al., 2014). To test the importance that planes of weakness have on the propagation of a fracture, the semicircular bend test was applied on 21 samples from Marcellus shale formation. All the samples contained calcite-cemented fractures used to analyze the interplay between the preexisting natural fractures and the induced hydraulic fractures.

3.3.1. Procedure

The procedure of the semicircular bend test is similar to that of the SNBD test, however, unlike the central notch and the predefined angles used in the SNBD test, the semicircular bend test places the notch at the semicircular base of the sample, and the angle used is usually ranging from 25° to 90° relative to the preexisting fracture. Then, the samples undergo continues loading until they crack. Unlike with the previous two tests, the samples are supported by two rollers throughout the loading. Finally, broken samples undergo a petrographic microstructural analysis. The equation used to calculate the fracture toughness for the semicircular bend test is:

$$K_{IC} = [P_{max}\ sqrt(\pi a) / 2rt)]Y_I \quad (4)$$

where K_{IC} is the fracture toughness, P_{max} is the maximum load, a is notch length, r is sample radius, t is thickness, and Y_I is a dimensionless coefficient calculated using the following equation:

$$Y_I = 5.6 - 22.2\ (a/r) + 166.9\ (a/r)^2 - 576.2\ (a/r)^3 + 928.8\ (a/r)^4 - 505.9\ (a/r)^5 \quad (5)$$

3.3.2. Test Results

The semicircular bend test conducted on the arrester and divider configuration produced results that highly stressed the importance of bedding angle on the measured sample toughness. The bedding angle of around 30° in the arrester configuration lowered the fracture toughness to one below that of the divider configuration (Lee et al., 2014). This behavior could be explained through physics. In the divider configuration, once vertical load reaches its maximum, it is reduced to zero. On the other hand, residual load is observed at maximum vertical load for the arrester configuration. As the bedding angle is increased to 30°, the residual load decreases to zero. Another result of the test concerns the preexisting calcite veins in the sample rocks. The induced fractures propagate parallel to the notch and extend from its tip until they cross the preexisting fractures orthogonally. At near orthogonal angles, the induced fractures also propagate from the notch, however they travel for a shorter distance, then divert their path to the top of the sample. Fractures at angles close to 40° and 50° are diverted completely through the preexisting fractures and move toward the top of the rock sample where pressure is significantly lower (Lee et al., 2014). The behavior of the fracture propagation can be explained through elastic properties and Young's modulus of the sample. Another result of this test showed how induced fractures usually propagate through the thickest veins. This implicitly indicates that fracture toughness of a vein is lowered as its thickness increases.

The last observation and perhaps the most surprising one was how fracturing only occur within the calcite veins in the shale sample, not along the boundary separating the calcite and the rock sample. Fracture propagation for different angles is shown in the following figure.

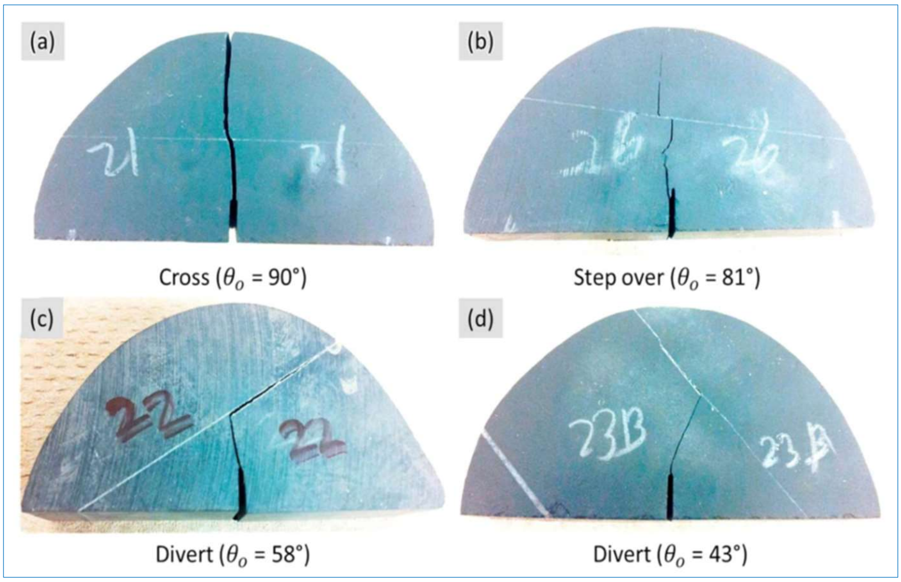

Fig. 1. This is a figure. Schemes follow the same formatting (Lee et al., 2014)

4. Comparison of Test Methods

Although all three tests produced numerical values for rock toughness, three differences were observed when the procedures, equations, and results for each test were compared. The three differences are convenience, variables, and accuracy. Some of the tests require sample preparation and longer procedures, thus becoming less convenient. Since each test uses a different equation, it is natural to have a different set of variables for each. Lastly, some tests provided more accurate results.

4.1. Convenience

The first difference between those three tests arises from convenience. Although the scratch test produced accurate results for toughness, it required a lot of sample preparation before the test was conducted. Samples had to go through grinding, polishing, and coating to ensure the creation of a smooth surface with no irregularities. Inaccurate values for fracture toughness were observed whenever an irregularity was present no matter how small. In comparison, the SNBD and semicircular bend tests do not need such an extensive preparation and are more convenient to use when the number of samples to be tested is high.

4.2. Variables

The second difference is present in the equations used for each test. Both the SNBD and semicircular bend tests could account for mode I and mode II of fracture toughness without any geometrical restrictions. The scratch test, in comparison, is the complete opposite. Its equation depends on the geometry of the diamond stylus used, and it does not account for mode I and mode II in its fracture toughness calculations. However, it is important to note that even the SNBD test can fail to produce mode I and mode II fractures across the sample under specific conditions, including when the notch is too small compared to the central hole in the sample.

4.3. Accuracy

The third difference concerns uncertainty. The scratch test, which worked on a microscopic scale, produced more accurate results than the other two macroscopic tests, the SNBD and semicircular tests. This result is expected because it agrees with the physical properties of shale, including multi-scale grains and nanometer voids. Since shale behaves differently on a finer scale, uncertainty exists every time a macroscopic test is used to estimate fracture toughness.

4.4. Limitation

Although the three tests were successful in producing numerical values for fracture toughness through unique approaches, they all had one common limitation; they used a different fracturing mechanism than the one used for hydraulic fracturing in the subsurface. All three tests relied heavily on the application of vertical load under different conditions from varying angles to roller supports, however none of them used a highly pressurized fluid to induce a fracture. That resulted in the experimental tests producing an unstable fracture growth, unlike the stable fracture propagation hydraulic fracturing induces. This drawback could greatly limit the applicability of those three tests. Nevertheless, the tests are still useful in calculating fracture toughness, therefore providing a rough estimation of the required pressure for the fracturing fluid.

5. Conclusions

In conclusion, the importance of hydraulic fracturing in the oil industry has been greatly increasing throughout the years ever since the discovery of the exponential amounts of gas encompassed in the unconventional shale reservoirs. In order to successfully fracture a rock and determine the required pressure for the fracturing fluid (Alagoz et al., 2020; Alagoz and Sharma, 2021; Alagoz et al., 2022; Alagoz and Yaradilmis, 2023), an estimation of the toughness of a shale sample from the formation must be made.

Three tests were developed to estimate fracturing toughness, which are the scratch test, the straight-notched Brazilian disk specimen (SNBD) test, and the semicircular bend test. Each test had its unique procedure, but they all shared one common feature, the application of a vertical load on the sample. This same feature was the limitation that restricted the applicability of the three tests, because, unlike with a regular hydraulically fractured well, no pressurized fluid was used. The results of each test were also studied to produce correlations between rock toughness and shale properties, including bedding angle, elasticity, and preexisting calcite cemented veins.

A comprehensive comparison of the tests presented three primary differences between them and proved that experimentally none of the three tests is always superior. The three differences observed were convenience, variables, and accuracy. Nevertheless, each test had its own field of application that depends on the number of samples, the geometry of the stylus, and the need to calculate mode I and mode II of fracturing toughness. Incorporating SEM and optical microscopy imaging into the tests produced more accurate results and enhanced the fine-scale examination of the shale sample. It also shed light on the complex microstructure of grains and pores present in shale. Overall, all three tests stressed the importance of understanding how hydraulic fractures interact in the subsurface, but their limitations proved the need for more research in the field of fracture toughness measurement.

References

Abes, A., Irofti, D., Ifrene, G. E., Rasouli, V., Djemai, S., 2021. The Impact of Geometric Attributes of Fractures on Flu-id Flow Characteristics of Reservoir: A Case Study in Alrar Field, Algeria. In 55th US Rock Mechanics/Geomechanics Symposium. OnePetro, Paper Number: ARMA-2021-1803.

Abid, S.R., Murali, G., Amran, M., Vatin, N., Fediuk, R., Karelina, M., 2021. Evaluation of mode II fracture toughness of hybrid fibrous geopolymer composites. Materials 14 (2), 349.

Aihar, A., Bouabdallah, N., Ifrene, G., Irofti, D., 2023. Comparing Fishbone Drilling and Hydraulic Fracturing in Ultra-Low Permeability Geothermal Reservoirs. AAPG Rocky Mountain Section Meeting, Bismarck, North Dakota, June 4-6, 2023. https://doi.org/10.1306/80737Aihar2023.

Akono, A., Kabir, P., 2015. Microscopic fracture characterization of gas shale via scratch testing. Mechanics Research Communications, 66.

Akono, A., Ulm, F., 2012. Fracture scaling relations for scratch tests of axisymmetric shape, Journal of Mechanics and Physics of Solids 60 (3), 379-390.

Alagoz, E., Sharma, M.M., 2021. Investigating Shale-Fluid Interactions and Its Effect on Proppant Embedment Using NMR techniques. Paper ARMA 2021-1129, 55th US Rock Mechanics/Geomechanics Symposium held in Houston, Texas, USA, 20-23 June. https://onepetro.org/ARMAUSRMS/proceedings-abstract/ARMA21/All-ARMA21/ARMA-2021-1129/467923.

Alagoz, E., Wang, H., Russell, R.T., Sharma, M.M., 2020. New Experimental Methods to Study Proppant Embedment in Shales. Paper ARMA 2020-1933, 54th US Rock Mechanics/Geomechanics Symposium held in Golden, Colorado, USA, 28 June-1 July. https://onepetro.org/ARMAUSRMS/proceedings-abstract/ARMA20/All-ARMA20/ARMA-2020-1933/447713.

Alagoz, E., Wang, H., Russell, R.T., Sharma, M.M., 2022. New Experimental Methods to Study Proppant Embedment in Shales. Rock Mechanics and Rock Engineering 55, 2571-2580. https://doi.org/10.1007/s00603-021-02646-1.

Alagoz, E., Yaradilmis, Y., 2023. Evaluation of Resin Coated Proppants: A New Custom Method. International Journal of Earth Sciences Knowledge and Applications 5 (2), 237-243. http://www.ijeska.com/index.php/ijeska/article/view/278.

Ifrene, G.E., Irofti, D., Khetib, Y., Rasouli, V., 2022. Shear Waves Anisotropy and Image Logs Integration for Im-proved Fracture Characterization. In 56th US Rock Mechanics/Geomechanics Symposium. https://doi.org/10.56952/ARMA-2022-0319.

Ifrene, G., Irofti, D., Ni, R., Egenhoff, S., Pothana, P., 2023. New Insights in Fracture Porosity Estimation using Machine Learning and Advanced Logging Tools. Fuels 4 (3), 333-353. https://doi.org/10.3390/fuels4030021.

Imani, D. M., Aliha, M. R. M., Linul, E., Marsavina, L., 2022. A suitable mixed mode I/II test specimen for fracture tough-ness study of polyurethane foam with different cell densities. Theoretical and Applied Fracture Mechanics 117, 103171.

Irofti, D., Ifrene, G.E., Pu, H., Djemai, S., 2022. A Multiscale Approach to Investigate Hydraulic Attributes of Natural Fracture Networks in Two Tight Sandstone Fields, Ahnet, Algeria. In 56th US Rock Mechanics/Geomechanics Symposium. https://doi.org/10.56952/ARMA-2022-0450.

Irofti, D., Ifrene, G., Cheddad, F.A., Djemai, S., 2023. Integrating Borehole Imaging and Full Waveform Dipole Sonic Data to Estimate Fracture Porosity in Tight Formations: A Workflow for Accurate Characterization of Natural Fractures. https://doi.org/10.1306/42582Irofti2023.

Kramarov, V., Parrikar, P.N., Mokhtari, M., 2020. Evaluation of fracture toughness of sandstone and shale using digital image correlation. Rock Mechanics and Rock Engineering 53, 4231-4250.

Lee, H., Olson, J., Holder, J., Gale, J., Myers, R., 2014. The interaction of propagating opening mode fractures with preexisting discontinuities in shale [Image]. Journal of Geophysics Solid Earth 120 (1), 169-181.

Mazhnik, E., Oganov, A.R., 2019. A model of hardness and fracture toughness of solids. Journal of Applied Physics 126 (12), 125109.

Zhao, Y., Zhang, L., Liao, J., Wang, W., Liu, Q., Tang, L., 2020. Experimental study of fracture toughness and subcritical crack growth of three rocks under different environments. International Journal of Geomechanics 20 (8), 04020128.

Zijian, C., Ulm, Y., Junliang, Y., Yanan, Z., Jingen, D., 2016. Determination of fracture toughness of rocks of a shale gas reservoir using straight-notched Brazilian Disc (SNBD) specimen and well logs. Journal of State Higher Educational Institution 3, 10-15.