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Review Article

Evaluating Methods for Measuring Rock Toughness in Hydraulic Fracturing: A Research Note

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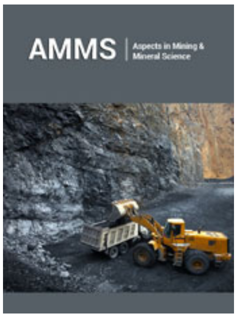

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Abstract

Rock toughness, a critical property, defines a rock's ability to resist deformation or fracturing. It is quantified through three primary modes: opening (Mode I), shearing (Mode II), and tearing (Mode III). Estimating rock toughness is essential for effective hydraulic fracturing, and three key tests developed to address this requirement are the scratch test, the straight-notched Brazilian disc specimen test, and the semicircular bend test. This paper aims to outline the procedures, governing equations, and results for each test, providing a detailed analysis of their outcomes. The study reveals significant correlations between rock toughness and shale properties. It also presents a comprehensive comparison of the three tests, focusing on their convenience, variable dependencies, and accuracy. However, a shared limitation across all methods is the technique used to induce fractures, which constrains their broader applicability. This highlights the need for further research to enhance the accuracy and practicality of fracture toughness measurement techniques.

Keywords: Rock toughness; Scratch test; Straight-notched Brazilian test; Semi-circular bend test

Introduction

The role rock toughness plays in the hydraulic fracturing industry is substantial, thus three tests where 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 [1]. 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 proportional to rock density and transit time, but it is inversely proportional to shale content [2]. 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. The 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 [3,4], 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.

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 [5], and are composed of multi-scale constituents [6]. 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 [7,8], through the injection of highly pressurized fracturing fluid. That enhances the permeability of the reservoir by al-lowing 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 [9]. 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.

Assessing Rock Toughness

Advancements in the field of fracture mechanics highlighted the importance of fracture characterization through rock properties [4,7,10] 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 [11], 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 [12,13]. 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 ex-traction.

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 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 Okla-homa, US [14]. 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.

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.

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 6mm/min covering a scratch path of 3mm. 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 [14]. 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:

$$K_S = F_T \Big/ sqrt\left(2PA\left(d\right)\right) \qquad (1)$$

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.

Test results: The scratch test provided a detailed estimation of rock toughness on a finer scale by utilizing nano-indentation techniques and heavily relying on advanced microstructural analyses, such as optical microscopy and scanning electron microscopy. These methods allowed for a meticulous examination of the shale samples, revealing intricate granular microstructures, including pockets of organic matter and the presence of micropores. The results were particularly notable for identifying a record of micro-cracks, which produced a horizontal force curve characterized by distinct peaks at nano-crack formations, followed by a sudden drop in force magnitude. This detailed force curve provided valuable insights into the fracture mechanics at a micro-level [14].

Additionally, the scratch test results highlighted three significant properties of the shale samples. First, it was observed that the width of the notch progressively increased along the scratching path. This phenomenon can be attributed to the way increasing linear force generates a greater number of micro-cracks in the horizontal direction, leading to a broader notch. Second, the fracture toughness was found to decrease with increasing depth. This trend reflects the natural transition of shale samples from ductile to brittle behavior as depth increases, a crucial characteristic for under-standing subsurface rock behavior. Lastly, the residual grooves formed during the test exhibited a composition of both soft and rigid constituents. The mixed stress directions in the grooves led to complex mechanisms such as crack bridging and crack branching, which ultimately pulled out the softer sections of the groove, further illustrating the interplay between material properties and stress responses. This comprehensive analysis underscores the scratch test's ability to provide in-depth insights into the micro-mechanical properties of shale.

The straight-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 con-duct another test, which is the Straight-Notched Brazilian Disk Specimen Test (SNBD). Zijian applied the SNBD test on 14 shale samples from a gas reservoir in China with average thickness of 2.5cm [13]. 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).

Procedure: The test starts out by initiating a central 1.4cm long crack on all samples. Then a vertical load is applied at a rate of 0.1mm/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° [13]. 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:

$$K_I = [\, P\, \mathrm{sqrt}(a) / RB\, \mathrm{sqrt}(\pi) \,]\, N_I \qquad (2)$$

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

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.

Test results: The results of the SNBD test were especially interesting because of how dispersed the values for mode II were be-tween 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 [13]. 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.

The Semi-Circular Bend test (SCB)

"Preexisting discontinuities in shale, including natural fractures and bedding, act as planes of weakness that di-vert fracture propagation" [15]. 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.

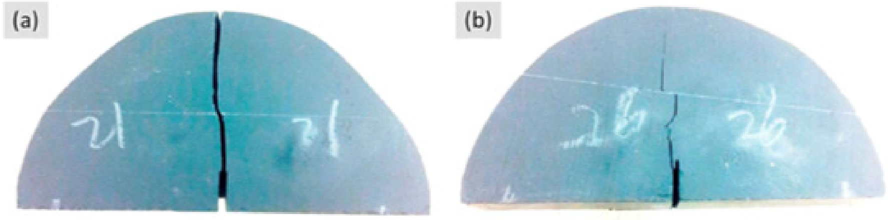
Procedure: The procedure of the semicircular bend test is similar to that of the SNBD test, however, unlike the central notch and the predefined angles used in the SNBD test, the semicircular bend test places the notch at the semicircular base of the sample, and the angle used usually ranges from 25° 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:

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

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:

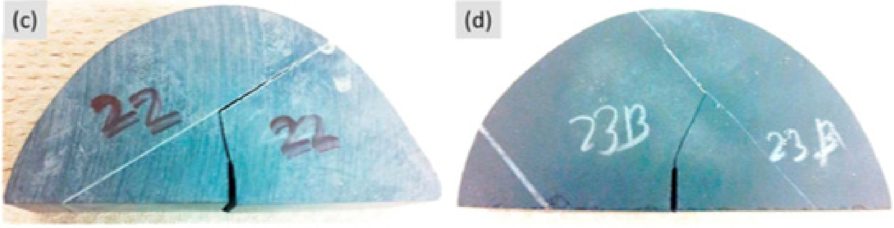
$$Y_I = 5.6 - 22.2\,(a/r) + 166.9\,(a/r)^2 - 576.2\,(a/r)^3 + 928.8\,(a/r)^4 - 505.9\,(a/r)^5 \qquad (5)$$

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 [15]. 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 [15]. 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 prop-agate through the thickest veins. This implicitly indicates that fracture toughness of a vain 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 1.



Cross (θ_o = 90°)

Step over (θ_o = 81°)



Divert (θ_o = 58°)

Divert (θ_o = 43°)

Figure 1: This is a figure schemes follow the same formatting [15].

Evaluation of Testing Methods

Although all three tests successfully produced numerical values for rock toughness, notable differences became evident when comparing their procedures, governing equations, and outcomes. These differences primarily revolved around three key aspects: convenience, variable dependency, and accuracy. In terms of convenience, certain tests demanded extensive sample preparation and longer, more intricate procedures, making them less practical and time-efficient compared to others. The second difference lay in the variables involved; since each test was governed by a distinct equation, the parameters required for calculations varied significantly, reflecting the unique methodologies of each approach. Lastly, the accuracy of the results differed among the tests, with some methods demonstrating a higher level of precision and reliability in their measurements. These distinctions underscore the importance of selecting the appropriate test based on specific research needs and operational constraints.

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 num-ber of samples to be tested is high.

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.

Accuracy

The third notable difference relates to uncertainty. Among the three tests, the scratch test, operating on a microscopic scale, provided significantly more accurate results compared to the macroscopic methods, namely the SNBD test and the semicircular bend test. This outcome aligns with the known physical properties of shale, which include its multi-scale grain structure and the presence of nanometer-scale voids. These characteristics make shale behavior highly scale-dependent, with notable variations between fine-scale and bulk material responses. As a result, when macroscopic tests are employed to estimate fracture toughness, a degree of uncertainty is introduced. This is because such tests do not fully account for the intricate microstructural features and behaviors that dominate at finer scales. Consequently, the scratch test's ability to operate on a microscopic level offers a more precise under-standing of shale's fracture mechanics, underscoring the limitations of macroscopic approaches in capturing the true toughness of such complex materials.

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.

Conclusion

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 [16-20], 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 be-tween 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 sub-surface, but their limitations proved the need for more research in the field of fracture toughness measurement.

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