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Research Article

FRACTURE TOUGHNESS ASSESSMENT OF DEEP WELL ROCK USING CCNBD AND SCB TEST PROTOCOLS

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ABSTRACT

Fracture mechanics is widely deployed in stone fracture modeling, digging with hydraulic, and dynamic fracture techniques for assessing the effects of rock fracture mechanical properties on different hydraulic fracture digging process. To get a better insight about the process, testing the actual rock samples can be extremely imperative. This study, indeed, attempts to evaluate the fracture toughness of actual rock samples using two different test protocols, i.e., Cracked Chevron Notched Brazilian Disc (CCNBD) and Semi-Circular Bend (SCB). The results indicate that similar behavior is observed for the samples under the two tests. However, due to the geometry, created crack, and the loading conditions of the prepared samples, the fracture occurs for the SCB samples under a less needed force. The results also indicate that the SCB test samples yield more fracture toughness.

Keywords: fracture toughness; SCB; CCNBD; coring; deep well rock.

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1. INTRODUCTION

1.1. Crack Propagation

In most cases, cracks are the main reason for structural failure. Failures and ruptures usually occur suddenly and unexpectedly and result in tremendous disasters. Fractures are basically the result of the incompetence of the materials in response to the applied load, which in uncontrolled and extreme scenarios leads to structural failure [1]. On the other hand, in a controlled situation, the fracture can consider as a practical tool for many engineering applications. Using fracture mechanics principles to minimize the required force of cutting and digging of rock materials are an example of these applications. Another important example is increasing oil and gas wells efficiency with less permeability by utilizing the fracture methods [2]. Hydraulic fracturing is a process in which cracks are created as a result of increasing pore pressure using fluid injection [3-6]. Developing contact surfaces between the structure and the well by these cracks leads to more efficiency of wells.

The main goal of rock fracture mechanics is understanding the mechanical relationship between rock material strength and the mechanical and geometrical parameters. Earlier studies in the field of rock fracture mechanics were conducted in the mid-1960s with a focus on Griffith balancing theory and maximum stress fracture theory and their modification [7]. Researches on the brittle rock material fractures made tremendous progress in rock fracture mechanics studies [8-12]. The linear elastic fracture mechanics role was thus well understood throughout the crack fracture mechanics concept. The initial application of linear elastic fracture mechanics in rock engineering was based on the rate of critical strain energy release [13]. In 1970, after recognizing the fracture toughness as an intrinsic property of rock materials, researchers were concentrated on this parameter as the most important resisting parameter against nucleation and elastic crack growth of different materials including rocks [14-16]. Crack growth is normally the main reason for the fracture. Crack growth in rock material is complicated and needs advanced techniques to predict the geometry of the fracture. Fracture starts by nucleation of crack that is dependent to fracture energy of the material, defined by fracture toughness which is equivalent with elastic parameters of material in linear elastic fracture mechanics. Therefore, the precision of any modeling and its results are highly dependent on these key parameters both in elastic models and models including plastic behavior.

1.2 Fracture Toughness

Today, 8 to 40 steps of hydraulic fracture process are operating for a target well [17, 18]. International Society for Rock Mechanics (ISRM) has developed standards and methods for calculating the first mode of fracture toughness of rocks by disk samples. Except for SCB sample which has edge notch and is introduced recently by Kuruppu et al. [19], other proposed samples have chevron notch. Thereupon, many researchers have conducted their research by samples with chevron notch as mentioned in ISRM. Khan and Al-Shayea [20] investigated the effect of testing with different samples and geometric factors such as diameter, thickness and crack length on fracture toughness of first, second and a combination of first and second modes of Limestone. They found out that samples diameter and crack type considerably affect fracture toughness. They also reported that the effects of loading rate, crack length and samples thickness on first mode fracture toughness are negligible, while these effects are highly significant in second mode fracture toughness. Chang et al. [21] studied the first, second and the combination of first and second modes of fracture toughness fracture and investigated the effect of dimension for different values of thickness, diameter and crack length in their CCNBD samples. The authors found that fracture envelopes can be achieved by application of different regression curves. They showed that the mixed-mode test results are comparable with the other mixed-mode failure criteria in the literature. Dai et al. [22] introduced a new method for calculating the first mode of fracture toughness of rocks by several tests on half-disk bending samples with chevron notch (CCNSCB).

Based on the background, regularly studies upon fracture toughness employ CCNBD samples due to the great ability of this sample in fracture simulation, simple loading, and ability to do the test with common devices in rock mechanics laboratories. In addition, tests with CCNBD sample enable researchers to test all loading conditions between first and second mode of fracture with changing the notch angle with respect to the loading axis.

The study of rock fracture of SCB samples for different modes has been drawing the attention of several researchers [23-25]. This sample was first introduced by Chong and Kuruppu [26] to define the first mode fracture toughness of rocks. Also, other researchers extended its application in order to be able to capture the second mode and combined first and second modes of rocks to study the fracture parameters of their materials. Lim et al. [27] used SCB sample for toughness tests of pure mode I to pure mode II on an artificial stone rose called “Johnstone” and presented the complete curve of combined fracture modes of this material. Khan and Al-Shayea [20] used SCB samples for the fracture tests of limestone samples, but their results did not cover the whole area of mode I to mode II.

2. PROBLEM STATEMENT

This study attempts to investigate the effects of rock fracture mechanical parameters on the different methods of oil wells hydraulic fracture designing processes. For this purpose, two test protocols including CCNBD and SCB are implemented using the actual samples extracted from the oil wells. The following sections explain the utilized test protocols followed by the results.

3. SAMPLE PREPRATION AND MECHANICAL PROPERTIES

In order to analyze the effects of rock fracture mechanical parameters on the different methods of oil wells hydraulic fracture designing processes, it was necessary to obtain actual rock samples from existing oil wells to study, which is an extremely diligent process. Coring the samples was a significant undertaking due to the difficulties of obtaining decent samples from the depth of thousands of meters which needs a lot of expenses and efforts. A number of four rock cores were extracted from the oil wells at the depth of 3500 m located at Bangestan area located in Khuzestan Province in the southwest of Iran. The physical properties of the four samples are summarized in Table 1. The extracted cores are shown in Fig. 1. Prior to the cutting and creating the artificial cracks on them, since the rock cores are impregnated with oil, Soxhlet extractor was used to remove the oil from the pores and surfaces to provide samples free of additional materials. The presence of additives could affect the crack propagation process in an uncontrolled way. As the next stage, the unsmoothed ends of rocks were taken out for wave velocity (V_s and V_p) measurements.

Table 1. Physical properties of the extracted samples

Sample	Depth (m)	Diameter (mm)	Length (mm)	Mass (gr)	Density (gr/cm^3)
I	3389	100	67	1232	2.32
II	3450	100	127	2737	2.74
III	3726	100	67	1345	2.50
IV	3386	100	42	797	2.36

Fig.1. Extracted samples before cleaning and preparation

Afterward, Brazilian Disk (BD) samples were cut with required thicknesses, and SCB samples were prepared by cutting BD samples to two equal parts, in the way that BD cutting direction was parallel to the small crack direction of rock cores (see Fig. 2).

These samples were tried to have smooth parallel surfaces. After that chevron notch was created for BD sample, using a diamond disc blade with 60 mm diameter and 0.5 mm thickness which is based on dimension limitations of a CCNBD sample of 100 mm diameter and 22 mm thickness which lead to the blade penetration of 13.4 mm in the sample (Fig. 2b). Edge notch was also created for SCB sample with the dimension of 50 mm diameter and 20 mm thickness. During creating cracks, because of the existence of intensive natural cracks, some of the samples were crushed, and only one rock core which had the highest quality remained in good physical shape from the four samples, and fortunately, two CCNBD samples were generated precisely.

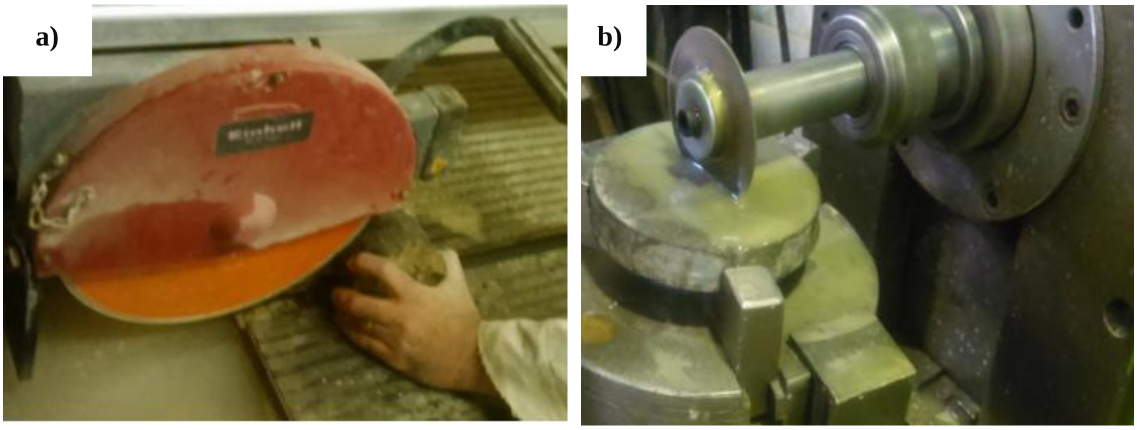

Fig.2. Preparation of the samples; (a) CCNBD and SCB cutting; (b) creating chevron notch

As a result of reviewing previous studies about rock fracture parameters with chevron notch samples, the authors convinced to use standard CCNBD samples in order to investigate the fracture mechanics of the obtained core rocks from oil wells of Bangestan in the southwest of Iran. After choosing the first method of rock fracture parameters calculation with the CCNBD sample through the proposed methods of ISRM with chevron notch samples, SCB sample under three-point bending was chosen as the second suitable method to attain the goals of this study. In addition, defining toughness fracture of the first mode with the SCB sample under three-point bending is the newest method proposed by ISRM and using that enables us to compare fracture parameters of non-chevron notched, and chevron-notched specimens through a standard method. Another fact should be pointed out is by choosing SCB samples we were able to produce more quantity of samples in comparison with any other types of test samples.

In order to know the mechanical behavior and obtain the required parameters for rock fracture calculation, destructive and non-destructive tests were conducted on the available rock cores. Ultrasonic tests were used to define mechanical parameters of elastic behavior of rock, and three-point bending was used to obtain the tensile strength of the rock. Ultrasonic tests of defining shear and compaction wave velocity were conducted per ASTM D-2845 as shown in Fig. 3). The results of the tests for both shear wave velocity (V_s) as well as compaction wave velocity (V_p) are shown in Table 2.

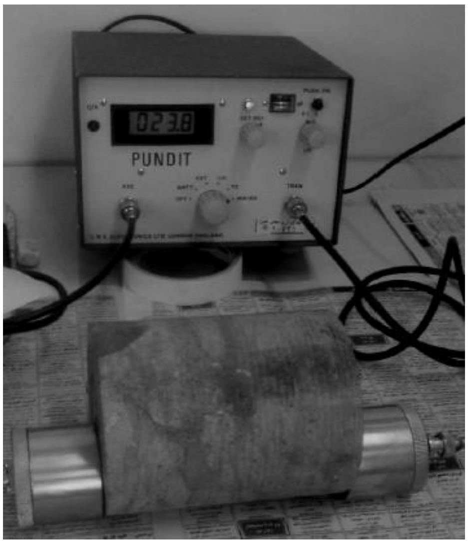

Fig.3. Ultrasonic tests of shear and compaction wave velocity per ASTM D-2845

Table 2. Measured shear and compaction wave velocity of the extracted cores

Sample	V_s (m/s^2)	V_p (m/s^2)
I	2313	4205
II	3170	5283
III	1392	3323
IV	2125	4087

According to Equations 1-4 per ASTM D-2845, dynamic elastic parameters of rock can be measured.

$$E_d = \rho V_s^2 (3V_p^2 - 4V_s^2) / (V_p^2 - V_s^2), \qquad (1)$$

$$\nu = (V_p^2 - 2V_s^2) / (2V_p^2 - 2V_s^2), \qquad (2)$$

$$G = \rho V_s^2, \qquad (3)$$

$$K = \rho\ (3V_p^2 - 4V_s^2)/3, \qquad (4)$$

where E_d , ρ, υ, G and K are dynamic Young's modulus, density, dynamic Poisson's ratio, dynamic shear modulus, and dynamic bulk's modulus of rock, respectively. The elastic parameters of the tested samples are summarized in Table 3.

Considering dynamic elastic parameters, static elastic parameters can be obtained using empirical relationships (Eq. 5 and 6) introduced by Ameen et al. [28] and Najibi et al. [29] specifically for limestone samples of the south-west of Iran.

$$E_S = 0.541E_d+12.852, \quad (5)$$

$$E_S = 0.352E_d^{1.149}, \quad (6)$$

Table 3. Dynamic elastic properties of the extracted cores

Sample	Bulk modulus (GPa)	Shear modulus (GPa)	Poisons ratio	Young's modulus (GPa)
I	24.42	12.38	0.28	31.77
II	39.83	27.58	0.21	67.22
III	21.67	4.96	0.39	13.82
IV	25.20	10.66	0.32	28.02

Substituting test results in the aforementioned equations, static Young's modulus can be found, respectively. In this respect, the average value was considered for the material. Also, Poisson's ratio was taken to 0.21.

In order to find the Fracture Process Zone (FPZ) and comparing the results, the tensile strength of the rock is needed. Since rock material is weak to the tensile loading intrinsically, it is hard to implement tensile tests directly, and usually indirect methods are employed including compression loads. To this end, disk or prismatic shape samples under diagonal compression or bending loading are used (see Fig. 4).

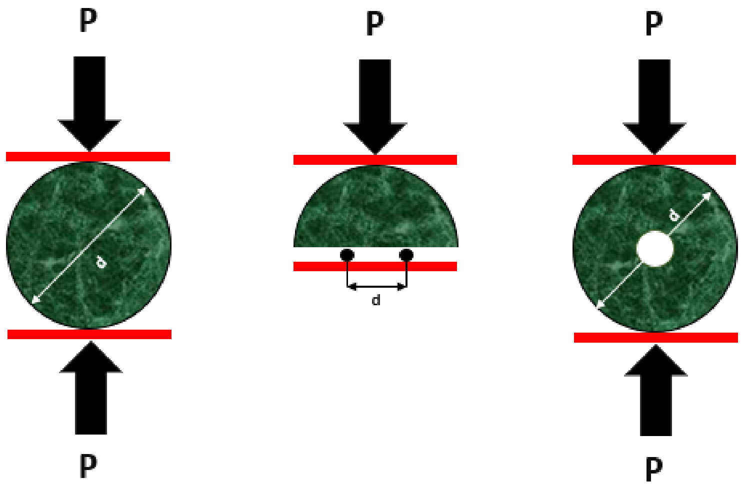

Fig.4. Disk shape samples under diagonal compression or bending loading

Due to the simplicity in preparation, disk samples are more common to be used for such tests, among which the Brazilian disk under compression loading is introduced by ISRM as the standard method for an indirect finding of tensile strength test in rock materials [30]. According to this method, the circular disk is under diagonal compression loading, therefore, the stress at the center of the disc would be the tensile stress. When loading is critical, failure occurs from the center across the diagonal loading. According to this procedure, fracture loading was measured to be 7449 N, and the tensile strength was calculated to be 6.67 MPa. As such, by finding tensile strength from the non-cracked sample and FPZ, it is possible to analyze geometry effects of the test sample for rock fracture parameters by MMTS criteria.

4. RESULTS AND DISCUSSION

To define the fracture energy of well rock, fracture toughness of mode I for two samples of CCNBD has been measured in this study. CCNBD samples were prepared as explained before and were inserted vertically in the testing device by two flat fixtures as if the notch is vertical and the sample is under pressure loading mode I study. Fig. 5 shows the sample and loading condition. Loading with the rate of 0.5 mm/s continued to the fracture point.

Fig.5. Fracture testing mechanism and sample after fracturing for CCNBD test

Fig.6 shows the force-displacement relationship during the test procedure in which linear behaviour of limestone rock can be observed in mode I loading. It was observed when the fracture starts from chevron notch, after a critical point the fracture suddenly happens. Moreover, the two samples have similar behaviour since the geometry, crack, and the loading conditions are identical. This means the inherent cracks have not affected the crack propagation from the chevron area and the results are reliable to calculate the fracture parameters of oil well core rocks.

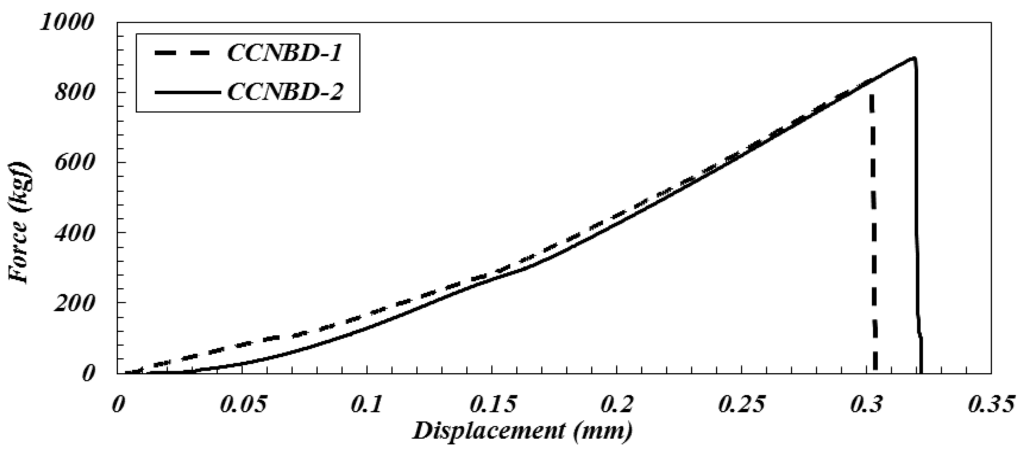

Fig.6. Force-displacement relationship for CCNBD tests

As shown in Figure 2 an ultimate load value for the CCNBD-1 and CCNBD-2 samples are

8354N and 8976 N, respectively, indicating that the difference between the two test samples is about 7 percent. Therefore, the average value of 8665 N was considered as the ultimate load for CCNBD sample in mode I to calculate rock fracture parameters.

ISRM proposed the following equation to calculate mode I fracture toughness of CCNBD sample:

$$K_{Ic}= Y^*_{min} \frac{P_{max}}{B.\sqrt{D}}, \quad (7)$$

where Y^*_{min} is the minimum value of dimensionless stress intensity factor of sample defined by geometric dimensions of the sample and dimensionless parameters of α_0, α_B, and α_1 are obtained using the following equation:

$$Y^*_{min} = u.e^{v.\alpha_1}, \quad (8)$$

where *u* and *v* are the constants available in ISRM tables and considering values existing in the literature, Y^*_{min} is equal to 0.71 for the rock sample in this test. Accordingly, fracture toughness parameter of mode I for CCNBD sample is calculated to be 0.88 Mpa.m$^{0.5}$.

In addition to previous tests, fracture toughness measurement of mode I was tested for SCB sample of this rock material. SCB samples were prepared as explained before and were inserted vertically in the testing device by three-point bending fixture with support distance of 50 mm as if the groove is vertical and the sample is under pressure loading for mode I study. All the tests are conducted as strain-controlled with a constant rate of 0.5 mm/min to the fracture point. Fig. 7 shows the SCB sample and loading condition for the three-point bending test.

Fig.7. Fracture testing mechanism and sample after fracturing for SCB test.

Fracture results of SCB samples are plotted in Fig. 8. Although there are some differences in the behavior of SCB-1 and SCB-2 samples around 6000N and 1200N forces that can be due to the inherent cracks of samples, fracture occurred for both samples with similarly 2139 N and 2087 N forces, respectively, indicating less than 2 percent difference for the SCB test samples (see Fig. 8).

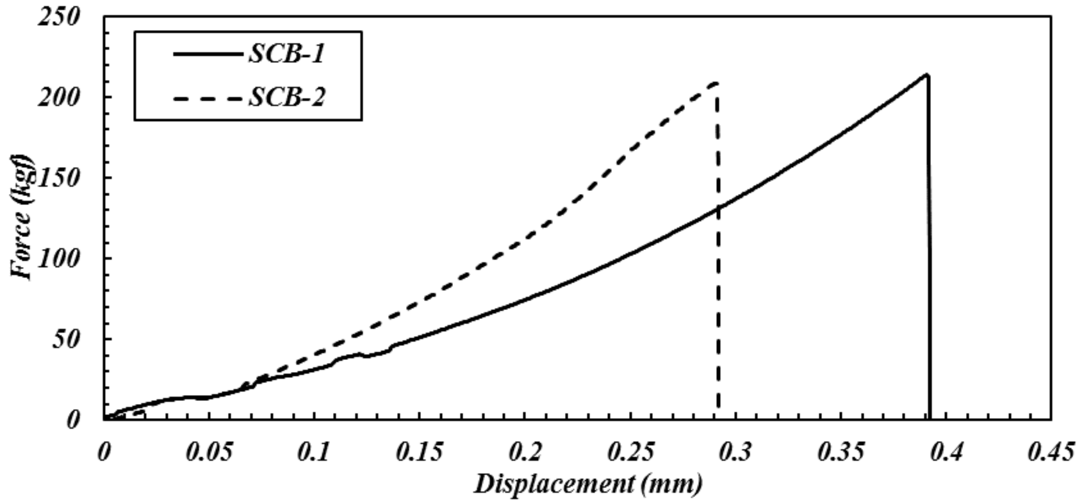

Fig.8. Force-displacement relationship for SCB tests

Since at the current analysis to find the fracture parameters (fracture toughness and fracture energy) only the ultimate value of loading is important for which both samples have similar behavior, our results are assumed to be reliable and can be used to this end. Recommended by ISRM, the following equation is employed to obtain the fracture toughness of mode I for SCB sample:

$$K_{Ic} = Y' \frac{P_{max}\sqrt{\pi a}}{2RB}, \quad (9)$$

where Y' is the dimensionless parameter of stress intensity that can be obtained iteratively considering the geometry of sample and parameters $S/2R$ and β. Y' was iterated to be 3.679 for this study. Thus, considering geometric dimension and crack length of SCB sample in Equation 9 and also 2113 N as an ultimate load for fracture, fracture toughness parameter of mode I for SCB sample was determined to be about 1.09 Mpa.m$^{0.5}$.

In addition, based on the estimated values for Young's modulus and Poisson's ratio (i.e., 46.745 MPa and 0.21, respectively), the first mode fracture energy (G_{Ic}) for the two different tested samples, i.e., CCNBD and SCB can be calculated as reported in Table 4. The results show that the fracture energy under SCB test protocol can be greater by the factor of 1.5. The difference between the two test protocols can be due to several factors such as mechanism of loading, notch's shape and dimensions and finally the required force for the fracture occurrence (see Figures 2 and 4).

Table 4. Fracture energy and its average value for the two tested protocols

Sample	Fracture Energy (N/m)
CCNBD	15.84
SCB	24.30
Average	20.04

Fig. 9 summaries the maximum force required for fracture propagation for each of the test samples. The CCNBD test samples require more force about four times greater as compared to the SCB tests showing the effect of the geometry and shape of the test samples on the fracture mechanism.

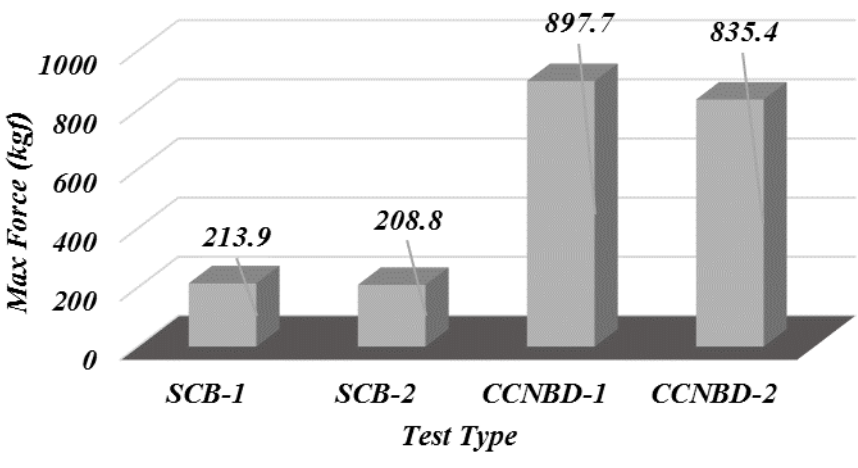

Fig.9. Maximum load of the tested samples

5. CONCLUSION

Rock fracture mechanical properties can impact oil wells hydraulic fracture digging process. Therefore, a good understanding of the material behavior using actual rock samples can be necessary. For this purpose, two test protocols were employed using four rock cores extracted from the oil wells of the southern part of Iran. After extensive preparation and evaluation of the test samples, two test protocols including CCNBD and SCB were employed to measure fracture toughness of mode I of the extracted samples. Even though, the two tests show similar behavior as judged by the force-displacement relationships. The results obtained from the SCB show less difference between the needed force for the fracture occurrence as compared to CCNBD method. Moreover, the results showed that the fracture toughness obtained from the SCB method was 1.24 times the corresponding results obtained from CCNBD. However, the average fracture toughness of 0.99 was found as a good estimation of the extracted samples.

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