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DETERMINATION OF FRACTURE TOUGHNESS OF ROCK UNDER IN-SITU CONDITIONS USING SEMI-CIRCULAR SPECIMEN

M.D. Kuruppu[1] and M. Seto[2]

[1] Curtin University of Technology, PMB 22, Kalgoorlie, WA 6430, Australia
[2] National Institute for Resources and Environment, 16-3 Onogawa, Tsukuba,
Ibaraki 305-8569, Japan

ABSTRACT

Fracture toughness of several types of rock is determined using the semi-circular bend (SCB) specimen and the single edge-cracked round bar in bending (SECRBB). The methodology for the evaluation of level I and level II fracture toughness and K-resistance curve using a single specimen is presented. K-resistance curve is shown to yield true fracture toughness even when under-sized specimens are employed. In order to simulate the in-situ conditions, tests were also done at elevated temperatures, high confining pressures, and different moisture levels. Fracture toughness of Kimachi sandstone increases moderately with increasing temperature up to 200^0C. In addition, it increases rapidly with increasing confining pressure before reaching a steady value. Increasing moisture content was found to reduce the fracture toughness.

KEYWORDS

Fracture toughness, rock, K-resistance, elevated temperature, confining pressure, moisture content, pore pressure

INTRODUCTION

The fracture behaviour of rocks is different from those in most man made materials due to their inherent properties. Sedimentary rocks such as sandstone and oil shale can be categorised as transversely isotropic as their properties are uniform in the plane of bedding, but may differ from those in the direction normal to bedding [1]. In addition, rocks behave nonlinearly under stress. They are subjected to explosive as well as non-explosive fragmentation for resource extraction. Fracture toughness is a valuable property in predicting the behaviour of material during fracture processes. A number of test specimens and methods have been suggested to determine the fracture toughness of rock materials [2-4]. The chevron-notched bend specimen [3] and the short rod specimen [2] have been incorporated into a standard method for the fracture toughness measurement of rock by the International Society for Rock Mechanics (ISRM) [5]. The semi-circular bend (SCB) specimen proposed by Chong et al. [6] and the single edge-cracked round bar in bending (SECRBB) specimen [7] are complimentary to the standard method. For example, the SCB specimen can be used as a third specimen for the complete characterisation of fracture toughness from a single core in materials such as sedimentary rocks [6]. It is suitable for measuring the plane strain fracture toughness of materials undergoing substantial nonlinear deformation before failure [8]. Lim et al. [8] has successfully used the specimen to measure the fracture toughness of a synthetic mudstone which is a relatively weak rock behaving nonlinearly.

In past most rock fracture toughness tests have been performed under ambient conditions. However, it is essential that the measurements be carried out at in-situ conditions such as elevated temperatures and pressures, and in wet environments. This paper presents the methodology of determining levels I and II fracture toughness using the SCB specimen. Level II fracture toughness is especially required for materials behaving nonlinearly. Furthermore, methods of determining fracture toughness of rock at elevated temperatures and high confining pressures are given. Tests were done over a wide range of temperatures varying from ambient conditions up to 200^0C. It was observed that the effect of increasing confining pressure on the fracture toughness dies down at moderately high pressures. Therefore, the confining pressure of the tests was restricted to a maximum value of 7.5 MPa.

TEST PROGRAM

Most tests were done using SCB specimen. However, SECRBB specimen was also used for comparison and verification of some of the results. Both specimens are core based and therefore easy to prepare. The testing program covered the following areas:

(a) Fracture toughness of Kimachi sandstone was determined at ambient condition using 100 mm diameter SCB specimens. Fracture toughness was also measured according to the ISRM standard method.

(b) Effect of elevated temperatures on fracture toughness was measured using a custom built test system that facilitated loading the specimen in three-point bending while immersed in an oil bath. The oil bath can be heated to a desired temperature up to 200^0C. SCB specimens of 60 mm diameter and SECRBB specimens of 30 mm diameter were tested.

(c) The effect of confining pressure on fracture toughness was measured using the same test rig described in b above. The jacketed oil bath containing the test specimen was subjected to a confining pressure up to 7.5 MPa. However, the test specimen was not heated simultaneously.

(d) The effect of moisture content on fracture toughness of Kimachi sandstone was determined using dry as well as partially wet test specimens.

Specimens are made such that the notch is aligned with one of three principle orientations known as the arrester, the divider and the short transverse (ST) [6]. Specimens are prepared by slicing rock cores while noting the direction of bedding. Each core disc is then split into two halves producing two specimens having almost identical properties. Finally, a straight notch is introduced using a diamond impregnated wire saw or a thin circular saw. A circular saw having a thickness of 0.3 mm was used to cut the notch during this test program. SECRBB specimens were also made of cores with their notches oriented in the arrester and the ST orientations. Very little machining is required as only a straight edge-notch is introduced. The specimens were oven dried at 60^0C for a few days and all dimensions were recorded prior to testing.

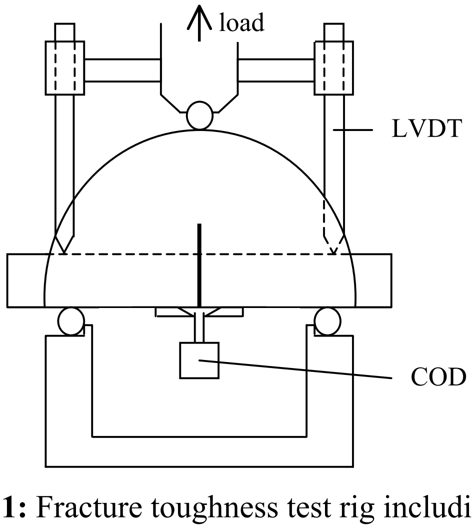

Figure 1: Fracture toughness test rig including SCB specimen

Tests at Ambient Conditions

SCB specimens made of Kimachi sandstone were tested using a MTS closed loop servo hydraulic test system (Figure 1). The sizes of specimens were approximately 100 mm diameter, 25 mm thickness and a crack length to radius ratio, a/R, of 0.5. A special fixture was used to load the specimen in three-point bending. The fixture allows the two support rollers to rotate and move apart slightly as the specimen was loaded, thus permitting roller contact and minimising frictional effects. The top loading pin was attached to the upper platen of the load frame. This fixture helps to achieve the proper alignment in the load transfer system. In addition, the SCB specimen must be properly aligned parallel to the axes of the loading pins as the pins make line contact with the specimen. A crack opening displacement (COD) gauge was attached to the specimen using knife-edges positioned across the mouth of the notch. The load-line displacement was measured by taking the average reading of two linear variable differential transducers (LVDTs) that were placed between the top and the bottom loading platens. Tests were done using COD control mode at a constant rate of 0.06 mm/min. At least one partial unloading was done before reaching the peak load and a number of partial unloading-reloading cycles were done in the post-peak region (Figure 2). The high stiffness of the test frame enabled recording the complete post-peak behaviour in each test. In addition, a number of tests in the ST orientation was done using partially wet Kimachi sandstone specimens.

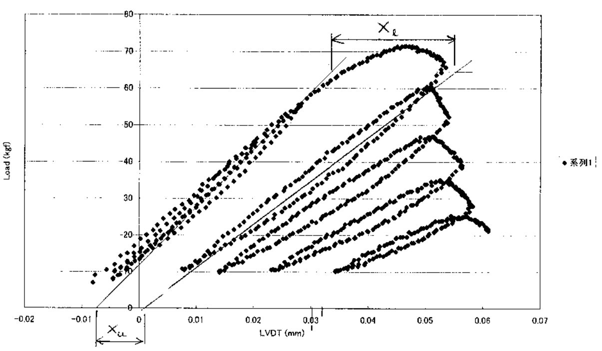

Figure 2: Typical load-displacement record illustrating the determination of p factor

Measurement of Fracture Toughness at Elevated Temperatures and Pressures

The machine facilitates testing specimens under three-point bending while immersed in a jacketed oil bath that can be subjected to hydraulic pressures up to 30 MPa and temperatures up to 200^{0}C. It can accommodate a number of different types of specimens including SECRBB and SCB specimens. SCB specimens of 60 mm diameter and 25 mm thickness as well as SECRBB specimens of 30 mm diameter were used for these tests. Kimachi sandstone specimens prepared in all three orientations were included in the test program. The notches of the specimen were covered with either several layers of taped paper (for high-pressure applications) or aluminium foil (for high temperature applications). Knife-edges for the COD gauge were attached and the specimens were covered with a layer of silicone to prevent any oil contamination. The specimens were placed in the loading platform with COD gauge attached and then immersed in the jacketed oil bath. In the case of elevated temperature tests, the oil bath was heated to the desired temperature and allowed approximately 2 hours to stabilize the conditions of the specimen. Specimens were then tested to failure under either LVDT or COD control. LVDT measured the load-line displacement. Partial unloadings were done at regular intervals before and after the peak load similar to the tests done at ambient conditions. The strain rate of each of the tests was 0.075 mm/min.

Method of testing at high confining pressures was similar to that of elevated temperature except that a desired confining pressure was applied instead of raising the temperature of the oil bath containing the test specimen. Most tests were done under LVDT control while a few was performed under COD control. As the silicone layer does not permit pressures to be applied on the free surfaces of the notch, the resulting closure of the crack due to the confining pressure was measured using the COD gauge. The load, load-point displacement and the crack opening displacement were recorded as a function of time during each test.

EVALUATION OF RESULTS

The level I fracture toughness, K_I, is determined using the peak load, the non-dimensional stress intensity factor and the specimen dimensions [5]. For the SCB specimen it may be given as

$$K_I = Y\,F\,(\sqrt{\pi\,a})/2Rt \tag{1}$$

where Y is a non-dimensional stress intensity factor, F is the peak load, a is the crack length, R is the specimen radius and t is the thickness. The span to diameter ratio is 0.8. The stress intensity factor Y is a function of the crack length to radius ratio, α. The best fit curve for Y is given by [6,9]

$$Y = 5.6\text{-}22.2\alpha+167\alpha^2\text{-}576\alpha^3+929\alpha^4\text{-}506\alpha^5 \tag{2}$$

The stress intensity factor for SECRBB specimen is given in reference [10]. For level II testing, a nonlinearity correction factor is incorporated. The evaluation closely followed the procedure adopted in the ISRM standard method. As shown in Figure 2 the displacement ratio

$$p = X_u / X_l \tag{3}$$

defines the degree of nonlinearity. The two chosen unloading lines must span the maximum load. In addition, the average value of loads at unloading positions must be as close as possible to the peak load. Then the nonlinearity corrected fracture toughness is determined from the following equation:

$$K_{Ic} = \sqrt{(1+p)/(1\text{-}p)}\,K_I \tag{4}$$

The corrected fracture toughness is equivalent to the upper limit of the K-resistance curve of the rock. If specimens smaller than those satisfying the minimum dimensional requirements are employed, fracture toughness must be evaluated using a K-resistance curve instead of using level II value [11]. If the crack length is known, using Eqn. 2 the stress intensity factor can be determined for each cycle. Then the K-resistance for each cycle can be derived as

$$K_{I,R} = \sqrt{(1+p)/(1\text{-}p)}\,K_{Ii} \tag{5}$$

where K_{Ii} is a level I value determined using the non-dimensional stress intensity factor and the load at the unloading point of the cycle. In this case, p is taken as the average degree of nonlinearly of the given cycle and two adjacent cycles. The crack length is measured using the experimentally determined compliance. The non-dimensional compliance, C' is given as

$$C' = E'DC \tag{6}$$

where C is the compliance, which is the ratio of the load-point displacement and the load, D is the diameter and $E' = E/(1-\upsilon^2)$. E and ν are Young's modulus and Poisson's ratio respectively. For example, for SCB specimen the relation between the non-dimensional compliance and the crack length is given by

$$C' = 1366\,\alpha^3 - 867\,\alpha^2 - 51.9\,\alpha + 129.4 \tag{7}$$

Fracture Toughness at Ambient Conditions

Table 1 gives fracture toughness of Kimachi sandstone. Figure 3 shows a K-resistance curve derived using a single SCB specimen. The curve reaches a limit of 1.0 $\text{MPa}\sqrt{\text{m}}$. This value is higher than the level II toughness. It also agrees with the fracture toughness measured using chevron bend specimen according to ISRM standard, which yielded 0.99 $\text{MPa}\sqrt{\text{m}}$. Furthermore, this result agrees with that published by

Matsuki et al. [11]. This observation further reiterates the minimum specimen size requirement unless a K-resistance curve is used to determine the fracture toughness. Also, fracture toughness of Kimachi sandstone decreases almost linearly with increasing moisture content. At about 8% water content the fracture toughness is only about 33% of its value for dry material. This decrease is usually attributed to the build up of pore pressure that reduces the inter-particle bonds between grains in the process zone.

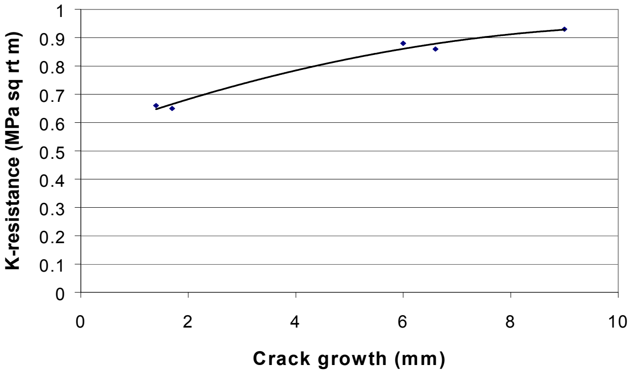

Figure 3: K-resistance curve for Kimachi sandstone

TABLE 1
FRACTURE TOUGHNESS OF KIMACHI SANDSTONE

Orientation	No. of specimens	Level I fracture toughness ($MPa\sqrt{m}$)	Level II fracture toughness ($MPa\sqrt{m}$)
Divider	6	0.45	0.65
Arrester	6	0.48	0.69
ST	9	0.41	-

Tests at Elevated Temperature and High Confining Pressure

Figure 4 gives the level I fracture toughness of Kimachi sandstone at elevated temperatures. Note that this result for ST orientation was produced using both SCB and SECRBB specimens. Fracture toughness shows a gradual increase with temperature. There is nearly 50% increase compared to the value at room temperature.

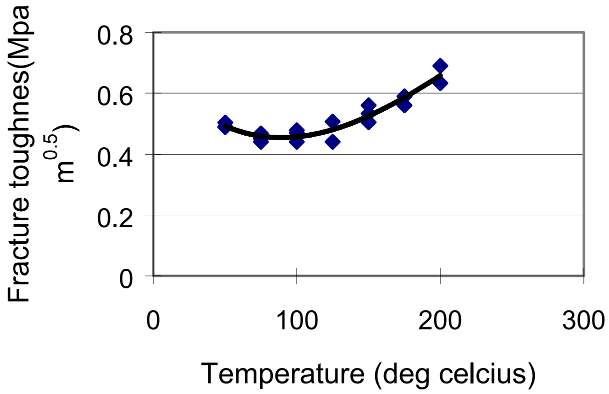

Figure 4: Fracture toughness of Kimachi sandstone at elevated temperature

Figure 5 shows fracture toughness of sandstone subjected to confining pressure (Note: mostly level I). Fracture toughness is quite significantly influenced by the confining pressure. In addition, it reaches a steady value when the confining pressure is about 4 MPa. This may be caused by the closure of the pre-existing microcracks and other discontinuities within the material due to the application of the confining pressure. Once that happens, rock behaves as if it has a uniform matrix and the fracture toughness remains constant. However, this limit value is several orders of magnitude higher than the fracture toughness of unconfined rock. As the silicone layer prevents the hydraulic pressure act on the notch, the notch tends to close due to the pressure on the remaining surfaces. This was adjusted using a suitable mathematical formulation [12]. Notch closure measured using the COD gauge assisted the adjustment.

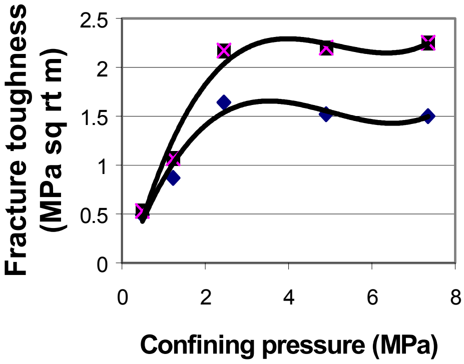

Figure 5: Variation of fracture toughness of Kimachi sandstone with confining pressure. Upper and lower graphs are for ST and divider orientations respectively

CONCLUSIONS

Fracture toughness tests were performed using SCB and SECRBB specimens. Firstly, level I and level II fracture toughness was measured for Kimachi sandstone. The crack growth was determined using the elastic unloading compliance measured at regular intervals of each test. Following a procedure similar to the analysis of level II fracture toughness, the crack growth resistance was measured using the unloading-reloading cycles following the peak load. This result in combination with crack growth data enabled the construction of K-resistance curve using a single specimen. The methodology also yields fracture toughness unaffected by the specimen size.

The fracture toughness of Kimachi sandstone increases moderately with increasing temperature. The level I fracture toughness increased by approximately 50% at 200^0C compared to the value at ambient temperature. The elevated temperatures appear to make the rock tougher and allow it to absorb more strain energy prior to failure. Fracture toughness was also found to increase substantially with increasing confining pressure. For example, for the divider orientation, fracture toughness of Kimachi sandstone increases from 0.45 $\mathrm{MPa}\sqrt{\mathrm{m}}$ at atmospheric pressure to 1.5 $\mathrm{MPa}\sqrt{\mathrm{m}}$ at a confining pressure of 2.5 MPa, an increase of 230%. However, it reaches a steady value and is not affected by further increase of confining pressure.

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