The importance of testing method to evaluate the most representative mode I fracture toughness value of brittle rocks

Abstract

One of the most fundamental parameters in rock mechanics is critical fracture toughness ($K_c$), which describes the resistance of rock material to crack propagation. $K_c$ is an important material property, which corresponds to the critical state of the stress intensity factor required for crack initiation and subsequent propagation. Therefore, assessment of resistance to crack propagation is crucial for understanding the behavior of structures involving brittle materials. To determine fracture toughness values of rocks, the International Society of Rock Mechanics (ISRM) suggests three methods: Short Rod (SR) specimen tests, Chevron Bend (CB) specimen tests and Cracked Chevron Notch Brazilian Disc (CCNBD) tests. In order to determine the mode I fracture toughness of tuff specimens, SR and CCNBD, were used in this study. It was found that CCNBD has more advantages over the SR method in terms of sample preparation and failure load consistency. The obtained fracture toughness values are different because of different dimensionless stress intensity factor values. The fracture toughness values obtained by the SR method were higher compared with the fracture values obtained by the CCNBD method. The obtained $K_c$ results were compared by using some well-known relationships between fracture toughness and rock physical properties to confirm the validity of those results.

Keywords: fracture toughness of rocks, short rod test, CCNBD test, Rock fracture, crack coalescence, crack initiation, rock boring equipment, rock bursting, rock drilling forces, wellbore stability, geometric parameters, hard rock types, dimension notations, tuff SR specimens, self-pre crack

Introduction

Rock materials are discontinuous at all scales. At the micro scale, defects causing stress concentrations are micro cracks, grain boundaries, pores and bedding planes, while at the macro scale geologic fractures are referred to as joints (opening) or faults (shearing), based on their genesis. Numerous experimental and theoretical efforts have been devoted to the understanding of crack initiation, propagation, and coalescence in brittle materials. Under tension, these three processes take place almost simultaneously in brittle rocks. However, the failure process is more complex under compression. Under both kinds of loading, rupture (failure) of the material results primarily from stable and unstable fracture propagation and crack coalescence, rather than directly from fracture initiation. Rock fracture toughness is a key parameter in rock fracture mechanics used to determine crack initiation and propagation, which is important in the design of rock boring equipment, tunneling, rock cutting, rock bursting, and determination of rock drilling forces, wellbore stability and stability of jointed rock masses. As a result, it is important to test rock fracture toughness with adequate accuracy. To assess fracture toughness values of brittle materials like rocks, the ISRM suggests three methods: Short Rod (SR) specimen, Chevron Bend (CB) specimen and Cracked Chevron Notch Brazilian Disc (CCNBD) specimen.

Comparisons between ISRM suggested methods have been mostly focused on SR and CB specimens, or on CCNBD and CB specimens. Although some consistency has been provided by these suggested methods, a variation of 20–30% was still obtained for the same rock type. Recent research has indicated that CCNBD values are markedly smaller than other comparable tests. However, the consistency of tested mode I fracture toughness between CCNBD and SR specimens has not been validated adequately and needs to be compared after performing more experiments. The geometry of a CCNBD specimen is illustrated in Figure 1. The chevron notch causes crack propagation to start at the tip of the V alignment and to proceed radially outwards in a stable fashion until the point where the fracture toughness is calculated.

Figure 1 The CCNBD specimen geometry with a recommended test fixture

All dimensions of the geometry should be converted into dimensionless parameters with respect to the specimen radius, $R$, and diameter, $D$. The suggested standard specimen dimensions are given in the ISRM suggested methods. Other selections of specimen geometrical dimensions are possible, but in order to have a valid test,
the two most important selected dimensions; dimensionless final
notched crack length \( a_1 \) and the dimensionless quantity, \( \alpha_{\text{min}} \), must
fall within the range outlined in Figure 2. The length of initial crack
\( a_R \), final notched crack \( a_1 \) and \( a_R \) \((B/R)\) are the three geometric
parameters for the CCNBD specimens. All specimen geometries
used in this research were in the valid ranges indicated by the red
circle in Figure 2; the full validity range is also shown. For fracture
toughness testing, the important stress intensity factor value for the
specimen is the minimum stress intensity factor, denoted as \( K'_{\text{min}} \),
as it corresponds to the failure load \( (P_{\text{max}}) \) recorded during testing.
The fracture toughness value of a CCNBD specimen is calculated as
follows:

\[
K_C = \frac{P_{\text{max}}\alpha_{\text{min}}}{B\sqrt{R}}
\]

where \( P_{\text{max}} \) is the maximum failure load in N, \( B \) is the thickness in
mm, \( R \) is the radius of the CCNBD specimen in mm, and \( \alpha_{\text{min}} \) is the
critical dimensionless stress intensity factor. For CCNBD specimens
within the valid range shown in Figure 2, the critical dimensionless stress intensity value \( \gamma_{\text{min}} \), which is determined by the
specimen geometry dimensions \( a_R \), \( a_1 \) and \( \alpha_R \) \((B/R)\) only, can
be calculated as given by the ISRM: \( \gamma_{\text{min}} = \frac{u.e^{-v}}{a} \) where constants \( u \)
and \( v \) are listed in the ISRM suggested methods. SR method is used to
evaluate mode I fracture toughness values only. The SR method was
introduced by Barker and it became an ISRM-suggested method after
the studies by Ouchterlony. The specimen is a typical core-based one
with a machined notch along the rod axis. The external load is applied
to the notch mouth to split the specimen into two identical halves. As
tensile loading is applied perpendicular to the plane of the notch, this
may result in failures at the specimen and loading equipment contacts,
especially for hard rock types. Figure 3 shows schematically the
specimen configuration and the loading and dimension notations. The
specimen geometry is restricted in dimensions as listed in Figure 3.

\[
K_{\text{SR}} = C_k \cdot \frac{24.0P_{\text{max}}}{D^{1.5}}
\]

Where \( K_{\text{SR}} \) is fracture toughness \((\text{MPa}\sqrt{\text{m}})\), \( P_{\text{max}} \) is failure load
\((\text{MN})\), \( D \) is the specimen diameter \((\text{m})\), and \( C_k \) is the correction factor
to account for the size variation of the specimen, given by

\[
C_k = 1 - \frac{0.6\Delta W}{D} + \frac{1.4\Delta a_0}{D} - 0.01\Delta \theta
\]

Where \( \Delta W \) is variation in specimen height \((\text{m})\), \( \Delta a_0 \) is the initial
position of the chevron notch apex \((\text{m})\) and \( \theta \) is the chevron notch
angle (in radians). What is important in both texts is to determine
where the crack will start. Then, the fracture toughness will be the
value of the crack where the transition point from the stable crack to
unstable crack after the crack initiation site is determined.

\[\text{Figure 3 Tuff SR specimens before testing}\]

**Methods**

The tests were carried out on tuff specimens. A circular 40mm
diamond saw was used to cut the required notch Figure 5. A precisely
designed jig was used to ensure that the chevron notches are exactly
in the center of the disc. Additionally, the jig was controlled by an
electronic alignment device with displacement calculated on \( x, y \),
\( z \) coordinates for accuracy in controlling the center alignment and
penetration of the saw Figure 4. The thickness, \( t \), of the notches was
1.4mm and the thickness of the sample, \( B \), was 25mm. The initial
chevron notch crack length, \( a_R \), was 7.5–8 mm and the final chevron
notch crack length was 36–37mm. An Instron 6027 with 100 kN load
cell hydraulic servo-control testing system with Blue hill software

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was used to conduct the tests. Diametral displacement parallel to the loading direction was measured by means of an extensometer with 50 mm gauge length. The crack displacement was measured as CMOD across the crack mouth. The opening of the notch was measured by a clip gauge by attaching special knives. Instron 2670 model crack opening displacement gauge was used to measure CMOD values.

Six CCNBD samples were tested under load control test conditions. The specimens were placed under the platens with zero crack inclination angle \(\theta = 0^\circ\) to provide mode I loading conditions. The loading rate was chosen as 9kN/s to cause failure within 20s as suggested by ISRM\(^7\). The load and CMOD readings were recorded continuously until failure. The tuff SR specimens’ diameter and length were 52mm and 75mm respectively. The chevron angle, \(\theta\), was 55\(^\circ\), and the chevron tip position was at 25mm. Figure 5 shows the SR samples before testing. The end plates were mounted parallel to and equidistant from the notch center plane. Each specimen was placed in the testing machine in such a way that the load transfer system was properly aligned. A small bias load was used to secure it in the correct position. Level I presume that the test will be run under load control. The load was recorded and the test was run until the specimen failed. The average stress intensity rate during the test was 0.25 MPa\(\sqrt{m}\)/sec so that failure occurs within 10s of initial load application. Eight SR samples were tested and results are given in the following sections.

Table 1 Mode I fracture toughness values of tuff specimens obtained by SR and CCNBD tests

<table>
<thead>
<tr>
<th>Rock type</th>
<th>(P_{max}) (kN) SR</th>
<th>(K_{IC}(SR)) (MPa(\sqrt{m}))</th>
<th>(P_{max}) (kN) CCNBD</th>
<th>(K_{IC}(CCNBD)) (MPa(\sqrt{m}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuff-1</td>
<td>1.0</td>
<td>2.02</td>
<td>5.25</td>
<td>1.38</td>
</tr>
<tr>
<td>Tuff-1</td>
<td>0.99</td>
<td>2.01</td>
<td>5.1</td>
<td>1.34</td>
</tr>
<tr>
<td>Tuff-1</td>
<td>1.3</td>
<td>2.63</td>
<td>6.18</td>
<td>1.63</td>
</tr>
<tr>
<td>Tuff-1</td>
<td>0.85</td>
<td>1.72</td>
<td>5.87</td>
<td>1.55</td>
</tr>
<tr>
<td>Average</td>
<td>1.03</td>
<td>2.1</td>
<td>5.6</td>
<td>1.48</td>
</tr>
<tr>
<td>Tuff-2</td>
<td>1.10</td>
<td>2.23</td>
<td>4.68</td>
<td>1.21</td>
</tr>
<tr>
<td>Tuff-2</td>
<td>1.07</td>
<td>2.18</td>
<td>6.47</td>
<td>1.68</td>
</tr>
<tr>
<td>Tuff-2</td>
<td>1.12</td>
<td>2.26</td>
<td>6.35</td>
<td>1.64</td>
</tr>
<tr>
<td>Tuff-2</td>
<td>1.05</td>
<td>2.12</td>
<td>7.10</td>
<td>1.83</td>
</tr>
<tr>
<td>Average</td>
<td>1.08</td>
<td>2.19</td>
<td>6.15</td>
<td>1.59</td>
</tr>
</tbody>
</table>

Figure 6 (a) SR and (b) CCNBD specimens after testing

### Results

In general, a load to achieve opening mode crack propagation can be applied to the specimen by direct tension, compression or bending. These two SR and CCNBD methods could be classified in terms of their loading conditions. The SR method is one of the methods suggested by ISRM\(^1\) in which a tensile load is directly applied perpendicular to the initial notch plane. In contrast, a CCNBD specimen is loaded in compression along the diametric plane. Hence, a comparison of these two methods has attracted attention in recent researches. Failure load and fracture toughness values of the tuff specimens determined with the CCNBD method were compared to the results of SR tests. The maximum failure loads for CCNBD specimens were found higher than those for SR specimens in general. Figure 6 shows the SR and CCNBD specimens after testing. The maximum recorded load and the calculated fracture toughness values obtained from both ISRM standard tests are shown in Table 1 mode I fracture toughness values of tuff specimens obtained for the CCNBD specimens are lower than those obtained by the SR method although bigger failure loads were obtained with CCNBD tests than with SR tests.
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K value to be 1.21 using the STCA method. Further, there is a close correlation. In contrast, K = 0.87 obtained using the formula. The fracture toughness obtained value calculated using the formula given by ISRM is too small compared with their calibrated value. The obtained results in this research confirm findings. The Y_min value is found 0.98 using the ISRM suggested formula and the calculated fracture toughness of tuff to be 1.48 MPa/√m. In contrast, the Y_min value to be 1.21 using the STCA method and the relevant fracture toughness value of the tuff to be 1.74 MPa/√m.

In contrast, the fracture toughness values obtained by the SR method have been found to be overestimated when compared with the fracture toughness of rocks found with CCNBD within the same ranges of uniaxial compressive strength (120–140 MPa) and uniaxial tensile strength (12–14 MPa). In order to check the validity of fracture toughness values obtained by CCNBD, the relationship between fracture toughness and the physic-mechanical properties of rocks has been considered. One might expect that the mode I fracture toughness, in which the rock is separated by a tensile stress, would be related to the tensile strength of the rock. The mode I fracture toughness of rock is directly proportional to its tensile strength. As given by an equation for the direct relation between uniaxial tensile strength and fracture toughness of rocks, the expected fracture toughness of tuff should be between 1.12–2 MPa/√m. The fracture toughness obtained from the CCNBD specimens is within this range; in contrast, the fracture toughness values obtained with the SR specimens are out of this range. Similar findings were made by for the relationship between fracture toughness and tensile strength of rocks. According to the equation, the expected fracture toughness of tuff should be between 1.5–1.9 MPa/√m. Further, there is a close correlation of mode I fracture toughness with uniaxial compressive strength. According to the derived equation, the expected fracture toughness should be 1.58 MPa/√m for tuff-1 and 1.78 MPa/√m for tuff-2. When a general comparison between the two methods is concerned, the CCNBD method had advantages in terms of easy sample preparation and less material required for testing. It is also unnecessary to perform pre-cracking for a CCNBD test specimen because it uses a chevron notch that self-pre-crack during testing and leads to stable crack propagation. Another remarkable advantage of the CCNBD method over the SR method in terms of precision is higher load capacity and consistent results for each test. In our research, all the CCNBD samples show high precision in maximum load measurements. In addition, it is possible to measure mode I, mode II and mixed-mode I–II maximum SIF values by inclining the notch at different angles with respect to the axis of the diametric load.

According to the rock fracture mechanics, the stress intensity factor (K) decreases with increasing crack length under a constant applied load and then a sharp crack initiates at the tip of the chevron notch, requiring an increasing load to grow stably at K_c = K_c to the notch base. After that propagated crack, unstable crack propagation starts because further growth would not require an increasing load.

Thus, fracture toughness (K_c) is calculated as that recorded ultimate load and the start of unstable crack propagation. According to the critical crack length a is between the initial chevron notch crack length, a_c, and the final chevron notch crack length, a_f. An analysis was done to obtain critical crack length in front of the chevron tip using the Straight-Through Crack Assumption (STCA) approach. Figure 7 shows the normalized stress intensity factor versus normalized crack length for both CSTBD and CCNBD geometries. Assumed that the critical crack length is between the initial chevron crack length and final chevron notch crack length. According to the critical crack length a is between the initial chevron notch crack length, a_c, and the final chevron notch crack length, a_f. As shown in Figure 7, unstable crack propagation starts at the dimensionless crack length where the dimensionless stress intensity factor is a minimum Y_min which equals to 1.21, and the relevant fracture toughness value of the Brisbane tuff is 1.74 MPa/√m where the critical crack length is equal to 13mm (x=0.5). This critical crack length indicates that unstable crack propagation starts between the initial chevron notch crack and final chevron notch crack lengths. It should be pointed out that the value of Y_min = 0.87 obtained using the formula is too small when it is compared with the corresponding value of Y_min = 1.21 obtained by STCA method. The obtained fracture toughness values are different because of different dimensionless stress intensity factor values.

In order to determine the mode I fracture toughness of tuff specimens, two ISRM suggested methods, SR and CCNBD, were used. It was found that CCNBD has more advantages over the SR method in terms of sample preparation and failure load consistency. The obtained fracture toughness values are different because of different dimensionless stress intensity factor values. The fracture toughness values obtained by the SR method were higher compared with the fracture values obtained by the CCNBD method. To confirm the validity of those methods, the results were compared with some relationships between fracture toughness and rock physical properties. Also, an analytical analysis was done to find the most accurate dimensionless stress intensity factor to calculate the fracture toughness of tuff specimens. The fracture toughness of tuff specimens obtained from the CCNBD specimens was found more precise compared with the results obtained from the SR method.

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Figure 7 Dimensionless stress intensity factors for CSTBD and CCNBD specimens
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Conflict of interests
Authors declare that there is no conflict of interest

References