Effect of Specimen Size on Mode I Fracture Toughness by SCB Test

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ABSTRACT
The semi-circular bend (SCB) specimen was suggested in 1984 for testing mode I fracture toughness of rock. Recently, SCB specimen was extended and improved for many other applications by various researchers due to ease in handling though short rod (SR) specimen is recommended method. However, there are still rooms to consider for determining the fracture toughness of rock exactly by SCB specimen. This paper discusses the application of the SCB specimen for determining the fracture toughness of rock by comparison between the result of SCB specimen and SR specimen, and size effect using the SCB specimen.

KEY WORDS: Fracture toughness / SCB specimen / SR specimen / Size effect

1. INTRODUCTION
Determination of the strength and stability of mine structures is particularly important for not only development of underground mine and mountain tunnel but also development and utilization of underground such as nuclear waste containment in proposed underground repositories. Rock mass consists of intact rock, joint, crack and discontinuity plane like fault. Since discontinuity plane located eccentrically influence mechanical rock property, to understand a characteristic of discontinuity plane is becoming increasingly important in designing underground space. Evaluation of crack in rock mass is one of effective method to quantify characteristic of discontinuity plane. Fracture toughness can evaluate crack initiation and propagation quantitatively. Therefore, it is desirable to investigate the fracture toughness, which is an important rock property that characterizes the fracture behavior. A number of test specimen configurations and methods have been suggested to determine the fracture toughness of rock materials. The International Society for Rock Mechanics (ISRM) has incorporated the chevron-notched bend specimen [1] and short rod specimen [2] into a standard method for measurement of the fracture toughness of rock [3]. The semi-circular bend (SCB) specimen proposed by Chong et al. [4] is complementary to the standard method. The semi-circular bend (SCB) specimen has been widely used for fracture toughness determination of geomaterials owing to inherent favorable properties such as its simplicity, minimal requirement of machining and the convenience of testing that can be accomplished by applying 3-point compressive loading using a common laboratory load frame. However, fracture toughness determined by SCB specimen is easily influenced by the size of specimen and rate of loading. Thus, the careful consideration about test condition is required in order to obtain the exact value. Especially there is no clear criteria about the size of specimen for SCB test. Therefore, it is important to make clear the effect of specimen size on fracture toughness by SCB specimen. For these reasons, in this research, SCB test for two kinds of rock with different specimen diameters and SR fracture toughness testing using the ISRM standard method was carried out. This paper describes the size effect by SCB specimen and comparison between the result of SCB fracture toughness testing and SR fracture toughness testing.

2. METHOD
2.1 Mechanical properties
The rock sample adopted in this study is Isahaya sandstone produced in Nagasaki Prefecture, Japan and Kimachi sandstone produced in Shimane Prefecture, Japan. These specimens in various sizes were prepared by various diameter size of core drilling from each rock samples. In order to understand mechanical properties of two kinds of sandstones, uniaxial compression test, diametral compression test and elastic wave test were implemented. The results of these mechanical testing are summarized in Tab. 1. Compared to mechanical properties of their sandstones, the uniaxial compressive strength and tensile strength of Isahaya sandstone is about three times higher than that of Kimachi sandstone.
Tab. 1 Mechanical properties of Isahaya sandstone and Kimachi sandstone

<table>
<thead>
<tr>
<th></th>
<th>Isahaya</th>
<th>Kimachi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus (GPa)</td>
<td>10.69</td>
<td>10.77</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.19</td>
<td>0.26</td>
</tr>
<tr>
<td>Uniaxial compressive strength (MPa)</td>
<td>144.5</td>
<td>50.8</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>9.11</td>
<td>3.78</td>
</tr>
<tr>
<td>P-wave rate (m/sec)</td>
<td>3,200</td>
<td>2,900</td>
</tr>
</tbody>
</table>

2.2 SCB testing

Fig. 1 Model of the SCB specimen

The shape of the SCB specimen is a half disc with an artificial notch (Fig.1). The mode I fracture toughness is evaluated by using Equation (1).

\[ K_{IC} = Y' \sigma_0 \sqrt{\pi a} \] (1)

where
\[ K_{IC} \]: Mode I fracture toughness (MPa√m), \( Y' \): Normalized stress intensity factor, \( a \): Notch length (m), \( \sigma_0 = P/2R t \) (MPa) , \( P \): Maximum load, \( R \): Specimen radius, \( t \): Specimen thickness

Normalized stress intensity factor is calculated by following Equation (2) [5].

\[ Y' = -1.297+9.516(s/2R)- (0.47+16.457(s/2R))\beta + (1.071+34.401(s/2R)) \beta^2 \] (2)

where
\( s \): Span of support rollers (m), \( \beta = a/R \).

2.3 SR testing

The shape of the SR specimen, which incorporated by ISRM, is a columnar form with a chevron notch. In level I, fracture toughness is determined only from the maximum load by the following equation [6], which assumes that the rock is linearly elastic and that the fracture toughness is constant with crack length:

\[ K_{SR} = 24F_{max} / D^{1.5} \] (3)

where
\( K_{SR} \): Level I fracture toughness, \( F_{max} \): Maximum load (kN), \( D \): Specimen diameter (m).

However, since the rock is rarely linearly elastic, a non-linearity correction is made in level II, as previously described. In level II, the evaluation point \( E_k \) (kN), which corresponds to the minimum stress intensity factor, is found from the graph as the point where the stiffness \( S \) decreases to 50% of the initial stiffness \( S_i \) using the linearized unloading line determined for each cycle. The crack extension at this point is about 0.34D from the apex of the chevron notch. Then using the degree of non-linearity \( p \) as shown in Fig. 2, the corrected fracture toughness is determined from the following equation:

\[ K_{SR}^c = \sqrt{(1+ p)/(1- p)} \cdot F_c / F_{max} \cdot K_{SR} \] (4)
2.4 The size of SCB specimen

In order to investigate the size effect on the mode I fracture toughness by SCB specimen, the specimen size shown in the following were prepared.

Isahaya sandstone: 2R = 50, and 75mm
Kimachi sandstone: 2R = 50, 60, 70, and 100mm

The thickness of samples and dimension such as a/R, s/2R are constant in all specimens. All specimens were dried using high-temperature oven before conducting fracture toughness testing.

3. RESULTS AND DISCUSSION

Fig. 4 shows the relationship the size of SCB specimen and fracture toughness. It was found that the fracture toughness of Isahaya sandstone and Kimachi sandstone increased with increasing the specimen diameter. These results lead to the suggestion that the size effect of SCB specimen on fracture toughness was observed in both sandstones. However, in the Kimachi sandstone, it can be seen that the impact of specimen size on fracture toughness was not more remarkable than Isahaya sandstone.

Figs. 5 and 6 are load-displacement curve obtained from SCB fracture toughness testing in Isahaya sandstone. It was found that while the behavior of load-displacement curve was linearly-increasing right before maximum load point in Isahaya sandstone. On the other hand, the behavior of load-displacement curve in Kimachi sandstone was non-linearly-increasing. The results of SR fracture toughness testing are summarized in Tab. 2 and Fig. 7 shows the comparison of fracture toughness evaluated by SCB and SR fracture toughness testing. For these results, it was found that the fracture toughness obtained from SCB specimen in 2R=50mm was nearly equal to KIc. By contrast, the fracture toughness evaluated by SCB specimen in 2R=75mm was about equal to KIc. It is considered that these results caused by the effect of process zone. Process zone means the area generated macro cracks growth near the crack tip. The SCB specimen in 2R=50mm is influenced by process zone because the behavior of load-displacement shows non-linearly-increasing. In this case, it can be considered that some corrections or improvement have to be applied to obtain the exact fracture toughness as well as SR testing. On the other hand, the specimen size in 2R=75mm shows the behavior of linearly-increasing in load-displacement curve. Therefore, fracture toughness evaluated by 2R=75mm was comparable in magnitude to level II fracture toughness due to less effect of process zone. Considering these results, appropriate predicting the range of process zone have to be needed in order to determine the exact fracture toughness in SCB testing.
Fracture toughness by SR specimen

<table>
<thead>
<tr>
<th>$K_{SR}$ (MPa$\cdot\sqrt{m}$)</th>
<th>$p$</th>
<th>$K_{SR}$ (MPa$\cdot\sqrt{m}$)</th>
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<tbody>
<tr>
<td>1.00</td>
<td>0.390</td>
<td>1.59</td>
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Fig. 7 Comparison between SCB testing and SR testing

The size effect of SCB specimen on fracture toughness was discussed by several researchers and the minimum size requirement was proposed as Equation (4) [4]:

$$D \geq 2.0 \left( \frac{K_{Ic}}{\sigma_t} \right)^2$$  \hspace{1cm} (4)

where $\sigma_t$: Tensile strength

According to Equation (4), the minimum diameters in Isahaya sandstone are $2R=60\text{mm}$. The specimen in $2R=75\text{mm}$ can meet the Equation (4) though the specimen in $2R=50\text{mm}$ did not satisfy. For this reason, it seems that fracture toughness evaluated by $2R=75\text{mm}$ was comparable in magnitude to level II fracture toughness. In case of Kimachi sandstone, the minimum diameter of specimen was calculated to 198mm by Equation (4). Any specimens are not satisfied the requirement because the largest diameter in this study is 100mm. It seems that this could be attributed to differences in tensile strength. That is to say, tensile strength of Kimachi sandstone is lower than that of Isahaya sandstone. In this case, some considerations have to be needed such as the correction of results by degree of non-linearity $p$, or crack length on the evaluation point of fracture toughness is evaluated by the process zone size.

4. CONCLUSIONS

The fracture toughness by SCB specimen is affected by specimen size with both Isahaya and Kimachi sandstone. The fracture toughness is increasing with increasing specimen radius. For the comparison to fracture toughness by SR specimen, in satisfying the Equation (4), fracture toughness by SCB specimen shows same level with the fracture toughness by SR specimen. However, it is also indicated that the determining the exact fracture toughness is difficult in SCB specimen in weak tensile strength. In order to evaluate fracture toughness accurately, the more detailed studies such as some corrections of the value and effect of process zone have to be needed.

REFERENCES