Estimation of Fracture Toughness of Sandstone by Three Testing Methods

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Abstract

Several testing methods have been proposed for evaluating the mode I fracture toughness of rocks. Since the fracture toughness of rocks estimated from the different testing methods is generally not compared, it is still not well-known the effect of type of the testing methods on the fracture toughness. Therefore, in this paper, three testing methods, chevron bend (CB) test, semi-circular bend (SCB) test and straight notched disk bending (SNDB) test, were performed using Kimachi sandstone in order to evaluate the mode I fracture toughness. The CB specimen is cylindrical shape with a V-shaped notch, called chevron notch, perpendicular the specimen axis. The SCB specimen is a semi-circular disk and has a straight edge notch throughout the specimen thickness. In the SNBD test, a circular disk specimen with a straight edge notch throughout the diameter is used. In a series of tests, load was applied by three-point bending to produce the tensile stress state at the notch tip indirectly for all the specimens, and controlled by the constant displacement rate. As a result, the average fracture toughness was estimated as 0.64 $MN/m^{3/2}$ in the CB test, 0.66 $MN/m^{3/2}$ in the SCB test, and 0.46 $MN/m^{3/2}$ in the SNDB tests, respectively. The fracture toughness obtained from the CB and SCB tests were compatible each other. However, the SNDB tests estimated lower value of the fracture toughness than the others. Based on the results, the differences of the fracture toughness obtained from the three testing methods were discussed.

Keywords: Mode I fracture toughness, Chevron bend (CB) test, Semi-circular bend (SCB) test, Straight notched disk bending (SNDB) test, Kimachi sandstone

1. Introduction

Fracture toughness is one of the basic material properties in linear elastic fracture mechanics, and indicates the resistance to crack initiation. For brittle materials such as rocks, estimation of the fracture toughness is important for understanding of the fracture process. It has been applied as a parameter for classification of rock materials, an index for rock fragmentation, and a material property in interpretation of geological features and in stability analysis of rock structures, as well as in modeling of fracturing of rocks (Whittaker et al., 1992).

Several testing methods have been proposed for evaluating the mode I fracture toughness of rocks, such as the short rod (SR) test (Barker, 1977), chevron bend (CB) test (Ouchterlony, 1980), cracked chevron notched Brazilian disk (CCNBD) test (Shetty et al., 1985), cracked straight through Brazilian disk (CSTBD) test (Atkinson et al., 1982), semi-circular bend (SCB) test (Chong and Kurruppu, 1984), and straight notched disk bending (SNDB) test (Tutluoglu and Keles, 2011). The SR, CB, CCNBD and SCB tests have been suggested for determining the mode I fracture toughness by International Society for Rock Mechanics (ISRM) (ISRM, 1988; 1995; Kuruppu et al., 2014). Since the fracture toughness obtained from the different testing methods is generally not compared (Ouchterlony, 1982), it is still not well-known the effect of type of the testing methods on the fracture toughness of rocks.

In this paper, three types of fracture toughness tests, the CB, SCB and SNDB test, were performed using Kimachi sandstone in order to evaluate the mode I fracture toughness. Based on the results, the fracture toughness obtained from these testing methods was compared with each other, and the differences of the values were discussed.

2. Experimental method and procedure

2.1 Fracture toughness tests

The CB, SCB and SNDB test were performed to evaluate the mode I fracture toughness of the rock. As shown in Fig.1, these specimens are core-based type. The CB specimen has a V-shaped notch, called chevron notch, as shown in Fig.1 (a). In the SCB and SNDB test, a specimen with a straight edge notch is used, as shown in Fig.1 (b) and (c). Load is applied by three-point bending for all the specimens. The chevron notch causes crack initiation at the tip of the V and this crack proceeds in the notch plane in a slow and stable manner. In the straight edge notch, crack initiates and then propagates rapidly just after the initiation. The mode I fracture toughness K_{Ic} is evaluated using Eqs. (1), (2) and (3) in the CB, SCB and SNDB test, respectively (ISRM, 1988; Kuruppu et al., 2014; Tutluoglu and Keles, 2011).

$$K_{\mathrm{Ic}} = Y_{\mathrm{I}} \frac{P_{\max}}{d^{1.5}} \quad \text{in CB test} \tag{1}$$

$$K_{\mathrm{Ic}} = Y_{\mathrm{I}} \frac{P_{\max}\sqrt{\pi a}}{2rt} \quad \text{in SCB test} \tag{2}$$

$$K_{\mathrm{Ic}} = Y_{\mathrm{I}} \frac{P_{\max}\sqrt{\pi a}}{2td} \quad \text{in SNDB test} \tag{3}$$

where $P_{\max}$ is the maximum load, and d, a, r, and t are the diameter, notch length, radius, and thickness of each specimen, respectively. Y_{I} is dimensionless stress intensity factor depended on the specimen geometry and given by a function of the specimen dimensions and the loading span (ISRM, 1988; Kuruppu et al., 2014; Tutluoglu and Keles, 2011).

The geometrical dimensions of the CB and SCB specimens and its loading span as shown in Fig.1 (a) and (b) satisfy the ISRM suggested values (ISRM, 1988; Kuruppu et al., 2014). For the SNDB specimen, the values of t/r and a/t recommended by Tutluoglu and Keles (2011) were used.

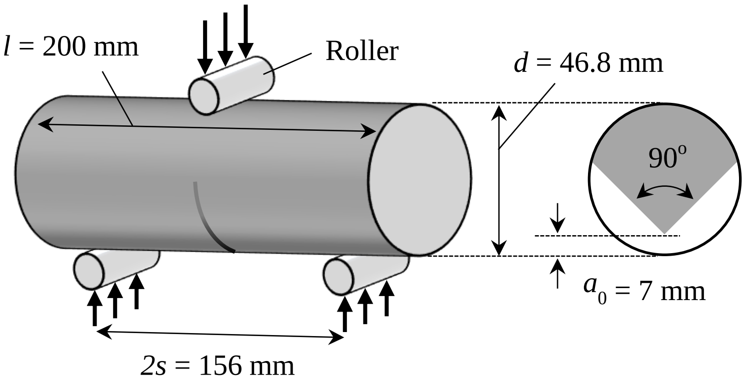
2.2 Specimen and its preparation

Kimachi sandstone, which is tuffaceous sandstone produced in Japan, was used as a test material. The grains composed of this rock are mainly andesitic clastics with the average diameter of 0.4 to 0.6 mm (Kataoka et al., 2012). The porosity of this rock is approximately 20 % (Takahashi et al., 2011). The other material properties are summarized in Table 1.

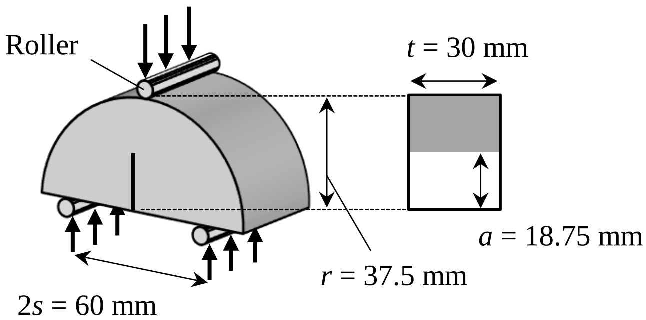
The CB, SCB and SNDB specimens were prepared from cores with each diameter drilled from blocks of this rock. For the CB specimens, the ends of the cores were cut off to form cylinders with the specified length. For the SCB and SNDB specimens, the cores were cut into disks. In the case of the SCB specimen, each disk was cut into halves to form two semi-circular specimens. Finally, the chevron or straight edge notch was produced using a diamond blade with a thickness of 1.5 mm, 1 mm or 0.4 mm in the CB, SNDB, or SCB specimens, respectively. The direction of the notches was normal to the bedding plane for all the specimens. After the preparation, they were kept in an electric drying oven at 60 $^{\circ}$C for more than 30 days before the tests in order to remove the water within the specimens.

Table 1 Material properties of Kimachi sandstone (Kataoka and Obara, 2015).

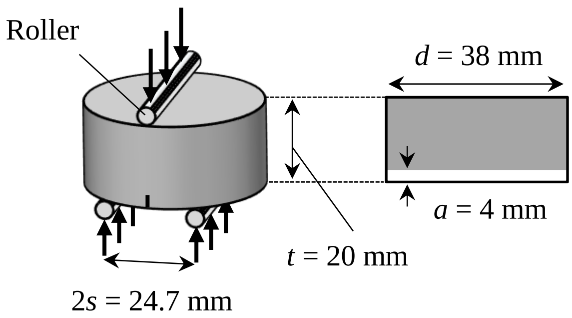
Material property	Values
Uniaxial compressive strength (MPa)	59.3
Young’s modulus (GPa)	7.7
Poisson’s ratio	0.22
Tensile strength (MPa)	6.17
Density (g/cm^3)	2.23
Elastic wave velocity (km/sec)	2.6-2.9



(a) CB specimen



(b) SCB specimen



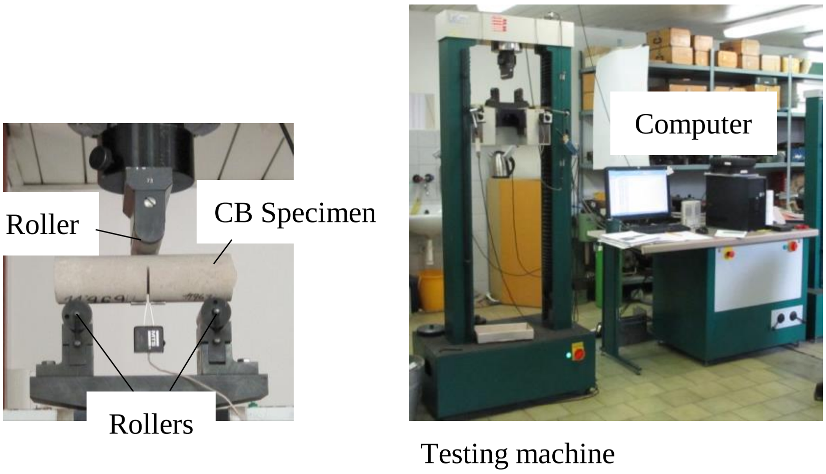
(c) SNDB specimen

Fig.1. Specimens and loading configuration;
d diameter, *l* length, *r* radius, *t* thickness, a_0 initial notch length, *a* notch length.

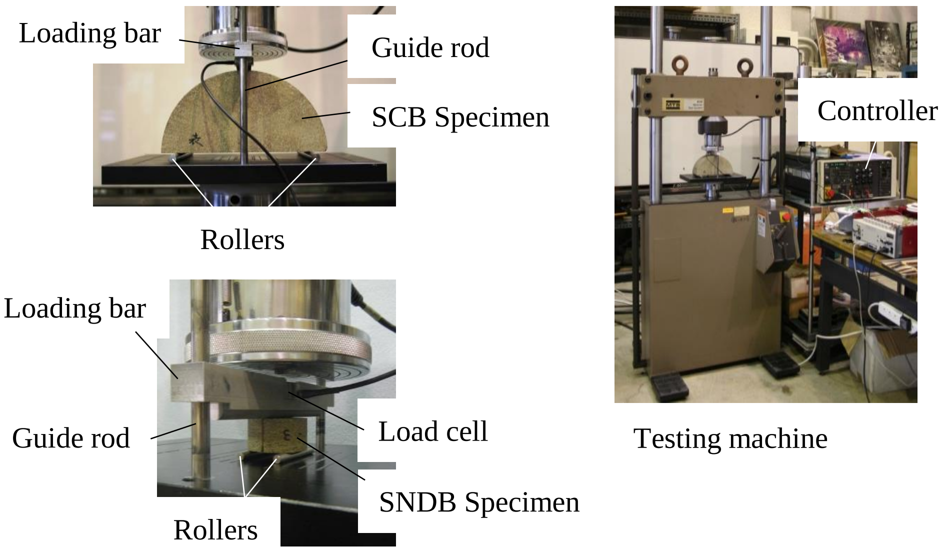
2.3 Testing systems and conditions

Fig.2 shows loading setups for the specimens and testing machines used. In the CB test, the specimen was placed on two support rollers set on a testing machine as shown Fig.2 (a). One roller was attached to the upper frame of the testing machine. During the test, the load was applied to the specimen through these rollers and measured using the load cell equipped at the testing machine. On the other hand, the loading apparatus as shown in Fig.2 (b) was used in the SCB and SNDB tests. The specimen was placed on two support rollers. A loading bar, which can move up and down vertically aided by guide rods, with a roller was put on the upper loading point of the specimen. The specimen was loaded through the upper and bottom rollers. The load was measured using the load cell equipped at the loading bar. The loading apparatus with the specimen was placed at the testing machine.

The displacement was controlled by a constant rate ranging from 0.001 to 0.1 mm/min in all the tests. It was found that these low displacement rates do not affect the fracture toughness value (Lim et al., 1994; Kataoka et al., 2014).



(a) CB test



(b) SCB and SNDB tests

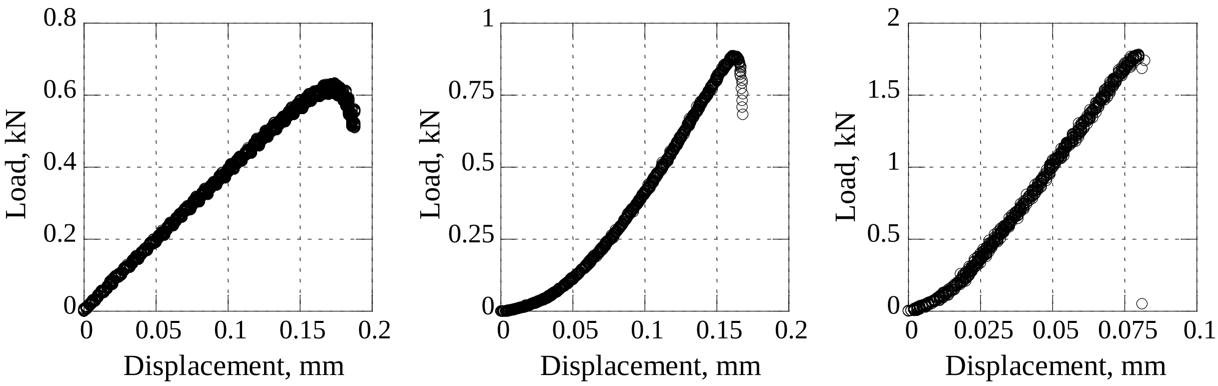
Fig. 2. Setup of specimen with loading apparatus placed on testing machine.

3. Results and discussion

Examples of load-displacement curves in the CB, SCB and SNDB tests are shown in Fig.3. The curves, except those of the SCB and SNDB test at a low load level, were linear until a specimen fractured at the maximum load P_{max}.

A series of tests were performed using al least 4 specimens for each test type. The mode I fracture toughness K_{Ic} evaluated by the three tests is shown in Fig.4. Some plots are small shifted in lateral axis for clarity in this figure. The average fracture toughness was estimated as 0.64 MN/m$^{3/2}$ in the CB test, 0.66 MN/m$^{3/2}$ in the SCB test, and 0.46 MN/m$^{3/2}$ in the SNDB tests, respectively. The values obtained from the SCB tests are almost same as those from the CB tests and larger than those from the SNDB tests.

Kataoka and Obara (2015) investigated the effect of the specimen size on K_{Ic} in the SCB test, using the specimens which have the radius r ranged from 12.5 to 150 mm with the thickness t given by t = 0.8r. The experimental results showed that K_{Ic} increased with increasing r in a range less than approximately 70 mm of r. Based on this result, it is considered that the fracture toughness evaluated by the CB and SNDB tests is also dependent on its specimen size. In this discussion, a specimen size in the direction of the fracture propagation, namely d, r, and t for the CB, SCB and SNDB specimens, respectively, was focused on as a representative geometrical dimension. The dimension of the SCB specimen (r = 37.5 mm) was similar to that of the CB specimen (d = 46.8 mm), while that of the SNDB specimen (t = 20 mm) was less than those of the two tests. These differences of the dimension may induce the differences of K_{Ic} evaluated by the three tests shown in Fig.4. The experimental results may be interpreted, based on the specimen size effect in the CB and SNDB tests, and understanding of the size effect is needed as a further study.



(a) CB specimen (b) SCB specimen (c) SNDB specimen

Fig. 3. Examples of load-displacement curves.

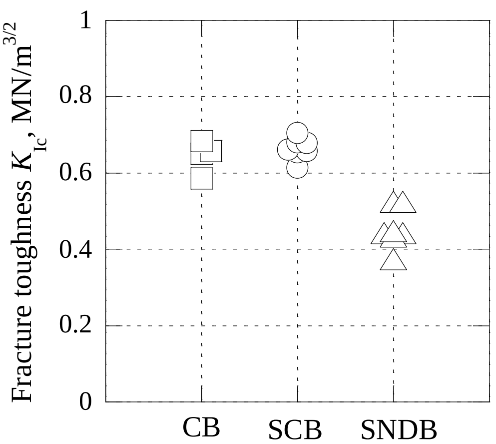


Fig. 4. Mode I fracture toughness obtained by the three tests.

4. Conclusions

In this paper, three types of fracture toughness tests, the chevron bend (CB) test, semi-circular bend (SCB) test and straight notched disk bending (SNDB) test, were performed using Kimachi sandstone in order to evaluate the mode I fracture toughness K_{Ic}. As a result, the values obtained from the SCB tests were almost same as those from the CB tests and larger than those from the SNDB tests. It is concluded that the differences of K_{Ic} obtained from the three testing methods were produced from the size effect of the specimens.

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