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報告
Technical Report

Effect of Testing Method Type and Specimen Size on Mode I Fracture Toughness of Kimachi Sandstone*

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Several testing methods have been proposed for evaluating the mode I fracture toughness of rocks. Since the fracture toughness evaluated from the different testing methods is generally not compared, what is still not well-known is the effect of the testing method type on the fracture toughness. The effect of not only the testing method type but also the specimen size exists in the fracture toughness of rock materials. To clarify the effect of the testing method type and specimen size on the fracture toughness, many fracture toughness tests were performed in the previous experimental studies. However, the effect has not been elucidated because the number of the specimens is limited and the range of the specimen size is relatively small in the previous works. In this paper, firstly, three types of the fracture toughness test, the chevron bend (CB) test, semi-circular bend (SCB) test and straight notched disk bending (SNDB) test, were performed using Kimachi sandstone. Then, the SCB test was carried out using the same sandstone with various specimen sizes. As a result, 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. From the results of the SCB tests with various specimen sizes, the fracture toughness increased with increasing radius. Based on the results, the effect of the specimen size on the fracture toughness and the differences of the fracture toughness obtained from the three testing methods were discussed.
KEY WORDS: Mode I Fracture Toughness, Testing Method Type, Specimen Size, Kimachi Sandstone

1. Introduction

Fracture toughness is a basic material parameter in linear elastic fracture mechanics for a wide range of brittle materials, including rocks. It is considered to be an intrinsic material property and defined as the resistance to crack initiation. The fracture toughness of rocks has been applied as a parameter for classification of rock materials, an index for rock fragmentation, and a rock material property in the interpretation of geological features and in the stability analysis of rock structures, as well as in modelling rock fracturing[1, 2].

Several testing methods for evaluating the rock fracture toughness under mode I loading (opening mode) have been proposed, such as the short rod (SR) test[3], chevron bend (CB) test[4], single edge crack round bar in bending test[4, 5], cracked chevron notched Brazilian disk (CCNBD) test[6], cracked straight through Brazilian disk (CSTBD) test[7, 8], semi-circular bend (SCB) test[9], and straight notched disk bending (SNDB) test[10]. These specimens are of the core-based type with an artificial notch. The specimen shape (cylinder, disk or semi-circular disk typed), the notch shape (the chevron or straight edge), and the notch direction (along or perpendicular to the core axis) are different with each testing method, as well as the loading configuration (direct tensile loading, three- or four-point bending or Brazilian type compressive loading). The International Society for Rock Mechanics (ISRM) suggested the SR test, CB test, CCNBD test and SCB test for determining the mode I fracture toughness of rocks[11-13]. Since the fracture toughness evaluated from the different testing methods is generally not compared[11, 12, 14], what is still not well-known is the effect of the testing method type on the fracture toughness of rocks.

The determined fracture toughness of rocks is also changed with the specimen size. It is well known that the uniaxial compressive strength and tensile strength of rocks vary significantly with specimen size. A larger specimen has a greater number of flaws such as microcracks, grain boundaries and pores, thus the likelihood of having weaker flaws is greater. As a result, these measures of mechanical strength tend to be low for larger specimens. This explanation was described by Bieniawski[15] for the compressive strength of coal. To clarify the effect of the specimen size on the fracture toughness of rocks, many fracture toughness tests were performed using various specimen sizes[16-19]. However, the effect of size on the fracture toughness has not been made clear until now because, in the previous experimental studies, the range of the specimen size is relatively small and it was difficult to discuss about size effect sufficiently. Experimental work is required, especially evaluating the fracture toughness using specimens with a wider range of the sizes.

The objective of this study is to investigate the effect of the testing method type and the specimen size on the mode I fracture toughness of rocks. Firstly, three types of fracture toughness tests, the CB test, SCB test and SNDB test, were

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performed using Kimachi sandstone[20]. Secondly, the SCB test was performed using the same sandstone with various specimen sizes[21]. The fracture toughness values evaluated by these tests were compared with each other, and the effect of the size of the SCB specimen was discussed. Based on these experimental results, an explanation of the trend of the effect of the testing method type and the specimen size on the fracture toughness were presented.

2. Fracture toughness tests

2・1 Chevron bend (CB) test

The geometry of the CB specimen with loading configuration is illustrated in Fig. 1 (a). The specimen is a cylindrical shape with a V-shaped artificial notch, called a chevron notch. Load is applied in three-point bending to produce indirectly the tensile stress state at the notch tip. The fracture initiates at the tip of the V in the chevron notch in a stable manner until the applied load reaches its maximum value $P_{\max}$ then unstable crack propagation takes place. The corresponding crack length is called the critical crack length a, at which the fracture toughness is evaluated. It is one of the suggested methods by ISRM[11].

The mode I fracture toughness K_{Ic} can be calculated from $P_{\max}$ as follows:

$$K_{\mathrm{Ic}} = Y_{\mathrm{Imin}} \frac{P_{\max}}{d^{1.5}} \quad \cdots\cdots (1)$$

where Y_{Imin} is a minimum normalized stress intensity factor and d is a specimen diameter. Y_{Imin} is independent of material properties of the tested material and a function of a dimensionless initial notch length a_0/d and support span to diameter ratio $2s/d$, as follows:

$$Y_{\mathrm{Imin}} = \left\{1.835 + 7.15\frac{a_0}{d} + 9.85\left(\frac{a_0}{d}\right)^2\right\}\frac{2s}{d}$$

2・2 Semi-circular bend (SCB) test

The geometry of the SCB specimen is shown in Fig. 1 (b). This specimen is a semi-circular disk and has a straight edge notch throughout the specimen thickness which required relatively little machining effort. Load is applied in three-point bending. Its compact shape formed by cutting a core into slices and duplicating semi-circular disks is suitable for conveniently investigating the effect of various parameters such as loading rate, moisture content, and temperature on the fracture toughness of rocks[17, 22-26]. This test was also added to the ISRM-suggested methods[13].

K_{Ic} is estimated using the following equation:

$$K_{\mathrm{Ic}} = Y_{\mathrm{I}} \frac{P_{\max}\sqrt{\pi a}}{2rt} \quad \cdots\cdots (2)$$

where Y_{I} is a normalized stress intensity factor, a is a notch length of the specimen, r is a specimen radius, and t is a specimen thickness. Y_{I} is dimensionless and given as a function of a/r and s/r, as follows:

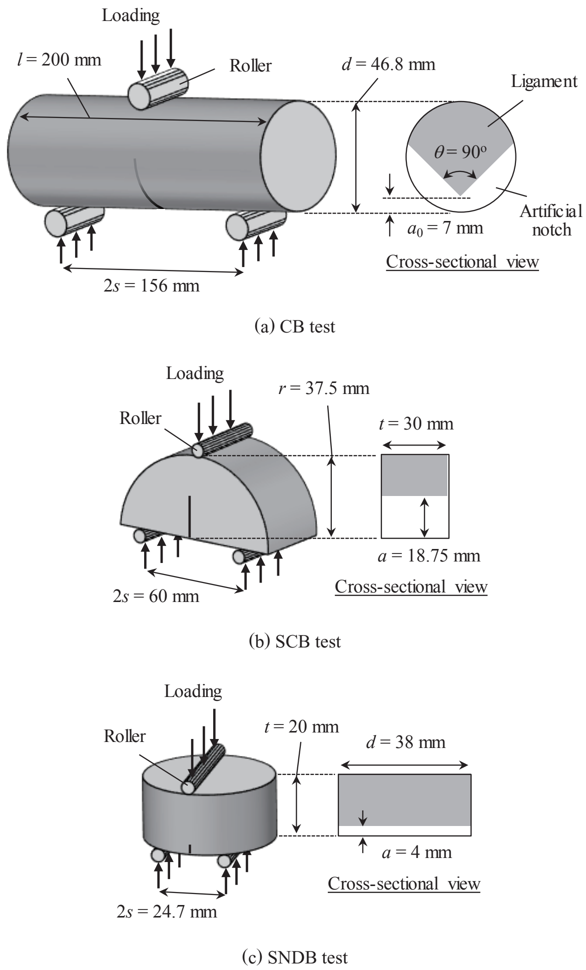

Fig.1 Specimens and loading configuration.

$$Y_{\mathrm{I}} = -1.297 + 9.516\frac{s}{r} - \left(0.47 + 16.457\frac{s}{r}\right)\frac{a}{r} + \left(1.071 + 34.401\frac{s}{r}\right)\left(\frac{a}{r}\right)^2$$

2・3 Straight notched disk bending (SNDB) test

The geometry of the SNDB specimen is shown in Fig. 1 (c). A disk specimen with a straight edge notch throughout the diameter is under three-point bending load. There are few practical experiments using this test, however, this test has an advantage that three-dimensional disk type geometry is inherently stiffer than other types of geometry[10].

K_{Ic} is evaluated using the following equation:

$$K_{\mathrm{Ic}} = Y_{\mathrm{I}} \frac{P_{\max}\sqrt{\pi a}}{2td} \quad \cdots\cdots (3)$$

Y_{I} for the SNDB specimen is given as a function of a/t, t/r and s/r, as follows:

$$Y_{\mathrm{I}} = m\frac{s}{r} + n$$

where m and n are dependent on t/r and a/t and listed in the reference[10].

3. Experimental methods

3・1 Specimen

Kimachi sandstone used for testing work is tuffaceous sa-

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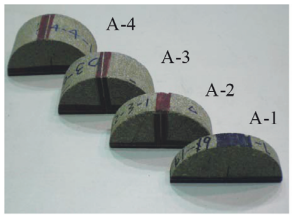
Table 1 Material properties of Kimachi sandstone[20].

Material property	Values
Uniaxial compressive strength	59.3 MPa
Young's modulus	7.7 GPa
Poisson's ratio	0.22
Tensile strength	6.17 MPa
Elastic wave velocity	2.6–2.9 km/s

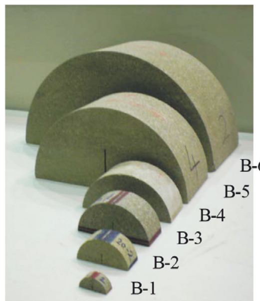
Table 2 Geometrical parameters of SCB specimens with various sizes.

Group	Radius r (mm)	Thickness t (mm)	t/r	Notch length a* (mm)	Number of specimens
A-1	37.5	10	0.27	18.8	7
A-2	37.5	20	0.53	18.8	5
A-3	37.5	30	0.8	18.8	7
A-4	37.5	37.5	1	18.8	7
B-1	12.5	10	0.8	6.25	7
B-2	25	20	0.8	12.5	7
B-3	37.5	30	0.8	18.8	7
B-4	50	40	0.8	25	7
B-5	100	80	0.8	50	6
B-6	150	120	0.8	75	6

*a/r = 0.5 for all the specimen.



(a) Group-A specimens



(b) Group-B specimens

Fig.2 Photographs of SCB specimens with various sizes[21].

ndstone. The grains are mainly andesite clastics with average diameters of 0.4–0.6 mm[23]. The porosity of this rock is approximately 20 % [27]. Other material properties of Kimachi sandstone are summarized in Table 1.

The CB, SCB and SNDB tests were performed as a series of "Experiment-T", to examine the effect of the testing method type on K_{Ic} of a rock. The size of the CB and SCB specimens used in this study illustrated in Figs.1 (a) and (b) satisfied the ISRM-suggested dimensions[11, 13]. The dimension ratios recommended by Tutluoglu and Keles[10] were used in the SNDB specimen as shown in Fig. 1 (c) (t/r = 1.05 and a/t = 0.2). Four of the CB specimens and seven of the SCB and SNDB specimens were prepared and used in this study.

The effect of the specimen size was considered in the SCB test only. A series of SCB tests using specimens with various sizes were performed as a series of "Experiment-S". The geometrical parameters of the specimens are summarized in Table 2. In "Group-A", the specimen thickness t was changed from 10 to 37.5 mm with a constant specimen radius r of 37.5 mm as shown in Fig. 2 (a). In "Group-B", r was changed from 12.5 to 150 mm with a constant t/r of 0.8 as shown in Fig. 2 (b). These ranges are wider than the other past studies[16-18]. The notch length a was given by a/r = 0.5 for all the specimens. The SCB specimens used in Experiment-T were as the specimens of Group-A-3 and Group-B-3 in Experiment-S.

For the preparation of the specimens, rock cores with specific diameters were prepared for each testing method type: 46.8 mm for the CB test, 38 mm for the SNDB test, and, for the SCB test, various diameters were used as shown in Table 2. For the specimens of Group-B-5 and Group-B-6 in Experiment-S, rock blocks were cut and scraped to form cylindrical shapes with diameters of 20 and 30 cm, respectively. Then, for the CB specimens, each end of the cores was cut off to form cylinders with a length l of approximately 200 mm. For the SCB specimens, cores were cut into disks of a given thickness and each disk was cut into halves to form two semi-circular specimens. For the SNDB specimens, cores were cut into disks with a thickness t of 20 mm. Finally, the chevron or straight edge notch was produced using a diamond blade in the CB, or SCB and SNDB specimens, respectively. The thickness of the notch is 1.5 mm in the CB specimens and 1 mm in the SNDB specimens. As for the SCB specimens, those in Group-B-5 and Group-B-6 had a notch thickness of 1 mm, and those in other groups was 0.4 mm. The direction of the notch was normal to the sedimentation for all the specimens. In ISRM-suggested[13] the thickness of the notch is preferred less than 1.5∓0.2mm. After the preparation, the specimens were dried in an electric drying oven at 60 °C for more than 30 days before the tests to remove the water from within the specimens.

3・2 Testing system and experimental conditions

Three-point bend type loading apparatuses and testing machines used in the CB, SCB, and SNDB tests are shown in Fig. 3. The CB specimen was placed on two bottom support rollers set on the testing machine with a capacity of 100 kN (FPZ 100, VEB Thuringer Industriawerk) as shown in Fig. 3 (a). The support span 2s is shown in Fig. 1 (a) and the value of s/r is 3.33. An upper roller is attached to the upper platen of the testing machine and loads to the specimen. The load was measured using a load cell equipped at the testing machine.

In the SCB and SNDB tests, each specimen was placed on two support rollers of a loading apparatus as shown in Fig. 3 (b). The value of s/r was 0.8 and 0.65 in all the SCB and SNDB tests, respectively. A loading bar which can move up and down vertically aided by guide rods is put on the upper loading point of the specimen. Load was applied in three-point bending. The load was measured using a load cell equipped at the loading bar. The loading apparatus was placed at the testing machine with a capacity of 100 kN (MTS 810, MTS Systems Corporation).

The load application was controlled by a constant displacement rate. The displacement rate in Experiment-T was 0.01 mm/min in the CB and SCB test, and 0.001 or 0.1 mm/min in the SNDB tests, respectively. In the SCB tests of Experiment-S, to suit the fracture time for the various sizes of the specimens, the displacement rate was in proportion to the specimen radius r, as r/3750 mm/min. As a result, the displacement rate was 0.0033 mm/min for Group-B-1 specimens (r = 12.5 mm) and 0.04 mm/

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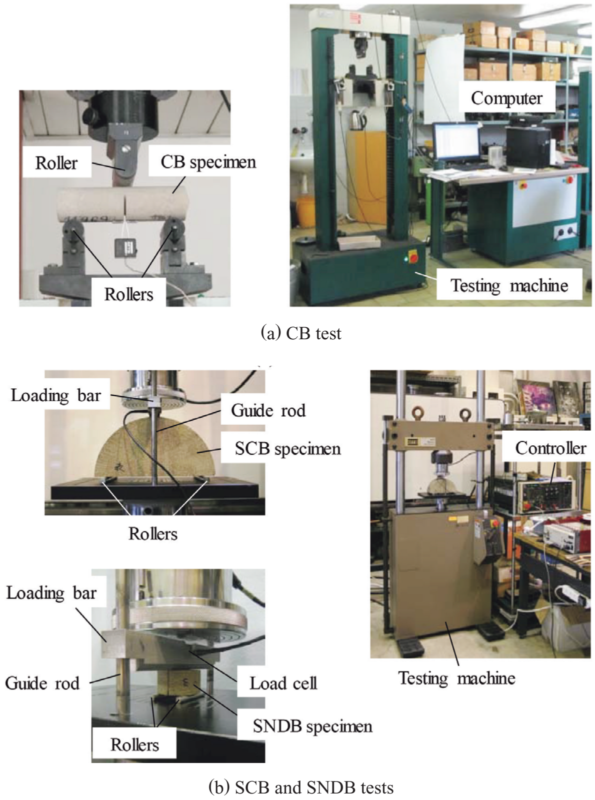

Fig.3 Setup of specimen with loading apparatus placed on testing machine[20].

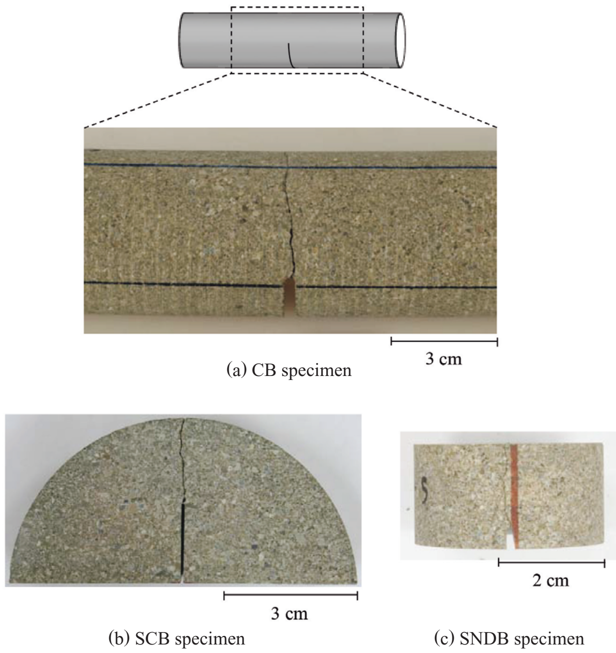

Fig.4 Photographs of specimens after the tests.

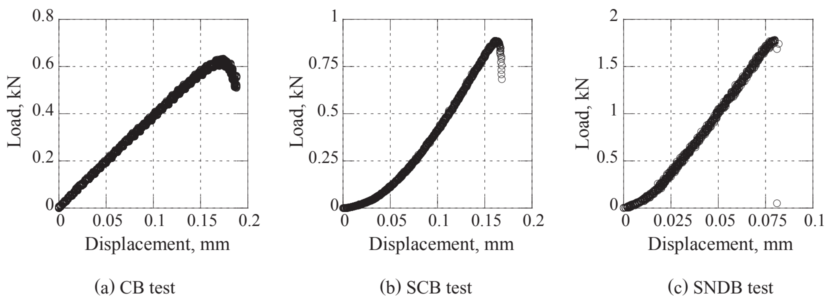

Fig.5 Example of load-displacement curves.

min for Group-B-6 specimens (r = 150 mm), and the fracture time fell within 12 to 20 min for all the specimens. Moreover, these low displacement rates do not affect the fracture toughness value[17, 24]. All the tests were performed at room temperature.

4. Results

An example of fractured specimens after the CB, SCB and SNDB tests is shown in Fig. 4. The fracture propagated from the notch tip to the upper loading point. An example of load-displacement curves is shown in Fig. 5. The curves, except those of the SCB and SNDB tests at a low load level, are linear until a specimen fractured at the maximum load P_{max}.

All of the results of the CB, SCB, and SNDB tests in Experiment-T and the SCB tests in Experiment-S are summarized in Tables 3-5 and 6-7, respectively. Then the summarized results of each test are shown in Tables 8 and 9 with ideal scale values of specimen and average, standard deviation of fracture toughness.

As a result of the CB, SCB, and SNBD tests in Experiment-T (Tables 3-5), K_{Ic} obtained from the SCB tests were almost the same as those from the CB tests and larger than those from the SNDB tests. The results of the two ISRM-suggested methods (the CB and SCB tests) were compatible with each other. However, the SNDB test estimated a lower value of K_{Ic} than the others.

The result of the SCB tests using the specimens in Group-A of Experiment-S in Table 6, which had a thickness t ranging from 10 to 37.5 mm with a constant radius r of 37.5 mm, is shown in Fig. 6. K_{Ic} was almost constant at different thicknesses. The average K_{Ic} value for all specimens in Group-A was 0.64 MN/m$^{3/2}$. Although K_{Ic} varied widely in the case of smaller thicknesses, the scattering became smaller in a range larger than 30 mm of thickness. The ISRM-suggested method[13] recommended thickness is larger than 0.8 times of radius, or 30 mm. The test result was compatible with the suggested method.

The test result obtained from the specimens in Group-B in

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Table 3 Results of CB test in Experiment-T.

No.	d (mm)	l (mm)	a_0/d	Y_{Imin}	P_{max} (N)	K_{Ic} (MN/m$^{3/2}$)
CB-1	46.8	197	0.15	10.4	568	0.585
CB-2	46.8	198	0.15	10.4	633	0.651
CB-3	46.8	197	0.15	10.4	640	0.658
CB-4	46.8	201	0.15	10.4	665	0.684

Table 4 Results of SCB test in Experiment-T.

No.	r (mm)	t (mm)	a (mm)	Y_I	P_{max} (N)	K_{Ic} (MN/m$^{3/2}$)
SCB-1	37.5	30.9	18.7	6.63	887	0.614
SCB-2	37.5	30.4	18.8	6.65	924	0.654
SCB-3	37.5	30.4	18.8	6.65	928	0.658
SCB-4	37.5	31.5	18.7	6.61	976	0.661
SCB-5	37.5	30.9	18.6	6.59	986	0.677
SCB-6	37.5	30.9	18.6	6.57	991	0.680
SCB-7	37.5	30.0	18.7	6.61	991	0.705

Table 5 Results of SNDB test in Experiment-T.

No.	d (mm)	t (mm)	a (mm)	Y_I	P_{max} (kN)	K_{Ic} (MN/m$^{3/2}$)
SNDB-1	38.0	20.0	4.0	3.41	1.49	0.374
SNDB-2	38.0	20.0	4.0	3.41	1.76	0.442
SNDB-3	38.0	20.0	4.0	3.41	1.76	0.443
SNDB-4	38.0	20.0	4.0	3.41	1.72	0.433
SNDB-5	38.0	20.0	4.0	3.41	1.78	0.447
SNDB-6	38.0	20.0	4.0	3.41	2.09	0.524
SNDB-7	38.0	20.0	4.0	3.41	2.09	0.525

Table 6 Results of SCB test in Experiment-S: Thickness.

No.	r (mm)	t (mm)	a (mm)	Y_I	P_{max} (N)	K_{Ic} (MN/m$^{3/2}$)
A-1-1	37.5	10.5	18.70	6.63	252	0.515
A-1-2	37.5	12.5	18.65	6.61	301	0.516
A-1-3	37.5	11.0	18.70	6.63	296	0.577
A-1-4	37.5	10.1	18.70	6.63	295	0.625
A-1-5	37.5	12.5	18.70	6.63	371	0.636
A-1-6	37.5	11.0	18.75	6.65	330	0.647
A-1-7	37.5	10.9	18.80	6.67	370	0.733
A-2-1	37.5	20.8	18.60	6.59	491	0.502
A-2-2	37.5	21.7	18.70	6.63	594	0.587
A-2-3	37.5	20.5	18.65	6.61	582	0.605
A-2-4	37.5	19.9	18.75	6.65	607	0.656
A-2-5	37.5	21.7	18.85	6.69	701	0.701
A-4-1	37.5	38.3	18.65	6.61	1074	0.598
A-4-2	37.5	37.8	18.75	6.65	1133	0.645
A-4-3	37.5	39.5	18.75	6.65	1172	0.638
A-4-4	37.5	38.1	18.65	6.61	1152	0.646
A-4-5	37.5	38.3	18.70	6.63	1197	0.669
A-4-6	37.5	38.0	18.75	6.65	1233	0.698
A-4-7	37.5	38.1	18.65	6.61	1250	0.701

The results in Group-A-3 are shown in Table 4 as the results obtained from Experiment-T.

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Table 7 Results of SCB test in Experiment-S: Radius.

No.	r (mm)	t (mm)	a (mm)	Y_I	P_{max} (N)	K_{Ic} (MN/m$^{3/2}$)
B-1-1	12.5	10.5	6.4	6.77	95	0.344
B-1-2	12.5	10.7	6.3	6.71	120	0.427
B-1-3	12.5	10.1	6.4	6.77	118	0.445
B-1-4	12.5	10.6	6.4	6.83	122	0.446
B-1-5	12.5	10.7	6.4	6.83	126	0.458
B-1-6	12.5	10.6	6.3	6.71	131	0.469
B-1-7	12.5	10.6	6.5	6.89	133	0.495
B-2-1	24.7	19.7	12.3	6.61	384	0.513
B-2-2	24.7	19.8	12.3	6.61	408	0.543
B-2-3	24.7	20.0	12.4	6.67	411	0.547
B-2-4	24.7	20.1	12.4	6.64	418	0.551
B-2-5	24.7	20.0	12.5	6.70	425	0.570
B-2-6	24.7	20.3	12.2	6.55	457	0.586
B-2-7	24.7	19.8	12.4	6.67	455	0.614
B-4-1	49.8	41.1	22.6	6.00	1754	0.684
B-4-2	49.8	40.8	24.9	6.64	1598	0.730
B-4-3	49.8	40.8	22.8	6.06	1822	0.727
B-4-4	49.8	40.5	22.8	6.06	1847	0.743
B-4-5	49.8	40.5	25.0	6.67	1622	0.752
B-4-6	49.8	40.8	22.7	6.03	1988	0.788
B-4-7	49.8	40.9	25.3	6.76	1756	0.822
B-5-1	100	80.3	56.7	7.77	3740	0.764
B-5-2	100	80.8	56.5	7.74	4078	0.823
B-5-3	100	81.4	53.6	7.22	4680	0.852
B-5-4	100	80.8	52.5	7.04	4875	0.863
B-5-5	100	80.1	56.7	7.77	4291	0.878
B-5-6	100	81.6	52.2	6.99	5289	0.917
B-6-1	150	121	83.1	7.53	7744	0.823
B-6-2	150	121	84.5	7.70	7915	0.867
B-6-3	150	120	84.0	7.64	7996	0.871
B-6-4	150	121	85.3	7.81	7923	0.884
B-6-5	150	120	83.5	7.59	8241	0.888
B-6-6	150	121	82.5	7.47	8468	0.889

The results in Group-B-3 are shown in Table 4 as the results obtained from Experiment-T.

Table 8 Summarized results of CB, SCB and SNDB tests in Experiment-T.

Test	Number of specimen	Average of fracture toughness K_{Ic} (MN/m$^{3/2}$)	Standard deviation K_{Ic} (MN/m$^{3/2}$)
CB	4	0.64	0.04
SCB	7	0.66	0.03
SNDB	7	0.46	0.05

Table 9 Summarized results of SCB tests in Experiment-S.

Group	Number of specimen	Radius r (mm)	Thickness t (mm)	Average of fracture toughness K_{Ic} (MN/m$^{3/2}$)	Standard deviation K_{Ic} (MN/m$^{3/2}$)
A-1	7	37.5	10	0.61	0.08
A-2	5	37.5	20	0.61	0.08
A-3	7	37.5	30	0.66	0.03
A-4	7	37.5	37.5	0.66	0.04
B-1	7	12.5	10	0.44	0.05
B-2	7	25	20	0.56	0.03
B-3	7	37.5	30	0.66	0.03
B-4	7	50	40	0.75	0.04
B-5	6	100	80	0.89	0.05
B-6	6	150	120	0.88	0.02

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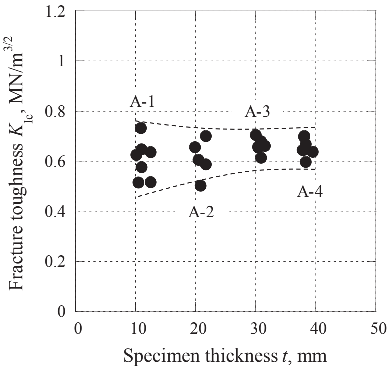

Fig.6 Relation between mode I fracture toughness and thickness of SCB specimen.

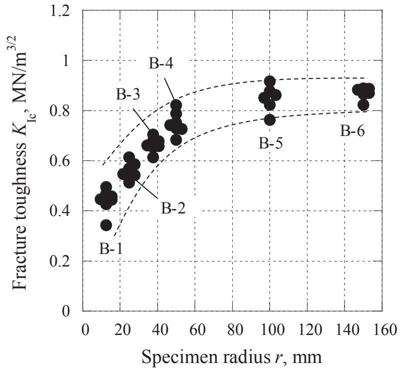

Fig.7 Relation between mode I fracture toughness and radius of SCB specimen.

Table 7, which had a radius r ranging from 12.5 to 150 mm and a thickness t given by $t = 0.8r$ is shown in Fig. 7. Some plots are shifted slightly along the horizontal axis for clarity in this figure. The scattering was almost the same at each radius and similar to the value of the specimens of Group-A-3 and Group-A-4 which had sufficiently large thickness, namely $t \geq 0.8r$. K_{Ic} increased with increasing radius and converged at a constant value in a range larger than approximately 70 mm of the radius. In the ISRM-suggested method[13)], the recommended radius is larger of 5 times grain size, or 38 mm. A larger radius seemed to be needed for evaluating K_{Ic} of the rock by the SCB test. The following size requirement was also suggested for the SCB specimen[16)]:

$$r \geq \left(\frac{K_{Ic}}{\sigma_t}\right)^2 \quad \cdots\cdots (4)$$

where σ_t is tensile strength of the tested material. Although all the specimens used in this study satisfied this requirement, K_{Ic} was changed at small radius.

5. Discussion

The mode I fracture toughness K_{Ic} of Kimachi sandstone evaluated by the CB and SCB tests are almost identical to each other and larger than that evaluated by the SNDB tests as summarized in Table 8 (the results of Experiment-T). The results may show that the two ISRM-suggested methods, the CB and SCB tests, ensure consistency. However, the SNDB test tends to estimate a lower value of K_{Ic} than the others. The differences between the K_{Ic} values obtained from these tests will be discussed later.

K_{Ic} evaluated by the SCB test in Experiment-S was almost constant at different thicknesses (Fig. 6). The tendency observed in this test result agreed with the SCB test performed by Lim *et al.*[17)]. On the other hand, the scattering was relatively large for smaller thicknesses and became smaller in a range larger than 30 mm of the thickness. The fracture toughness estimated by testing methods such as the SCB test assumes that a stress state near the artificial notch tip reaches a plane-strain condition. For a specimen with infinite thickness, a plane-stress condition appears near the specimen surface and a plane-strain condition is approached in the interior part of the tested sample. At some still larger thickness, the plane-stress zone is insignificant compared with the portion dominated by plane-strain behavior, and the plane-strain fracture toughness can be obtained. Once the thickness reaches a sufficient value, the fracture toughness is no longer dependent on the thickness[28)]. The proportion of these stress states at the notch tip is dependent on the specimen thickness and might affect the scattering change with the thickness observed in Fig. 6. From this test result, the sufficient value of the thickness can be considered to be 30 mm.

K_{Ic} increased with increasing the radius and converged on a certain constant value in a range larger than approximately 70 mm of the radius (Fig. 7). The tendency of the result is similar with that in the CSTBD test using marble[19)]. In general, mechanical strengths of rocks, such as uniaxial compressive strength and tensile strength, decrease with increasing specimen volume. This size effect is interpreted as follows: a larger specimen has a greater number of flaws, therefore the likelihood of having weaker flaws becomes greater. As a result, the mechanical strengths are small for larger specimens[15, 29)]. This interpretation is based on weakest link theory, namely a fracture initiated from one material element, especially from the weakest one, causes the whole material to fail. However, in fracture toughness tests, the specimen has a notch which guides the location of fracture initiation. This fracture condition makes it difficult to apply the weakest link theory to explain the results of the fracture toughness tests.

In the case of the fracture toughness, it is considered that the crack resistance decreases with decreasing the specimen size, because the flaws near the notch tip of the specimen can be assumed to be relatively large. On the other hand, the resistance increases with increasing the size and the fracture toughness becomes larger. As the resistance in a sufficiently large specimen is not influenced by flaws, the fracture toughness would not be dependent on the specimen size with further increases in size. That is, the fracture toughness converges onto a certain constant value. In this test result, the constant value of 0.89 MN/m$^{3/2}$ appeared in a range larger than approximately 70 mm of the radius (Fig. 7). This fracture toughness value can be regarded as a bulk material property. As a future work, theoretical explanation of the experimental results[19)] and modification considering the non-linearity[30, 31)] will be also necessity to make clear the size effect on the fracture toughness of rocks.

Considering the above discussion on the size effect in the SCB test, K_{Ic} evaluated by the CB and SNDB tests might be

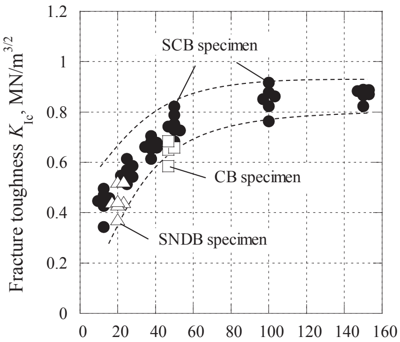

Fig.8 Relation between mode I fracture toughness and specimen representative dimensions.

dependent on its specimen size. As shown in Fig. 8, K_{Ic} from the CB and SNDB tests in Experiment-T are plotted with the SCB test result using Group-B in Experiment-S. The horizontal axis indicates the representative dimension of each specimen, defined as a length of the notch plus the ligament in the direction of the fracture propagation, namely the diameter d for the CB specimens, radius r for the SCB specimens, and thickness t for the SNDB specimens. It shows that K_{Ic} of the CB and SNDB tests is on the trend curve of the size effect in the SCB test. The differences of the representative dimension may induce the differences of K_{Ic} values between the testing methods. The SNDB test results might be compatible with the CB and SCB ones if its specimen thickness increased. Understanding of the size effect in the CB and SNDB tests will be needed as a further study to make clear the effect of the testing method type on K_{Ic} of rocks.

6. Conclusions

The objective of this study was to examine the effect of the testing method type and specimen size on the mode I fracture toughness K_{Ic} of rocks. Firstly, three types of fracture toughness tests, the chevron bend (CB), semi-circular bend (SCB) and straight notched disk bending (SNDB) tests, were conducted using Kimachi sandstone. Secondly, the SCB test was performed using the same sandstone specimens with various sizes. The obtained results are as follows:

- K_{Ic} evaluated by the SCB tests was almost the same as that evaluated by the CB tests. However, the value evaluated by the SNDB tests was smaller than the others in this study.
- In the SCB tests using the specimens with various sizes, K_{Ic} was almost constant with a different thickness on average. Although it varied widely in the case of smaller thickness, the scattering became smaller in a range larger than 30 mm of thickness.
- The result of the SCB tests also showed that K_{Ic} increased with increasing the radius and converged on a certain constant value in a range larger than approximately 70 mm of radius.
- The differences of the representative dimension may induce the differences of K_{Ic} values obtained from the CB, SCB and SNDB tests. Understanding of the size effect in the fracture toughness tests will be needed to make clear the effect of the testing method type on the fracture toughness of rocks.

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来待砂岩のモードI破壊靭性に及ぼす試験法および供試体寸法の影響*

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岩石のモードI破壊靭性を評価するための試験法がこれまでに数多く提案されてきているが，同じ岩石の破壊靭性を異なった試験法で評価し，得られた結果が比較されることはまれである。このため，破壊靭性に及ぼす試験法の違いが明らかにされているとは言い難い。また，岩石の破壊靭性は試験法の違いだけでなく，用いる供試体寸法によっても影響を受けると考えられる。これらの影響を明らかにするために，様々な破壊靭性試験が行われてきた。しかし，これまでの実験では，同じ岩石で作製された供試体数が十分でなかったり，あるいは供試体寸法の違いの範囲が狭かったために，それらの影響を明らかにするまでに至っていないと考えられる。

本論文では，来待砂岩を供試体として用い，3種類の破壊靭性試験法，すなわち，CB試験，SCB試験およびSNDB試験を実施し，破壊靭性に及ぼす試験法の影響を検討するとともに，半径12.5mm～150mmの範囲の供試体を用いたSCB試験を実施し，供試体寸法の影響を検討した。この結果，CB試験とSCB試験による破壊靭性はほぼ同等の結果を得ることができたが，SNDB試験の破壊靭性はそれらの値より小さく評価されることを示した。また，供試体寸法が大きくなるとともに破壊靭性も増大することを明らかにした。

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