1. INTRODUCTION

We conducted microfracture toughness (MFT) tests on minerals that compose Inada granite (quartz, K-feldspar, plagioclase and biotite) to evaluate and elucidating the fracture phenomenon of rock, which is an inhomogeneous body with fine mineral particle. For the purpose of this study, the following were performed. Firstly, to evaluate the scale dependence of the MFT, we conducted MFT tests with three cantilevered specimens. (10 μm × 10 μm × 50 μm, 20 μm × 20 μm × 50 μm, 20 μm × 20 μm × 100 μm). Finally, the relationship between the macroscopic fracture toughness determined by SCB tests and microscopic fracture toughness of rock was discussed.

2. PROPERTIES OF INADA GRANITE

Inada granite was used as the test material. This rock was produced from Iwase to Inada in Ibaraki Prefecture, Japan. A thin section was observed using a microscope. quartz, plagioclase, K-feldspar, biotite, were found, as shown in Fig.1. The uniaxial compression test and tensile stress test of this rock were conducted using a few centimeters of specimens and the results are listed in Table 1.

Table 1 Mechanical properties of Inada granite.

Material property	Values
Uniaxial compressive strength [MPa]	67.3
Young's modulus [GPa]	39.5
Poisson's ratio	0.19
Tensile strength [MPa]	6.2

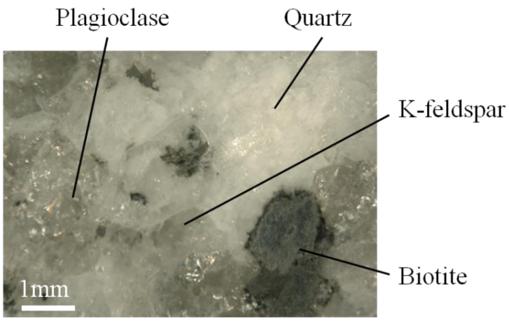

Fig.1. Mineral grains of Inada granite as shown in a thin section.

3. EVALUTION OF MACROSCOPIC FRACTURE TOUGHNESS

SCB test is used to determine macroscopic Mode I fracture toughness of Inada granite. In the tests, the semicircular disk specimens with various diameter ranging from 15.0 to 80.5 mm were used. Fig.2 shows the relation between the fracture toughness and the specimen size (the radius *R* of the SCB specimens). In this graph, the curve calculated result based on the Bazant size effect law (Bazant 1984) is also plotted. According to this size effect law, the fracture toughness value approaches a constant value as the size is increased. The convergent fracture toughness value was predicted to be 1.20 [$MN/m^{2/3}$] in order to compare it with the MFT.

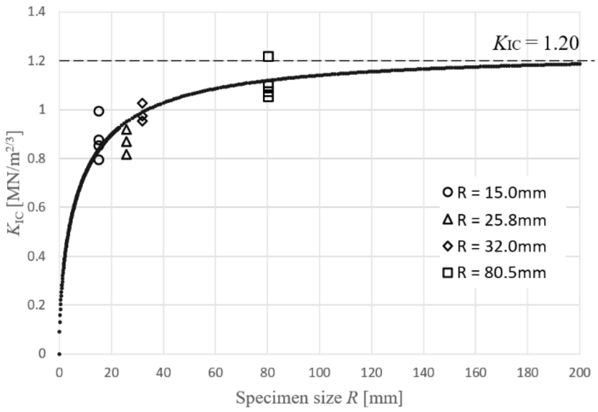

Fig.2. Relation between mode I fracture toughness and radius of SCB specimen.

4. EVALUTION OF MICROSCOPIC FRACTURE TOUGHNESS

Experiments to evaluate the MFT of rock minerals was performed using the previously proposed method (Kataoka et al. 2019). Fig.3 (a) shows a view and a block diagram of the MFT testing system. The loading pin and the specimen were aligned with the x, y stage and the rotation stage. Loading state observed by the digital microscope with a magnification of 2500 shown in Fig.3 (b).

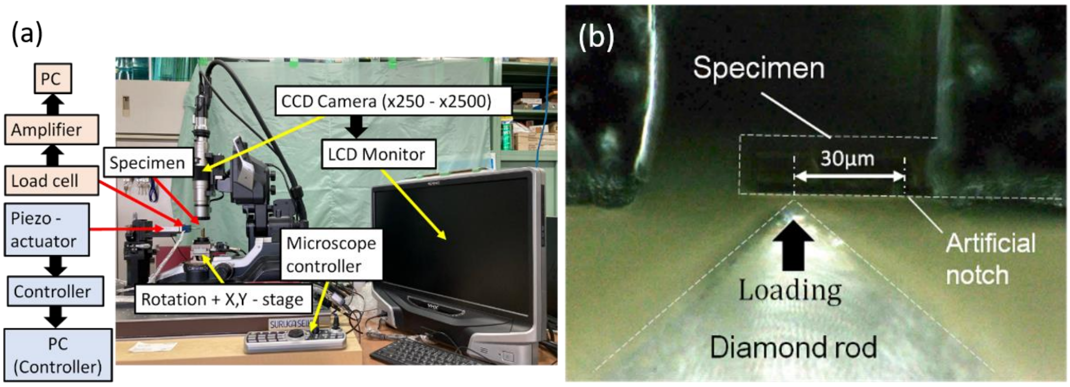

Fig. 3. (a) View and a block diagram of the MFT testing system and (b) Loading state observed by the digital microscope with a magnification of 2,500.

The Mode I fracture toughness, K_{IC}, is estimated from maximum load P_{max} using the following equation for the stress intensity factor for a single edge notched cantilever beam (Tada et al. 1973).

$$K_{IC} = \frac{6P_{max}S\sqrt{\pi a}}{W^2 B} F\left(\frac{a}{W}\right) \tag{1}$$

where a is depth of the artificial notch, W is thickness of the cantilever beam, B is width of the cantilever beam, S is distance between the loading point and the notch, and F is function of dimensionless notch length (a/W). In this study, three types of specimens with different dimensions were prepared, and up to four tests were conducted for each mineral. Fig. 4 shows a specimen with the standard dimensions, and two tests were conducted on each mineral. Fig. 5 (a) shows the third specimen, which has twice the width B, thickness W, and crack length a of the standard dimensions. Fig. 5 (b) shows the fourth specimen, in which all the standard dimensions, including S, are doubled.

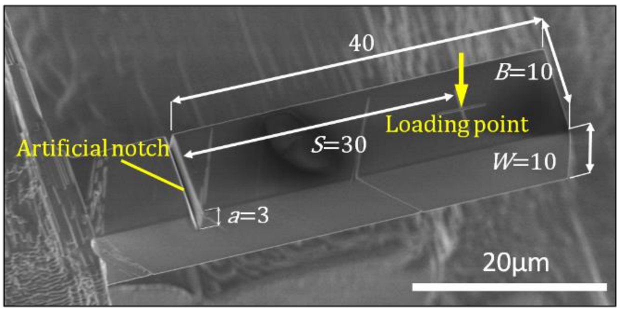

Fig. 4. SEM image of micro-sized specimen with the standard dimensions, which is using biotite (B-1) in Inada granite.

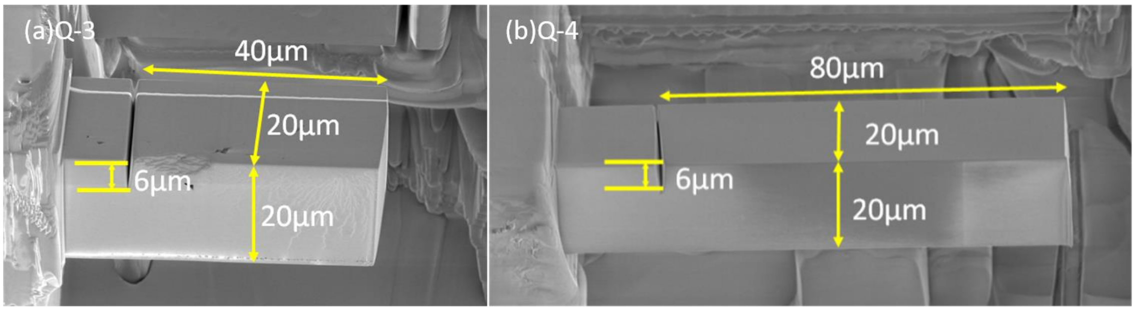

Fig. 5. SEM image of the (a) third specimen, which is using quartz (Q-3) and (b) forth specimen, which is using quartz (Q-4).

Table 2 shows the results of the test. The value of MFT K_{IC} was determined from the value of P_{max} using Eq (1). The MFT can be greatly affected by weak surface such as mineral cleavage and crystal orientation. For all minerals, the fracture toughness values of the third and fourth specimens were close to each other. For all dimensions, quartz showed the largest trend and biotite showed a smaller trend.

Table 2 Experimental results.

Minerals	No.	W [μm]	B [μm]	S [μm]	a [μm]	P_{max} [mN]	K_{IC} [MN/m$^{3/2}$]
Quartz	Q-1	10.70	10.90	30.00	3.09	1.7	0.85
	Q-2	10.41	10.64	30.78	3.00	1.84	1.00
	Q-3	20.12	20.89	30.39	6.00	7.47	0.79
	Q-4	20.86	20.32	59.86	6.48	3.75	0.77
Plagioclase	P-1	10.16	10.39	30.60	3.00	0.50	0.29(*1)
	P-2	10.00	10.48	30.62	3.00	1.17	0.71
	P-3	20.12	19.81	30.04	6.09	5.58	0.62
	P-4	20.50	19.96	60.00	6.48	2.69	0.59
K-feldspar	K-1	10.85	11.33	30.87	3.00	1.12	0.53
	K-2	10.25	10.56	30.00	3.00	0.95	0.54
	K-3	20.5	20.00	30.01	6.00	5.01	0.69(*2)
	K-4	20.00	20.14	60.94	6.48	2.79	0.66
Biotite	B-2	10.27	10.73	40.64	3.00	0.14	0.11(*2)
	B-4	20.50	20.00	59.86	6.66	0.502	0.11

(*1) Reference value due to voids in the specimen.

(*2) The distance between the destruction point and the loading point was corrected because the destruction did not extend from the artificial notch.

5. DISCUSSION

Fig. 6 shows the relationship between the MFT K_{IC} and the thickness *W*. Since there was no significant change due to the difference in dimensions, it is possible that MFT does not show the size effect. As the thickness *W* increases, the K_{IC} usually increases because the process zone for crack extension is larger, but at the same time, low toughness microstructure is more likely to exist near the crack. It is possible that these two factors cancel each other out and size effect did not show.

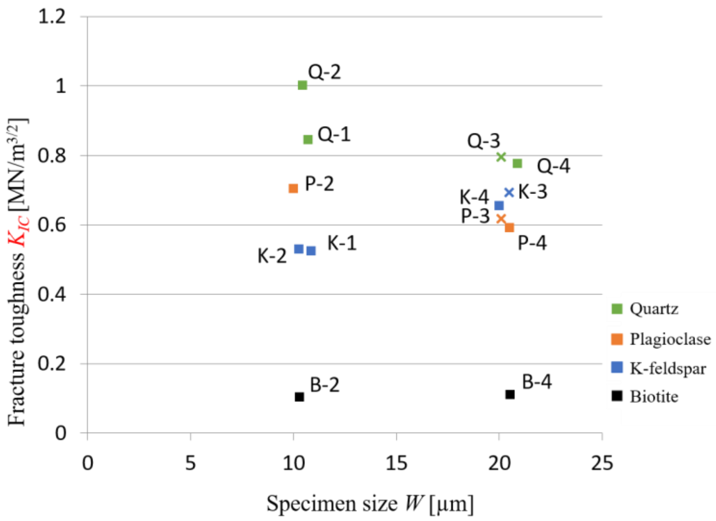

Fig.6. The relationship between the MFT K_{IC} and the thickness *W*.
(x marks indicate the third specimen.)

The average MFT at a mineral level was determined by summing the average MFT determined from up to four tests for each mineral, multiplied by the mode composition of the Inada granite. In other words,

$$(0.86\times0.37)+(0.64\times0.33)+(0.60\times0.24)+(0.11\times0.06)=0.68$$

This value of 0.68 [MN/m$^{2/3}$] is used as the representative microscopic fracture toughness of the Inada granite. This value is smaller than the macroscopic fracture toughness value of 1.20 [MN/m$^{2/3}$] determined by SCB test. One of the reasons for this gap between the macroscopic and microscopic fracture toughness is that quartz, which has a large compositional function and shows a large MFT in the Inada granite, may have a large influence in the macroscopic fracture toughness.

When $K_{IC}=0.68$ [MN/m$^{2/3}$], the specimen for SCB test is determined to be R = 7.9 [mm] based on the Bazant's size effect law. This size is four to five times larger than the mineral grain size of the Inada granite. Another factor affecting the macroscopic facture toughness may be not only the MFT of each mineral, but also the grain boundaries of minerals in the crack extending direction.

Fig. 7 shows the relationship between the MFT and Vickers hardness, an index of hardness of minerals (Vickers hardness was estimated by Adebayo et al. 2007). The linear relation (zero intercept) is shown as follows:

$$K_{IC}=(8.1\times10^{-4})H_V, R=0.998 \tag{2}$$

Although mineral toughness and hardness are different physical property values, the strong correlation between MFT and Vickers hardness is considered to be significant. If the MFT is used as a parameter in numerical simulations for rock fracturing, this would be useful to understand the fracture behavior of rocks more accurately.

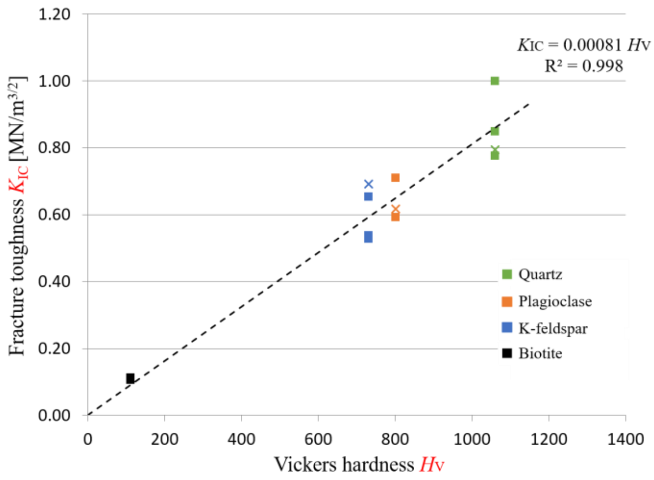

Fig.7. Relation between Vickers hardness H_V and MFT.

6. CONCLUSIONS

1) The MFT of mineral was in order of quartz, plagioclase, K-feldspar, and biotite from the largest value.

2) We found no significant scale dependence for the MFT itself.

3)The MFT values of each minerals were lesser than the macroscopic fracture toughness of the rock evaluated in the SCB test: quartz (7%), plagioclase (53%), K-feldspar (50%), and biotite (9%).

4) If the MFT is used as a parameter in numerical simulations for rock fracturing, this would be useful to understand the fracture behavior of rocks more accurately.

7. REFERENCES

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