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Fracture Toughness of Granite Measured Using Micro to Macro Scale Specimens

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Abstract

The objective of this study is to examine any variation from micro to macro scale mode-I fracture toughness of granite using micro-sized specimen and semi-circular specimen. The rock used in the tests is Iksan granite (Korea) which is composed of minerals, such as plagioclase and alkali feldspar, quartz. In order to investigate micro scale fracture toughness, a mechanical testing machine was used. This machine is an original one and developed by ourselves. In the test, a micro-sized cantilever beam type specimen was used. Its dimension is 10 × 10 × 50 μm. On the other hand, in order to examine macro scale fracture toughness, Semi-Circular Bend (SCB) test is adopted. This is one of ISRM-suggested methods for estimation of the mode-I fracture toughness of rocks. The semi-circular specimens are prepared with a radius of 12.5mm to 50mm. Based on the fracture toughness obtained from both tests, the size effect of granite is discussed in the range from micro to macroscale.

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Keywords: Fracture toughness; Granite; Size effect

1. Introduction

It is known that a brittle fracture of rock under a stress state occurs through the following process: pre-existing cracks initiate and propagate, then connect to other cracks and a fracture surface is finally developed. In order to explain this process, fracture mechanics, which was started in the field of metallurgical engineering in the 1920s and established in the 1950s, was introduced to rock mechanics in the 1980s. Some textbooks for fracture mechanics of

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rocks were published at that time [1–3]. Rock can be considered an inhomogeneous material. For example, granite consists of a completely crystalline assemblage of minerals. The structure contains lots of micro-cracks within mineral grains and at grain boundaries, representing mechanical weakness.

The objective of this study is to examine any variation from micro to macro scale mode-I fracture toughness of granite using micro-sized specimen and semi-circular specimen. The rock used in the tests is Iksan granite (Korea) which is composed of minerals, such as plagioclase, alkali feldspar and quartz. In order to investigate micro scale fracture toughness, a mechanical testing machine was used. This machine is an original one and developed by ourselves. In the test, a micro-sized cantilever beam type specimen was used. Its dimension is 10 × 10 × 50 μm. On the other hand, in order to examine macro scale fracture toughness, Semi-Circular Bend (SCB) test is adopted. This is one of ISRM-suggested methods for estimation of the mode-I fracture toughness of rocks [4]. The semi-circular specimens are prepared with a radius of 12.5 mm to 50 mm. Based on the fracture toughness obtained from both tests, the size effect of granite is discussed in the range from micro to macro scale.

Nomenclature

K_{IC}	mode-I fracture toughness
P_{max}	maximum load in both tests
S	length between loading point and artificial notch of micro-sized specimen in bending test
a	artificial notch length
W	thickness of micro-sized specimen
B	width of micro-sized specimen
F	function for estimation of K_{IC} in bending test
r	radius of SCB specimen
t	thickness of SCB specimen
Y_I	stress intensity factor of SCB specimen
s	half of support span of SCB specimen

2. Test methods

2.1. Bending test for estimating micro scale fracture toughness

A micro-sized specimen in a bending test is a cantilever beam type with an artificial notch as a crack shown in Fig. 1. The specimen has dimensions of *a* in depth of the notch, *W* and *B* in thickness and width of the beam respectively, and *S* in length between the loading point and artificial notch. Using this specimen, the bending test is performed.

The micro scale mode-I fracture toughness (K_{IC}), which is the maximum value of stress intensity factor, is estimated from maximum load (P_{max}) using Eq. (1) for stress intensity factor for a single edge notched cantilever beam [5],

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

where, $F(a/W)$ is calculated as:

$$F(a/W) = 1.12 - 1.40(a/W) + 7.33(a/W)^2 - 13.08(a/W)^3 + 14.0(a/W)^4 \tag{2}$$

2.2. Semi-Circular Bend (SCB) test for estimating macro scale fracture toughness

A SCB test to estimate macro scale fracture toughness is performed using a semi-circular disc type with an artificial notch as shown in Fig. 2. The details of this test are described in the ISRM-suggested methods published in 2014 [4]. The macro scale mode-I fracture toughness (K_{IC}) is represented using normalized stress intensity factor (Y_I), maximum load (P_{max}) and dimension of specimen as in Eq. (3),

$$K_{IC} = \frac{P_{max}\sqrt{\pi a}}{2rt} Y_I \quad (3)$$

where, *r*, *t* and *a* are radius, thickness and artificial notch length of the specimen respectively. The normalized stress intensity factor is calculated as:

$$Y_I = -1.297 + 9.516(s/r) - (0.47 + 16.457(s/r))\beta + (1.071 + 34.401(s/r))\beta^2 \quad (4)$$

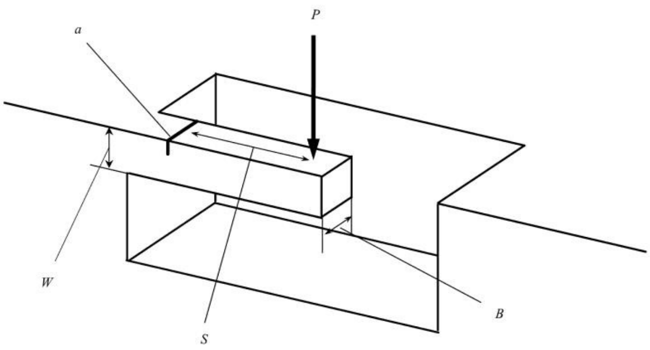

Fig. 1. Geometry of micro-sized specimen.

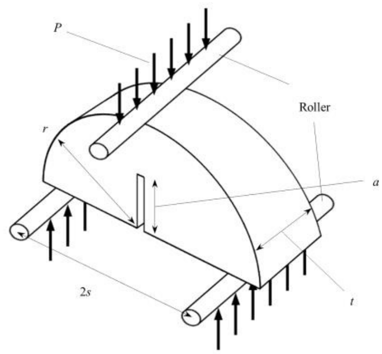

Fig. 2. Geometry of SCB specimen.

3. Specimen and testing apparatus

3.1. Specimen preparation

In both tests, Iksan granite (Korea) shown in Fig. 3 is used. The compositions of minerals are quartz, plagioclase, alkali feldspar, biotite, etc. as shown in Fig. 4. The average grain size of this rock was estimated as 0.6–0.8 mm [6, 7].

In order to prepare the micro-sized specimen, the rock block was cut into a rectangular parallelepiped with dimensions of 3×5×7 mm. The rectangular parallelepiped was fixed into a holder to allow micro-machining by a Focused Ion Beam (FIB) instrument. The micro-sized specimen was made within the mineral as shown in Fig. 5. The dimensions of the beam are 10 μm in thickness and in width, and 50 μm in length. The notch with a depth of 3 μm is located 10 μm from the fixed end of the cantilever beam. [8, 9].

On the other hand, in order to examine macro scale fracture toughness of rocks, the SCB specimens were prepared with various radii (*r*) ranged from 12.5 to 50 mm of semi-circular disc with an artificial notch as shown in Fig. 6. The artificial notch was cut using diamond blade with a thickness of 0.4 mm. The artificial notch length (*a*) and thickness (*t*) are given by a/r = 0.5 and t/r = 0.8, respectively. The half of support span to radius ratio is maintained at constant value of 0.8 in the test [10].

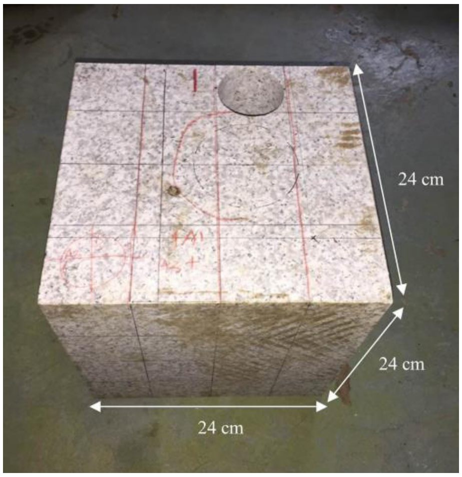

Fig.3. Rock block of Iksan granite.

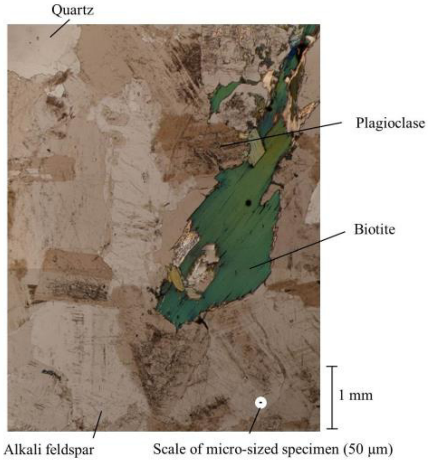

Fig. 4. Thin section of Iksan granite.

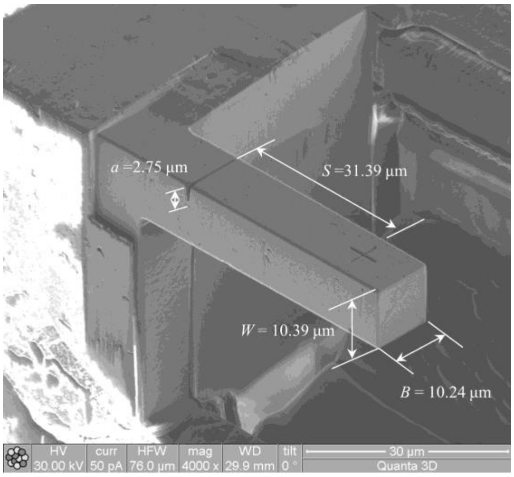

Fig.5. Micro-sized specimen made by FIB.

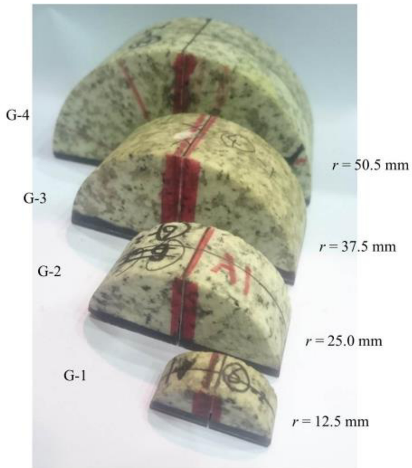

Fig. 6. SCB specimen with various diameters.

3.2. Testing apparatus

The bending test was conducted using a testing machine for micro-sized specimens. The loading state can be observed by a digital microscope with a magnification of 250 to 2500 (Keyence VHX-5000) as shown in Fig. 7. A load cell with a resolution of 20 μN and a maximum of 200 mN are equipped to the actuator. The loading rate was 0.1 μm/s and the sampling time of the load and displacement was 10 μs.

On the other hand, the SCB test was conducted using a servo-controlled testing machine (MTS 810) with a capacity of 100 kN as shown in Fig. 8. The specimen is placed on two stainless steel rollers providing the support span. The load is applied through a loading bar and two stainless steel rollers, and is measured using a load cell equipped at the loading bar. The loading rate in conventionally-sized SCB specimen (radius 37.5 mm) was set at 0.01mm/min. In order to ensure the loading rate for the various radius of specimen, the loading rate was in proportion to the radius (r) of specimen by $r \times 0.00027$ mm/min. As a result, the loading rate was 0.0033 mm/min for radius of 12.5 mm and 0.0133 mm/min for radius of 50 mm [11, 12].

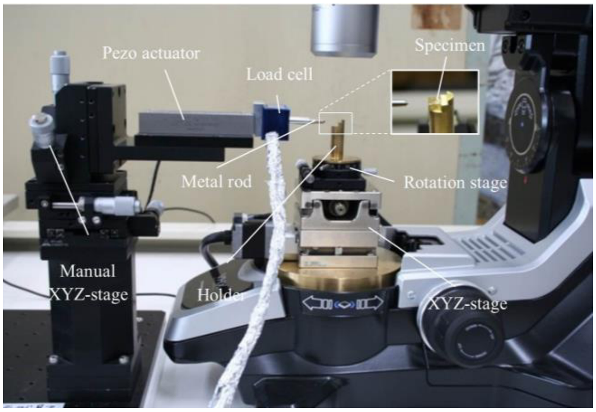

Fig. 7 Testing machine view around the micro-sized specimen.

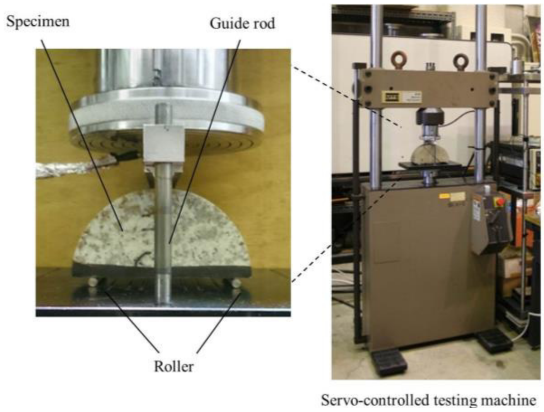

Fig. 8. SCB testing equipment and testing machine.

4. Results and discussion

4.1. Load-displacement curve

Example of load-displacement curve in the bending test is shown in Fig. 9. Each curve is shifted its origin at every 0.5 μm in displacement for clarity. Specimen No.1 is in a grain of plagioclase, Nos.2 and 3 are in those of alkali feldspar and Nos.4–6 are in those of quartz. The load increases linearly with increasing displacement and the fracture suddenly occurs just after reaching maximum load P_{max} for all specimens. This is a brittle fracture. The value of K_{IC} is estimated using Eq. (1) from the value of P_{max}.

Example of load-displacement curve in the SCB test is shown in Fig. 10. Each curve is shifted its origin at every 0.1 mm in displacement for clarity. These curves are downward convex at a low load level and the load increases linearly with increasing displacement and the fracture suddenly occurs just after reaching maximum load P_{max} for all specimens. The value of K_{IC} is estimated using Eq. (3) from the value of P_{max}.

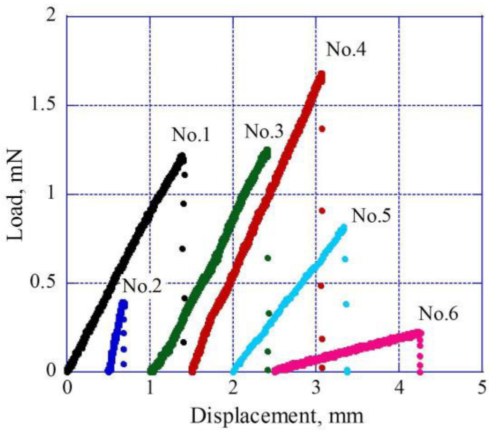

Fig. 9. Load-displacement curve in bending test.

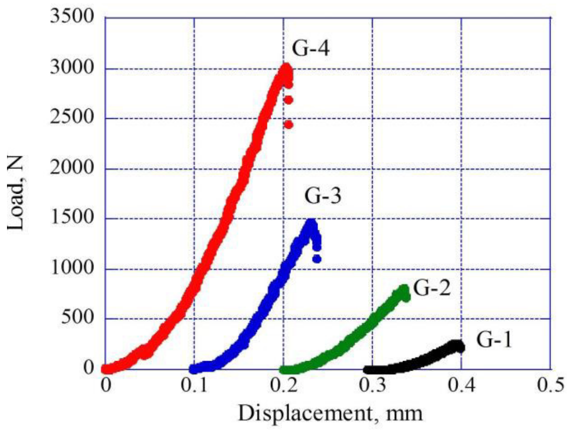

Fig. 10. Load-displacement curve in SCB test.

4.2. Discussion

The relation between size (radius) and fracture toughness is shown in Fig. 11. The fracture toughness increases with increasing the size of the specimen. The micro scale fracture toughness of quartz, plagioclase and alkali feldspar are plotted at almost zero of size. Micro scale fracture toughness value range is from 0.13 to 0.82 $MN/m^{3/2}$ and varies widely. However, value of conventionally-sized SCB specimen (radius 37.5 mm) is in the range from 0.97 to 1.15 $MN/m^{3/2}$ and higher than micro scale fracture toughness. Then it is found that fracture toughness increases with increasing the size and that a size effect exists in the fracture toughness of the rock.

The scattering of micro scale fracture toughness is dependent on an existence of mechanical weak planes within the micro-sized specimens. As shown in Fig. 12, the fractures of the plagioclase and alkali feldspar do not initiate and propagate in the direction of the notch straightly. The plagioclase and alkali feldspar group has two planes of cleavage meeting at or near 90 degrees as a mechanical weak plane. It is concluded that this fracture state can indicate the existence of cleavage within the specimens. On the other hand, the fractures of the quartz propagate in almost the same direction as the notch. Micro scale fracture toughness of quartz group is also dependent on the direction of fracture [9]. The mechanical weak plane can influence micro scale fracture toughness of mineral grains of rock. If mechanical weak planes exist near a crack tip, a fracture initiates more easily from any weak plane and may penetrate into the specimen. It is considered that the fracture toughness of a micro-sized specimen becomes smaller than that of a conventionally-sized specimen in cases where there are many weak planes in the mineral grains and/or large weak planes relative to the specimen size. It is difficult to confirm the difference in stiffness of micro-sized specimen because the number of micro-sized specimen is three specimens. Therefore, additional experiments will be conducted by more specimens to discuss the stiffness of micro-sized specimen.

In general, mechanical strengths of rocks, such as uniaxial compressive strength and tensile strength, decrease with increasing specimen size. However, in the case of the fracture toughness of rocks, the fracture toughness increases with increasing the size of the specimen. It is considered that the crack resistance decreases with decreasing specimen size because that flaws within the specimen can be assumed to be relatively large. On the other hand, the influence of flaws on the resistance is assumed to become small in large radius specimens. Therefore, the fracture toughness may not depend on the specimen size with further increase [12].

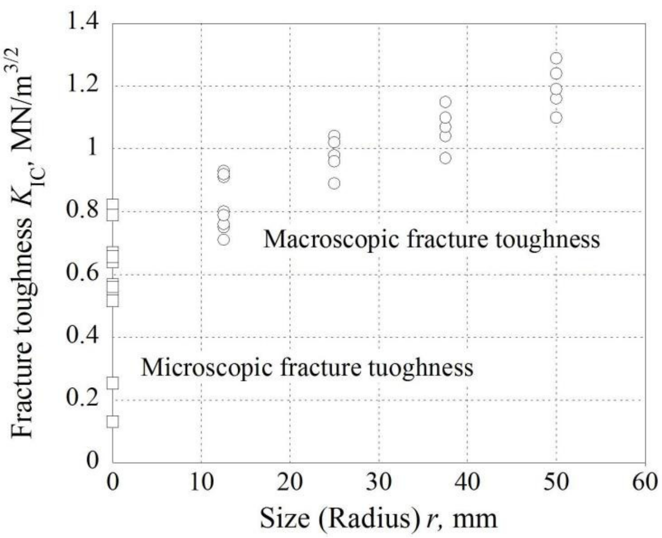

Fig. 11. Relation between size (radius) and fracture toughness.

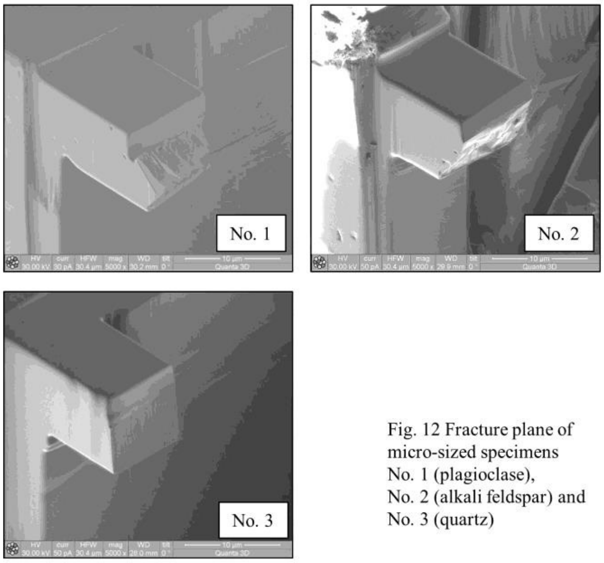

Fig. 12. Fracture plane of micro-sized specimens No.1 (plagioclase), No.2 (alkali feldspar) and No.6 (quartz).

5. **Conclusion**

In order to examine the variation from micro to macro scale mode-I fracture toughness of granite, the bending test and the SCB test were conducted, using micro-sized specimen and SCB specimen respectively. Based on the obtained fracture toughness from both tests, the size effect of granite is discussed. As a result of the tests, it is shown that micro scale fracture toughness varies widely, depending on mechanical weak planes within mineral grains. These values are lower than macro scale fracture toughness. Then it was concluded that fracture toughness increases with increasing the size and that a size effect exists in the fracture toughness of granite.

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