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Influence of calcium ions on subcritical crack growth in granite

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1. Introduction

Granite rock masses are used for various geomechanical and engineering purposes such as the construction of caverns to store liquid natural gas or liquid petroleum gas, extraction of geothermal energy from hot dry rock, and underground repositories for radioactive waste. Investigating the fracturing in granite, especially time-dependent fracturing, is crucial to consider the long-term integrity of granite rock mass surrounding structures.

Subcritical crack growth is one of the main causes responsible for the time-dependent behaviors in rocks in the brittle regime.[1,2] SCG was initially attributed to stress corrosion, which is the chemical reaction between siloxane at the crack tip under tension and water.[3,4] However, SCG is also influenced by the surrounding environment. Nara and Kaneko[5,6] reported that the crack velocity in igneous rock in air increases when the partial pressure of water vapor is high. Nara et al.[7,8] reported that the crack velocity in igneous rocks and sandstones in air increases as the temperature and/or relative humidity increases. The influence of water on SCG in glass, silicate minerals and rocks has been studied by various researchers. It is well-known that the crack velocity in glass in water is higher than that in water.[9–12] According to the results in Atkinson[13], Waza et al.[14], Meredith and Atkinson[15], Sano and Kudo[16], and Nara et al.[17,18], the crack velocity in quartz and silicate rocks in water is much higher than that in air. Swanson[19,20] reported that the addition of water on silicate rocks affected the deformation of rock and accelerated the crack velocity. The increases of the crack velocity in carbonate rocks in water have been reported by Henry et al.[21] for micrite and Nara et al.[22] for marble. Sano and Kudo[16] also showed that the pH influences the crack velocity of rock in water. Nara et al.[23] reported that the crack velocity in sandstone containing a large amount of clay minerals (illite and smectite) is influenced by the electrolyte concentration in water.

These previous studies of SCG in rock demonstrate SCG is influenced by the surrounding environmental conditions. In particular, the quality of water remarkably influences SCG of rock in water. Considering the construction of structures using a rock mass such as an underground repository of radioactive waste and underground power plant, numerous amounts of cementitious materials will be used. The calcium ion concentration in water in the surrounding rock mass should be high. Therefore, it is important to investigate the influence of calcium ions on SCG in rock to ensure the long-term stability of the rock mass.

In this study, SCG in distilled water and a calcium hydroxide ($Ca(OH)_2$) solution was investigated using granite as the rock sample to clarify the influence of calcium ions on SCG. Specifically, the difference of the crack velocity in distilled water and a calcium hydroxide solution was investigated using a fracture mechanics test.

2. Rock sample

The rock sample was Oshima granite from Ehime Prefecture, Japan. It is comprised of quartz (36%), plagioclase (37%), K-feldspar (22%), biotite (4%) and hornblende (less than 1%).[24] The mean grain size was about 1 mm.[25] Any clay minerals were not included.[24,25]

Several granites possess a preferred orientation of pre-existing microcracks.[26–28] According to the microscopic observation by Sano et al.[27], Oshima granite has two sets of preferred orientations of pre-existing microcracks. Most of the microcracks are distributed within the

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Table 1
Elastic compliance of the Oshima granite (after Nara and Kaneko[6]).

Elastic compliance s_{ij} [$\times 10^{-12}$ Pa^{-1}]

		j					
		1	2	3	4	5	6
i	1	16.7	−3.28	−3.28	0	0	0
	2	−3.28	18.9	−3.28	0	0	0
	3	−3.28	−3.28	19.7	0	0	0
	4	0	0	0	46.0	0	0
	5	0	0	0	0	43.4	0
	6	0	0	0	0	0	42.4

rift plane, and the secondary orientation of microcrack is distributed almost perpendicular to the rift plane, which is known as the grain plane. Additionally, Sano et al.[27] and Nara and Kaneko[6] concluded that Oshima granite has an orthorhombic elasticity due to the preferred orientation of the microcracks. For the sample block used in this study, the P-wave velocities measured in the direction normal to the rift plane, grain plane, and hardway plane (the third plane with the smallest distribution of microcracks) are 4.91, 4.61 and 4.51 km/s, respectively. We call these directions as axes-1, −2, and −3 in the order of the P-wave velocity. Table 1 summarizes the orthorhombic elastic compliance of Oshima granite.[6]

Sano and Kudo[16], Nara and Kaneko[6], and Nara et al.[29] reported that the crack velocity of Oshima granite has anisotropy. According to Nara and Kaneko,[6] the crack velocity propagating parallel to the rift plane is 3–5 orders of magnitude higher than the velocity of a crack propagating parallel to the hardway plane. Nara[30] reported that the fracture toughness of Oshima granite is anisotropic and is the lowest when the crack propagated parallel to the rift plane. Therefore, it is necessary to consider the loading direction and specimen orientation which influence the crack propagation direction when preparing the specimens to measure SCG. We oriented our granite specimens so that the loading direction and the tensile direction are parallel to axis-3 and axis-1, respectively. This specimen is the same as “specimen 3.1” in Sano and Kudo[16], Nara and Kaneko[6], and Nara et al.[29].

3. Methodology

3.1. Experimental method

In this study, the load relaxation method of the double-torsion (DT-RLX) test was used to measure SCG. Fig. 1 schematically illustrates the specimen and loading configuration for the DT-RLX test. As

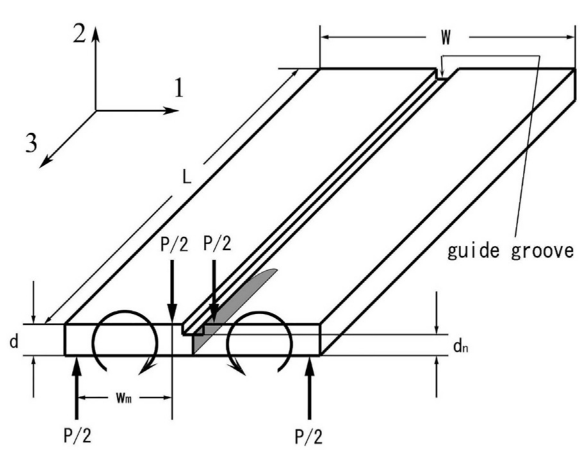

Fig. 1. Schematic illustration of the specimen and loading configuration in the double-torsion test.

summarized by Evans[31], Williams and Evans[32], and Sano[33], the stress intensity factor is independent of the crack length in the DT test. For this reason, various researchers have used the DT test to investigate SCG in rock.[34]

In the RLX method, the displacement of the loading points must be kept constant during the experiment while the temporal decrease (load relaxation) due to the crack growth is measured. Considering the orthorhombic elasticity of Oshima granite,[6,16] the directions of the principal axes, the orientation of the specimen, and the loading direction on the specimen, it is appropriate to use the equations introduced by Sano and Kudo[16] to evaluate the stress intensity factor and crack velocity for Oshima granite. In this study, the loading direction and tensile direction are parallel to axis-1 and axis-3, respectively. Therefore, following the methodology by Sano and Kudo[16] and Nara and Kaneko,[6] the stress intensity factor and the crack velocity are evaluated from following equations:

$$K_{\mathrm{I}} = \left(\frac{3P^2 w_{\mathrm{m}} s_{55}}{(2d^3 d_{\mathrm{n}} (2s_{11}((s_{33}s_{11})^{1/2} + s_{31} + s_{55}/2))^{1/2}} \right)^{1/2} \tag{1}$$

$$\frac{\mathrm{d}a}{\mathrm{d}t} = -0.2 \times \frac{2P_{\mathrm{i}}\lambda_{\mathrm{i}} d^3}{3s_{55} w_{\mathrm{m}} P^2} \frac{\mathrm{d}P}{\mathrm{d}t} \tag{2}$$

where K_{I} is the stress intensity factor, a is the crack length, and $\mathrm{d}a/\mathrm{d}t$ is the crack velocity. P is the applied load, w_{m} is the moment arm (18 mm in this study), and ν is Poisson's ratio. W is the width, while d is the thickness of the specimen, and d_{n} is the reduced thickness of the specimen. P_{i} is the initial value of the applied load, λ_{i} is the compliance of the specimen at the initial crack length a_{i}, and $\mathrm{d}P/\mathrm{d}t$ is the load relaxation rate. s_{11}, s_{33}, s_{31} and s_{55} are the elastic compliance of the sample.

Because these are approximate solutions based on a thin-plate assumption, the size of the specimen must satisfy the following condition[35–37]:

$$12d \le W \le L/2 \tag{3}$$

where L is the specimen length. According to the previous studies by Ciccoti and co-workers,[38–41] thicker specimens (W: d = 8: 1) can be used for DT-RLX test.

Trantina[42] reported that the stress intensity factor is independent of the crack length over the following range:

$$0.55W < a < L - 0.65W \tag{4}$$

Considering these restrictions, the specimen size in this study was set to a width W = 45 [mm], thickness d = 3 [mm], reduced thickness d_{n} = 2 [mm], and length L = 140 [mm].

It is necessary to make a guide groove in a DT specimen to control the crack path. It has been suggested that the shape of the guide groove should be rectangular for rock because the crack often propagates away from the guide groove in cases with semi-circular or triangular guide grooves.[5] Nara[43] reported that a crack often propagates away from the guide groove when the width of the guide groove is smaller than the grain size in granite. Considering previous studies, the width of the guide groove was set to 1 mm because the grain size of Oshima granite is around 1 mm. In addition, a 20 mm long notch was cut in the central part of the DT specimen from one end in order to help crack propagate in the central part of the specimen. This is called the “initial notch”. In the DT test, the load was applied near the initial notch.

3.2. Experimental apparatus

Fig. 2 shows the experimental apparatus for the DT-RLX test. In this apparatus, the load was applied to the specimen from the loading cylinder placed above the specimen. A stepping motor controlled the loading cylinder. All measurements were conducted at a constant temperature by placing the apparatus in a thermostat chamber, in which the change of the temperature was less than 0.1 K during a