Observation of long-term permeability of a single rock fracture under different thermal conditions

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Considering the variation in the fracture aperture under various thermal conditions, a suite of permeability experiments using a granite specimen with a single rock fracture was performed at the confining conditions of 3.0 MPa and the temperature of 20 and 60 ºC. The results confirmed that the permeability decreased with time at 20 ºC, and the permeability at 60 ºC was always lower than that at 20 ºC, which implicates that chemo-mechanical phenomena such as the pressure solution is likely to change the contacting situation within the fracture and to result in the permeability reduction with time.

Key Words: *granite, single rock fracture, long-term, permeability, time-dependent*

1. INTRODUCTION

Since the underground geothermal system and radioactive waste repositories have been focused many years[1)], the fluid in the fractured rock mass is influenced by the chemical reaction, thermal-hydro-mechanical deformation in the long-term[2)]. The hydro-thermal interaction such as the mineral precipitation may occur over years and had a significant influence to the fractures[3)]. Few previous experimental studies investigated the long-term permeability evolution of fractured rocks under the hydro-thermal condition. Polak et al. (2004) experimentally observed the permeability of a rock fracture. They reported that the permeability had a spontaneous reducing over 900 hours, and then it increased inversely through changing the fracture fluid from the water to the distilled water[4)]. Yasuhara et al. (2006) investigated the permeability in the fissures of the novaculite exposed to t the confining pressure of 1.4 MPa and the temperature of 20 - 120 ºC. The results indicated that the permeability decreased, and then it increased under a high temperature and a faster flow rate.[5)].Those two experiments mentioned above imply that the hydro-thermal interaction obviously affects the fracture permeability. The long-term fluid flow in a fracture may redistribute the mineral mass around the fracture asperities, which would alter the width of fracture aperture and decrease its permeability[6)]. Therefore, we should give a special attention to the substance transportation due to mineral dissolution and re-precipitation in a fracture[7)].

There are few laboratory works that examined the long-term permeability of rock fractures considering various thermal conditions[8)]. This study conducted a long-term loading experiment to a granite fracture in laboratory under the temperature of 20 ºC and 60 ºC, and investigated temporal change in the permeability.

2. EXPEIMENTAL METHODOLOGY

2.1 Measurement of the roughness surface

A cylindrical core with the diameter and length 50 mm ×100 mm as shown in **Fig. 1(a)** was used in this experiment. It was split into two halves (A, B side) as shown in **Fig. 1(b)**. A single vertical fracture was made. The physical properties of the tested rock are given in **Table 1**.

Table 1 Physical property of granite specimen

Diameter (mm)	Height (mm)	Density (g/cm^2)	Weight (g)	Volume (mm^2)	Cross area (cm^2)
49.3	101.2	2.589	499.48	192.9	19.07

The morphological information of the fracture surface (A side) is shown in **Fig.2**. This was measured by the two different means, one is the VR-3200 3D measurement system (a) and the other is the laser scan profiler from Kyoto-University (b). The VR-3200 equipment has a relatively high magnification, with the measurement coordinate interval of 46.846 micrometer. The total coordinate number is 4012890. In comparison, the laser scanning has the spot diameter of 0.05 mm and the measurement interval of 0.25 mm. The total number is 74277.

Roughness degree of the fracture surface was evaluated with the Barton's JRC value (Joint Roughness Coefficient). The JRC value is easier to illustrate the morphology of the fracture surface[9]. In addition, the dimensionless parameter Z_2 was used, which is defined by the the Tse & Cruden`s formula[10]:

$$Z_2 = \left[\frac{1}{M-1} \sum_{i=1}^{M-1} \left(\frac{\Delta y}{\Delta x} \right)_i^2 \right]^{\frac{1}{2}} \qquad (1)$$

where M is the number of sampling intervals, Δx is the sampling interval and Δy is the difference between two adjacent points. The JRC profile is changed by the different length interval (0.25 mm and 0.5 mm). In the Tse's equation, there is a correlation between the JRC and Z_2 value:

$$\begin{aligned} JRC &= 60.32 Z_2 - 4.51 \quad (\Delta x = 0.25mm) \\ JRC &= 61.79 Z_2 - 3.47 \quad (\Delta x = 0.50mm) \end{aligned} \qquad (2)$$

The calculated JRC values with two different means are listed in **Table 2**. It is inferred that the JRC value became smaller with a highly accurately coordinate measurement.

Fig.1(a) Cross section of the granite specimen

Fig.1(b) Cylindrical granite core is splited into two halves (A,B) to create a vertical single fracture

Table 2 The JRC value with two different means

	JRC	(JRC=60.32×Z2-4.51) 0.25 mm		(JRC=61.79×Z2-3.47) 0.5 mm	
Samp 1#	**Laser Scanning**	**A Side** 24.7	**B Side** 27.4	**A Side** 18.0	**B Side** 18.5
	VR-3200	19.9	20.1	15.9	15.9

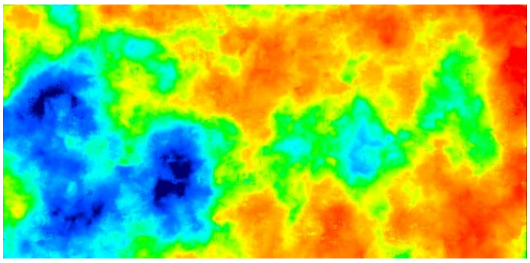

Fig.2(a) Morphology of the roughness surface (A side) by VR-3200

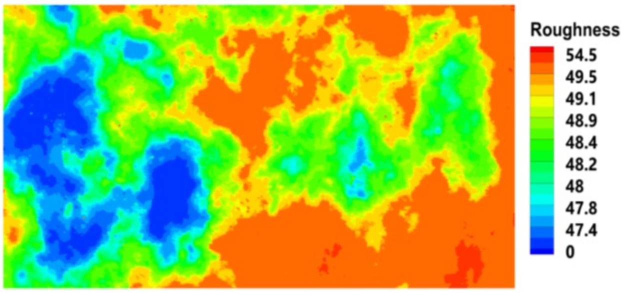

Fig.2(b) Morphology of the roughness surface (A side) by laser scanning

2.2 Experimental conditions

This study used the triaxial apparatus shown in **Fig.3,** which is designed to resist the maximum pressure of 20 MPa and the maximum temperature of 200 ºC. The experimental procedure is shown in Fig.4. First, the confining pressure of 3.0 MPa was applied at 20 ºC, and it was kept for 180 days. Second, after the temperature was elevated to 60 ºC, the confining pressure of 3.0 MPa was applied and kept for 30 days. Fig.4 also shows the timings of the permeability test. At each timing, we conducted the transient pulse permeability test several times. The water pressure condition in the permeability test is summarized in Table 3. When the confining pressure was 3.0 MPa, 0.15 MPa-differential water pressure was employed for the permeability test.

In this study the transient pulse technology was applied in the permeability test. The long-term experimental was performed under 20 and 60 ºC. The confining pressure was set as the constant value. Permeability was measured at several times.

The permeability test condition is listed in **Table 3**, The fluid viscosity and compressibility value are determined by the temperature change. The constant confining pressure of the permeability is 3.0 MPa, the duration of the permeability test is 180 days in 20 ℃, and 28 days in 60 ℃. **Fig.4** shows the experimental procedure. It illustrates the test interval, the total period and the temperature conditions.

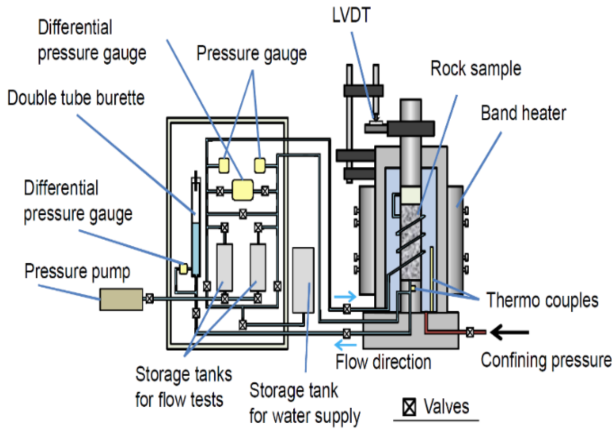

Fig.3 Triaxial vessel used in this study[11)]

Table.3 Pressure variation and fluid conditions under different temperature

Confining pressure [MPa]	1.0	1.5	2.0	2.5	3.0
Pressure at upstream tank [MPa]	0.200	0.250	0.300	0.350	0.400
Pressure at downstream tank [MPa]	0.150	0.175	0.200	0.225	0.250
fluid	fluid viscosity (10^{-10} Pa s)		compressibility (10^{-3} Pa)		
T=20 ℃	1.0017		4.5883		
T=60 ℃	0.467		4.3		

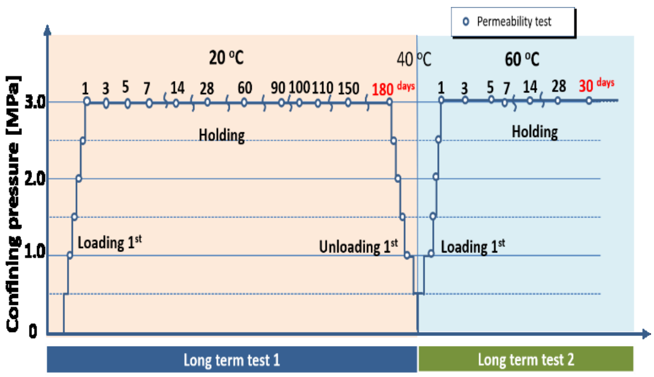

Fig.4 The experimental procedure

3. RESULT AND COMPARISON

Fig.5 shows the temporal change in fracture permeability under 20 °C and 3 MPa condition. As seen in the figure, the permeability, k = 3.7× 10^{-13} [m^2] at the beginning of the long-term test, was reduced to 20% (k = 0.7× 10^{-13} [m^2]) in 180 days under the constant confining pressure and temperature condition. However, the decreasing rate is neither constant nor monotonic. In the first seven days, the permeability dropped rapidly to 60% of the initial value and it reached almost stable (7 - 28 days). And it starts decreasing again from 28 days to 120 days. After 120 days, we can see that the permeability is gradually increasing. Although logical explanation of this transition in permeability is difficult at present, the authors believe that the fracture was slowly closing with time under constant confining pressure because of the mechanical creep deformation around the contact asperities on the fracture surfaces. **Fig.6** shows the change in fracture permeability with confining pressure before and after the long-term test. The black line indicates the permeability in the loading process before the long-term test, and the red line indicates that in the unloading process after long-term test.

From this figure, it is clearly found that the permeability after the long-term test does not show increasing against unloading of the confining pressure. This means that the closure of the fracture during the long-term test was the permanent deformation. This is a large difference to the experimental result of Yasuhara et al. (2013) shows in **Fig. 7**. Yasuhara et al. (2013) carried out the long-term test using a granite core with a single fracture similar to our study. They kept the confining pressure at 10 MPa under 20 °C for 35 days[11]. From their result of 20 °C long-term experiment, the permeability shows increasing against the unloading of the confining pressure after the long-term test, and it recovers to almost the same level when the confining pressure reaches to the initial value (1 MPa). From comparison of our result (**Fig.6**) and their result (**Fig.7**), there is almost no doubt that the long time compression of the fracture, more than five times longer than Yasuhara's experiment, caused permanent deformation in the fracture, and it made the contact asperities lose their elasticity. We have to investigate the mechanism of this permanent deformation in the future, namely, mechanical deformation like consolidation or chemical dissolution like pressure solution.

Fig. 8 shows the permeability of 20 °C and 60 °C tests in the loading process of the confining pressure. The permeability is not sensitive to the confining pressure. In the case of 60 °C, permeability did not show obvious change by comparing with 20 °C results in **Fig.5**. The permeability value in 180 day is nearly the same while the confining pressure is 3 MPa. In addition, in the loading process at 60 °C the permeability showed a minute increase in spite of loading the confining pressure. Mechanical influence can not be the important factor to explain after the long-term test. The viscosity of the distilled water decreased in a relative high temperature which can be inferred by the formula $\nu = \mu / \rho$, the fluid kinematic viscosity changed with the fluid viscosity. When the fluid kinematic viscosity reduced, the velocity of the fluid became faster than in 20 °C , which can be inferred that at the initial time of 60 °C the permeability increased.

Fig.9 illustrated the permeability had a minor decrease until 28 days, the fracture gradually closed when the rock temperature became stable. The initial fracture aperture dilated in this stable period, the aperture closed and made the fluid difficultly flow through the rock fracture. And it is needed a further verification in the future experimental work.

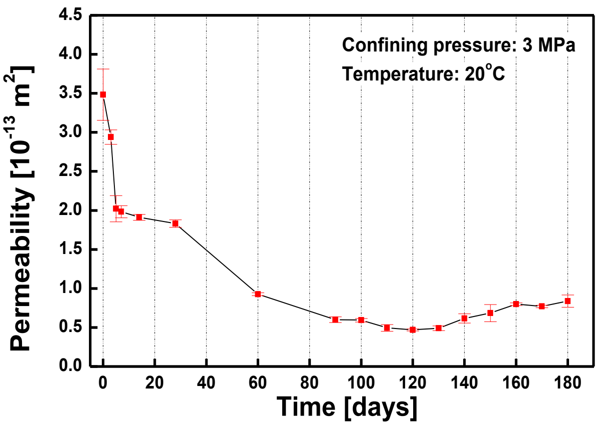

Fig.5 Temporal change in fracture permeability under condition of 20 °C and 3 MPa

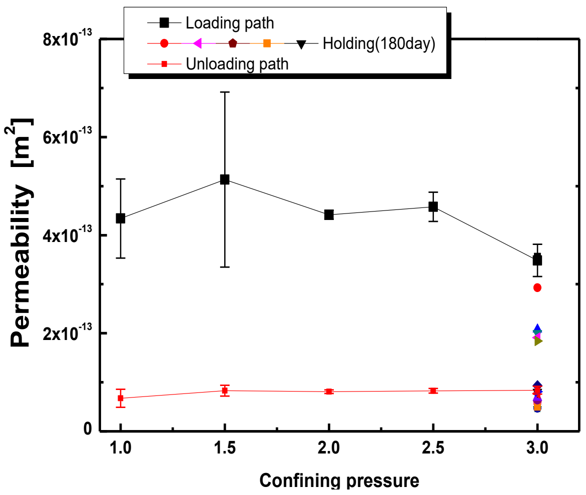

Fig.6 Change in fracture permeability with confining pressure under 20 °C condition (black: loading path, red: unloading path)

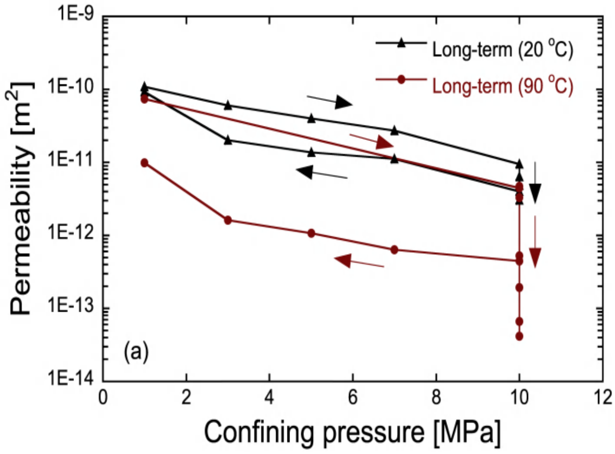

Fig.7 Change in fracture permeability with confining pressure under 20 °C condition by Yasuhara et al. (2013). The confining pressure of 10 MPa kept applied for 35 days[11].

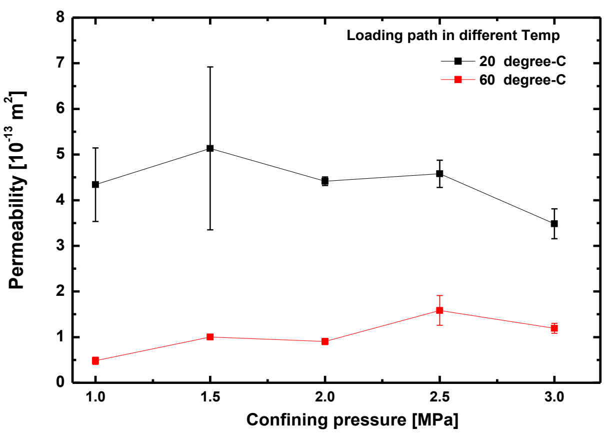

Fig.8 Comparison with loading path in different temperature

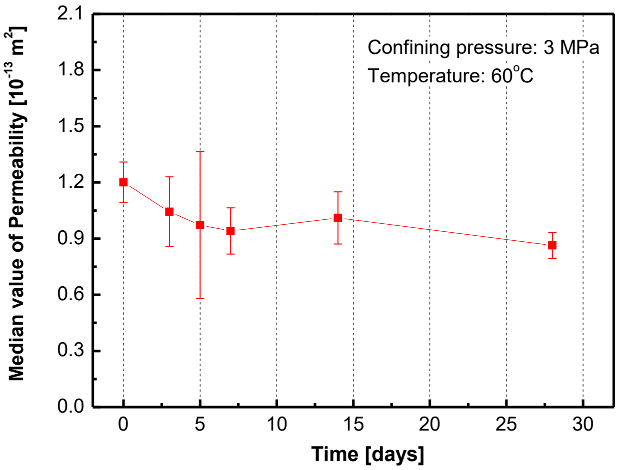

Fig.9 Temporal change in fracture permeability under condition of 60 °C and 3 MPa

4. CONCLUSION

Long-term permeability evolution was studied under two different temperatures, separated 20 and 60 °C. In 20 °C permeability evolution represented three different stages, at first the permeability was sharply decreased, then it kept a stable stage, after that it reduced remarkably once again with the time. From the 120 day permeability showed a minor increase, that means the irreversible deformation occurred and it should not be negligible that the mechanical creep deformation influenced the fracture asperities and affected the permeability change.

In 60 °C, results showed the permeability value is lower than in 20 °C.The thermal expansion reduced the permeability and made the fracture aperture narrower. The permeability has a reducing tendency until 28days. Chemical reaction on the fracture asperities might happen to change the permeability performance. That is, the pressure solution, the mineral dissolution or the mineral re-precipitation. It is indispensable to illustrate this evolution in the further experimental study.

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