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Temporal change in permeability in macro-fractured granite by accumulation of fine-grained minerals

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Abstract

It is essential to understand the long-term migration of radionuclides when considering rock engineering projects such as the geological disposal of radioactive waste. The network of fractures and pores in a rock mass plays a major role in fluid migration as it provides a pathway for fluid flow. The geometry of the network can change due to fracture sealing by some fine-grained materials over long-term periods. Groundwater usually contains fine-grained minerals such as clay minerals. Therefore, it is possible that the accumulation of such fine-grained minerals occurs within a rock fracture under groundwater flow. In this case, the aperture of a fracture may decrease, which brings about the decrease of the permeability. It is therefore essential to conduct permeability measurements using water including fine-grained minerals in order to understand the permeability characteristics of a rock. However, this has not been investigated well. In this study, we use a macro-fractured granite sample to investigate the temporal change of the permeability that occurs under the flow of water that includes two different amounts of clay.

It was shown that the clay accumulated in the macro-fracture and that the permeability of the macro-fractured granite sample decreased over time. It was also recognized that the decrease of the permeability was more significant under the water flow with the higher clay content. As a result of the observation using microscope, it was recognized that the clay minerals accumulated in the macro-fracture in the granite sample, which decreased the aperture of the fracture. We concluded that the accumulation of clay minerals in the fracture decreased the permeability of the rock. Furthermore, it is concluded that the filling and closure of fractures in rock is possible under the flow of groundwater including clay minerals.

1. Introduction

Understand the long-term migration of fluid is important for various rock engineering projects, such as the extraction of petroleum, carbon capture and storage, and the geological disposal of radioactive wastes. The network of fractures and pores in a rock plays a major role in fluid migration, because it provides a pathway of flow.

Fractures and pores are ubiquitous on all scales in crustal rocks. Fractures and pores influence the physical, mechanical, and transport properties of rocks in the upper crust strongly. It is well known that the introduction of open macro- and micro-fractures increase the permeability of rock when the initial permeability is low, and that the permeability decreases as the confining pressure increases due to the closure of fractures (e.g., Nara et al., Tectonophysics, 2011).

The geometry of a network can change due to the sealing of a fracture over long-term periods. The results of various measurements have suggested that the permeability of fractured igneous rock decreased due to the sealing of fractures by fine-grained materials (e.g., Wang et al., J. Geophys. Res. – Solid Earth, 2016; Pérez-Flores et al., J. Struct. Geol., 2017; Nara et al., Pure Appl. Geophys., 2018). The results of previous studies have been obtained by permeability measurements that used distilled water; however, groundwater usually contains fine-grained minerals such as clay minerals. It is possible that the accumulation of fine-grained minerals occurs in a fracture when groundwater flows into the fracture. In addition, the aperture of the fracture can decrease if fine-grained minerals accumulate, which influences the permeability. Therefore, it is necessary to conduct permeability measurements using water that includes fine-grained minerals in order to further understand the permeability characteristics of a rock. However, to date, no studies have reported the change in permeability that occurs under the flow of water containing fine-grained minerals; hence, in the present study, we investigate this using a macro-fractured granite rock sample and water that includes clay minerals.

2. Methodology

In this study, the permeability measurements were conducted using the flow pump method. For this method, the permeability of a material is determined by Darcy's law under a steady state flow condition, where the flow rate of the water is constant. In particular, the difference between the upstream and downstream hydraulic pressure must be determined under a constant flow rate. For the flow pump method, the permeability (hydraulic conductivity, K (m/s)) is evaluated using Eq. (1):

$$K = \frac{Ql}{A(h_u - h_d)} \tag{1}$$

where Q is the flow rate (m^3/s), l is the length of the specimen (m), A is the cross-sectional area of the specimen (m^2), h_u is the upstream hydraulic head (m), and h_d is the downstream hydraulic head (m).

Figure 1 shows a schematic illustration of the permeability measurement system used in this study. The permeability measurement system mainly consisted of a pressure vessel where the rock specimen was placed, a hand pump to apply the confining pressure (1 MPa), a cylinder of water that included clay minerals, a syringe pump to control the flow rate (0.01 ml/min) of the pore fluid (i.e., water including clay), a data logger, and temperature controllers. When measuring permeability, it is important to avoid temperature change; hence, the measurements were performed in a temperature-controlled room at 22 ± 0.5 °C.

We used water that included clay minerals: 15.9 g or 1.5 g of clay samples were included in 1.0 L of distilled water. The water was stirred using a magnetic stirrer that was placed beside the cylinder to disperse the clay particles widely within the water.

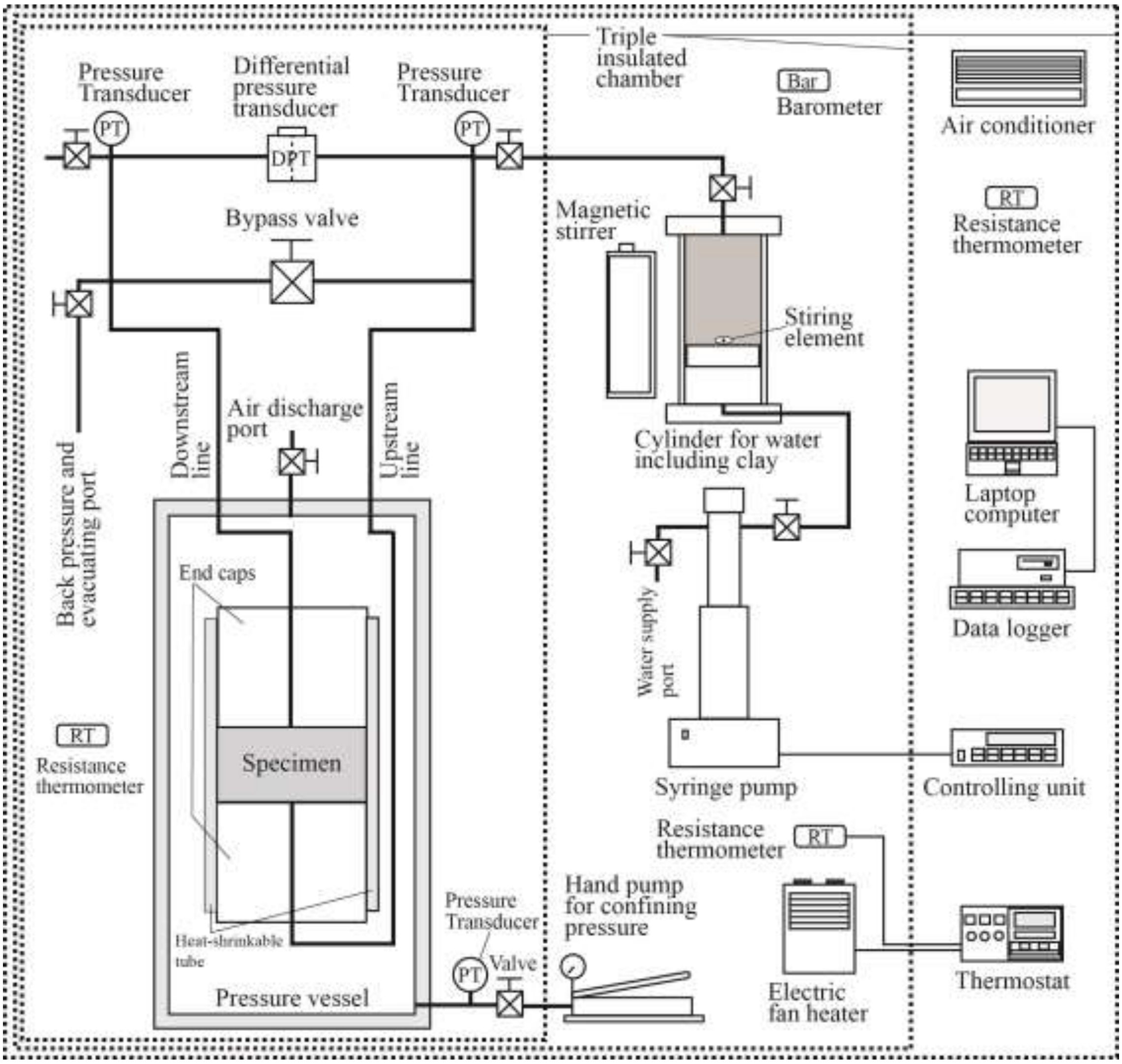

Figure 1 Schematic illustration of the permeability measurement system.

3. Rock sample

In this study, the rock sample was Toki granite. The rock sample was obtained from a depth of 200 m in the Mizunami Underground Research Laboratory in Mizunami-City, Japan (e.g., Nara et al., Int. J. Rock Mech. Min. Sci., 2011). Figure 2 shows a photomicrograph of Toki granite taken by a polarization microscope under crossed-nicols. We prepared a macro-fractured cylindrical specimen (50 mm diameter and 25 mm length) from a naturally macro-fractured rock core sample of Toki granite (Figure 3) for the permeability measurements.

Figure 2 Photomicrograph of Toki granite under crossed nicols.
(width: 1.95 mm, height: 1.25 mm)

Figure 3 Photograph of a macro-fractured granite specimen.

The clay that was mixed with water was also obtained from the Mizunami Underground Research Laboratory at the same depth, and was the same as that used by Kato et al. (Mater. Trans., 2018). A scanning electron photomicrograph and the particle size distribution of the clay sample are shown in Figures 4 and 5, respectively.

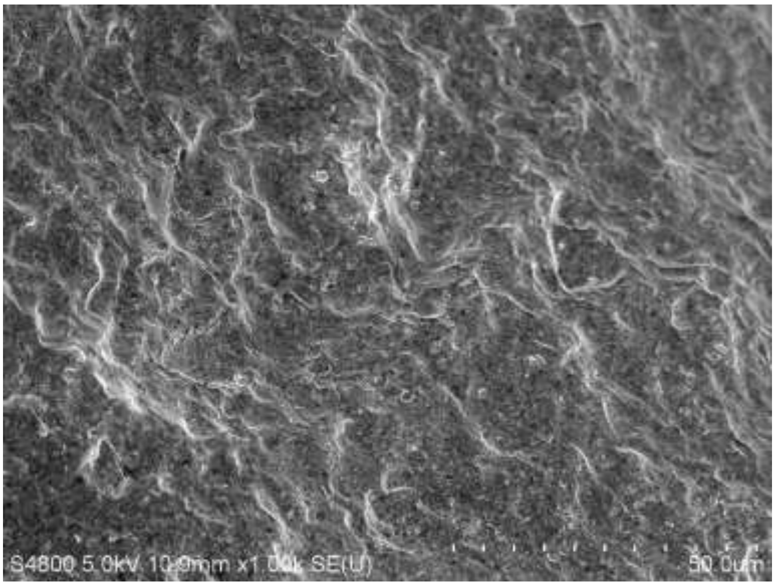

Figure 4 Scanning electron photomicrograph of a clay sample
(after Kato et al., Mater. Trans., 2018)

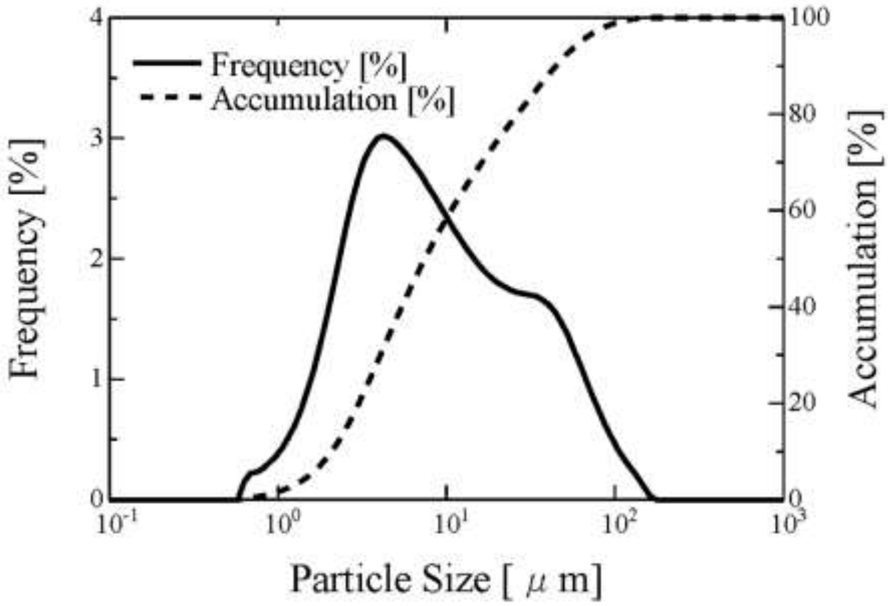

Figure 5 Particle size distribution of a clay sample
(after Kato et al., Mater. Trans., 2018)

4. Results

Permeability measurements were first conducted by the flow pump method on two macro-fractured specimens using distilled water (with no clay). These specimens were termed TG-f2 and TG-f3, and are different from specimen TG-f used in Nara et al. (Pure Appl. Geophys., 2018). The temporal changes of the pressure difference between the upstream and downstream locations for the macro-fractured granite specimens TG-f2 and TG-f3 are shown in Figure 6. From Eq. (1), we estimated the hydraulic conductivity using the mean value of the pressure difference where the value almost converges to be 2.09×10^{-6} m/s for specimen TG-f2 and 1.53×10^{-8} m/s for specimen TG-f3.

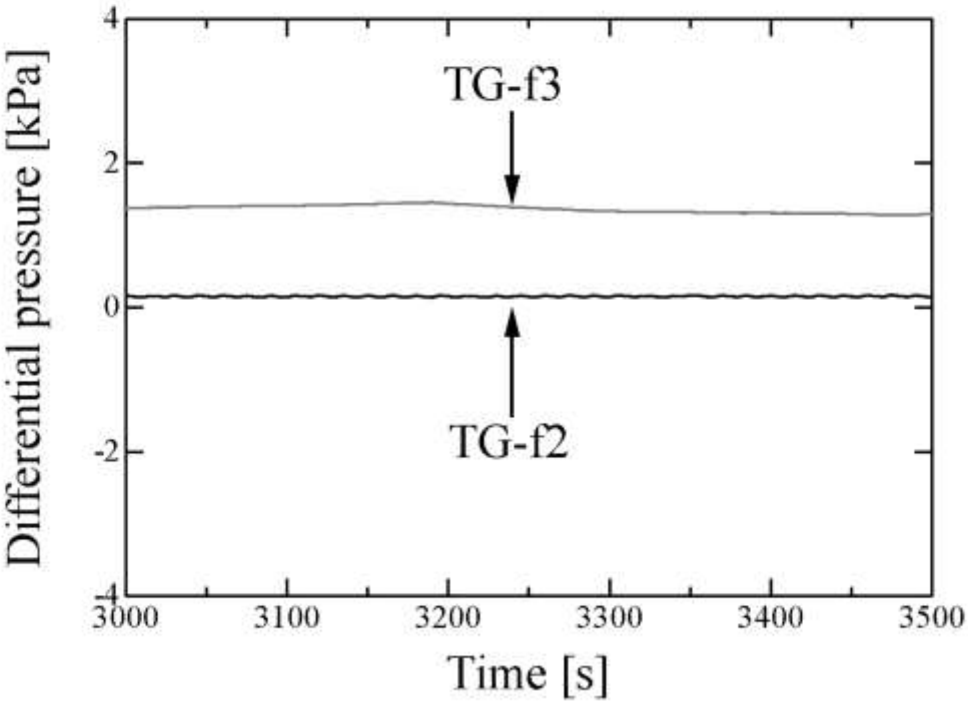

Figure 6 Temporal change of the pressure difference between upstream and downstream for macro-fractured specimens “TG-f2” and “TG-f3” using distilled water (no clay).

The two macro-fractured specimens were used to conduct the permeability measurements using the water that included the clay; TG-f2 was used with the 15.9 g clay/L water and TG-f3 was used with the 1.5 g clay/L water. Figure 7 presents the temporal change of the pressure difference between the upstream and downstream locations in the TG-f2 and TG-f3 granite specimens. Although fluctuations are observed for the values of the pressure difference, it suggests a general increase over time, which indicates the decrease of the permeability of the rock over time.

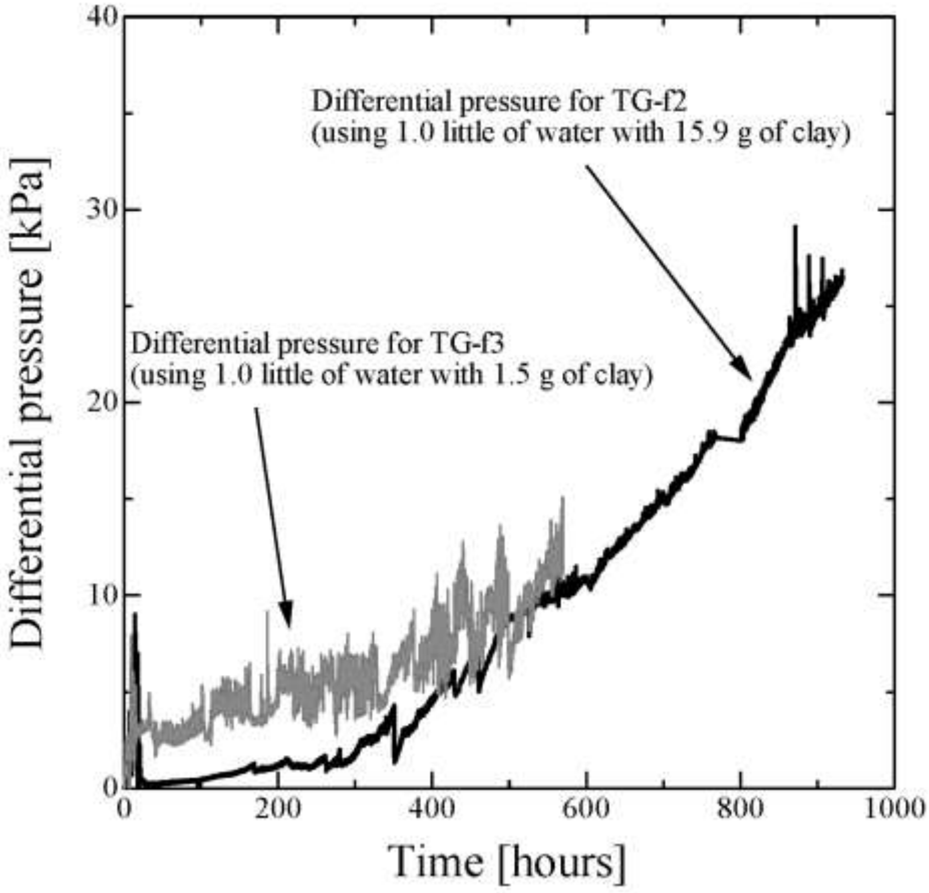

Figure 7 Temporal change of pressure difference between upstream and downstream for a flow pump permeability test with a fractured Toki granite specimen.

Figure 8 shows the temporal change of the hydraulic conductivity. For the estimation of the hydraulic conductivity, the values of the pressure difference were chosen when the fluctuation was relatively small. As shown in Figure 8, the decrease of the permeability is obvious with elapsed time in both cases.

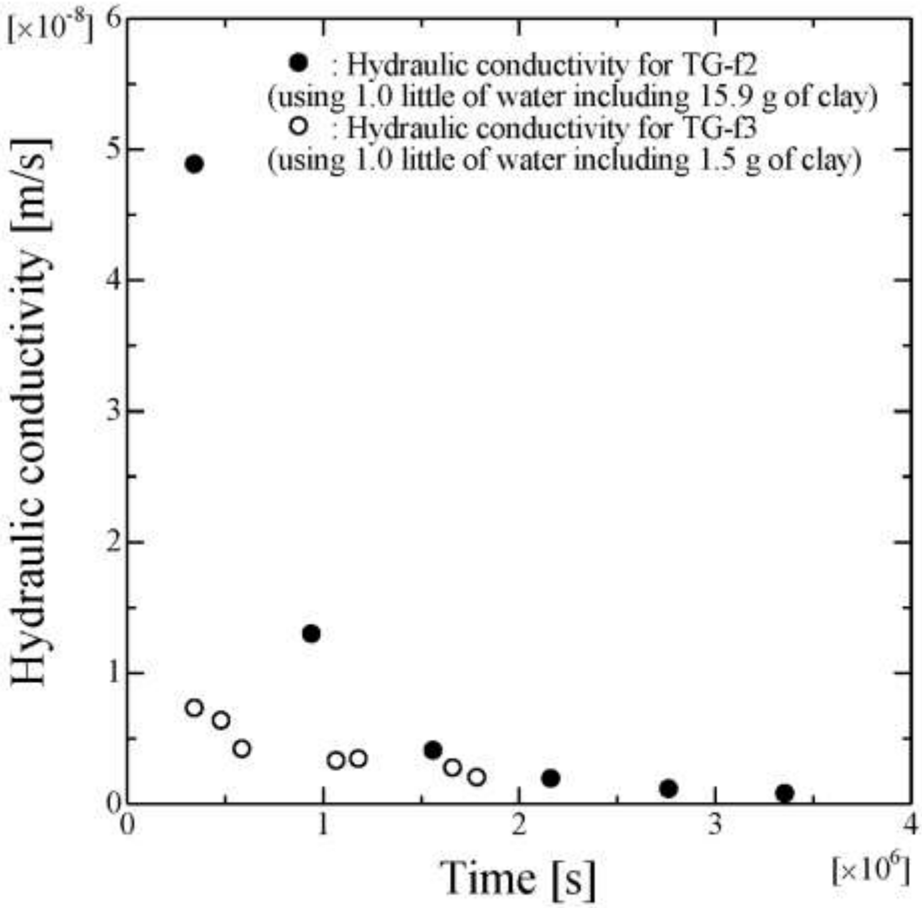

Figure 8 Temporal change of hydraulic conductivity under flow of water including clay.

5. Discussion

Findings in this study suggested that the clay in the water decreased the permeability and thus increased the confining ability of rock. Figure 9 shows the temporal change of the hydraulic conductivities that were normalized by the values obtained under the flow of distilled water (with no clay), which were 2.09×10^{-6} m/s for TG-f2 and 1.53×10^{-8} m/s for TG-f3. Normalization indicated that the decrease of the hydraulic conductivity was more obvious for the water with the higher clay content. This suggests that more clay precipitated on the fracture in specimen TG-f2, which led to the decreased hydraulic conductivity.

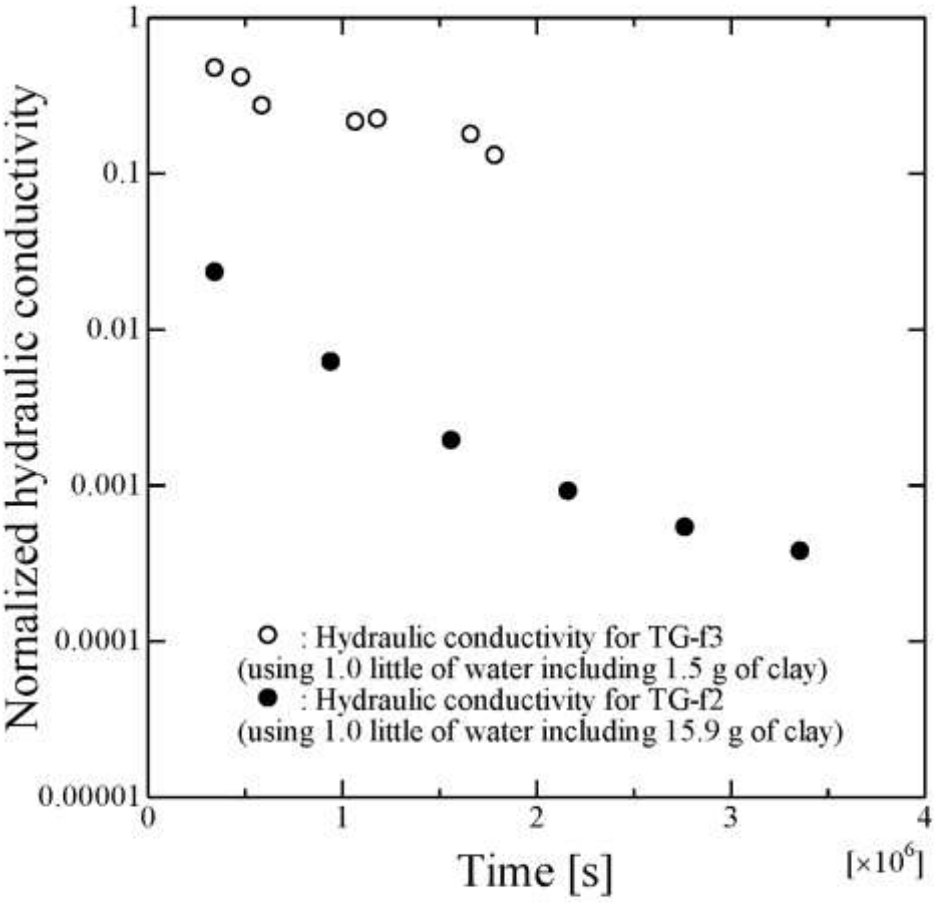

Figure 9 Temporal change of hydraulic conductivity normalized by values obtained under the flow of distilled water (no clay).

It is well-known that the aperture of the fracture strongly affects permeability. Nara et al. (Pure Appl. Geophys., 2018) obtained the relationship between the aperture of the fracture and the hydraulic conductivity, as follows:

$$a = \sqrt[3]{\frac{3\pi\mu DK}{\rho g}} \tag{2}$$

where a is the hydraulic aperture, μ is the viscosity of the water (0.001 Pa/s), D is the diameter of the specimen (0.05 m), K is the hydraulic conductivity, ρ is the bulk density of the water (1000 kg/m^3), and g is the gravitational acceleration (9.8 m/s^2). Figure 10 shows the temporal change of the aperture and the change in the permeability, and illustrates that the aperture decreases with elapsed time. In particular, the decrease of the hydraulic aperture was more significant for the water with the higher clay content.

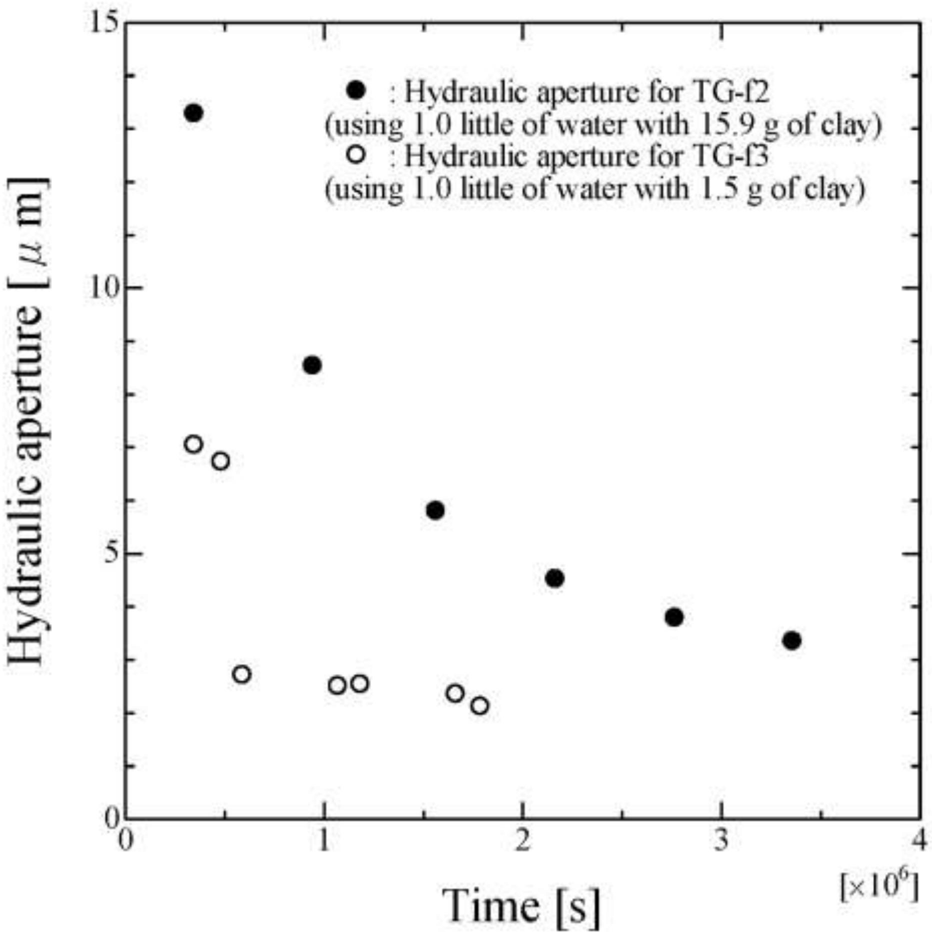

Figure 10 Temporal change of the hydraulic aperture.

Figure 11 shows the temporal change of the hydraulic aperture normalized by the values obtained under the flow of distilled water (with no clay), which were 4.65×10^{-5} m for TG-f2 and 9.03×10^{-6} m for TG-f3. It is recognized that the decrease in the aperture was more significant when the amount of clay included in the water was greater.

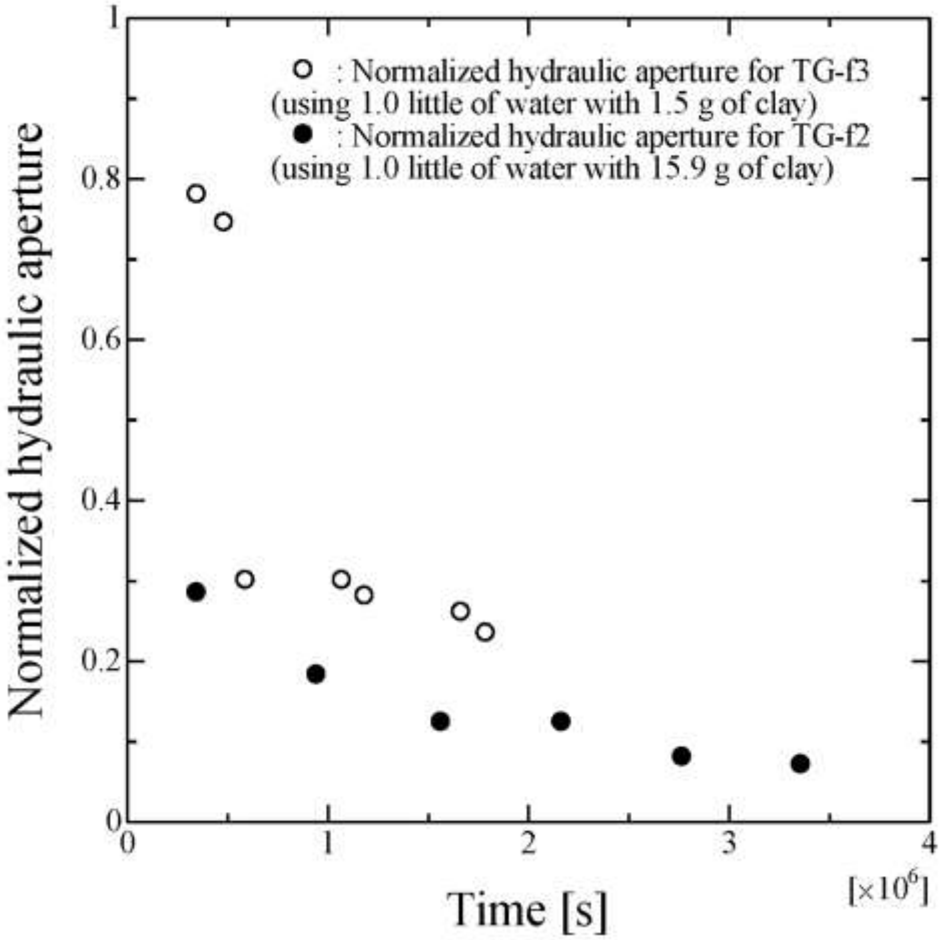

Figure 11 Temporal change of the hydraulic aperture normalized by the values obtained under the flow of distilled water (no clay).

We observed the fracture in the specimen after the permeability measurement to assess how the clay influenced the changes (decreases) in the permeability and aperture of the fracture. Figure 12 shows the photographs of the fracture in the rock sample after the permeability measurement. The areas with light color in the central part of the photographs indicate the clay that accumulated in the fracture, and shows that this was an obvious accumulation. Therefore, we considered that the clay included in water accumulated in the fracture of the specimen, and subsequently caused the decreases in the aperture of the fracture and hydraulic conductivity of the macro-fractured granite.

(a)

(b)

Figure 12 Photograph (width 570 μm) of fracture sealed by clay. (a) Photograph for TG-f2 (using 1.0 L of water including 15.9 g of clay), (b) Photograph for TG-f3 (using 1.0 L of water including 1.5 g of clay).

The existence of fractures and their network are undesirable for the geological disposal of radioactive wastes. In the case of granite, however, it has been reported that fractures are often filled naturally with fine-grained minerals. Nara et al. (Pure Appl. Geophys., 2018) showed that the permeability of fractured granite decreased if fractures were naturally closed by clays. It is considered that the existence of fractures in granitic rocks can be nonproblematic with respect to the long-term use of an underground granite rock mass.

It is essential to use an underground rock mass as a natural barrier for the long-term geological disposal of radioactive waste. In this case, a low rock permeability is desirable. The results of this study suggest that the confining ability of a granite rock mass can be maintained by the filling and closure of fractures by clay minerals, which is favorable for the radioactive waste disposal.

6. Conclusions

The change in permeability of a macro-fractured granite sample was investigated under the flow of water that included clay. It was found that the hydraulic conductivity decreased with elapsed time. It was also shown that the decrease of the hydraulic conductivity was more significant when the amount of clays in the water was greater. The accumulation of clay was observed in the fracture. We conclude that the accumulation of fine-grained minerals in the fracture decreased the permeability of the fractured rock. The filling and closure of fractures in rock are considered to be possible under the flow of groundwater that includes clay minerals.

Acknowledgement

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Precious studies by our research group

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