Temperature and confining pressure effects on the permeability of rocks under triaxial compression

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Introduction

Excavation disturbed Zone (EdZ) and Excavation Damaged Zone (EDZ) occur at all types of excavation (Fig. 1a). The EdZ is the zone with recoverable elastic deformation and EDZ is the zone with irrecoverable rock failure. Stress redistribution and changes in permeability due to the excavations happen within these zones. The interaction between these changes, known as hydromechanical (HM) coupling, significantly affects the short- and long-term stability of excavations for a wide range of applications, including tunneling, coal mining and coal methane extraction, oil and gas extraction, hydrogeological and well test analyses, geothermal energy, deep well injection of liquid and solid wastes, geologic storage of natural gas, and geologic sequestration of CO₂, as well as a variety of geologic processes.

The influences of temperature–confining-pressure coupling on rock permeability as a thermo-hydromechanical (THM) process under compression is very important considering the radioactive waste disposal site. As excavations proceed at different depths and in different types of rock, the permeability of rock, either it is intact or fractured, can be changed by confining pressure as HM processes. Many physical properties of rocks, including permeability, are also influenced by temperature. The temperature change of rock masses can be induced by human activity or natural processes. In particular, radioactive waste repositories, which must be maintained for long periods even after closure are affected by heat from the decaying waste.

Objectives

The specific objectives of this research are:

- To clarify the permeability change of three rocks during triaxial compression.
- To clarify the effects of confining pressure and temperature on the permeability under compression of three rocks.
- To have dominant mechanisms for the permeability behavior for each rock.
- To estimate sealability of rockmass and its change due to EDZ progression. Sealability is defined here as a property of rock which is inversely proportional to flow rate per unit pore pressure gradient. Namely, it is proportional to viscosity and inversely proportional to permeability whereas, the permeability and viscosity are the function of temperature.

Contents of the research

To clarify the temperature–confining-pressure coupling effects as thermo-hydromechanical (THM) processes triaxial tests were carried out at confining pressures of 1–15 MPa at 295 K and 353 K measuring permeability. The types of rock considered were Shikotsu welded tuff as a soft pyroclastic rock, Kimachi sandstone as a medium-hard clastic rock, and Inada granite as a hard crystalline rock to cover very wide range of physical properties of rock. The samples were held for 24 h at the target consolidation pressure, and then constant strain-rate compression was applied. Permeability was measured by the constant flow or transient pulse method. In addition, X-ray computed tomography (CT) observation and thin-section image analysis were carried out on the specimens after compression. CT images were obtained in three perpendicular planes to determine the macroscopic failure conditions. Microstructure analysis was conducted using thin-section images of specimens that had been impregnated with blue resin.

A maximum effective confining pressure of 15 MPa was established by the maximum capacity of the apparatus. Although this effective confining pressure may not seem sufficiently high, especially for Inada granite, it corresponds to the effective vertical stress at a depth of 882 m and the effective horizontal stress at a depth of 3528 m, considering the effective stress. As most underground caverns are constructed to depths of less than 1000 m, this maximum confining pressure value is meaningful.

The rock temperature increases from initial temperature by decay heat after emplacement of the waste up to around 353 K. The experiments were therefore carried out at 295 K and 353 K, considering also that the limitation of the ultra compact triaxial vessel was 353 K.

In case of the radioactive waste disposal sites (Fig. 1b), the in situ confining pressure is released due to excavation. After the excavation and the waste is backfilled, temperature and confining pressure increase due to decay heat from the waste. The confining pressure remains the same after decay heat disappeared. Although the stress path of the real field and the experiment is different, the effect may not be fatal to investigate the confining pressure and temperature effects on the permeability in particular in the post-failure region.

Originality of the research

Many studies have been conducted to understand the
behavior of permeability under compression. This research, however is unique because (1) The confining pressure and temperature-confining pressure coupling effect on the minimum and post compression permeability under compression (2) the number of tests densely covered the range of confining pressures, (3) axial compression was applied so as to observe the entire permeability–axial strain relationship up to the residual strength, (4) results for three different rocks were compared, and (5) both CT scanning and thin-section analysis were carried out to determine the macroscopic and microscopic structures of the specimens after the experiments. Points (2) and (3), although not applicable for all rocks, enabled to propose equations to represent the minimum and final permeability with respect to confining pressure. Points (4) and (5) enabled to define the mechanisms behind the permeability behavior and to describe the different influences of axial compression and confining pressure on permeability based on mechanical properties that differed by origin, mineral composition, and microstructures.

Materials and methods

Rock types

Rock masses, which consist of different types of rock, are being considered for radioactive waste disposal sites including crystalline and clastic rocks, clay, tuff, rocksalt, etc. Inada granite, Kimachi sandstone and Shikotsu welded tuff were chosen for consideration of the effects of temperature and confining pressure as THM processes on wide range of physical properties of rock. Shikotsu welded tuff comprises mainly plagioclase, hypersthene, augite, hornblende, and transparent glass, having a felt-like structure with an amoebic form in the matrix. The rock is characterized by its volcanic glass matrix and pores. It exhibits very high effective porosity of up to 35.6 % with low P- and S-wave velocities. It has low uniaxial compressive strength and dry density.

Inada granite contains quartz, feldspar, biotite, and allanite, with zircon, apatite, and ilmenite as accessory minerals. The rock is characterized by its grain-to-grain contact and microcracks. It has very low effective porosity with very high uniaxial compressive strength and dry density having high P- and S-wave velocities.

Experimental procedure

The rock blocks were collected from undisturbed parts of quarries and the specimens were prepared from the blocks by the following procedure. Firstly, the P-wave velocity along each pair of opposite sides of the rock blocks was measured with 140-kHz sensors. Then, cylindrical cores that had a diameter of 30 mm and a length of 60 mm were prepared in the direction of the slowest P-wave velocity. Next, the core ends were polished to a parallelism of 2/100. The diameter of the specimen exceeded 10 times the maximum particle size, except for the pumice fragments of Shikotsu welded tuff. Whether or not the objectives were achieved may have been unaffected by the size of the specimens, including those of the tuff, as long as the specimens were of the same size.

Specimens were saturated fully in pure water in a water-submergible vacuum jar before two stainless steel endpieces were attached to the saturated specimen with vinyl tape. The endpieces had a hole in their centers to allow water to flow through the specimen. Two cross-type strain gauges were glued to the center of opposite sides of the specimen to measure the strain. To maintain the water flow within the
specimen, a coating of silicon sealant was applied to the specimen up to the curvature of the endpieces. Later, a heat-shrinkable tube was used to jacket the specimen and the attached endpieces to prevent direct contact with the confining fluid (water) confined within the specimen. Then, the sample was submerged in water for 24 h.

Each sample was inserted into the ultra compact triaxial cell (Fig. 2a) covered with a band-type heater (Acim Jouanin, L6060C57A5, 230 V, 575 W) with a controller (Three High, THC-15, 273 K-1272 K). Then, axial stress and confining pressure were applied. The triaxial tests were carried out under 1–15 MPa of confining pressure at 295 or 353 K. The 353 K is the predicted maximum temperature of the surrounding rock mass of a nuclear waste disposal site. It was also the limit of the triaxial cell. To reach the target consolidation pressure, the axial stress was applied first and, then, the confining pressure was increased in 1-MPa steps (Fig. 2b). After reaching the target consolidation pressure, the sample was held in this state for 24 h at 295 K or 353 K. The time for consolidation to stabilize the initial time-dependent deformation could be shorter than 24 h. The authors, however, used a longer period of 24 h without precise calculations.

After consolidation, a constant strain rate (10^{-5} s^{-1}, i.e., 0.036 mm/min)-controlled compression was applied until the stroke-based strain reached 10% for the Shikotsu welded tuff or 7% for the Kimachi sandstone and Inada granite. The large strain values were chosen so that the stable residual strength state would be achieved.

The stress path of the real field and the experiment differ and this may affect the results. The effects, however, in investigating the influence of confining pressure and temperature on the permeability of rocks may not be fatal, particularly on the permeability of rocks in the post-failure region.

The permeability of the Shikotsu welded tuff was measured by the constant flow method. The permeability of Kimachi sandstone and Inada granite was measured by the transient-pulse method with the approximate solution by Brace et al. During the experiment, the load, stroke, pore pressure, axial strain, lateral strain, confining pressure, and flow rate were recorded on a data logger at a sampling interval of 10 s.

**Micro- and macrostructure analysis**

Microstructures of the post-compression specimen (pore characteristics of Shikotsu welded tuff, thickness of the cementing material for Kimachi sandstone, and crack characteristics of Inada granite) were analyzed after the stress was released. Thin-section images of the blue-resin-impregnated specimens with Scion Image software were viewed at a resolution of 8.8 × 8.8 μm. Macrostructures (number, orientation, and geometry of the rupture planes and fractures) of the post-compression specimens were observed after the stress was released using a microfocus X-ray-computed tomography (CT) scanner with a 37 × 37 × 80 μm resolution.

**Results**

**The effects of deformation and failure on permeability**

For Shikotsu welded tuff, the peak strength at 353 K was lower than at 295 K. The tangent modulus and residual strength at 353 K were slightly lower than those at 295 K. The permeability during deformation and failure at 295 K, as well as at 353 K, monotonously decreased (Fig. 3). The post-compression permeability decreased with the confining pressure at 295 K, but the permeability at 353 K was almost independent of the confining pressure and as low as that under 15 MPa CP at 295 K (Fig. 4i). The flow velocity per unit pore pressure gradient, which was calculated by substituting the permeability of rock and the viscosity of water into the Darcy’s law, was slightly lower at 1 MPa CP. It was almost the same at 15 MPa CP as the values at 295 K (Fig. 4j). The permeability change (Fig. 5) was calculated from the permeability after 24 hours of consolidation ($K_{con}$)
and the post-compression permeability ($K_{\text{con}}$) as

$$K_{\text{change}} = \left( \frac{(K_{\text{con}} - K_{\text{con}})/K_{\text{con}}}{100} \right)$$

(1)

The change in permeability showed that the decrease became greater with increasing confining pressure from $-3.05\%$ to $-92.12\%$ at 295 K (Fig. 5). No confining-pressure dependency was observed at 353 K ($-84.21\%$ to $-93.93\%$).

For Kimachi sandstone, the peak and residual strengths at 295 K were slightly lower than those at 353 K. No significant influences were observed in the tangent modulus. No significant effects of temperature on critical extensile strain (CES, circumferential or lateral extensile strain value at peak load point) were observed. However, the critical compressive strain (CCS, axial strain value at peak load point) at 353 K was larger than that at 295 K. FUJII et al. (1998) showed that critical extensile strain was much less sensitive to confining pressure, water content or anisotropy than peak stress or critical axial strain. The present results showed that critical extensile strain was also less sensitive to temperature.

The permeability during deformation and failure at 295 K, as well as at 353 K, first decreased, then began to increase before the peak stress, and nearly stabilized in the residual strength state (Fig. 3). The minimum permeability declined with the confining pressure, and no obvious difference was apparent between 295 and 353 K (Fig. 4a). The flow velocity per unit pore pressure gradient was slightly higher at 353 K (Fig. 4b). The post-compression permeability declined with the confining pressure, and the permeability at 353 K was slightly lower (Fig. 4c). However, the flow velocity per unit pore pressure gradient at 353 K was slightly higher (Fig. 4f). At 295 K, the permeability became higher for failure under low confining pressure, and the permeability change (Equation 1) was as high as 179.0% (Fig. 5). The permeability showed a decrease under high confining pressure by as much as $-47.0\%$. The permeability decreased at 353 K, except for 1 MPa CP. The amount of the decrease was almost the same as that at 295 K.

The peak and residual strengths at 353 K of Inada granite were almost identical to those at 295 K. The tangent modulus at 353 K was slightly lower than at 295 K. No significant effects of temperature on critical extensile strain (CES) were observed, whereas critical compressive strain (CCS) at 353 K was larger than that at 295 K. The permeability during deformation and failure at 295 K, as well as at 353 K, behaved in a manner similar to that of Kimachi sandstone (Fig. 3). The minimum permeability declined with the confining pressure at both 295 and 353 K, although the permeability at 353 K was lower than at 295 K (Fig. 4c). The flow velocity per unit pore pressure gradient at 353 K was almost the same as at 295 K (Fig. 4d). The post-compression permeability declined with the confining pressure up to 7 MPa CP at 353 K or 9 MPa CP at 295 K, and then increased again. The permeability (Fig. 4g) and flow velocity per unit pore pressure gradient (Fig. 4h) at 353 K were obviously lower than those at 295 K. At 295 K, the permeability increased with failure, and the permeability change became as great as 4780%. The ratio decreased to 394% with confining pressure until it attained 9 MPa CP, and then increased again to 6640% at 15 MPa CP. At 353 K, the permeability increase was nearly independent of the confining pressure, except for 15 MPa CP, and was as small as the smallest increase at 295 K (Fig. 5).

The effects of deformation and failure on rock structure

In the case of Shikotsu welded tuff, a main rupture plane with sub-rupture planes and several fractures appeared in the CT image for 1 MPa CP at 295 K, whereas only one main rupture plane appeared at 353 K. The porosity near the rupture plane was higher than the porosity far-removed from it. The porosity far-removed from the rupture plane at 353 K was 10.0% less than at 295 K. The rupture plane was absent in 15 MPa cases, and their porosity at 353 K was less than at 295 K by 4.63%. The number of pores with an equivalent diameter of 0.06 mm - 0.18 mm at 353 K was lower than that at 295 K at 1 MPa CP far from the rupture plane. Pores with a smaller equivalent diameter of 0.06 mm were dominant at 353 K, but pores with a diameter of 0.10 mm were dominant under 15 MPa CP at 295 K.

The pores with an aspect ratio of 0.50 decreased more at 353 K than at 295 K under 1 MPa CP and far from the rupture plane. The aspect ratio frequency of 0.35 was dominant at 353 K, whereas a frequency of 0.45 was dominant at 295 K under 15 MPa CP. These pore properties suggest that pore collapse at 353 K under 1 MPa CP and far
from the rupture plane and at both 295 K and 353 K under 15 MPa CP.

In the case of Kimachi sandstone, main and sub-rupture planes occurred as well as several fractures in the CT image for 1 MPa CP at 295 K. However, only one main rupture plane and one sub-rupture plane appeared under 1 MPa CP at 353 K. The average thickness of the cementing material was approximately 0.20 mm at both temperatures. There were two rupture planes under 3 MPa CP at 295 K. On the other hand, only one rupture plane was observed at both 295 K and 353 K at 353 K. The rupture planes were absent for the 15 MPa CP cases. The thickness of cementing materials was approximately 0.15 mm.

In the case of Inada granite, one distinct, thick main rupture plane with many sub-rupture planes and fractures appeared in the CT image for 1 MPa CP at 295 K. The rupture plane comprised the network of microcracks that were observed in the thin-section image. Axial cracks that had propagated from biotite also were observed. One main thin rupture plane was formed under 7 MPa CP without axial cracks from biotite at 295 K. In the cases of 1 and 7 MPa CP at 353 K, one main thin rupture plane and one sub-rupture plane were observed with elongated biotite grains along the rupture planes in the thin-section images. For 15 MPa CP, two main rupture planes formed at 295 K. One rupture plane with sub-rupture planes and many fractures appeared at 353 K.

**Discussion**

The mechanisms of permeability change by failure

In the post-compression state, the largest permeability decrease was achieved for Shikotsu welded tuff at 15 MPa CP at 295 K. The decrease was even greater for 1 MPa CP at 353 K (Fig. 5) due to the low porosity of the matrix. The main cause of this phenomenon was enhanced pore collapse by temperature–confining-pressure coupling, as the number of pores declined by confining pressure or temperature.

The post-compression permeability of Kimachi sandstone at 353 K (Fig. 4e) was slightly lower than at 295 K, because of the relatively smaller thickness of cementing materials. The decrease in thickness was mainly caused by plastic deformation since the clay minerals are weaker than the mineral grains and the yielded clay deformation is plastic and may include some viscous deformation. The plastic deformation was enhanced mainly by confining pressure. For example, the greatest permeability decrease took place below 15 MPa CP at 353 K. The thickness of the cementing material was only 1.8% lower than that at 295 K, but was 23.8% lower than that under 1 MPa CP at 353 K.

The post-compression permeability of Inada granite at 353 K (Fig. 4g) was also lower than at 295 K (Fig. 4g). This was due to the decrease in the number and thickness of sub-rupture planes and fractures, including the axial microcracks from biotite, because of the enhancement of viscous deformation of unfailed mineral particles by thermal activation. The elongation of biotite particles along the rupture plane by temperature–confining pressure coupling was another reason for the low permeability.
The seability of rock around underground openings in fractured rock masses

From the experimental results, a rough estimate of the change in seability of underground openings due to the progress of EdZs and EDZs could be inferred. This was accomplished by considering the rupture plane in the triaxial compression tests to be analogous to a fracture in a rock mass by ignoring the differences in thickness, unevenness, existence of gauge, origin (e.g., joint sets are caused by tension), etc.

For Shikotsu welded tuff, the groundwater flow along fractures (Fig. 1a) does not have to dominate since the permeability is decreased by failure even under low confining pressure (Fig. 5). Permeability decreases and seability improves with progress of EdZs and EDZs for the same reason. The seability will not have deteriorated due to decay heat since the flow velocity per unit pore pressure gradient under the low confining pressure was lower at 353 K (Fig. 4j).

For Kimachi sandstone, groundwater flow along fractures under low stress dominates openings at shallow depths since permeability is increased by failure under low confining pressure (Fig. 5). The seability does not change significantly if EdZs and EDZs form because the seability in this case is controlled by the fractures. On the other hand, the groundwater flow along fractures does not have to dominate under high stress openings at great depth since permeability is decreased by failure under high confining pressures (Fig. 5). Permeability may increase in EDZ2 under a low support pressure around the opening, but may decrease in EDZ1 or EdZ under a relatively high confining pressure.

For Inada granite, the groundwater flow along fractures dominates because the permeability is increased due to failure (Fig. 5). The seability is unchanged, regardless of EdZ and EDZ progress, since the fractures control the ground water flow. Decay heat will not cause the seability to deteriorate because of the lower flow velocity per unit pore pressure gradient at 353 K (Fig. 4h).

Conclusions

To clarify the permeability of rock during deformation and failure, and the influences of confining pressure and temperature on that behavior, triaxial compression tests were carried out on Shikotsu welded tuff, Kimachi sandstone, and Inada granite under confining pressures of 1–15 MPa at 295 K and 353 K. In the case of Shikotsu welded tuff, the permeability declined monotonously with axial compression. In the cases of Kimachi sandstone and Inada granite, the permeability declined at first, and then began to increase before the peak load, and showed values that were almost constant or the residual strength state.

For Shikotsu welded tuff, the post-compression permeability decreased with rock failure. The permeability of Kimachi sandstone, increased due to rock failure under low confining pressures, but declined under higher confining pressures. The permeability of Inada granite increased due to rock failure.

For all types of rock, the permeability at 353 K was lower than at 295 K, and the influence of the confining pressure was less at 353 K than at 295 K. The principal mechanisms causing the permeability decrease were enhancement of pore collapse for the Shikotsu welded tuff, plastic deformation of the cementing material for Kimachi sandstone, and viscous deformation of mineral particles for Inada granite by thermal activation.

The flow velocity of the fractured specimens with the unit pore pressure gradient at 353 K was slightly lower under low and moderate confining pressures, but higher under high confining pressures for the Shikotsu welded tuff, slightly higher for the Kimachi sandstone, and obviously less for Inada granite than the values at 295 K.

Not on permeability but it was also clarified that the critical extensile strain (extensile strain at peak load point) of Kimachi sandstone and Inada granite was less sensitive to temperature than peak stress or critical compression strain (compressive strain at peak load point).

These findings are very important considering the optimum design of man-made caverns, although the differences between rupture planes in fractured specimens and fractures in rock masses, and the thermal stress effects should be investigated further for more precise evaluation of the effects of EdZs and EDZs on rock mass seability.

Reference