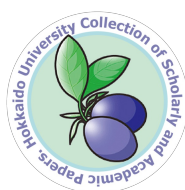




Title	Fractured Rock Permeability as a Function of Temperature and Confining Pressure
Author(s)	Alam, A. K. M. Badrul; Fujii, Yoshiaki; Fukuda, Daisuke et al.
Citation	Pure and Applied Geophysics, 172, 2871-2889 https://doi.org/10.1007/s00024-015-1073-2
Issue Date	2015-04-01
Doc URL	https://hdl.handle.net/2115/61126
Rights	The final publication is available at link.springer.com
Type	journal article
File Information	PAG, 2015-4, 1-19. pdf



Fractured Rock Permeability as a Function of Temperature and Confining Pressure

A.K.M. Badrul ALAM^{*1}, Yoshiaki FUJII², Daisuke FUKUDA², Jun-ichi KODAMA²,
and Katsuhiko KANEKO¹

¹ Northern Advancement Center for Science and Technology, H-RISE

5-3 Sakaemachi, Horonobe-cho, Teshio-gun, Hokkaido 098-3221, Japan

² Rock Mechanics Laboratory, Graduate School of Engineering, Hokkaido University,

Kita 13 Nishi 8, Kita-ku, Sapporo, Hokkaido 060-8628, Japan

*Corresponding author: A.K.M. Badrul ALAM

e-mail: badrul@eng.hokudai.ac.jp; rock.hrise.badrul14@gmail.com

TEL: +81-1632-9-4112

FAX: +81-1632-9-4113

ABSTRACT

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. The permeability of the tuff declined monotonically with axial compression. The post-compression permeability became smaller than that before axial compression. The permeability of Kimachi sandstone and Inada granite declined at first, and then

began to increase before the peak load, and showed values that were almost constant in the residual strength state. The post-compression permeability of Kimachi sandstone was higher than that before axial compression under low confining pressures, but lower under higher confining pressures. On the other hand, the permeability of Inada granite was higher than that before axial compression regardless of the confining pressure values. For the all rock types, the post-compression 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 above temperature effects were observed apparently for Inada granite, only the latter effect was apparent for Shikotsu welded tuff, and they were not so obvious for Kimachi sandstone. The mechanisms causing the variation in rock permeability, and sealability of underground openings were discussed.

Key Points:

The influence of confining pressure on permeability is less at 353 K than at 295 K.

The flow speed at 353 K is nearly the same as at 295 K or significantly slower.

Pore collapse, and plastic and viscous deformation are dominant mechanisms.

Keywords

Temperature-confining pressure coupling, Permeability, Sealability, Pore collapse, Plastic deformation, Viscous deformation

1. Introduction

Excavation-disturbed zones (EdZs) and excavation-damaged zones (EDZs) result from the excavation of underground openings. The former are zones of mainly elastic disturbance whereas the latter are zones that have irrecoverable damage [Tsang et al., 2005]. Stress redistribution and permeability changes within these zones [Sato et al., 2000; Fujii et al., 2011; Tsang et al., 2005] can affect the sealability. This represents the tightness of an opening and is defined as inversely proportional to the flow velocity per unit pore pressure gradient of the surrounding rock mass, due to hydromechanical (HM) coupling. The confining pressure in an EDZ can be either low in the vicinity of the opening (EDZ2 in Fig. 1a) or relatively high (EDZ1 in Fig. 1a). HM coupling is important for tunneling, coal mining, coal-bed methane extraction, oil and gas extraction, hydrogeological and well-test analyses, geothermal energy development, deep-well liquid and solid waste injection, geologic storage of natural gas, and geologic sequestration of CO₂, as well as a variety of natural geologic processes [Neuzil, 2003].

The scatters in the figures are mainly due to heterogeneity among specimens because the measurements were made on a series of different samples rather than on a single sample at different hydrostatic confining pressures to clarify also permeability variation during failure. 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 [Backblom and Martin, 1999; Kwon and Cho, 2008; Hudson et al., 2005; Rutqvist et al., 2005], are affected by heat from the decaying waste. A simulation [Kwon and Cho, 2008] showed that the rock temperature can be increased to about 353 K.

The loading path of the surrounding rock mass of a radioactive waste disposal site can be qualitatively considered as follows based on the previous numerical studies [Kwon and Cho, 2008, Rutqvist et al., 2014 etc.]. The in-situ stress (Fig. 1b (1)) is disturbed due to excavation (Fig. 1b (2)). The temperature rises due to the heat generated by decay after the waste has been emplaced and the opening has been backfilled. Confining pressure increases due to swelling of the backfill. Axial stress increases due to thermal stress caused by the temperature gradient in the surrounding rock mass (Fig. 1b (3)). The thermal stress decreases after the decay heat disappears, but the confining pressure remains unchanged (Fig. 1b (4)).

We have previously described the effects of confining-pressure on rock permeability as hydromechanical (HM) processes under compression [Alam et al., 2014]. This paper will clarify the temperature–confining-pressure coupling effects on rock permeability as thermo-hydromechanical (THM) processes under compression.

2. Materials and methods

2.1 Rock types

Rock masses, which consist of different types of rock, are being considered for radioactive waste disposal sites [Heinonen et al., 2001], 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 [Doi, 1963]. The rock is characterized by its volcanic glass matrix and pores. It exhibits very high effective porosity of up to 35.6 % (Table 1) with low

P- and S-wave velocities [Alam et al., 2014]. It has low uniaxial compressive strength and dry density (Table 1).

Kimachi sandstone is relatively well-sorted clastic rock. It consists primarily of rock fragments of andesite; crystal fragments of plagioclase, pyroxene, hornblende, biotite, and quartz; calcium carbonate and iron oxides; and matrix zeolites [Dhakal et al., 2002]. The rock is characterized mainly by its mineral particles, which are cemented by clay with pore spaces between them (Fig. 5). It has almost half of the effective porosity of Shikotsu welded tuff with relatively high uniaxial compressive strength and dry density (Table 1) with high P- and S-wave velocities [Alam et al., 2014].

Inada granite contains quartz, feldspar, biotite, and allanite, with zircon, apatite, and ilmenite as accessory minerals [Lin and Takahashi, 2008]. 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 (Table 1) having high P- and S-wave velocities [Alam et al., 2014].

2.2 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 lowest P-wave velocity. It is important to make specimens in the same direction since rocks are in general more or less anisotropic. It is also expected that there are most cracks perpendicular to the lowest velocity direction for igneous rocks or the shortest axes of most mineral grains

coincide to the lowest velocity direction for clastic rocks. Compression in the lowest velocity direction may give less unstable axial crack growth along existing cracks or grain boundaries leading less scattered results than that in the other directions. Next, the core ends were polished so that the unevenness of them became within 20 μm . 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 not been significantly affected 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 de-ionized 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. Then, the sample was submerged in de-ionized 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; Fig. 2). 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 [Kwon and Cho, 2008]. 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 was long enough since the volumetric deformation was stabilized within 20 h for all rocks.

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 (Fig. 1b) 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 pore pressure gradient was less than 1 MPa/60 mm. This pressure gradient might have slightly affected the measured permeability values. It however would not have caused fatal errors in clarifying effects of confining pressure and temperature on permeability. The permeability of Kimachi sandstone and Inada granite was measured by the transient-pulse method [Alam et al., 2014] with the approximate solution by Brace et al. [Brace et al., 1968]. 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.

2.3 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. Thin-section images of the blue-resin-impregnated specimens with Scion Image software [<http://scion-image.software.informer.com>] were viewed at a resolution of $8.8 \times 8.8 \mu\text{m}$. Macrostructures (number, orientation, and geometry of the rupture planes and fractures) of the post-compression specimens were observed using a microfocus X-ray-computed tomography (CT) scanner with a $37 \times 37 \times 80 \mu\text{m}$ resolution. It should be noted that rather the residual permanent effects of compression than elastic deformation were viewed since the observation was carried out after the stress was released.

3. Results

3.1 Effects of consolidation on the matrix permeability

After a 24-hour consolidation, the permeability decreased with effective confining pressure for all three rock types (Fig. 3). The calculation of effective confining pressure considering the pore pressure gradient has been previously detailed [Alam et al., 2014]. Each data point represents the result from each specimen.

A decrease in the permeability by confining pressure was obvious for Inada granite. However, the results showed a variation of as much as one order under identical conditions. The scatters in the figures are mainly due to heterogeneity among specimens because the measurements were made on a series of different samples rather than on a single sample at different hydrostatic confining pressures to clarify also permeability variation during failure.

The lines to show the upper and lower limits of 95% confidence interval were drawn twice the standard deviation above and below the regression line in Fig. 3. The regression line itself was not shown for simplicity. Influence of temperature will be

basically represented with such qualifiers as "significantly" when the intervals for 295 K and 353 K are not overlapped, without any qualifiers if they are overlapped roughly less than 30% total area. The qualifier "slightly" will be used when they are overlapped roughly 30 - 60% total area whereas they will be regarded as almost the same if the overlapping is roughly more than 60%.

In the case of Shikotsu welded tuff, the permeability at 353 K was slightly lower than at 295 K (Fig. 3a). The permeability was lowest under 15 MPa of confining pressure (CP). For Kimachi sandstone, no significant difference between the permeability at 353 K and 295 K (Fig. 3b). For Inada granite, the permeability at 353 K was slightly lower than at 295 K (Fig. 3c).

3.2 Effects of consolidation on matrix structure

The porosity of Shikotsu welded tuff without any loading and based on thin-section image analysis was 31.10%. It decreased by 6.49% from 295 to 353 K under 15 MPa CP, and by 2.49% from 1 to 15 MPa CP at 353 K (Fig. 4b). Pores with an equivalent diameter of 0.14 mm at 295 K significantly shrank at 353 K. That with a 0.06-mm equivalent diameter dominated at 15 MPa CP, although pores with a 0.10-mm equivalent diameter dominated in a specimen without any loading (Fig. 4c). Pores with an aspect ratio of 0.45–0.65, which were dominant under 1 MPa CP at 353 K, decreased with CP increasing to 15 MPa (Fig. 4d). Pores parallel to the horizontal flow layering of the tuff dominated at 15 MPa CP (Fig. 4e). These observations suggest pore collapse [Zaman et al., 1994] due to stress concentration at the sides of the larger curvature of the elliptical pores.

The thickness of the cementing materials of Kimachi sandstone, declined due to the confining pressure and temperature. The amount of decrease under 15 MPa CP

was greater than that under 1 MPa CP at 295 K. It was even greater under 1 MPa CP at 353 K than at 15 MPa CP at 295 K (Fig. 5b).

With Inada granite, no effects were observed with changes in either the confining pressure or temperature (Fig. 6).

3.3 *The effects of deformation and failure on permeability*

For Shikotsu welded tuff, the peak stress and tangent modulus at 353 K were slightly lower than those at 295 K (Fig. 7a). No significant differences were observed between the residual strength (axial stress value at the end of the test) at 353 K and that at 295 K (Fig. 7a). The permeability during deformation and failure at 295 K, as well as at 353 K, monotonically decreased even after the specimen began to expand (Figs. 9 and 10, Table 2). 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. 11i). 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. 11j). The permeability change (Fig. 12) was calculated from the permeability after 24 hours of consolidation (K_{con}) and the post-compression permeability (K_{com}) as

$$K_{change} = ((K_{com} - K_{con}) / K_{con}) / 100. \quad (1)$$

The change in permeability showed that the decrease became greater with increasing confining pressure from -3.05% to -92.12% at 295 K (Fig. 12a). No confining-pressure dependency was observed at 353 K (-84.21% to -93.93%).

For Kimachi sandstone, the peak stress at 295 K was slightly lower than those at 353 K (Fig. 7b). No significant influences were observed in the tangent modulus and the residual strength. No significant effects of temperature on the critical extensile strain (CES, circumferential or lateral extensile strain value at peak load point) [Fujii et al., 1998]) 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 (Fig. 8). 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 specimen began to expand. The onset of dilatancy should be before the specimen expansion although a detailed investigation was not carried out in this paper. It continued to increase showing peak stress and was nearly stabilized in the residual strength state (Figs. 9 and 10, Table 2). The stress relaxations occurred since the platen was stopped during permeability measurement by transient pulse method. The minimum permeability declined with the confining pressure, and no obvious difference was apparent between 295 and 353 K (Fig. 11a). The flow velocity per unit pore pressure gradient was almost the same at 353 K (Fig. 11b). The post-compression permeability declined with the confining pressure, and the permeability at 353 K was slightly lower (Fig. 11e). However, the flow velocity per unit pore pressure gradient at 353 K was almost the same (Fig. 11f). 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. 12b). 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 stress, the tangent modulus and the residual strength at 353 K of Inada granite were almost identical to those at 295 K (Fig. 7c). No significant effects of temperature on critical extensile strain (CES) were observed, whereas critical compressive strain (CCS) at 353 K was significantly larger than that at 295 K (Fig. 8). 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. The minimum permeability declined with the confining pressure at both 295 and 353 K, although the permeability at 353 K was slightly lower than at 295 K (Fig. 11c). The flow velocity per unit pore pressure gradient at 353 K was almost the same as at 295 K (Fig. 11d). 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. 11g) and flow velocity per unit pore pressure gradient (Fig. 11h) at 353 K were lower than those at 295 K up to 10 MPa CP. At 295 K, the permeability increased with failure, and the permeability change became as great as 4780% (Fig. 12c). 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. 12c).

3.4 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 (Fig. 13a), whereas only one main rupture plane appeared at 353 K (Fig. 13b). The porosity near

the rupture plane was higher than the porosity far-removed from it (Fig. 13i). 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 (Fig. 13e and f), and their porosity at 353 K was less than at 295 K by 4.63% (Fig. 13i). 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 (Fig. 14 a). 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 (Fig. 14 b). The pores with an aspect ratio of 0.50 decreased more at 353 K than that at 295 K under 1 MPa CP and far from the rupture plane (Fig. 14 c). 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 (Fig. 14 d). 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 (Fig. 15a). However, only one main rupture plane and one sub-rupture plane appeared under 1 MPa CP at 353 K (Fig. 15b). The average thickness of the cementing material was approximately 0.20 mm at both temperatures (Fig. 15h). There were two rupture planes under 3 MPa CP at 295 K (Fig. 15c). On the other hand, only one rupture plane was observed at both 295 K and 353 K (Fig. 15h) at 353 K (Fig. 15d). The rupture planes were absent for the 15 MPa CP cases (Fig. 15e and f). 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 (Fig. 16a). 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 (Fig. 16c). One main thin rupture plane was formed under 7 MPa CP without axial cracks from biotite (Fig. 16f) at 295 K. In the cases of 1 and 7 MPa CP at 353 K (Fig. 16b and g), 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 (Fig. 16d and e). For 15 MPa CP, two main rupture planes formed at 295 K (Fig. 16i). One rupture plane with sub-rupture planes and many fractures appeared at 353 K (Fig. 16h).

4. Discussion

4.1 The mechanisms of permeability change by consolidation

After a 24-hr consolidation at the target confining pressure and temperature for Shikotsu welded tuff, the matrix permeability at 353 K was slightly lower than at 295 K, and the permeability under 15 MPa CP at 353 K was the lowest (Fig. 3, Table 2). The reason for this was that the pores became smaller and narrower due to pore collapse [Zaman et al., 1994] as the small equivalent diameter and small aspect ratio became dominant (Fig. 4). The rate V of the subcritical crack growth in rock due to stress corrosion by water at a crack tip is accelerated by either temperature rise (thermal activation) or increase in stress intensity factor K_I [Freiman, 1984].

$$V = V_0 a(\text{H}_2\text{O}) \exp\left(\frac{-E_{\text{act}} + \alpha K_I}{RT}\right) \quad (6)$$

where V_0 is a constant depending on the reactants and the environmental factors, $a(\text{H}_2\text{O})$ is the activity of water, E_{act} is the activation energy of the corrosion, α is a constant depending on the volume of activation and the curvature of the crack tip, R is

the gas constant and T is the absolute temperature. The mechanism of the acceleration of pore collapse could be explained by the increase in crack growth rate due to thermal activation of stress corrosion rate at the tips of the microcracks in the rock matrix.

For Kimachi sandstone, the permeability after a 24-hr consolidation under 15 MPa CP at 353 K was the lowest (Fig. 3b) because the thickness of the cementing materials was smaller by 10.5% than that under 15 MPa CP at 295 K (Fig. 5). The decrease in the cement thickness was caused by plastic deformation.

In the case of Inada granite, the permeability after a 24-hr consolidation decreased with the confining pressure, and the permeability at 353 K was slightly lower than at 295 K (Fig. 3c, Table 2). The decrease in permeability was due to the closure of inclined cracks by the elastic and viscous deformation enhanced by temperature–confining-pressure coupling. Thermal elastic expansion of mineral particles can be another cause of further crack closure at 353 K [Darot et al., 1992]. The elastic deformations, however, was not observed in the thin-section images, because they were prepared after unloading.

4.2 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. 12a) due to the low porosity of the matrix (Fig. 13i). 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 (Fig. 14 a, c).

The post-compression permeability of Kimachi sandstone at 353 K (Fig. 11e) 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 (Fig. 15h).

The post-compression permeability of Inada granite at 353 K was also lower than at 295 K (Fig. 11g). This was due to the decrease in the number and thickness of sub-rupture planes and fractures, including the axial microcracks from biotite (Fig. 16), 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 (Fig. 16d and e) was another reason for the low permeability.

4.3 The sealability of rock around underground openings in fractured rock masses

From the experimental results, a rough estimate of the change in sealability 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.

The sealability is defined here as inversely proportional to flow rate per unit pore pressure gradient (Eq. 7) of the rock mass surrounding the underground opening.

Namely, it is proportional to fluid viscosity and inversely proportional to permeability. The permeability is a function of temperature, strain state etc. and fluid viscosity is a function of temperature (Eqs. 8 and 9).

$$\text{Sealability} \propto \left(\frac{\text{Flow rate}}{dp_p / dx} \right)^{-1} \propto \frac{\text{Fluid viscosity}}{\text{Permeability}} \quad (7)$$

$$\text{Permeability} = f_1(T, \varepsilon, \dots) \quad (8)$$

$$\text{Fluid viscosity} = f_2(T) \quad (9)$$

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. 12a). Permeability decreases and sealability improves with progress of EdZs and EDZs for the same reason. The sealability will not have deteriorated due to decay heat since the flow velocity per unit pore pressure gradient under the low confining pressure was almost the same at 353 K (Fig. 11i).

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. 12b). The sealability does not change significantly if EdZs and EDZs form because the sealability 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. 10b). 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. Sealability deterioration is not expected also for this rock since the flow velocity per unit pore pressure is almost the same for 295 K and 353K (Fig. 11f).

For Inada granite, the groundwater flow along fractures dominates because the permeability is increased due to failure (Fig. 10c). The sealability is unchanged, regardless of EdZ and EDZ progress, since the fractures control the ground water flow. Decay heat will not cause the sealability to deteriorate because of the lower flow velocity per unit pore pressure gradient at 353 K (Fig. 11h).

5. 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 monotonically 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 the all rock types, 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 above temperature effects were observed apparently for Inada granite, only the latter effect was apparent for Shikotsu welded tuff, and they were not so obvious for Kimachi sandstone. 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 confining pressures for the Shikotsu welded tuff, almost the same for the Kimachi sandstone, and 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 [Fujii et al., 1998]) of Kimachi sandstone and Inada granite was much less sensitive to temperature than critical compression strain (compressive strain at peak load point).

We hope that these findings will contribute toward the reasonable design of man-made caverns although the authors fully realize that the differences between rupture planes in fractured specimens and fractures in rock masses and that effects of thermal stress should be investigated further for more precise evaluation of the effects of EdZs and EDZs on rock mass sealability.

Acknowledgements

This research work was partially supported by KAKENHI (22560804).

References

- Alam, A.K.M. B., M. Niioka, Y. Fujii, D. Fukuda, and J. Kodama (2014), Effect of confining pressure on the permeability of three rock types under compression, *Int. J. Rock Mech. Min. Sci.*, 65(1), 49-61.
- Backblom, G., and C.D. Martin (1999), Recent experiments in hard rock to study the excavation response: Implication of the performance of a nuclear waste geological repository, *Tunnel Undergr. Space Technol.*, 14(3), 377–394.
- Brace, W.F., J.B. Walsh, and W.T. Frangos (1968) Permeability of granite under high pressure, *J. Geophys. Res.*, 73, 2225– 2236.
- Darot, M., Y. Gueguen, M.-L. Baratin (1992), Permeability of thermally cracked granite. *Geophys. Res. Letter*, 19(9), 869-872.
- Dhakal, G., T. Yoneda, M. Kato, and K. Kaneko (2002), Slake durability and mineralogical properties of some pyroclastic and sedimentary rocks, *Eng. geol.*, 65(1), 31–45.
- Doi, S. (1963), Petrological and petrochemical studies of welded tuff, *Rep. Geol. Surv. Hokkaido*, 29, 30–103.
- Freiman, S. W. (1984), Effects of Chemical Environments on Slow Crack Growth in Glasses and Ceramics, *J. Geophys. Res.* 89 (B6), 4072-4076.
- Fujii Y., T. Kiyama, Y. Ishijima and J. Kodama (1998), Examination of a Rock Failure Criterion Based on Circumferential Tensile Strain, *Pure and Applied Geophys.*, 152(3), 551-577.
- Fujii, Y., Y. Ishijima, Y. Ichihara, T. Kiyama, S. Kumakura, M. Takada, T. Sugawara, T. Narita, J. Kodama, M. Sawada, E. Nakata (2011), Mechanical properties of abandoned and closed roadways in the Kushiro Coal Mine, Japan, *Int. J. Rock Mech. Min. Sci.*, 48, 585–596.

- Heinonen, J., P. Lalieux, P. Lebon, B. Neerdael, J.-M. Palut, M. Raynal, L. Shephard, M. Thury, D.R. Williams, and P. Wikberg (2001), The use of scientific and technical results from underground research laboratory investigations for the geological disposal of radioactive waste, IAEA, 67.
- <http://scion-image.software.informer.com/>> cited 27 December, 2011.
- Hudson, J.A., O. Stephansson, and J. Anderson (2005), Guidance on numerical modeling of thermo–hydro–mechanical coupled processes for performance assessment of radioactive waste repositories, *Int. J. Rock Mech. Min. Sci.*, 42, 850–870.
- Kwon, S., and W.J. Cho, The influence of an excavation damaged zone on the thermal–mechanical and hydro–mechanical behaviors of an underground excavation, *Eng. Geol.*, 101, 110–123.
- Lin, W., and M. Takahachi (2008), Anisotropy of strength and deformation of Inada granite under uniaxial tension, *Chin. J. of Rock Mech. Eng.*, 27, 2463–2472.
- Neuzil, C.E. (2003), Hydromechanical coupling in geologic processes, *Hydrogeol. J.*, 11, 41–83.
- Rutqvist, J., D. Barr, R. Datta, A. Gens, A. Millard, S. Olivella, C.–F. Tsang, and Y. Tsang (2005), Coupled thermal–hydrological–mechanical analysis of the Yucca Mountain Drift Scale Test– Comparison of field measurements to predictions of four different numerical models, *Int. J. Rock Mech. Min. Sci.*, 42, 680–697.
- Rutqvist, J., L. Zheng, F. Chen, H.-H., Liu, J. Birkholzer (2014), Modeling of coupled thermo-hydro-mechanical processes with links to geochemistry associated with bentonite-backfilled repository tunneled in clay formations, *Rock Mech. Rock Eng.*, 47:167-186, doi: 10.1007/s00603-013-0375-x

- Sato, T., T. Kikuchi, and K. Sugihara (2000), In-situ experiments on an excavation disturbed zone induced by mechanical excavation in neogene sedimentary rock at Tono mine, central Japan, *Eng. Geol.*, 56(1-2), 97–108.
- Tsang, C.-F., F. Bernier, C. Davies (2005), Geohydromechanical processes in the excavation damaged zone in crystalline rock, rock salt, and indurated and plastic clays—in the context of radioactive waste disposal, *Int. J. Rock Mech. Min. Sci.*, 42, 109–125.
- Zaman, M., J.-C. Roegiers, A. Abdulraheem, and M. Azeemuddin (1994), Pore collapse in weakly cemented and porous rocks, *J. of Energy Resour. Tech.*, 116, 97-103.

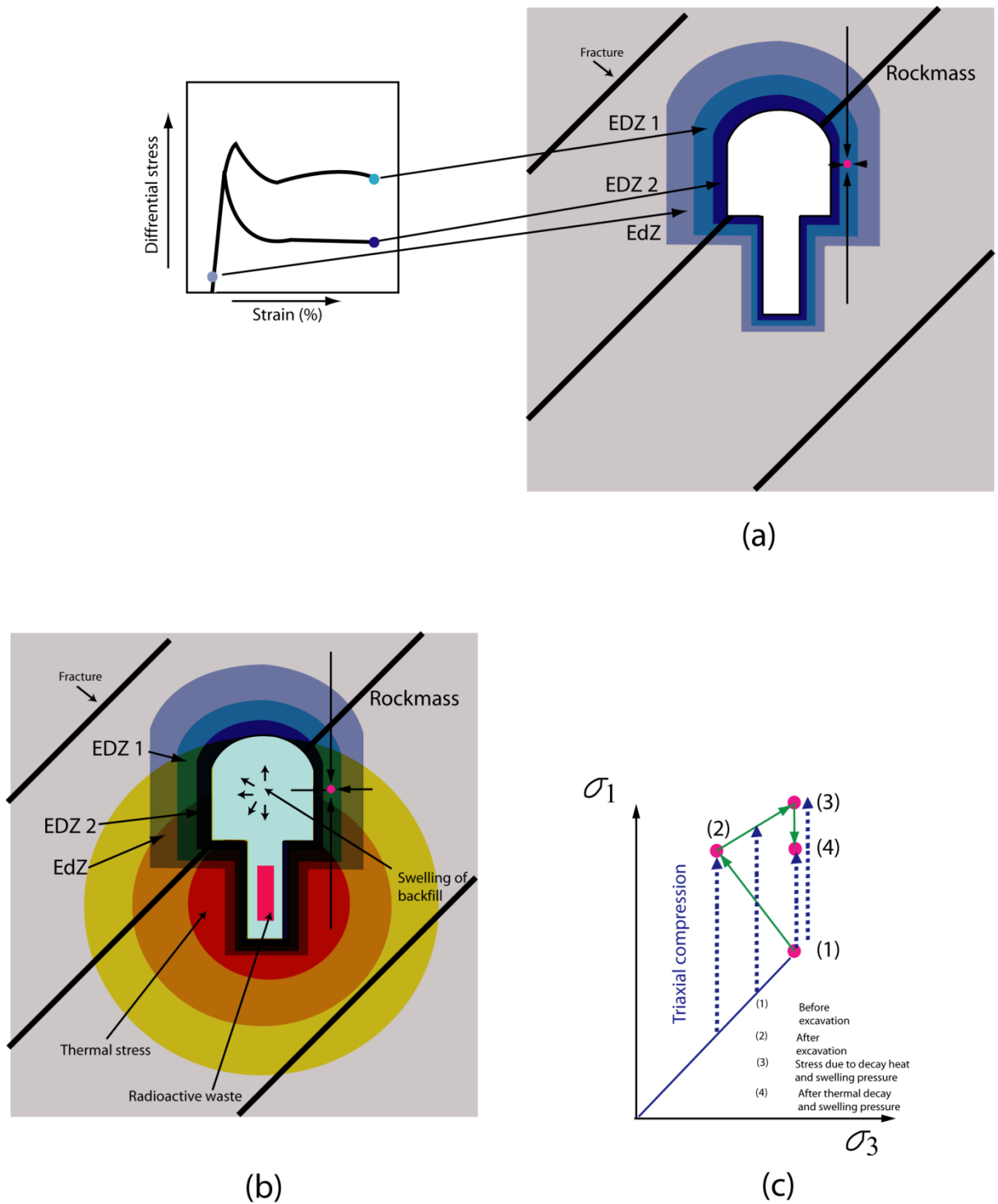


Fig. 1. Schematic diagram of the EdZ, EDZs and, fractures around an underground opening (a), thermal stress from radioactive waste and swelling pressure from backfill (b), and, comparison of comparison of the stress paths of a radioactive disposal site and that adopted in the triaxial compression tests (c).

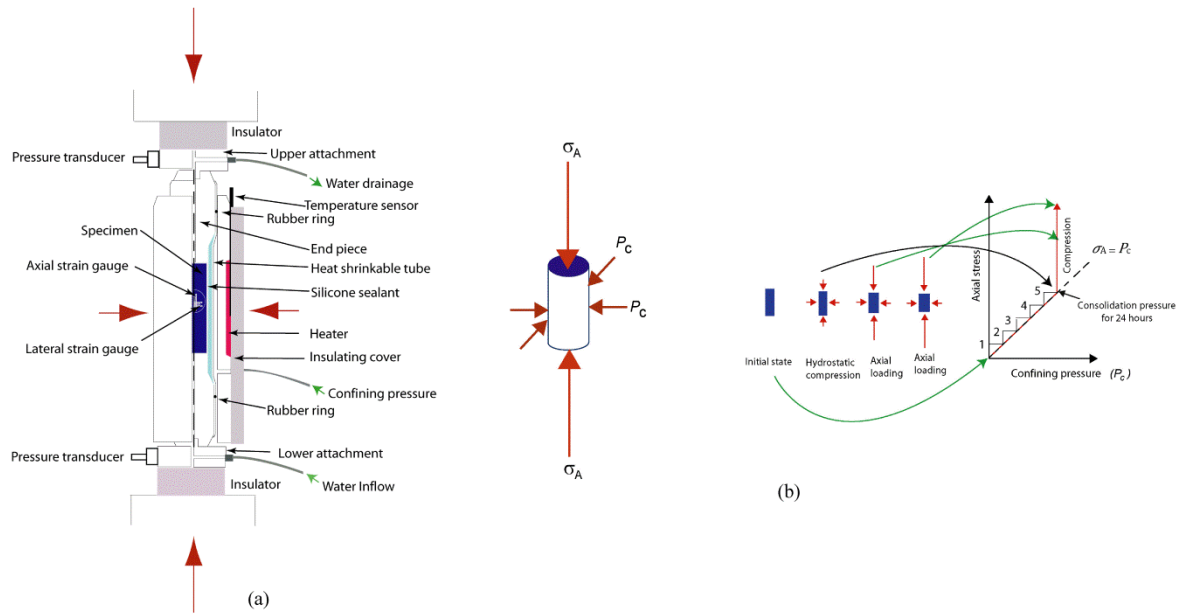


Fig. 2. The ultra compact triaxial cell with a heater and the experimental loading path. (a) The triaxial cell with the arrangement to apply confining pressure and temperature, (b) The loading path of the experiment.

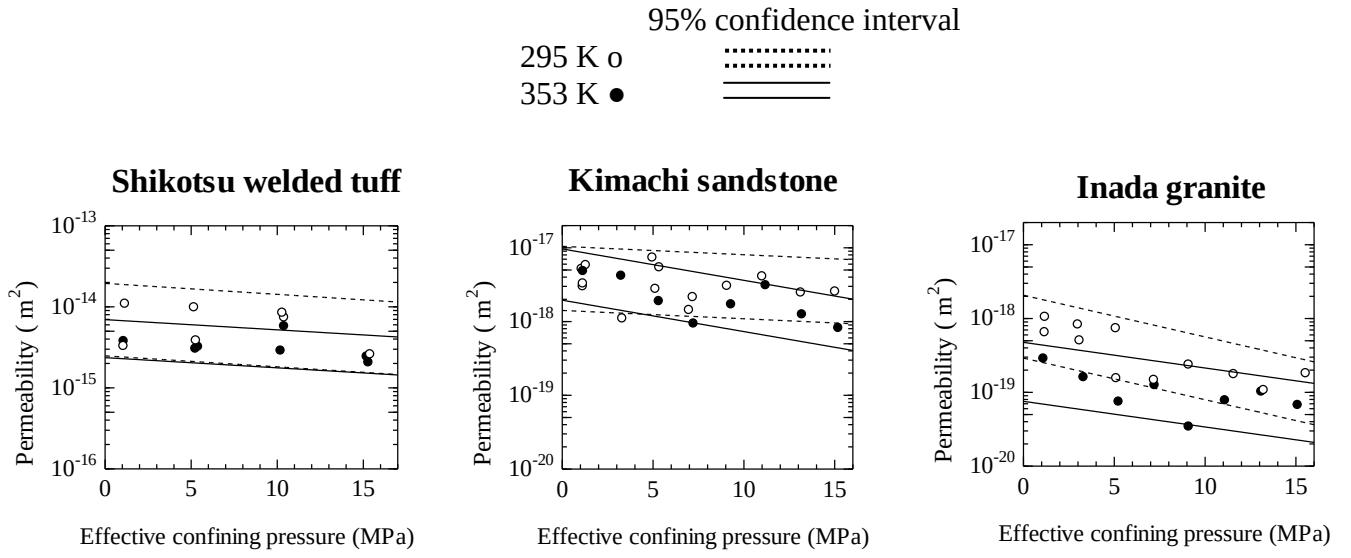


Fig. 3. Matrix permeability change after 24-hour consolidation. Broken and solid lines show upper and lower limits of 95% confidence intervals for 295 K and 353 K, respectively. They are used also in Figs. 3, 7, 8 and 11.

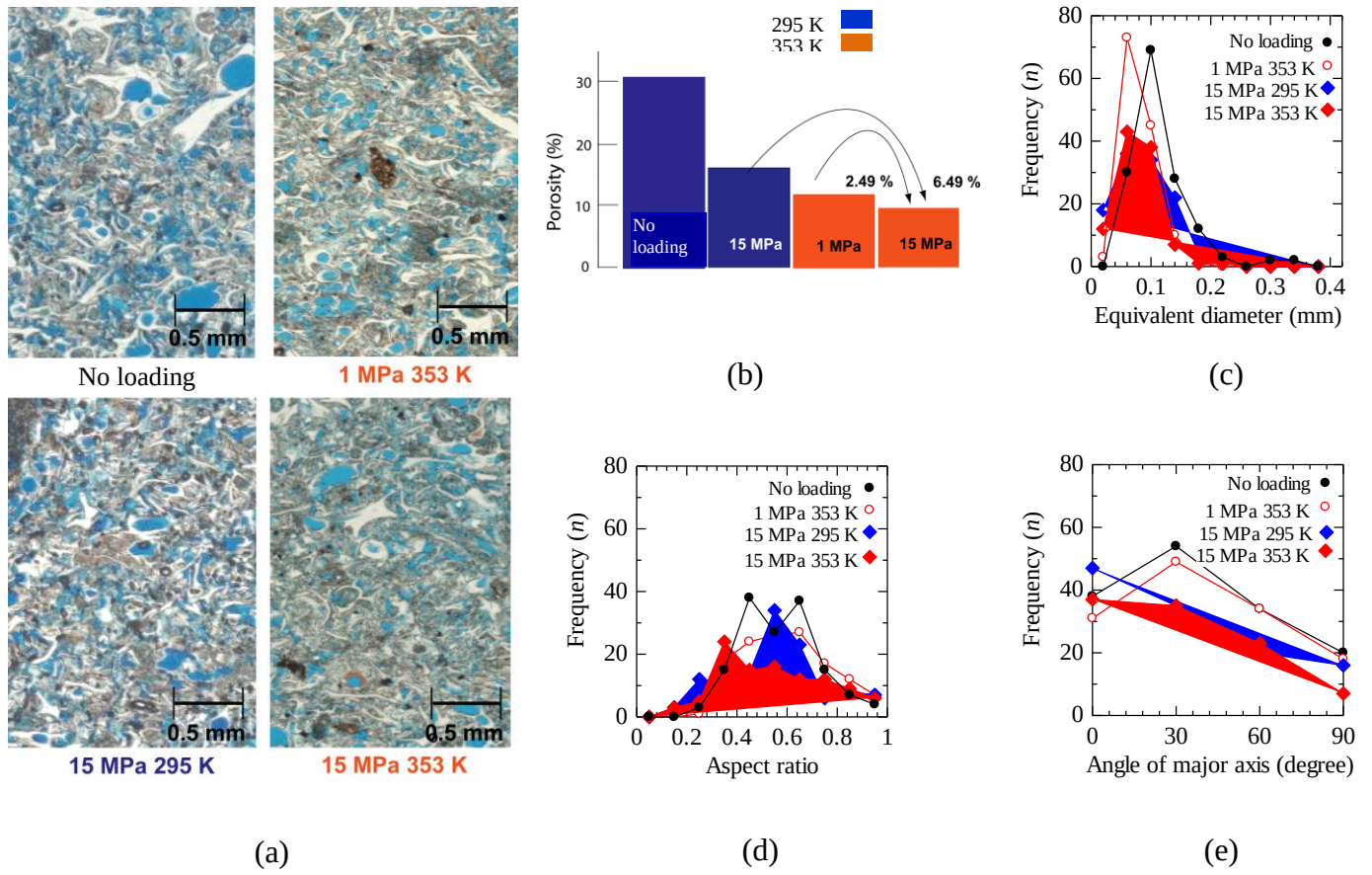


Fig. 4. Thin-section images and analyses for 24-hour consolidated specimens of Shikotsu welded tuff. (a) Thin-section images (blue spots are pores), (b) total porosity, (c) equivalent diameter, (d) aspect ratio, and (e) angle of major axis.

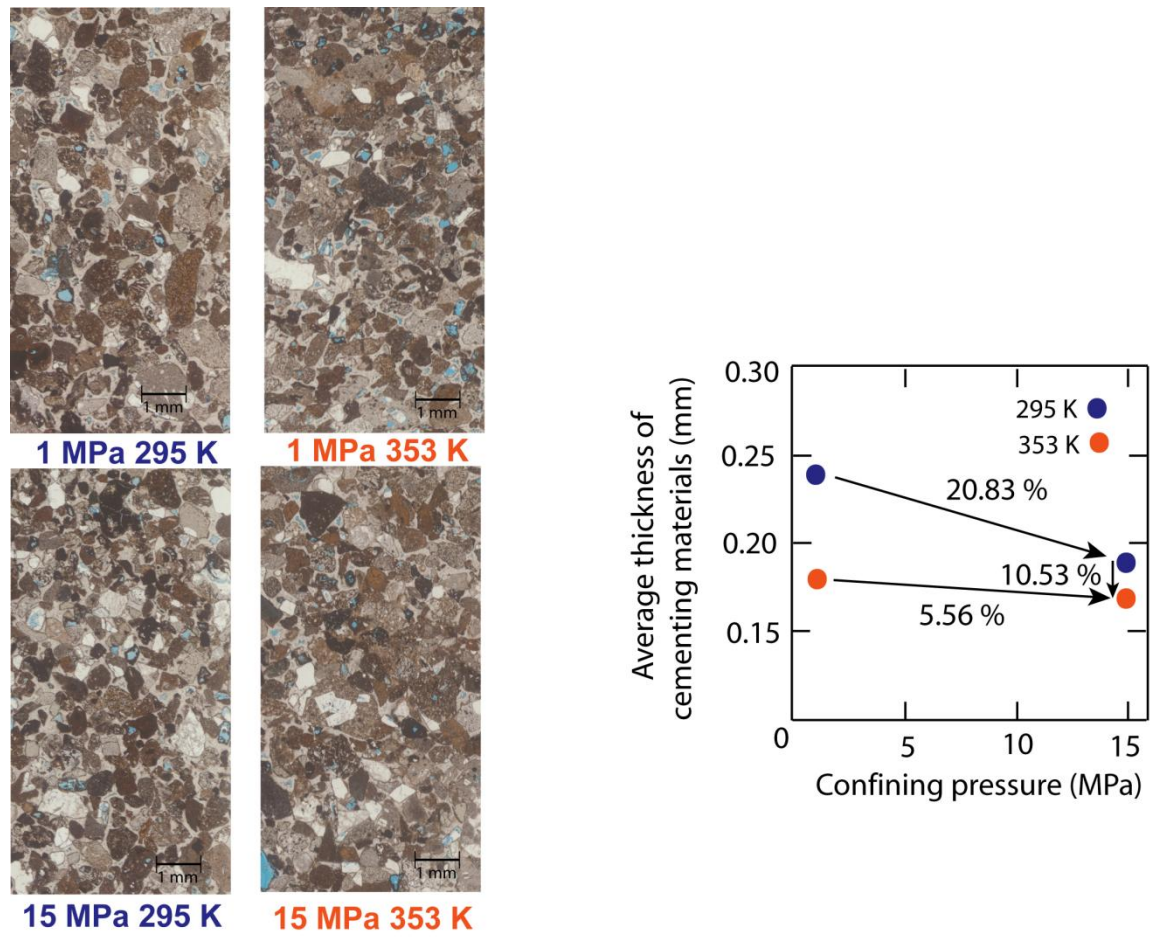


Fig. 5. Thin-section images and thickness of cementing material for 24-hour consolidated specimens of Kimachi sandstone.

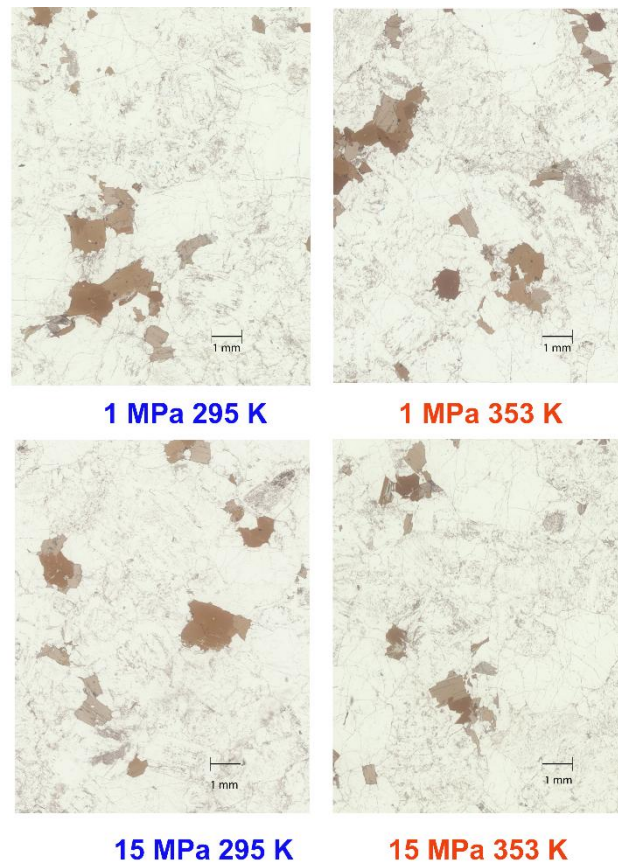


Fig. 6. Thin-section images for 24-hour consolidated specimens of Inada granite.

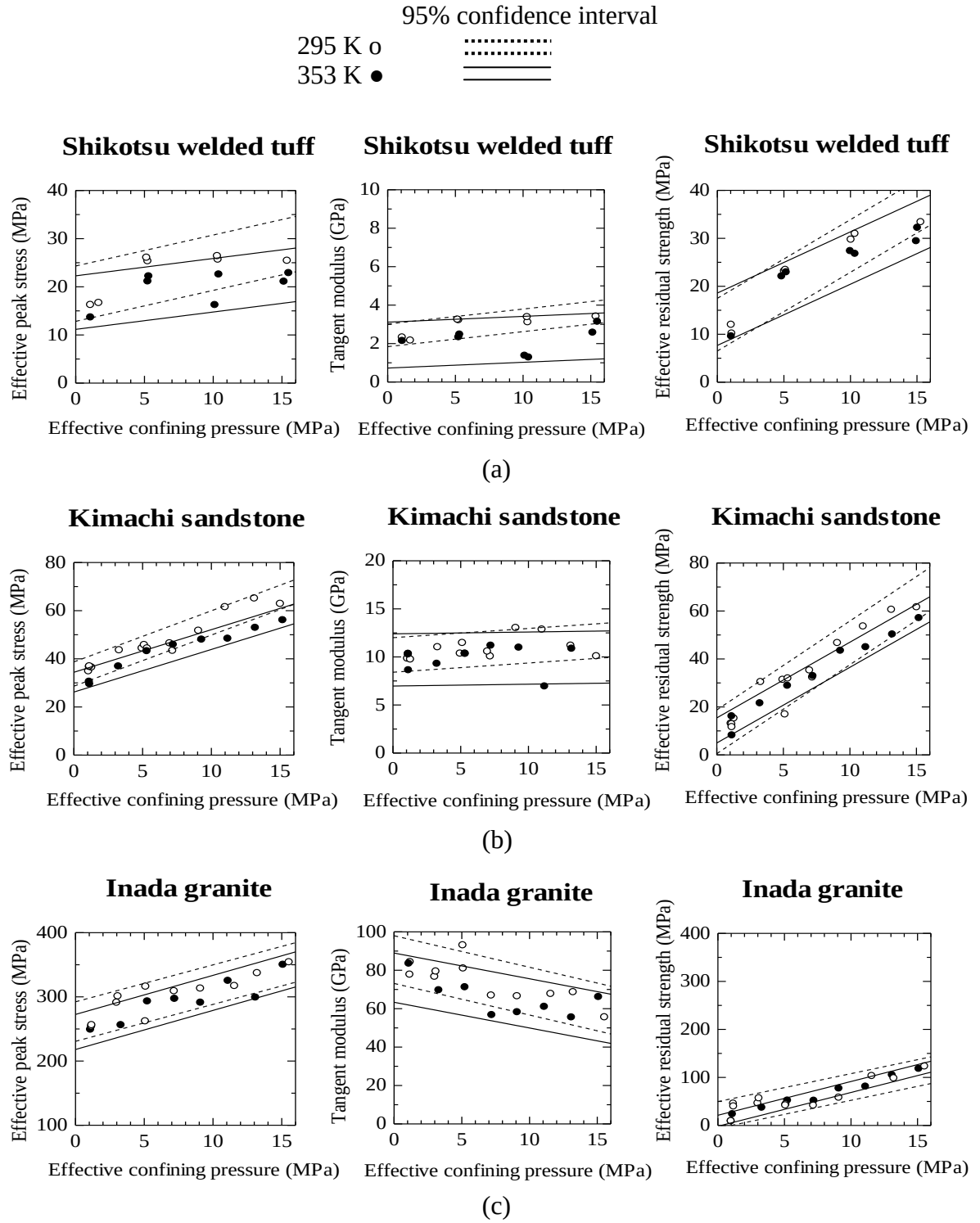


Fig. 7. Mechanical properties of the rocks. Peak stress and residual strength are represented in Terzaghi's effective stress. Tangent modulus was strain-based for Kimachi sandstone and Inada granite, and stroke-based for Shikotsu welded tuff.

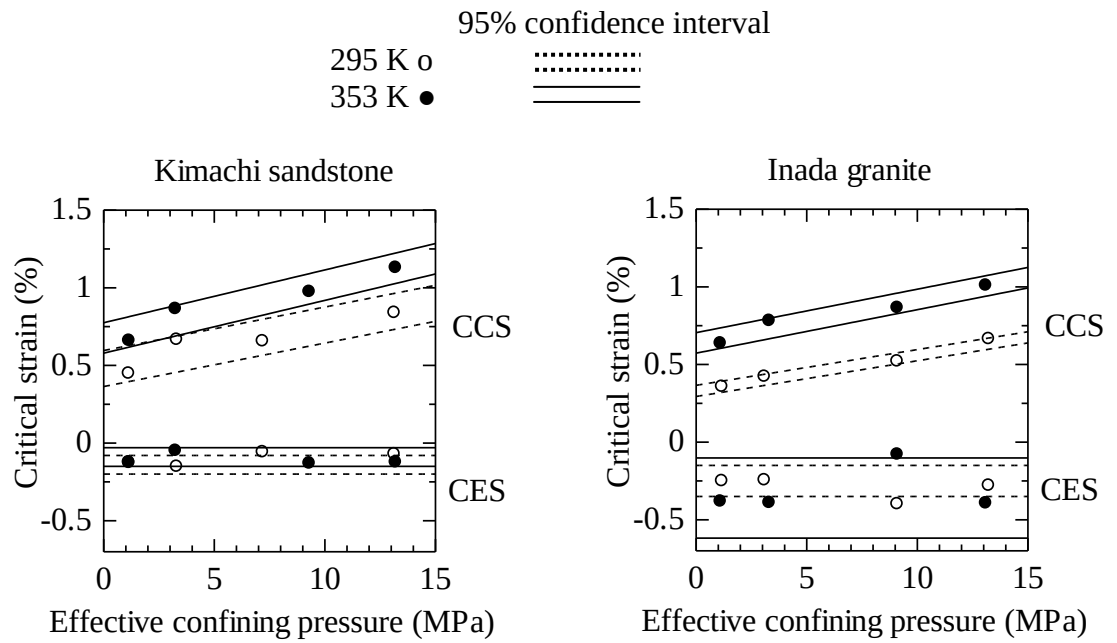


Fig.8 Critical extensile strain (CES) and critical compressive strain (CCS) of the Kimachi sandstone and Inada granite. The strains here are change in strain from those before application of confining pressure.

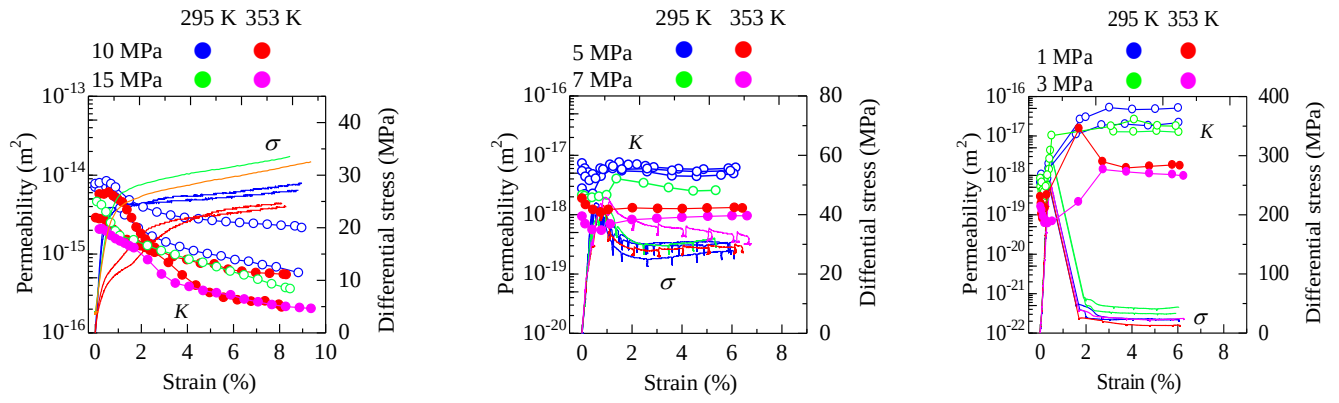
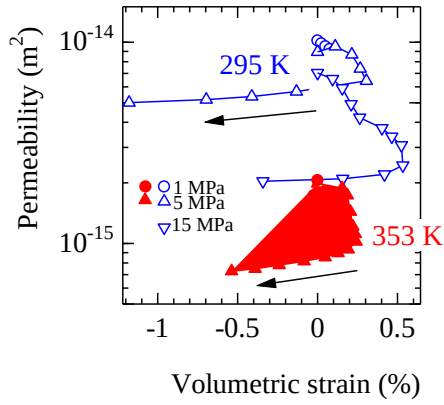
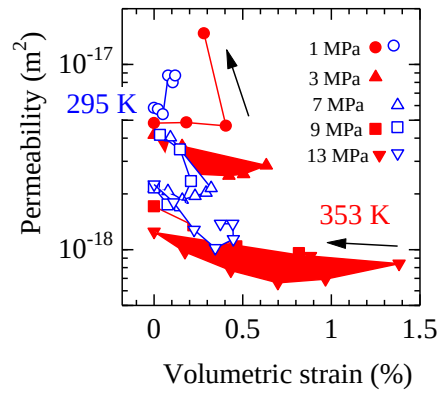


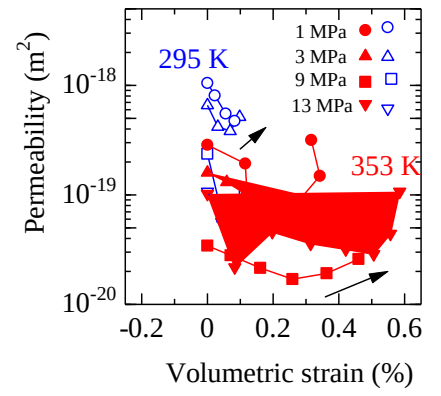
Fig. 9 . Examples of stress-strain curves and evolution of permeability due to deformation and failure. The axial strain here is defined as change in strain during axial compression.



(a) Shikotsu welded tuff



(b) Kimachi sandstone



(c) Inada granite

Fig. 10 Permeability behavior with volumetric strain during axial compression. Most of the curves are not to the residual strength since the strain gages often broke during axial compression.

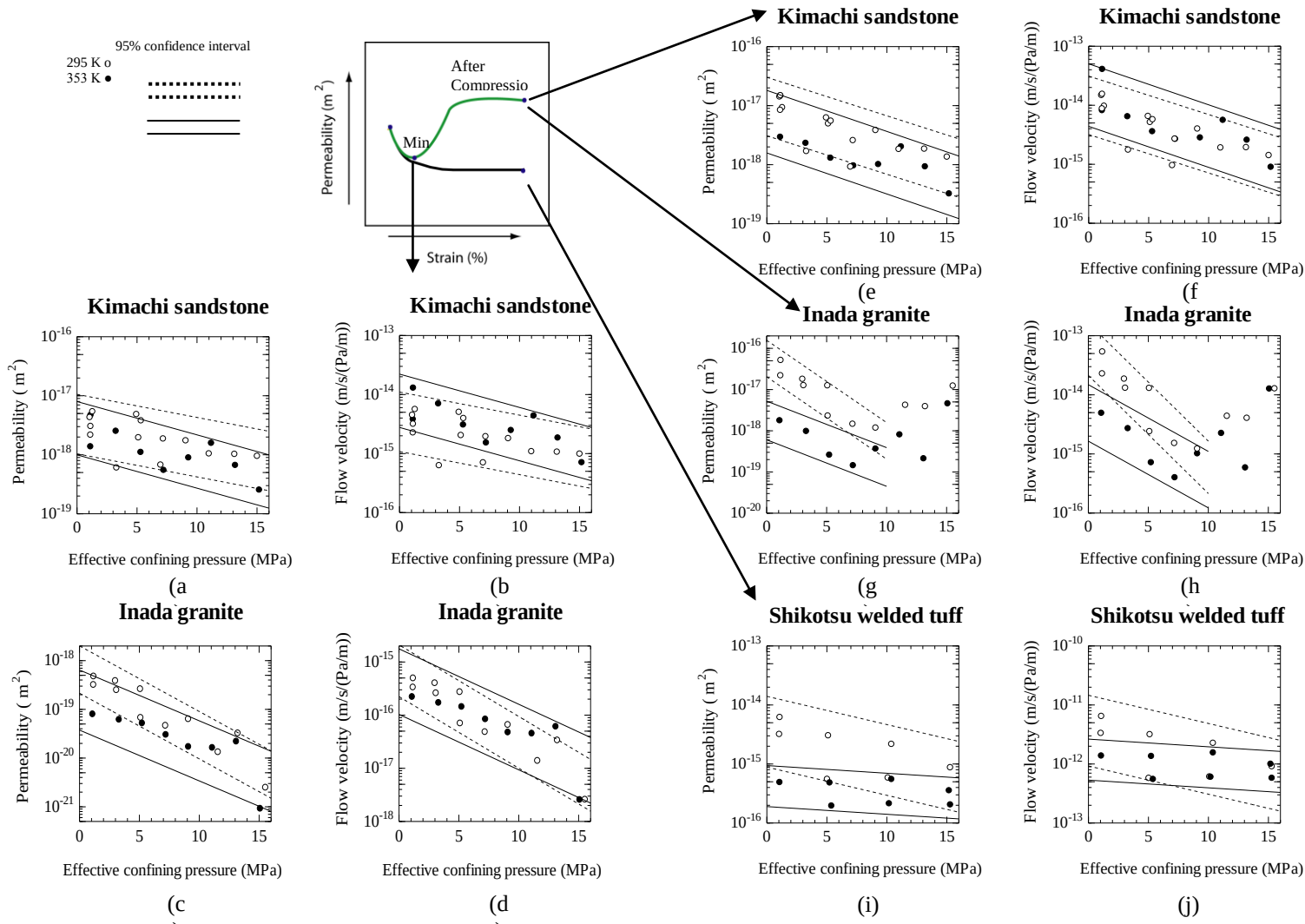


Fig.11. Minimum and post-compression permeability and flow velocity per unit pore pressure gradient. The upper and lower limit lines were drawn only for data under less than 10 MPa PC in (g) and (h).

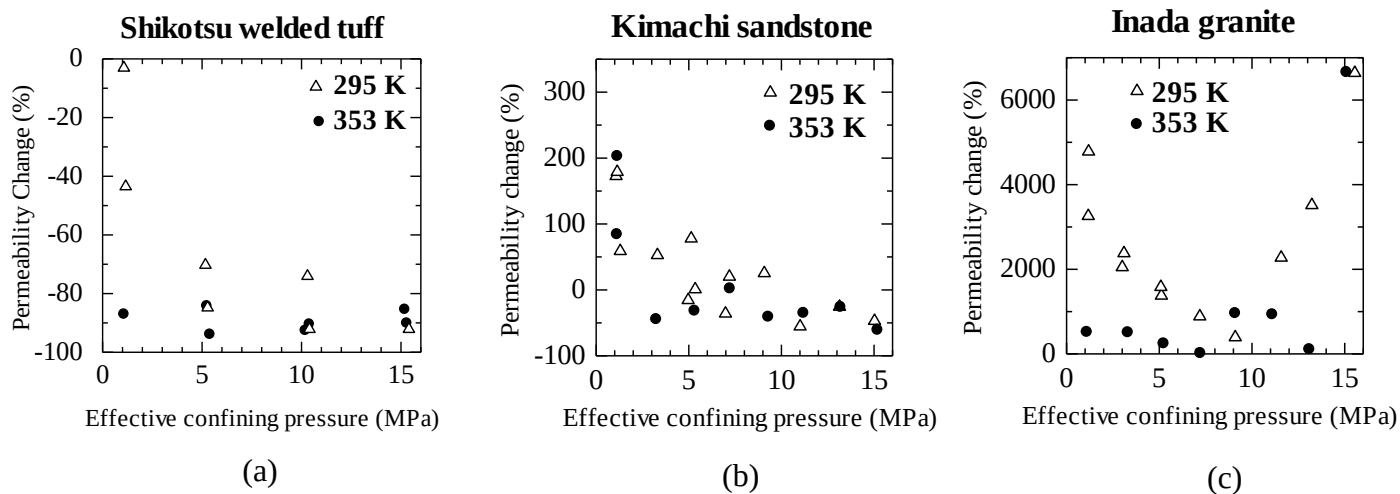


Fig. 12. Temperature–confining-pressure coupling effect on sealability showing the permeability change from pre- to post-compression.

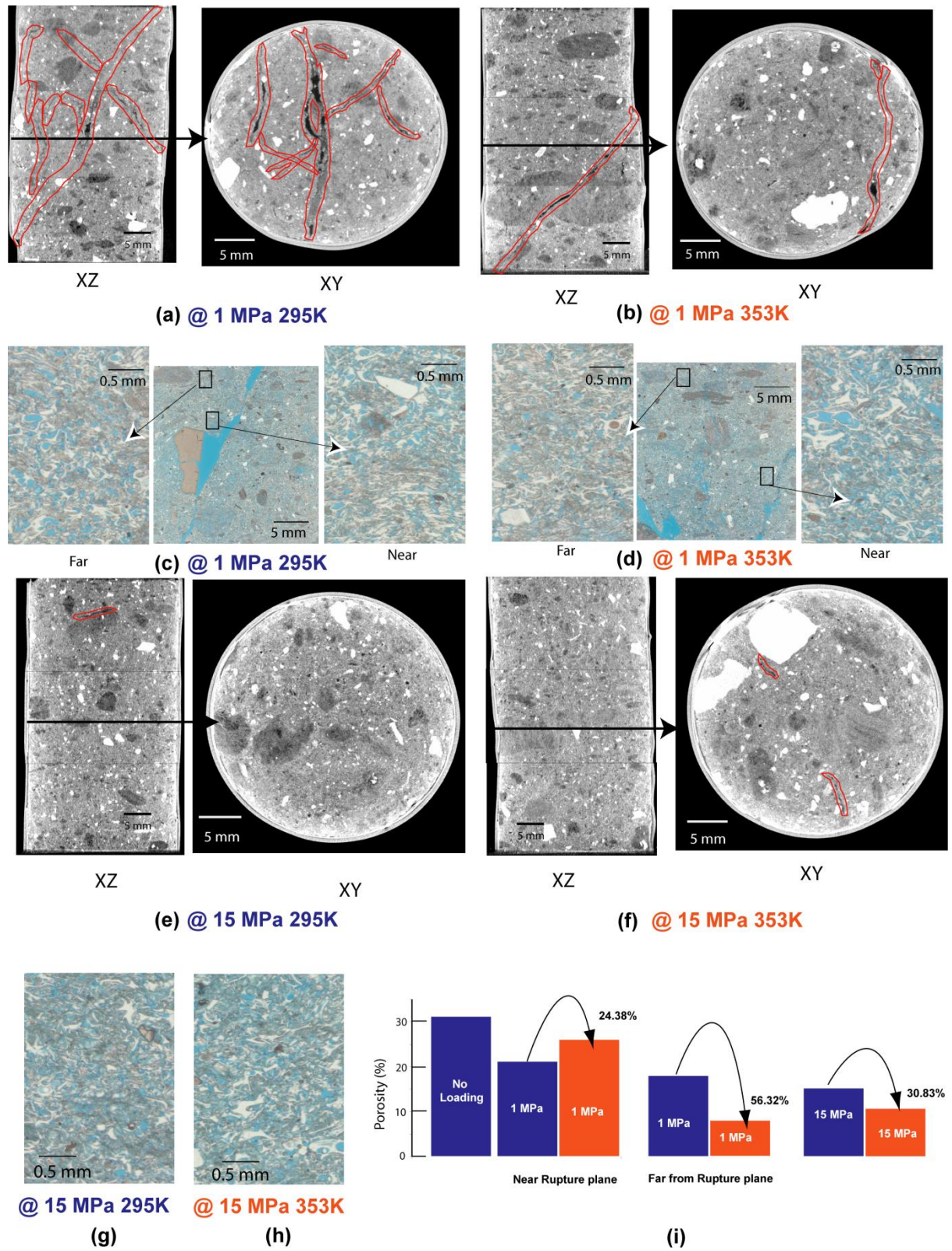


Fig. 13. CT and thin-section images for post-compression specimens of Shikotsu welded tuff. (Red and blue areas represent fractured zones, and blue spots are pores in the images)

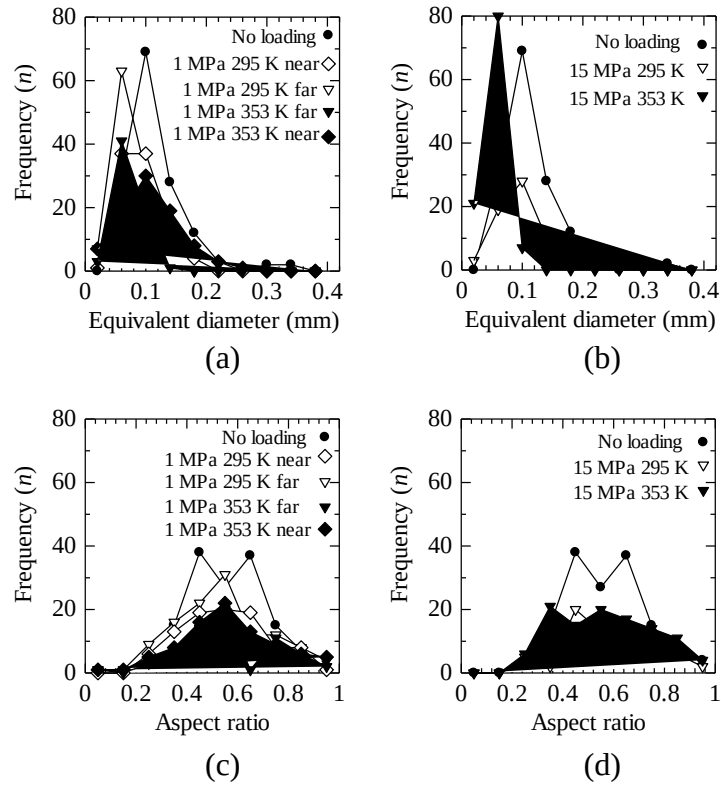


Fig. 14. Thin sectional image analysis of the blue resin impregnated thin sectional images of the post compression specimen. (a) equivalent diameter at 1 MPa CP, (b) equivalent diameter at 15 MPa CP, (c) Aspect ratio at 1 MPa CP, (d) Aspect ratio at 15 MPa.

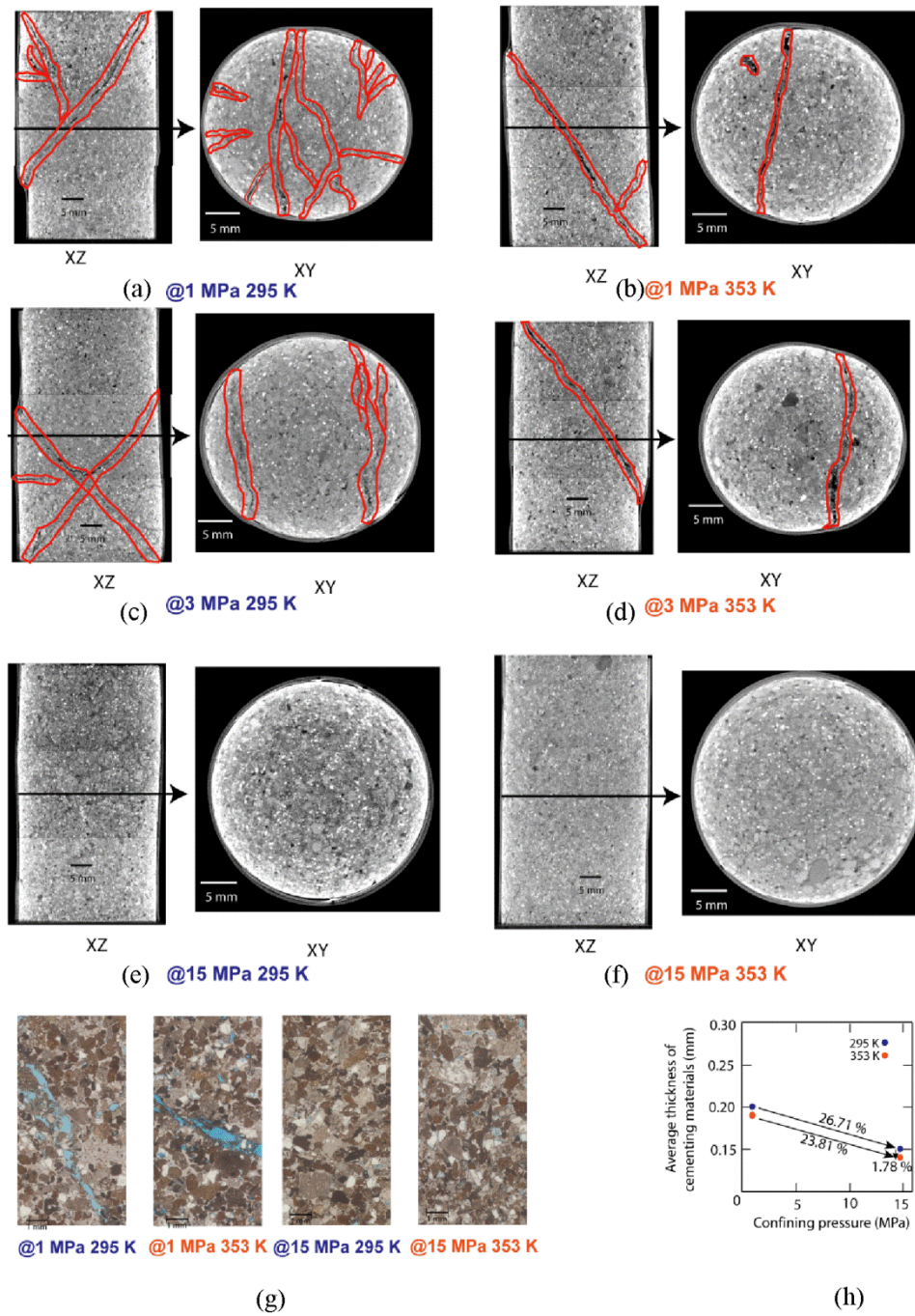


Fig. 15. CT and thin-section images for post-compression specimens of Kimachi sandstone.
(Red and blue areas in the images represent fractured zones)

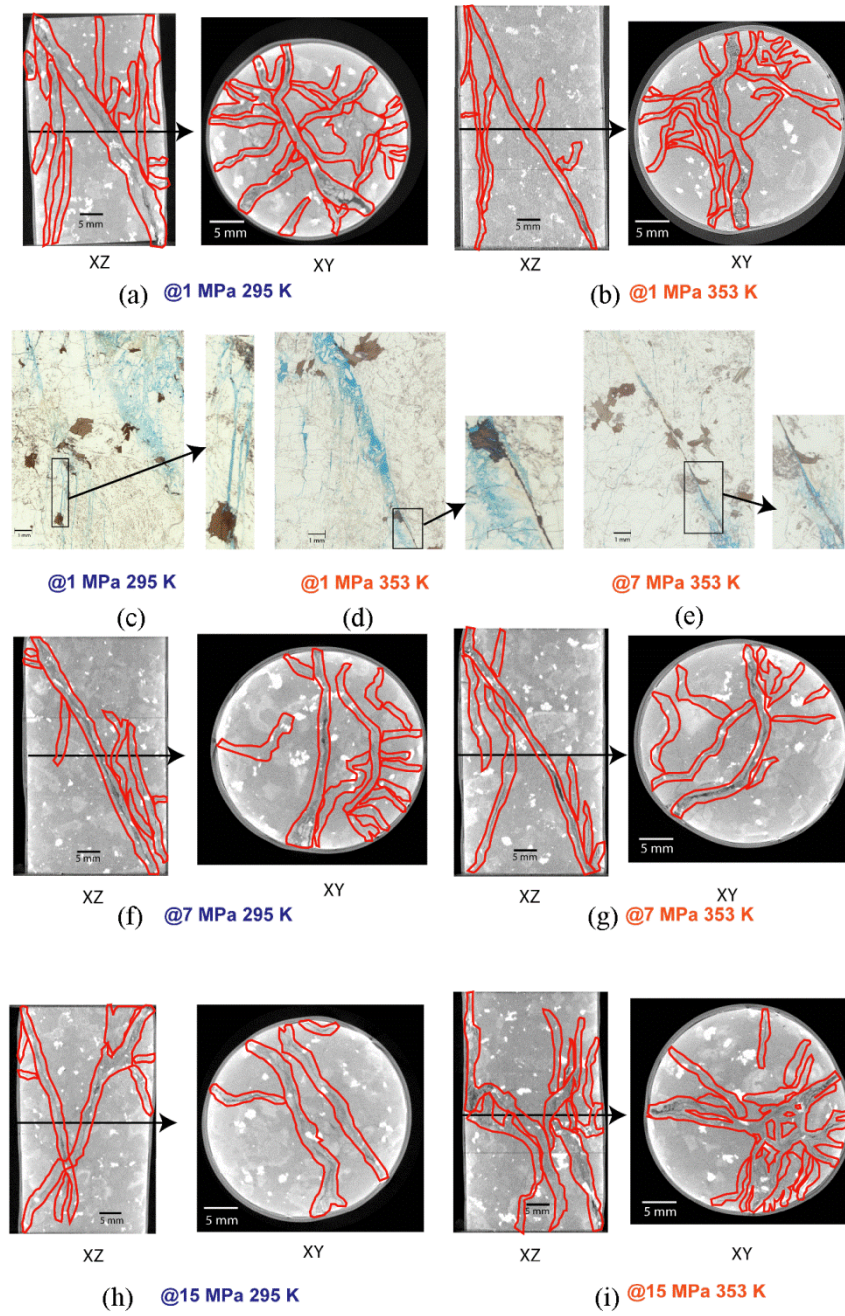


Fig. 16. CT and thin-section images for post-compression specimens of Inada granite. (Red and blue areas in the images represent fractured zones)