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

Dissertation for the Degree of Doctor of Engineering

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ABSTRACT

To clarify the permeability behavior of rock during deformation and failure, and the influences of confining pressure and temperature on that behavior, triaxial compression tests were carried out for Shikotsu welded tuff, Kimachi sandstone, and Inada granite under confining pressures of 1–15 MPa at 295 K and 353 K. Main findings are (1) Effects of confining pressure: For Shikotsu welded tuff, the permeability monotonously decreased with axial compression. The decrease ratio increased with confining pressure; the main cause of the decrease was attributed to pore collapse. For Kimachi sandstone, the permeability first decreased with increasing axial stress, but then began to increase when the total lateral strain recovered its value before the application of confining pressure, and finally showed an almost constant value in the post-peak region. The minimum and final permeability decreased with confining pressure. Compared to the permeability before axial compression, the final permeability became larger under small confining pressure but smaller under high confining pressure. The main cause of the decrease was attributed to either compaction or large plastic deformation of clay cementing materials. For Inada granite, the permeability behavior during axial compression was almost the same as that for the Kimachi sandstone. Compared to the permeability before compression, the final permeability was larger, and it decreased with smaller confining pressures. The main causes of the decrease were attributed to a decrease in the number and width of rupture planes and a decrease in the axial cracks from biotite; however, the permeability increased under larger confining pressures because of the formation of subrupture planes due to high stress concentration at the rough and stiff rupture plane. (2) Effect of temperature-confining pressure coupling: 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 almost same under high confining pressures for the Shikotsu welded tuff, slightly higher for the Kimachi sandstone, and obviously less for Inada granite compared to values at 295 K. The change in sealability of underground openings due to the progress of EdZs and EDZs were also inferred by considering the rupture plane in the triaxial compression tests analogous to a fracture in a rock mass.

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1. Introduction

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1.1 Background

Excavation disturbed Zone (EdZ) and Excavation Damaged Zone (EDZ) (Fig. 1.1) occur at all types of excavation. The EdZ is the zone with recoverable elastic deformation and EDZ is the zone with irrecoverable rock failure [Tsang et al., 2005]. Stress redistribution and changes in permeability due to the excavations happen within these zones [Borgesson et al., 1992; Olsson, 1992; Emsley, 1997; Sugihara et al., 1999; Backblom & Martin, 1999; Sato et. al., 2005; Kwon & Cho, 2008; Fujii et al., 2011; Wang et al., 2001; Tsang et al., 2005]. 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 [Rutqvist & Stephansson, 2003; Neuzil, 2003].

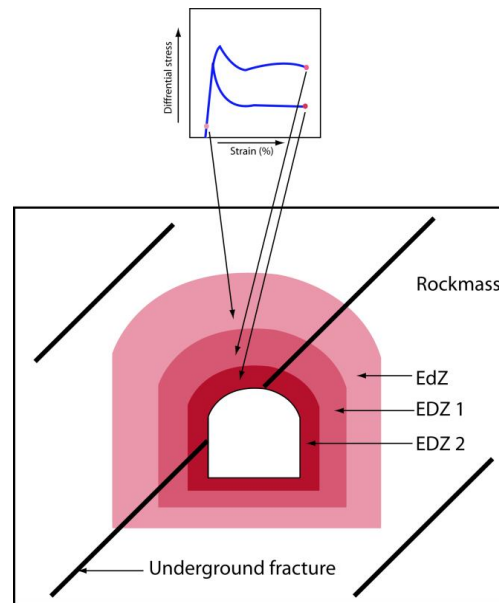


Figure 1.1 Schematic diagram of an underground opening having Excavation disturbed Zone (EdZ), Excavation Damaged Zone (EDZ) and fractures in the rockmass. [Alam et al., 2014(c)]. EDZ 1: Under relatively high confining pressure. EDZ 2: Under low confining pressure.

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 [Darot et al., 1992; David et al., 1999; Geraud, 1994; Hardin et al., 1967; Homand-Etienne & Houpert, 1989; Kern, 1978; Kumar, 1978; Naseri et al., 2007; de Pater et al., 1989; Zhao, 1994]. The temperature change of rock masses can be induced by human activity or natural processes. In particular, radioactive waste repositories (Fig. 1.3), which must be maintained for long periods even after closure [Backblom & Martin, 1999; Kwon & Cho, 2008; Hudson et al., 2005; Rutqvist, 2005] are affected by heat from the decaying waste.

1.2 Objectives

The specific objectives of this research are

- (i) To clarify the permeability change of three rocks during triaxial compression.
- (ii) To clarify the effects of confining pressure and temperature on the permeability under compression of three rocks.
- (iii) To have dominant mechanisms for the permeability behavior for each rock.
- (iv) To estimate sealability of rockmass and its change due to EDZ progression.

Sealability is defined here as inversely proportional to flow rate per unit pore pressure gradient (Eq. 1.1). Namely, it is proportional to viscosity and inversely proportional to permeability. The permeability and viscosity are function of temperature (Eqs. 1.2 and 1.3, and Fig. 1.2).

$$\text{Sealability} \propto \left(\frac{\text{Flow rate}}{dp/dx} \right)^{-1} \propto \frac{\text{Viscosity}}{\text{Permeability}} \quad (1.1)$$

$$\text{Permeability} = f_1(T, \sigma) \quad (1.2)$$

$$\text{Viscosity} = f_2(T) \quad (1.3)$$

1.3 Content 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

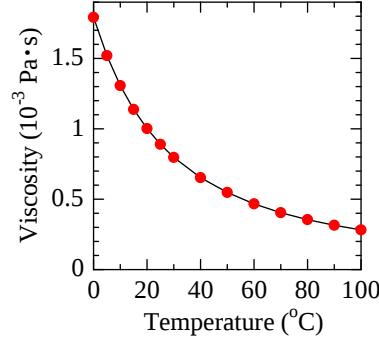


Figure 1.2 Relationship between viscosity and temperature of water (Chronological Scientific Tables, National Astronomical Observatory (ed.), Maruzen Co. Ltd., 2001).

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 (Eqs. 1.4 and 1.5). As most underground caverns are constructed to depths of less than 1000 m, this maximum confining pressure value is meaningful.

$$\sigma'_v = \gamma H - P_p \quad (1.4)$$

$$\sigma'_h = \frac{\nu}{1-\nu} \sigma'_v \quad (1.5)$$

where σ'_v and σ'_h are effective vertical and horizontal stresses, γ is unit weight, H is depth, P_p is pore pressure and ν is Poisson's ratio.

The rock temperature increases from initial temperature by decay heat after emplacement of the waste up to around 353 K [Kwon et al., 2008]. 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, the in situ confining pressure (Fig. 1.3a) is released

due to excavation (Fig. 1.3b). After the excavation and the waste is backfilled (Fig. 1.3c), temperature and confining pressure increase due to decay heat from the waste (Fig. 1.3d). The confining pressure remains the same after decay heat disappeared (Fig. 1.3e). Although the stress path of the real field and the experiment (Fig. 1.3f) 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.

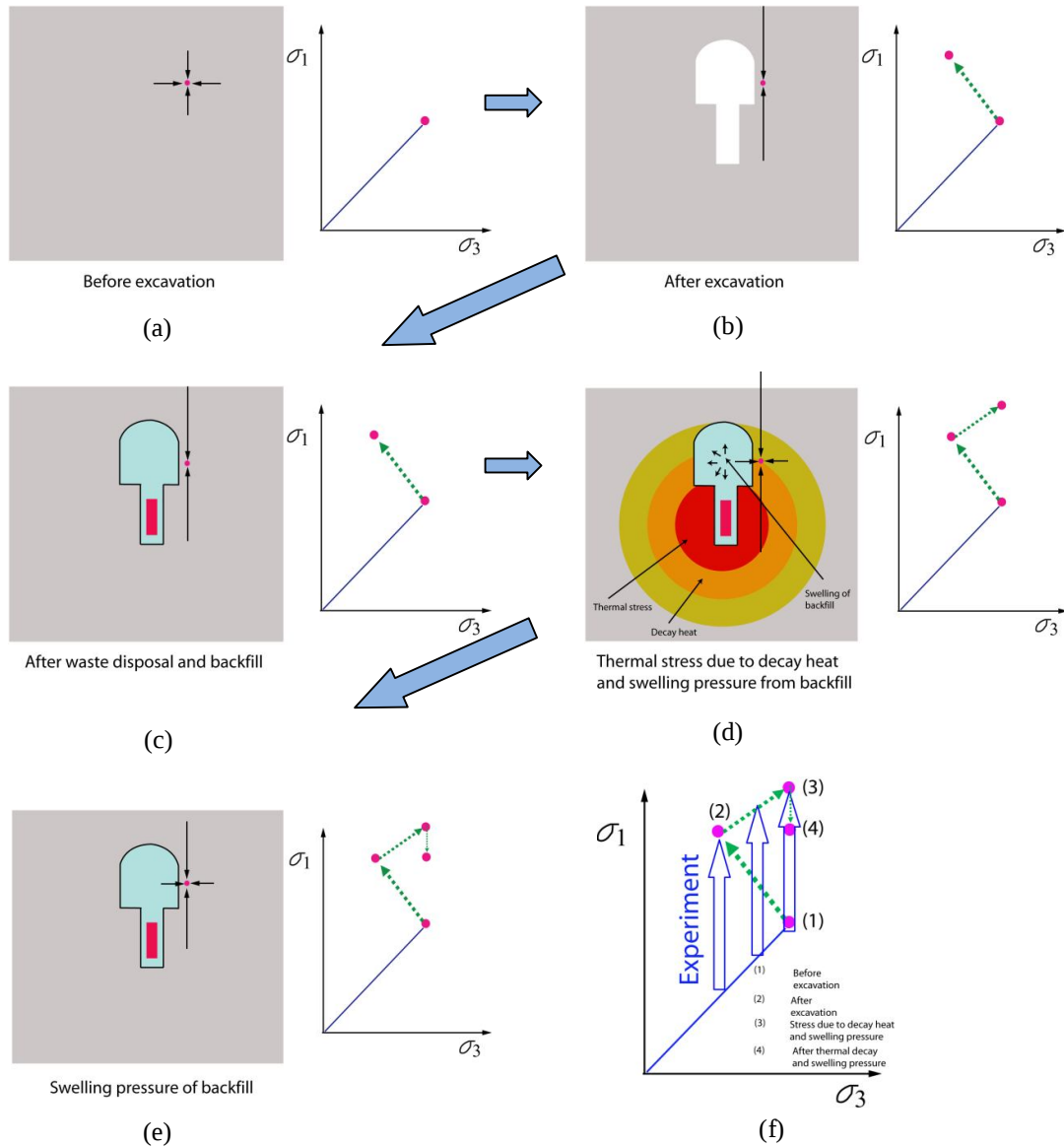


Figure 1.3 Schematic diagram of the stress path of a radioactive waste disposal site and the experimental condition.

1.4 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.

2. Experiment on Shikotsu welded tuff

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2.1 Materials and Method

2.1.1 Specimen and sample preparation

The Shikotsu welded tuff was sampled at Hokkaido, Japan, and consists of plagioclase, hypersthene, augite, hornblende, and transparent glass having a felt-like structure with amoebic form in the matrix. The grain sizes of the minerals are 0.3–1.5 mm for plagioclase, about 0.5 mm for hypersthene, 0.3–0.7 mm for augite, and 0.5–1.0 mm for hornblende [Doi, 1963]. The physical properties of the rock are listed in Table 1.

Table 1: Physical properties of the Shikotsu welded tuff shown as “average value (number of specimen) $\pm$ standard deviation”. UCS: Uniaxial Compressive Strength [Alam et al., 2014(d)].

V_p of specimen (km/s)	V_s of specimen (km/s)	Dry density (g/cm ³)	Effective porosity (%)	UCS (saturated) (MPa)
1.745 (2) $\pm$ 0.007	1.245(2) $\pm$ 0.021	1.304 (10) $\pm$ 0.012	36.5 (10) $\pm$ 2.3	13.53 (2) $\pm$ 2.74

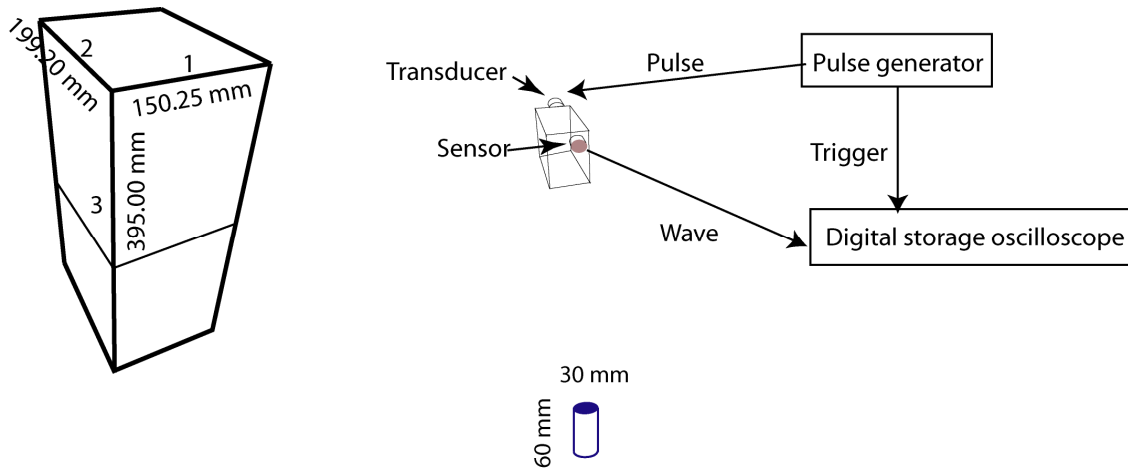


Figure 2.1 Specimen from block of Shikotsu welded tuff. (a) Block (b) Measuring P-wave velocity of the block (c) Specimen after coring, cutting and polishing [Alam et al., 2012].

The specimens were prepared from a rock block using the following steps (Fig. 2.1). (1) The P-wave velocity along each pair of opposite sides of the rock blocks was measured with 140-kHz sensors. (2) Cylindrical cores with a diameter of 30 mm and a length of 60 mm were prepared in the direction of the slowest P-wave velocity. (3) The core ends were polished to a parallelism of 2/100.

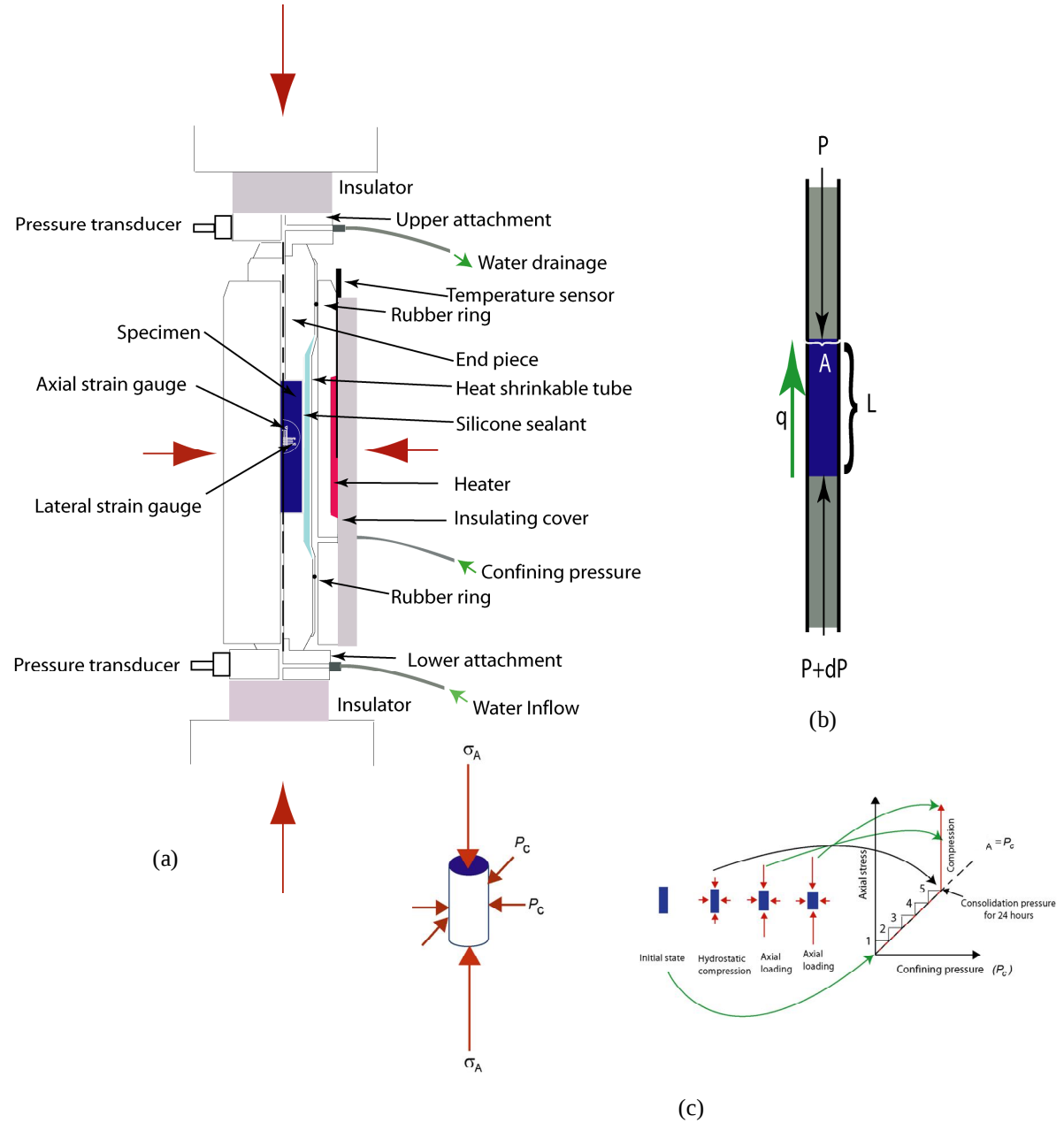


Figure 2.2 Experimental setup. (a) Pressure vessel with sample and accessories, (b) Sketch of permeability measurement basis [Alam et al., 2012], (c) Schematic diagram showing the steps for reaching the desired confining pressure and compression [Alam et al., 2014(d)].

The samples were prepared using the following procedure. (1) Each specimen was made fully pure-water saturated in a water-submergible vacuum jar. (2) Two stainless steel endpieces were attached to a saturated specimen with vinyl tape. The endpieces had a central hole to allow water flow through the specimen. (3) Two cross-type strain gauges were glued to the center of opposite sides of the specimen. (4) A coating of silicon sealant was applied to maintain the water flow within the specimen up to the curvature of the endpieces. (5) A heat-shrinkable tube was jacketed to the endpieces-attached specimen to prevent direct contact of the confining fluid (water) with the specimen. (6) The sample was then held in water for 24 h.

2.1.2 Experimental setup (Fig. 2.2a)

A loading frame was used to apply the axial load. A double ball plunger pump with a relief valve that was connected to the ultra-compact triaxial cell was used to maintain the confining pressure throughout the experiment.

The triaxial cell was covered with a band-type heater (Acim Jouanin, L6060C57A5, 230 V, 575 W) with a controller (Three High, THC-15, 273 K-1272 K) [Alam et al., 2014(c)]. A pair of stainless steel attachments was attached to the jacketed sample. Each attachment had a hole for water flow and a pore pressure sensor. The water flow path of the upper attachment was open to the atmosphere; a syringe pump was connected to the lower attachment and used to produce a constant flow of water.

2.1.3 Experimental procedure

The experimental procedure was as follows. (1) The sample was inserted into the triaxial cell. (2) The upper and lower attachments were attached to the endpieces. (3) Axial stress and confining pressure were applied to the specimen through 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. 2.2c). After reaching the target consolidation pressure, the sample was held in this state for 24 h at 295 K or 353 K. (4) After consolidation for 24 h, 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. During the experiment, the load, stroke, pore pressure, axial strain, lateral strain, confining pressure, and flow rate were measured at a sampling interval of 10 s.

2.1.4 Effective confining pressure, differential stress, and strain correction

The effective confining pressure ($P_{c\text{-effective}}$) was calculated as:

$$P_{c\text{-effective}} = P_c - \frac{P_{pu}}{2} \quad (2.1)$$

The differential stress (σ_{diff}) was calculated using the following equation:

$$\sigma_{diff} = \sigma_{axial} - P_c \quad (2.2)$$

where σ_{axial} is the axial stress.

The effective stress coefficient should be less than 1 for usual rocks and sometimes its value more than 1 was reported for clay-rich rocks [Al-Wardy & Zimmerman, 2004]. It was however assumed as 1 for the above calculations. The assumption did not cause significant errors for the effective stress values since the pore pressure was as large as slightly more than 1 MPa. When testing the Shikotsu welded tuff, the strain gauges were damaged under some relatively high confining pressures because of pores on the rock surface.

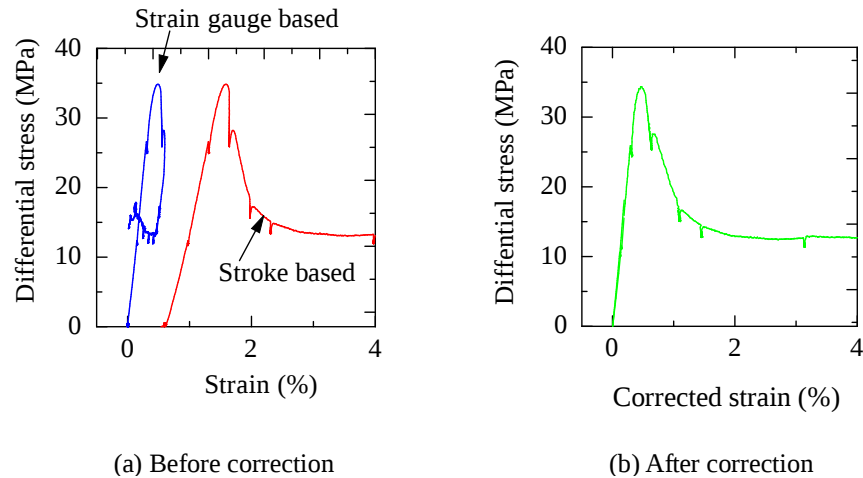


Fig. 2.3 Example of strain correction.

To obtain the entire stress-strain (ϵ') and permeability relationship, the strain gauge strain (ϵ) was used up to 50% of the peak stress, σ_{50} :

$$\epsilon' = \epsilon, \sigma < \sigma_{50} \quad (2.3)$$

A correction was made for the stroke-based strain (ϵ_s) (Fig. 2.3):

$$\epsilon'' = \epsilon_s - C\sigma \quad (2.4)$$

$$\varepsilon' = \varepsilon'' - \varepsilon''_{50} + \varepsilon_{50}, \sigma \geq \sigma_{50} \quad (2.5)$$

$$C = \frac{1}{E_{s50}} - \frac{1}{E_{50}}, \quad (2.6)$$

where E_{s50} is the stroke-based 50% tangent modulus, E_{50} is the strain gauge-based 50% tangent modulus, ε''_{50} is ε'' at the 50% stress level, and ε_{50} is ε at the 50% stress level.

2.1.5 Measurement of permeability

The permeability of the Shikotsu welded tuff was relatively high, and was measured by the constant flow method. In this method, a constant flow (0.3 ml/min) of pure water was maintained in the axial direction by using the syringe pump (Fig. 2.2). Based on Darcy's law, the permeability K (m^2) was calculated by

$$K = \frac{q \cdot \mu}{A} \cdot \left(\frac{dP}{dL} \right)^{-1} \quad (2.7)$$

where q is the flow rate (m^3/s), μ is the fluid viscosity ($\text{Pa}\cdot\text{s}$), A is the cross-sectional area (m^2) of the specimen, and dP/dL is the pressure gradient (Pa/m).

2.1.6 Micro- and macrostructure analysis

Microstructure analysis was conducted from thin-section images of the blue resin-impregnated specimens using Scion Image software [scion-image.software.informer.com, 2011] with a resolution of 8.8 μm . A micro-focus X-ray computed tomography (CT) scanner, installed at Hokkaido University, Japan, was also used to determine the number, orientation, and geometry of the rupture planes (i.e., the post-compression macrostructure of the specimens). A detailed description of micro-focus X-ray CT for rock-like materials is provided in [Fukuda et al., 2012]. The CT images were obtained in three perpendicular planes with a resolution of 37 μm .

2.2 Results

2.2.1 Effect of confining pressure [Alam et al., 2014(d)]

2.2.1.1 Deformation and permeability

This rock exhibited strain softening at a confining pressure (P_c) of 1 MPa, almost perfect plastic behavior at $P_c = 5$ MPa, and strain hardening at $P_c = 10$ and 15 MPa (Fig. 2.4a). The peak differential stress

increased up to $P_c = 5$ MPa (Fig. 2.4b). At $P_c > 10$ MPa, i.e., strain hardening, the yield stress decreased slightly with increasing confining pressure and the residual strength increased with the confining pressure (Fig. 2.4b), but no clear relationship was observed for the tangent modulus or Poisson's ratio (Fig. 2.4c).

The permeability was lowest at a confining pressure of 15 MPa, compared to $P_c = 1$ –10 MPa, after 24 h of consolidation (Fig. 2.5a). The permeability did not decrease significantly at $P_c = 1$ MPa, showed a significant decrease after the peak load at $P_c = 5$ –10 MPa, and decreased monotonously at $P_c = 15$ MPa due to axial compression (Fig. 2.4a).

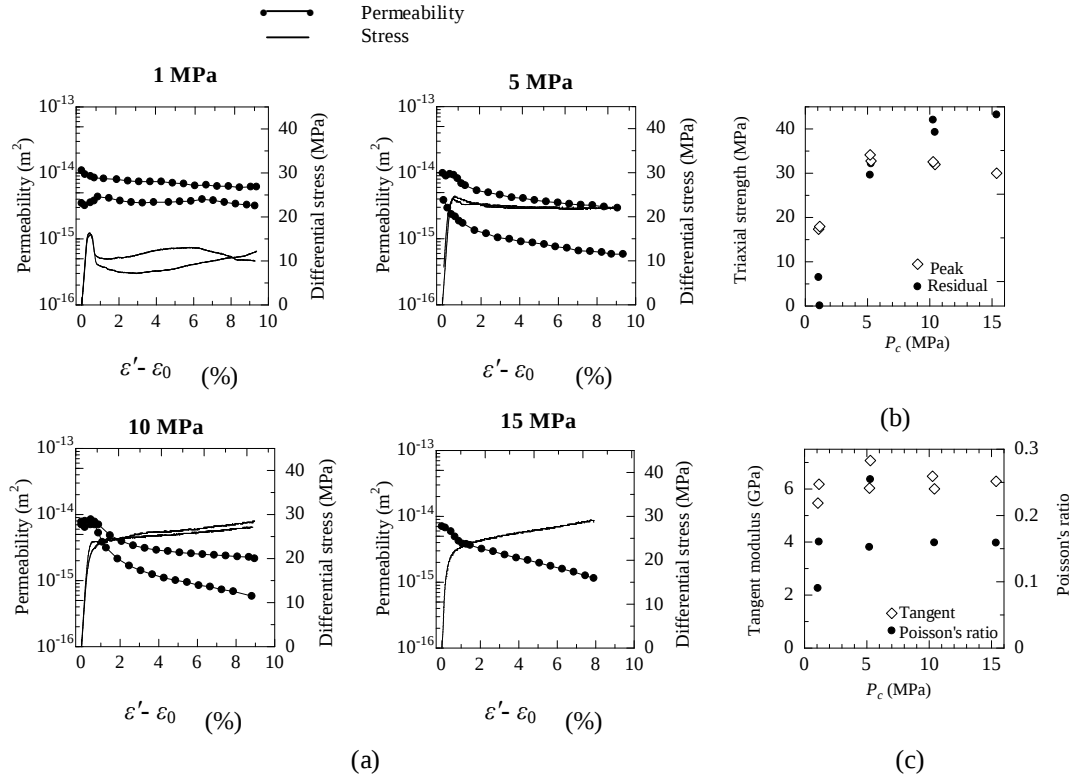


Fig. 2.4 Stress-strain, permeability relationship and mechanical properties of Shikotsu welded tuff. (a) Stress, axial strain and permeability relationship. (b) Peak or yield differential stress, residual strength ratio with confining pressure. (c) Tangent modulus and Poisson's with confining pressure. [Alam et al., 2014(d)]

The permeability change was calculated from the permeability after consolidation (K_{con}) and the permeability after compression (K_{com}):

$$K_{\text{change}} = \frac{K_{\text{com}} - K_{\text{con}}}{K_{\text{con}}} \times 100 \quad (2.8)$$

The permeability change increased with increasing confining pressure (Fig. 2.5c)

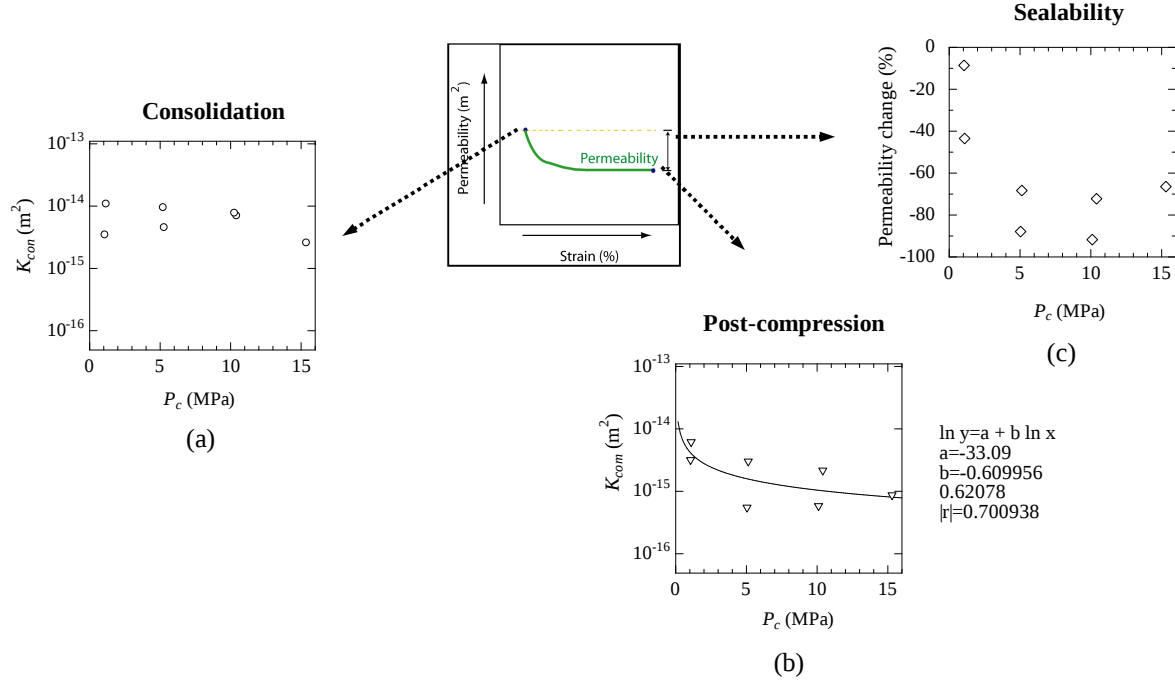


Fig. 2.5 Confining pressure effect on the permeability change of the Shikotsu welded tuff. Permeability after (a) consolidation and (b) axial compression. (c) Decrease of permeability. [Alam et al., 2014(d)]

The post-compression permeability decrease was small at $P_c = 1$ MPa, but the amount of the decrease became larger with increasing confining pressure (Fig. 2.5b). The relationship between permeability (m^2) after compression and confining pressure, P_c (MPa), can be approximated by the following equation:

$$\log K_{\text{com}} = -14.37 - 0.61 \log P_c \quad (2.9)$$

2.2.1.2 Micro- and macrostructures

Microstructure analysis was conducted using the blue resin-impregnated thin-section images. The thin section of the 15-MPa consolidated specimen was compared with that of the intact specimen to investigate the consolidation effect (Fig. 2.6a and b; blue spots represent pores). The porosity decreased by 41.23% (Fig. 2.6c) due to consolidation. The equivalent diameter of pores (d_{pore}) in the intact specimen was

0.04–0.16 mm. The frequency of $d_{\text{pore}} \geq 0.08$ mm decreased, and $d_{\text{pore}} \leq 0.08$ mm became dominant at $P_c = 15$ MPa (Fig. 2.6d). Pores with a smaller aspect ratio increased at $P_c = 15$ MPa (Fig. 2.6e), but pores with a small angle to the horizontal flow layer remained dominant in the 15-MPa consolidated specimen (Fig. 2.6f).

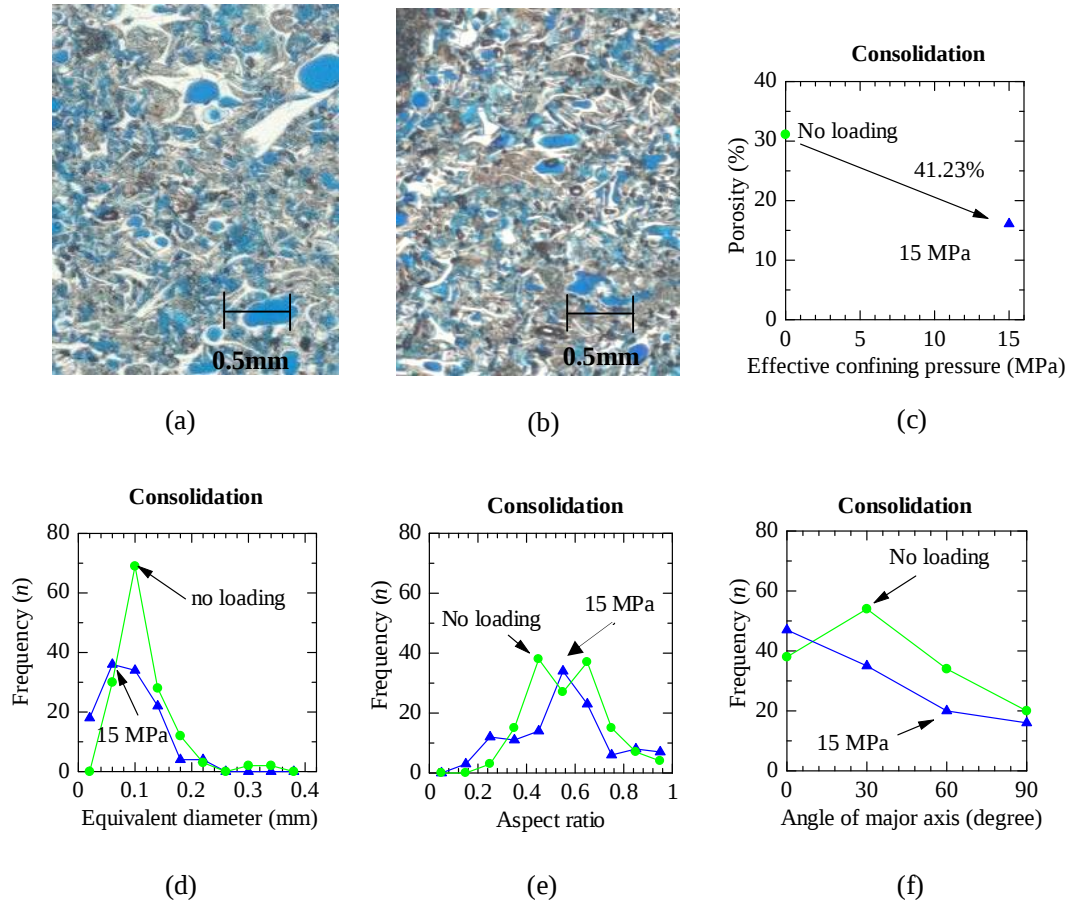


Fig. 2.6 Blue resin-impregnated thin-section images and analyses of the fresh and consolidated specimens of Shikotsu welded tuff. The blue spots represent pores in the rock. (a) Image of the intact specimen. (b) Image after consolidation at 15 MPa. (c) Porosity. (d) Equivalent diameter. (e) Aspect ratio. (f) Angle of major axis to the horizontal flow layer. [Alam et al., 2014(d), 2013(b)]

In the X-ray CT images at $P_c = 1$ MPa, a rupture plane was observed in the X-Z plane of the specimen after axial compression (Fig. 2.7a). However, macroscopic fractures were not observed for the $P_c = 15$ MPa case (Fig. 2.7b).

An analysis of the pores around the rupture plane was performed using the blue resin-impregnated

thin-section images of the specimens after axial compression at $P_c = 1$ MPa. The porosity near the rupture plane increased by 16.99%, and was greater than that far from the rupture plane (Fig. 2.7f). The frequency value of $d_{\text{pore}} = 0.10$ mm increased near the rupture plane (Fig. 2.7g), and the frequency value of $d_{\text{pore}} = 0.06$ mm was dominant far from the rupture plane. The frequency of a pore aspect ratio of around 0.5 decreased near the rupture plane (Fig. 2.7h).

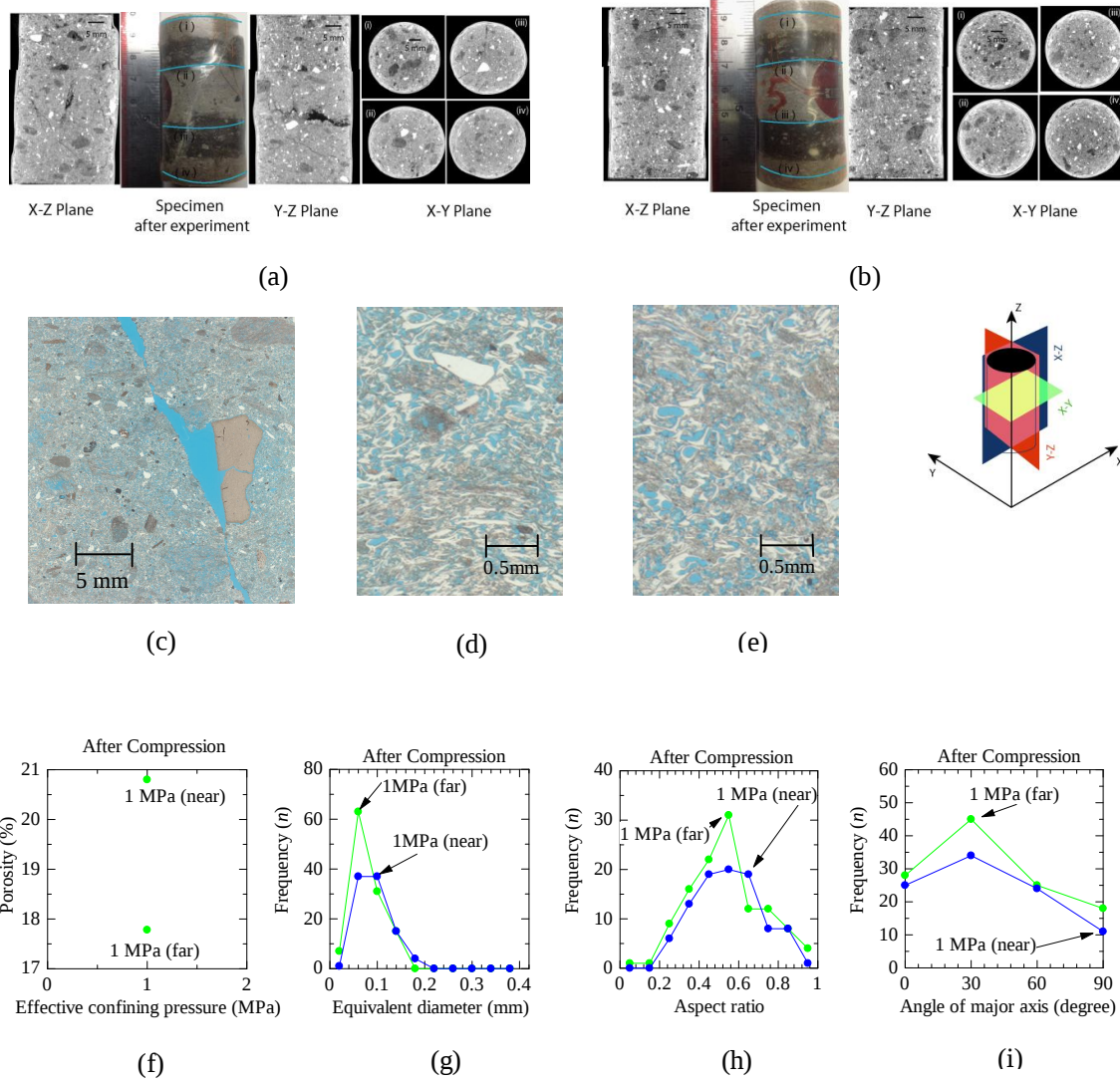


Fig. 2.7. Specimen, CT images, blue resin-impregnated thin-section images, and analyses after axial compression of Shikotsu welded tuff. Specimen and CT images at (a) 1 MPa and (b) 15 MPa. (c) Image at 1 MPa. Image at 1 MPa (d) near the shear plane and (e) far from the shear plane. (f) Porosity near and far from the rupture plane. (g) Equivalent diameter. (h) Aspect ratio. (i) Angle of major axis to the flow layer (horizontal). The loading direction is vertical. [Alam et al., 2014(d), 2013(b)]

2.2.2 Effect of temperature-confining pressure coupling [Alam et al., 2014(c)]

2.2.2.1 Deformation and Permeability

The permeability during deformation and failure at 353 K, as well as at 295 K, monotonously decreased (Fig. 2.8a). The peak strength at 353 K was lower than at 295 K (Fig. 2.8b). The tangent modulus and residual strength at 353 K were slightly lower than those at 295 K (Fig. 2.8c and d).

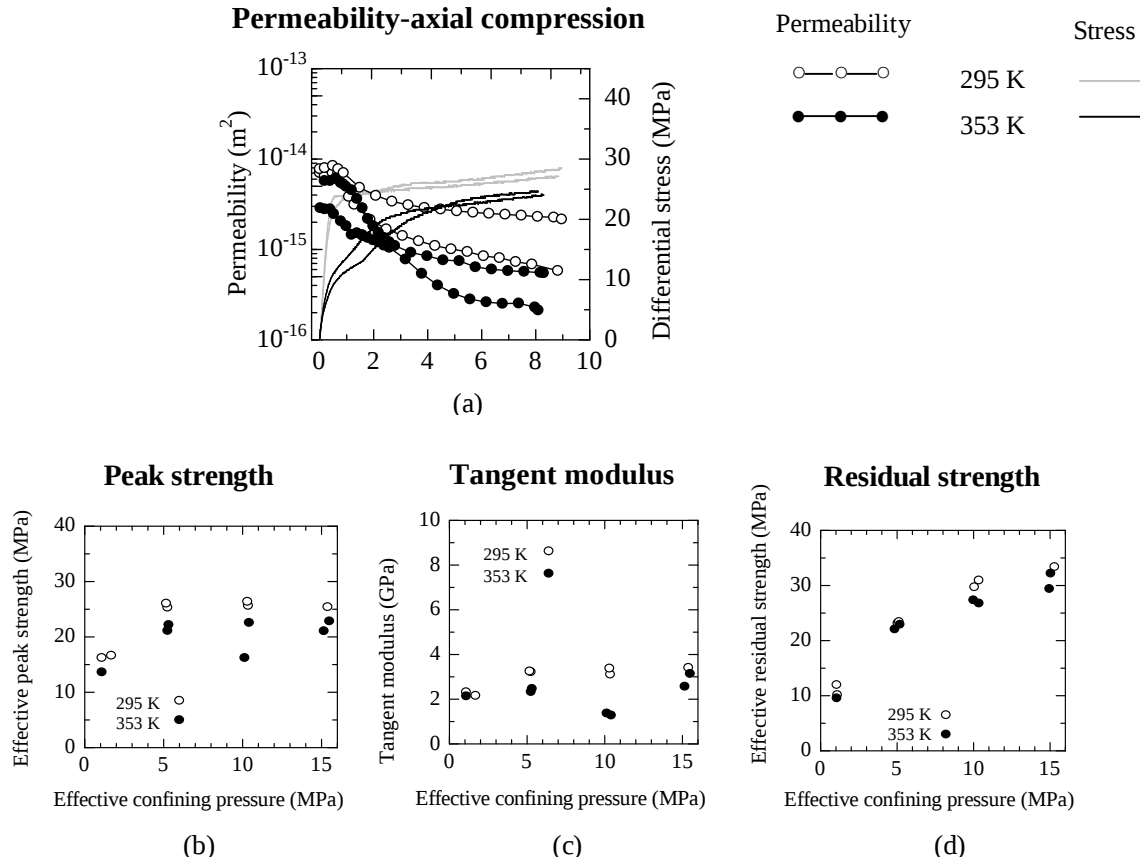


Fig. 2.8 Effects of deformation and failure on permeability change, and mechanical properties of the rocks. [Alam et al., 2014(c)]

After 24-hour consolidation, the permeability decreased with effective confining pressure (Fig. 2.9). The permeability at 353 K was lower than at 295 K (Fig. 2.9a), and that under 15 MPa confining pressure (CP) was the lowest.

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. 2.9b). The flow velocity per unit pore pressure gradient, considering the change in water viscosity due to temperature, was lower than the values at 295 K (Fig. 2.9c). The permeability change (Fig. 2.9) was calculated from the permeability after 24 hours of consolidation (K_{con}) and the post-compression permeability (K_{com}) by Eq. 2.8.

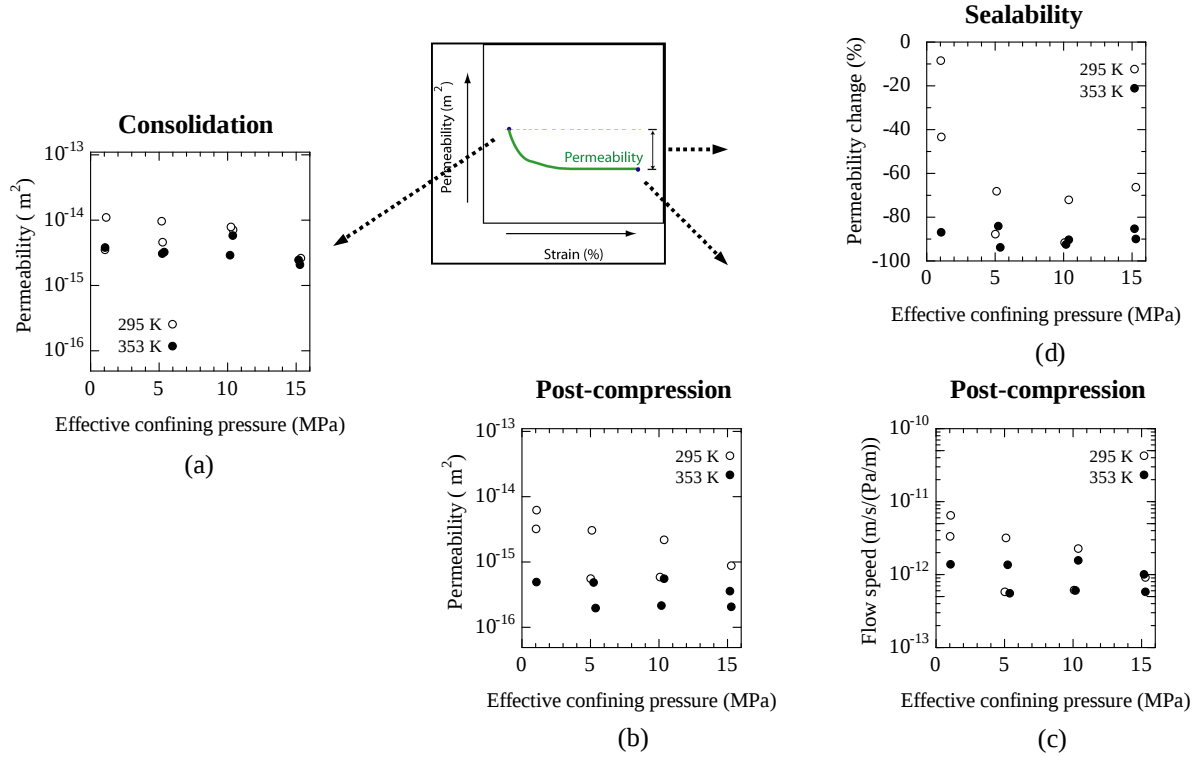


Fig. 2.9 Pre and post-compression permeability and flow velocity per unit pore pressure gradient, and permeability change. [Alam et al., 2014(c), 2014(a)]

The permeability change showed that the decrease in permeability became greater with increasing confining pressure from -3.05% to -92.12% at 295 K (Fig. 2.9d). A confining-pressure dependency was not observed at 353 K (-84.21% to -93.93%).

2.2.2.2 Micro- and macro structures

The pre-experimental porosity of Shikotsu welded tuff based on thin-section image (Fig. 2.10a) analysis was 31.10%, which 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. 2.10b). Pores with an equivalent diameter of 0.14 mm at 295 K significantly decreased at 353 K to a 0.06-mm equivalent diameter, although pores in a fresher specimen sustained a

0.10-mm equivalent diameter (Fig. 2.10c). 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. 2.10d). Pores parallel to the horizontal flow layering of the tuff dominated at 15 MPa CP (Fig. 2.10e).

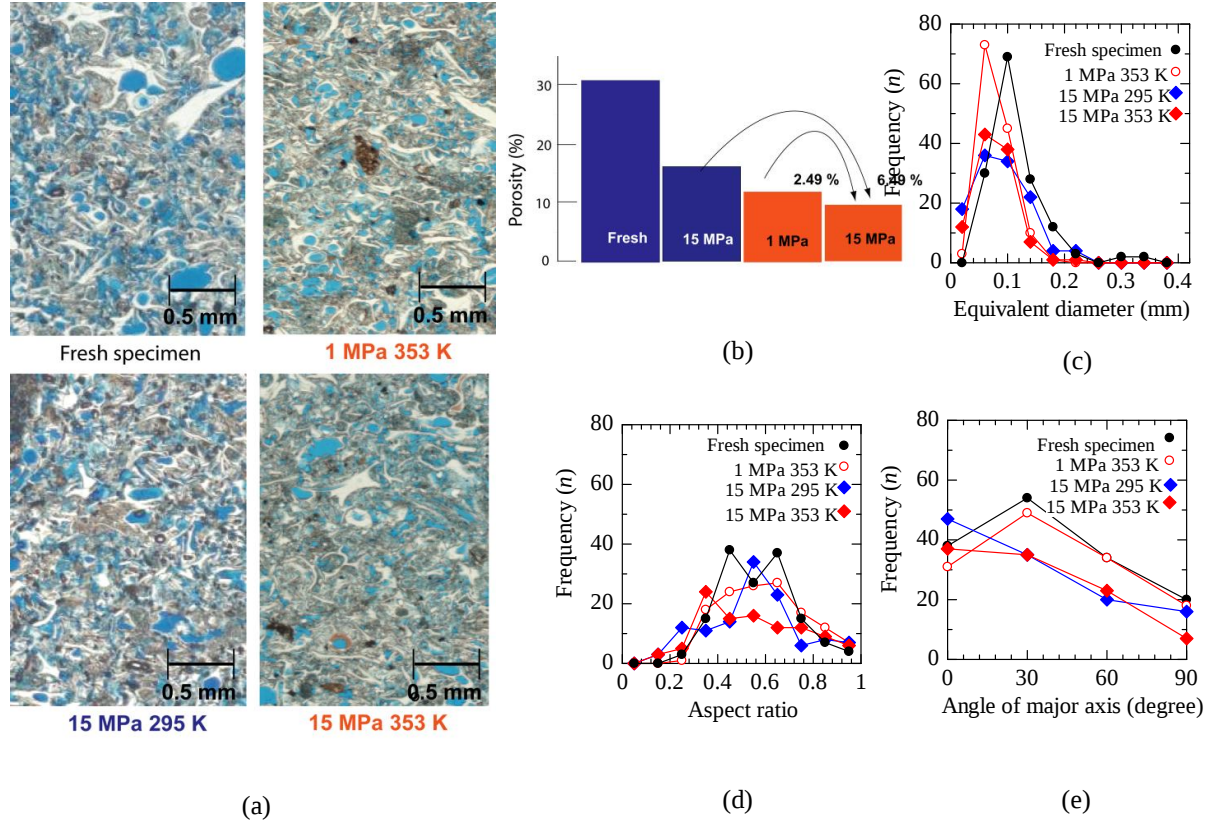


Fig. 2.10 Thin-section images and analyses for 24-hour consolidated specimens of Shikotsu welded tuff. (a) Thin-section images, (b) total porosity, (c) equivalent diameter, (d) aspect ratio, and (e) angle of major axis. (Blue spots are pores). [Alam et al., 2014(c)]

A main rupture plane with sub-rupture planes and several fractures appeared in the CT image for 1 MPa CP at 295 K (Fig. 2.11a), whereas only one main rupture plane appeared at 353 K (Fig. 2.11b). The porosity near the rupture plane was higher than that far from it (Fig. 2.11i). The porosity far from the rupture plane at 353 K was 10.0% less than at 295 K. The rupture plane was absent for 15 MPa cases (Fig. 2.11e and f), and the porosity at 353 K was less than at 295 K by 4.63% (Fig. 2.11i).

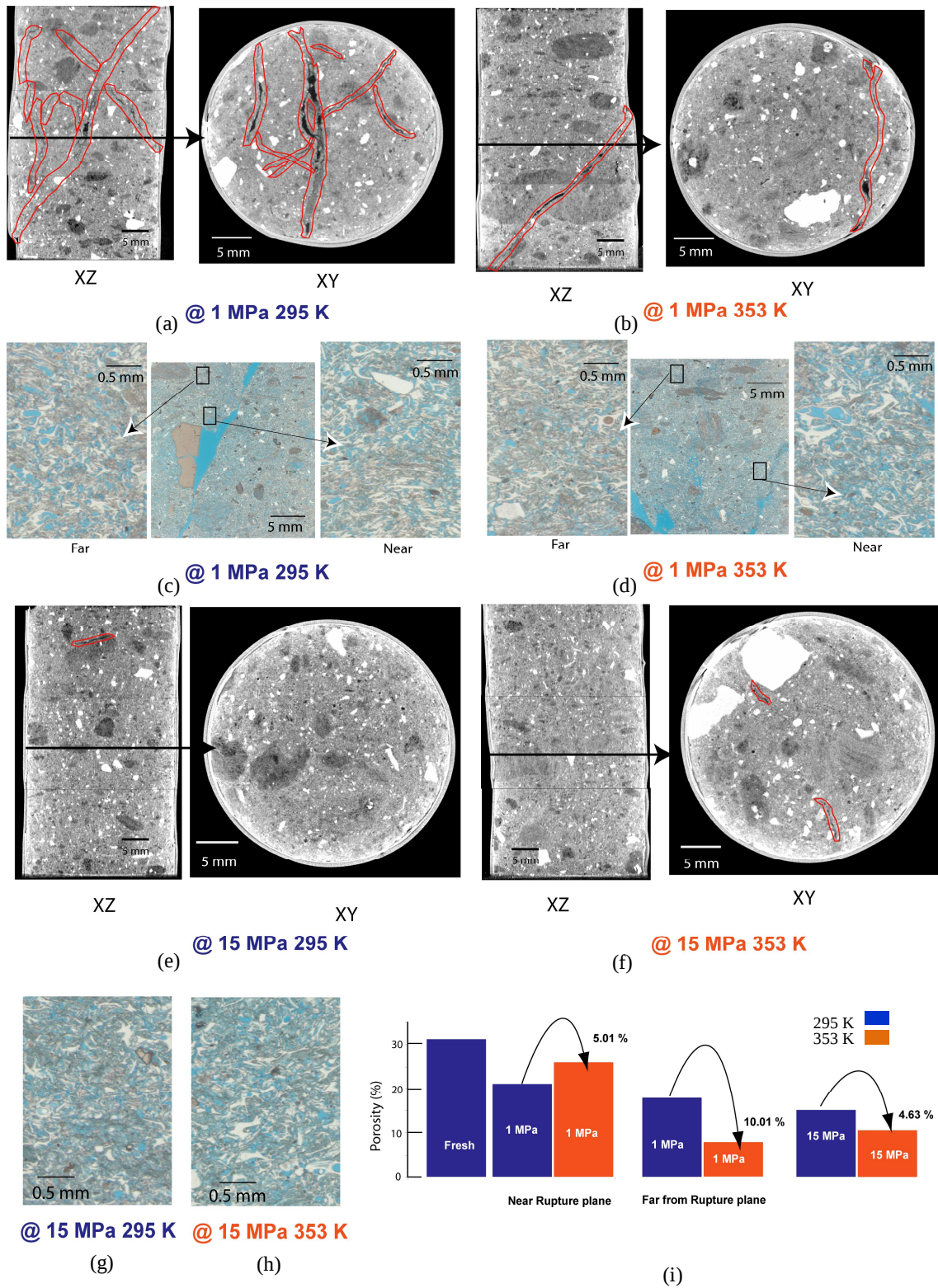


Fig. 2.11 CT and thin-section images for post-compression specimens of Shikotsu welded tuff. (Red and blue areas represent fractured zones, and blue spots are pores in the images). [Alam et al., 2014(c)]

3. Experiment on Kimachi sandstone

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3.1 Materials and Method

3.1.1 Specimen and sample preparation

The Kimachi sandstone was sampled at Shimane, Japan, and is a relatively well-sorted clastic rock with a typical grain size range of 0.4–1.0 mm. It consists mostly 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 physical properties of the rock are listed in Table 2.

Table 2: Physical properties of the Kimachi sandstone shown as “average value (number of specimen) $\pm$ standard deviation”. UCS: Uniaxial Compressive Strength. [Alam et al., 2014(d)]

V_p of specimen (km/s)	V_s of specimen (km/s)	Dry density (g/cm ³)	Effective porosity (%)	UCS (saturated) (MPa)
2.24(13) ± 0.08	1.478 (13) ± 0.039	1.981(13) $\pm$ 0.01	18.54(13) ± 0.95	20.5 (2) ± 2.4

The specimen and sample preparation were same as section 2.1.2

3.1.2 Experimental setup (Fig. 3.1a)

Same experimental setup was used as section 2.1.2. Only for the transient pulse method, an upstroke accumulator was connected to the upper attachment and the syringe pump was used to control the pore pressure and acted as a downstream accumulator (Fig. 3.1a).

3.1.3 Experimental procedure

The experimental procedure was as section 2.1.3 having the constant strain rate (10^{-5} s^{-1} , i.e., 0.036 mm/min)-controlled compression until the stroke-based strain reached 7%.

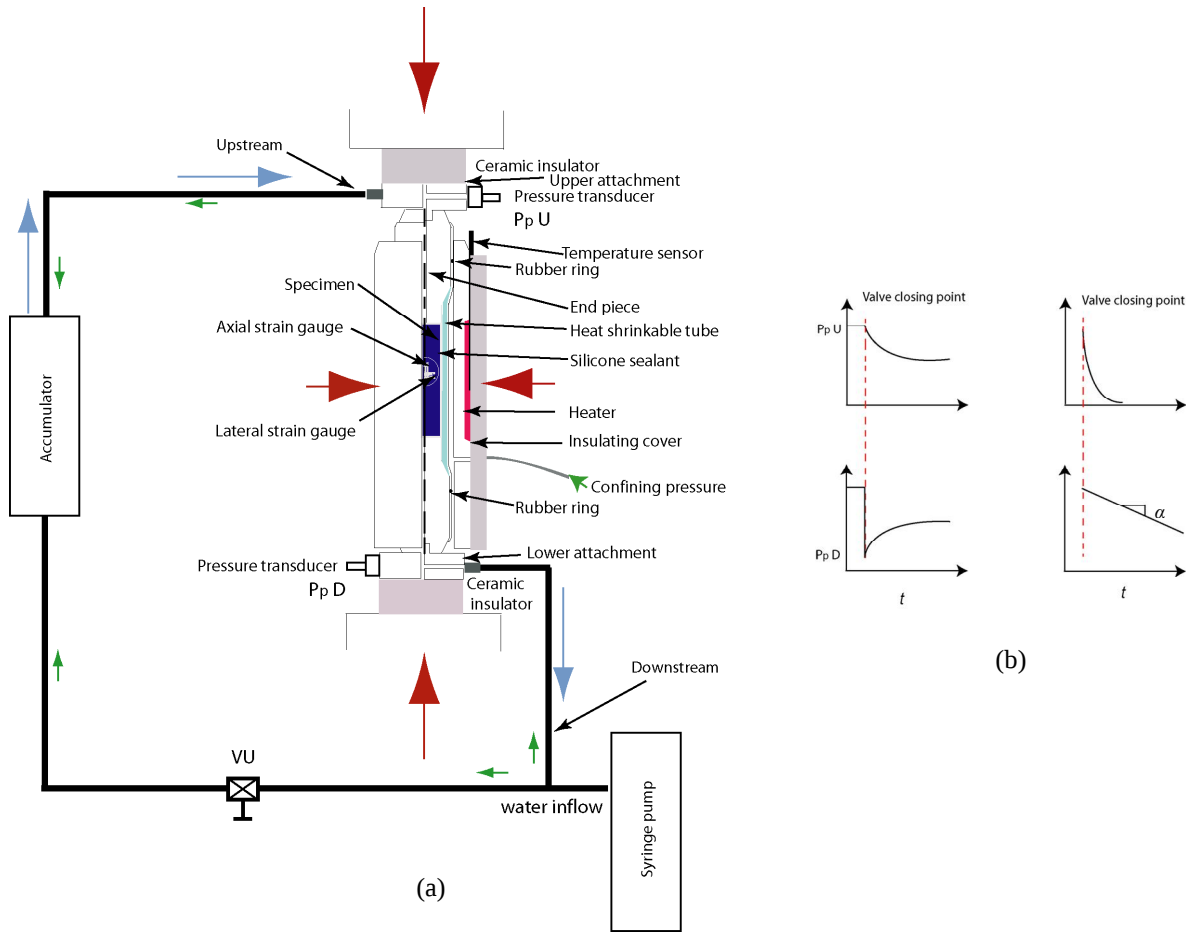


Figure 3.1 Experimental setup for transient pulse method. (a) Pressure vessel with sample and accessories, (b) Sketch of permeability measurement basis [Alam et al., 2014(d)]

3.1.4 Effective confining pressure, differential stress, and strain correction

Same procedure was followed as section 2.1.4 only the difference was in $P_{c\text{-effective}}$ and was calculated as:

$$P_{c\text{-effective}} = P_c - P_p \quad (3.1)$$

3.1.5 Measurement of permeability

The permeability of the Kimachi sandstone was measured by the transient pulse method. A constant pore pressure of 1 MPa was maintained in the entire system during consolidation and compression. At every permeability measurement point, the platen was stopped. Then, the accumulator and syringe pump were separated by closing the valve, and a -0.5 MPa pore pressure was applied downstream and the syringe pump was stopped. This condition was maintained for 30 min. Considering the upstream and downstream

volumes and a pressure pulse based on the Brace principle [Brace, W.F., et al., 1968], we can write:

$$P_1 - P_f = \Delta P_0 \cdot \frac{V_2}{V_1 + V_2} \cdot e^{-\alpha t} \quad (3.2)$$

$$P_2 - P_f = -\Delta P_0 \cdot \frac{V_1}{V_1 + V_2} \cdot e^{-\alpha t} \quad (3.3)$$

$$\alpha = \frac{KA}{\mu\beta L} \cdot \frac{V_1 + V_2}{V_1 V_2} \quad (3.4)$$

where P_1 is the upstream pressure (Pa), V_1 is the upstream volume (m^3), V_2 is the downstream volume (m^3), P_f is the converged pressure value (Pa), ΔP_0 is the pressure pulse (Pa), t is the elapsed time (s), K is the permeability (m^2), A is the sectional area (m^2), L is the length of the specimen (m), μ is the viscosity of water ($\text{Pa}\cdot\text{s}$), and β is the compressibility of water (Pa^{-1}). Then, we obtain

$$P_1 - P_2 \equiv \Delta P = \Delta P_0 \cdot e^{-\alpha t} \quad (3.5)$$

Defining G_1 and G_2 as the upstream and downstream stiffness (Pa/m^3) of the hydraulic system, respectively, the upstream and downstream volumes are expressed as

$$V_i = \frac{1}{\beta G_i}, \quad i = 1, 2 \quad (3.6)$$

Substituting Eq. 3.4 into Eq. 3.2, we obtain the following expression:

$$\alpha = \frac{KA}{\mu L} \cdot (G_1 + G_2) \quad (3.7)$$

Therefore, the resultant expression for K is

$$K = \frac{\mu L \alpha}{(G_1 + G_2) A} \quad (3.8)$$

After obtaining the gradient α (s^{-1}) from the time- $\ln\Delta P$ curve (Fig. 3.1b), the permeability was calculated from Eq. 3.6.

3.1.6 Micro- and macrostructure analysis

Same as section 2.1.6

3.2 Results

3.2.1 Effect of confining pressure [Alam et al., 2014(d)]

3.2.1.1 Deformation and permeability

This rock exhibited brittle behavior under low confining pressure (1–7 MPa) (Fig. 3.2a). The magnitude of the stress drop due to failure decreased at $P_c = 9$ –11 MPa, and almost perfect plastic behavior was observed at $P_c = 13$ –15 MPa (Fig. 3.2a). The peak and residual strength increased (Fig. 3.2b) and Poisson's ratio decreased with increasing confining pressure, but no clear relationship was observed for the tangent modulus (Fig. 3.2c).

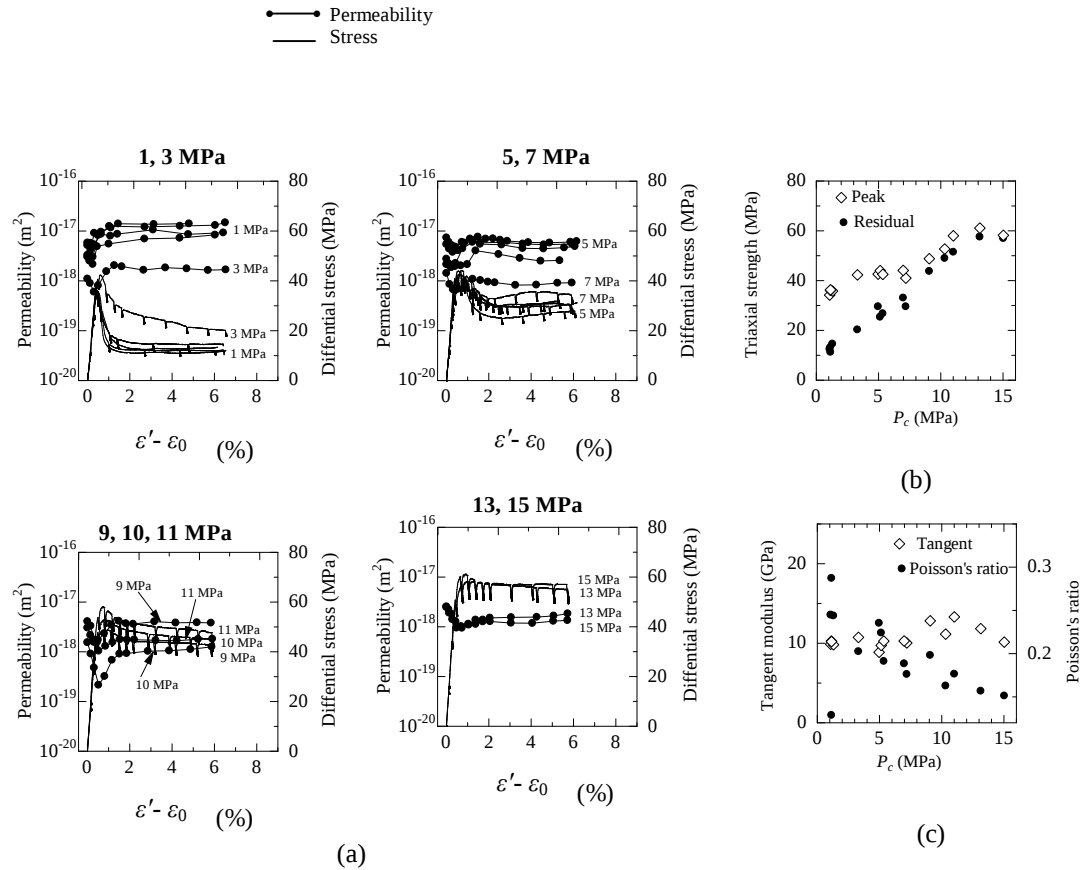


Fig. 3.2 Stress-strain, permeability relationship and mechanical properties of Kimachi sandstone. (a) Stress, axial strain and permeability relationship. (b) Peak differential stress, residual strength with confining pressure. (c) Tangent modulus and Poisson's ratio with confining pressure. [Alam et al., 2014(d)]

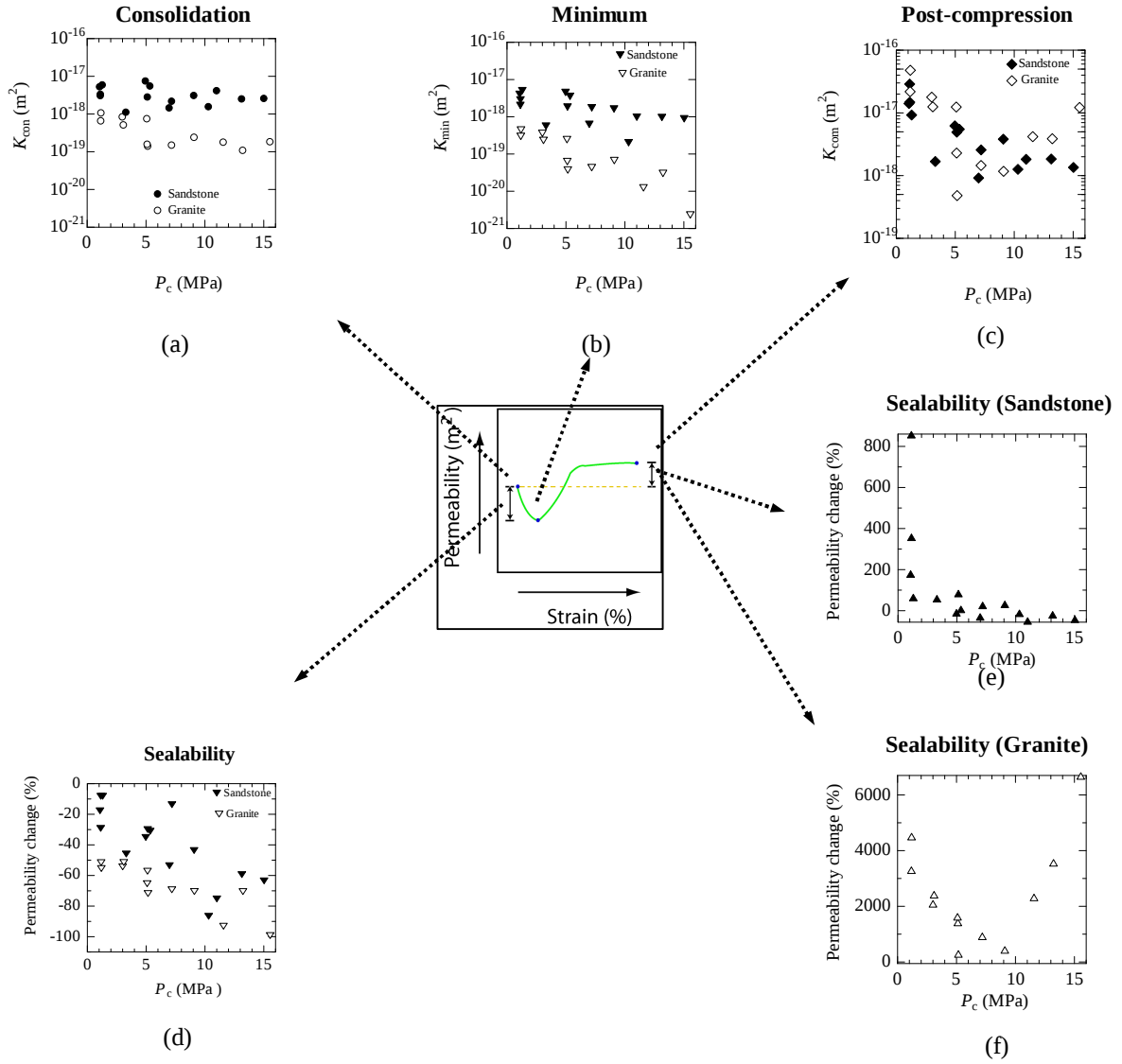


Fig. 3.3 Confining pressure effect on the permeability change of Kimachi sandstone and Inada granite. (a) Permeability after consolidation. (b) Minimum permeability. (c) Permeability after axial compression. (d) Permeability decrease from consolidation to the minimum value. (e) Permeability change from consolidation to post-compression. [Alam et al., 2014(d)]

The permeability at $P_c \geq 7$ MPa after 24 h of consolidation was slightly lower than that at $P_c \leq 5$ MPa (Fig. 3.3a). The permeability began to decrease in the initial stage of the axial compression and reached a minimum before the peak stress, but it then began to increase and reached an almost stable value at the residual strength state (Fig. 3.2a). The minimum value of the permeability at and after $P_c = 7$ MPa was less than that at $P_c \leq 5$ MPa (Fig. 3.3b). After compression, the permeability decreased with increasing

confining pressure (Fig. 3.3c).

By expressing the decrease ratio of permeability K_{change} from consolidation (K_{con}) to minima (K_{min}) by the equation

$$K_{\text{change}} = \frac{K_{\text{min}} - K_{\text{con}}}{K_{\text{con}}} \times 100 \quad (3.9)$$

It was found that K_{change} decreased with increasing confining pressure (Fig. 3.3d). In addition, the permeability increased from consolidation to the post-compression state (see Eq. 8) at $P_c = 1$ MPa, had almost the same values at $P_c = 5-9$ MPa, and decreased at $P_c = 10-15$ MPa (Fig. 3.3e).

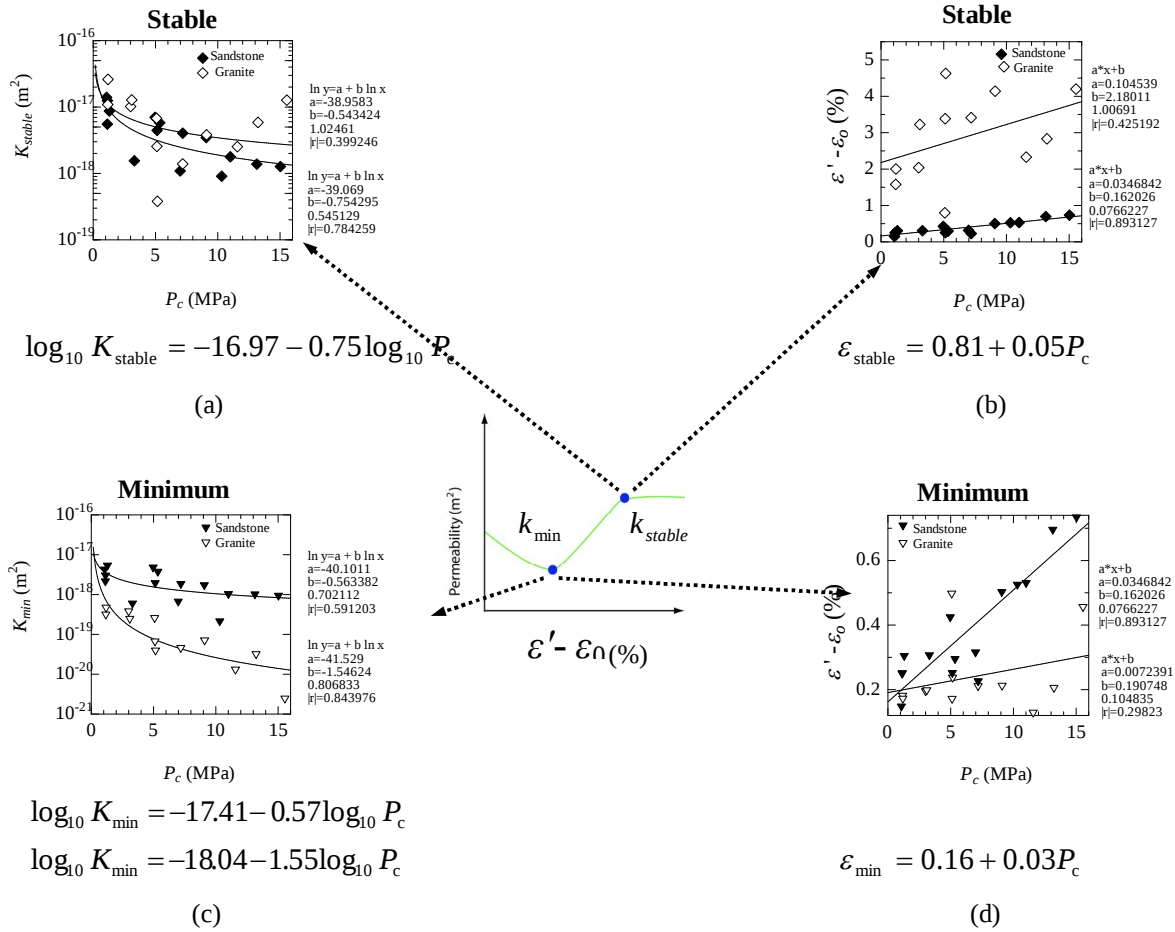


Fig. 3.4 Confining pressure dependency of minimum and stable permeability in relation to axial stain for Kimachi sandstone (KS) and Inada granite (IG). (a) Stable permeability and confining pressure. (b) Axial strain at stable permeability and confining pressure. (c) Minimum permeability and confining pressure. (d) Axial strain at minimum permeability and confining pressure. [Alam et al., 2014(d)]

The effect of confining pressure on the minimum and stable permeability values with respect to axial strain was evaluated by the following equations (Fig. 3.4):

$$\log K_{\min} = -17.41 - 0.57 \log P_c \quad (3.10)$$

$$\varepsilon_{\min} = 0.16 + 0.03 P_c \quad (3.11)$$

$$\log K_{\text{stable}} = -16.97 - 0.75 \log P_c \quad (3.12)$$

$$\varepsilon_{\text{stable}} = 0.81 + 0.05 P_c \quad (3.13)$$

where K is in m^2 , P_c is in MPa, and ε is in %.

The specimen diameter decreased due to confining pressure, but recovered under axial compression to its value under atmospheric pressure at σ_L (Fig. 3.5a). The permeability became lowest around this point, but began to increase afterward. A similar phenomenon for residual strength was reported by Fujii et al. [Fujii et al., 1999], which was confirmed and is almost the same as that for σ_L (Fig. 3.5b).

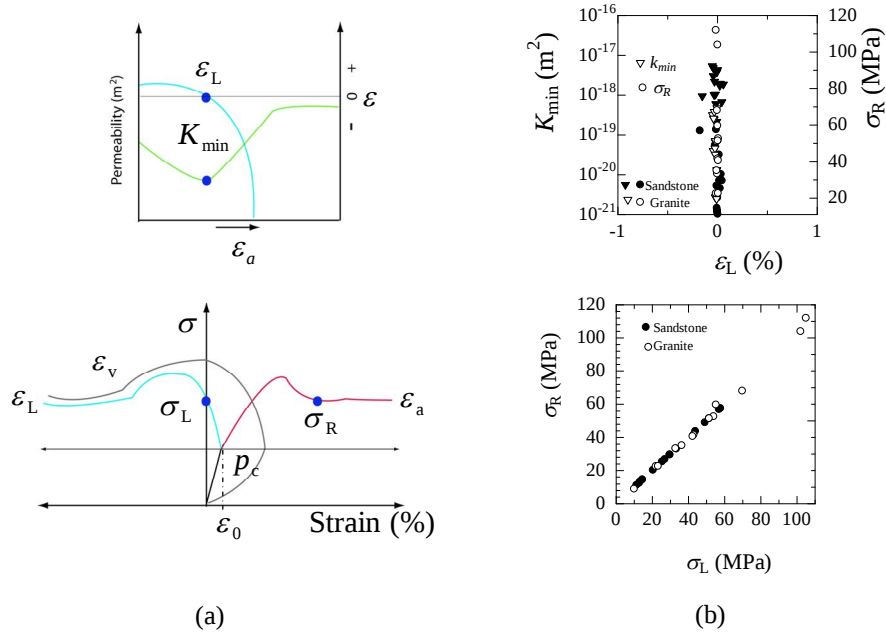


Fig. 3.5 Relationship between permeability, lateral strain, residual strength, and stress at zero lateral strain.

(a) Schematic diagram showing the point of lateral strain at minimum permeability (ε_L , $K_{\min}$) and σ_L ; σ_R is the stress at the lateral strain of residual strength. (b) The experimental results of the ε_L , $K_{\min}$ and σ_L , σ_R .

[Alam et al., 2014(d)]

3.2.1.2 Micro- and macrostructures

From the blue resin-impregnated thin-section analysis, the 0.39-mm average thickness of cementing materials in the case of consolidation at 1 MPa was much thicker than the 0.25-mm average at 15 MPa (Fig. 3.6).

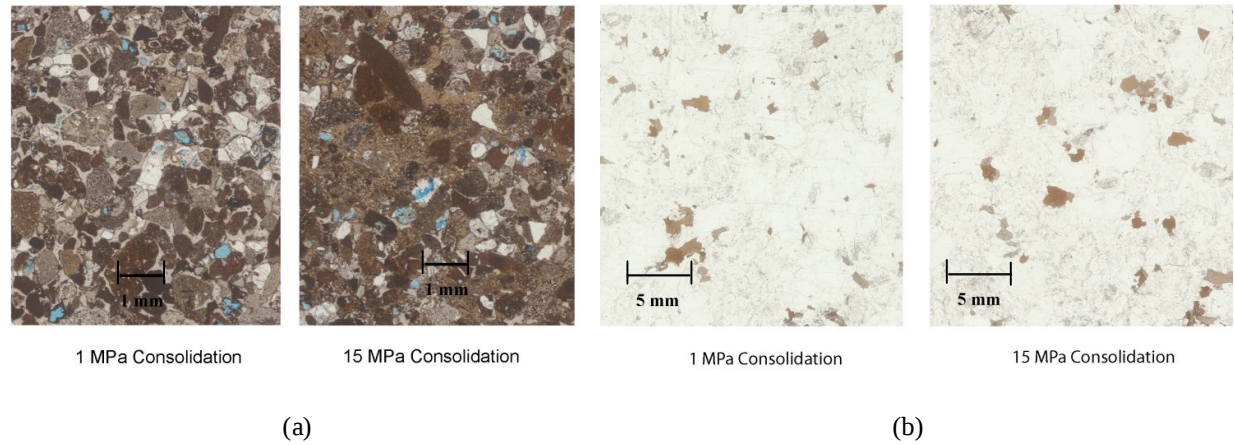


Fig. 3.6. Blue resin-impregnated thin-section images and analysis of the specimen after experiments with the Kimachi sandstone and Inada granite under consolidation. (a) Kimachi sandstone. (b) Inada granite. [Alam et al., 2014(d), 2013(b)]

From the CT observations, a distinct main rupture plane was observed in the X-Z plane of the specimen after axial compression at $P_c = 1$ MPa (Fig. 3.7a and d). Several subrupture planes were discovered in the Y-Z and X-Y planes (Fig. 3.7b) and the average thickness of cementing materials was 0.27 mm under this confining pressure. At $P_c = 7$ MPa, only one main rupture plane was found in the X-Z and Y-Z planes (Fig. 3.7b). At $P_c = 15$ MPa, no macroscopic rupture planes were observed in either the CT images (Fig. 3.7c) or the blue resin-impregnated thin section (Fig. 3.7e). Under this confining pressure the thickness of the cementing materials was 0.20 mm.

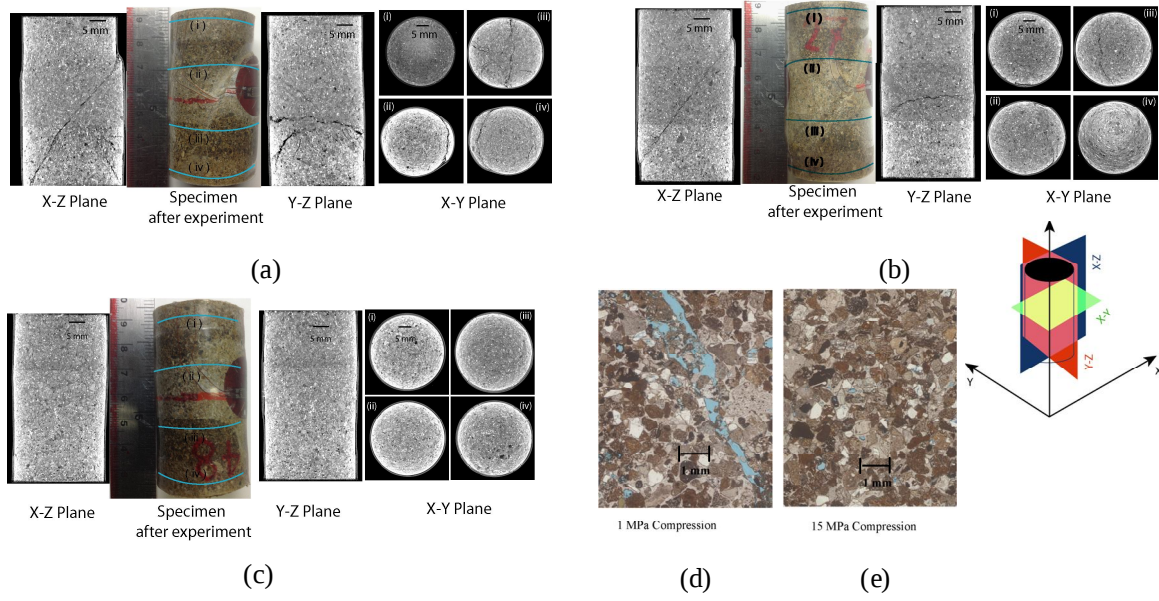


Fig. 3.7 Specimen, CT images, and blue resin-impregnated thin-section images of the specimens after axial compression of Kimachi sandstone. Specimen and CT images at (a) 1 MPa, (b) 7 MPa, and (c) 15 MPa. Blue resin-impregnated thin-section image at (d) 1 MPa and (e) 15 MPa. The loading direction is vertical. [Alam et al., 2014(d), 2013(b)]

3.2.2 Effect of temperature-confining pressure coupling [Alam et al., 2014(c)]

3.2.2.1 Deformation and Permeability

The permeability during deformation and failure at 353 K as well as at 295 K first decreased, then began to increase before the peak stress, and nearly stabilized in the residual strength state (Fig. 3.8a). The peak and residual strengths at 353 K were slightly lower than those at 295 K (Fig. 3.8b and c). No significant influences were observed in the tangent modulus (Fig. 3.8c).

After 24-hour consolidation, the permeability at 353 K was slightly lower than at 295 K under $CP \geq 5$ MPa (Fig. 3.9a).

Under compression, the minimum permeability decreased with the confining pressure, and no obvious difference was apparent between 295 and 353 K (Fig. 3.9b). The flow velocity was slightly higher at 353 K (Fig. 3.9c). The post-compression permeability decreased with the confining pressure, and the permeability at 353 K was slightly lower (Fig. 3.9d), but the flow velocity at 353 K was slightly higher (Fig.

3.9e). At 295 K, the permeability became higher for failure under low confining pressure, and the permeability change (Eq. 2.8) was as high as 179.0%. The permeability change showed a permeability decrease under high confining pressure by as much as -47.0%. The permeability however decreased at 353 K except for 1 MPa CP. The amount of the decrease was almost the same as that at 295 K (Fig. 3.9f).

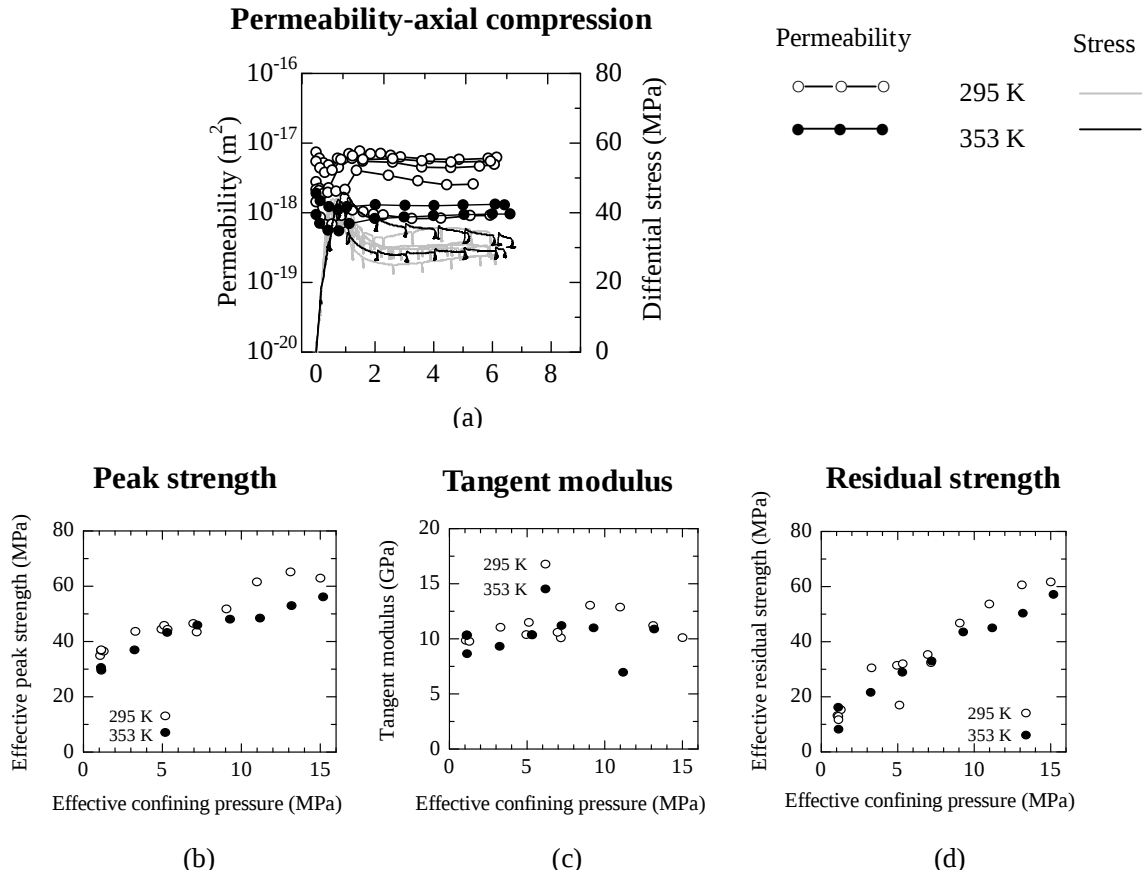


Fig. 3.8 Effects of deformation and failure on permeability change, and mechanical properties of the rocks. [Alam et al., 2014(c)]

3.2.2.2 Critical strains

The Critical compressive strain (CCS) under 353 K was larger than that under 295 K (Fig. 3.10). There was no influence of temperature on critical extensile stain (CES).

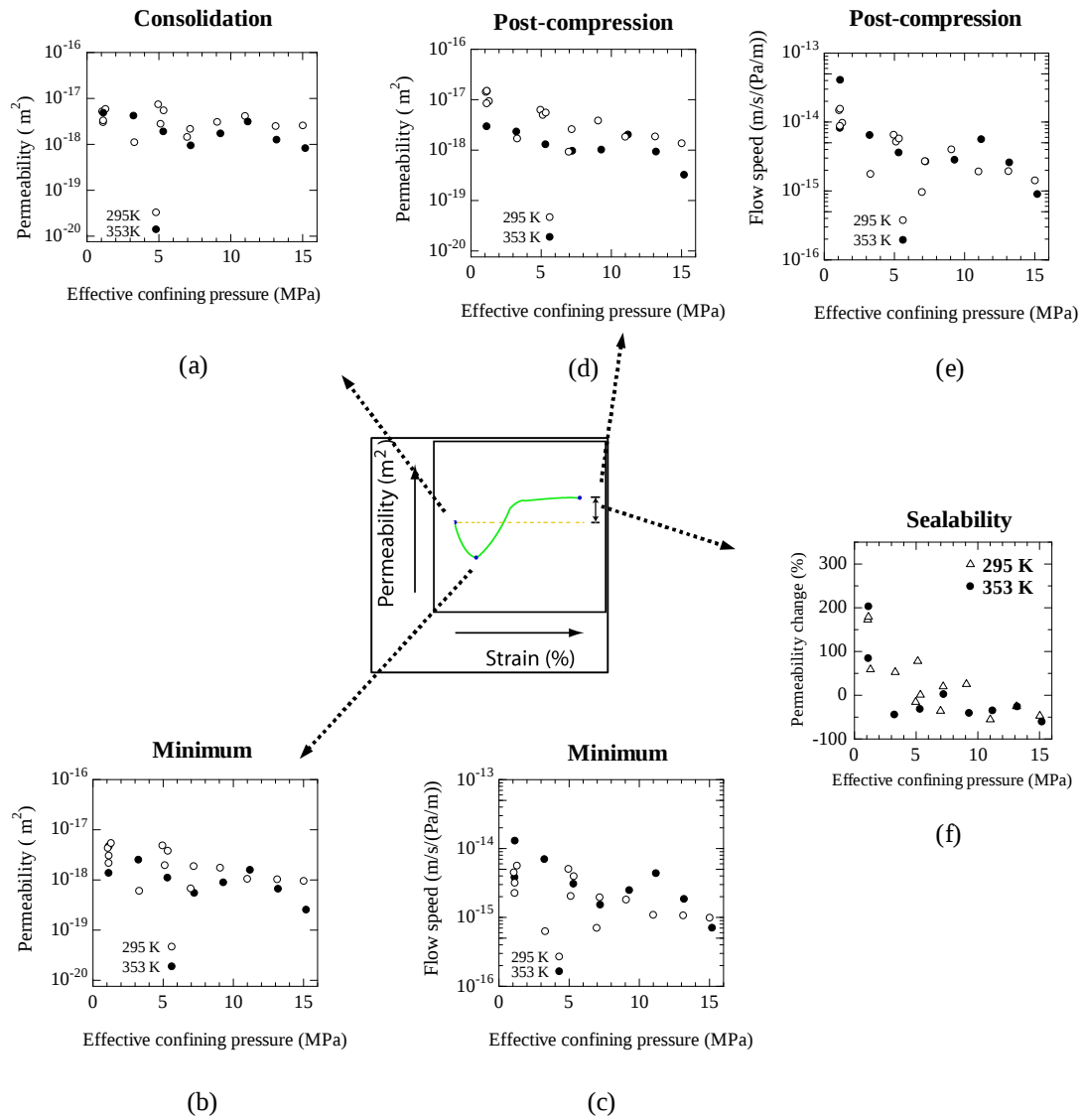


Fig. 3.9 Pre, minimum and post-compression permeability and flow velocity per unit pore pressure gradient, and permeability change. [Alam et al., 2014(c), 2014(a)]

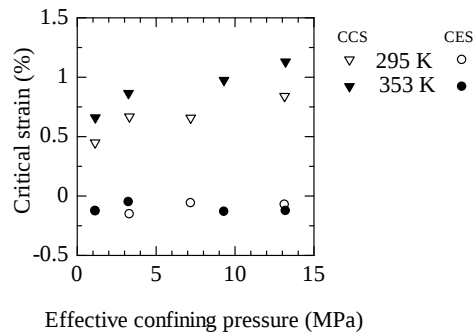


Fig. 3.10 Critical strain of Kimachi sandstone. Critical compressive strain (CCS), Critical extensile strain (CES).

3.2.2.3 Micro- and macro structures

In consolidation, the thickness of the cementing materials (Fig. 3.11a) decreased due to both the confining pressure and temperature (Fig. 3.11b).

After compression, main and sub-rupture planes occurred as well as several fractures in the CT image for 1 MPa CP at 295 K (Fig. 3.12a), whereas one main rupture plane and one sub-rupture plane appeared under 1 MPa CP at 353 K (Fig. 3.12b). The average thickness of the cementing material was around 0.20 mm at both temperatures (Fig. 3.12h). There were two rupture planes under 3 MPa CP at 295 K (Fig. 3.12c). On the other hand, only one rupture plane was observed for both cases at 353 K (Fig. 3.12d). The rupture planes were absent for the 15 MPa CP cases (Fig. 3.12e and f). The thickness of cementing materials was around 0.15 mm.

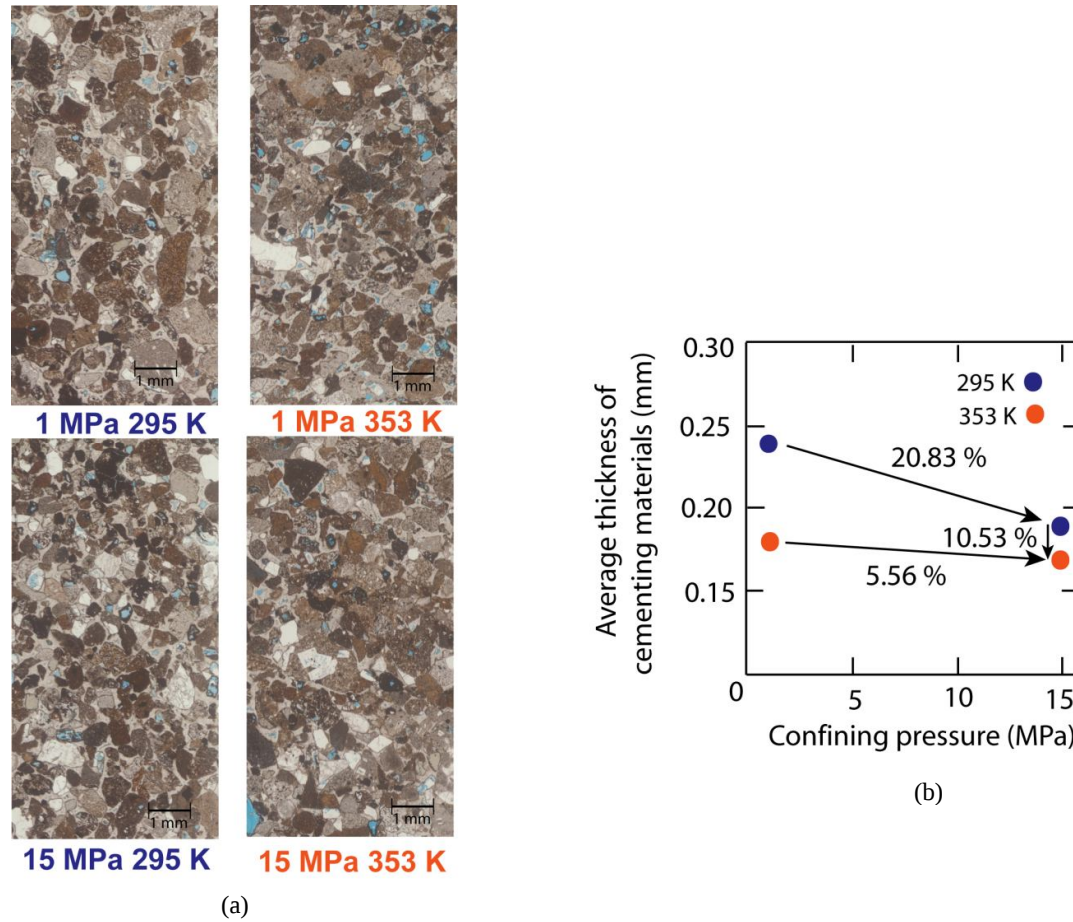


Fig. 3.11 Thin-section images and thickness of cementing material for 24-hour consolidated specimens of Kimachi sandstone. [Alam et al., 2014(c)]

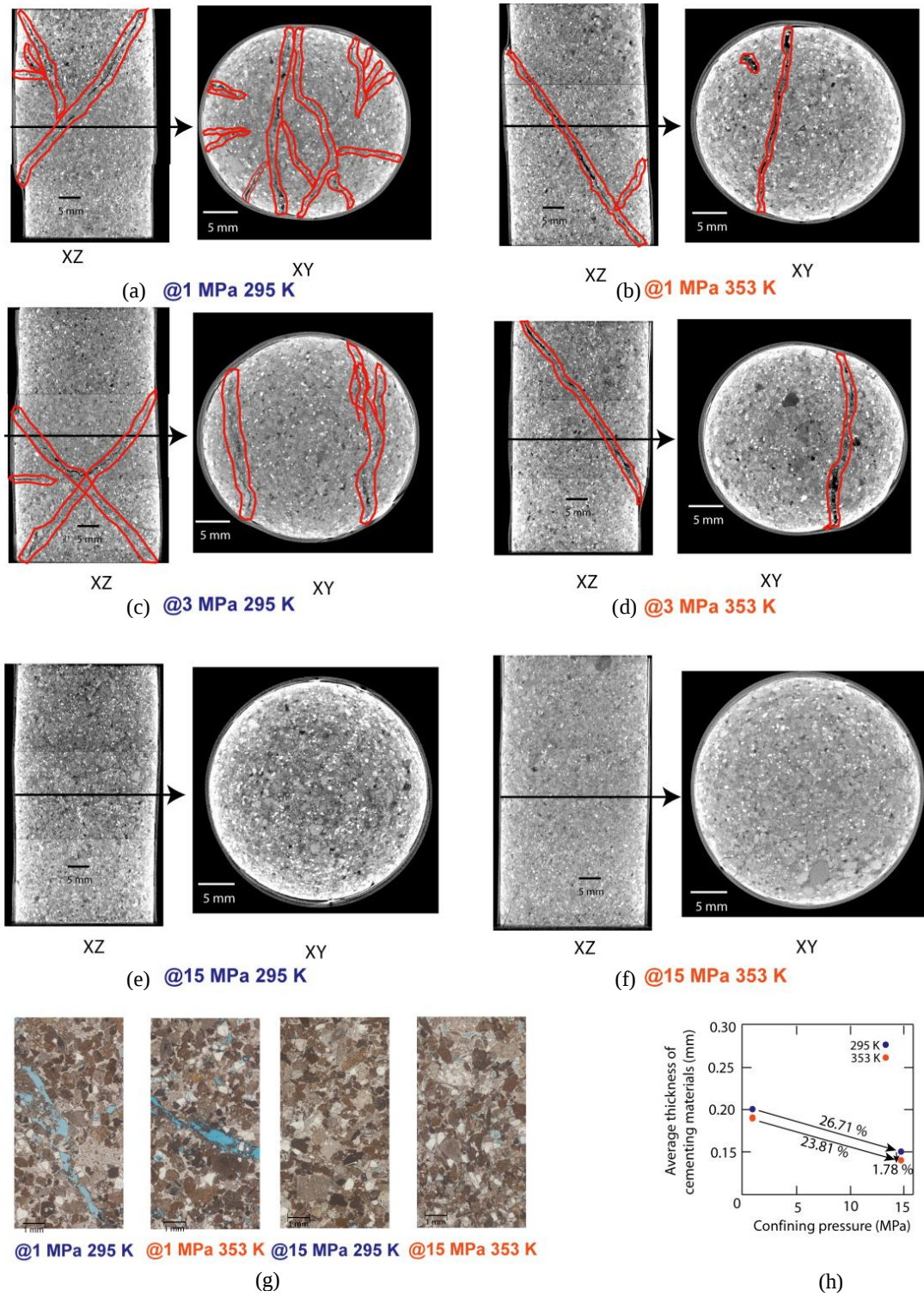


Fig. 3.12 CT and thin-section images for post-compression specimens of Kimachi sandstone. (Red and blue areas in the images represent fractured zones). [Alam et al., 2014(c)]

4. Experiment on Inada granite

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4.1 Materials and Method

The Inada granite was sampled in Ibaraki, Japan. The composition of the rock was mainly quartz, feldspar, biotite, and allanite, with zircon, apatite, and ilmenite as accessory minerals. The grain sizes of the minerals were 3.0–4.0 mm (on average) for quartz, approximately 2.0–3.0 mm for plagioclase, approximately 2.0–4.0 mm for alkali feldspar, and generally less than 1.0 mm for biotite [Lin & Takahashi 2008]. The physical properties of the rock are listed in Table 3.

Table 3: Physical properties of the Inada granite shown as “average value (number of specimen) $\pm$ standard deviation”. UCS: Uniaxial Compressive Strength. [Alam et al., 2014(d)]

V_p of specimen (km/s)	V_s of specimen (km/s)	Dry density (g/cm ³)	Effective porosity (%)	UCS (saturated) (MPa)
2.87 (17) $\pm$	2.09 (17)	2.70 (17) $\pm$	0.584 (17)	180.9 (2)
0.07	± 0.06	0.01	± 0.023	± 16.9

Experimental method (Specimen and sample preparation; Experimental setup; Experimental procedure; Effective confining pressure, differential stress, and strain correction; Measurement of permeability; Micro- and macrostructure analysis) was the same as Chapter 3.1.

4.2 Results

4.2.1 Effect of confining pressure [Alam et al., 2014(d)]

4.2.1.1 Deformation and permeability

This rock exhibited brittle failure for all of the confining pressure values considered (Fig. 4.1a). The peak and residual strength increased slightly with the confining pressure (Fig. 4.1b). The tangent modulus and Poisson’s ratio seemed to decrease slightly (Fig. 4.1c), but no clear relationship was observed. The reason for the lack of a clear relationship between the mechanical properties and confining pressure was the relatively low confining pressure values compared to the strength of the rock.

After 24 h of consolidation, the permeability at $P_c \geq 5$ MPa was slightly lower than it was at $P_c \leq 3$ MPa (Fig. 3.3a). The permeability began to decrease at the initial stage of axial loading, and reached a

minimum before the peak stress. The permeability then began to increase and reached an almost stable value at the residual strength state (Fig. 4.1a). This tendency was the same as that observed in the case of the Kimachi sandstone.

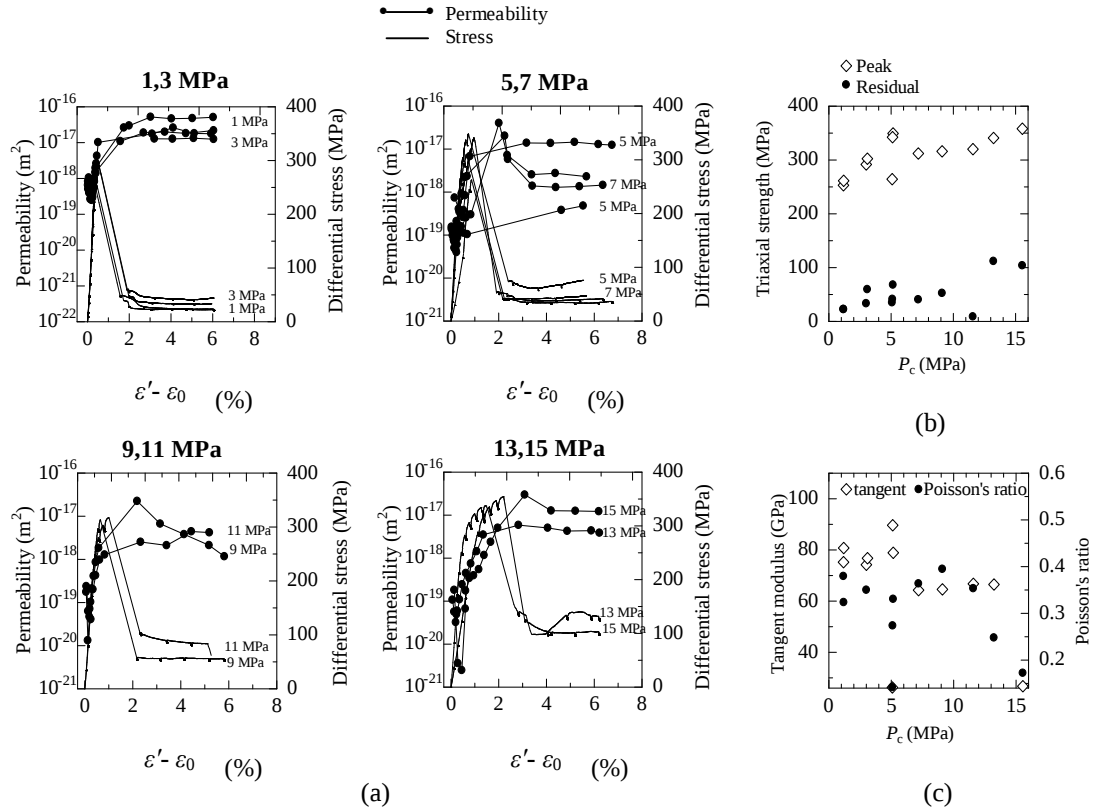


Fig. 4.1 Stress Stress-strain, permeability relationship and mechanical properties of Inada granite. (a) Stress, axial strain and permeability relationship (b) Peak differential stress, residual strength with confining pressure. (c) Tangent modulus and Poisson's ratio with confining pressure. [Alam et al., 2014(d)]

The minimum value at $P_c = 3$ MPa was less than it was at $P_c \leq 3$ MPa (Fig. 3.3b). The minimum permeability after compression did not follow the axial strain–confining pressure relationship observed for the Kimachi sandstone. The relationship between the minimum permeability value ($K_{\min}$) and confining pressure (P_c) (Fig. 3.4c) was clearly described by the following equation:

$$\log K_{\min} = -18.04 - 1.55 \log P_c \quad (4.1)$$

The permeability was greater after compression than it was after consolidation, but the increase ratio

decreased with increasing confining pressure up to $P_c = 9$ MPa. The ratio began to increase again at $P_c = 11\text{--}15$ MPa (Fig. 3.3f). The permeability was lowest when the lateral strain was around zero (Fig. 3.5), as was observed for the Kimachi sandstone. The residual strength was almost the same as σ_L (Fig. 3.5b), as stated by Fujii et al. [Fujii et al., 1999].

5.2 Micro- and macrostructures

No consolidation effect was observed from the blue resin-impregnated thin-section analysis of the granite (Fig. 3.6b).

From the CT observations, a main rupture plane in the X-Z plane, with subrupture planes in the Y-Z plane, was observed at $P_c = 1$ MPa (Fig. 4.2a). The main rupture plane consisted of a network of microcracks (Fig. 4.2d). Numerous axial cracks from biotite grains were also observed. As described in detail by Nishiyama et al. [Nishiyama et al., 2002], this type of microcracking was induced because biotite is softer than quartz or plagioclase. The distinct single rupture plane in the CT image (Fig. 4.2b) was also observed in the thin section at $P_c = 9$ MPa (Fig. 4.2e). This rupture plane also consisted of a network of microcracks; however, it had a smaller width than that at $P_c = 1$ MPa, and axial cracks from biotite were not observed. Multiple rupture planes were observed at $P_c = 15$ MPa (Fig. 4.2c).

4.2.2 Effect of temperature-confining pressure coupling [Alam et al., 2014(c)]

4.2.2.1 Deformation and Permeability

The peak and residual strengths at 353 K were almost identical to those at 295 K (Fig. 4.3b and d). The tangent modulus at 353 K was slightly lower than at 295 K (Fig. 4.3c).

After 24 h consolidation, decrease in the permeability was most obvious for Inada granite and the permeability at 353 K was lower than at 295 K (Fig. 4.4a). The permeability during deformation and failure at 353 K, as well as at 295 K, behaved in a similar manner to that of Kimachi sandstone (Fig. 4.3). The minimum permeability decreased with the confining pressure, both at 295 and 353 K, but the permeability at 353 K was lower than at 295 K (Fig. 4.4b). The flow velocity at 353 K was almost the same as those at 295 K (Fig. 4.4c). The post-compression permeability decreased with the confining pressure up to 7 MPa CP at 353 K or 9 MPa CP at 295 K, and afterward it increased again. The permeability (Fig. 4.4d) and flow velocity (Fig. 4.4e) 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%

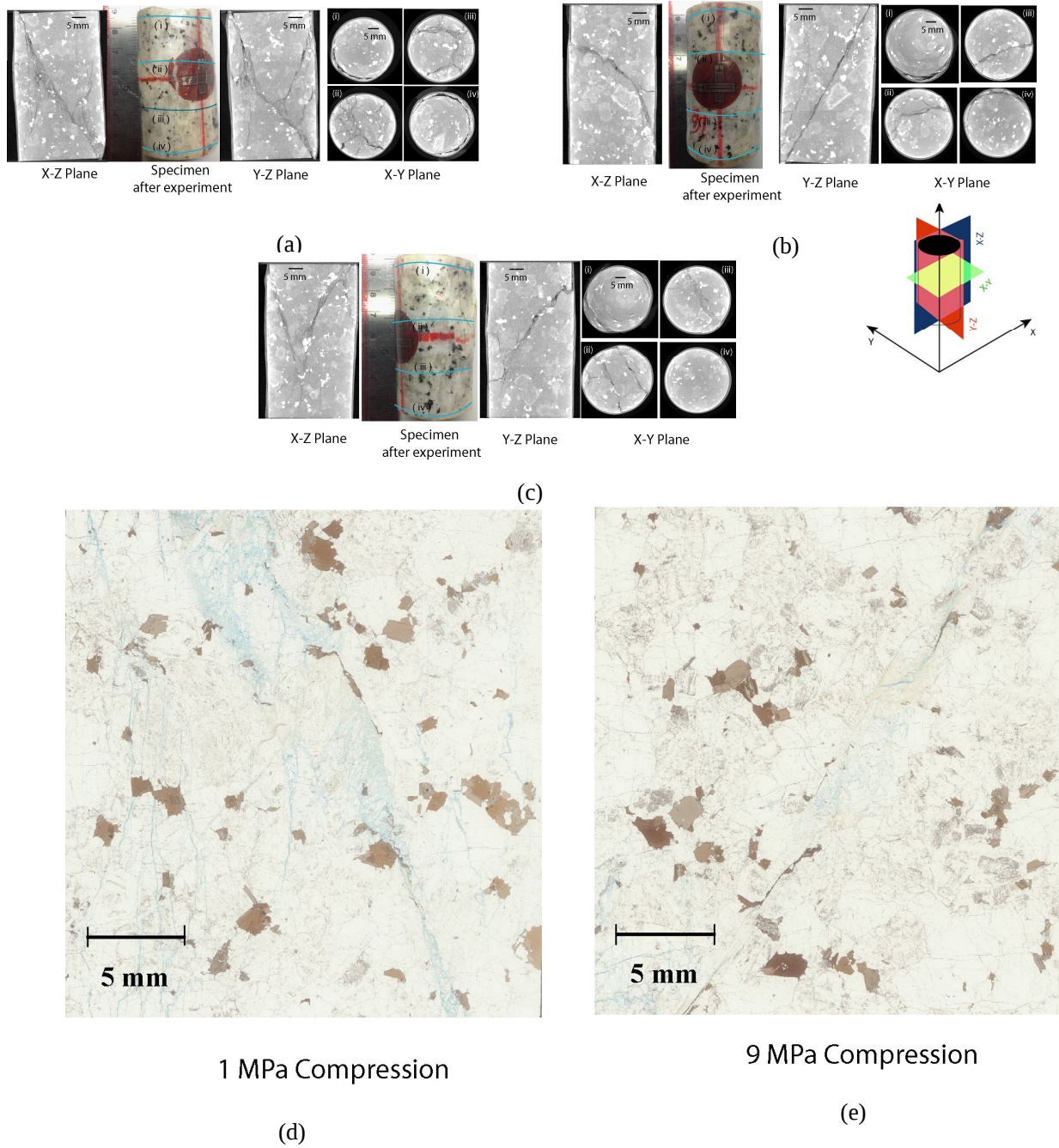


Fig. 4.2 Specimen, CT images, and blue resin-impregnated thin-section images of the specimens after axial compression of Inada granite. Specimen and CT images at (a) 1 MPa, (b) 7 MPa, and (c) 15 MPa. Blue resin-impregnated thin-section image at (d) 1 MPa and (e) 9 MPa. The loading direction is vertical. [Alam et al., 2014(d), 2013(b)]

with confining pressure until it attained 9 MPa CP, and increased again up 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 as small as the smallest increase at 295 K (Fig. 4.4f).

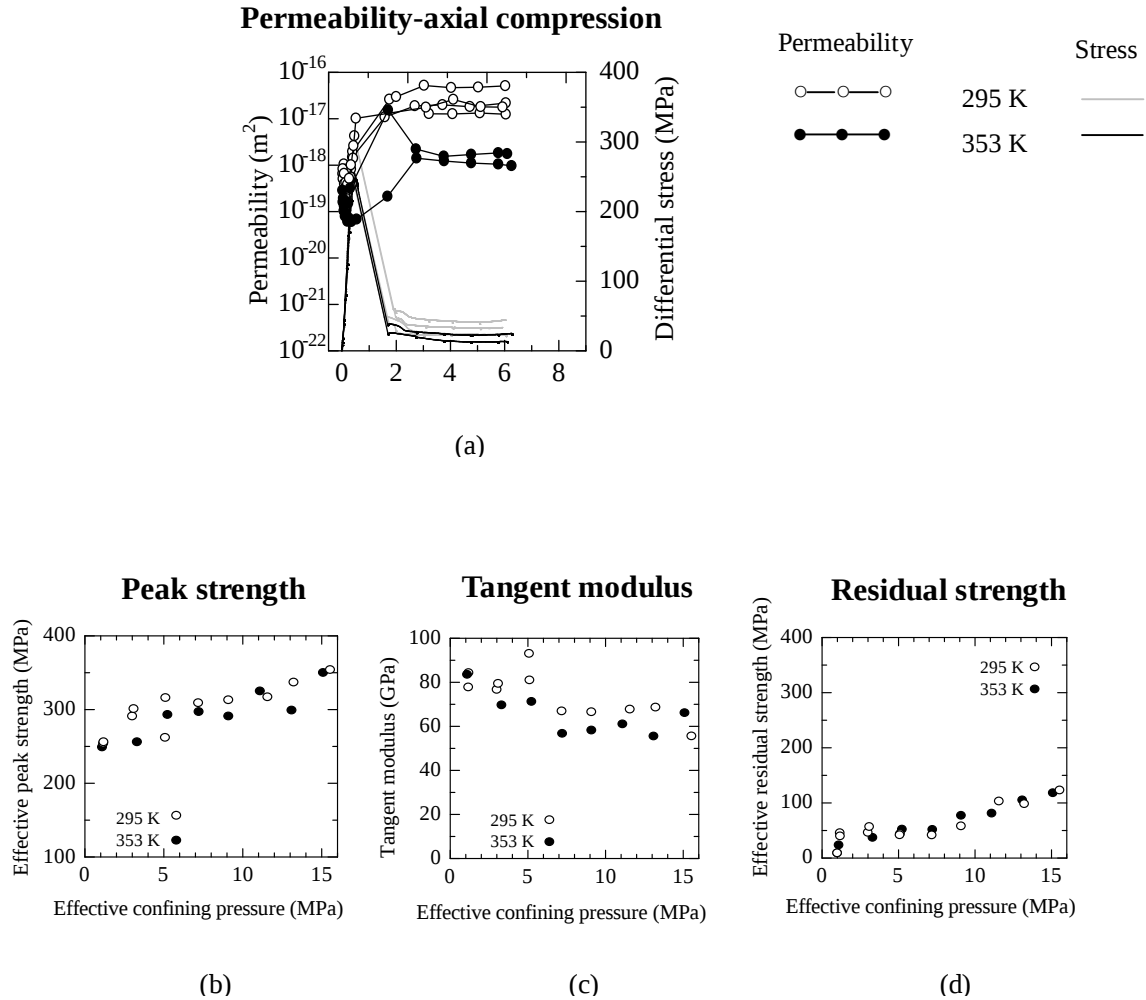


Fig. 4.3 Effects of deformation and failure on permeability change, and mechanical properties of the rocks.

[Alam et al., 2014(c)]

4.2.2.2 Critical strains

The Critical compressive strain (CCS) under 353 K was larger than that under 295 K (Fig. 4.5). There was no influence of temperature on critical extensile stain (CES).

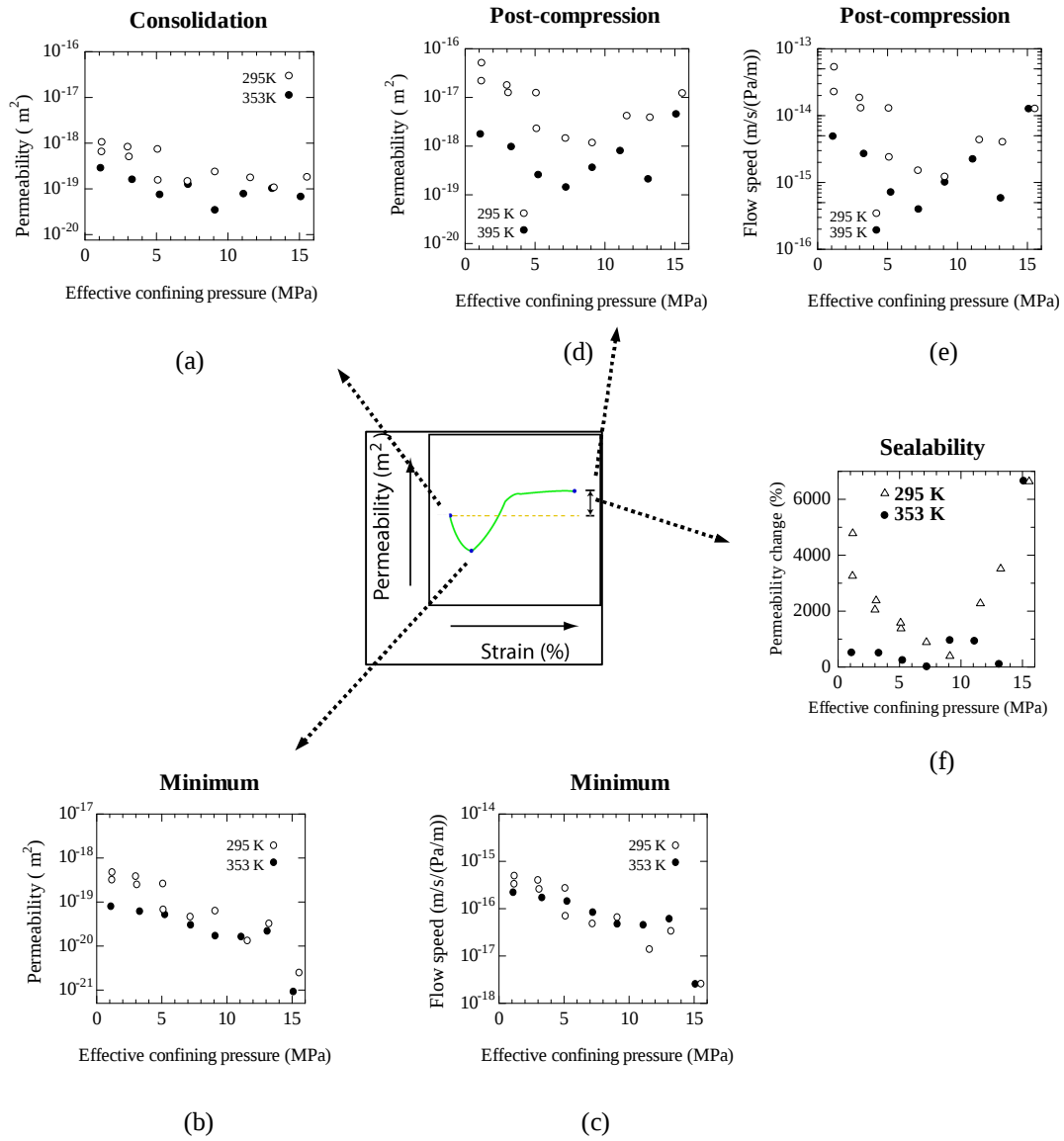


Fig. 4.4 Pre, minimum and post-compression permeability and flow velocity per unit pore pressure gradient, and permeability change. [Alam et al., 2014(c), 2014(a)]

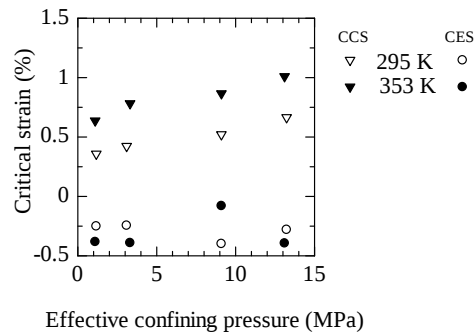


Fig. 4.5 Critical strain of Inada granite. Critical compressive strain (CCS), Critical extensile strain (CES).

4.2.2.3 *Micro- and macrostructures*

For Inada granite, no effects were observed with changes in either the confining pressure or temperature on pre-compression specimen. One distinct, thick main rupture plane appeared with many sub-rupture planes and fractures in the CT image for 1 MPa CP at 295 K (Fig. 4.6a). The rupture plane comprised the network of microcracks observed in the thin-section image, and axial cracks that had propagated from biotite were observed (Fig. 4.6c). One main thin rupture plane was formed under 7 MPa CP without axial cracks from biotite (Fig. 4.6f) at 295 K. In the cases of 1 and 7 MPa CP at 353 K (Fig. 4.6b and g), one main thin rupture plane and one sub-rupture plane were observed with elongated biotite grains along rupture planes in the thin-section images (Fig. 4.6d and e). For 15 MPa CP, two main rupture planes formed at 295 K (Fig. 4.6h). On the other hand, one rupture plane with sub-rupture planes and many fractures appeared at 353 K (Fig. 4.6i).

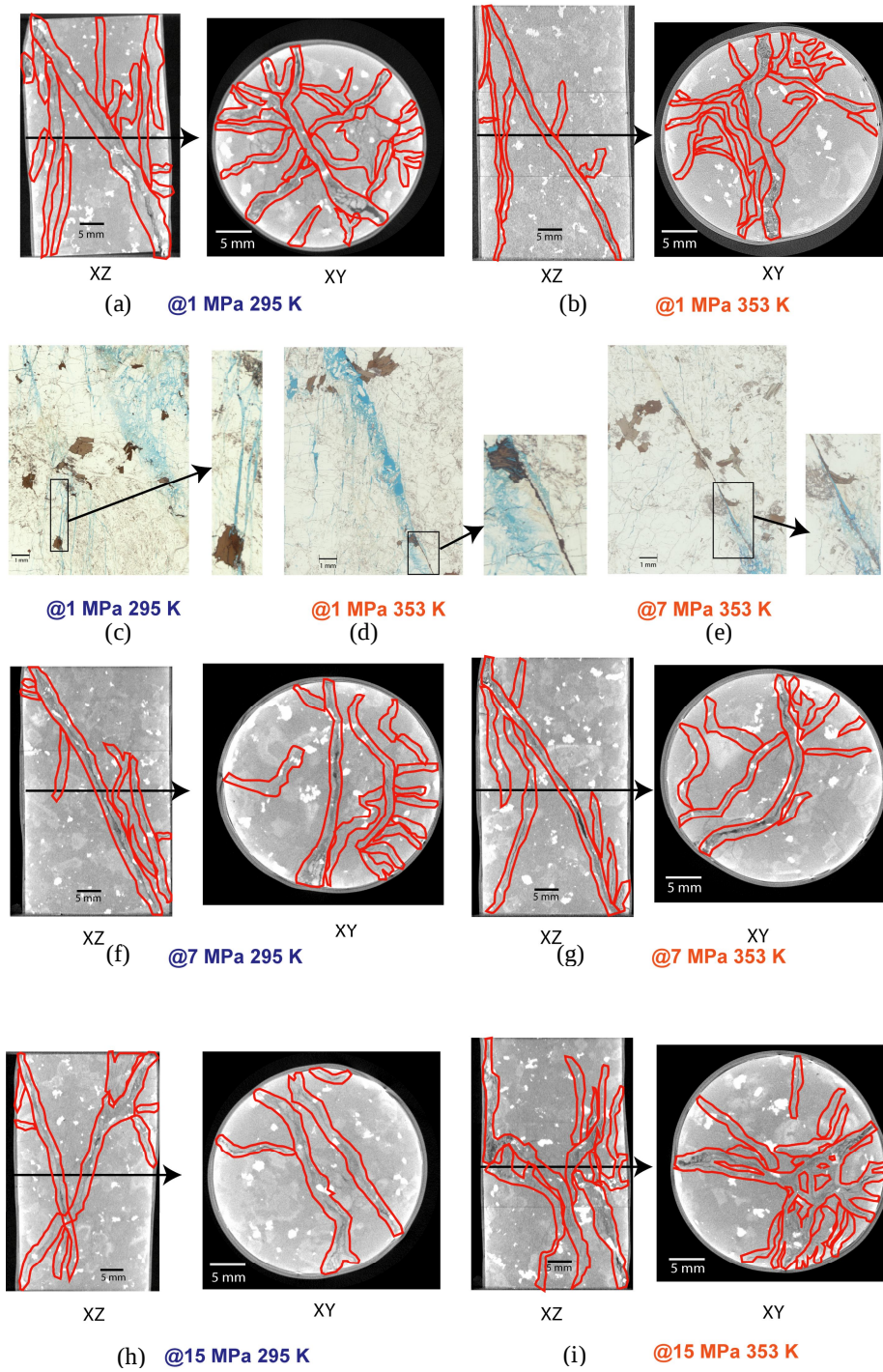


Fig. 4.6 CT and thin-section images for post-compression specimens of Inada granite. (Red and blue areas in the images represent fractured zones). [Alam et al., 2014(c)]

5. Discussions

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5.1 Effect of confining pressure

5.1.1 Mechanisms of permeability change by consolidation

For consolidation under a confining pressure of 15 MPa, the permeability was the lowest in the Shikotsu welded tuff. This occurred because the confining pressure was close to the unconfined compressive strength (UCS) and was sufficiently high to cause pore collapse (Fig. 2.5a) [Zaman et al., 1994].

A decrease in the permeability due to consolidation was observed in sandstone. The main reason for the decrease was compaction because the cementing materials became thinner at $P_c = 15$ MPa (Fig. 3.6a).

A decrease in the permeability due to consolidation was also observed in granite. The main reason for the in the granite was elastic closure of microcracks; however, this was not observed in the thin sections because they were prepared after unloading (Fig. 3.6b).

5.1.2 Mechanisms of permeability change by failure

In case of Shikotsu welded tuff, pore collapse occurred during axial compression at even lower confining pressures and caused the permeability to decrease (Fig. 2.5). A decrease in the permeability under axial compression was also reported for Indiana limestone [Azeemuddin, M., et al., 1995], but the confining pressure effect has not been considered in the literature. At a confining pressure of 1 MPa, the permeability did not decrease significantly in the residual strength state (Fig. 2.4a) because of the rupture plane formation (Fig. 5.1). In the residual strength state (Fig. 5.1), the rupture plane and the higher-porosity rock matrix near the plane (Fig. 2.7f) were responsible for the relatively high and relatively stable permeability (Fig. 2.4a).

In case of sandstone, the permeability decreased at the initial stage of axial compression, increased after this stage, and finally reached an almost stable value in the residual strength state (Fig. 3.2a). Other researchers [Azeemuddin et al., 1995; Morita et al., 1992; Zhu & Wong, 1997; Heiland, 2003; Keaney et al., 1998] have also mentioned about this behavior under axial compression, but the confining pressure effect on the minimum permeability and the permeability in the residual strength state were not considered. The decrease in permeability (Figs. 3.2a, 5.2) was due to closure of microcracks under compression, as described in [Batzle et al, 1980]. In particular, the closure of inclined microcracks significantly affects permeability. The increase in permeability after the initial stage of axial compression (Figs. 3.2a) occurred because of the nucleation, growth, and coalescence of microcracks (Fig. 5.3a). This property under

compression was described in [Kranz, 1983]. The permeability increase began when the lateral strain started to exceed its value corresponding to the atmospheric pressure (Fig. 3.5). The increase in permeability around the peak load was due to the linking of locally dense microcracks (Fig. 5.3). This characteristic under compression was also described in [Kranz, 1983].

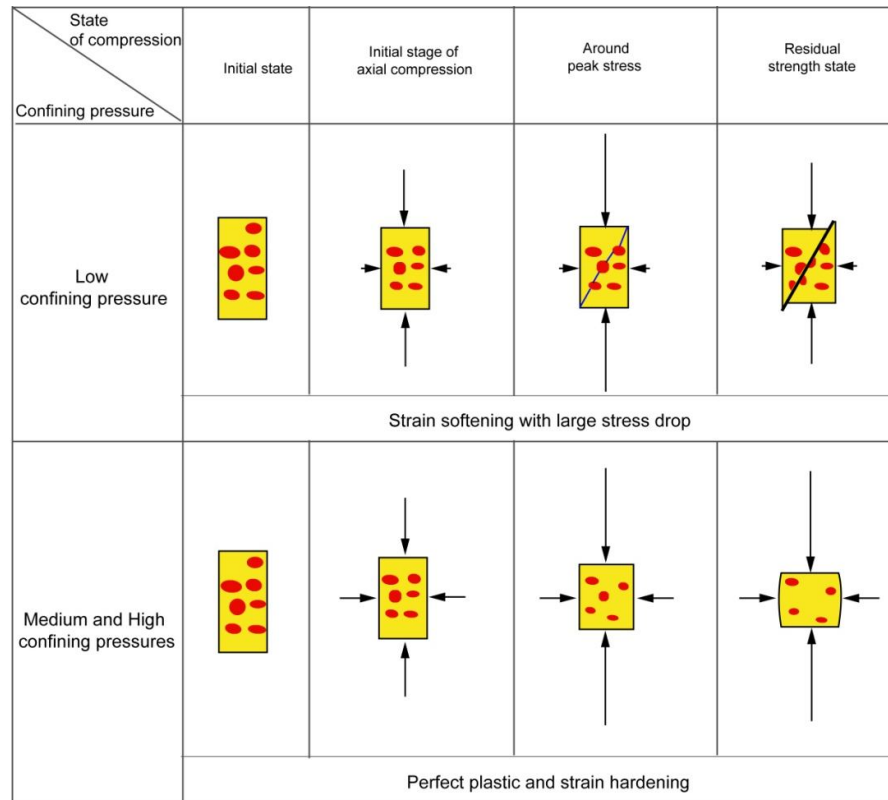


Figure 5.1 Confining pressure effects on structural changes of Shikotsu welded tuff. [Alam et al., 2014(b)]

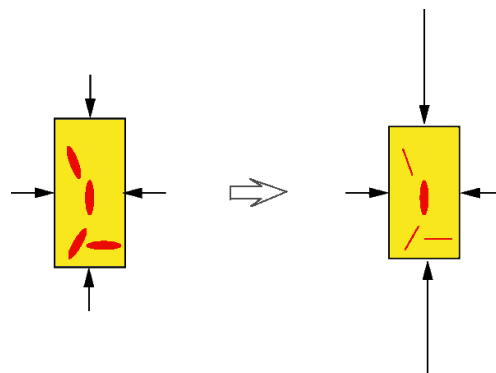


Fig. 5.2 Permeability decreased before peak stress due to closure of microcracks which are not parallel to the loading axis [Alam et al., 2013(a)].

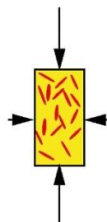
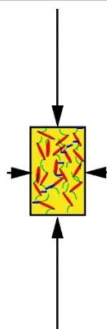
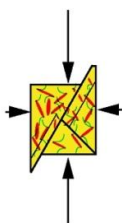
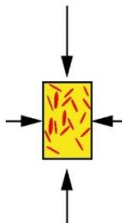
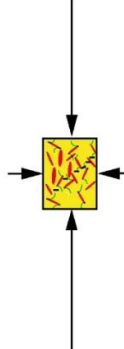
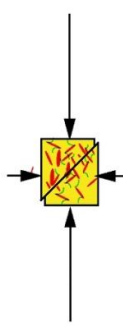
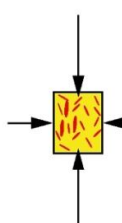
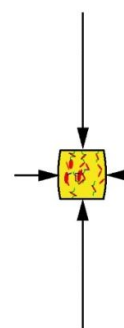
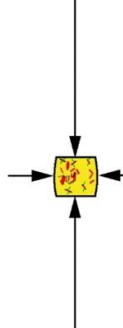
State of compression Confining pressure	Initial state	Initial stage of axial compression	Around peak stress	Residual strength state
Low confining pressure				
	Strain softening with large stress drop			
Medium confining pressure				
	Strain softening with small stress drop			
High confining pressure				
	Perfectly plastic			

Figure 5.3 Confining pressure effect on structural changes of Kimachi sandstone [Alam et al., 2014(b)].

The permeability became stable in the residual strength state (Figs. 3.2a). The stable permeability was attained at a certain axial strain, which depended on the confining pressure for sandstone (Fig. 3.4). Several rupture planes appeared under low confining pressures for sandstone and this was the reason for the increase in permeability following axial compression (Figs. 3.7a and 5.3). At a confining pressure of 5–7 MPa for the Kimachi sandstone (Fig. 3.7b), only a single rupture plane formed, causing the lower post-axial compression permeability. Almost perfectly elasto-plastic deformation was observed in the Kimachi sandstone under high confining pressure (Fig. 3.2a, 5.3), and rupture plane was absent (Fig. 3.7c). This occurred because large plastic deformation took place in the cementing materials (Fig. 3.7).

In case of the granite, the permeability decreased at the initial stage of axial compression, increased after this stage, and finally reached an almost stable value in the residual strength state like sandstone and the mechanism was the same. The permeability increase also began when the lateral strain started to exceed its value corresponding to the atmospheric pressure (Fig. 3.5) and the increase in permeability around the peak load was due to the linking of locally dense microcracks like sandstone (Fig. 5.4).

The permeability became stable in the residual strength state (Figs. 4.1a). The stable permeability was attained at a certain axial strain, which did not depend on the confining pressure for granite (Fig. 3.4). Several rupture planes and axial cracks from biotite appeared under low confining pressures for granite, and this was the reason for the increase in permeability following axial compression (Figs. 4.2a). At a confining pressure of 7 MPa for the Inada granite (Fig. 4.2b), only a single rupture plane formed, causing the lower post-axial compression permeability. The absence of microcracks from biotite [Alam et al., 2013(b)] is another reason for the permeability decrease in the Inada granite.

Under high confining pressure (≥ 12 MPa), in the case of Inada granite, subrupture planes occurred (Fig. 4.2 and 5.4), as was the case at the confining pressure of 1 MPa (Fig. 4.2a and c). Thus, the permeability after axial compression again increased. The subrupture planes formed because there were no soft cementing materials between mineral grains, so a large amount of plastic deformation could not occur. Because of that significant stress concentration occurred on the stiff and rough main rupture plane under these high confining pressures.

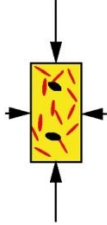
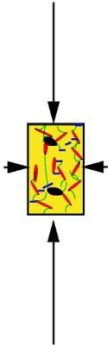
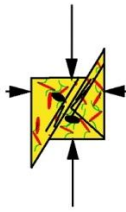
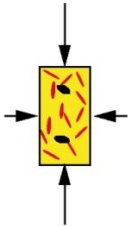
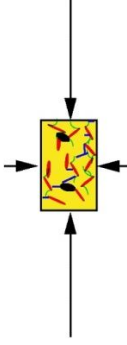
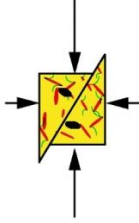
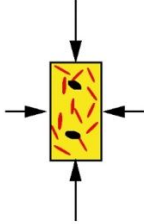
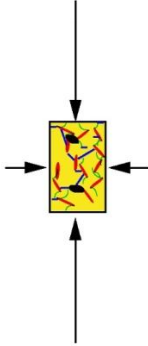
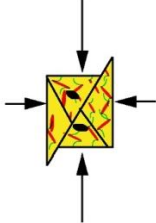
State of compression Confining pressure	Initial state	Initial stage of axial compression	Around peak stress	Residual strength state
Low confining pressure				
Medium confining pressure				
High confining pressure				

Figure 5.4 Confining pressure effect on structural changes of Inada granite [Alam et al., 2014(b)].

5.2 Effect of temperature-confining pressure coupling

5.2.1 Permeability change by consolidation

After 24-hr consolidation at the target confining pressure and temperature for Shikotsu welded tuff, the matrix permeability at 353 K was lower than at 295 K, and the permeability under 15 MPa CP at 353 K was the lowest (Fig. 2.9a). This happened because the pores became smaller and narrower by pore collapse [Zaman et al., 1994] enhanced by temperature-confining-pressure coupling as the small equivalent diameter and small aspect ratio became dominant (Fig. 2.10).

For Kimachi sandstone, the permeability after 24-hr consolidation under 15 MPa CP at 353 K was the lowest (Fig. 3.9a) because the thickness of the cementing materials was smaller by 10.53% compared to that under 15 MPa CP at 295 K (Fig. 3.11). The decrease in the cement thickness was caused by plastic deformation enhanced by temperature–confining-pressure coupling.

In the case of Inada granite, the permeability after 24-hr consolidation decreased with confining pressure, and the permeability at 353 K was lower than at 295 K (Fig. 4.4a). The decrease in permeability was due to the closure of inclined cracks because of elastic and viscous deformation enhanced by temperature–confining-pressure coupling. The elastic deformation, however, was not observed in the thin-section images because they were prepared after decompression.

5.2.2 Permeability change by failure

In the post-compression state, for Shikotsu welded tuff, the largest permeability decrease of 15 MPa CP at 295 K was achieved under 1 MPa CP at 353 K (Fig. 2.9d) due to the low matrix porosity (Fig. 2.11i). The main mechanism behind the above phenomenon was enhanced pore collapse by temperature–confining-pressure coupling [Alam et al., 2014(a)].

The post-compression permeability of Kimachi sandstone at 353 K (Fig. 3.9d) was slightly lower than at 295 K because of the relatively smaller thickness of cementing materials. The decrease in thickness was caused by plastic deformation that was enhanced mainly by confining pressure. For example, the greatest permeability decrease happened under 15 MPa CP at 353 K. The thickness of the cementing material was only 1.8% lower than that at 295 K, but it was 23.8% lower than that under 1 MPa CP at 353 K (Fig. 3.11h).

The post-compression permeability of Inada granite at 353 K was also lower than at 295 K (Fig. 4.4d). This was due to the decrease in the sub-rupture planes and fractures, excluding the axial cracks from

biotite (Fig. 4.6), because of the enhancement of viscous deformation of the unfailed mineral particles by thermal activation. The elongation of biotite particles along the rupture plane by the temperature–confining-pressure coupling (Fig. 4.6d and e) was another reason for the low permeability.

5.3 Sealability of an underground opening in a fractured rock mass

From these experimental results, change in sealability of an underground opening due to progress of EdZs and EDZs are estimated. Assumptions are as follows.

$$\begin{aligned} K_{\text{Rock mass}} &= K_{\text{Post-failure}} \\ K_{\text{EdZ}} &= K_{\text{Rock mass}} + \Delta K_{\text{EdZ}} \\ K_{\text{EDZ 1}} &= K_{\text{Rock mass}} + \Delta K_{\text{EDZ 1}} \\ K_{\text{EDZ 2}} &= K_{\text{Rock mass}} + \Delta K_{\text{EDZ 2}} \end{aligned}$$

and also

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

$$\begin{aligned} \text{Permeability} &= f_1(T) \\ \text{Viscosity} &= f_2(T) \end{aligned}$$

where ΔK_{EdZ} , ΔK_{EDZ1} and ΔK_{EDZ2} is the change in permeability before axial loading to the minima, to the post-failure under high confining pressure and under low confining pressure, respectively. The differences in scale and origin (e.g., joint sets are caused by tension), chemical process and thermal stresses are ignored for convenience.

For Shikotsu welded tuff, groundwater flow along fractures does not have to dominate. Permeability decreases and sealability improves with progress of EdZs and EDZs. At 353 K the sealability is better at shallow depth.

For Kimachi sandstone, groundwater flow along fractures dominates under low stress for openings at shallow depths. The sealability does not change if EdZs and EDZs are formed. On the other hand, groundwater flow along fractures does not have to dominate under high stress for openings at great depth. Permeability may increase in EDZ2 under a low support pressure around the opening, but may decrease in either EDZ1 or EdZs under relatively high confining pressure. Permeability in EDZ2 may slightly increase at 353 K, that is, the total sealability is slightly deteriorated.

For Inada granite, the groundwater flow along fractures dominates. Sealability is unchanged

regardless of EdZ and EDZ progress. The sealability becomes slightly better at 353 K because of the lower flow rate.

6. Concluding remarks

To clarify the permeability behavior of rock during deformation and failure, and the influences of confining pressure and temperature on that behavior, triaxial compression tests were carried out for Shikotsu welded tuff, Kimachi sandstone, and Inada granite under confining pressures of 1–15 MPa at 295 K and 353 K. Main findings are as follows.

(1) Effects of confining pressure:

For Shikotsu welded tuff, the permeability monotonously decreased with axial compression. The decrease ratio increased with confining pressure; the main cause of the decrease was attributed to pore collapse.

For Kimachi sandstone, the permeability first decreased with increasing axial stress, but then began to increase when the total lateral strain recovered its value before the application of confining pressure, and finally showed an almost constant value in the post-peak region. The minimum and final permeability decreased with confining pressure. Compared to the permeability before axial compression, the final permeability became larger under small confining pressure but smaller under high confining pressure. The main cause of the decrease was attributed to either compaction or large plastic deformation of clay cementing materials.

For Inada granite, the permeability behavior during axial compression was almost the same as that for the Kimachi sandstone. Compared to the permeability before compression, the final permeability was larger, and it decreased with smaller confining pressures. The main causes of the decrease were attributed to a decrease in the number and width of rupture planes and a decrease in the axial cracks from biotite; however, the permeability increased under larger confining pressures because of the formation of subrupture planes due to high stress concentration at the rough and stiff rupture plane.

(2) Effect of temperature-confining pressure coupling:

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 almost same under high confining pressures for the Shikotsu welded tuff, slightly higher for the Kimachi sandstone, and obviously less for Inada granite compared to values at 295 K.

The change in sealability of an underground opening due to the progress of EdZs and EDZs were also inferred by considering the rupture plane in the triaxial compression tests analogous to a fracture in a rock mass. The difference in size and origin between rupture planes in a fractured specimen and fractures in a rock mass should be further investigated.

The author hopes that these findings will contribute toward the reasonable design of manmade caverns.

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