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Shear (Mode II) fractures with shear displacements of 1 and 5 mm were generated by direct shear on granite under normal stresses of 1, 20, and 60 MPa. Fracture surface mapping showed that the surface roughnesses of the shear fractures decreased with increasing shear displacement and normal stress and were smaller than those of tensile fractures reported in our previous study. Fluid flow experiments on the shear fractures provided fracture permeabilities at a wide range of confining pressures of 10–100 MPa. Nonmonotonic permeability was usually observed to decrease with increasing confining pressure. However, the permeability changes were different between the shear fractures generated at the normal stress of 20 MPa and 60 MPa. In addition, obvious permeability changes with shear displacement were observed for 60 MPa, whereas no significant difference was observed for ≤20 MPa. Comparing the shear fractures with the tensile fractures having shear displacements revealed clear differences, even for equivalent shear displacements. Numerical models that were constructed using the data of the fracture surface mapping by matching their permeabilities with the experimentally evaluated fracture permeabilities revealed the development of preferential flow paths, i.e., channeling flows, for the shear fractures, providing a diversity of channeling flow in heterogeneous aperture distributions of rock fractures in the Earth’s crust.


1. Introduction

Fluid flows through rock fractures in the Earth’s crust have been a subject of interest for some time because rock fractures usually have much greater permeability than the rock matrix and are therefore recognized as the predominant pathways of resources or hazardous materials, e.g., groundwater, geothermal fluids, hydrocarbons, and radioactive wastes. The fluid flow and transport properties of rock fractures have been investigated with respect to the geological disposal of high-level radioactive waste. As a result, our understanding of the subsurface flow system has been greatly improved and has been applied to the development of geothermal and oil/gas fractured reservoirs. Recently, the prediction of flow and transport phenomena through rock fractures based on precise modeling of the flow system in a fractured rock mass with natural heterogeneities has become increasingly important because recent environmental and energy problems require urgent solutions using underground space based on the safe and effective development of reservoirs. A modeling with a natural heterogeneity of a fracture network has been established by the Discrete Fracture Network (DFN) modeling technique [Min et al., 2004]. In DFN modeling, rock fractures are described by smooth parallel plates, although, in nature, rock fractures have heterogeneous aperture distributions due to rough surfaces. Therefore simple description requires an ideal fracture aperture (hydraulic aperture), rather than a physical fracture aperture obtained by field observations, to predict fracture permeabilities. However, detailed analyses have suggested that DFN modeling requires further improvement of the heterogeneous aperture distributions and the resulting flow paths within them. This requires a good understanding of the relationships among the aperture distributions, flow paths, hydraulic apertures, and geological conditions, which include a wide range of confining pressures at depths of up to several thousand meters. In addition to engineering applications, such detailed analyses appear to be essential to improve our understanding of some important Earth processes, including those of diagenesis, strength gain on faults, evolving pressure solution, development of reservoir seals, and evolution of flow pathways [Durham et al., 2001; Morrow et al., 2001; Yasuhara and Elsworth, 2004].

[1] Shear (Mode II) fractures with shear displacements of 1 and 5 mm were generated by direct shear on granite under normal stresses of 1, 20, and 60 MPa. Fracture surface mapping showed that the surface roughnesses of the shear fractures decreased with increasing shear displacement and normal stress and were smaller than those of tensile fractures reported in our previous study. Fluid flow experiments on the shear fractures provided fracture permeabilities at a wide range of confining pressures of 10–100 MPa. Nonmonotonic permeability was usually observed to decrease with increasing confining pressure. However, the permeability changes were different between the shear fractures generated at the normal stress of 20 MPa and 60 MPa. In addition, obvious permeability changes with shear displacement were observed for 60 MPa, whereas no significant difference was observed for ≤20 MPa. Comparing the shear fractures with the tensile fractures having shear displacements revealed clear differences, even for equivalent shear displacements. Numerical models that were constructed using the data of the fracture surface mapping by matching their permeabilities with the experimentally evaluated fracture permeabilities revealed the development of preferential flow paths, i.e., channeling flows, for the shear fractures, providing a diversity of channeling flow in heterogeneous aperture distributions of rock fractures in the Earth’s crust.

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[3] Rock fractures are characterized as having a three-dimensional distribution of local apertures formed by rough surfaces that, depending on the confining pressure, are in partial contact with each other with, presumably, preferen-
tial flow paths (i.e., the occurrence of channeling flow [Brown, 1987; Pyrak-Nolte et al., 1988; Tsang and Tsang, 1989; Durham, 1997; Brown et al., 1998; Bruderer-Weng et al., 2004]). In general, fracture permeability changes not only with confining pressure, but also with shear displacement [Raven and Gale, 1985; Esaki et al., 1999; Chen et al., 2000; Gutierrez et al., 2000; Plouraboué et al., 2000; Olsson and Barton, 2001]. The changes indicate that the aperture distributions and the resulting flow paths are affected by both confining pressure and shear displacement. Fluid flows through numerically generated aperture distributions have therefore been studied extensively and channeling flows have been observed [Unger and Mase, 1993; Yang et al., 1993; Pyrak-Nolte and Morris, 2000; Lespinasse and Sausse, 2000; Sausse, 2002; Koyama et al., 2006; Matsuki et al., 2006]. In numerical studies, the relationships between numerical observations and geological conditions, particularly with respect to confining pressures, have not been accurately clarified due to difficulties associated with demonstrating model robustness through experimental observations [Cheng et al., 2004] for a rock fracture under a confining pressure. This failure to incorporate experimental observations into numerical techniques means that numerical observations, such as observations of channeling flow, can only rarely be applied to rock fractures under actual geological conditions. On the other hand, casting techniques [Hakami and Larsson, 1996; Kostakis et al., 2003; Konzuk and Kueper, 2004; Yasuhara et al., 2006], X-ray CT techniques [Bertels et al., 2001; Polak et al., 2004], and the coupled casting X-ray CT technique [Pyrak-Nolte et al., 1997; Montemagno and Pyrak-Nolte, 1999] have been used to characterize the aperture distributions of rock fractures experimentally. However, applying these techniques to the determination of the aperture distributions under a varying confining pressure or a wide range confining pressures is technically difficult [Gertsch, 1995; Fredrich et al., 1995; Montoto et al., 1995].

Recently, we analyzed water flows within aperture distributions of the granite tensile fractures for a range of shear displacements of up to 10 mm at confining pressures of 10–100 MPa by numerical modeling in fluid flow experiments [Watanabe et al., 2008]. In a previous study, we showed the development of preferential flow paths in aperture distributions, which suggest that the concept of channeling flow, can only rarely be applied to rock fractures under actual geological conditions. On the other hand, casting techniques [Hakami and Larsson, 1996; Kostakis et al., 2003; Konzuk and Kueper, 2004; Yasuhara et al., 2006], X-ray CT techniques [Bertels et al., 2001; Polak et al., 2004], and the coupled casting X-ray CT technique [Pyrak-Nolte et al., 1997; Montemagno and Pyrak-Nolte, 1999] have been used to characterize the aperture distributions of rock fractures experimentally. However, applying these techniques to the determination of the aperture distributions under a varying confining pressure or a wide range confining pressures is technically difficult [Gertsch, 1995; Fredrich et al., 1995; Montoto et al., 1995].

Direct shear experiments were performed on granite cores (diameter: 95 mm, length: 200 mm) in order to create granite samples that contained a single shear (Mode II) fracture with final dimensions of 95 mm × 150 mm. The direct shear was performed using the Multipurpose Testing machine for Rock Mass (MTRM) at the Obayashi Corporation Technical Research Institute, Tokyo, Japan. The test machine was used to subject a fracture to different shear displacements (1 and 5 mm) along prescribed shear planes in the cores for various normal stresses (1, 20, and 60 MPa). In principle, two samples were prepared with respect to each condition (combination of shear displacement and normal stress) for the fracture surface mapping (section 2.2) and for the fluid flow experiment (section 2.3). This was because debris associated with the fracturing made it impossible to return a fracture to its original state once the fracture was opened for surface mapping.

A granite core obtained from Inada medium-grained granite (Ibaraki, Japan) was placed in the MTRM with a jig and roller bearings (Figure 1). The jig was used to constrain the shear plane in the core, and the roller bearings were used to reduce the friction between the jig and the loading platens. Vertical and horizontal loads of 5 kN were used to hold the components. A displacement transducer was attached to the jig to monitor the shear displacement along the shear plane. The horizontal load was increased so that the prescribed normal stress was applied to the shear plane. The vertical displacement was applied to the jig at a rate of 0.2 mm/min while maintaining the normal stress and was stopped when the core was fractured and the prescribed shear displacement was achieved. The fractured core was retrieved from the MTRM carefully so that the shear displacement did not
change. The sample that contained the single fracture generated along the shear plane was prepared by cutting both ends of the core to a prescribed length.

2.2. Fracture Surface Mapping

One of the two samples prepared for a given condition was used in the fracture surface mapping for data acquisition and analysis of fracture surface geometry. For convenience, the samples were separated into upper and lower fracture surfaces. In this procedure, great care was taken not to disturb the original surface geometry, where the debris associated with the fracturing was left on the surfaces because debris was present on the samples in the fluid flow experiment. The asperity heights $z_i$ were measured for the upper and lower fracture surfaces in a 250-$\mu$m square grid system using laser scanning equipment having a resolution of 10 $\mu$m along the $z$ axis and a positioning accuracy of 20 $\mu$m in the $x$-$y$ plane, providing $380 \times 600$ data points for each 95 mm $\times$ 150 mm fracture surface. The data was used as input data for the numerical model described in section 2.4 and for roughness analyses to evaluate the influence of the condition of fracture generation on the fracture surface roughness.

The fractal nature is usually observed for surfaces of natural rock fractures [Power and Durham, 1997; Tsuchiya et al., 1994; Brown, 1995; Tsuchiya and Nakatsuka, 1995, 1996; Lee and Bruhn, 1996]. In the present study, the fractal nature of the artificial fractures was examined using the spectral method [Power and Durham, 1997], where the relationship between the logarithms of power spectral density and spatial frequency was linear for a fractal surface, and the slope of the line provides the fractal dimension. In addition, the roughness coefficient ($Z_2$) and the tortuosity ($\tau$) were evaluated for the surfaces [Sausse, 2002]:

$$Z_2 = \sqrt{\frac{1}{N-1} \sum_{i=0}^{N-2} \left( \frac{z_{i+1} - z_i}{\Delta x} \right)^2}, \quad (1)$$

$$\tau = \frac{\sum_{i=0}^{N-2} \sqrt{(z_{i+1} - z_i)^2 + (\Delta x)^2}}{L}, \quad (2)$$

where $z_i$ is the asperity height, $\Delta x$ is the distance between adjacent data points, $L$ is the direct linear length, and $N$ is the number of the data points, with respect to a two-dimensional ($x$-$z$ or $y$-$z$) surface profile. The roughness coefficient is
defined as the root mean square of local slopes, which provides a measure of the microscopic (grid scale) roughness. The tortuosity is defined as the ratio of the length of the profile line to the direct linear length, which provides a measure of macroscopic (sample scale) roughness.

2.3. Fluid Flow Experiments

[10] The second of the two samples prepared for a given condition was used in the fluid flow experiment to evaluate the permeability of the generated fracture for a range of confining pressures. The experiment was performed using the Rubber-Confining Pressure Vessel (R-CPV) [Hirano et al., 2005]. The permeability was calculated based on the relationships between the flow rates through the fracture and differential pressures between the ends of the fractures at confining pressures ranging from 10 to 100 MPa (equations (3) and (4) in the next section). The experimentally obtained permeability was also used in the numerical model (described in the next section) to determine fluid flow through the measured aperture distribution of a fracture for a range of confining pressures. A comparison of the measured permeability to the numerically determined permeability was required.

[11] A sample with a stainless steel jacket (thickness: 2 mm) was placed in the R-CPV (Figure 2). The jacket was used to prevent the sample from failure in the R-CPV.
because preliminary tests revealed that samples prepared by direct shear usually failed, even at relative low confining pressures of from 10 to 20 MPa. The sample failure is hypothesized to originate in microscopic cracks generated in the rock matrix. The jacket is attached to the rock with silicone sealant. Note that the jacket had slits filled with Neoprene® strips (width: 2 mm, thickness: 2 mm) to ensure that the jacket did not affect the fracture normal displacement without short-circuiting the flow. The R-CPV with the sample was placed in the load machine (maximum load: 250 kN). The prescribed confining pressures (normal stress) were applied to the sample (fracture) by compressing the Neoprene® sleeve (thickness: 5 mm) of the sample as per Pascal’s principle [Bloomfield, 2006]. Distilled water (at room temperature) was pumped into the R-CPV at a constant flow rate (maximum flow rate: 0.3 cm³/s). The fluid flowed from the bottom to the top of the sample and out from the R-CPV at ambient pressure. Small pressure gradients were applied so that pore pressures were kept smaller than the applied confining pressure by at least one order of magnitude. Therefore in the present study, the term “confining pressure” refers to the effective confining pressure. The flow rate through the fracture was measured by weighing the effluent using an electronic balance. The differential pressure between both ends of the fracture was measured using a differential pressure gauge.

[12] A fluid flow experiment on tensile fracture of granite performed using the same experimental system revealed that the relationships between the flow rates and the various pressures were linear at the confining pressures of 10–100 MPa [Watanabe et al., 2008], indicating that the permeability of the fractures could be calculated based on the cubic law assumption. Therefore the permeability (\(k\)) of the fractures generated in the present study will be evaluated using the following equation when the hypothesis is confirmed [Witherspoon et al., 1980; Tsang and Witherspoon, 1981; Zimmerman and Bodvarsson, 1996]:

\[
k = \frac{e_b^2}{12}
\]

where \(e_b\) is the hydraulic aperture, which can be calculated from the following equation:

\[
e_b = \left(\frac{-12\mu Q}{W\Delta P}\right)^{\frac{3}{2}},
\]

where \(Q\) is the flow rate, \(\Delta P\) is the differential pressure, \(\mu\) is the viscosity of water, and \(L\) and \(W\) are, respectively, the apparent lengths of the fracture in the directions parallel and perpendicular to the macroscopic flow direction.

### 2.4. Numerical Modeling

[13] The data obtained from the surface mapping and the fluid flow experiments were used in the numerical simulation of the water flow through the aperture distribution of the fracture in the samples. The numerical modeling technique used in the present study is based on the work of Watanabe et al. [2008]. This technique determines aperture distributions and water flows within the structures at given confining pressures by matching the permeability of the numerical model constructed from the surface mapping data of a fracture with the experimentally evaluated fracture permeability for a given confining pressure of the same fracture or an equivalent fracture generated under the same condition.

[14] The aperture distribution was modeled by the two-dimensional distribution of local apertures that was calculated using the data from the surface mapping (250-μm square grid system), with local apertures represented by vertical separations between opposite fracture surfaces. In the determination of aperture distributions and resulting water flows, a model with at least a single contact point was initially constructed. The model was then modified to simulate the normal deformation of a rock fracture to match the permeability of the model with the fracture permeability from the fluid flow experiment. In the simulation, all local apertures were reduced uniformly, and overlapped asperities were eliminated (set to be zero local apertures), precluding the formation of local apertures [Brown, 1987; Power and Durham, 1997; van Genabeek and Rothman, 1999; Matsuki et al., 2006].

[15] The fluid flow through an aperture distribution was simulated using the Reynolds equation for a steady state laminar flow in a two-dimensional (x-y) field of a viscous fluid (water) [Brown, 1987; Mourzenko et al., 1995; Zimmerman and Bodvarsson, 1996; Ge, 1997; Oron and Berkowitz, 1998; Yeo et al., 1998; Lespinasse and Sausse, 2000; Pyrak-Nolte and Morris, 2000; Sausse, 2002; Brush and Thomson, 2003; Konzuk and Kueper, 2004]:

\[
\frac{\partial}{\partial x}\left(\frac{e^3}{12\mu} \frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{e^3}{12\mu} \frac{\partial P}{\partial y}\right) = 0,
\]

where \(e\) is the local aperture, \(\mu\) is the water viscosity, and \(P\) is the water pressure. Since the viscosity was assumed to be constant, this parameter can be removed from equation (5). Using the Deterministic/Stochastic Crack network modeler (D/SC) [Tezuka and Watanabe, 2000], linear equations derived from a finite difference form of equation (5) were solved under boundary conditions equivalent to those in the fluid flow experiments (Figure 3). Once the flow field is calculated, the volumetric flow rate \(Q\) in equation (4) can be obtained. Therefore the permeability of the aperture distribution can be calculated using equations (3) and (4). Note that the zero local apertures were replaced with significantly small nonzero local apertures of 1 μm in the D/SC. This was done primarily because the pressures at the zero local apertures cannot be defined, but also zero permeability should be invalid, even for the contacting asperities. The permeability of the contacting asperities should not be much smaller than that of the rock matrix \((10^{-19}–10^{-18} \text{ m}^2)\). However, the permeability of the contacting asperities may be much smaller than that of noncontacting points. The local aperture of 1 μm, which corresponds to a local permeability of \(8.3 \times 10^{-14} \text{ m}^2\), was selected for contacting asperities because this generally allowed results that were not significantly different compared to those obtained by a much smaller local aperture of \(1 \times 10^{-13} \mu\text{m}\), which corresponds to a local permeability of \(8.3 \times 10^{-20} \text{ m}^2\), to be obtained in reasonable calculation times of less than a day. The resolution of the surface mapping in the present study provides a relatively large number of calculation
points. Therefore a relatively long calculation time is required for convergence in an iterative solution of the D/SC. A model with a wider range of local apertures, associated with smaller local apertures at contacting asperities, generally requires a longer calculation time. Comparing several results by substituting contacting asperities with local apertures of 1 and $1 \times 10^{-3}$ m, the differences in hydraulic apertures were less than 5%, depending on the percentage of contacting asperities among the total data points, which was as high as approximately 50%, and no significant differences were observed in flow rate distributions. In addition, the calculation times were usually several hours when the local aperture was 1 mm, which is reasonable for permeability matching because the matching procedure involved a number of calculations. However, the local aperture of 1 mm precludes numerical models with permeabilities smaller than the local permeability of $8.3 \times 10^{-14}$ m$^2$. The numerical models were therefore constructed only when the experimentally evaluated permeability was greater than the local permeability.

The aperture distributions determined from the numerical modeling were evaluated by means of the geostatistical analysis of size and spatial distributions of the local apertures (histogram and semivariogram). The obtained flow paths were evaluated with respect to the development of preferential flow paths (channeling flow). The area of the preferential flow paths was calculated when channeling flow was observed.

3. Results

3.1. Generated Fracture

In the direct shear on the granite cores, single shear (Mode II) fractures could be generated under specific conditions. At the lowest normal stress, however, only one core with a single fracture with a shear displacement of 1 mm could be obtained due to the difficulty of single fracture generation (occurrences of multiple fractures). Therefore this sample was used in the fluid flow experiment. Figure 4a shows the core that fractured at a shear displacement of 5 mm and a normal stress of 60 MPa. The single fracture with the given shear displacement was clearly observed along the core long axis, i.e., the shear plane. The shear stress calculated for the shear plane changed with shear displacement, as is typically observed in direct shear on rocks or rocks containing a single fracture without shear displacement [Bernaix, 1969; Rosso, 1976; Barton et al., 1985]. The shear stress increased to the peak shear stress of approximately 130 MPa with increasing shear displacement and then decreased to the constant residual shear stress (Figure 4b). Therefore the observed peak shear stresses indicated the shear stress at failure. Similar results were observed under all given conditions, and the relationships between the shear stresses at fracture and the given normal stresses from all of the cores was indicated by a unique linear curve (Figure 5), indicating that Mode II fracturing occurred along the shear plane in all of the cores.

3.2. Surface Roughness

The results of the surface roughness analyses of the shear fractures generated in the present study and those of the tensile fractures generated in our previous study [Watanabe et al., 2008] are summarized in Table 1. Roughness analyses were performed on the surface profiles with respect to the directions parallel to and perpendicular to the shear displacements in the case of the shear fractures. The fractal nature of the fractures generated under each condition was confirmed, indicating that the shear fractures were an acceptable substitute for natural rock fractures. The fractal dimensions were 1.36–1.53, with greater values for the parallel direction. The roughness coefficients (grid-scale roughness) and the tortuosities (sample-scale roughness) tended to be smaller for higher normal stresses, greater shear displacement, and the parallel direction.

The range of fractal dimensions of the shear fractures was similar to that of the tensile fractures of granite in our previous study (Table 1). The fractal dimension showed no significant difference between the shear and tensile fractures. However, the roughness coefficients and the tortuosities showed clear differences between the shear and tensile...
fractures. Figure 6 shows the relationships between the tortuosities and the roughness coefficients, where the plotted values are the averages of the values for the two orthogonal directions. Figure 6 shows that the roughnesses in both the grid and sample scales of the shear fractures were out of the range obtained for the tensile fractures. The differences in the roughness coefficient and the tortuosity between the tensile fractures and the shear fractures generated at a normal stress of 20 MPa were comparable to those between the natural fractures in sandstone and granite [Sausse, 2002].

3.3. Permeability

For fluid flow experiments, the linear relationships between the flow rates and the differential pressure were confirmed for each given confining pressure for all of the samples. The permeability was therefore calculated using equations (3) and (4). In general, although the permeabilities of the shear fractures decreased with increasing confining pressure, the permeabilities at 100 MPa remained much greater than those of the granite matrix permeability of $10^{-19} - 10^{-18} \text{m}^2$ (Figure 7a), as observed in our previous study for the tensile fractures with different shear displacements of 0–10 mm [Watanabe et al., 2008]. This showed that it was not likely for a fracture in granite to get complete closure associated with plastic deformation at contacting asperities [Yoshioka and Scholz, 1989a, 1989b].

Permeability changes with confining pressure or shear displacement were remarkably different between the shear fractures generated at the lower normal stresses of \(\leq 20\) MPa and the higher stress of 60 MPa (Figure 7a). Although, for all of the generated fractures, the permeabilities decreased up to a confining pressure of 50 MPa and

![Figure 4. Fracture generation in a granite core by direct shear under the condition of a shear displacement of 5 mm and a normal stress of 60 MPa. (a) The single fracture generation in the shear plane and (b) the relationship between shear stress and shear displacement measured for the shear plane.](image)

![Figure 5. Relationship between shear stress and normal stress in the shear plane at failure. The solid line shows the liner regression by the least squares method.](image)
then became approximately constant, the additional permeability decrease at the confining pressures of 70–100 MPa was observed only in the case of the fractures generated at higher normal stress. The difference between the fractures generated at the different normal stresses was also observed in the permeability change with the shear displacement. A notable difference (enhancement) was observed with increasing shear displacement only in the case of the shear fractures generated at the higher normal stress.

[24] The results for the shear fractures were clearly different from those for the tensile fractures with equivalent shear displacements obtained in our previous study [Watanabe et al., 2008, Figure 7b]. For the tensile fractures, permeabilities became systematically greater with increasing shear displacement. In addition, the permeabilities became less stress dependent when the shear displacement was greater than 3 mm. However, even in the case of the shear fractures generated at the low normal stresses of 1 and 20 MPa, such results were not observed for the shear fractures.

### 3.4. Aperture Distribution and Flow Path

[24] For the numerical models constructed from the surface mapping data of fractures with the experimentally evaluated fracture permeability, the histograms of the aperture distributions were always characterized by the number of contact points (local apertures of 1 μm) and the skewed distributions of noncontact points (local apertures of >1 μm) with long tails, i.e., lognormal-like distributions, as shown in Figure 8. The histograms were therefore evaluated by contact areas as percentages of contact points, geometric means, and geometric standard deviations of local apertures, as well as the histograms of the tensile fractures in our previous study [Watanabe et al., 2008]. In addition, the aperture distributions were evaluated by semivariograms. In the case of the aperture distributions of the shear fractures generated at the lower normal stress of 20 MPa, the semivariograms with no clear sills (long spatial correlation exceeding the sample scale) did not provide the spatial correlation lengths, i.e., ranges (Figure 9a). On the other hand, the semivariograms of the aperture distributions of the shear fractures generated at the higher normal stress of 60 MPa had clear sills, providing the spatial correlation lengths by good fitting with the exponential model (Figure 9b), as well as the semivariograms of the tensile fractures in our previous study [Watanabe et al., 2008]. The results in the geostatistical analyses are summarized in Table 2 with the values for the tensile fractures.

![Figure 6](image)

**Figure 6.** Relationships between tortuosities and roughness coefficients of the shear fractures generated in the present study and of the tensile fractures generated in our previous study [Watanabe et al., 2008].

### Table 1. Fractal Dimensions, Roughness Coefficients, and Tortuosities of the Shear Fractures Generated in the Present Study and the Tensile Fractures Generated in Our Previous Study [Watanabe et al., 2008]

<table>
<thead>
<tr>
<th>Condition at Generation</th>
<th>Tensile Fractures Generated in Our Previous Study</th>
<th>Shear Fractures Generated in the Present Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture Type</td>
<td>[Watanabe et al., 2008]</td>
<td>[Watanabe et al., 2008]</td>
</tr>
<tr>
<td>Normal Stress (MPa)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Normal Stress (MPa)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Normal Stress (MPa)</td>
<td>5</td>
<td>60</td>
</tr>
<tr>
<td>Normal Stress (MPa)</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Shear Displacement (mm)</td>
<td>Parallel (-)</td>
<td>Parallel (-)</td>
</tr>
<tr>
<td>Shear Displacement (mm)</td>
<td>Perpendicular (-)</td>
<td>Perpendicular (-)</td>
</tr>
<tr>
<td>Fractal Dimension</td>
<td>Parallel (-)</td>
<td>Parallel (-)</td>
</tr>
<tr>
<td>Fractal Dimension</td>
<td>Perpendicular (-)</td>
<td>Perpendicular (-)</td>
</tr>
<tr>
<td>Roughness Coefficient</td>
<td>Parallel (-)</td>
<td>Parallel (-)</td>
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<tr>
<td>Roughness Coefficient</td>
<td>Perpendicular (-)</td>
<td>Perpendicular (-)</td>
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<tr>
<td>Tortuosity</td>
<td>Parallel (-)</td>
<td>Parallel (-)</td>
</tr>
<tr>
<td>Tortuosity</td>
<td>Perpendicular (-)</td>
<td>Perpendicular (-)</td>
</tr>
</tbody>
</table>

a Parallel and perpendicular denote directions to the shear displacement in the analyses.
b Omnidirection.
aperture of 1 μm, the no-flow condition can essentially be assumed at these points. In addition, the noncontact area can be divided into flow and stagnant areas, where the flow and stagnant areas are the areas in which flowing and stagnant fluids exist, respectively. Such fluid flow was usually observed in the aperture distributions at confining pressures of up to 100 MPa with respect to the various shear fractures generated in the present study (Figure 11). Table 3 lists the results of evaluation of the flow area (total areas of preferential flow paths), the ratios of the flow area to the noncontact area, the hydraulic apertures, the ratios of hydraulic apertures to geometric mean of the local apertures, and the permeabilities. Note that hydraulic apertures and corresponding permeabilities are identical to the experimental values. The values for the tensile fractures are also listed in Table 3 for comparison.

As observed in the semivariograms, the models showed obvious differences when the shear fractures were generated at the different normal stresses of 20 MPa and 60 MPa. In addition, the models for the shear fractures generated at the lower normal stress of 20 MPa were similar, despite the different shear displacements (Figure 11a).

![Figure 7](image-url) Changes in permeability with confining pressure for shear fractures generated under various conditions (various shear displacements at various normal stresses). (a) Shear fractures and (b) comparison between the shear fractures generated at a normal stress of 20 MPa and tensile fractures with equivalent shear displacement in Watanabe et al. [2008].
whereas the models for the shear fractures generated at the higher normal stress of 60 MPa differed between the different shear displacements (Figure 11b). For the shear fractures generated at the smaller normal stress, the values in Tables 2 and 3 were similar, regardless of the shear displacement. However, for the shear fractures generated at the higher normal stress, the spatial correlation lengths and anisotropy of the spatial correlation lengths were greater for the smaller shear displacement (Table 2). In addition, the ratios of the hydraulic apertures to the geometric means of the local apertures were smaller for the smaller shear displacement (Table 3).

[26] The shear fractures generated at the lowest normal stress of 1 MPa may be relevant, as compared to a tensile fracture with a shear displacement. However, numerical results for 1 MPa were not obtained. Therefore the models of the shear fractures generated at the lower stress of 20 MPa were compared with those of the tensile fractures with equivalent shear displacements (1 mm and 5 mm) in our previous study [Watanabe et al., 2008]. Although no numerical result was obtained for the fractures generated at the lowest normal stress of 1 MPa, the similar permeabilities indicate that there was no significant difference between the shear fractures generated at 1 MPa and those generated at 20 MPa. In comparison, at the same shear displacements, the major difference in the aperture distributions between the shear and tensile fractures with shear displacements was the spatial correlation lengths, although other differences were observed. For example, the spatial correlation lengths of the tensile fractures with shear displacements were smaller (did not exceed the sample size) and had clear anisotropy with greater values for the direction perpendicular to the shear (Table 2). On the other hand, at the same confining pressures, the major difference was the change in the geometric means of the local apertures with the shear displacement. In the case of the tensile

Figure 8. Histograms of the local apertures of the aperture distributions at a confining pressure of 10 MPa for the shear fractures. Shear fractures generated at normal stresses of (a) 20 MPa and (b) 60 MPa.
fractures, the geometric means increased dramatically with increasing shear displacement (Table 2). The ratios of the flow areas to the noncontact areas also tended to be smaller for the tensile fractures (Table 3).

4. Discussion and Conclusions

Experimental results on fluid flow through shear fractures generated in granite were presented. Fluid flow through fractures is important in numerous crustal processes. Laboratory studies on fluid flow through various types of fractures provide important constraints in many geological and geotechnical problems. Since generating shear fractures is much more challenging than generating tensile fractures, the present study provides valuable experimental data on the fluid flow properties of shear fractures.

In the present study, direct shear experiments were performed on granite cores in order to create granite samples that contained a single Mode II fracture. The linear relationship between the shear stress at failure and normal stress indicated that all of the prepared samples contained Mode II fractures (Figure 5). Due to the debris associated with fracture, a number of samples were required for the fracture surface mapping and the fluid flow experiments. Although two samples were generally prepared for each condition at fracture generation, the sample preparation required considerable effort, particularly due to multiple fractures, which resulted in an insufficient number of samples for quantitative discussion on the reproducibility.

Figure 9. Semivariograms of the local apertures of the aperture distribution at a confining pressure of 10 MPa for the shear fractures. (a) Shear fracture with a shear displacement of 1 mm generated at a normal stress of 20 MPa and (b) shear fracture with a shear displacement of 5 mm generated at a normal stress of 60 MPa, wherein the dashed lines are the fits by the exponential model.
of the experimental results. However, the fracture surface mapping and the fluid flow experiments on different samples prepared under the same conditions provided consistent results for the fracture surface roughness and fracture permeability, which implied that the fracture generation and resulting fluid flow properties were reproducible. The roughness coefficient and tortuosity of the fracture surface changed systematically with shear displacement and normal stress, which supports the reproducibility of the fracture generation (Figure 6). The surface roughness was significantly different between the shear fractures generated at normal stresses of 20 MPa and 60 MPa. The difference between natural fractures in sandstone and granite was comparable, whereas the fluid flow properties were reported to differ for natural fractures in different rocks [Sausse, 2002]. Since the influences of microcracks and/or debris formation associated with the fracture generation at different stresses are expected to differ for permeability and surface roughness, the different results obtained in the fluid flow experiments were reasonable for shear fractures generated at different normal stresses (Figure 7). Similarly, the difference in the results for the shear and tensile fractures with equivalent shear displacements was also reasonable. Although further experiments are required for quantitative discussion, the fluid flow properties of shear fractures are thought to depend on the conditions of fracture generation and are essentially different from those of tensile fractures with shear displacements.

[29] In the present study, numerical models were also constructed using the data of fracture surface mapping by matching the numerical and experimental fracture permeabilities to determine the aperture distributions at the confining pressures of up to 100 MPa in the experiments and fluid flow within the apertures (Figure 11). The numerical results provided findings that were fundamentally consistent with the experimental results. An especially valuable contribution of the numerical results to understanding the fluid flow through rock fractures was the observation of the developments of preferential flow paths, i.e., channeling flow, in the heterogeneous aperture distributions. Although it remains unclear as to whether the channeling flow was likely for shear fractures, the present study demonstrated the channeling flow for both shear fractures at a wide range of confining pressures and tensile fractures. Fluid flow through rock fractures should take place essentially within a limited region, with a diversity associated with fracture types.

[30] The numerical results may provide important information regarding the diversity of channeling flow of rock fractures in the range of confining pressures considered in the present study. Since the contact area may account for approximately 30% to 70% of the fracture plane, depending on the confining pressure (Table 2), the area in which fluids

Table 2. Contact Areas, Mean Apertures, Standard Deviations, and Spatial Correlation Lengths of the Aperture Distributions at Confining Pressures of 10, 60, and 100 MPa for the Shear Fractures in the Present Study and the Tensile Fractures in Our Previous Study [Watanabe et al., 2008]a

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<th>Mean Aperture (µm)</th>
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aThe mean apertures and standard deviation are geometric means and geometric standard deviations of local apertures at noncontact points, respectively. Parallel and perpendicular denote directions to the shear displacement in the analyses.

bGiven after fracture generation.
can easily flow (i.e., noncontact area) may be approximately 70% at maximum. However, aperture distributions that are far from uniform should cause fluid flow only along preferential (least resistant) flow paths, which account for a smaller area than the noncontact area. As a result, the noncontact area is divided into flow and stagnant areas. The flow area in particular may be relevant to the flow wetted surface (FWS), which is significant for radionuclide transport analyses in fractured rock masses [Rasmuson and Neretnieks, 1986; Crawford et al., 2003; Neretnieks, 2006]. The flow area may be only approximately 5% to 20% of the fracture plane, in other words, only approximately 10% to 30% of the noncontact area may contribute to fluid flow (Table 3). Although the flow area seemed surprisingly small, such a small flow area has previously been indicated by field investigations at depths of up to 600 m in the Stripa mine in Sweden, where more than 90% of the water flow was thought to take place in channels, accounting for approximately 5% to 20% of the fracture plane depending on the confining pressure [Abelin et al., 1985]. A small flow area is therefore likely to occur in nature, which would emphasize the significance of prediction of the channeling flow in many geological and geotechnical problems. The numerical results presented herein may provide useful information for the prediction of the channeling flow. Since the relationships among contact/flow/stagnant areas and the permeability were roughly linear (Figure 12), it may be possible to predict the channeling flow simply by a permeability measurement.

Although the numerical results provided findings of significant interest, a thorough investigation should be conducted in the future because of the limitations of the fracture deformation model employed in the present study. The present model, which uses a uniform reduction of local apertures, does not take into account any deformation of a fracture surface as a function of stress, even for contacting

Figure 10. Relationship between a numerically determined aperture distribution and resulting water flow in the structure for a shear fracture. (a) The aperture distribution at 10 MPa for a shear fracture with a shear displacement of 1 mm (95 x 150 mm) generated at a normal stress of 60 MPa, (b) the water flow in the structure, and (c) a composite image showing the development of the preferential flow paths (occurrence of the channeling flow) in the aperture distribution. The preferential flow paths consist of the points at which the ratios of the local flow rate to the total flow rate are greater than 0.01 in the image of water flow.
Figure 11. Changes in the water flows in the aperture distributions with confining pressure for shear fractures generated under various conditions. Shear fractures (95 × 150 mm) generated at normal stresses of (a) 20 MPa and (b) 60 MPa.
Table 3. Flow Areas, Ratios of Flow Area to Noncontact Area, Hydraulic Apertures, Ratios of Hydraulic Aperture to Mean Aperture, and Permeabilities at Confining Pressures of 10, 60, and 100 MPa for the Shear Fractures in the Present Study and the Tensile Fractures in our Previous Study [Watanabe et al., 2008]a

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<th>Shear Displacement (mm)</th>
<th>Confining Pressure (MPa)</th>
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<th>Flow Area/Noncontact Area (-)</th>
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Where the mean apertures are geometric means of local apertures at noncontact points. Given after fracture generation.

Figure 12. Relationships between the contact/flow/stagnant areas and the permeability of various types of fractures generated in granite. Drawn using data in Tables 2 and 3. The solid lines are intended to clarify the linear relationships between the areas and the permeability.
asperities [Gangi, 1978]. Therefore the model that uses a uniform reduction in local apertures cannot be used to clarify the aperture distribution or resulting flow paths as a function of applied confining pressure. In future studies, we hope to implement more realistic models [Pyrk-Nolte et al., 1988; Pyrk-Nolte and Morris, 2000] to examine fracture deformation as a function of confining pressure.

[32] Acknowledgments. The authors would like to thank Drs. Kazuhiko Tezuka and Tetsuya Tamaegawa (Research Center of Japan Petroleum Exploration Co., Ltd.), Dr. Kimio Watanabe (RicStone Limited), and Dr. Kenichiro Suzuki (Technical Research Institute of Obayashi Corporation) for their assistance with the sample preparations and numerical simulations.

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