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**Evaluation of Fluid Flow Path in a Single Fracture Undergoing Normal Stress and Shear Offset**

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**Abstract.** We report on an evidence of anisotropy in flow path in a single fracture on the basis of measurements of a contact area in a fracture with shear offset of up to 5 mm undergoing normal stress of up to 90 MPa. An area of contact in a fracture undergoing normal stress is measured by using a pressure-sensitive sheet inserted between fracture surfaces. This method allows simple measurements of contact area in the stressed conditions. Our results show that contact area increases with an increase in normal stress, on the contrary, contact area decreases with an increase in the offset. These dependencies in a contact area suggests that an open area, i.e., aperture area, which is illustrated as an area except for contact area in a fracture, can change associated with normal stress even under the condition of 100 MPa. In addition, we observed that contact area distributes in the direction perpendicular to the direction of offset, which indicates an anisotropy in aperture distribution that become possible flow path in a fracture. Results of numerical simulation of fluid flow in a fracture support the anisotropy in aperture distribution and consequent anisotropy in fluid flow in a fracture. The anisotropy in aperture distribution suggests an anisotropy in fracture permeability since tortuosity in a flow path could be affected by the aperture distribution.

**Keywords:** Fracture permeability, Fluid flow, Laboratory experiment, shear offset

**PACS:** 91.60.Np

**INTRODUCTION**

Considering the transfer of materials in the Earth's crust, understanding of flow characteristics in fractures is important since fractures in the crust can be major migration pathways and would play a significant role in the transfer properties in the crust. Many researchers have conducted fracture permeability tests for a characterization of flow properties in fractures (e.g., Gale, 1982, 1987; Raven and Gale, 1985; Pyrak-Nolte et al., 1987; Duham, 1997). For example, Watanabe et al. (2004) performed fracture permeability tests using a granite sample containing a large single tensile fracture (fracture area of 150 * 100 mm²) with offset displacement of up to 5 mm under confining pressure condition of up to 100 MPa. Their results showed normal stress and offset displacement dependencies in fracture permeability, i.e., the permeability decreased as increasing confining pressure and increased as increasing offset displacement. They explained that the parameter dependencies in fracture permeability resulted from the change in aperture distribution due to normal stress or offset displacement since the aperture in a fracture should behave as a hydrologically conductive area in the fracture and would directly affect flow characteristics. Considering their explanation, it is essential to determine parameter dependencies in aperture distribution of a fracture in order to reveal mechanisms of the parameter dependencies in the fracture permeability.

We report on direct measurements of a hydraulically ineffective area on a single tensile fracture subjected to normal stress and offset displacement to delineate the aperture area in a fracture under the experimental conditions. In this paper, we describe details of our experiment for measurement of a hydraulically ineffective area on a single tensile fracture under normal stress of up to 90 MPa with the aim of understanding mechanisms of the normal stress and offset displacement dependencies in fracture permeability. First, our experimental method is described. Subsequently, results of our experiments using a pressure sensitive sheet for the measurement of a hydraulically ineffective area are shown and parameter dependencies in aperture distribution based on contact area measured in our experiments are described.
MEASUREMENT OF A CONTACT AREA ON FRACTURE SURFACES UNDERGOING NORMAL STRESS AND SHEAR OFFSET

Our experiments were performed at room temperature using cubic rock specimens containing a single tensile fracture. The rock type of the specimen is lidate granite and the cube is 50 mm in length, 50 mm in width and 60 mm in height. Rock samples were prepared with a single tensile fracture with offset displacement of 0, 1 and 3 mm, respectively. Offset displacement mentioned in this paper is defined as horizontal displacement that is applied to a fracture surface of the split specimen in a direction parallel to the fracture surface.

We used a commercially available pressure-sensitive sheet (Fuji film Co., FPL-S-MS) for detection of contact area on a fracture. Microcapsules containing dye are administered on the sheet surface. When the sheet is pressurized, the microcapsules break and the sheet is colored with the dye from the broken microcapsules. Based on the catalogue specification, the detection resolution of the sheet is 0.1 * 0.1 mm² square, and the measurable range of pressure is from 10 MPa to 50 MPa. The thickness of a sheet is 0.115 mm. The sheet was inserted into a fracture. The thickness of a sheet does not allow detection of the aperture area where the width is less than 0.115 mm. This raises a possibility that the aperture area might affect fluid flow in a fracture. However, we believe that the aperture where the width is less than 0.115 mm would not contribute significantly to fluid flow in a fracture compared to other apertures. Thus we regard the fracture aperture less than 0.115 mm as part of contact area of a fracture.

FIGURE 1. (a) Schematics and (b) picture of sample assembly of experiment for measurement of contact area.

FIGURE 2. Color sheet images obtained with an optical scanner.
Sample assembly and test procedure

Figure 1 shows the sample assembly of our experiments. A pressure-sensitive sheet was inserted between fracture surfaces of a rock sample. Axial load was applied to the rock sample using a 25 ton-loading machine. Normal stress was increased sequentially from 10 MPa to 90 MPa with an increment of 20 MPa for each rock sample containing the offset displacement of 0, 1, and 3 mm. In order to avoid horizontal movements of the fracture associated with the loading, we attached a steel frame around the fracture. After applying normal stress for 2 minutes, the rock sample was unloaded and the pressure-sensitive sheet was retrieved. After that, a full color image of the sheet was obtained by using an optical image scanner in order to investigate contact area on the fracture surfaces. The scanning of images was conducted with a resolution of 1200 dpi (corresponding to a detection resolution of 0.54 mm²). The resolution of the image is higher than that of the pressure-sensitive sheet and is enough to detect contact area.

Experimental results

Figure 2 shows images of pressure-sensitive sheets obtained with an optical scanner for each normal stress and offset displacement condition. These images are shown as a function of applied normal stress on a horizontal axis and offset displacement on a vertical axis. In Figure 2, contact area presented as colored areas appear to increase with increasing normal stress in all the offset displacement conditions. In contrast, contact areas decrease with increasing offset displacement applied to the fracture in all the normal stress conditions. Moreover, contact area, indicated by the black area, appears to connect perpendicularly to the direction of offset displacement with increasing offset displacement. For example, the perpendicular distribution of contact area is obvious in the case that normal stress is 30 MPa (Figure 2). The perpendicular connection in contact area implies anisotropy in permeability of a fracture.

Quantification of contact area

To quantify contact area of fracture surfaces, intensity distributions of color in the obtained images

![Image](image-url)
were investigated for each normal stress and offset displacement condition. Figure 3 shows a procedure of image data processing to determine contact area from the color image. First, the color images were converted into gray scale of 8 bits (256 levels). Figure 4(a) shows a representative sheet image obtained as a color image and Figure 4(b) shows the sheet image converted into the gray scale. Next, the intensity distribution of the gray scale images (Figure 4b) was examined using a histogram to determine a threshold level to convert the images from gray scale to black-and-white. Figure 4(c) shows a representative histogram of the monochrome intensity distribution of a retrieved sheet image. Two peaks of monochrome intensity can be identified in the histogram. We regard a local minimum value in the monochrome intensity between these two peaks as a threshold to distinguish the contact area from non-contact area. Figure 4(c) shows the sheet image converted to binary scale. In the binary scale, black areas are interpreted as the contact areas of the fracture.

**Normal stress and offset dependencies in contact area**

Figure 5 shows the ratio of the quantified hydraulically ineffective area to the apparent fracture area (50 * 50 mm²) plotted as a function of normal stress in all the offset conditions. In all the offset conditions, contact area increases with increasing normal stress. In the case that offset displacement is 0 mm, particularly, contact area increased until approximately 90 % at normal stress of around 50 MPa, keeping a constant ratio of 90 % in normal stress of over 50 MPa. On the other hand, contact area decreases with increasing offset displacement; contact area decreases by less than 20% in the case that offset displacement is 5 mm (Figure 5). Furthermore, contact area becomes insensitive to an increase in normal stress with increasing offset displacement, particularly in the lower normal stress condition of less than 40 MPa.

In addition, our results show that contact area is distributed in the direction perpendicular to the direction of offset displacement applied to the fracture with increasing offset displacement, which indicates that the fracture aperture is distributed perpendicularly to the direction of offset displacement (Figure 2). The change in aperture distribution suggests that perpendicular flow to the direction of offset displacement would become predominant in fluid flow in a fracture. The predominance in perpendicular flow would cause increasing anisotropy in macroscopic fracture permeability with increasing offset displacement.

**NUMERICAL SIMULATION FOR FLUID FLOW THROUGH A FRACTURE**

Numerical simulation for fluid flow was conducted to investigate effects of the direction of the offset displacement on anisotropy in fluid flow path and possible anisotropy in fracture permeability due to the direction of offset. Details of the flow simulation have been reported by Watanabe et al. (2005). We briefly explain outline of the simulation. We assume that fluid flowing fracture aperture is incompressible, local flow rate and local permeability obey Darcy's law and Cubic law. There is no flow on the sidewall of the aperture. We assume that fluid pressures at inlet and at outlet are 1.0 MPa and 0 MPa, respectively.

Fracture aperture for the flow simulation is calculated so that a percentage of contact area in a calculated aperture from fracture surface topography has the same value as that estimated in our contact area measurements. Aperture width at contact area is assumed to be 0.001 mm for a limitation of our simulator in the flow simulation.

Figure 6 shows the result of flow simulation in the case of 3 mm in offset displacement at 70 MPa in normal stress (corresponding to contact area of approximately 24%). We can identify that predominant flow paths are more tortuous in the case that direction of the offset is perpendicular to the macroscopic flow direction, compared to the flow paths in the case that the macroscopic flow direction is parallel to the offset direction. Fracture permeabilities in each offset condition are calculated to be 8.4 x 10⁻¹⁰ [m²] for the offset perpendicular to the direction of macroscopic flow and 4.5 x 10⁻¹⁰ [m²] for the offset parallel to the direction of macroscopic flow. We can interpret that the difference in tortuosity of fluid flow
due to the offset direction affects fracture permeability from the result of flow simulation.

**DISCUSSION**

Our results showed an increase in contact area with an increase in normal stress in all the offset displacement condition (Figure 5). The normal stress dependency in contact area indicates a decrease in the aperture area of a fracture with increasing normal stress. Furthermore, we observed that contact area leveled off (approximately 90% of apparent fracture area) at a normal stress of 40-50 MPa under the conditions of no offset displacement. The leveling off in contact area suggests that a fracture do not completely close and that 10% of the fracture area remains as aperture area even under a relatively high normal stress of 100 MPa.

Considering that the aperture area would act as the hydrologically conductive area in a fracture, the saturation in contact area supports the concept of fractures in a rock mass as major flow pathways even in a relatively high stress condition. According to the permeability tests using a rock specimen containing a single tensile fracture (Watanabe et al., 2004), permeability of a single fracture had a higher value than that in intact rock by seven orders of magnitude even under a confining pressure of up to 100 MPa. Our results qualitatively support the difference between permeability in a fracture and that in an intact rock observed in the permeability test.

In addition, Watanabe et al. (2004) reported that the permeability in a single tensile fracture decreased with increasing confining pressure and became constant at a certain value after confining pressure reached around 40-50 MPa. The stress dependency in the permeability is similar to that in contact area observed in our experiments (Figure 5). Thus we can interpret that the stress dependency in the fracture permeability observed the permeability tests (Watanabe et al., 2004) would result from the stress dependencies in contact area that cause the change in the aperture area.

Focusing on the offset displacement dependency in contact area, our results showed a decrease in hydraulically ineffective area, which indicates an increase in the aperture area of a fracture, with increasing offset displacement (Figure 5). On the other hand, the permeability test (Watanabe et al., 2004) showed obvious increase in fracture permeability as increasing offset displacement. Figure 7 shows the relationship between contact area observed in our experiment and fracture permeability estimated by Watanabe et al. (2004) in each offset displacement condition, which presents an obvious trade-off relationship between them. From the comparison between our results and the results in the permeability test, we can explain the increase in fracture permeability observed in the permeability test as an increase in the aperture area due to the increase in offset displacement.

In this study, we regarded the aperture area of a fracture as the white area in monochrome image of the sheet (Figure 4d). Therefore we didn't consider...
aperture width that would affect microscopic flow characteristics in a fracture. In actual fractures, there seems to be deviation of the aperture width from place to place, which might cause a change in macroscopic permeability. However, we can quantitatively interpret the cause of parameter dependencies in the fracture permeability as change in aperture distribution resulting from change in contact area by our direct observation of contact area.

Our result in flow simulation (Figure 6) showed that tortuosity in predominant flow paths changed associated with the difference between a direction of offset displacement and macroscopic flow direction, that is, predominant flow paths become more tortuous in the case that a direction of macroscopic flow is parallel to a direction of offset displacement. In addition, our results showed fracture permeability changed with the change in tortuosity. In Figure 6, we can identify anisotropy in aperture distribution in the calculated aperture distribution, which was observed in our results of contact area measurement (Figure 2). We can infer that the offset direction dependence in tortuosity is caused by the anisotropy in aperture distribution, that is, connectivity between local aperture areas in a direction perpendicular to the offset direction increased with the offset, which made it easier to flow in a perpendicular to the offset direction. In addition, it is inferred that the change in tortuosity resulted in the change in fracture permeability due to the difference in offset direction. Therefore, we can infer that offset direction dependency in fracture permeability observed in our flow simulation is due to the change in tortuosity of predominant flow paths associated with the change in aperture distribution.

CONCLUSIONS

Our measurements of contact area on a single tensile fracture showed that contact area increased up to 90% in the apparent fracture area with increasing normal stress and decreased with increasing offset displacement by less than 20%. In addition, contact area was saturated at approximately 90% when normal stress reached around 50 MPa. The normal stress dependency and the offset displacement dependency in contact area are similar to that in fracture permeability estimated by Watanabe et al (2004). The similarity in parameter dependencies implies a strong relationship between hydraulically ineffective area and permeability in a fracture.

Fracture aperture, which is regarded as the remaining area in the apparent fracture area except for contact area we measured, would directly contribute to the permeability of a fracture. Therefore, we can conclude that the change in permeability of a fracture observed by Watanabe et al. (2004) resulted from change in aperture area that is in turn caused by the change in contact area with change in normal stress/confining pressure.

In addition, we observed a perpendicular distribution of contact area relative to offset displacement direction with increasing the offset displacement. This heterogeneity in contact area distribution indicates heterogeneity in the aperture area, which would result in heterogeneity in fracture permeability.

Our results of flow simulation indicate that the anisotropy in the aperture distribution results in anisotropy in fracture permeability. Results of the flow simulation showed the anisotropy in fracture permeability is caused by the difference in tortuosity of major flow pathways in a fluid flow.

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