EXPERIMENTAL STUDY ON WATER FLOW IN A SHEARD FRACTURE

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1. INTRODUTION

Evaluation of the hydraulic properties of a fracture under compressive stress becomes more and more important such as for underground disposal of high-level radioactive wastes, hot dry rock (HDR) type geothermal energy extraction and oil reservoir engineering. To evaluate the fluid flow in a fracture, we need to consider the direction between flow and shear. Experimental study using a flat-jack type triaxial compressive test apparatus has been carried out for macroscopic flow parallel to the shear direction (2005, Takanishi, 2007, Goto) [1][2]. However, because of a number of technical difficulties, macroscopic flow perpendicular to the shear displacement has not been fully understood experimentally. Therefore, the objective of this study is to evaluate the characteristics of the hydraulic properties of a rock fracture experimentally when macroscopic flow perpendicular to the shear displacement. In this study, mortar replicas of specimen with a tensile fracture specimen are manufactured. The shear-flow test are carried out by using this replica to evaluate the hydraulic conductivity under different normal stresses. In this paper, we also conducted numerical simulation of water flow for fracture which taken from the aperture distribution of rock specimen. In numerical simulation, flow direction is parallel/perpendicular to the shear direction. We evaluated the heterogeneity of the permeability numerically, and made discussion on results of experiment and simulation for macroscopic water flow perpendicular to the shear direction.

2. EXPERIMENTAL SYSTEM

2.1 OUTLINE OF THE SYSTEM

Fig. 1 shows a schematic diagram of the experimental system. Fig. 2 shows the stress state in the experiment with the coordinate system and water flow direction. Specimen made by mortar is put into inside of the triaxial compressive test apparatus so that the fracture of the specimen is perpendicular for horizontal plane. Flat-jacks for applying uniform stresses to the specimen are set to the *X* and *Y* side surfaces of the specimen. Two flat-jacks of the different size are set to the both surfaces normal to the *Y*-direction, able to catch up with the displacement of the specimen. In this study, the specimen is not loaded to the *Z*-direction.

In the shear-flow test, firstly, stresses of σ_X and σ_Y were applied to the specimen up to 1.5 MPa so that shear displacement does not occur. Then water is supplied from the top of the specimen by the constant flow rate pump. We defined this time as the initial state when the pressure difference between water inlet and outlet became 0.02 MPa, and volume flow rate became 0.04 ℓ/min. And from this time, stresses, water pressures, and displacements (normal and shear) are measured. Afterward, the shear stress is increased while keeping the normal stress to the fracture constant by controlling σ_X and σ_Y. At several stage of shear displacement, the hydraulic conductivity of the fracture is evaluated by measuring water volume that is drained from the fracture. Water outlet of the water drain platen is divided into 10 ports and these ports are numbered by ① to ⑩. Thus, the heterogeneity of the water flow in the fracture can be evaluated. The shear displacement and normal displacement of the fracture were measured by displacement transducers set on the top of the specimen.

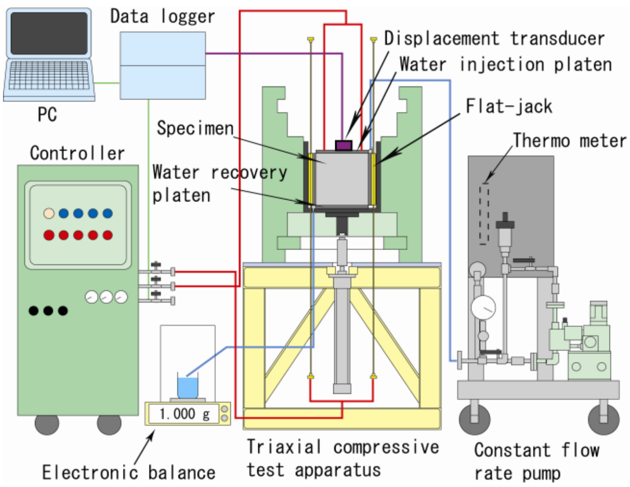

Fig.1 Experimantal system.

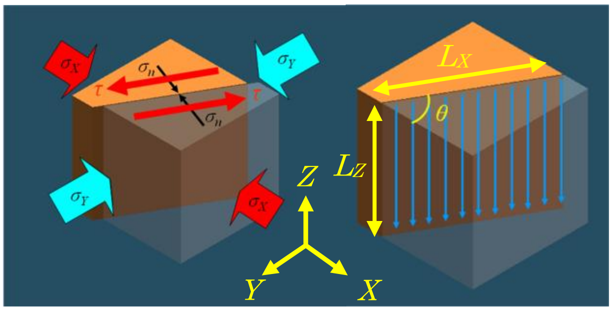

Fig.2 Shear and flow direction.

2.2 SPECIMEN

In this study, a tensile fracture of the Inada granite created by wedges was used as the parent fracture. The upper and the lower surface of the surface was firstly re-cast by using epoxy resin, and then the mortar replicas were manufactured based on the resin replica. In doing it this way, fracture surface of mortar replicas become the same that of the parent fracture. Fig. 3 shows the external view of upper and lower replicas. Table 1 shows the mechanical properties of the mortar replica. For comparison, the mechanical properties of Inada granite are also shown.

Fig.3 External view of the pecimen.

Table 1 Mechanical properties of specimen.

	Mortar	Inada granite
Compressive strength (MPa)	165.1	168
Young's modulus (GPa)	50.0	37.0
Poisson's ratio (-)	0.27	0.16
Tensile strength (MPa)	7.2	5.82

2.3 PROCEDURE FOR ESTIMATING PERMEABILITY

In this study, mass permeability M_p is defined by equation (1) to evaluate the heterogeneous water flow from measured water volume drained from each outlet port.

$$M_p = \frac{M_w}{\Delta p \cdot t} \quad (1),$$

Where M_w is the water volume drained from each outlet port, Δp is pressure difference between water inlet and outlet of the fracture, and t is measurement time.

The hydraulic aperture e_h is evaluated by equation (2)[3]:

$$e_h = \left\{ \frac{12\mu Q}{L_X \Delta p / L_Z} \right\}^{\frac{1}{3}} \quad (2).$$

Where μ is the viscosity of the water and Q is the volume flow rate.

3. NUMERICAL SUMULATION

3.1 APERTURE DISTRIBUTION

In numerical simulation, the aperture distribution with shear displacement was calculated from the measurement data of upper and lower fracture surfaces of the granite. Then the fracture is closed to have a mean aperture of 2.0 mm. Fig. 4 shows the 3D graph of the aperture distribution with no shear displacement.

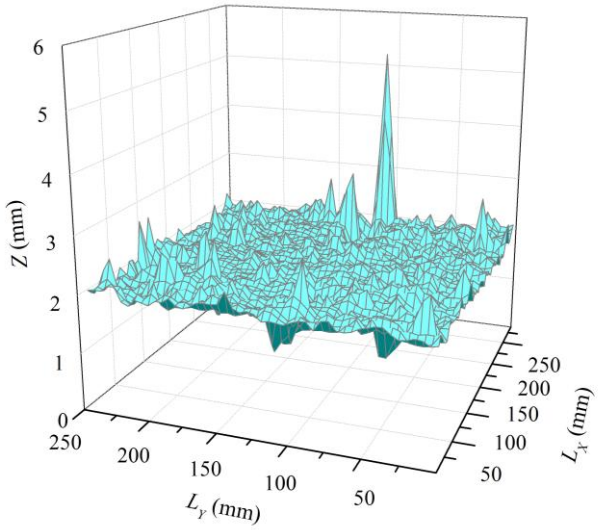

Fig.4 Aperture distribution for simulation.

3.2 METHOD FOR SIMULATION

In this study, the following equation, called Reynolds equation, was used to describe the flow in fracture. This equation is obtained for laminar flow through a fracture with rough surfaces.

$$\frac{\partial}{\partial x} \cdot \left(\frac{e^3}{12\mu} \cdot \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \cdot \left(\frac{e^3}{12\mu} \cdot \frac{\partial p}{\partial y} \right) = 0 \quad (3).$$

Where e is mechanical aperture, μ is the viscosity of the water and p is pressure difference. Eq. (3) was solved by a finite difference method. The fracture area for simulation is rectangular area of 242 × 289 mm and aperture data was taken at constant interval of 1.0 mm from measured data. The boundary conditions were given so that macroscopic water flow may occur in one direction.

4. RESULTS AND DISCUSSION

4.1 SHEAR-FLOW TEST RESULTS

Fig. 5 shows the changes in the stresses (σ_X, σ_Y, normal stress σ_n, and shear stress τ), the pressure difference Δp, the shear displacement δ, and the normal displacement d_1, d_2, with time during shear-flow test.

At several stage of shear displacement, the hydraulic conductivity of the fracture is evaluated, and this tests were carried out 13 times at the time from ① to ⑬ shown the lines in Fig. 5. However, breaking of the specimen was observed after the shear displacement of 5 mm, the hydraulic conductivity of the fracture was not evaluated successfully after 5 mm. Therefore the change of M_p and e_h were shown as dashed lines after the shear displacement of 5 mm, and were not considered as correct results.

Fig. 6 shows the relation between the shear displacement and the mass permeability M_p. The numbers of ① to ⑩ indicate the outlet ports number.

At the beginning of the shear, the values of M_p increased drastically. After that, all values of M_p changed little or decrease gently with the shear displacement until the shear displacement of 5 mm. The value of M_p at the outlets varied in place by place, which showed that the water flow in the fracture is heterogeneous.

Fig. 7 shows the relation between the shear displacement and e_h, σ_n, and τ. The value of e_h greatly increase at the beginning of the shear and change little or decrease gently with shear displacement until the shear of 5 mm.

4.2 SIMULATION RESULTS

Fig. 8 shows the velocity and pressure fields for two directions of macroscopic flow obtained by numerical simulation. The magnitude of velocity is indicated as the length of the arrow. And the hydraulic pressure is higher as the color becomes deep. From this results, both flows parallel (flow//shear) and perpendicular (flow⊥shear) with shear direction become more heterogeneous and also were localized with shear displacement. In both case, continuous flow paths appear where a shear displacement of 6 mm. The flow paths of flow ⊥shear was less tortuous and larger than that of flow//shear. From these phenomena, the heterogeneity of the permeability in the fracture was indicated numerically.

Fig. 9 shows the normalized hydraulic aperture e_h/e_m and the percentage of contact point between upper and lower fracture surfaces. Where e_m is the mean mechanical aperture of the fracture with shear displacement, equal to 2 mm in this simulation.

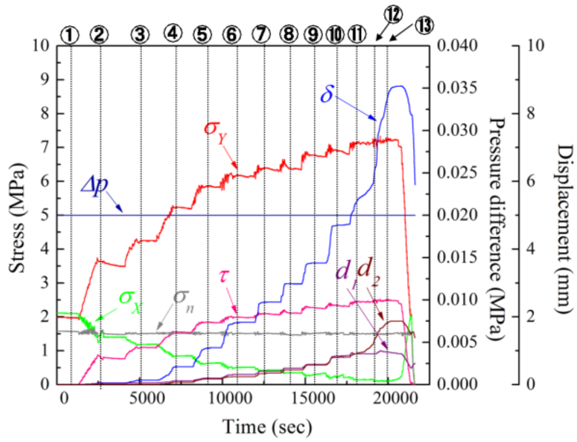

Fig.5 Change in stresses, pressure difference, and displacements with time.

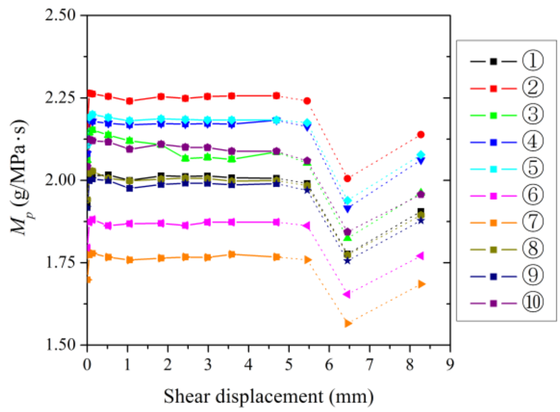

Fig.6 Results of permeability test.

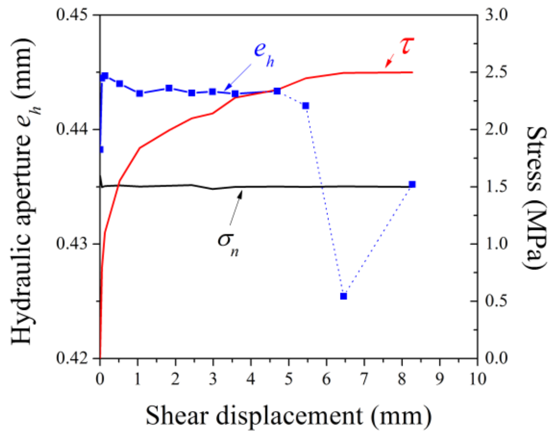

Fig.7 Relation between shear displacement and hydraulic aperture in permeability test.

From Fig. 9, e_h/e_m of flow⊥shear is larger than that of flow//shear.

The increase of contact ratio causes the decrease of e_h/e_m of flow⊥shear and flow//shear. In the case of flow//shear, tortuous flow paths are created and prevent water flow. Therefore e_h/e_m for flow// shear is smaller than that for flow⊥shear.

4.3 DISCUSSION

From Fig. 6, the value of M_p at outlets ②, ⑤, ③, ④, and ⑩ were comparatively large. In Fig. 8 (d), there were large flow paths towards outlets ②, ⑤, ③, ④, and ⑩. On the other hands, M_p at outlets ⑥ and ⑦ were small in Fig. 6 and the fluid flow towards outlets ⑥ and ⑦ were small in Fig. 8. Therefore, the distribution of volume of flow at each outlet well matched from the results of shear-flow test and those of simulation.

From Fig. 9, e_h/e_m is nearly-constant at 1.0 until the shear displacement of 5 mm for fluid flow perpendicular to the shear direction. e_h is nearly-constant until the shear displacement of 5 mm when e_m is 2 mm. Considering the change of e_h in Fig. 7, the change of e_h matches qualitatively until the shear displacement of 5 mm in the results of shear-flow test and those of simulation.

5. CONCLUSIONS

In this study, the shear-flow tests when the flow direction is perpendicular to the shear direction were carried out using the specimen with a fracture re-casted by mortar using the triaxial compressive apparatus. And the numerical simulation was also conducted. Main results obtained in this study are summarized as follows:

1) The characteristics of the hydraulic conductivity of a tensile fracture with shear displacement were successfully evaluated by the experimental system developed in this study.
2) In the numerical simulation, the heterogeneity and anisotropy of the flow in the fracture was shown. The value of e_h/e_m of flow⊥shear was larger than that of flow//shear.
3) From shear-flow test, the hydraulic conductivity of the fracture has heterogeneous character, and distribution of volume flow rate at each outlet well matched from the results of shear-flow test and those of simulation.
4) The change of e_h matches qualitatively until the shear displacement of 5 mm in results of shear-flow test and those of simulation.

REFERENCES

[1] Takanishi, 2005, Experimental study of the evaluation of permeability of a fracture with shear deformation under triaxial compressive stress, Tohoku Univ. Master Thesis.

[2] Goto, 2007, Experimental study on permeability of a fracture subjected to shear deformation, Tohoku Univ. Master Thesis.

[3] Brown SR. Fluid flow through rock joints : The effect of surface roughness, JGR, 1987;92:1337-47.

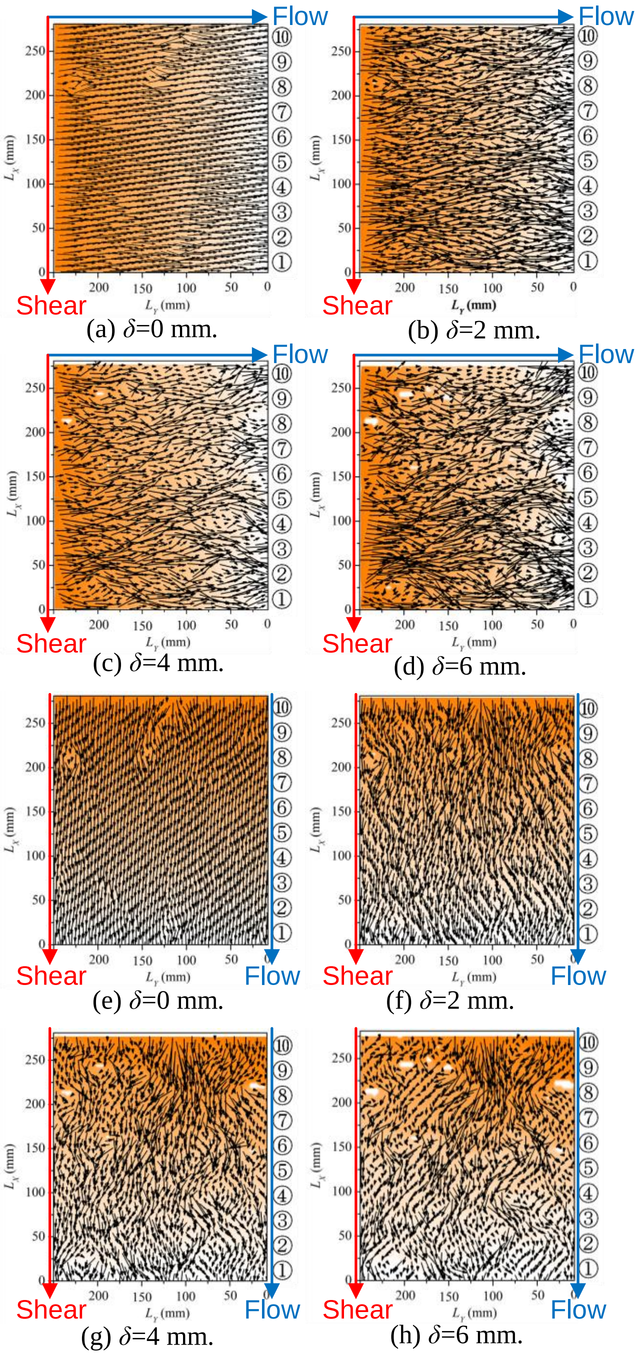

Fig.8 Results of simulation.

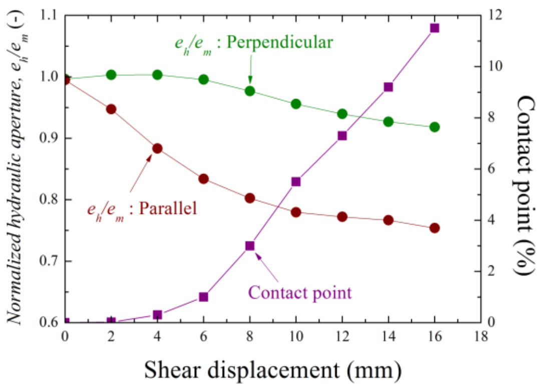

Fig.9 Change in e_h/e_m and contact point with shear displacement.