Loading rate-dependent frictional resistance of a sawcut fracture in granite for prediction of thermoshearing

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Abstract. The coupled TM behavior of fractured rock masses should be evaluated for the long-term safety of the deep geological repository. Thermally induced fracture shear slip, i.e., fracture thermoshearing, might cause increase in fracture permeability. In this study, the thermally induced shear slip of a sawcut granite fracture was investigated in laboratory. Multistage biaxial shear test, consisting of mechanical shear test and thermoshearing test, was conducted on the true triaxial apparatus, and acoustic emission (AE) signals were recorded throughout the experiment. Effect of loading rate on frictional resistance of the fracture was investigated by conducting mechanical shear tests, and we found that friction coefficient of the fracture decreases in proportion to the increase in the logarithm of loading rate. Under mechanical loading rates of 1×10^3 MPa/s and 5×10^3 MPa/s, the failure envelopes with friction coefficients of 0.78 and 0.74 were obtained, respectively. Thermoshearing test was conducted via heating in the direction of the constant minimum principal stress while expansion was restricted in the other direction of the maximum principal stress. A maximum loading rate caused by thermal stress was observed at around 0.9×10^3 MPa/s. Shear slip of the fracture occurred during the heating, and this can be well predicted by the Mohr–Coulomb failure envelope, which was obtained from the mechanical shear test at a similar loading rate.

1. Introduction

Deep underground repository is being developed to safely contain and isolate the high-level nuclear waste (HLW) from both human activities and biosphere for a very long time [1–5]. The geological formation acts as a natural barrier that the transport of these nuclides will be restrained, and the released nuclides from formation will be in such low concentration that they do no harm to human health and our environment [6]. The repository should have such low permeability that the seepage is moderate [7]. However, apart from ubiquitous natural fractures, the excavation of deposition tunnels and holes inevitably induces discontinuities that transect the host rock [8–10]. Moreover, canisters with spent nuclear fuel in the final repository would generate considerable heat during long-term radioactive decay [11]. By heat transport from the spent nuclear fuel via the canister and the buffer to the host rock, thermal stress is predominately generated in the horizontal direction assuming that the semi-infinite geological formation is horizontally confined; the vertical stress originating from the overlaying strata weight remains constant [12]. Under the coupled TM condition, the deviatoric stress increases, and fracture shear slip may occur, particularly for the critically stressed fractures. Shear slip
of pre-existing fractures due to thermal stress, i.e., thermally induced fracture shear slip or fracture thermoshearing, has been recognized as the dominant source of permeability increase in the surrounding rock [13].

To evaluate the thermally induced fracture shear slip, the thermal loading history should be considered. Thermal stress evolution around repository is time-dependent and space-dependent, e.g., the average thermal stress rate in the horizontal direction is around 0.2 MPa/y at simultaneous heating condition, and the increment of thermal stress decreases with the increasing distance from repository [14]. Thermal stress increases very slowly, and the thermal stress rate, the time derivative of thermal stress, is very low. The thermally induced shear displacement of the embedded fracture is also very small for a very long time [15]. The very low increasing rate of maximum principal stress or very low shear velocity along fracture may result from thermal stress in the case of permanent underground storage of nuclear waste. At laboratory scale, the thermal stress is created by any change in temperature of rock (i.e., granite in this study) in the constrained direction. The magnitude of the thermal stress rate and its effect on the frictional resistance of fracture are still unclear.

Displacement rates of 0.1–0.2 mm/min are suggested by ISRM for displacement-controlled mechanical shear test to investigate rock joint frictional strength [16]. Results of the mechanical shear tests showed that the fracture shear strength is velocity-dependent. Both the peak and residual shear strength of the split granite fracture tend to decrease with increasing shear rates from 0.001 mm/s to 0.1 mm/s [17], and the frictional resistance of smooth and polished fracture follows the same trend [18]. Even though rock type and normal stress level might influence the velocity-dependent shear strength of fracture [19, 20], most previous studies concluded that the shear strength of fractures increases with decreasing shear rate because of the relatively large increase contact in the real area of asperities contact [21, 22]. One plausible mechanism is that the fracture asperities sheared under low shear displacement rate keep contact for a relatively long time before fracture fails, increasing the real contact area. The slide-hold-slide experiments also presented that the friction coefficient increases in proportion to the logarithm of hold time [23]. However, most previous mechanical shear tests mentioned above were conducted under displacement rate-control, and thermal stress rate has not yet been considered.

In this study, the relation between the fracture friction coefficient and the mechanical loading rate was firstly discussed through biaxial mechanical shear test. And then thermally induced shear slip of the fracture under given initial stress conditions and boundary conditions was investigated. Acoustic emission (AE) monitoring was applied for assessing fracture shear slip.

2. Experimental materials and methods

2.1. Experimental specimens and setups

Pocheon granite mined from the Pocheon region of South Korea was used. The granite has an effective porosity of 0.66% and shows moderate anisotropy due to the abundance of pre-existing microcracks in preferred orientation [25]. The elastic modulus and Poisson’s ratio for the sample with the grain plane perpendicular to the maximum principal stress were measured at 55.09 GPa and 0.275, respectively. For details on the physical and mechanical properties of the anisotropic granite, we refer to Zhuang et al. [26]. The side length of the prepared cubic granite is 100 mm. In order to avoid any contact interaction between the loading plates of the true triaxial testing apparatus and stress concentration, the edges of the cubic granite were cut at the angle of 45° to form effective contact areas of 90 × 90 mm between the loading plates and the specimen surfaces. A single sawcut fracture was created without polishing treatment. The normal to the fracture plane is inclined at around 42° (β) to the maximum principal stress axis. The geometries of the granite specimen and fracture are illustrated in Figure 1 (a). Three specimens, numbered with #1, #2 and #3, were used in this study. Experiments were conducted on a true triaxial test apparatus with its details being shown in Figure 1 (b). It consists of load frames, pressure generators, a hydraulic unit, and a data-acquisition system. The loading capacity is 1,100 kN, and the maximum heat output is 150 °C. In Figure 1 (c), The loading rams in Z and Y directions of the true triaxial testing apparatus were controlled to apply the minimum and maximum principal stresses (σmin and σmax). Each loading ram is comprised of an adapter and a
contact plate. The adapter is equipped with four 125-W heat probes. Four high-temperature-resistant acoustic emission (AE) sensors are embedded in the contact plate, and a ceramic disc provides the steel column with thermal insulation. The deformation of testing materials is measured using LVDTs with accuracy 0.1 μm installed at the back of the steel columns, and the device deformation calibration constant is 1.17 μm/kN in both the Y and Z directions. The multi-channel AE system was utilized to record acoustic AE data throughout the experiment. The AE data were collected via the AEwin software provided by the Physical Acoustics Corporation. The system uses eight 16.5-mm-diameter and 18-mm-height, 50–400-kHz R15S sensors fixed in the contact plate with bolts, and silicone grease was used to fill the gaps (see Figure 1 (c)). The sensitivity range is from -63–+69 dB, and the working temperature range is from -65–+177 °C. Before conducting the multistage biaxial loading shear tests, pencil lead-break tests were carried out to ensure that all sensors were functioning properly and could monitor signals. Eight sensors embedded in contact plates in the Y1 and Y2 sides were connected to the MISTRAS 2/4/6 pre-amplifiers. The voltage gain of all preamplifiers was set to 40 dB, and the AE signal threshold was 60 dB.

Figure 1. (a) Geometries of the sawcut granite fracture, (b) true triaxial test apparatus and multi-channel AE system used in this study, and (c) heat probes and AE sensors in loading rams.

2.2. Experimental procedure
Multistage biaxial loading tests, or biaxial shear tests, were conducted in this study. The experimental procedure consisting of two steps, multistage mechanical shear test and thermoshearing test, is schematically illustrated in Figure 2.

Step 1: Multistage mechanical shear test, Figure 2 (a). At first, the minimum principal stress and the maximum principal stress increased to 0.5 MPa. Then the minimum principal stress remained constant, while the maximum principal stress increased with constant mechanical loading rate, $p = \Delta \sigma_{\text{max}} / \Delta t$, till fracture failure occurred. The fracture failure stresses under different minimum principal stress ($\sigma_{\text{min}} = 0.5$ MPa, 1.0 MPa, and 1.5 MPa) were obtained at the onset of fracture shear slip; and the fracture failure envelope was fitted. Then the fracture was finally critically stressed by remaining the minimum principal stress constant ($\sigma_{\text{min}} = 2.0$ MPa) and increasing the maximum principal stress to the critical stress that was less than the predicted fracture failure stress.

Step 2: Thermoshearing test, Figure 2 (b). The minimum principal stress still remained constant, while the rams in the maximum principal direction were sealed. If we ignored the friction between the
specimen and the plate, the boundary condition in the maximum principal direction was similar to a roller boundary. The temperature of heaters in the minimum principal direction increased to a given value (75°C) and remained constant to transfer heat to granite specimen. The thermal stress ($\Delta \sigma_T$) resulted in the increasing of the initial maximum principal stress.

Two multistage biaxial shear tests, labelled Test #3-1 and Test #3-2, were conducted on Specimen #3. To discuss the effect of mechanical loading rate on prediction of thermally induced fracture shear slip, mechanical shear tests were conducted with mechanical loading rates ($p$) of $1 \times 10^{-3}$ MPa/s and $5 \times 10^{-3}$ MPa/s, respectively.

**Figure 2.** Experimental procedure of the multistage biaxial shear test including two steps: (a) Multistage mechanical shear test and (b) thermoshearing test.

### Results and discussion

2.3. **Failure criterion of the sawcut granite fracture**

In the multistage mechanical shear test of Test #3-1, the stresses and displacements along fracture were calculated; and the cumulative AE hits and absolute energy were recorded, as shown in **Figure 3 (a).**

At each stage, the ratio of shear stress and normal stress increased, and the increasing rate gradually decreased. When the stress ratio increased to the friction coefficient of fracture, fracture shear slip occurred. There were two types of fracture shear slips: fracture shear slip accompanied by shear stress drop, shear displacement jump, and peak shear displacement rate (Stage 1 in **Figure 3 (a) and (b)); and**
fracture shear slip where shear displacement rate gradually increased to the shear slip rate, from $1.21 \times 10^{-2} \text{ } \mu \text{m/s}$ to $6.12 \times 10^{-2} \text{ } \mu \text{m/s}$ in Figure 3 (a) and (c). The fracture shear slip with shear displacement jump occurred at the time of the peak shear displacement rate. The fracture shear slip with a constant shear slip rate began at the intersecting point of the fitted lines of the shear displacement data before and after fracture shear slip (Figure 3 (c)), referring to the bilinear decay method reported in Kim and Jeon [27]. The cumulative AE hits and absolute energy generally increased faster during fracture shear slip than the period before it, or they increased abruptly at the onset of fracture shear slip. There was, however, an abnormal abrupt increase of cumulative absolute energy at the beginning of Stage 2, and the reason was unclear. In Stage 3, the shear slip determined by the fitting method was accompanied by an abrupt increase of cumulative energy. A three-stage mechanical shear test was also conducted in Test #3-2. The mechanical loading rate was $5 \times 10^{-3} \text{ MPa/s}$. The fracture shear displacement rate gradually increased to shear slip rate. And the fitting method in Figure 3 (c) was used to determine the onset of fracture shear slip.

The normal stress ($\sigma_n$) and shear stress ($\tau$) at the onset of the fracture shear slip are listed in Table 1. We fitted the experimental data of the mechanical shear tests in Test #3-1 and -2. The linear Mohr–Coulomb (M–C) failure envelope for the sawcut granite, $\tau = \mu \cdot \sigma_n$, was obtained. The friction coefficient ($\mu$) of the sawcut granite fracture was measured to be 0.78 and 0.74, corresponding to a low and high loading rate of $1 \times 10^{-3}$ MPa/s and $5 \times 10^{-3}$ MPa/s, respectively. Cohesion of natural fractures in granite has been reported to be around 0.1~1.0 MPa depending on the fracture surface roughness and testing conditions [28]. For clean sawcut fracture with no obvious alternation during the experiment, it is more reasonable to assume that the apparent cohesion is ignorable [27].

2.4. Effect of mechanical loading rate on friction coefficient

In the thermoshearing test, fracture shear slip is expected to be induced by the increased initial maximum principal stress. The fracture failure envelope was determined by mechanical shear tests prior to the heating test. Prediction on the fracture shear strength is therefore important for setting of initial stresses on the fracture before heating. In this study, when the temperature of heaters increased by 45°C, the maximum thermally induced stress reached about 2.0–3.0 MPa in an hour. The mechanical loading rate was always larger than the thermal stress rate. Consequently, the multistage mechanical shear tests with a variety of loading rates were conducted to discuss the effect of the loading rate on the determination of the fracture failure envelope, and to reflect the effect of thermal stress rate on the fracture thermoshearing. The Specimen #1 with a sawcut fracture was used to conduct the mechanical shear test with loading rate of $15 \times 10^{-3}$ MPa/s; and the Specimen #2 was used with loading rate of $15 \times 10^{-3}$ MPa/s and $2 \times 10^{-3}$ MPa/s. Experimental data are listed in Table 1.

| Test (Loading rate) | $\sigma_{\text{max}}$ (MPa) | $\sigma_{\text{min}}$ (MPa) | $\tau$ (MPa) | $\sigma_n$ (MPa) | $\mu$ |
|---------------------|-----------------------------|-----------------------------|--------------|----------------|------|
| Test #1-1 (15×10^{-3} MPa/s) | 9.48 | 1.23 | 4.11 | 5.79 | 0.7057 |
| Test #1-2 (2×10^{-3} MPa/s) | 18.92 | 2.47 | 8.14 | 11.56 | 0.7124 |
| Test #2-1 (15×10^{-3} MPa/s) | 28.11 | 3.70 | 12.14 | 17.19 | 0.7124 |
| Test #2-2 (5×10^{-3} MPa/s) | 37.26 | 4.94 | 16.08 | 22.79 | 0.7124 |
| Test #3-1 (1×10^{-3} MPa/s) | 6.41 | 0.61 | 2.88 | 3.82 | 0.7124 |
| Test #3-2 (5×10^{-3} MPa/s) | 11.34 | 1.23 | 5.03 | 6.82 | 0.7124 |

Table 1. Stress states on the fracture at the onset of fracture shear slip in the mechanical shear tests, and friction coefficient under different loading rate.
The friction coefficient decreased with the increase of loading rate. The linear relationship between friction coefficient and the $\lg(\rho)$ was also obtained in Figure 4. The friction coefficient is 0.77 in Figure 4 when the loading rate is very low, $1 \times 10^{-3}$ MPa/s, closing to the thermal stress rate in this study.

![Figure 4](image)

**Figure 4.** Relationship between friction coefficient ($\mu_s$) and mechanical loading rate ($\rho$). Experimental data were obtained from Specimen #1, #2, and #3.

2.5. Thermally induced fracture shear slip

In Test #3-1, and -2, after the three-stage mechanical shear tests, the minimum principal stresses were subsequently increase to 2.0 MPa; the initial critical maximum principal stresses were applied, and the deformation in this direction was constrained. The thermoshearing test results in Test #3-1, and -2 are illustrated in Figure 5. At the beginning of thermoshearing tests, the ratios of shear stress and normal stress were around 0.76 and 0.72 in Test #3-1, and -2. The temperature of heaters in Test #3-1 increased by 45°C from room temperature for more than 2 h (red solid curve in Figure 5 (a)). When the cumulative absolute energy abruptly increased, which might be accompanied by a small stress drop, the fracture thermoshearing might occur [17, 29]. There were four visible sudden increases of cumulative absolute energy during fracture thermoshearing. The stress ratio almost increased to the mechanically measured friction coefficient, 0.77. At the end of the thermoshearing test, the temperature increment of the granite measured at the front surface centre is around 20°C. In Figure 5 (b), the temperature of heaters in Test #3-2 was also increased by around 45°C; but the heating time was only 1 h. No sudden increase of AE energy and hits was recorded even though the stress ratio increased to mechanically measured friction coefficient, 0.74. There was no fracture thermoshearing. The friction coefficient determined according to the mechanical loading test with loading rate of $5 \times 10^{-4}$ MPa/s was smaller than the friction coefficient of fracture in thermoshearing test. Thermally-induced stress resulting in an increased maximum principal did not trigger a shear slip because the stress state on fracture did not reach the failure envelope.
In Figure 6, we presented temporal evolution of the maximum principal stress increment and cumulative AE energy with heating time in Test #3-1 and -2. Theoretically, one-dimensional thermal stress in the constrained region is determined by only temperature increment, elastic modulus and the coefficient of linear thermal expansion of the rock. If there was no fracture thermoshearing, the evolution of thermal stress in two tests should be same during the heating period. In the early period, from 0 to 1.0 MPa, the stress increased rapidly, and stress rates were almost same for both two tests, being around $9 \times 10^{-3}$ MPa/s. Thermal stress rate was approximately equal to the mechanical loading rate of Test #3-1, and much smaller than that in Test #3-2. The fracture failure envelope that was determined from the mechanical loading test with loading rate of $1 \times 10^{-3}$ MPa/s precisely predicted the fracture shear slip under the coupled TM condition. After the thermal stress increased to around 1.0 MPa, the fracture thermoshearing occurred in Test #3-1, which resulted in the difference of the maximum principal stress increment between Test #3-2 and Test #3-1, and was accompanied by the abrupt and intermittent increase of AE energy. There was no fracture thermoshearing in Test #3-2 because there was no abrupt increase of AE energy.

The effect of the loading rate-dependent frictional resistance of fracture on the prediction of thermally induced shear slip is schematically illustrated in Figure 7. The mechanical loading rate is the time derivative of the maximum principal stress, $p = \Delta \sigma_{\text{max}} / \Delta t$; the thermal stress rate is the time derivative of the thermal stress in the direction of the maximum principal stress, $\Delta \sigma_{T} / \Delta t$. If the thermal stress rate is closed to the mechanical loading rate, the predicted value is closed to the friction coefficient under thermoshearing test (Figure 7 (a)); however, if the thermal stress rate is much smaller than the mechanical loading rate, the friction coefficient at low loading rate under coupled TM condition is much larger than that obtained at high mechanical loading rate (Figure 7 (b)).
Conclusions

3. Increases in the range of 1–15 MPa/s, the coefficient of the saw fracture decreases in proportion to the increase of the logarithm of loading rate, the friction coefficient of the fracture is loading rate dependent. In the mechanical loading, the friction coefficient of the sawcut granite fracture is loading rate dependent. In the mechanical loading, the friction coefficient of the saw fracture decreases in proportion to the increase of the logarithm of loading rate, and the frictional resistance decreases in proportion to the increase of the logarithm of loading rate, the friction coefficient of the fracture is loading rate dependent. In the mechanical loading, the friction coefficient of the saw cut granite fracture, and the fracture coefficient of the fracture is loading rate dependent. In the mechanical loading, the friction coefficient of the saw cut granite fracture decreases in proportion to the increase of the logarithm of loading rate, in the range of 1–15×10^3 MPa/s.

Figure 7. Effect of the loading rate-dependent frictional resistance of fracture on the prediction of thermally induced shear slip: (a) Thermal stress rate closing to the mechanical loading rate, and (b) thermal stress rate much smaller than the mechanical loading rate. The blue Mohr circle is the critical stress condition; the red Mohr circle is the stress condition due to thermally induced increased maximum principal stress; and the dash red Mohr circle is the predicted failure stress condition underestimating the friction coefficient.

Under the coupled TM condition, another parameter possibly affecting the fracture friction coefficient is the temperature. Previous study has shown that the friction coefficient of granite fracture slightly increases with the increase of temperature in the low temperature range below 350 °C. In this study, however, the target temperature at the heater is 75 °C, and the temperature measured in the rock is even lower than the target temperature. And the granite fractures are not sensitive to a temperature below it. Consequently, the analysis with no consideration for temperature is reasonable.

3. Conclusions

We presented the experimental results of the thermally induced shear slip tests conducted on a sawcut fracture in granite. The multistage mechanical shear tests were also conducted to discuss the effect of mechanical loading rate on the friction coefficient. Conclusions are as follows.

(1) The linear M-C failure criterion can be used to predict shear slip of the saw cut granite fracture, and the friction coefficient of the fracture is loading rate dependent. In the mechanical loading, the friction coefficient of the saw fracture decreases in proportion to the increase of the logarithm of loading rate, in the range of 1–15×10^3 MPa/s.

(2) Under the unidirectional heating applied in this study, the maximum thermal induced loading rate on the granite sample was observed to be around 0.9×10^3 MPa/s. Shear slip of the fracture occurred during the heating, and this can be well predicted by the M-C failure envelope, which was obtained from the mechanical shear test at a similar magnitude of loading rate.

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