A Study on Shear Characteristics of a Smooth Rock Surface under Different Thermal and Mechanical Conditions

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Abstract. High-level radioactive waste repositories are designed to ensure long-term stability, and it is necessary to consider different effects at depth in various aspects. Many uncertainties are involved in characterizing rock mass deformation and failure in the designing process. The interactions between fluid flow, high temperature and stress disturbance must be considered. In this study, multi–stage triaxial compression tests were conducted to investigate the shear characteristics of a saw-cut surface of crystalline rock under different thermal-mechanical conditions. Granitic rock was taken from KURT (KAERI Underground Research Tunnel) for the tests. The artificial shear surface was cut, using diamond saw, at 28° from the direction of loading. The thermal-mechanical testing condition was decided by considering the actual condition at the vicinity of a canister. Three different confining pressures, 5, 10, 15 MPa, were applied during the test at two different temperatures 20° C and 80° C. The shearing behavior of a saw-cut surface was analyzed based on the Mohr-Coulomb failure criterion. From the experimental results, the shear characteristic of the granitic rock was observed to be sensitive to confining pressure but not to temperature. Numerical analysis was conducted using COMSOL to simulate the test, providing a good agreement with the experimental results.

Keywords: Multi-stage triaxial compression test, T-M coupled process, shear behavior, crystalline rock.

1 Introduction

A high-level radioactive waste disposal facility is usually designed to be stable for an extended period of time as long as 10,000 years. To ensure the mechanical, hydrological and chemical stability of the facility, long-term performance is assessed with respect to many different variables and their coupled effects. It is well-known that the international cooperative project DECOVALEX accumulated a lot of information and knowledge of coupled processes in fractured rock masses. In addition, many independent studies were carried out to investigate the T-H-M-C coupled effects in numerical and experimental methods. They include research

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works by Lockner et al. (1982), Elliott and Brown (1988), Yoon and Jeon (2004), Wanne and Young (2008) and many more.

However, few studies have been carried out on the shearing behavior of a shear surface of crystalline rock at an elevated temperature. In this study, a series of laboratory scale experiments were carried out to investigate the shearing behavior of a smooth surface of crystalline rock under triaxial compression with the simulated stress condition at depth and temperature condition in the vicinity of a canister for high-level radioactive waste. The test results were analyzed using Mohr-Coulomb criterion. In addition, numerical analysis was carried out using COMSOL Multiphysics to simulate the test.

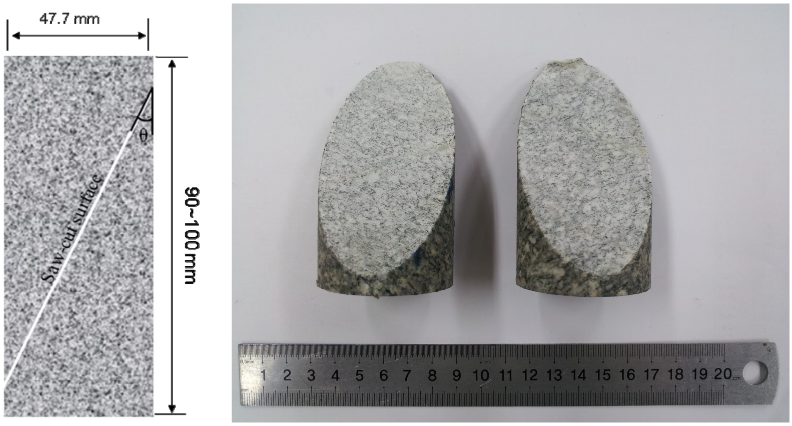
2 Experimental Study

2.1 Sample Preparation

Granitic rock cores obtained during site investigation at KURT (KAERI Underground Research Tunnel) were taken as test specimens. The specimens used in the tests were from a depth of 70 - 80 m. The size of the specimen for the triaxial compression test was approximately 47.7 mm in diameter and 100 mm in height. To make a smooth shear surface, the specimens were cut by a diamond saw and the angle of the saw-cut surface, θ, was 28° from the axis of the specimen as shown in Fig. 1. Table 1 presents the specification of a typical specimen.

2.2 Experimental Method

Multi-stage triaxial test can generate a full failure envelope using a single specimen (Kovari et al. 1983). In this study, the multi-stage triaxial compression tests were performed under various confining pressure and temperature conditions.



(a) (b)

Fig. 1 Configuration of the test specimen: (a) cross-sectional view of the specimen, and (b) picture of the specimen with saw-cut surface

Table 1 Specification of the specimens

Testing condition	Sample ID	Diameter (mm)	Height (mm)	Inclined angle θ (°)
M	A_M_1	47.7	96.5	28
	A_M_2	47.7	97.8	28
T-M	A_TM_1	47.7	101.6	28
	A_TM_2	47.7	86.7	28

Fig. 2 View of experimental set-up of multistage triaxial compression test under elevated temperature condition

To apply heat to the specimen during the test, the triaxial chamber was filled with oil and heated by a thermal jacket. The temperature was controlled at an accuracy of ±5°C. Pre-heating was required to make the temperature even throughout the chamber. The axial deformation of the specimen was not allowed during the pre-heating stage, which caused stress build-up in the specimen. Fig. 2 shows the view of the experimental set-up for the multi-stage triaxial compression test.

2.3 Testing Conditions

After preliminary study, variable testing conditions were decided as presented in Table 2. The temperature was set at 20°C and 80°C for the test. The rock temperature around the canister was reported to reach up to 80°C according to

Kwon and Cho (2009). The heating rate was set at 3°C per minute to prevent thermal shock to the specimen. In order to reduce the thermal gradient inside the specimen, the peak temperature was maintained for 90 minutes. Different confining pressures, 5, 10, 15 MPa, were applied to the specimen using a servo-controlled hydraulic unit with the accuracy of 0.1 MPa.

2.4 Results and Discussion

As the test specimen approached the peak axial stress, sliding occurred along the saw-cut surface creating small amount of gouge. Peak shear strength and friction angle of the shear surface were investigated using Mohr-Coulomb failure criterion. Results of the experiments are summarized in Table 3. Fig. 3 shows the relationship between the normal stress and shear stress acting on the shear surface.

Table 2 Variable conditions for the multi-stage triaxial compression test under various mechanical and thermal conditions

Temperature of specimen (°C)	Heating rate (°C/min)	Loading rate (mm/min)	Confining pressure (MPa)
20, 80	≤ 3.0	3.0	5, 10, 15

Table 3 Results of multi-stage triaxial compression test on saw-cut specimens under the room temperature (20° C) and the elevated temperature conditions (80°C)

<table>
<tr><th>Testing condition</th><th>Sample ID</th><th>Confining pressure, σ_3 (MPa)</th><th>Peak axial stress, σ_1 (MPa)</th><th>Normal stress, σ_n (MPa)</th><th>Shear stress, τ (MPa)</th><th>Friction angle (°)</th></tr>
<tr><td rowspan="6">M</td><td rowspan="3">A_M_1</td><td>5</td><td>10.28</td><td>6.16</td><td>2.19</td><td rowspan="3">30.47</td></tr>
<tr><td>10</td><td>23.96</td><td>13.08</td><td>5.78</td></tr>
<tr><td>15</td><td>40.89</td><td>20.71</td><td>10.73</td></tr>
<tr><td rowspan="3">A_M_2</td><td>5</td><td>10.73</td><td>6.26</td><td>2.38</td><td rowspan="3">28.13</td></tr>
<tr><td>10</td><td>25.24</td><td>13.36</td><td>6.32</td></tr>
<tr><td>15</td><td>38.75</td><td>20.23</td><td>9.85</td></tr>
<tr><td rowspan="6">T-M</td><td rowspan="3">A_TM_1</td><td>5</td><td>13.13</td><td>6.79</td><td>3.37</td><td rowspan="3">29.36</td></tr>
<tr><td>10</td><td>29.65</td><td>14.33</td><td>8.15</td></tr>
<tr><td>15</td><td>42.42</td><td>21.04</td><td>11.37</td></tr>
<tr><td rowspan="3">A_TM_2</td><td>5</td><td>9.46</td><td>5.98</td><td>1.85</td><td rowspan="3">26.38</td></tr>
<tr><td>10</td><td>25.55</td><td>13.43</td><td>6.44</td></tr>
<tr><td>15</td><td>35.50</td><td>19.52</td><td>8.50</td></tr>
</table>

The friction angle does not show much difference between room temperature (20°C) and the elevated temperature (80°C). The peak shear stress increased with the increase of confining pressure, but it did not show much variation with the increase of temperature. According to Lockner et al. (1982), the frictional property of sandstone was independent of temperature at 150°C and 240°C, the friction angle of granite was also independent **o**f the temperature in the range of 80°C in this study.

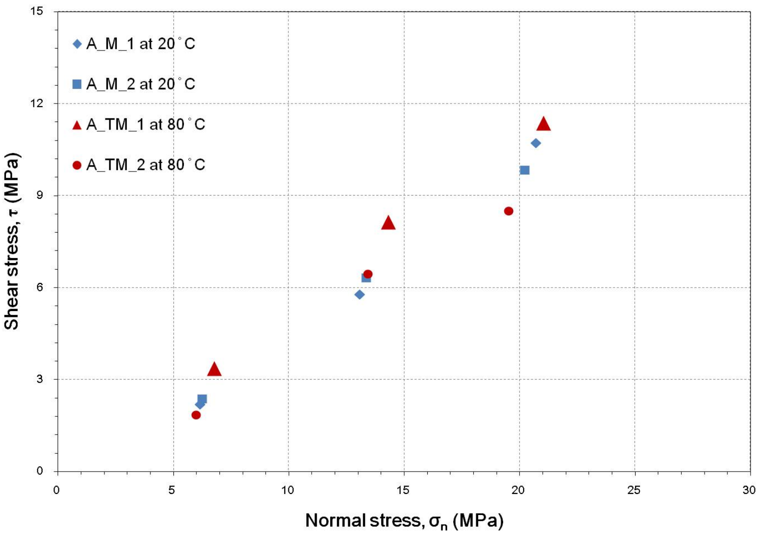


Fig. 3 Relations between normal stress and shear stress acting on shear surface under the room temperature (20°C) and the elevated temperature (80°C) conditions

3 Numerical Simulation

3.1 Model Introduction

The numerical analysis was carried out using COMSOL Multiphysics, which provides a powerful and flexible modeling environment for solving partial differential equations. The numerical simulation for multi-stage triaxial compression test on a saw-cut specimen was carried out under a plane strain condition in the two-dimensional model.

The built-in Structural Mechanics Module and Heat Transfer Module of COMSOL Multiphysics are used to simulate the thermal-mechanical coupled behavior. The saw-cut surface was set as a boundary contact pair and frictional characteristics were modeled based on the Coulomb friction criterion (COMSOL AB. 2008).

The numerical model has the same dimension as the test specimen. The linear quadrilateral element was used and 14,880 quadrilateral meshes were generated as shown in Fig. 4. Rock was assumed to be a homogeneous and isotropic material. The input parameters used in the numerical simulation are listed in Table 4.

For the simulation at the elevated temperature condition, the coefficient of thermal expansion of granite specimen was assumed to be 10×10^{-6}/°C (Kim et al. 2011). The model expands with the increase in temperature, causing thermal strain in the material. The thermal stress is induced by the thermal expansion of the model.

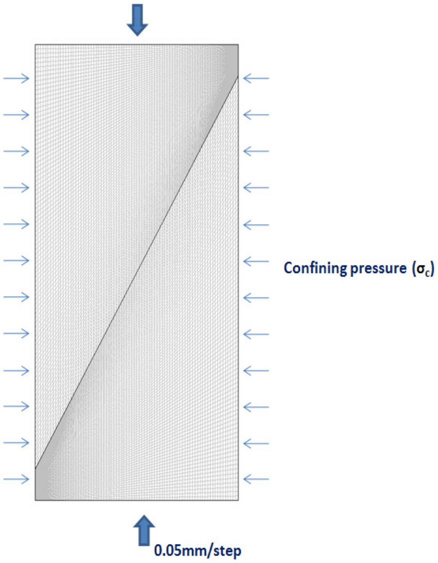


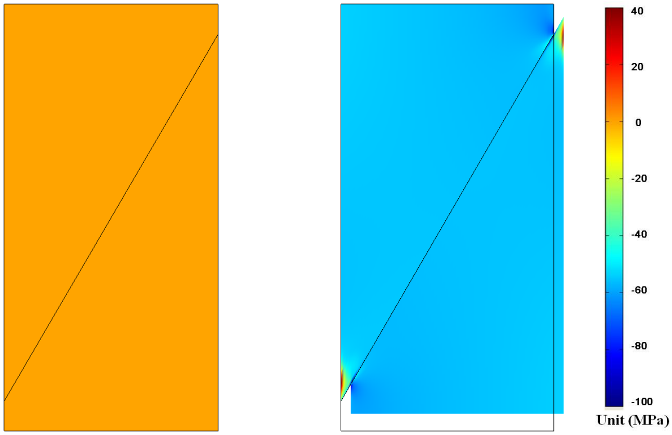
Fig. 4 Two-dimensional model setup and boundary condition

Table 4 Input parameters used in the numerical simulation

Parameter	Value
Young's modulus (GPa)	60
Poisson's ratio	0.20
Density (kg/m^3)	2660
Coefficient of thermal expansion (10^{-6}/°C)	10

3.2 Results and Discussion

Fig. 5 shows the deformation and maximum principal stress distribution in the specimen during the multi-stage triaxial compression test at room temperature. Sliding occurred along the saw-cut surface and the results of the numerical analysis are summarized in Table 5.



(a) Initial state (b) Final state

Fig. 5 Deformation presented in the numerical model with maximum principal stress distribution under the room temperature (20° C) condition

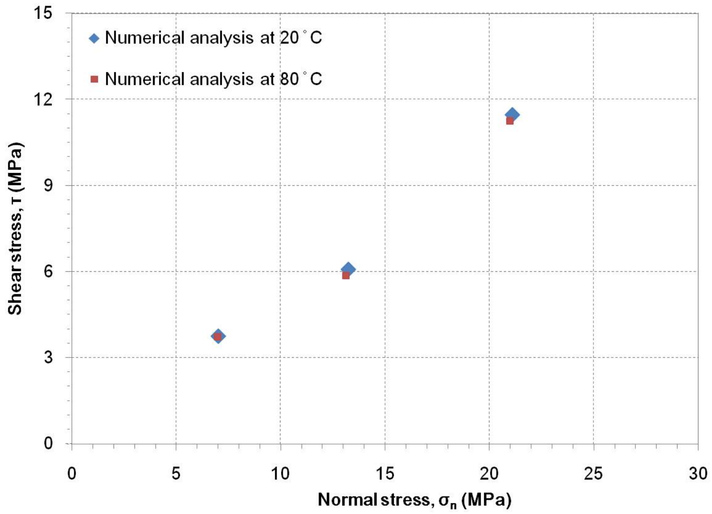


Fig. 6 Relations between normal stress and shear stress acting on shear surface at room temperature (20°C) and elevated temperature (80°C)

The shear behavior under multi-stage triaxial compression conditions and the friction angle of the numerical analysis coincided with those observed in the laboratory tests. Fig. 6 shows the relationship between the normal and the shear stress acting on the shear surface under different temperature conditions.

Table 5 Results of numerical simulation

Testing condition	Confining pressure, σ_3 (MPa)	Peak axial stress, σ_1 (MPa)	Normal stress, σ_n (MPa)	Shear stress, τ (MPa)	Friction angle (°)
Room temperature (20°C)	5	14.07	7.00	3.76	28.97
	10	24.70	13.24	6.09	
	15	42.71	21.11	11.49	
Elevated temperature (80°C)	5	14.05	7.00	3.75	28.53
	10	24.15	13.12	5.86	
	15	42.16	20.99	11.26	

The shear stress increased with the increase of normal stress however the friction angle and shear stress did not vary with the increase of temperature. From the analysis, the thermal stress due to the change in temperature was too small to cause a noticeable change in the shearing characteristics of the specimen.

4 Conclusions

A multi-stage triaxial compression test was carried out for a granitic rock specimen having a saw-cut shear surface. The confining pressure and temperature were varied in the test the values of which were decided considering the actual condition in the vicinity of the canister. The results were analyzed by Mohr-Coulomb failure criterion. Peak shear stress varied with the increase in confining stress however the peak shear stress and friction angle of the granitic rock did not vary much at the elevated temperature of 80°C in the present study.

In order to simulate the test, a series of biaxial compression tests were carried out using COMSOL Multiphysics, providing a good agreement with the experimental results.

In the present study, the thermal effect on shearing behavior of the crystalline rock was investigated. Based on the results, the shearing behavior under added hydraulic conditions is to be studied in the future.

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