AN EXPERIMENTAL STUDY ON THERMAL RESPONSE OF ROCK DISCONTINUITIES DURING CYCLIC SHEARING BY INFRARED (IR) THERMOGRAPHY

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Cyclic shear responses of discontinuities in relation to dynamic responses of rock structures are quite important when they are subjected to cyclic loads resulting from the machinery, traffic or earthquakes. As expected from the conservation of energy, the cyclic shearing of discontinuities would be resulting in heating along discontinuities, which may cause the degradation and softening of adjacent rocks. The authors carried out an experimental study on natural schistosity planes of two quartzite plates using a special set-up and thermal responses were measured using Testo 885 Infrared camera. In experiments, the normal stress was varied out. In this study, the authors would describe the experimental results and discuss their implications.

Key Words : *infrared, thermography, cyclic shear test, quartzite, discontinuity, degradation.*

1. INTRODUCTION

Discontinuities in rock mass is one of characteristics of rock masses in nature and they are found in various forms such as cracks, joints, schistosity, bedding and flow planes and faults. Discontinuties have a great influence on the overall response and stability of structures.

Rock discontinuities may be subjected to cyclic shear loads resulting from the machinery, traffic or earthquakes. Such conditions may be of great significance in relation to the long-term stability of the structures and during earthquakes as well as in the science of earthquakes. There are many experimental studies on the cyclic shearing response of rock discontinuities and interfaces. These studies are mostly concerned with the shear strength properties of rock discontinuities using conventional load-displacement responses without any attention to the thermal effects, which may result from cyclic shear loading.

Intuitively, it is well known that heat is produced during sliding and shearing movements associated with frictional forces. On the theoretical basis of energy conservation law, the cyclic shearing of discontinuities would be resulting in heating along discontinuities. It is well-known that rocks become weaker when they are heated. Therefore, the heating along discontinuities would undoubtedly affect the shearing properties of discontinuities and it may also cause the degradation and softening of adjacent rocks.

The authors performed an experimental study on natural schistosity planes of two quartzite plates using a special set-up and thermal responses were measured using Testo 885 Infrared (IR) Camera.. In experiments, the normal stress was varied and thermal response of discontinuities and adjacent rocks are monitored. The experimental setup, characteristics of infrared camera and discontinuities and experimental results are described and their implications in geomechanics and geoengineering are discussed.

2. EXPERIMENTAL SET-UP

The experimental set-up consists of a shaking table, Testo 885 infrared camera, accelerometers, non-contact displacement measurement acquisation system and a specimen. In addition a contact type temperature sensor is attached to next to the discontinuity plane on the upper block. The shaking table is utilized to induce cyclic shearing on the discontinuity planes. The stroke of shaking table is 20 mm with a maximum speed of 240 RPM and its speed can be adjusted any desired level.

The shearing motions are monitored using accelerometers and non-contact laser transducers produced by KEYENCE. A stand-alone type accelerometer QV3-OAM-SYC is attached to the shaking table to measure imposed accelerations , which may also be used to evaluate the other dynamic motion parameters.

The specimen consists of lower and upper blocks. The lower block is attached to the movable shaking table while the upper block is attached to unmovable support as illustrated in Figure 1. The reason to attach the lower block to the shaking table was to prevent rotational movements during shearing. Figure 2 shows a view of a typical experimental set-up .

A contact type temperature sensor was fixed to nearby the discontiuity plane in the first experiment. As the measured responses were not as accurate as those from the infrared camera, it was decided not use it in the rest of experiments.

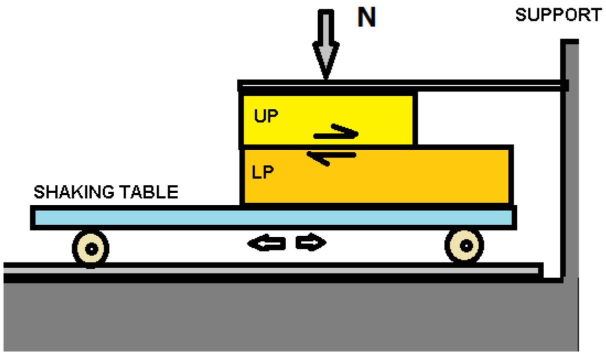


Figure 1. An illustration of experimental setup.

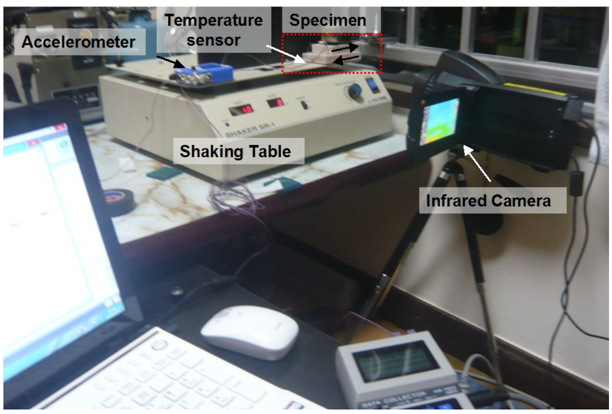


Figure 2. A view of experimental set-up and instrumentation

Some experiments were also carried out using Testo 880 IR camera. However, the sensitivity of the camera and the resolution of IR images were much lower than Testo 885 IR camera. Furthermore, the continuous recording was not possible due to limitations of the Testo 880 IR camera. Therefore, the experiments done using the Testo 880 IR camera would not be reported in this article.

3. EXPERIMENTAL MATERIALS

Experimental material is blocks of metamorphic quartzite. Geometrical dimensions, mechanical and frictional properties of blocks are given in Tables 1-3. Schistosity planes are chosen as shearing planes. Schistosity planes also include some micaceous minerals such as muscovite.

Table 1. geometry and weight of blocks

Block	Length (mm)	Width (mm)	Height (mm)	Weight (gf)
UB	73.1	49.7	14.8	134
LB	90.4	60.8	14.2	197

Table 2. Material properties

Unit Weight (kN/m^3)	UCS (MPa)	Elastic Modulus (GPa)	P-wave velocity (km/s)	S-wave velocity (km/s)
24.9-25.2	194	196	4.86	2.47

Table 3. Friction properties

State	Fresh Sample	Worn sample
Friction angle	23-26	21-23

4. EXPERIMENTS

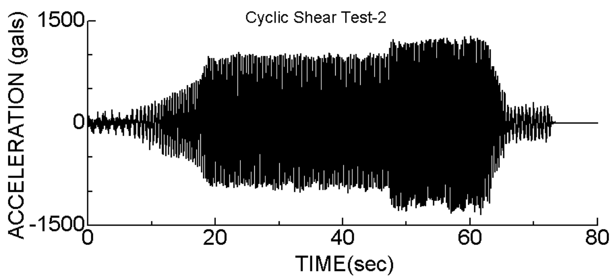
The number cyclic shear test was 5 and the normal stress was varied. Table 4 gives the normal stress levels in a respective cyclic shear test. Although the level of normal stress is lower compared with those used in conventional shearing test, these normal stress levels should be appropriate if distinct heating response is achieved. There is no doubt that the heating would be higher if normal stress level and/or shearing velocity becomes higher. Athough the normal stress level is comparatively small, the maximum shearing velocity was about 1 mm/s in all experiments. Furthermore, the duration of shearing is another factor influencing the thermal responses. The responses and results of experiments numbered CST-2, CST-3 and CST-5.

Table 4. Test names and normal streses

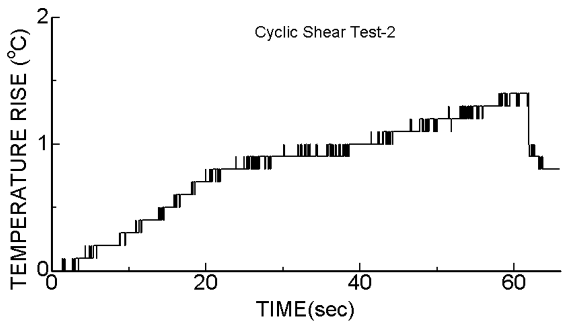
Test Name	Normal stress (kPa)
CST-1	0.37
CST-2	2.05
CST-3	3.73
CST-4	5.87
CST-5	11.37

(1) Cyclic Shear Test –2 (CST-2)

Figure 3 shows the acceleration applied to the shaking table and temperature response of the point with highest temperature rise during the experiment. . The maximum surface temperature rise was 1.4 Celcius at the point where the highest temperature was observed. The maximum amplitude of the acceleration was 1346 gals. Surface temperature of the sample during three selected time steps (namely, 0 s, 30 s and 60 s) are shown in Figure 4. Although the discontinuity plane is apparently almost planar, surface temperature distribution of the specimen was not uniform. The highest temperature rises apparently occur at contact areas over the discontinuity plane. In other words, the temperature rise or heat release would be higher at asperities of rock discontinuities during shearing process. It is also interesting to note that temperature rise is much steeper in relation to the increase of amplitude of acceleration.



(a) Applied acceleration



(b) Temperature response of the point with highest temperature rise

Figure 3. Applied acceleration and temperature response

(2) Cyclic Shear Test –3 (CST-3)

Figure 5 shows the applied acceleration to the shaking table and temperature response of the point with highest temperature rise during the experiment. The maximum amplitude of the acceleration was almost the same as that of the previous experiment. The maximum surface temperature rise was 1.8 Celcius at the point where the highest temperature was observed.. The increase in the temperature rise in this experiment compared to that in the previous experiment is directly associated with the increase in normal stress level..

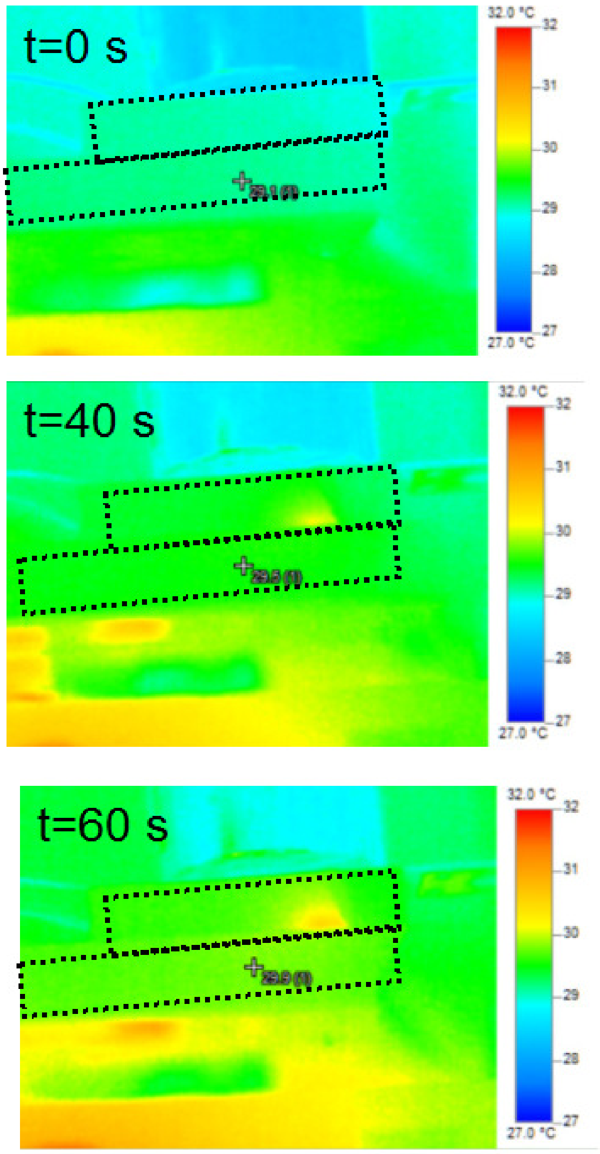
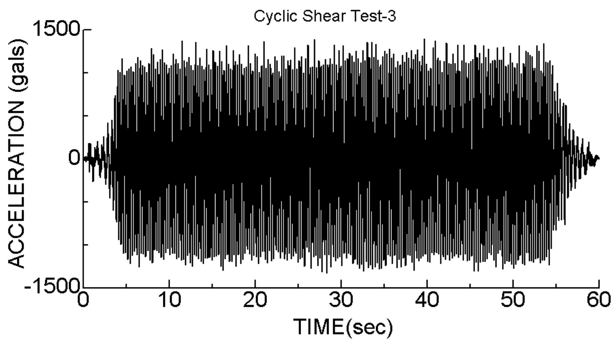
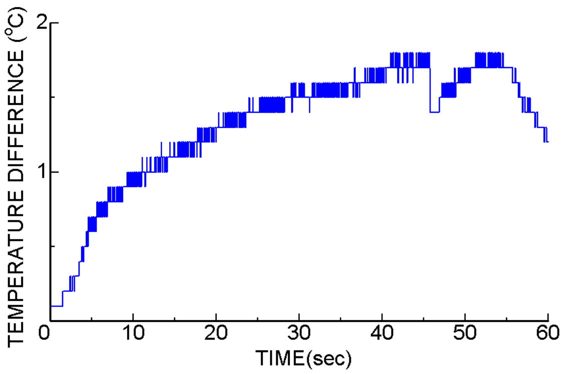


Figure 4. Temperature distribution at selected time steps

Surface temperature of the sample during three selected time steps (namely, 0 s, 25 s and 55 s) are shown in Figure 6. Surface temperature distribution of the specimen was not uniform and the highest temperature rises apparently occurred at contact areas (namely asperities) over the discontinuity plane. It is also interesting to note that temperature rise is also much steeper while the amplitude of acceleration is increasing. On the other hand, if the shearing speed in constant, the heat release or temperature rise increase at a constant rate. A drop in time-temperature rise response is probably due to external causes related to temperature fluctuations in the vicinity of the testing environment.



(a) Applied acceleration



(b) Temperature response of the point with highest temperature rise

Figure 5. Applied acceleration and temperature response

(3) Cyclic Shear Test –5

The normal stress level increased and it was almost twice that of the experiment denoted Cyclic Shear Test –5. Figure 7 shows the applied acceleration to the shaking table and temperature response of the point with highest temperature rise during the experiment. The maximum amplitude of the acceleration was slightly lower that that in other experiments and its maximum amplitude was 1186 gals. The maximum surface temperature rise was 3.6 Celcius with a fluctuation range of ±0.3 Celcius. The initially selected point moves in space during shaking while the selected point in the thermographic image remains the same. Nevetheless, the maximum temperature rise is twice that of the experiment denoted Cyclic Sheat Test-3. The increase in the temperature rise in this experiment compared to that in the previous experiment is directly associated with the increase in normal stress level .

Regarding the temperature rise, it is again worth to notice that temperature rise is much steeper while the amplitude of acceleration is increasing. On the other hand, if the shearing speed in constant, the heat release or temperature rise increases at a constant rate.

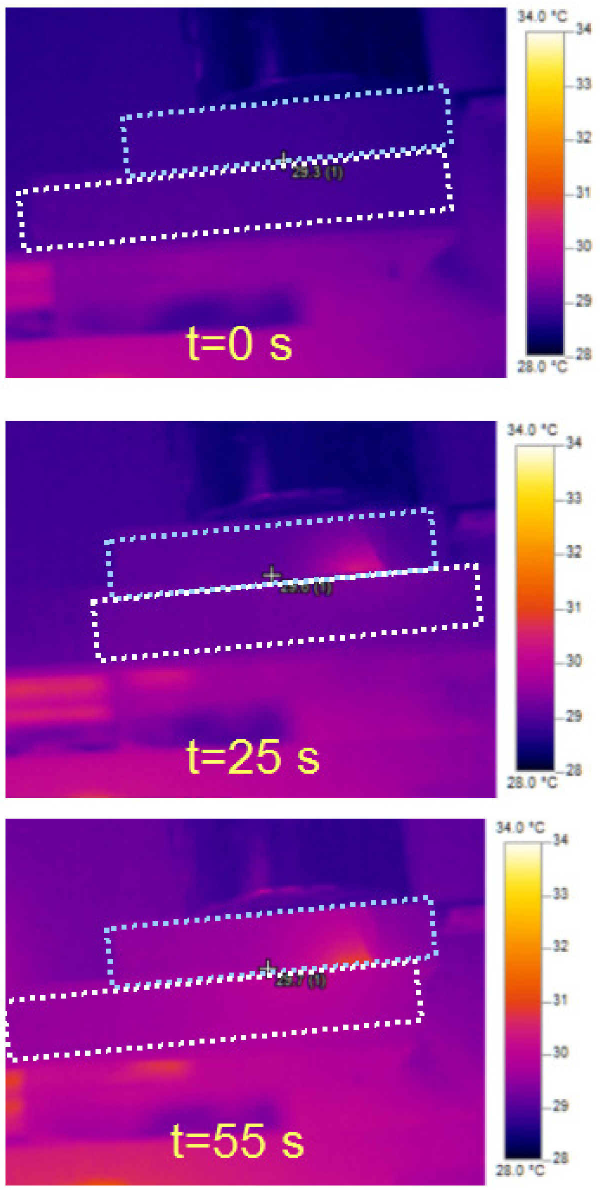
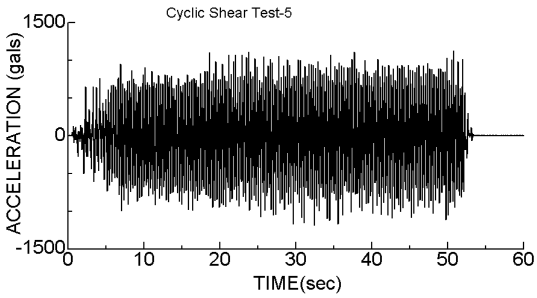


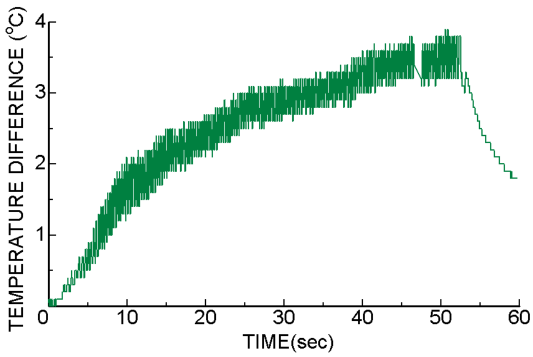
Figure 6. Temperature distribution at selected time steps

Surface temperature of the sample during three selected time steps (namely, 0 s, 25 s and 50 s) are shown in Figure 8. It is also noted that the surface temperature distribution of the specimen was not uniform and the highest temperature rises apparently occurred at contact areas (namely asperities) over the discontinuity plane. Compared to the contact areas in the previous experiments, the number of contact areas increased due to higher normal stress applied in the experiment.

After the experiments, it was noted that a thin powder layer accumulated on the surface of discontinuity surfaces as seen in Figure 9. In other words, asperities were partially worn out and the damage to asperities of the lower mobile block was higher than that of those at the stationary upper block.



(a) Applied acceleration



(b) Temperature response of the point with highest temperature rise

Figure 7. Applied acceleration and temperature response

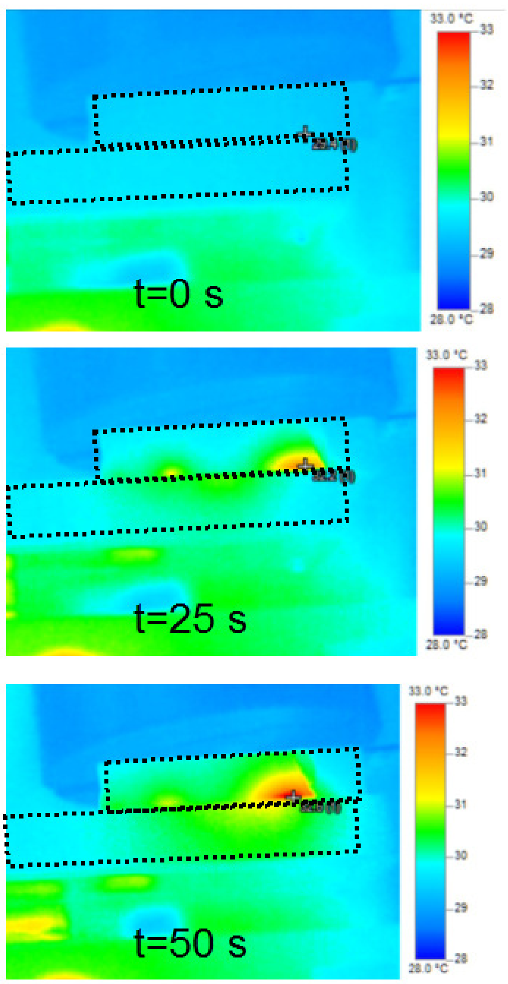


Figure 8. Temperature distribution at selected time steps

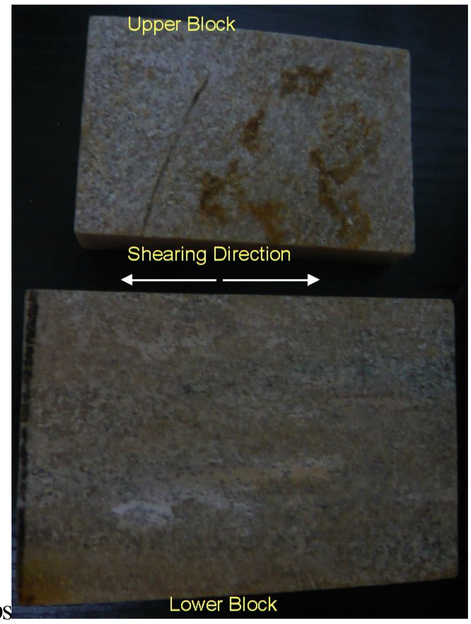


Figure 9. Views of sheared surfaces

5. DISCUSSIONS AND IMPLICATIONS

The responses of temperature rises for all experiments are plotted in Figure 10. As noted from the figure, the temperature rise is highest for the experiment denoted Cyclic-Shear-test-5 while it is lowest for the the experiment denoted Cyclic-Shear-test-1. The temperature rise is higher during the increase of shearing rate and temperature increase become linear as the shearing rate becomes constant. The temperature rise is also related to the duration of shearing. The temperature becomes higher as the duration of shearing increases.

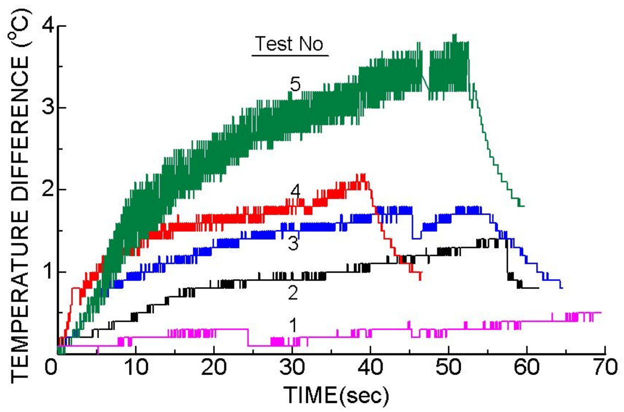


Figure 10. Comparison of responses of temperature rises for all experiments.

The responses observed throughout experiments can be explained through the consideration of the energy conservation law of the continuum mechanics (i.e. Eringen, 1980; Aydan 2000; 2009) . The energy conservation law for shearing experiments may be written as

$$\rho c \frac{\partial T}{\partial t} = -\nabla q + \tau \dot{\gamma} \quad (1)$$

Where $\rho, c, T, q, \tau, \dot{\gamma}$ are density, specific heat, temperature, heat flux, shear stress, shear strain rate , respectively. The heat flux is related to temperature through Fourier law and it is given for one-dimensional case as

$$q = -k \frac{\partial T}{\partial x} \quad (2)$$

where k and x are thermal conductivity and physical space, respectively. Temperature rises observed in the experiments reported in this study can be easily evaluated using the imposed cyclic shearing condition, frictional characteristics of discontinuities and thermal properties of adjacent rock blocks.

The experimental results should have also some implications in the science of earthquakes besides those in geo-engineering. It is often reported that new hot-springs appear soon after the earthquake and some illumination of sky (particulary in nights. The author has personally observed the same phenomena in the 1999 Kocaeli earthquake (Aydan et al. 1999)) occurs during and after earthquakes.

4. CONCLUSIONS

The following conclusions can be drawn from the experiments reported in this study:

1) Cyclic shearing induces temperature rises along discontinuities and adjacent rock mass.

2) Temperature rise depends on the dynamic shearing rate, normal stress and frictional properties of discontinuities as well as thermal properties of adjacent rocks. The increase of normal stress, dynamic shearing rate and frictional properties proportionally increase the temperature rise. Particularly normal stress and dynamic shearing rate have great influence on the overall rise of temperature.

3) Surface temperature distribution of the specimens was not uniform and the highest temperature rises apparently occurred at contact areas (namely asperities) over the discontinuity plane.

4) A thin powder layer accumulated on the surface of discontinuity surfaces after completion of the experiment. This thin layer observed on asperities were partially worn. Furthermore, the damage to asperities of the lower mobile block was higher than that of those at the stationary upper block..

5) The responses observed throughout the experiments reported in this study can be explained through the consideration of the energy conservation law of the continuum mechanics

6) The experimental results have also some implications in the science of earthquakes such as the illumination phenomenon besides those in geo-engineering.

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赤外線カメラによる岩盤不連続面の繰り返しせん断時の温度応答に関する実験的研究

藍檀 オメル、布施 剛、伊東 孝

機械・交通や地震などによって繰り返しせん断を受ける岩盤不連続面の繰り返しせん断挙動の把握は岩盤構造物の応答・安定性の観点から最も重要である．エネルギー保存則から推定されるように，繰り返しせん断を受ける不連続面とその周辺岩盤に温度変化が発生するであろう．その結果、岩盤不連続面のせん断剛性とせん断強度の低下が生じることが考えられる．本研究で、変成質硅岩の構成された片理面の繰り返しせん断試験を行い，赤外線カメラ（Testo 885）によってその温度応答を計測その意味合について論じている．