EXPERIMENTAL STUDY ON CRACK DEVELOPMENT OF ROCK SPECIMENS BY FREEZING AND THAWING CYCLES

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ABSTRACT

Studying freezing and thawing mechanisms is important to understand rock slope failures in cold regions. This study investigated crack development in rock specimens by freezing and thawing action. Rock specimens were prepared from welded tuff. A freezing test was conducted in a temperature-controlled chamber where the temperature varied from +5°C to -18°C. The frozen rock specimens were thawed in distilled water. The test lasted 3.5 hours for each freeze-thaw cycle, including 2 hours for freezing and 1.5 hours for thawing. The P-wave velocity, acoustic emission, and porosity were measured, and observations on the change in appearance of the outer surface and section of the specimen were made. The results obtained are summarized as follows: (1) cracks in rock developed during the freezing of pore water; (2) the initial cracks in rock caused by freezing and thawing action formed at a weak position of the surface layer and then propagated to the inside of the specimen; (3) the patterns of cracks produced by freezing and thawing cycles depended on the rock structure, such as its geometry, porosity and pore diameter; and (4) the rate of crack development was affected by the degree of water saturation and mechanical properties of the rock.

Key words: crack development, degree of saturation, freezing and thawing, pore water migration, rock structure, welded tuff (IGC: F0)

INTRODUCTION

Rock slope failures on a large scale in Hokkaido regularly occur and cause disasters (Committee of Investigation of Sounkyo Tenzyogan Collapse, 1988; Committee of Investigation of Toyohama Tunnel Failure, 1996; Committee of Investigation of 2nd Hirodo Tunnel Failure, 1998). According to these investigation reports, the stability of a rock slope is influenced by interaction between internal factors of the slope, such as topographic and geological features, and external factors, such as rainfall, snowmelting, freezing and thawing actions, and earthquakes. Freezing and thawing are emphasized by authors as among the most important external factors of rock slope failure, especially in cold regions. Weathering of a rockmass, and opening and development of cracks are hastened by repeated freezing and thawing of water in the rockmass (Kikuchi, 1997; Takahashi, 1997). Meteorological information suggests that the freezing and thawing of a rock is repeated 5~16 cycles/year in the Hokkaido region. The 1.5~2.0 m freezing depth of rockmass has been reported in this region by Fukuda (1988, 1996) and Takahashi (1997). Freezing and thawing as a direct cause affects the stability of a rock slope only to a certain limit. However, from these investigations,

large scale rock slope failures can be concluded to be related to the climate in cold regions.

Rock slope failure on a large scale can be predicted to a certain extent if indications for the failure exist (Yamaguchi, 1986). However, the predictions have been recognized to be quite difficult because many rock slope failures have no obvious indications in advance and occur suddenly. Understanding the mechanism of rock slope failure on rock slopes subjected to freezing and thawing in cold regions like Hokkaido is more difficult. Cracks or joints existing in rock slopes will gradually grow if a rockmass is subjected to freezing and thawing, but observing crack growth in a rock slope from the outside is difficult (Negishi, 1992). The mechanism of crack growth due to freezing and thawing will be clearly understood by experiments. Although many studies on freezing and thawing have been made to evaluate the durability of rock, most studies have been on the change in rock parameters, such as physical, mechanical and thermal properties (Ehara, 1985; Fukuda, 1974; Nakamura, 1979, 1984, 1996; Norikazu, 1990). Little experimental research has been made on the process of crack development in rock subjected to freezing and thawing action, and knowledge of these aspects is still limited. This study attempted to understand the mechanism of crack develop-

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Manuscript was received for review on December 17, 1998.

Written discussions on this paper should be submitted before November 1, 2000 to the Japanese Geotechnical Society, Sugayama Bldg. 4F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101-0063, Japan. Upon request the closing date may be extended one month.

ment in rock specimens by observing and measuring, using direct and indirect methods.

TESTS

Specimen

The rock specimens tested were prepared from welded tuff (Sapporo soft rock) in Sapporo Ishiyama. Welded tuff consists of minerals including volcanic glass (about 90%), pumice, plagioclase and particles of clay mineral, as well as andesite fractions. Welded tuff, which has a lower strength and a higher capability to absorb water, has been classified as a soft rock in civil engineering. Figures 1 and 2 show its microstructures. To study its anisotropy, two types of section were cut from the same block of welded tuff with a size 90 cm × 90 cm × 45 cm (length × width × thickness). One was perpendicular and

Fig. 1. Microphotograph of perpendicular section to sedimentary plane

Fig. 2. Microphotograph of parallel section to sedimentary plane

the other was parallel to the sedimentary plane. The physical and mechanical properties of rock specimens, thought to control the rate of crack growth, were measured or calculated as shown in Table 1. Welded tuff is a volcanic sedimentary rock with anisotropy according to its microstructure, physical and mechanical properties.

The specimens used to study crack development in this research were perpendicular to the sedimentary plane. The end planes of the cylindrical specimen (30 mm in diameter, 60 mm in length) were smoothed to a tolerance of less than 0.05 mm in height and perpendicularity. Then the smoothed specimens were dried in a drying oven at 105°C for 48 hours. Each dried specimen was immersed in distilled water at 14°C for 72 hours and was incompletely saturated to a 70% to 80% degree of water saturation.

Experimental Procedures

To understand the laws of crack development by freezing and thawing, the change in physical appearance of the outside and inside of the specimens was investigated directly under a microscope and CCD camera. To investigate the general change, measurements were made on P-wave velocity, porosity, pore size and strength of the specimens. The sections of the specimens were studied using the rock "examine medicinal" method. A freeze-thaw test, a method to measure the acoustic emission and a pore size test are explained clearly in the following.

The freeze-thaw test attempted to form rock specimen cracks by freezing and thawing cycles. The freezing test was conducted in a temperature-controlled chamber, and the thawing test was designed in distilled water of 14°C. The test temperature was determined by considering the weather conditions of Hokkaido and referring to JSCE-G501 (Japan Society of Civil Engineers, 1986). The temperature of the chamber was lowered from +5°C (±2°C) to -18°C (±2°C) during freezing. Figure 3 shows the temperature of the surface and the center of the specimen during freezing. A freeze-thaw cycle continued for 3.5 hours, including 2 hours for freezing and 1.5 hours for thawing. A thermal electrode was used to measure the temperature of the surface and the center of another specimen that was specially prepared only to measure the temperature. A longitudinal hole 1 mm in diameter was excavated at the center of the end plane to the middle of the specimen to insert a temperature sensor. The specimen with the inserted temperature sensor was

Table 1. Physical and mechanical properties of welded tuff

Specimen	Bulk density	Water content	Degree of saturation	Porosity	Median pore radius
	1.80 (kg/m ³)	25%	72%	43%	52417 Å (volume)
=	1.78 (kg/m ³)	24%	72%	—	—
Specimen	P-wave velocity		Uniaxial compressive strength		Tensile strength
	1.81 (km/s)		13.5 (MPa)		1.35 (MPa)
=	2.36 (km/s)		11.1 (MPa)		1.04 (MPa)

"||": perpendicular to sedimentary plane, "=": parallel to sedimentary plane

Fig. 3. Temperature of specimen surface and center during freezing

Fig. 4. Schematic diagram of acoustic emission measuring

placed close to other specimens and the temperature data of the surface and the center of the specimen were recorded continuously using a temperature recorder (Process IV). After a freeze-thaw cycle, the P-wave velocity was measured and external features of the specimen were observed using a CCD camera.

Many microcracks were predicted to be produced during the freezing (Chen, 1997). Acoustic emission (AE), which is produced by rapid microcrack formation and growth, is a ubiquitous phenomenon associated with brittle fracture and has provided a wealth of information regarding the failure process in rock (Ehara, 1986; Lockner, 1993; Mlakar, 1993). The AE counts were measured during freezing in each cycle. We used an AE sensor AE-901S type with a resonance frequency of 140 kHz which can operate with high accuracy between -20°C and $+80^{\circ}\text{C}$. Figure 4 shows a schematic diagram of the acoustic emission apparatus used in this study. The AE of the specimen was measured here using two channels. The noise in the low temperature chamber was reduced to the lowest limit, and the AE by noise was measured using the same type of AE sensor placed near the specimen. The AE rate counts and AE accumulative counts were calculated using

Fig. 5. Mercury autopore meter III 9420

$$\text{AE rate} = \text{total AE measured} - \text{AE by noise.}$$

Figure 5 shows a mercury autopore meter III 9420 used to measure the porosity and pore radius of the rock specimens in this study. Oven-dried specimens were broken into fractions, and then the pore radius and porosity of the fractions of sample size 2.5 mm to 5 mm were measured.

RESULTS

Acoustic Emission

Figure 6 shows the change in AE accumulative counts of the rock specimen during freezing. AE accumulative counts during the initial 3 cycles were less than those of other cycles, but had no obvious relation to the cycles from the measurements. Figure 7 shows the AE rate counts/second during the freezing. AE rate counts began to increase around 90 minutes from the beginning of the test, and 15 minutes later reached a peak. The spikes of AE rate counts from the beginning to 90 minutes were produced by an unknown cause like accidental vibrations, but AE rate counts from the specimens were almost continuous and regular, while AE rate counts in the chamber by noise and vibrations were discrete and sudden. AE is a reliable indication of microcrack development so here we believe that cracks began to develop from 90 minutes after the test started according to the data of AE rate counts.

P-wave Velocity

The P-wave velocity of the specimens subjected to freezing and thawing cycles was measured at room temperature. Figure 8 shows the change in the P-wave velocity of the specimens. The P-wave velocity of the specimens decreased about 27% after 30 cycles of freezing and thawing. Thus, we believe that cracks in the specimens were produced from the decrease in the P-wave velocity.

Porosity and Pore Size

Figure 9 shows the change in porosity of the specimens subjected to freezing and thawing cycles. The porosity of the specimens increased as the freezing and thawing cycles increased. The mean of porosity of specimens sub-

Fig. 6. Change of AE accumulative counts of specimen during freezing

Fig. 7. AE rate counts during freezing in 7th cycle

Fig. 8. Change of P-wave velocity of specimen by freezing and thawing cycles

jected to 10 cycles increased to 24.3% from 20.5% porosity of the primary specimens. Figure 10 shows the relation between incremental volume and incremental porosity. The incremental porosity was directly proportional to the incremental volume. Figure 11 shows the pore radius distribution of a primary specimen and a specimen subjected to 10 cycles of freezing and thawing. The pore volume of the specimens subjected to freezing and thawing cycles was more than that of the primary specimen at the range of radius 17.8 to 56.2 ($\times 1000$ Angstroms), but the pore

Fig. 9. Change of rock porosity by freezing and thawing cycles

Fig. 10. Relation between incremental volume and incremental porosity

Fig. 11. Change of pore radius distribution of specimen subjected to 10 cycles of freezing and thawing

radius of the larger size showed little change. In this freeze-thaw test, the specimens were cylindrical specimens 30 mm in diameter and 60 mm in length. While measuring the porosity and pore size using an autopore meter, the specimens subjected to freezing and thawing cycles were broken into fractions and the fractions of size 2.5 mm to 5.0 mm were measured, so that few large

cracks existed in the fractions. From this result, only some pores or microcracks of the specimen had developed when the specimen was subjected to freezing and thawing. The same conclusion was obtained from the surface observation of the specimens subjected to freezing and thawing cycles.

Strength

Figure 12 shows the change in the uniaxial compressive strength of the specimens subjected to 5 cycles and 10 cycles of freezing and thawing. Figure 13 shows the change in the tensile strength of the specimens subjected to 10 cycles. The decrease in the uniaxial compressive strength and tensile strength showed indirectly that cracks were produced in the specimens by freezing and thawing cycles.

Development of Cracks

Figure 14 shows a sketch of cracks of the specimen subjected to freezing and thawing cycles. The specimen was separated from a middle position, and the separated plane was almost parallel to the sedimentary plane.

After each cycle of freezing and thawing, the appearance of the specimens was recorded using a CCD camera at room temperature. Figure 15 shows the patterns of crack development. Figure 15-1 shows that the crack was produced and propagated around the boundary of vol-

canic glass and plagioclase or andesite fraction and did not propagate to the inside of the plagioclase or andesite fraction. This pattern of crack development was also confirmed from the microcrack analysis of the thin sections. Figure 15-2 shows that two cracks in the specimen were developed at almost the same time and were joined together later. Figure 15-3 shows that microcracks were produced in a radial pattern by the expansion of water changing to ice during freezing, and then a few of the cracks were advanced by later freezing and thawing. Figure 15-4 shows that cracks were developed in the pumice of the specimen. Many cracks were produced in the white pumices, because these pumices have many larger pores and a lower strength than that of other minerals. These larger pores were more easily enlarged by freezing and thawing action. The frost action of water existing in pores or cracks had an important role in crack development. Figure 16 shows an example of crack development by freezing and thawing cycles. The crack was extended and widened with increase in cycles. The rate of crack growth changed with freezing and thawing cycle, which agrees well with the conclusion obtained from AE accumulative counts.

Section Observation

The investigation from the sketches and CCD camera

Fig. 12. Change of uniaxial compressive strength of specimens by freezing and thawing cycles

Fig. 13. Change of tensile strength of specimens by freezing and thawing cycles

Fig. 14. Sketch of cracks of specimen subjected to 27 cycles of freezing and thawing

Fig. 15. Crack patterns of specimen by freezing and thawing cycles

Fig. 16. Crack development of specimen by freezing and thawing cycles

photographs was restricted to the outer surface of the specimen, but the inside of the specimen was more difficult. Section observation is frequently used to investigate the inside of rock, but successfully observing soft rocks like welded tuff is difficult because cracks are produced when a specimen is cut. Recently, the examination of sections using rock “examine-medicinal” has been reported (Yamashita, 1997). Rock “examine-medicinal” is a cyanoacrylate adhesive with a fluorescent paint that can permeate through very small rock pores. One of our specimens subjected to freezing and thawing cycles was immersed in rock “examine-medicinal” liquid under vacuum condition. When the pores and cracks of the specimen were full of the rock “examine-medicinal” liquid, the rock “examine-medicinal” was solidified by heating to 65°C to 70°C for 24 hours, and then the specimen was cut. Figure 17 shows a section of the specimen subjected to freezing and thawing cycles. The initial cracks

Fig. 17. Section of specimen subjected to freezing and thawing cycles

were produced in the surface layer and then developed to the inside of the specimen.

DISCUSSION

The extent of rock deterioration due to frost action in cold regions is controlled by temperature, lithology and moisture content (William, 1967; Fukuda, 1983). The importance of temperature condition, such as the lowest temperature and temperature gradient, has been emphasized in laboratory studies. Lithology, however, is an important factor in studying crack development. Specimens parallel to the sedimentary plane were prepared to study the influence of anisotropy on rock deterioration. Figure 18 shows the change in the uniaxial compressive strength of the specimens subjected to freezing and thawing cycles. The uniaxial compressive strength of specimens subjected to 5 cycles and 10 cycles decreased by 11.5% and 17.5% respectively compared with primary specimens. However, the uniaxial compressive strength of specimens perpendicular to the sedimentary plane decreased only 1.9% and 9.3% respectively when the specimens were subjected to 5 cycles and 10 cycles (Fig. 12). This result indicates that the extent of rock deterioration is affected by the sedimentary plane of the rock. Figure 19 shows cracks of a specimen parallel to the sedimentary plane subjected to 20 cycles of freezing and thawing. The cracks were parallel and perpendicular to the sedimentary plane. If the direction of length of a specimen was perpendicular to the sedimentary plane, cracks produced by freezing and thawing were parallel to the sedimentary plane (Fig. 14). This result shows that crack development is influenced by the sedimentary plane of a rock. If a slope, such as the Sounkyo rock slope (Committee of Investigation of Sounkyo Tenzyogan, 1988), is parallel to the joint plane, cracks of rockmass produced by freezing and thawing are parallel and perpendicular to the slope, and the stability of the slope is seriously influenced.

The effect of pore water on rock failure is that water expands when changing to ice. When the pores of the rock are filled with water above nine-tenths, the pores will be subjected to particular pressure during freezing. If this pressure exceeds the tensile strength of rock, cracks are produced. This theory is based on the fact that 1 cm³

Fig. 18. Change of uniaxial compressive strength of specimens by freezing and thawing cycles

Fig. 19. Sketch of cracks of specimen subjected to 20 cycles of freezing and thawing

Fig. 20. Ice distribution at surface of specimen during freezing

water occupies about 1.09 cm^3 space after freezing. To understand the influence of pore water on crack development in a rock, three types of specimen with different water content were used in a freeze-thaw test. (1) When oven-dried specimens were subjected to 30 cycles of freezing and thawing, the appearance of the specimens remained unchanged and its P-wave velocity decreased 0.5%, in contrast with that of the primary specimens. Dried specimens showed little change by freezing and thawing cycles from these results. (2) Specimens with 100% degree of saturation were subjected to only one cycle of freezing and thawing; cracks in almost specimens were produced and the specimens failed. This result suggests that if specimens are completely saturated, cracks in the specimen develop very rapidly by freezing and thawing. (3) Specimens with 70% to 80% degree of saturation were subjected to freezing and thawing cycles; the results are shown in Fig. 6 to Fig. 19. According to the Hirschwald's theory (William, 1967), completely saturated rocks yield to frost action no matter what their strength, while incompletely saturated rocks resist this action even when their strength is low. In our tests, rock failure was produced in the incompletely saturated specimens, and one cause may be that repeated freezing and thawing lead to fatigue failure. However, we were interested in another reason, namely that pore water migrates during freezing. When the porousness, such as moisture cohesive soil, is filled with water, water tends to migrate to the surface of growing ice. Figure 20 shows part of the ice distribution at the surface of the specimen. During freezing, the surface of the specimen was first frozen and the pore water at the surface began to turn to ice. The pore water inside the specimen migrated to the surface, and ice grew continuously. This hypothesis was proven by the following experiment. The incompletely saturated specimen was frozen and then was cut into many small blocks in a low temperature chamber. The degree of saturation of all small blocks was measured, and the distribution of degree of saturation in the frozen specimen was clear. We found that the degree of saturation in the surface layer was higher than in the center of the specimen, and the reason can be concluded to be pore

water migration during freezing (Chen, 1999). Pore water migrates easily in the pumice or porousness parallel to the sedimentary plane where many pores and microcracks exist, so that a degree of saturation above 90% is possible at a certain surface layer of the specimen and cracks are produced there. Crack patterns of a specimen surface such as in Fig. 15 are related to the pore water distribution, which is related to the rock structure. Rock slopes in nature are generally incompletely saturated, due to water migration, however, part of the slope becomes completely saturated and slope failure starts from this. Water migration accompanied by frost action plays an important role in rock slope failure.

CONCLUSIONS

In this study, direct and indirect methods were used to investigate the crack development by freezing and thawing cycles. From the results of the tests, crack development can be described as follows.

- (1) Cracks in rock are produced and then developed by freezing and thawing. Many cracks are produced during the process of pore water turning to ice.
- (2) The initial cracks in rock by freezing and thawing cycles start from a weak position at the surface layer of a rock specimen, such as in pumice, volcanic glass/andesite fraction interface and sedimentary

plane, and then develop to inside of the rock. Due to pore water migration, an increasing degree of saturation becomes possible at a certain position in the surface layer of rock, and cracks are produced there.

- (3) The pattern of cracks by freezing and thawing depends on the rock structure, such as geometry, porosity, pore diameter and crack distribution. Growth of ice is possible and cracks are produced easily where pore water migrates easily. A detailed investigation of the rock structure is necessary to study the patterns of cracks by freezing and thawing.
- (4) The rate of crack development is affected by water content, property of rock and temperature condition.

ACKNOWLEDGEMENTS

Grateful acknowledgement is made to Sado, K. for permission to use the low temperature chamber. We would like to thank Maeda, H. for taking the microphotographs, Hirata, H. for making the thin sections and Wang, Xin for measuring the pore radius. We also acknowledge Hiramatsu, M., Sawada, S., and Maeda, H. for their helpful suggestions.

REFERENCES

- 1) Chen, T. C., Goto, T., Hiramatsu, M. and Mori, N. (1997): "AE and strain properties of rock specimen during freeze-thaw processes," 42nd Symp. on Geotech. Engrg., JGS, pp. 77-82 (in Japanese).
- 2) Chen, T. C., Mori, N. Y., Goto, T. S. and Hiramatsu, M. H. (1999): "Redistribution of degree of saturation in the rock specimen due to frost action," Proc. of the 34th Japan National Conf. on Geotech. Engrg., Vol. 1, pp. 655-656 (in Japanese).
- 3) Committee of Investigation of the Sounkyo Tenzyougen Collapse (1988): "The report of the collapse of Sounkyo Tenzyougan," (in Japanese).
- 4) Committee of Investigation of the Toyohama Tunnel Failure (1996): "The report of the Toyohama Tunnel Failure," (in Japanese).
- 5) Committee of Investigation of the 2nd Hiroido Tunnel Failure (1998): "The report of the 2nd Hiroido Tunnel Failure," (in Japanese).
- 6) Ehara, S., Yanagidani, T. and Terada, M. (1985): "Thermal expansion of saturated rocks subjected to cyclic temperature change between 110 K and 300 K," Mat. Japan, Vol. 34, No. 382, pp. 864-869 (in Japanese).
- 7) Ehara, S., Yanagidani, T. and Terada, M. (1986): "AE and thermal expansion of Oshima granite during slow cyclic temperature change between 210 K and 370 K," Mat. Japan, Vol. 35, No. 392, pp. 490-495 (in Japanese).
- 8) Fukuda, M. (1974): "Rock weathering by freezing-thawing cycles," Low Temperature Science, Ser. A, 32, pp. 243-249 (in Japanese).
- 9) Fukuda, M. (1983): "An experiment of freeze-thaw cycles of rock specimens from the wall of Otaru Museum Building," Low Temperature Science, Ser. A, 42, pp. 163-169 (in Japanese).
- 10) Fukuda, M. (1988): "Freezing-thawing tests of welded tuff samples from Sounkyo," The 1987 Collapse of Sounkyo Welded Tuff, Central Hokkaido and Associated Disaster, pp. 41-48 (in Japanese).
- 11) Fukuda, M., Harimaya, T. and Harada, K. (1996): "The study on effect of rock weathering by freezing and thawing to rockmass collapse," Gekkan-Chikyuu, Japan, Vol. 18, No. 9, pp. 574-578 (in Japanese).
- 12) Japan Society of Civil Engineers (1986): "Freeze-thaw test method of concrete," JSCE-G501, pp. 409-411 (in Japanese).
- 13) Kikuchi, H. (1997): "The study of rock slope failures," Hokkaido Geotechnics '97, No. 8, pp. 197-207 (in Japanese).
- 14) Lockner, D. (1993): "The role of acoustic emission in the study of rock fracture," Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., Vol. 30, No. 7, pp. 883-899.
- 15) Matsuoka, N. (1990): "Mechanisms of rock breakdown by frost action: an experimental approach," Cold Regions Science and Technology, pp. 253-270.
- 16) Mlakar, V., Hassani, F. P. and Momayez, M. (1993): "Crack development and acoustic emission in Potash rock," Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., Vol. 30, No. 3, pp. 305-319.
- 17) Nakamura, Y. (1979): "Estimation of durability and deterioration characteristics of rock by laboratory freezing and thawing test," J. Japan Soc. Engrg. Geology, Vol. 20, No. 4, pp. 2-11 (in Japanese).
- 18) Nakamura, Y. and Ishizaka, K. (1984): "Comparison of rock durability tests," J. Japan Soc. Engrg. Geology, Vol. 25, No. 4, pp. 21-31 (in Japanese).
- 19) Nakamura, Y. (1996): "Experimental study of rock deterioration and weathering," Tsuchi-to-Kiso, JSSMFE, Vol. 44, No. 9, pp. 55-60 (in Japanese).
- 20) Negishi, M. (1992): "The mechanism and prediction of rock slope failures," Special Report for the 6th (1992) Lecture Meeting of the Civil Engrg. Research Institute, pp. 49-71 (in Japanese).
- 21) Takahashi, M. and Hazaka, J. (1997): "The rock collapse of Toyohama tunnel and 2nd Hiroido tunnel," Chishitsu News, Japan, No. 520, pp. 5-15 (in Japanese).
- 22) Takahashi, T. (1997): "On the rock fall caused by snow-melting and ground freezing in the cold district," Geotechnical Report, Hokkaido '97, JGS, Vol. 37, pp. 65-72 (in Japanese).
- 23) William, A. C. (1967): "Freezing and thawing of concrete mechanisms and control," American Concrete Institute, pp. 29-30.
- 24) Yamaguchi, U. and Shimotani, T. (1986): "A case study of slope failure in a limestone quarry," Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., Vol. 23, No. 1, pp. 95-104.
- 25) Yamashita, S., Sugimoto, F., Yamauchi, M., Mori, S. and Namauchi, D. (1997): "Change of microstructures of a soft rock on the creep loading process - Studies on the creep mechanism under compressive load of rock (part-1) -," Shigen-to-Sozai, Japan, Vol. 113, pp. 817-824 (in Japanese).