Uniaxial Compressive Strength of Rock under Non-atmospheric Environments

Hae-Sik Jeong and Yuzo Obara

Department of Civil Engineering, Kumamoto University, Japan

In order to investigate the influence of surrounding environment on strength of rock, the uniaxial compression test under non-atmospheric environments was conducted on Kumamoto andesite. The environments used in this study are water vapor, organic vapor environments as methanol, ethanol and acetone and inorganic gas environments as oxygen, nitrogen and argon. From the experimental results, it is clarified that water is the most effective agent which promotes stress corrosion of rock. Furthermore, the strength of rock increases with decreasing water vapor pressure. From the relation between uniaxial compressive strength and water vapor pressure, the stress corrosion index of Kumamoto andesite is estimated 24.

1. Introduction

The strength of rock is strongly affected by the properties of rock itself such as the compositions and textures of minerals in rock, and the quantity, shape and orientation of pre-existing cracks. From recent researches, however, it has been known that rock shows time-dependent failure due to subcritical crack growth under static stress below a critical stress intensity factor. This failure is related to surrounding environment, such as stress/strain rate, stress condition, temperature, humidity, pH and so on. Among them, the water environment, such as liquid phase or vapor phase, affects the subcritical crack growth in rocks due to stress corrosion (*Obara et al.*, 1996a, b; *Obara et al.*, 2000; *Jeong and Obara*, 2002a, b; *Jeong et al.*, 2003). However, few experimental results have been reported to confirm the fact that water relates to the stress corrosion. Furthermore, there are few experiments to clarify the effect of surrounding environment of rock on mechanical properties and strength of rock.

In this study, the influence of surrounding environment of rock on its strength is investigated experimentally. For this purpose, uniaxial compression tests are performed in various environments different from atmosphere, using Kumamoto andesite. The environments used in the tests are water vapor, organic vapor such as methanol, ethanol and acetone and inorganic gas such as argon, nitrogen, oxygen and hydrogen. Also, uniaxial compression test is conducted under various water vapor pressures to investigate the influence of water vapor pressure on strength.

2. Experimental Apparatus and Method

A vacuum chamber was made to control the surrounding environment of rock as shown in Fig.1. The chamber has six ports and a valve to inject gases.

Non-atmospheric environment can be made by injecting a new vapor or gas environment after evacuating the air in the chamber using vacuum pumps. The change of the pressure in the chamber during test is shown in Fig.2. At first, after the air in the chamber was evacuated by using two vacuum pumps until the pressure of about 10^{-3}Pa, then the distilled water was injected through the injection valve to a pressure of about 10^{3}Pa. As the result, it is considered that the pressure in the chamber becomes the saturated water vapor pressure at room temperature and

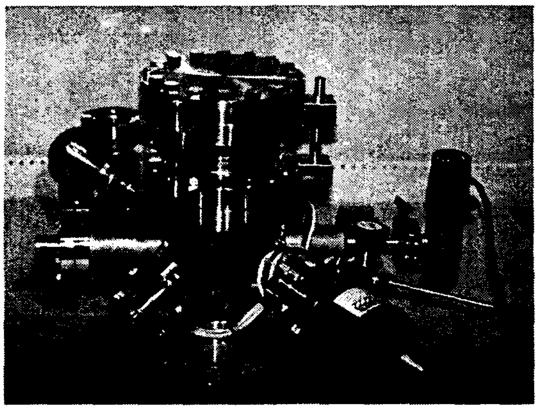

Fig.1 Photograph of a vacuum chamber.

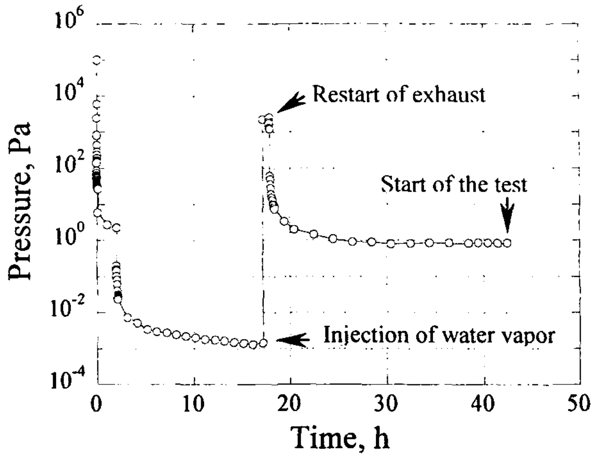

Fig.2 Change of the pressure in the chamber.

that the chamber is filled with only water vapor. Then the water vapor in the chamber was exhausted again. After the required water vapor pressure was maintained for about 24 hours, the uniaxial compression test was performed.

Kumamoto andesite is used as specimen. Since Kumamoto andesite is isotropic and homogeneous (*Obara et al.*, 1992), the core is drilled from a cubic block randomly. The diameter and length of the specimen are 35mm and 70mm respectively. In order to achieve complete dry condition of the rock specimens, these were kept in the electric drier oven at constant temperature 197°C.

The uniaxial compression test was performed using 500kN servo-controlled testing machine. The applied load is controlled by a constant strain rate.

3. Experimental Results

The uniaxial compressive strength of each environment is shown as Fig.3. The plots are scattered with environments. The uniaxial compressive strength in water vapor was 77MPa in average and in methanol, ethanol and acetone were 85MPa, 92MPa and 104MPa in average respectively. It was clear that the strength decreases in order of acetone, ethanol, methanol and water vapor. In inorganic environments of argon, nitrogen, oxygen and hydrogen, the uniaxial compressive strength was 129MPa in average in spite of a scatter in nitrogen. It is considered that the inorganic environmental dependence on uniaxial compressive strength doesn't exist. The uniaxial compressive strength in inorganic environments is 1.7 times of that in water vapor

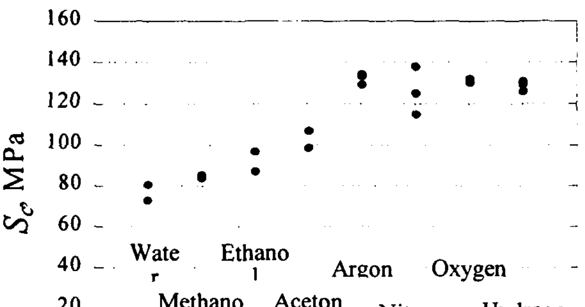

Fig.3 Uniaxial compressive strength in each environment.

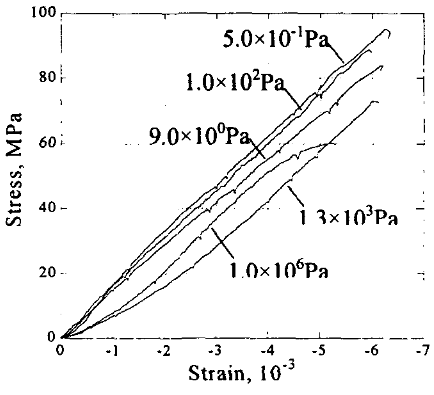

Fig.4 Stress-axial curves of uniaxial compressive test under various water vapor pressures.

environment. It is shown that the uniaxial compressive strength is the weakest in water vapor environment and the strongest in inorganic environment.

The typical stress-axial strain curves under various water vapor pressures are shown in Fig.4. The curves show straight lines generally for Kumamoto andesite. The uniaxial compressive strength is relatively high in case of lower water vapor pressure. The failure mode of the specimen for Kumamoto andesite after the tests, can be classified two types as shown in Fig.5, namely I: failure with one or two shear planes; II: failure with tension failure and shear planes.

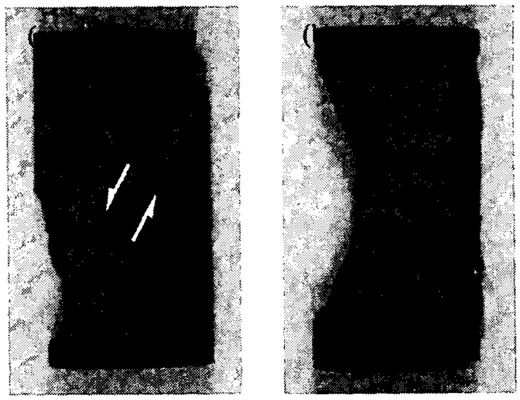

Fig.5 Failure mode of the specimen: (a) Failure with one or two shear planes; (b) Failure with tension failure and shear planes.

4. Discussion

The stress corrosion of rock is a chemical reaction between hydroxyl group OH^- and $Si-O$ bonds of silicates as follows:

$$H-O-H \;+\; [\equiv Si-O-Si] \;\Leftrightarrow\; 2[\equiv Si-OH] \qquad (1)$$

The effect of water vapor pressure p on the uniaxial compressive strength S_c under constant strain rate can be represented as follows, using stress corrosion index n (*Sano et al.*, 1981):

$$\log S_c \propto -\frac{1}{n+1}\log p \qquad (2)$$

According to the stress corrosion reaction (1), it is clear that stress corrosion is the most active in water vapor environment and that the stress corrosion cannot occur in inorganic environment, since there are no hydroxyl groups in inorganic gases.

The chemical reaction may take place in methanol and ethanol environments in the same manner to that in water vapor environment as following equations.

$$SiO_2 + 4CH_3OH \rightarrow Si(OCH_3)_4 + 2H_2O \qquad (3)$$

$$SiO_2 + 4C_2H_5OH \rightarrow Si(OC_2H_5)_4 + 2H_2O \qquad (4)$$

Water is generated from these reactions and is used for the reaction of stress corrosion represented by the reaction (1). Furthermore, the solubility of silica in ethanol is lower than that in methanol at the same condition of high temperature (*Iler*, 1979). Therefore, the amount of water generated from the reaction in methanol environment may be more than

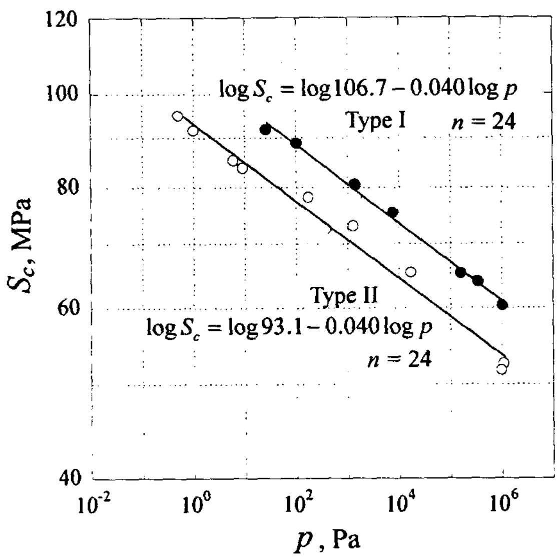

Fig. 6 Relations between uniaxial compressive strength and water vapor pressure.

that in ethanol environment. It is considered that the degree of stress corrosion in methanol is greater than that in ethanol environment.

Fig.6 shows the relation between uniaxial compressive strength S_c and water vapor pressure p for Kumamoto andesite, plotted on double logarithmic coordinates. The strengths of two failure types I and II are plotted as closed and opened circles, respectively. It is clear that the S_c increases with decreasing p. The slopes of the straight lines calculated by the least squares method are -0.04 in both types. This means that the effect of water vapor in the rock is similar regardless of different failure type.

The slope of the regression line coincides with the term $1/(n+1)$ in eq.(2). Therefore, based on the strength of uniaxial compression test, the stress corrosion index of Kumamoto andesite can be evaluated 24.

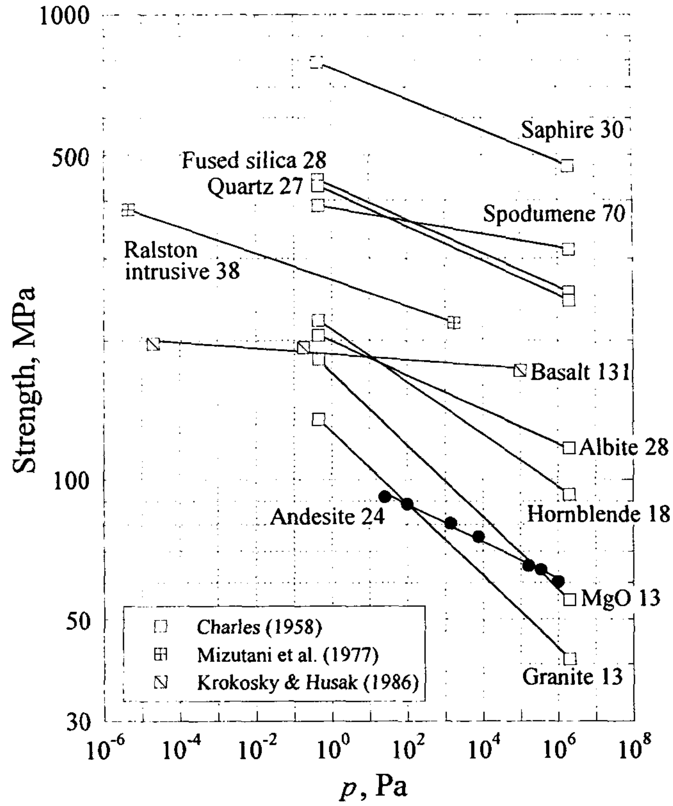

Fig. 7 Relation between the strength of rock and water vapor pressure, and comparison of stress corrosion indexes of various rocks and minerals with those in this research.

The results of other researchers for minerals and rocks (*Charles*, 1958; *Mizutani et al.*, 1977; *Krokosky and Husak*, 1968) are also plotted together with those in this research (Type I in uniaxial compression test for Kumamoto andesite) on double logarithmic coordinates as shown in Fig.7. The values in the figure represent stress corrosion index of the mineral or rock. The stress corrosion index for Kumamoto andesite commonly consisted of plagioclase mostly coincides with that of albite after Charles.

Furthermore, the stress corrosion index obtained from uniaxial compression test under various stress or strain rates (*John*, 1972; *Peng*, 1973; *Sano et al.*, 1981) and double torsion test (*Waza et al.*, 1980) for rocks other by researchers is between 26 and 62. The results in this study are harmony with those of other researchers.

5. Conclusions

The uniaxial compression test was conducted on Kumamoto andesite in water vapor, organic vapor and inorganic gas environments. The obtained results are as follows:

1. The uniaxial compressive strength of Kumamoto andesite decreases in order of the environment of acetone, ethanol, methanol and water vapor. The strength in inorganic environments was independent of environments. The average uniaxial compressive strength in inorganic environments was 1.7 times of that in water vapor environment.
2. Water is the most effective agent which promotes stress corrosion of rock among the

materials used in this research.

3. As a result of uniaxial compression test under various water vapor pressures, it was clarified that the uniaxial compressive strength increases with decreasing water vapor pressure.
4. The stress corrosion index is estimated 24 for Kumamoto, then this index is harmony with those of other researchers.

References

Charles, R. J., 1958, Static fatigue of glass, *J. Appl. Phys.*, 29, 1554-1560.

Iler, R. K., 1979, *The chemistry of silica: Solubility, polymerization, colloid and surface properties, and biochemistry*, Wiley-Interscience Publication, New York, 866p.

Jeong, H. S. and Obara, Y., 2002a, Influence of surrounding environment on the strength of rock under Brazil test, *Proc. 3rd Korea-Japan Joint Symposium on Rock Engineering*, Seoul, Korea, 139-144.

Jeong, H. S. and Obara, Y., 2002b, Strength of Kumamoto andesite in non-atmospheric environments, *Shigen-to-Sozai*, 118, 599-604 (in Japanese).

Jeong, H. S., Obara, Y. and Sugawara, K., 2003, The strength of rock under water vapor pressure, *Shigen-to-Sozai*, 119, 9-16 (in Japanese).

John, M., 1972, The influence of loading rate on mechanical properties and fracture processes of rock, *CSIR Rep. ME*, 1115.

Krokosky, E. M. and Husak, A., 1968, Strength characteristics of basalt rock in ultra-high vacuum, *J. Geophys. Res.*, 73, 2237-2247.

Mizutani, H., Spetzler, H., Getting, I., Martin, R. J., III and Soga, N., 1977, The effect of outgassing upon the closure of cracks and the strength of lunar analogues, *Proc. Lunar Sci. Conf.*, 8, 1235-1248.

Obara, Y., Hirokawa, H. and Sugawara, K., 1996a, The strength of rocks under lower water vapor pressure, *Proc. 1st Korea-Japan Joint Symposium on Rock Engineering*, Seoul, Korea, 109-114.

Obara, Y., Jeong, H. S., Hirata, A., Sato, A. and Sugawara, K., 2000, Influence of surrounding environment on strength of rock under uniaxial compression, *Proc. Int. Conf. Geotech. Geolog. Eng., GeoEng2000*, Mellbourne, Australia, CD-ROM:¥paper¥pf¥0536.pdf.

Obara, Y., Sakaguchi, K., Nakayama, T. and Sugawara, K., 1992, Anisotropy effect on fracture toughness of rock, *Proc. ISRM Symposium Eurock '92*, Telford, T., London, 7-12.

Obara, Y., Sugawara, K. and Tokashiki, N., 1996b, Influence of water vapor pressure on strength of rocks under uniaxial compression, *Proc. 2nd North American Rock Mechanics Symposium: NARMS '96*, Balkema, A. A., Rotterdam, 1337-1342.

Peng, S. S., 1973, Time-dependent aspects of rock behavior as measured by a servocontrolloed hydraulic tesing machine, *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.*, 10, 235-246.

Sano, O. Ito, I. And Terada, M., 1981, Influence of strain rate on dilatancy and strength of Oshima granite under uniaxial compression, *J. Geophys. Res.*, 86, 9299-9311.

Waza, T., Kurita, K. and Mizutani, H., 1980, The effect of water on the subcritical crack growth in silicate rocks, *Tectonophysics*, 67, 25-34.