Effects of water on the time dependent properties of rock

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ABSTRACT: For the long-term stability assessment of underground structures, it is essential to understand the effects of water on the time dependent properties of rock, such as loading-rate dependence, creep, and relaxation. In this study, the relation between the loading-rate dependence of strength and the stress dependence of creep lifetime in dry and wet conditions was examined on the basis of the previous experimental results of a tuff. It was found that the results of strength and short-term creep tests in dry and wet conditions are consistently explained with the rate process theory, which indicates that creep lifetime can be estimated from the loading-rate dependence of strength in a dry or wet condition. Using these theoretical and experimental findings, the creep lifetime in the ongoing 25-year creep test was predicted.

Keywords: rock, strength, loading-rate dependence, creep, water.

1 INTRODUCTION

It is well known that rock demonstrates various time dependent behaviors such as loading-rate dependence, creep under constant stress, and relaxation under constant strain (Cristescu & Hunsche 1998 and Brantut et al. 2013) and that these are closely related to each other (Hashiba & Fukui 2016). Previous studies have reported that the deformation and failure of rock are influenced by water; for example, rock strength and Young's modulus are lower in wet conditions than in dry conditions (Kirby 1984), and the time dependent behaviors are accelerated by water (Hashiba & Fukui 2015). For the long-term stability assessment of underground structures, it is essential to understand the effects of both time and water on the deformation and failure of rock.

Hashiba et al. (2018) explained the relation between the loading-rate dependence of strength and the stress dependence of creep lifetime in dry and wet conditions on the basis of the rate process theory and demonstrated that the results of an andesite are consistently elucidated with this theory. Hashiba et al. (2019) reported that the loading-rate dependence of strength of the andesite in various water saturation conditions are also consistently elucidated with this theory. These theoretical and experimental findings indicate that the effects of time and water are integrated and that creep lifetime can be estimated from the loading-rate dependence of strength and the results in arbitrary water saturation conditions can be estimated from the result in a certain water saturation condition. However, these studies examined the results of strength and short-term creep tests with a single type of rock, andesite, and hence it is not sure if this theory can be applied to other rocks or to long-term creep tests. In this study, the applicability of the theory derived from the results of the andesite was examined using the previous results of strength and short-term creep tests with a tuff. Then, the results of long-term creep tests with the tuff were used for comparative discussion with those of the short-term creep tests.

2 EXPERIMENTAL DATA USED IN THIS STUDY

2.1 Experimental methods

The target rock in this study is Tage tuff yielded in Japan, which is a dacitic-rhyolitic tuff formed in the Neogene. The specimens are cylindrical, 25 mm in diameter and 50 mm in height. The tests in dry conditions were conducted with specimens which had been dried for more than a month in a laboratory at 20±5°C and 65±15% humidity. The tests in wet conditions were conducted with specimens under water which had been saturated in a vacuum desiccator and stored under water for more than a month. The water used in this study has been ion-exchanged water.

The results of strength and short-term creep tests were obtained in the previous study (Chu 1995). The uniaxial compression strength tests were conducted with a 100 kN servo-controlled testing machine, with which the load and displacement were measured with a load cell and a linear-variable-differential-transformer, respectively. The strain rate was set to 10^{-6}, 10^{-5}, 10^{-4}, or 10^{-3} /s. The uniaxial compression creep tests were conducted with a 10 kN pneumatic-type testing machine. In this apparatus, compressed air was delivered from a compressor to a pneumatic cylinder through a pressure-reducing valve at a constant pressure. The tests were conducted under four creep stresses between 12 MPa and 15 MPa in dry conditions and under seven creep stresses between 5.8 MPa and 8.4 MPa in wet conditions. At the beginning of the tests, the predetermined creep stress was applied to the specimen within a second by opening a shut-off-valve. The displacement of the specimen was measured with two single-cantilever-type displacement transducers, and due to the long test duration, the final times when the displacement took some predetermined values were automatically recorded in a computer memory.

The results of long-term creep tests were obtained in the authors' previous study (Hashiba & Fukui 2020). The tests were conducted with the same machine as that used for the short-term creep tests and with specimens under water not to be influenced by moisture. The creep stress was set to 2.8 MPa. The test was started with the specimen No. 1 in November, 1994 and halted in August, 1996 due to the malfunction of the strain amplifier connected to the displacement transducers (Okubo et al. 2010). After the careful preparation of countermeasures against possible problems during a test on the basis of this experience, the test was started with another specimen No. 2 in May, 1997. At the beginning of the test, the final times when the displacement took some predetermined values were automatically recorded, and a few years later, the displacement has been manually recorded from the digital voltmeter every Monday and Friday. The long-term maintenance of the apparatus was detailed in Hashiba & Fukui (2020), such as exchanges of the compressor, drainage of the water from the compressor tank, cleaning of the pipes, calibration of the measurement devices, addition of the measurement of temperature and humidity, and addition of a pressure gauge. This test is going on, and its duration is more than 25 years. Although bending creep tests with rock were conducted for such a long duration (Kumagai et al. 1986), the authors believe that this test is the longest uniaxial compression creep test with rock that has been carried out.

2.2 Experimental results

Figure 1 shows some of the stress-strain curves obtained from the strength tests by Chu (1995). The strength and Young's modulus are higher in dry conditions than in wet conditions. The strength increases with an increase in strain rate, and the stress-strain curves under lower strain rates are included inside those under higher strain rates in both dry and wet conditions. The relation between strength and stress rate was obtained from these tests and shown with circles in Fig. 2. Here, the stress rate was calculated with multiplying the strain rate and the Young's modulus so that the theory in the next section would be applied to the experimental results. Although the strength under the same stress rate varies from specimen to specimen, the strength increases with an increase in stress rate. The slope of the straight lines was 0.70 MPa in both dry and wet conditions. The deference of the strengths in dry and wet conditions was 6.8 MPa under the same stress rate.

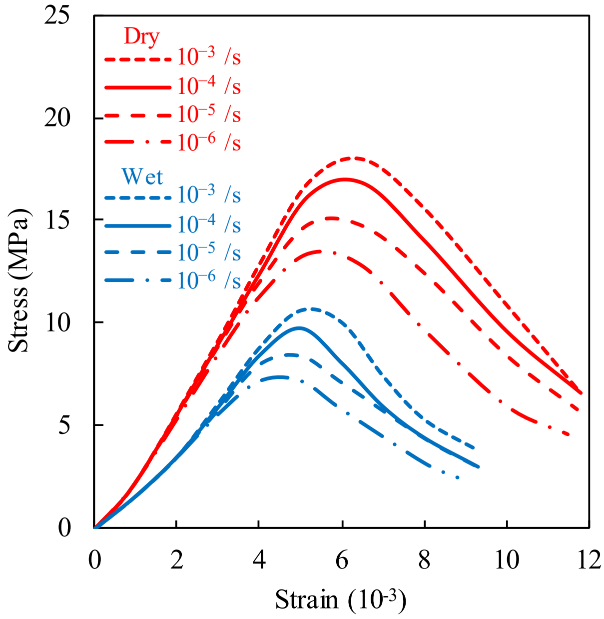

Figure 1. Stress-strain curves obtained from the strength tests by Chu (1995). The values in the legend are the strain rates.

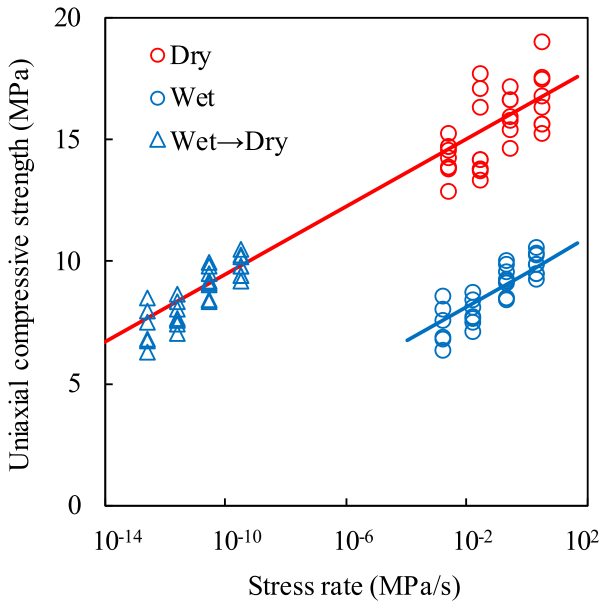

Figure 2. Relation between uniaxial compressive strength and stress rate. The red and blue circles represent the experimental results and are approximated by the straight lines. The blue triangles represent the calculated results from the experimental ones in wet conditions using Eq. (3).

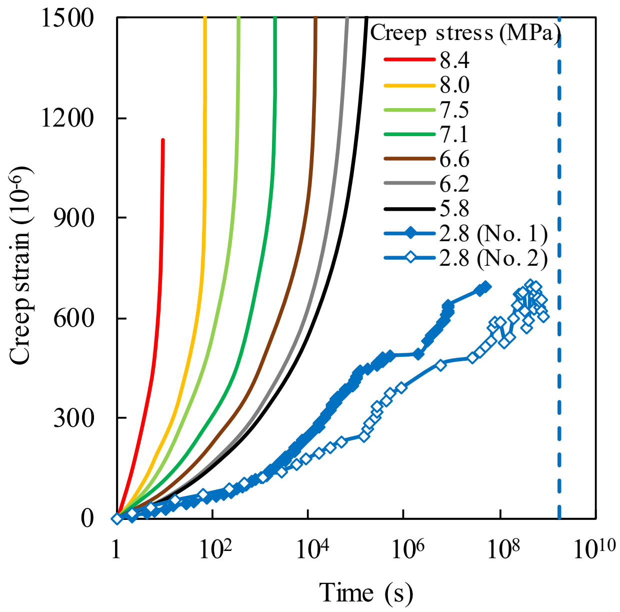

Figure 3. Creep strain curves in wet conditions obtained from the short-term creep tests under creep stresses between 5.8 and 8.4 MPa by Chu (1995) and the long-term creep tests under a creep stress of 2.8 MPa by the authors (Hashiba &Fukui 2020). The broken line indicates the estimated creep lifetime under a creep stress of 2.8 MPa using Eq. (4).

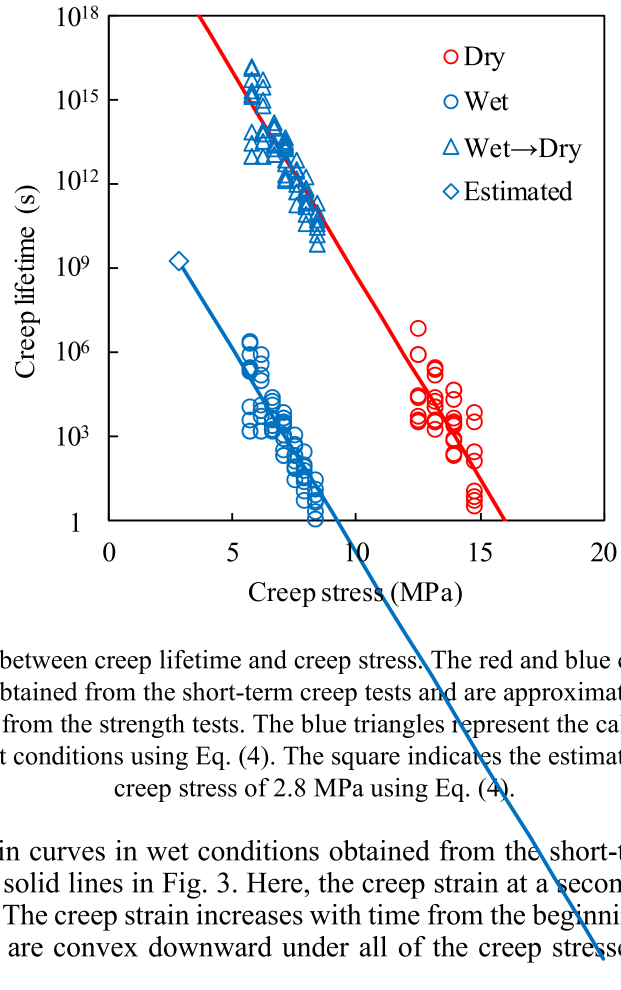

Figure 4. Relation between creep lifetime and creep stress. The red and blue circles represent the experimental results obtained from the short-term creep tests and are approximated by the straight lines calculated with Eq. (4) from the strength tests. The blue triangles represent the calculated results from the experimental ones in wet conditions using Eq. (4). The square indicates the estimated creep lifetime under a creep stress of 2.8 MPa using Eq. (4).

Some of the creep strain curves in wet conditions obtained from the short-term creep tests by Chu (1995) are shown with solid lines in Fig. 3. Here, the creep strain at a second after the beginning of the test was set to zero. The creep strain increases with time from the beginning of the test to the final failure, and the curves are convex downward under all of the creep stresses. The same trend was observed in not only wet but also dry conditions. The relation between creep lifetime and creep stress was obtained from these tests and shown with circles in Fig. 4. Although the creep lifetime under the same creep stress varies from specimen to specimen, the creep lifetime decreases with an increase in creep stress in both dry and wet conditions. The squares in Fig. 3 represent the results of the two long-term creep tests; the results for the No. 2 specimen after a lapse of 10^8 s that is about three years are the annual averages of the creep strain. The creep strains in the long-term creep tests fluctuate and increase in a similar manner to those in the short-term creep tests.

3 THEORETICAL DISCUSSION

On the basis of the rate process theory, the failure progression rate v of rock is assumed to be represented with an exponential function of stress σ and two constants a and b, as follows.

$$v = a\exp(b\sigma) \tag{1}$$

In addition, the failure is assumed to be occurred when the time integral of v will reach a value V.

$$V = \int_0^t v dt \tag{2}$$

The strength σ_f under the constant stress rate C is obtained using $\sigma = Ct$ and the above equations, as follows.

$$\sigma_f = \frac{1}{b}\ln\frac{bCV}{a} \tag{3}$$

Here, $\exp(b\sigma_f)$>>1. In this equation, the slope of the straight lines in Fig. 2 is $1/b\log e$. The value of b is calculated to be 3.3 MPa^{-1} in both dry and wet conditions from the slope, 0.70 MPa, obtained in the tests. In this equation, the difference of strengths in dry and wet conditions is $(1/b)\ln(a_w/a_d)$, where a_d and a_w are a in dry and wet conditions, respectively. The value of $\ln(a_w/a_d)$ is calculated to be 23 from the difference of strengths, 6.8 MPa, obtained in the tests. Equation (3) indicates that C and $1/a$ are equivalent, and hence C multiplied by a_d/a_w in wet conditions corresponds to C in dry conditions. The relation between the stress rate calculated in this manner and the strength is shown with triangles in Fig. 2. The red line approximates not only the experimental results in dry conditions but also the calculated results in wet conditions, which indicates that the theoretical relation is consistent with the experimental results for the loading-rate dependence of strength.

The creep lifetime t_c under the creep stress σ_c is obtained using $\sigma = \sigma_c$ and the above equations, as follows.

$$t_c = \frac{V}{a\exp(b\sigma_c)} = \frac{\exp\{b(\sigma_f - \sigma_c)\}}{bC} \tag{4}$$

The relation between creep lifetime and creep stress calculated with the rightmost side of Eq. (4) is shown with red and blue lines in Fig. 4. The lines are consistent with the experimental results in both dry and wet conditions. Equation (4) indicates that t_c multiplied by a_w/a_d in wet conditions corresponds to t_c in dry conditions. The relation between the creep lifetime calculated in this manner and the creep stress is shown with triangles in Fig. 4. The red line approximates not only the experimental results in dry conditions but also the calculated results in wet conditions, which indicates that the theoretical relation is consistent with the experimental results for the creep lifetime. Using these results, the creep lifetime under a creep stress of 2.8 MPa was estimated to be 1.8×10^9 s that is about 58 years and shown with a square in Fig. 4 and with a broken line in Fig. 3. This estimated creep lifetime is more than twice the test duration of the long-term creep test with the No.

2 specimen. However, the lifetime for the long-term creep test probably varies with specimens in a similar manner to that for the short-term creep test as shown in Fig. 4.

4 CONCLUSIONS

In this study, the relation between the loading-rate dependence of strength and the stress dependence of creep lifetime in dry and wet conditions was examined on the basis of the previous experimental results of the tuff. It was found that the change of strength with a tenfold change in loading rate is almost the same in dry and wet conditions and that the results of the tuff are consistently explained with the theory derived from the results of the andesite. It was also demonstrated that the relation between creep lifetime and creep stress in dry and wet conditions is consistently explained with this theory and that creep lifetime can be estimated from the loading-rate dependence of strength. Using these findings, the average creep lifetime in the ongoing 25-year creep test was predicted. This long-term creep test will be continued as long as possible for the further elucidation of time dependent behavior of rock.

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