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Effect of water on the strength and creep lifetime of andesite

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ABSTRACT

The authors' research group has investigated the close relation between the time-dependent behaviors under various loading conditions through laboratory tests, theories, and constitutive equations. It is well known that water accelerates the time-dependent behaviors of rocks; water enlarges the loading-rate dependence of strength and shortens the time to failure (creep lifetime) under constant stress level (ratio of creep stress to strength). This paper introduced the theory in the previous studies based on the rate process theory and the stochastic process theory, and found that the theory disregarded the effect of a change in water conditions on the strength and creep lifetime of rocks. The theory was briefly modified and then applied to the strength, creep lifetime, and their variability in both dry and wet conditions. To validate the modified theory, strength tests and creep tests were conducted under uniaxial compression with Sanjome andesite. The constants in the modified theory were calculated from the strength, and then the creep lifetime collected from the creep tests was examined with the formulae derived from the modified theory. The test results in dry and wet conditions were consistently elucidated by the modified theory, which indicates that the strength and creep lifetime of Sanjome andesite are approximated by the simple formulae in the theory. Creep lifetime was estimated from strength, and the results in dry conditions were estimated from those in wet conditions and vice versa, based on this study.

1. Introduction

For the long-term stability assessment of underground structures, it is essential to understand the time-dependent behaviors of rocks. Many previous studies on rocks have demonstrated that strength increases with an increase in loading rate (loading-rate dependence that includes stress- and strain-rate dependences), strain increases under constant stress (creep), and stress decreases under constant strain (relaxation).[1,2]

We have investigated the close relation between the time-dependent behaviors under various loading conditions through laboratory tests, theories, and constitutive equations.[3–6] Okubo et al.[3] proposed a constitutive equation which reproduces stress-strain curves, their loading-rate dependence, and creep-strain curves, based on test results of andesite and tuff. Shin et al.[4] clarified the close relation between the loading-rate dependence and the variability of strength and creep lifetime, based on test results of andesite and tuff. Hashiba and Fukui[5] proposed a theory which explains the relation between the loading-rate dependence of strength and the stress dependence of creep lifetime, the variability of strength and creep lifetime, and the scale effect of strength. The theory was reported to be applicable to test results of many rocks. Hashiba and Fukui[6] conducted alternating-loading-rate tests, creep tests, relaxation tests, and new tests in which both stress and strain change with time with granite. They proposed a constitutive equation which reproduces all the test results.

However, these previous studies covered the time-dependent behaviors under constant environment and disregarded the effect of a change in environment. It is well known that water accelerates the time-dependent behaviors of rocks; water enlarges the loading-rate dependence of strength[5] and shortens the time to failure (creep lifetime) under constant stress level (ratio of creep stress to strength).[7] The previous theories and constitutive equations reproduced the tests results in either dry or wet conditions, but not the tests results comprehensively in both dry and wet conditions. Water content in rock masses around underground structures changes with excavation progress and elapsed time, and hence it is essential to construct a theory and a constitutive equation including the effect of water on the time-dependent behaviors of rocks.

In this study, the relation between rock strength and creep lifetime in both dry and wet conditions was theoretically and experimentally investigated. First, the theory in the previous studies based on the rate process theory and the stochastic process theory was modified to include the effect of water. Second, the modified theory was validated through strength tests and creep tests with andesite in dry and wet conditions. In addition, the applications of the modified theory were

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examined, such as estimation of creep lifetime and formulation of a constitutive equation.

2. Theoretical background

2.1. Previous studies

Shin et al.[4] and Hashiba and Fukui[5] assumed that the failure progression rate $d\lambda/dt$ of rocks is proportional to a function of applied stress σ, based on the rate process theory and the stochastic process theory. These theories have been widely applied to the time-dependent deformation and failure of materials.[8–10] The researchers[4,5,8–10] used a power function as the stress function for its applicability to test results as well as its simplicity:

$$\frac{d\lambda}{dt} = m\sigma^n. \tag{1}$$

The authors also assumed that rock failure occurs when the time integral of $d\lambda/dt$ reaches a predetermined value Λ:

$$\Lambda = \int_0^t \frac{d\lambda}{dt}dt. \tag{2}$$

Physical meaning of $d\lambda/dt$ in rock mechanics will be discussed in Section 5.

In a strength test under constant stress rate ($\sigma = \dot{\sigma}t$), stress reaches the strength σ_f when $t = t_\mathrm{f}$. The stress-rate dependence of strength is derived from Eqs. (1) and (2) as follows:

$$\sigma_f = \left(\frac{n+1}{m}\Lambda\dot{\sigma}\right)^{\frac{1}{n+1}}. \tag{3}$$

In a creep test ($\sigma = \sigma_\mathrm{cr} = \mathrm{const.}$), creep failure occurs when $t = t_\mathrm{cr}$. The relation between creep lifetime and creep stress is derived from Eqs. (1) and (2) as follows:

$$t_{cr} = \frac{\Lambda}{m{\sigma_{cr}}^n}. \tag{4}$$

To discuss the variability of strength and creep lifetime, Λ in Eq. (2) was assumed to follow the Weibull distribution, which has been widely used for representing the variability and the scale effect of material strength[11]:

$$1 - F(\Lambda) = \exp\left\{-\left(\frac{\Lambda}{A}\right)^B\right\}, \tag{5}$$

where $F(\Lambda)$ is the cumulative distribution function of Λ, and A and B are the scale and shape parameters, respectively. The following formulae are derived by substituting Eqs. (3) or (4) into Eq. (5):

$$1 - F(\sigma_f) = \exp\left\{-\left(\frac{\sigma_f}{A_1}\right)^{B_1}\right\},$$

$$A_1 = \left(\frac{n+1}{m}A\dot{\sigma}\right)^{\frac{1}{n+1}},\ B_1 = (n+1)B, \tag{6}$$

$$1 - F(t_{cr}) = \exp\left\{-\left(\frac{t_{cr}}{A_2}\right)^{B_2}\right\},$$

$$A_2 = \frac{A}{m{\sigma_{cr}}^n},\ B_2 = B. \tag{7}$$

These formulae indicate that both strength and creep lifetime follow the Weibull distribution and that the shape parameter B_1 for strength is the product of the shape parameter B_2 for creep lifetime and $n + 1$.

Shin et al.[4] and Hashiba and Fukui[5] demonstrated with test results of various rocks that the loading-rate dependence of strength and the stress dependence of creep lifetime are represented by Eqs. (3) and (4), respectively, and that B_1 is almost equal to $(n + 1)B_2$. Their results indicate that the failure process of rocks is explained by the simple assumptions, Eqs. (1) and (2). Okubo and Fukui[12] and Hashiba and Fukui[6] proposed constitutive equations that reproduce the time-dependent behaviors of rocks, based on Eq. (1). However, the effect of water has not been sufficiently discussed in the previous studies. The above-mentioned formulae from Eqs. (1)–(7) were applicable to the behaviors in either dry or wet conditions, but not in both conditions, because the values of both m and n in Eq. (1) changed with water. Hence, the constitutive equations based on Eq. (1) could reproduce the behaviors only under constant water conditions.

2.2. This study

To explain the test results in both dry and wet conditions, the stress function in Eq. (1) is changed from a power function to an exponential function as follows:

$$\frac{d\lambda}{dt} = a\exp(b\sigma) \tag{8}$$

in which a and b are the degree of progression rate and time dependence of failure, respectively, as detailed below. Eq. (2) is also adopted as a failure criterion, and consequently the stress-rate dependence of strength and the stress dependence of creep lifetime are derived in a similar way to Eqs. (3) and (4), respectively, as follows:

$$\sigma_f = \frac{1}{b}\ln\frac{\Lambda b\dot{\sigma}}{a}, \tag{9}$$

$$t_{cr} = \frac{\Lambda}{a\exp(b\sigma_{cr})}, \tag{10}$$

where $\exp(b\sigma_\mathrm{f}) > > 1$ for further theoretical examination.

To compare the two theories before a detailed consideration in the following sections, the stress-rate dependence of uniaxial compressive strength (UCS) in dry conditions was obtained with Sanjome andesite in this study and shown in Fig. 1. In the uniaxial compression tests, the specimens, 25 mm in diameter and 50 mm in height, were loaded in a parallel direction to foliation. The petrological and mechanical properties of the andesite will be described in Section 3. The testing machine and the control method were the same as those used in the uniaxial compression tests in Section 3. As shown in the figure, the strength increases with an increase in stress rate in a similar manner to the previous results.[13] The figure also shows the results calculated by Eq. (3) using n of 39 and Eq. (9) using b of 0.45 /MPa; the basis for calculation of n and b will be described in Section 4.1. The difference of the calculated curves is sufficiently small under the stress rate between 10^{-2}

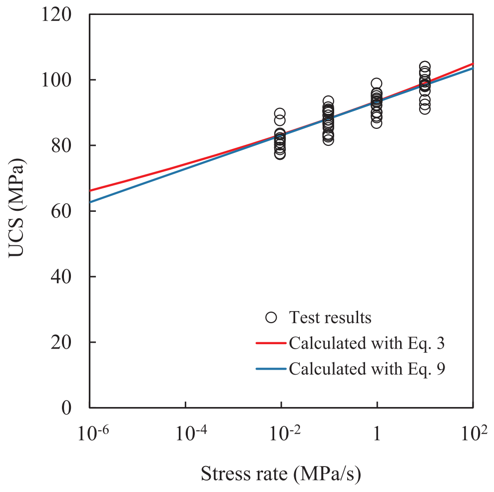

Fig. 1. Stress-rate dependence of uniaxial compressive strength (UCS) of Sanjome andesite in dry conditions. The red line was calculated with Eq. (3) using n of 39. The blue line was calculated with Eq. (9) using b of 0.45 /MPa.