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Effects of water on rock strength in a brittle regime

Koji Masuda*

National Institute of Advanced Industrial Science & Technology, AIST Tsukuba Central 7, Tsukuba 305-8567, Japan

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Abstract

Failure strengths of granite and andesite have been measured under various conditions of strain rate and confining pressure both in the dry and wet states. Constant-stress creep tests for granitic samples have been also conducted. All specimens show that the failure strength decreased linearly as the logarithm of the strain rate decreased. The strain rate dependence of the failure strength is increased at higher confining pressures. The strain rate effect is more apparent on the failure strengths of wet samples than dry samples in lower confining pressure ranges. In the constant-stress creep experiments, the creep failure strength decreased as the logarithm of the time to failure increased. Time-dependent failure strength of all rocks observed in the regime of the present study may be interpreted by subcritical crack growth assisted by the stress corrosion mechanism. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Granite; Andesite; Strain rate; Pressure

1. Introduction

Current models of the strength of the lithosphere are based on data from physical properties of rocks. Kohlstedt et al. (1995) summarized constraints imposed by laboratory experiments. The importance of the transition from brittle to semi-brittle deformation is now well recognized because the depth of the transition is an important parameter for the rheology of the lithosphere. Physical properties of rocks in a brittle regime, in particular, data on strength and its weakening are important to evaluate the transition and its depth. Although major questions concerning the strength of rocks in a brittle regime remain, only a limited amount of accurate experimental data are available to constrain the constitutive equations, which include the effects of water as well as strain rate. In particular, the effect of water on strength is critical to an accurate model.

Fluids in the brittle regime of the earth are linked to a variety of faulting processes, fault creep, and the long-term structural evolution of fault zones. The effect of water on the strength and other physical properties of rocks is important for understanding the deformation, failure, and slip processes in nature. Fluids affect rock strength through two important effects: mechanical and physico–chemical effects (Scholz, 1990; Hickman et al., 1995). The lowering of the effective stress lowers the fracture strength. The physico–chemical effect results in the strength of rock being time dependent.

In this paper, I focus on the physico–chemical effects of water on rock strength. I carried out a series of systematic experiments on time-dependent rock strength under dry and wet conditions. I summarize the previous data on time-dependent strength of granite and andesite in our laboratory experiments. New results from a series of experiments that carefully controlled the necessary parameters are presented.

2. Experiment procedure and samples

I carried out a series of conventional triaxial compression tests at constant strain-rate and constant stress. The sample was a very homogeneous Indian granite with grain size of about 0.3–0.5 mm. The apparent density is 2700 kg/m^3, and porosity as determined by the water saturation method is 0.55%. I carried out another series of experiments using andesite samples for comparison. The sample rock was Yugawara andesite, with a matrix size of 0.05–0.1 mm, phenocryst size of 0.5–1.0 mm, apparent density of 2770 kg/m^3 and porosity of 6.2%. All samples were cored in the same orientation from a granitic and an andesite block. This procedure allowed us to obtain cored samples with almost the same physical properties and provide a high level of replication under controlled test conditions. The sample shape was a cylinder of 25.0 mm in diameter and 62.5 mm in length. The sample end surfaces were made parallel to within 1/100 mm.

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* Tel.: +81-298-61-3994; fax: +81-298-61-3682.
E-mail address: koji.masuda@aist.go.jp (K. Masuda).

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Experiments were carried out in 'dry' and 'wet' conditions. To eliminate effects of contamination, all samples were immersed in trichloroethylene for 72 h, washed with an ultrasonic cleaner in distilled water, and immersed in distilled water for 24 h. The samples were dried in a vacuum chamber for 72 h at room temperature. These samples are referred to as 'dry' samples. Our dry samples include enough water to affect the strength through the stress corrosion mechanism. In triaxial compression tests in the dry state, samples were jacketed with 0.1-mm-thick copper foil.

In order to saturate rock samples with water, the dry samples were degassed in a vacuum at room temperature for 30 min and dropped into distilled water. These samples were kept in distilled water for 24 h under atmospheric pressure. This procedure is considered to be quite effective to introduce water into the pores and cracks of the samples. These samples are referred to as 'wet' samples. In uniaxial compression tests in the wet state, wet samples were wrapped in synthetic resin. In triaxial compression tests in the wet state, wet samples were jacketed with 0.1-mm-thick copper foil. The ends of the jacket and end-pieces were cemented by epoxy resin. Water was confined in pores but the pore pressure was not controlled. Water mass remained constant under the undrained condition. In wet samples, partial pressure of water is larger than that of dry samples. The degree of saturation of wet samples, however, decreases in the process of loading, especially after the dilatancy occurs. Pore pressure, therefore, did not have significant physical effects on results. It is difficult to quantitatively discuss effects of the partial pressure of water on the strength at the present stage. Experimental works in which pore pressure is controlled are necessary.

3. Constant strain-rate tests

Uniaxial and triaxial compression tests were carried out using granite and andesite samples under various constant axial strain rates in the dry and wet states. The strain rates varied from 10^{-4} to 10^{-8} s^{-1} and confining pressures varied from 0.1 to 200 MPa.

Fig. 1(a)–(d) shows the relation between the compressive strength and strain rate for granite samples under the confining pressures of 0.1, 50, 100 and 200 MPa (Masuda et al.,

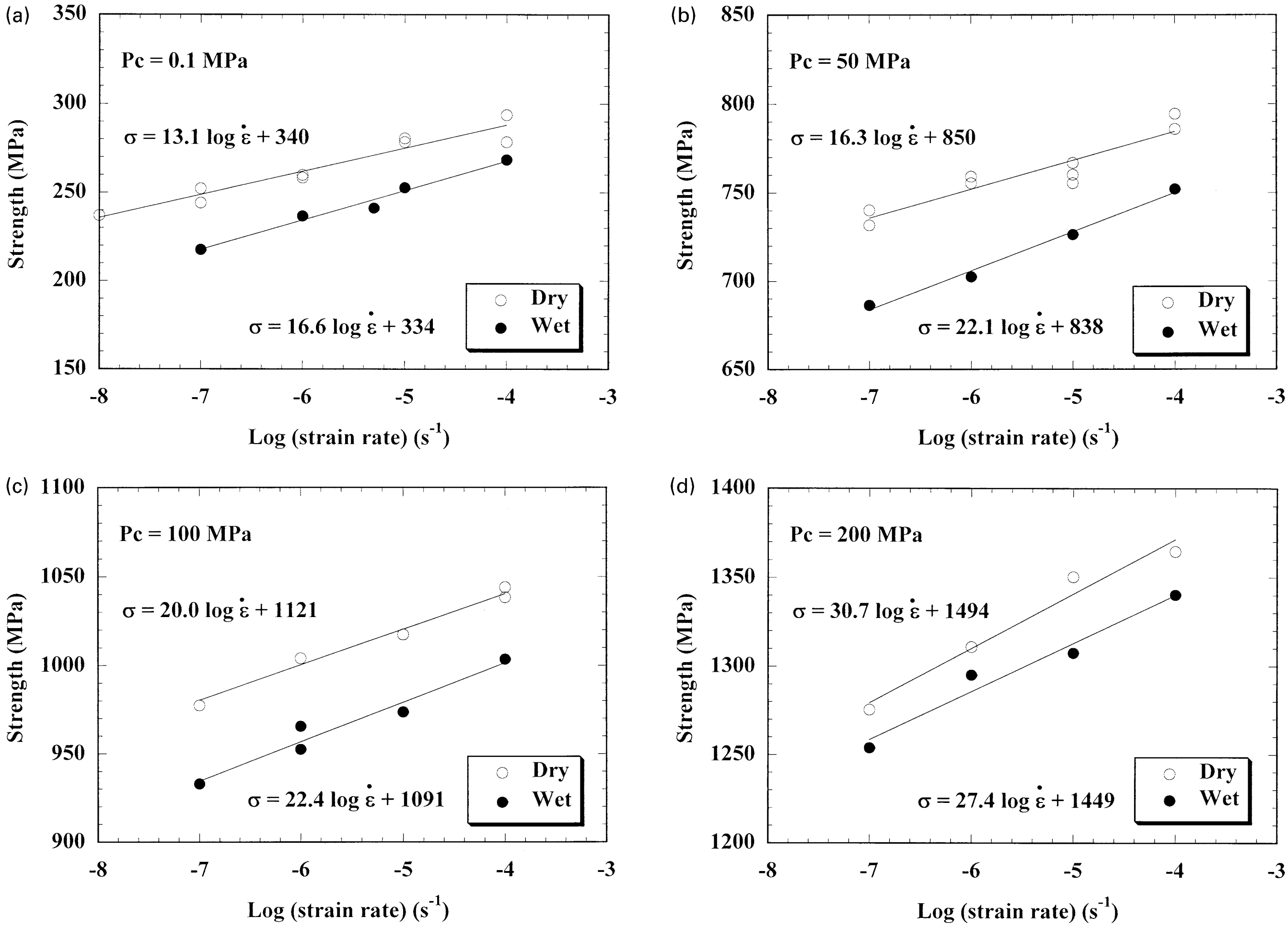

Fig. 1. Compressive strength of granitic rocks as a function of strain rate under the confining pressures of: (a) 0.1 MPa, (b) 50 MPa, (c) 100 MPa, and (d) 200 MPa.

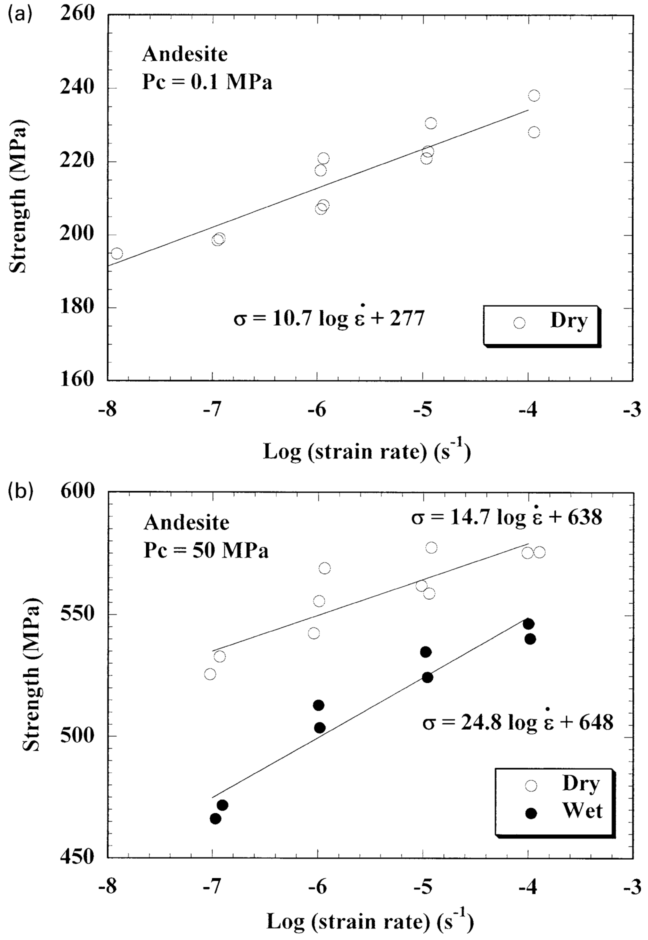

Fig. 2. Compressive strength of andesite rocks as a function of strain rate under the confining pressures of: (a) 0.1 MPa, and (b) 50 MPa.

1987, 1988). Fig. 2(a) and (b) shows the results for andesite samples under the confining pressures of 0.1 and 50 MPa. The open and closed symbols represent the data obtained in the dry and wet state conditions, respectively. The compressive strength decreases linearly with the decrease in the logarithm of the strain rate:

$$\sigma_F = C\log\dot{\varepsilon} + \sigma_0 \qquad (1)$$

where σ_F is the compressive strength, $\dot{\varepsilon}$ is the strain rate, and C and σ_0 are constants. Using the least squares fit to the data, we calculated the constants C and σ_0. Table 1 summarizes the calculated values for the constant C under various experimental conditions. The constant C represents the strain rate dependence of the compressive strength. Similar strain rate dependence of the compressive strength is shown by previous authors (Brace and Martin, 1968; Brace and Jones, 1971; Schock and Heard, 1974) who compiled the strength data of various rock types and experimental conditions. Strain rate dependence of rock strength is different for the different rock types, as shown in Figs. 1 and 2. On average, as Lockner (1995) reviewed, rate sensitivity is typically 5–10% strength increase per decade increase in strain rate.

In the present study, I can systematically evaluate the effects of confining pressure and water on the strain rate dependence of the compressive strength because I carried out a series of experiments under carefully controlled conditions using the samples with the same physical properties. Fig. 1(a)–(d) shows that the failure strength of granitic rocks decreased linearly as the logarithm of the strain rate decreased. The strain rate dependence of the failure strength is increased at higher confining pressures. The strain rate effect is more apparent on the failure strengths of wet than dry samples in a lower confining pressure range. Similar effects of water and confining pressure on the strain rate dependence of fracture strength were observed in another series of experiments on andesite rocks, as shown in Fig. 2(a) and (b).

4. Constant stress tests

A series of constant stress tests of the dry granitic rocks were carried out under confining pressure of 50 MPa. I applied differential stress to the sample under this confining pressure. The loading rate was 1.7 MPa/s. The failure strength of the sample under this loading rate and the confining pressure was 776 MPa. I kept the differential stress constant after the differential stress reached the desired stress level, σ_C, with the servo-controlled loading system, which monitored the output of the load cell. The differential stress was kept constant within 1% of the desired level. Table 2 summarizes the differential stress of the creep test and time to failure. In experiment no. 9, I stopped the experiment before the macroscopic fracture took place after 4×10^6 s (ca. 46 days). In a state of low differential stress, as in experiment no. 9, the stress level at the crack tip might not have been sufficient to assist the subcritical

Table 1
Calculated values for constant C in Eq. (1). The number of samples is shown in the parentheses

Pc (MPa)	Granite		Andesite	
	Dry	Wet	Dry	Wet
0.1	13.1 ± 1.4 (9)	16.6 ± 1.5 (5)	10.7 ± 1.3 (12)	
50	16.3 ± 2.5 (9)	22.1 ± 1.6 (4)	14.7 ± 2.9 (10)	24.8 ± 2.9 (8)
100	20.0 ± 1.4 (7)	22.4 ± 2.9 (5)		
200	30.7 ± 3.9 (4)	27.1 ± 3.7 (4)		

Table 2
Creep stress and time to failure. The creep experiment no. 9 was stopped after 4×10^6 s (ca. 46 days)

No.	σ_c (MPa)	t_f (s)
1	716.9	1.13×10^2
2	694.6	6.00×10^3
3	705.3	6.80×10^3
4	686.8	4.48×10^4
5	671.1	9.36×10^4
6	674.6	1.12×10^5
7	657.8	1.70×10^5
8	652.3	3.10×10^5
9	649.2	$> 4.00 \times 10^6$

crack growth. In this report, I use data from the first eight experiments after Table 2.

Scholz (1968), Kranz and Scholz (1977), Kranz (1980) and Kurita et al. (1983) observed the relationship between the applied stress level, σ_C, and logarithm of the time to failure, t_f, as

$$t_f \propto \exp(-D\sigma_C) \tag{2}$$

where D is a constant. Fig. 3 shows the relation between the applied stress and time to failure observed in this study. Using the least squares fit of the equation

$$\sigma_C = -E\log t_f + F \tag{3}$$

to the data, I obtain values of the constants $E = 18.6 \pm 3.1$ and $F = 764 \pm 14$. The straight line in Fig. 3 is drawn using Eq. (3) with the calculated constants of D and E.

5. Discussions and conclusion

Time-dependent effects of water on rock strength data using samples with the same physical properties are summarized. Carefully controlled experiments provide a useful addition to the data on the effect of wetting on the time-dependent brittle strength of granite and andesite. Results show that the presence of water leads to a greater strain rate sensitivity of the failure stress, which is greater at higher confining pressures.

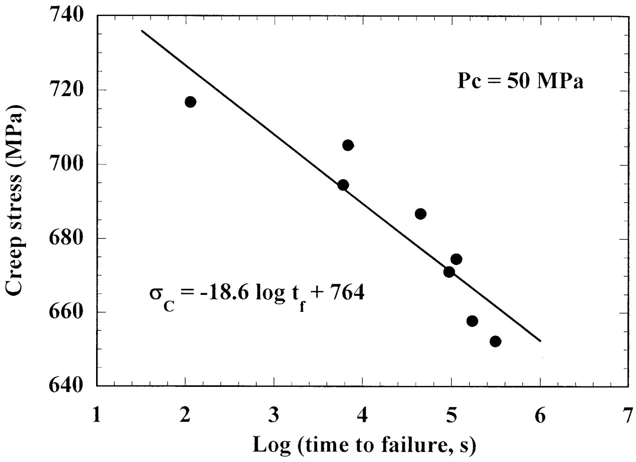

Fig. 3. Creep stress of granitic rocks and time to failure.

Since water reacts with silicate to break the Si–O bond, fluids can have a profound chemical effects on the physical properties of silicate rocks (Lockner, 1995). This effect is more imminent when there is enough time for the chemical reaction. Decreasing the strain rate enhances this effect and leads to a decrease in the strength. Subcritical crack growth (Atkinson and Meredith, 1987) assisted by the stress corrosion mechanism (Anderson and Grew, 1977; Michalske and Freiman, 1982; Freiman, 1984) may play the important role for this time-dependent rock strength. Chemically assisted crack growth is the primary mechanism for stress corrosion and static fatigue at temperatures in the 0–200°C range (Kranz et al., 1982; Lockner, 1993, 1995). In the brittle regime in the lithosphere, if fluids are present, stress corrosion and creep effects are significant. The weakening of the fracture strength, in other words the upper bound to the strength of the brittle regime, may be greater, especially at greater depth, than current strength models of the lithosphere, which may have to be reconsidered.

I did not examine the effect of temperature on the time-dependent rock strength in this report. However, the stress corrosion effect also depends on temperature as well as water, as shown by Atkinson and Meredith (1983) for example. The physico–chemical effects of water on rock strength, such as stress corrosion, seem important in a brittle regime. Even though previous authors obtained the constants in expressions (1) and (3), this report provides for the first time not only the constants themselves but also their dependence on various experimental conditions. These data are useful for reconsidering strength models of the lithosphere.

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