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ScienceDirect
International Journal of Rock Mechanics & Mining Sciences 44 (2007) 321–331
International Journal of Rock Mechanics and Mining Sciences
www.elsevier.com/locate/ijrmms

Influence of surrounding environments and strain rates on the strength of rocks subjected to uniaxial compression

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Accepted 3 July 2006
Available online 29 September 2006

Abstract

Uniaxial compression tests were performed under various non-atmospheric environments and constant strain rates on Kumamoto andesite. The environments considered were water vapor, organic vapor such as methanol, ethanol and acetone, and inorganic gas such as argon, nitrogen and oxygen. The strength of rock increased in the order of water vapor, methanol, ethanol and acetone vapor, and the stress corrosion index changed with changing environment even for the same rock type. The stress corrosion index was evaluated to be 31 in consideration of the water vapor pressure and strain rate. The stress corrosion index in this research showed good agreement with other researchers' results and it can be concluded that the stress corrosion index is one of the constants representing the mechanical properties of the rock. However, it is an environment-dependent factor and may vary owing to the difference of hydroxyl ion concentrations that may exist in the same rock. Finally, it was shown that the time to failure is delayed by decreasing water vapor pressure in the surrounding environment, and then the long-term strength of rock under water vapor pressure can be estimated, based on sub-critical crack growth due to stress corrosion.

Keywords: Rock; Uniaxial compression test; Non-atmospheric environment; Stress corrosion index; Long-term strength

1. Introduction

In completely brittle elastic materials, a crack is in a stable state for a stress intensity less than the critical stress intensity factor, the latter being known as the fracture toughness; however, the crack becomes unstable when the stress intensity factor reaches a critical value and it begins to propagate rapidly [1]. The critical value of the associated rock strength is largely dependent on mineralogical properties such as the compositions and textures of the minerals, and the quantity, shape and orientation of pre-existing cracks in the rock.

Under certain environmental conditions, especially high temperature and/or reactive environments, delayed failures dependent on the time for crack growth are observed for most materials when a static load below critical stress intensity factor is applied [2]. This phenomenon known as sub-critical crack growth, depends on several possible mechanisms, such as stress corrosion, dissolution, diffusion, ion-exchange and microplasticity [3]. Among them, stress corrosion is the main mechanism behind sub-critical crack growth in shallow crustal conditions, i.e. for the upper 20 km of the earth's crust [4,5].

First observed in 1899 by Grenet using glasses, stress corrosion has been reported in ceramics [6–9] and minerals and rocks [10–13]. Stress corrosion cracking was originally defined as environmentally induced sub-critical crack growth under static stress [14]. Recently, this definition has been extended to include mechanical failure, such as crack growth due to fatigue and creep stress in the absence of chemical phenomena. Therefore, stress corrosion has to be understood not only in terms of the chemical parameters of the surrounding environment but also in terms of the mechanical factors. However, there are few experiments to clarify the effect of a rock's surrounding environment on its

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1365-1609/$ - see front matter
doi:10.1016/j.ijrmms.2006.07.009

mechanical properties and strength. In this research, the influence of the surrounding environment and strain rate on the strength of rock is experimentally investigated.

The study of the long-term strength of rock is necessary for examining the stability of underground openings, such as caverns, for hydraulic power plant and nuclear waste disposal constructed underground, bearing in mind that the rock mass around an underground opening is generally in a high humidity state due to the presence of groundwater. Since water is considered to be the most effective agent to promote stress corrosion of rock [5], stress corrosion should be considered in estimating the long-term strength of rock in the water, or under a water vapor environment. However, there have been few experiments to investigate the influence of the water vapor environment on rock strength.

To rectify this situation, uniaxial compression tests were firstly performed under various environments (different from atmospheric) on Kumamoto andesite. The environments used in these tests were water vapor, organic vapor, such as methanol, ethanol and acetone, and inorganic gas such as argon, nitrogen and oxygen. The purpose was to establish whether water is the most effective agent in promoting stress corrosion of rock. Secondly, a series of uniaxial compression test was conducted under various water vapor pressures and strain rates. By analyzing the mechanical behavior and the strength of the rock specimens, the influence of water vapor pressure and strain rate on stress corrosion can be clarified. Furthermore, the stress corrosion index from the experiment can be compared with those of other researchers. Finally, the long-term strength of rock can be discussed, based on a theory and experimental results obtained in this research.

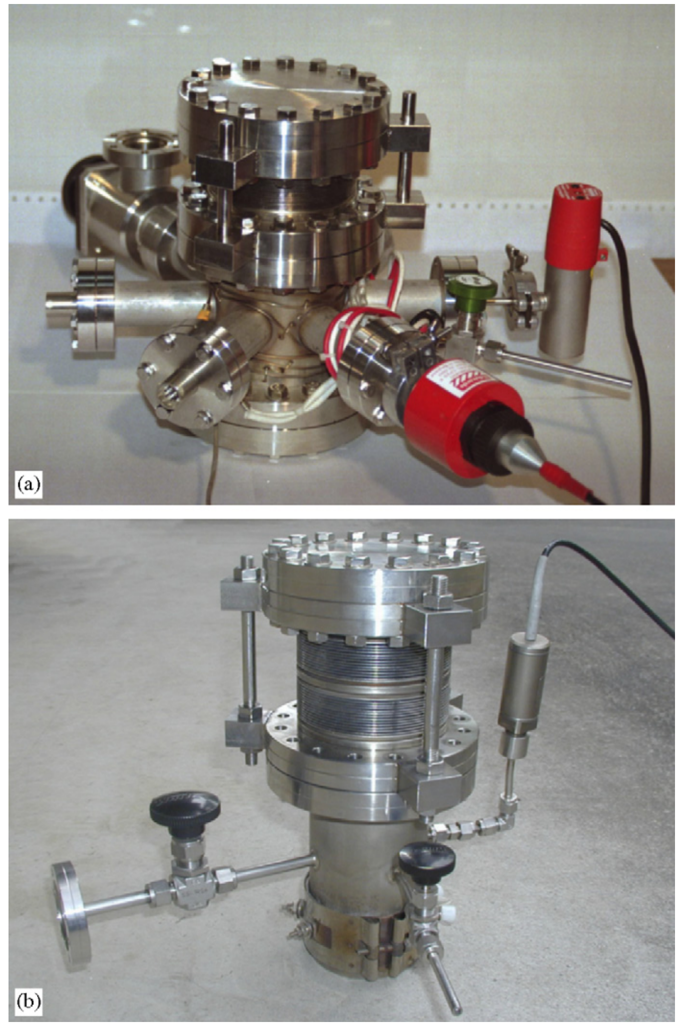

Fig. 1. Photograph of vacuum chambers: (a) chamber A for low pressure; (b) chamber B for high pressure.

2. Experimental apparatus and specimen

In order to control the surrounding environment of a sample rock, two chambers were made as shown in Fig. 1: chamber A is used for pressures below 2×10^3 Pa and room temperature; chamber B is used for high pressures and high temperature below 200 °C. chamber A, which was made of SUS304, has six ports and a valve to inject gases. In these ports, two ports were used to lead the output from the strain gauges glued to the specimen surface. Two other ports measured the vapor pressure in the chamber by two pressure gauges, namely the Pirani and Penning pressure gauges, which had a measurement range of 10^5–10^{-1} and 10^0–10^{-6} Pa, respectively. One port was the window for observing inside the chamber, and the other port with a valve was used to evacuate the air in the chamber by vacuum pumps.

Chamber B had two ports, a gas injection valve and a heater that controlled the temperature on the surface of the chamber. In two ports, the pressure transducer and the evacuation valve were connected.

The evacuation valve was linked to the two vacuum pumps: one was a turbo-molecular pump for high vacuum, and the other was a rotary pump for low vacuum. The evacuation velocity of the former was 160 l/s (N_2), and the ultimate pressure was 10^{-7} Pa. For the latter, those parameters were 90 l/s (N_2) and 10^2 Pa, respectively.

Kumamoto andesite was used as the experimental rock in this research. This rock type is porphyritic, consisting of plagioclase (about 50%), hornblende and augite (2∼3%) as phenocrysts in a fine-grained groundmass. Because Kumamoto andesite is isotropic and homogeneous [15], core was randomly drilled from a cubic block. The size of the specimens was 35 mm in diameter and 70 mm in length for uniaxial compression. The ends of the specimen were polished flat to 0.01 mm.

Because the purpose of the work is to clarify the influence of the surrounding environment on the mechanical behavior of rock, the water within a rock should initially be removed completely. For this purpose, the specimens were dried at 197 °C in the oven for about 80 days for the uniaxial compression tests. The changes of the longitudinal wave velocity V_P and unit weight γ of the specimen during drying are shown in Fig. 2. The vertical