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Influences of electrolyte concentration on subcritical crack growth in sandstone in water

Yoshitaka Nara [a,*], Ryo Nakabayashi [b], Megumi Maruyama [b], Naoki Hiroyoshi [c], Tetsuro Yoneda [c], Katsuhiko Kaneko [c]

[a] Department of Civil and Earth Resources Engineering, Graduate School of Engineering, Kyoto University, Kyoto Daigaku Katsura, Nishikyo-ku, Kyoto 615-8540, Japan
[b] Graduate School of Engineering, Hokkaido University, Kita 13 Nishi 8, Kita-ku, Sapporo, Hokkaido 060-8628, Japan
[c] Faculty of Engineering, Hokkaido University, Kita 13 Nishi 8, Kita-ku, Sapporo, Hokkaido 060-8628, Japan

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ABSTRACT

Information on subcritical crack growth in rock is essential to ensure the long-term stability of structures in a rock mass. Subcritical crack growth in rock is known to be affected by its surrounding environment. In most cases, rock found underground is saturated by water. The underground water can be fresh water or salt water with variable electrolyte concentrations. However, the influence of electrolyte concentration on subcritical crack growth in rock has not been fully elucidated. In this study, subcritical crack growth in Berea sandstone and Shirahama sandstone was measured when saturated with distilled water and with sodium chloride solutions of differing concentrations. Crack velocity in Berea sandstone changed very little with different electrolyte concentrations. By contrast, in the Shirahama sandstone, crack velocity became lower with increased electrolyte concentrations up to 1.0 mol/l. With increasing electrolyte concentration, the width of the electric double layer on the surface of mineral grains decreased, which caused a decrease in the repulsive force acting on the crack surface, leading to a decrease in crack velocity up to concentrations of 1.0 mol/l. However, when the electrolyte concentration was higher than 1.0 mol/l, crack velocity increased due to the nucleation of microscopic defects on the boundary between clays and stiff mineral grains. Thus, electrolyte concentration affects subcritical crack growth by decreasing the width of the electric double layer and the condensation of clay minerals.

1. Introduction

It is essential to understand the long-term stability of the rock mass surrounding certain structures, such as underground repositories of radioactive wastes, caverns in which liquid natural gas (LNG) or liquid petroleum gas (LPG) is stored, or underground power plants. Especially, it is supposed that ^{14}C is confined for 60,000 years, which corresponds to 10 times of the half-life of ^{14}C, for the geological disposal of radioactive wastes containing ^{14}C (Nara et al., 2010a). Therefore, studies of time-dependent behaviors in rock are important (Atkinson and Meredith, 1987a,b; Brantut et al., 2013). Subcritical crack growth is one of the main causes of time-dependent deformation and fracturing in rock (Atkinson, 1982; 1984; Atkinson and Meredith, 1987a). Information about subcritical crack growth is thus essential to ensure the long-term integrity of the rock mass.

Water has been shown to have a strong influence on subcritical crack growth in rock (Anderson and Grew, 1977; Kranz, 1983; Atkinson, 1984). The crack velocity at a given stress intensity factor in water is higher than that in air (Waza et al., 1980; Sano and Kudo, 1992; Nara et al., 2009). Higher relative humidity also leads to an increase in crack velocity in air (Nara et al., 2010b, 2011a).

In most cases, rock found underground is saturated by water. This underground water can be fresh water or salt water with variable electrolyte concentrations between 0.3 and 0.4 mol/l (Mizukami et al., 1977; Iwatsuki et al., 2005; Hama et al., 2007). However, the influence of electrolyte concentration on subcritical crack growth in rock has not yet been determined fully.

In this study, we investigated subcritical crack growth in sandstone when saturated with distilled water and salt water (sodium chloride solution) with different electrolyte concentrations. Specifically, we aimed to determine the influence of the electrolyte concentration in water, up to 1.7 mol/l, on the relationship between crack velocity and the stress intensity factor.

2. Rock samples

Berea sandstone (Ohio, USA, Mississippian period), and Shirahama sandstone (Wakayama Prefecture, Japan, Neogene period) were chosen as rock samples. Berea sandstone was chosen because it consists of

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* Corresponding author at: Department of Management of Social Systems and Civil Engineering, Graduate School of Engineering, Tottori University, 4-101 Koyama-Minami, Tottori 680-8552, Japan. Tel./fax: +81 857 31 5290.
E-mail address: nara@cv.tottori-u.ac.jp (Y. Nara).

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mainly quartz and feldspar and contains few clay minerals. By contrast, Shirahama sandstone was chosen because of the presence of clay minerals (Nara et al., 2011a, 2012). Fig. 1 shows the results of X-ray diffraction (XRD) analysis (Nara et al., 2011a). Fig. 1(a) shows clear peaks of clay minerals for Shirahama sandstone as well as those of quartz and feldspars. In Fig. 1(b), peaks of clay minerals are not significant for Berea sandstone, whereas those of quartz and feldspars can be recognized easily.

In Table 1, the results of X-ray fluorescence (XRF) analysis are summarized (Nara et al., 2011a). It is shown that the main component for sandstones in this study is quartz. Especially, the percentage of quartz for Berea sandstone is high. On the other hand, the percentages of Fe_2O_3 and Al_2O_3 are higher for Shirahama sandstone. In addition, the amounts of K_2O, CaO, MgO and Na_2O are higher for Shirahama sandstone, which are related to clay minerals.

In Figs. 2 and 3, the photomicrographs of Shirahama sandstone and Berea sandstone are shown, respectively. These photomicrographs are observed from thin sections with 0.03 mm thickness. In Figs. 2 and 3, (a) and (b) are obtained under crossed nicols and ultraviolet light by the fluorescent method (Ali and Weiss, 1968; Gardner and Pincus, 1968; Nishiyama and Kusuda, 1994, 1996), respectively. From these figures, the average grain sizes of Shirahama sandstone and Berea sandstone are 0.1 and 0.2 mm, respectively. Therefore, Shirahama sandstone consists of mineral grains with smaller size than Berea sandstone.

Physical and mechanical properties of sandstones are summarized in Table 2. P-wave velocities were measured by ultrasonic transmission method in three orthogonal directions called axes-1, -2 and -3 in the order of increasing velocity. Axis-3 is normal to the bedding plane. It is shown that both sandstones in this study possess P-wave velocity anisotropies. The values of Young's modulus and Poisson's ratio were obtained via uniaxial compression tests at a strain rate of 10^{-5} s^{-1} with loading normal to axis-3 (Nara et al., 2011a).

Table 1
Chemical composition of sandstones obtained from X-ray fluorescence analysis in weight percent. "nd" means "not detected".

	Berea sandstone	Shirahama sandstone
SiO_2	92.24	74.31
Al_2O_3	4.39	12.47
K_2O	1.46	3.95
Fe_2O_3	1.06	5.96
CaO	0.30	1.05
TiO_2	0.23	0.42
MgO	0.19	0.77
Na_2O	nd	0.90

In this study, all specimens for fracture mechanics tests were prepared so that the crack propagated parallel to the bedding plane.

3. Experimental method

3.1. Outline

To measure the crack velocity and stress intensity factor, we chose to use the double-torsion (DT) method, a typical testing method for studying subcritical crack growth (Kies and Clark, 1969; Evans, 1972; Williams and Evans, 1973; Fuller, 1979; Pletka et al., 1979). The loading

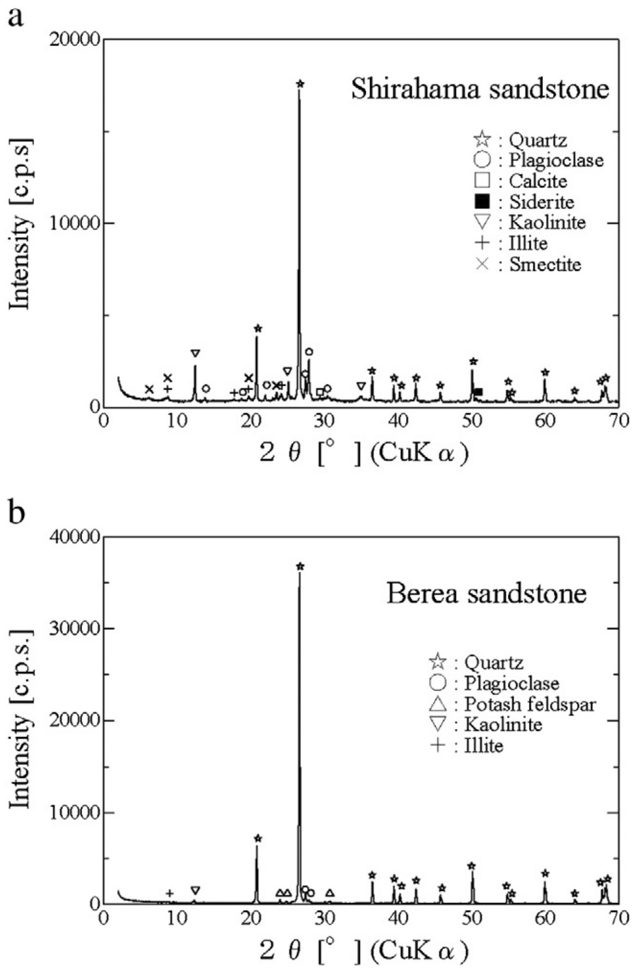

Fig. 1. X-ray diffraction patterns for sandstones. "c.p.s." means "counts per second". (a): Shirahama sandstone, (b): Berea sandstone (after Nara et al., 2011a).

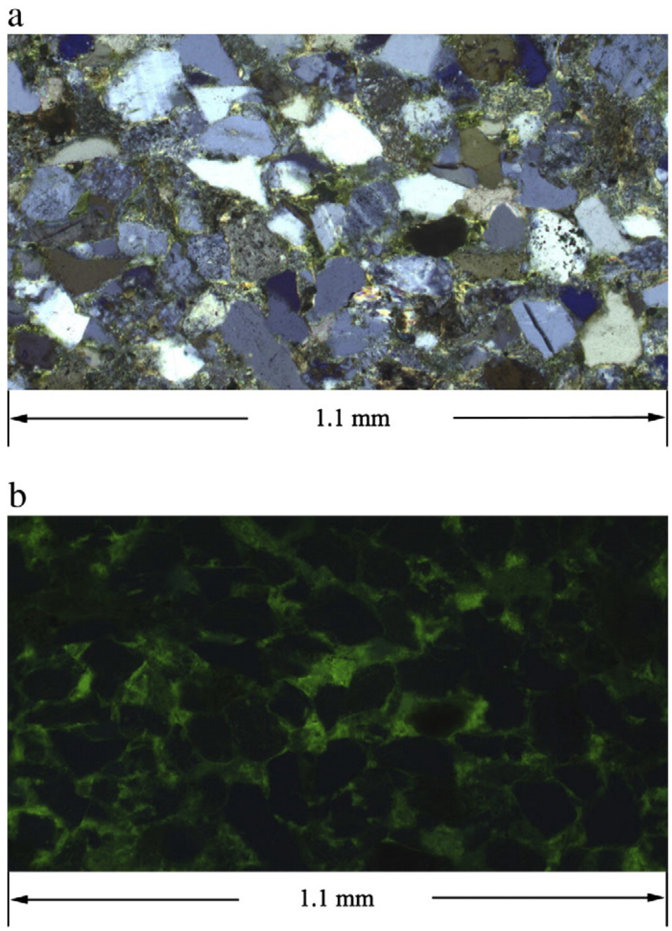

Fig. 2. Photomicrographs of Shirahama sandstone observed with polarizing microscope. (a): Image under crossed nicols, (b): image under ultraviolet light.