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Influence of surrounding environment on subcritical crack growth in marble

Yoshitaka Nara [a,*], Koki Kashiwaya [a], Yuki Nishida [a], Toshinori Ii [b]

[a] Graduate School of Engineering, Kyoto University, Kyoto-Daigaku-Katsura, Nishikyo-ku, Kyoto 615-8540, Japan
[b] Department of Civil Engineering, Tottori University, 4-101 Koyama-Minami, Tottori 680-8552, Japan

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ABSTRACT

Understanding subcritical crack growth in rock is essential for determining appropriate measures to ensure the long-term integrity of rock masses surrounding structures and for construction from rock material. In this study, subcritical crack growth in marble was investigated experimentally, focusing on the influence of the surrounding environment on the relationship between the crack velocity and stress intensity factor.

The crack velocity increased with increasing temperature and/or relative humidity. In all cases, the crack velocity increased with increasing stress intensity factor. However, for Carrara marble (CM) in air, we observed a region in which the crack velocity still increased with temperature, but the increase in the crack velocity with increasing stress intensity factor was not significant. This is similar to Region II of subcritical crack growth observed in glass in air. Region II in glass is controlled by mass transport to the crack tip. In the case of rock, the transport of water to the crack tip is important. In general, Region II is not observed for subcritical crack growth in rock materials, because rocks contain water. Because the porosity of CM is very low, the amount of water contained in the marble is also very small. Therefore, our results imply that we observed Region II in CM.

Because the crack velocity increased in both water and air with increasing temperature and humidity, we concluded that dry conditions at low temperature are desirable for the long-term integrity of a carbonate rock mass. Additionally, mass transport to the crack tip is an important process for subcritical crack growth in rock with low porosity.

1. Introduction

The long-term stability of rock masses surrounding structures, such as underground repositories of radioactive waste, caverns to store liquid natural gas and liquid petroleum gas, and underground power plants, is crucial. In addition, it is important to ensure the stability of rock slopes in open-pit mines for safety. Various studies have examined time-dependent fracturing in rock to determine the time-dependency of rock stability (Atkinson, 1984; Swanson, 1984; Meredith and Atkinson, 1985; Sano, 1988; Nara and Kaneko, 2005, 2006). In particular, studies of time-dependent fracturing in rock have been conducted to examine the natural hazards related to failure in rock, such as the increase in seismicity seen prior to earthquake rupture, fault formation, growth, sliding, and volcanic eruption (Kilburn and Voight, 1998; Ciccotti et al., 2000a, 2001; Heap et al., 2011; Brantut et al., 2013, 2014a; Violay et al., 2013). Additionally, several studies have evaluated the long-term strength and time-to-failure based on the measurement of time-dependent fracturing (Schmidtke and Lajtai, 1986; Jeong et al., 2007; Nara et al., 2013; Nara, 2015).

Although classical fracture mechanics postulates that crack propagation occurs when the value of the stress intensity factor reaches that of the fracture toughness, the crack can propagate even at a stress intensity factor lower than the fracture toughness. This is known as subcritical crack growth, which is considered to be one of the main mechanisms responsible for the time-dependent behaviour of rock in the brittle regime (Atkinson, 1984). Most studies of subcritical crack growth in rock have been conducted on silicate rocks, such as igneous rocks (Sano and Kudo, 1992; Nara et al., 2009, 2010), sandstones (Holder et al., 2001; Ponson, 2009; Nara et al., 2011, 2014), and novaculite (Atkinson, 1980).

Only a few studies have examined subcritical crack growth in carbonate minerals and rocks. Henry et al. (1977) reported that for micrite the crack velocity in water is higher than that in air. Røyne et al. (2011) suggested that some plastic processes might affect subcritical crack growth in calcite. Rostom et al. (2012) reported that the fluid salinity influences the crack velocity in calcite in a NaCl solution; specifically, they showed that the stress intensity factor decreased when the concentration of NaCl is <0.8 mol/L. Bergsaker et al. (2016) examined the impact of the fluid composition on subcritical crack growth in calcite single

* Corresponding author at: Department of Civil and Earth Resources Engineering, Graduate School of Engineering, Kyoto University, Kyoto Daigaku-Katsura, Nishikyo-ku, Kyoto 615-8540, Japan.
E-mail address: nara.yoshitaka.2n@kyoto-u.ac.jp (Y. Nara).

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crystal, and concluded that a pH in the range of 5–7.5 has a negligible influences. However, subcritical crack growth in carbonate rocks under different temperature and humidity conditions is poorly understood.

In this study, we investigated subcritical crack growth in marble experimentally in both air and water. We focused on examining the influence of the surrounding environment on the relationship between the crack velocity and stress intensity factor by conducting all measurements under controlled temperature and relative humidity.

2. Rock samples

We used examined two types of marble: Carrara marble (CM) quarried in Italy, and a marble quarried in Skopje in Macedonia (MM).

Fig. 1 shows photomicrographs of CM and MM observed with thin sections of 0.03 mm thickness. As shown in the photomicrograph, the grain size is around 0.2 mm and 0.3 mm for CM, and MM, respectively. Fig. 2 shows the results of X-ray diffraction analysis of the marbles. Remarkable peaks can be seen for calcite ($CaCO_3$) in CM and dolomite ($CaMg(CO_3)_2$) in MM. Small peaks of illite are also seen in MM.

For CM, the porosity determined by water saturation was 0.19%. The P-wave velocities in three orthogonal directions were 6.04, 5.98, and 5.90 km/s under dry conditions. CM is considered to be isotropic. The Brazilian tensile strength was 6.9 MPa. The uniaxial compressive strength, Young's modulus, and Poisson's ratio were 77.8 MPa, 51.0 GPa, and 0.32, respectively, which were determined from uniaxial compression tests with the loading rate at 10^{-5} strain/s.

For MM, the porosity measured by water saturation was 0.6%. The P-wave velocities in three orthogonal directions were 4.15, 4.06, and 3.74 km/s. We named these three orthogonal directions Axes 1, 2, and 3 in order of decreasing P-wave velocity. Furthermore, we named the planes normal to these axes Planes 1, 2, and 3, respectively. Slight anisotropy was observed in the P-wave velocity. Since investigation of anisotropic properties was beyond the scope of this study, we treated the marble sample as an isotropic material. The Brazilian tensile strength was 6.2 MPa when the fracturing was parallel to Plane 3. The uniaxial compressive strength, Young's modulus, and Poisson's ratio were 190 MPa, 80.2 GPa, and 0.46, respectively, which were determined from uniaxial compression tests with the loading rate at 10^{-5} strain/s.

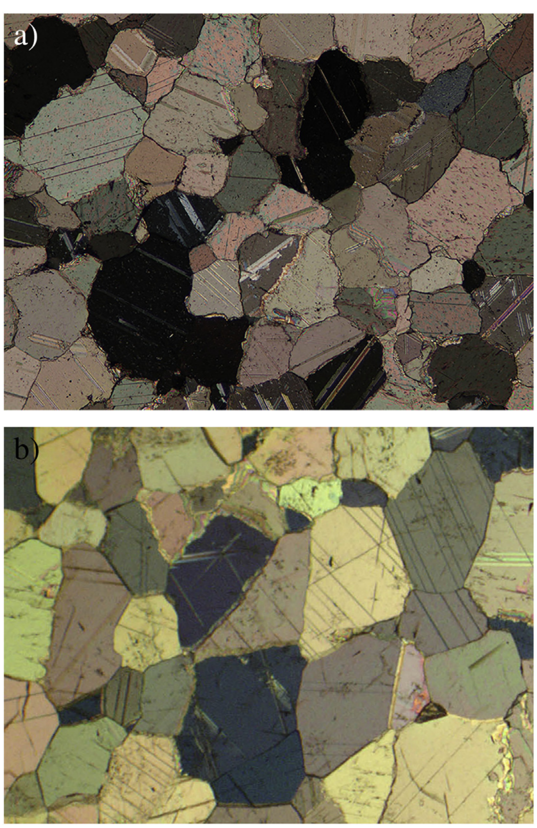

Fig. 1. Photomicrographs of (a) Carrara marble (CM) and (b) Macedonian marble (MM) observed with a thin section under crossed nicols. The width and height of the sections are 1.5 mm and 1.1 mm, respectively.

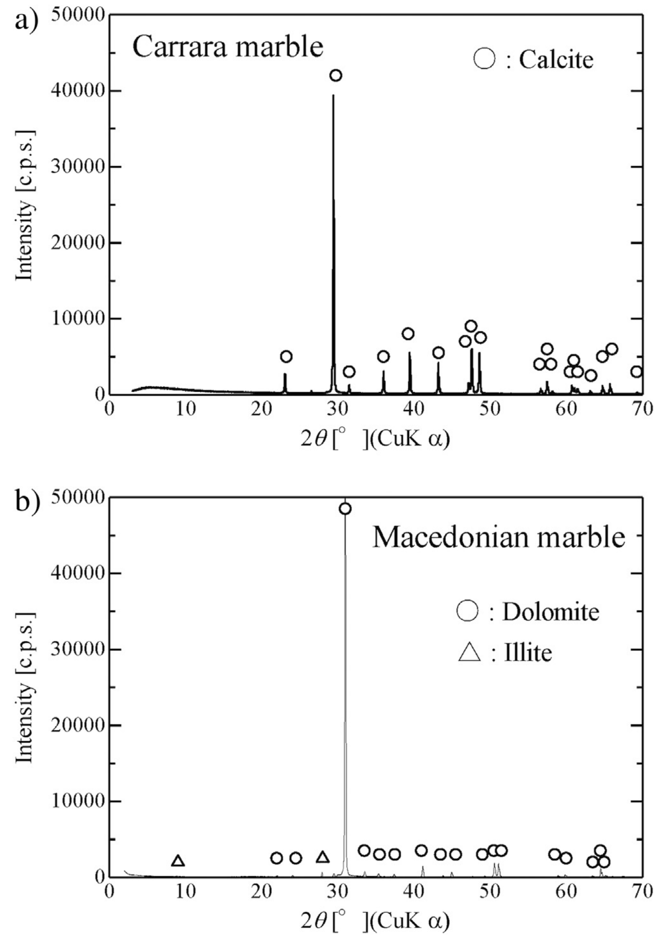

Fig. 2. X-ray diffraction patterns for (a) CM and (b) MM.

3. Methodology

3.1. Outline of double torsion method

In this study, the double torsion (DT) method was used. The DT method is a fracture mechanics testing method used commonly to study subcritical crack growth. The loading configuration of the DT method is shown in Fig. 3. Three different types of test can be performed using the DT arrangement, each using different loading conditions: the constant load method (Kies and Clark, 1969), the constant displacement rate method (Evans, 1972), and the load relaxation (RLX) method (Evans, 1972; Williams and Evans, 1973). Using the RLX method, we can obtain a large amount of data on the relationship between the stress intensity factor, K_I, and the crack velocity, da/dt (the K_I–da/dt relation), which, in general, ranges from 10^{-2} to 10^{-9} m/s, using only a single experimental run. Therefore, we used the RLX method to determine the K_I–da/dt relation in this study.

In the RLX method, the displacement of the loading points must be kept constant during the experiment while the temporally decreasing load (load relaxation) due to the crack growth is measured. The stress