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Failure mechanical and acoustic behavior of brine saturated-sandstone containing two pre-existing flaws under different confining pressures

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ABSTRACT

To better understand the mechanical, acoustic and failure behaviors of sandstone in deep saline aquifers, conventional triaxial compression tests were carried out on sandstone specimens containing two pre-existing three-dimensional (3D) flaws. First, pre-flawed sandstone specimens were saturated under NaCl solution with a salinity of 20 wt%. Then both dry and brine-saturated sandstone specimens were loaded under triaxial compression. As the flaw angle increased, the peak strength and crack damage stress of the dry and saturated pre-flawed sandstone specimens increased. The peak strength and crack damage stress of dry specimens increased linearly, while those of brine-saturated specimens increased nonlinearly with confining pressure. During triaxial loading, P-wave and AE signals were monitored in real-time for the sandstone specimens. The evolution of P-wave velocity and AE events can be characterized as having five stages based on the internal damage of sandstone specimens. In general, the accumulated AE count can be summarized as follows: very few or no AE counts, increases linearly, increases exponentially and increases stably. The P-wave velocity was also observed as: increases rapidly, increases stably, decreases unstably and keeps constant. Finally, by using X-ray micro CT observations, two crack coalescence modes between the two pre-existing flaws were identified, i.e., shear crack coalescence in the ligament region and indirect coalescence outside the ligament region. The second coalescence mode was only observed in the sandstone specimen with a flaw angle of 45° under low confining pressures. The internal opaque cracks were clearly displayed in the reconstruction images as a curved surface.

1. Introduction

Flaws often exist in natural rock masses, and they play a significant role in the strength and failure behavior of rock. In previous experimental or numerical studies, two-dimensional (2D) flaws (here, artificial fractures [1–5]) were cut as through-cracks in plate rock specimens. Then, researchers investigated the influences of pre-existing flaw and stress conditions on the strength, deformation and crack coalescence behavior of the rock [1–6]. Recently, many investigations have been carried out on rock or rock-like specimens with pre-existing three-dimentional (3D) flaws, which were often cut in cylindrical specimens. For example, Yang et al. [7] tested

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medium and coarse marble specimens with a pair of non-overlapping flaws under different confining pressures. They investigated the effect of crack propagation on the strength and deformation properties and found that the failure modes of pre-flawed specimens were dependent on both flaw geometry and the confining pressure. Huang et al. [8] performed a series of conventional triaxial compressions on sandstone specimens containing two pre-existing filled flaws with three arrangement types. The growth process of a surface crack was reproduced by using the numerical code AUTODYN, which showed a good agreement with their experimental results. Huang et al. [9] investigated the crack evolution of rock-like specimens containing two unparalleled flaws under triaxial compression. Their experimental and PFC3D simulation results showed that the failure mode was mainly affected by the flaw angle when the confining pressure was low. Horizontal and vertical cross sections of numerical specimens were derived to reveal the internal damage behavior of rock-like specimens. Yang and Huang [10] performed several conventional triaxial compression tests on granite specimens containing a single pre-existing flaw. Based on the experimental results, the effects of the confining pressure and the flaw angle on the strength and deformation parameters of granite specimens were evaluated.

Carbon dioxide (CO_2) capture and storage (CCS) is considered as an effective way to reduce CO_2 in the atmosphere. The geological sequestration of CO_2 in deep saline aquifers is a large-scale mitigation method. Investigations of saline-rock interaction have received more and more attention [11,12]. Zheng et al. [13] tested the short-term and long-term evolution of mechanical deformations of sandstone saturated in brine. The interaction between sandstone and brine was also studied by Rathnaweera et al. [14]. Their testing results showed that the strength of sandstone changed nonlinearly with the confining pressure and thus a modified failure criterion was proposed. However, the above-mentioned investigations were all carried out on the intact rock specimen without pre-existing flaws. In CO_2 storage projects, flaws that exist in cap rock are the potential pathways for CO_2 leakage. Therefore, the analysis of crack initiation, propagation and the coalescence behavior of rock under brine saturation is of great importance to the safety of CO_2 sequestration projects in deep saline aquifers.

As is well-known, acoustic signal monitoring (such as ultrasonic wave and acoustic emission (AE)) is an effective method to study the initiation and propagation of cracks. For example, Martínez-Martínez et al. [15] measured the P-wave velocity of low-porosity carbonate rocks during uniaxial loading. Their ultrasonic pulse velocity testing results demonstrated that the wave velocity was dependent on the damage extent of rock, in which P-wave velocity increased until the beginning of the unstable crack propagation and decreased only when rock damage was very high. Uniaxial compression tests were carried out on brittle shale specimens with different bedding angles by Yan et al. [16]. Based on the experimental results, they concluded that the variations in lateral P-wave velocity can characterize the damage development process but axial P-wave velocity cannot. Mechanical deformation and micro structural observations were conducted by Baud et al. [17] to investigate the constitutive behavior, failure mode, AE activity and spatial distribution of damage. To study the strength, deformability and failure behavior of rock, Yang et al. [18] conducted conventional triaxial compression and reducing confining pressure tests on sandstone. Based on the obtained spatial AE location, the evolutionary process of internal cracks was analyzed in detail. In addition to the methods mentioned above, X-ray computerized tomography (CT) is also an effective non-invasive, nondestructive method of detecting the internal fractures in opaque rock [19–22].

However, the mechanical properties and crack coalescence behavior of rock containing pre-existing flaws under saline saturation have been rarely investigated in the literature. Therefore, in this study, to enhance the understanding of strength and failure behaviors of rock in saline aquifers, conventional triaxial compression tests were performed on sandstone specimens containing two pre-existing flaws, which were saturated under vacuum for two months in brine water. Ultrasonic wave velocity and AE events were monitored in real-time for the sandstone specimens under triaxial loading. Finally, internal fracture characteristics in the post-test sandstone specimens were investigated by using high-resolution X-ray CT scanning.

2. Experimental methodology

2.1. Specimen preparation

The tested sandstone was located in Zunyi City of Guizhou Province, China. The mineral components were mainly quartz (95.8%) and minor K-feldspar (0.4%), plagioclase (0.1%), dolomite (0.5%) and clay minerals (3.2%), according to the result of X-ray diffraction analysis. The average bulk density was 2130 kg/m^3, with a porosity of 16.2%. The basic mechanical parameters (average values) of the tested intact sandstone specimens are described as follows: the uniaxial compressive strength (UCS) was 50.61 MPa, the elastic modulus was 12.06 GPa, the Poisson's ratio was 0.358, the Brazilian tensile strength was 2.95 MPa, and the cohesion and internal friction angle were 18.52 MPa and 38.82°, respectively.

All the tested specimens were machined from a large sandstone block as cylinders along the same direction. Then, the sandstone cylinders were carefully ground to produce flat parallel surfaces. Thus, an intact sandstone specimen, with a diameter of 50 mm and a height of 100 mm, was produced, which met the ISRM suggested method [23]. A high-speed electric cutting machine was used to cut flaws in the intact specimens. The machined flaw thickness was approximately 1.5 mm without filling materials. The detailed geometry for pre-existing flaws is shown in Fig. 1a. The length of the pre-exiting flaw ($2a$) was fixed to 22 mm, while the distance between the flaw and end of the specimen ($2b$) was fixed to 23 mm. The angle between flaw ① and horizontal direction was α, and that between flaw ② and the horizontal direction was β. To simplify the present analysis, three different flaw geometries were designed by varying α and β. A detailed description of the tested sandstone specimen is listed in Table 1.

Although the brine in a real saline aquifer is a mixture of ions, NaCl is dominant (typically 70–90%) [24]. Therefore, an NaCl solution with a salinity of 20 wt% was used to simulate the saline water. The prepared sandstone specimens were immersed in desiccators under vacuum (see Fig. 1b). The masses of the sandstone specimens were measured regularly to evaluate the extent of saturation. To ensure the maximum reaction between brine water and sandstone, the sandstone specimens were soaked in brine for