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Acoustic emission investigation of hydraulic and mechanical characteristics of muddy sandstone experienced one freeze-thaw cycle

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ABSTRACT

Artificial freezing technology has been proved to be one of the most effective methods to construct deep mine shafts in water-rich soft rock in western China. Water penetration and shaft flooding accidents are always the major problems during the construction and utilization. In this paper, using triaxial seepage testing and acoustic emission (AE) monitoring, the mechanical and hydraulic characteristics of muddy sandstone specimens taken from Meilin Temple Mine at a depth of 700 m in Ordos were studied under one full freeze-thaw loading cycle. Test results showed that the cementation of rock samples is deteriorated after one freeze-thaw cycle and the maximum width of secondary fractures on surface of samples are about 0.03 mm. While the failure process of rock sample is revealed by AE energy, the variation of permeability corresponds well to AE amplitude. For confining pressure lower than 25 MPa, as the confining pressure increases, the rock tends to fail in ductile mode. AE signals are not active in the beginning loading stage under higher confining pressure, on the contrary the maximum values of AE energy and amplitude during the whole test process increase. While the peak strength increases by 64.3%, both initial permeability and peak permeability decrease obeying negative exponential law. Additionally, the crack initiation ratio demonstrates a linear relation with confining pressure; the damage ratio shows an exponential trend.

1. Introduction

Artificial freezing technology is one of the most effective construction methods for deep mine shafts in China (Li et al., 2011; 2017; Zhao et al., 2015). In western area of China, there are some soft strata, such as Jurassic and Cretaceous, which are characterized by low strength, poor cementation ability, high water content and easy fracture development, artificial freezing technology is widely used in this area (Yang et al., 2014; Liu et al., 2016). During the construction process of mine shafts in this area using artificial freezing method, initially rock mass experiences damage in freezing condition due to the frost heave force from fracture water; after the shaft construction is finished, the frozen rock thaws from about −20 °C up to normal temperature. The annular space of freezing pipe formed during mine shaft construction connects the upper and lower strata, the fracture water in upper strata flows to lower strata through the annular space (Zhou et al., 2009; Yao et al., 2010; Liu et al., 2015). Both of these conditions could induce frozen wall breakage and shaft flooding.

Over the past five decades, many researchers have studied the mechanical and hydraulic characteristics of crack rocks (Yamabe and Neaupane, 2001; Connell et al., 2010; Bayram, 2012; Rabbani and Jamshidi, 2014). Liu et al. (2009) proposed a simple mathematical model to determine the equivalent permeability of fractured porous media. Lai et al. (2012) proposed a damage statistical constitutive relationship and a stochastic model of warm ice-rich frozen silt based on the probability distributions of parameters and random process theory, the calculated results of these two models are well aligned with experimental results. Ezersky and Goretsky (2014) pointed out the correlative relationships between porosity and permeability of salt samples and their relationships with compression and shear wave velocities and specific resistivity. Miao et al. (2015) proposed a fractal model of permeability for fractured rocks based on fractal geometry theory and cubic law for laminar flow in fractures; fractal scaling law for length distribution of fractures and the relationship among fractal dimension for fracture length distribution, fracture area porosity and the ratio of the maximum length to the minimum length of fractures were discussed.

Acoustic emission (AE) technique is a non-destructive method to detect the rock damage and has been used in mining science and rock engineering since late 1930s (Baud and Meredith, 1997; Eberhardt

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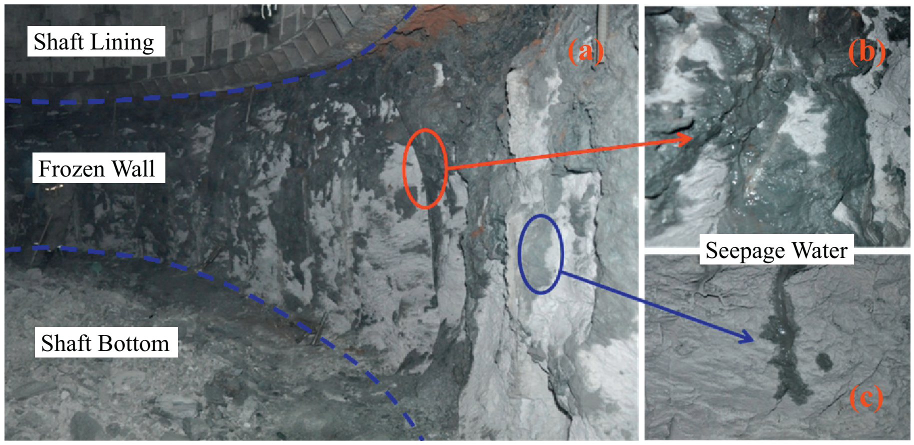

Fig. 1. Artificial freezing construction of mine shaft at 700 m; the section between two blue lines in picture (a) is frozen wall, 6 m in thickness; (b) and (c) show the seepage water in shaft. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 1999; Xie et al., 2011). A variety of researches on AE application to rock monitoring have been reported. Shiotani et al. (2001) installed AE sensors into the rock slope and proposed a criterion for classifying fracture states. Ranjith et al. (2010) detected the onset of crack initiation and damage stress threshold of black coal samples successfully with AE technique. Amitrano et al. (2012) used AE monitoring to investigate rock damage in a high-alpine rock-wall induced by natural freeze-thaw cycles.

So far, the most existing hydraulic researches mainly focus on the rocks under common condition, the research of rocks experienced freeze-thaw cycles remains insufficient. Fig. 1 presents the actual mine shaft constructed at 716 m. The 6 m thick frozen wall with a temperature of about −18 °C has been infiltrated by the water from outside of the shaft. Therefore, it is crucial to carry out researches on mechanical and hydraulic characteristics of soft rock for the construction of vertical mine shaft in western of China. This work is devoted to investigating how the one freeze-thaw cycle influences on the mechanical and hydraulic characteristics of muddy sandstone. Furthermore, AE technique is utilized to detect the real-time failure process of rock samples in the triaxial seepage tests.

2. Test apparatus

2.1. Triaxial seepage apparatus

The TAW-2000 triaxial electro-hydraulic servo-controlled seepage apparatus (shown in Fig. 2) used for the tests is developed by the institute of Geology and Geophysics, Chinese Academy of Sciences, the main device is based on MTS system. The maximum loading capacity is 2000 kN, the maximum confining pressure and pore pressure are 100 MPa and 60 MPa, respectively and the temperature scope is from −50 °C to 200 °C.

2.2. AE system

DS2 holographic acoustic emission signal analyzer (shown in Fig. 2) developed by Beijing Softland Times Scientific & Technology Co. Ltd. is utilized to detect the real-time failure process of rock samples during triaxial seepage tests. The AE system has 8 channels with 3 trigger modes, that is, software trigger, signal threshold trigger and external trigger. Plenty of sampling rates can be selected, including 3 MHz, 2.5 MHz 1 MHz, 500 KHz, 200 KHz, 100 KHz and parameters, such as AE counts, AE amplitude, AE energy, rise time and hits, can be obtained after tests. The system can be used to locate damaged zones in rock, metal and composite materials and perform non-destructive damage tests for concrete structure and bridge.

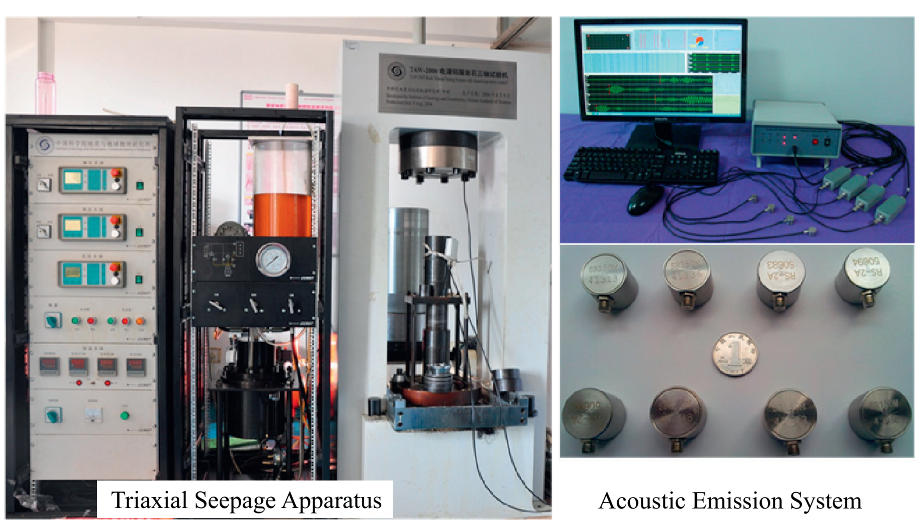

Fig. 2. Triaxial seepage apparatus associated with acoustic emission system.