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Experimental investigation on the micro damage evolution of chemical corroded limestone subjected to cyclic loads

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ABSTRACT

Micro damage evolution in chemical corroded limestone samples subjected to cyclic loads is investigated using Nuclear Magnetic Resonance (NMR) system. Based on the experimental data of Magnetic Resonance Imaging (MRI), T_2 values and porosity, the micro damage evolution process is visualized and analyzed. It is found that the porosity and micro cracking of the corroded limestone samples increase with the cyclic loading, and the micro damage evolution process consists of three distinct stages: micro crack emergence stage, micro damage development stage and damage development accelerated stage. Chemical erosion is found to have a significant influence on the propagation of micro cracks and accelerate the damage development of the limestone samples under cyclic loading. With the same number of load cycles, the chemical corroded samples always have lower peak strength than that of the water softened samples. Before the inflection point in the micro damage-loading cycles curve, the main damage is caused by new micro cracks increase inside the limestone; while after this point, the new micro crack emergence is being restrained, and the existed micro cracks connect into rupture bands. A damage model is finally proposed to quantify the damage evolution of the chemical corroded rocks subjected to cyclic loads.

1. Introduction

Underground construction excavation, such as tunnel and nuclear waste deposition, *etc*., leads to the cyclic loads near the excavation surface and subsequent stress-induced instabilities [1,2]. The instability and failure of engineering rocks is closely related to the initiation and propagation of micro cracks that are induced by cyclic loads [3]. Propagation of micro cracks inside rocks is determined by the external loads as well as the surrounding environment. Engineering rocks are always surrounded by water, which is a significant influential factor for the mechanical characteristics of rocks by reducing their strength and even causing geological disasters during the excavation processes [4,5]. This is because that the surrounding water often contains chemical icons [6,7], which can react with the mineral inside the rocks. Therefore, understanding the micro damage evolution of chemical corroded engineering rocks under cyclic loading conditions is vital in order to reduce the risk of causing potential engineering disasters during excavation.

Over the past few years, considerable efforts have been made to investigate the mechanical response of intact rocks under cyclic loading. Results have shown that the fatigue properties of rock materials are dependent on the maximum stress, loading frequency and amplitude, *etc*. Based on energy dissipation, Liu et al. [8] established damage evolution equations for two typical rocks using the uniaxial cyclic loading test results, and proposed a new damage constitutive model to describe the behaviour of rocks under cyclic loading. The amended damage constitutive model can describe the degree of compactness of rocks accurately. Shayea [9] reported that the dynamic elastic modulus and Poisson's ratio increased with the confining pressure, and under cyclic loading their values during unloading were slightly higher than those during loading. Ray et al. [10] concluded that failure strength and elastic modulus of Chunar sandstone subjected to cyclic stress decreased with the increase of strain rate, and the uniaxial compressive strength decreased with the increase of loading cycles. Yoshinaka et al. [11–13] conducted cyclic loading tests to investigate the deformation behaviour of the soft rocks, including Kobe mudstone, sandstone, Ohya tuff and Yokohama siltstone, and introduced a procedure for strain correction, Young's modulus estimation and yield location. Bagde and Petros [14,15] conducted cyclic loading tests on rock samples to investigate the relationship between loading amplitude and frequency and the fatigue strength and deformation behaviour. It was found that fatigue strength of the rock under dynamic cyclic loading is

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influenced by the micro structure of the rock samples, the Young's modulus decreases when increasing the cyclic loading frequency and amplitude, and there is no obvious relationship between the dynamic energy and the cyclic loading frequency. Sun et al. [16] carried out cyclic loading tests at multi-level amplitudes on sandstone samples to investigate the damage evolution law of the Chaboche and developed a multiaxial fatigue damage model for damage accumulation.

Meanwhile, a few studies investigated the influence of environment, such as cyclic temperature and freezing conditions, on the mechanical properties of rocks. Li et al. [17] conducted cyclic loading experiments to investigate the mechanical properties of a jointed rock mass under freezing and cyclic loading conditions, found that the original samples usually have a higher fatigue strength than the frozen and water saturated samples, and thus proposed a dynamic, fatigue damage model for cracked, frozen sandstones. Zhou et al. [18] conducted cyclic uniaxial stress-temperature tests on basalt rock specimens to investigate the deformation characteristics of the samples subjected to cyclic uniaxial stress and cyclic temperature. Results showed that the peak strain of damaged specimens undergoes initial, steady and acceleration stages; the Young's modulus decreases rapidly in the initial cycles, but the declining rate decreases further in subsequent cycles. A damage model for rocks subjected only to cyclic temperature was also proposed. Mahmutoglu [19] conducted several cyclic temperature tests on sandstones, and found that there is an obvious decrease in the mechanical properties of the sandstones after being treated with cyclic temperature.

Most studies of cyclically loaded rocks have focused on the changes of macro-mechanical properties. However, under the effect of different external loading conditions, great changes could take place inside the rock, such as micro-cracking [20,21], which then cause the macro-mechanical degradation of the rock [22]. However, experimental studies on chemical corroded rocks subjected to cyclic loads are rarely reported, and the influence of cyclic loading coupled with chemical erosions on micro damage evolution of rock still remains unclear. The micro-cracking inside the rock can be investigated using computerized tomography (CT) technique [23–26] or Nuclear Magnetic Resonance (NMR) System [27–30]. NMR has been widely applied in medical diagnosis, geotechnical engineering and oil and gas exploration [31,32]. It recently starts to be used in rock engineering for internal microstructure imaging and characterization [30].

In this study, NMR and cyclic loading tests are carried out to investigate the micro damage evolution of chemical corroded limestone samples subjected to cyclic loads. Through the analysis of the Magnetic Resonance Imaging (MRI) and T_2 values, the micro damage of the limestones has been visualized and calculated, and the relationship between peak strength degradation and micro damage is investigated. A damage model for rocks subjected to cyclic loads coupled with chemical erosion is established, which can be potentially used for predicting rock strength in practical design of underground constructions, slops and dams and roads in water surrounded regions.

2. Rock samples and experimental tests

2.1. Sample preparation

The rock samples are limestone, taken from Jinyun Mountain Tunnel in Chongqing China. The Jinyun Mountain Tunnel has two tunnels, each with a length of 7.379 km and have a maximum depth of 220 m. Limestone, a common sedimentary rock in southwest China and is the main rock of Jinyun Mountain, is selected as the test samples in this experiment. All the samples are drilled from a single block without macroscopic cracks and machined and finely ground into cylindrical shapes with a length of 100 mm and a diameter of 50 mm, as shown in Fig. 1. According to the X-ray diffraction (XRD) analysis it is found that the limestone samples are composed of 92% calcspar and quartz and 1% accessory minerals. A typical microstructure of the limestone is shown in Fig. 2.

Fig. 1. Limestone samples.

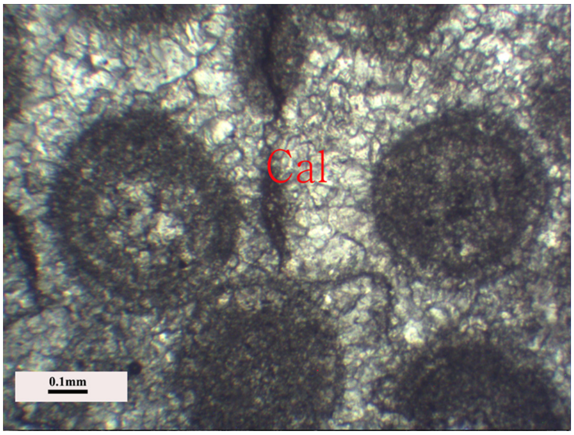

Fig. 2. Microscope image of a limestone sample: Cal, calcspar.

2.2. Chemical solutions

According to water sample analysis, the water samples collected from the Jinyun tunnel construction site in Chongqing, has a pH value of 6.5 and the main icons are Na^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^- and HCO^-. To simplify the experimental study, the complex ionic compositions of the water are replaced by Na_2SO_4 solution, which is made by NaCl solution added with H_2SO_4. Three pH values (3, 5 and 7) of the Na_2SO_4 solution are used in the tests and the initial concentration of the chemical solutions is all 0.01 $mol \cdot L^{-1}$.

2.3. Test methodology and process

Fig. 3 shows the NMR system, and a T_2 spectrum. The NMR system measures the signal intensity of hydrogen atoms, which depends on the number and size of pores inside the rock, in the fully-saturated rock and outputs transverse relaxation time distribution (T_2 spectrum), porosity and Magnetic Resonance Imaging (MRI), which can be used to investigate the pore size distribution and micro structure damage of the rock.

All the mechanical tests are conducted using the Rock Testing System, as shown in Fig. 4.

The test process is as follows:

(1) The samples are saturated using a vacuum saturation device. After saturation for 24 h, all the samples are warped with preservative film to prevent evaporation, and then putted into the test box of the NMR machine. With the help of the industrial computer of the NMR machine, the initial T_2 spectrum and the porosity of the limestone