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Damage evolution mechanism and constitutive model of freeze- thaw yellow sandstone in acidic environment

Dengxing Qu[a], Li Dengke[c], Xinping Li[b,*], Yi LUO[b], Xu Kun[a]

[a] School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan, China
[b] Hubei Key Laboratory of Roadway Bridge and Structure Engineering, Wuhan University of Technology, Wuhan, China
[c] School of Resources and Environmental Engineering, Wuhan University of Technology, Wuhan, China

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ABSTRACT

The study on the damage evolution mechanism of freeze-thaw of rock sample in acidic environment is of great theoretical and practical significance to the analysis and prevention of freeze-thaw disasters in cold area. Taking the yellow sandstone as the research object, the freeze-thaw cycle experiments, the NMR system experiments, the chemical composition analysis experiments and the uniaxial compression experiments under acidic environments with different pH are carried out to analyze the physical and chemical characteristics of the yellow sandstone. The damage evolution equation and constitutive model of rock are studied based on statistical strength theory, Lemaitre strain equivalent assumption and damage mechanics. In this paper, the damage evolution equation of chemical freeze-thaw sandstone under load is established. The damage correction coefficient is introduced to modify the total damage of chemical freeze-thaw sandstone under load. The constitutive model is deduced and the model parameters are deduced by the combination of theoretical derivation and experiment. The results show that the rock damage is the result of the coupling of freeze-thaw cycles and acid erosion, and the freeze-thaw cycle is the main reason and acidic erosion is the secondary reason. The experimental parameters are brought into the constitutive model, and the reliability of the model under uniaxial stress is verified by comparing with the experimental curve.

1. Introduction

Many engineering slopes, bridges and building foundations, culvert tunnels and other projects are facing the problem of freeze-thaw. In addition, part of the cold region in China is in an area where acid rain rages. According to statistics(Zhang et al., 2002), the extreme pH value of acid rain in some areas of China reached 3.05. In the middle of the last century, acid rain raged in areas such as New York, Vermont, New Hampshire and Maine, causing a huge damage to local buildings and vegetation. The mechanical properties, physicochemical characteristics, damage evolution rule and constitutive model of freeze-thaw rocks in the acidic environment are studied. It is of great importance to improve the mechanical properties of rocks and to establish the damage evolution equation and constitutive model of rock under the condition of multi-field coupling.

The changes of the related parameters (compressional, shear velocities, temperature cycling) of saturated brine Berea sandstone after freeze-thaw cycle were studied (Sondergeld and Rat, 2007). The P wave velocity, hardness and compressive strength of andesite under the combined action of freeze-thaw cycle and thermal shock cycles were studied by Yavuz and Ghobadi (Yavuz, 2011; Ghobadi and Babazadeh, 2015). Through the experiment of freeze-thaw cycle tests of two kinds of rocks under open saturated conditions, the corresponding mechanical properties were analyzed, and the temperature-seepage-stress damage constitutive model of rock freeze-thaw was established (Xu and Liu, 2005; Jiang et al., 2017; Freire-Lista et al., 2015; Tan et al., 2011). The influence of freeze-thaw cycle on the physical and mechanical properties of granites with coarse and fine grains was studied. Rock samples were detected by NMR, and the porosity variation, pore structure and evolution laws were discussed (Zhou et al., 2013; Tan et al., 2018). Based on mesoscopic damage theory and macroscopic statistical damage model, the damage model of freeze-thaw and loading rock masses were establishe(Li et al., 2013; Eslami et al., 2018; Huang et al., 2018; Dong et al., 2016). Determining the deteriorations of stones after freeze–thaw cycles is an important subject for natural building stones used in cold regions exposed excessive freezing and thawing during the year. The percentage loss values in uniaxial compression strengths from intact rock properties was predicted (Bayram, 2012;

* Corresponding author.
E-mail address: lixinping00@sina.com (X. Li).

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Wang and Yan, 2010; Wang et al., 2017). Mechanical experiments of the limestone samples under the action of coupled chemical solutions and freeze-thaw processes were carried out to investigate the infiltrated water erosion and freeze-thaw damage on the surrounding rocks (Ding et al., 2015; Ding and Feng, 2004; Ni et al., 2017; Han et al., 2017).

At present, the research of the influence of water chemical solution on rock strength, deformation and other physical and mechanical properties is much more, but the research on damage evolution law of freeze-thaw rock in acid environment is relatively less (Peng et al., 2011; Dunning et al., 1994; Li et al., 2003). The matter of rock freeze-thaw under acidic environment has become a widespread problem in the engineering field. Based on the research status and trend of freeze-thaw at home and abroad, taking Yunnan yellow sandstone as the research object, the damage evolution mechanism and constitutive model of freeze-thaw rock are studied.

2. Test scheme

The experiments of freeze-thaw cycle of yellow sandstone in different acidity environments are carried out. After immersing in different pH acid solution for different freeze-thaw cycles, the changes of the quality, appearance, elastic modulus, uniaxial compressive strength and NMR parameters of yellow sandstone are studied.

The rock samples used in this experiment originated in Sichuan Province and belonged to the yellow sandstone. The rock particle size is fine-grained with valley-yellow color. The main components are quartz and clay minerals. The rock samples are taken from the same intact and unweathered rock. The homogeneity of the rock is better and there is no macroscopic joint fissure. The sample is made into a standard cylinder with a diameter of (50 ± 1) mm and a height (100 ± 2) mm. The basic physical properties of the yellow sandstone are shown in Table 1. The mineral composition mass percentage of yellow sandstone samples is shown in Table 2.

The size and weight of all sandstone samples after natural water holding, drying for 48 h and vacuum saturated for 4 h were taken as the initial physical parameters of the samples. NMR system is used to measure the porosity of all samples after vacuum saturated water. The samples with larger porosity are removed and the remaining samples are grouped. Five different freeze-thaw cycles (0, 10, 20, 30 and 40 times) and four different pH values (7, 5.6, 4.2 and 2.8) are considered and orthogonal design is applied to them, plus a control group, each group of three samples. The samples are soaked in plastic containers filled with acid solutions. Then four plastic boxes are put into the freeze-thaw experimental machine. The parameters of freeze-thaw cycle are selected for reference to the relevant literature(Zhou et al., 2013; Tan et al., 2014). −20 degree is taken as freezing temperature, +20 degree is the melting temperature and the time of freezing and melting is four hours. After ten cycles of freeze-thaw, four plastic boxes are taken out, the pH of the acid solution in the plastic box is measured with a pH meter, and the rock samples are taken out and weighed. Then, the samples which finish freeze-thaw cycles are subjected to NMR experiments and rock mechanics experiments, and the rest of the rock sample groups will continue to freeze and thaw, until the end of the experiment. Fig. 1 is the Sandstone samples and Fig. 2 is the samples in the freeze-thaw test machine.

Table 1
Statistical table of basic physical parameters of sandstone samples.

Dry density (ρ)/(g/cm^3)	Natural moisture content(%)
2.21	2.92

Table 2
The mineral composition mass percentage of yellow sandstone samples.

Mineral composition	Quartz	Illite	Montmorillonite	Other metal oxide
Mass percentage (%)	85.1	5.32	4.48	5.1

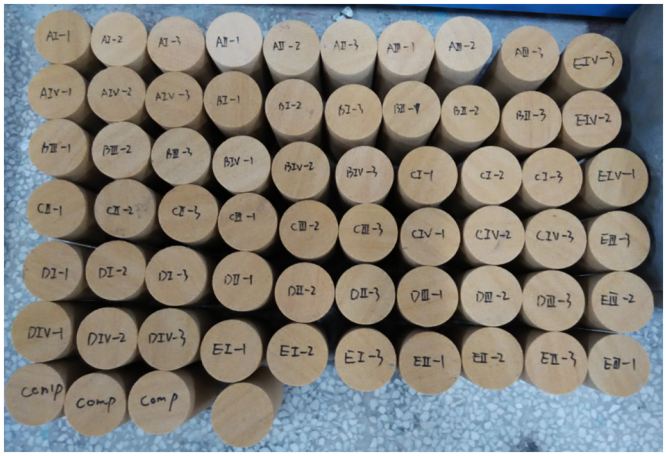

Fig. 1. The sandstone samples.

Fig. 2. The samples in the freeze-thaw test machine.

3. Analysis of experimental results and freeze-thaw load coupling mechanism of yellow sandstone in acidic environment

3.1. Analysis of the experimental results of freeze-thaw cycle

In the process of freeze-thaw cycles, the yellow sandstone sample dissolves and hydrolyzes in the acidic soak solution which leads to the dissolution of soluble components in acid solution. On the other hand, yellow sandstone subjects to the effects of freeze-thaw, resulting in crack initiation and development through the sample, which macroscopically appears as the rock exfoliation of the outer layer of the yellow sandstone sample. After the freeze-thaw cycle experiment, the mass of the hydrous sample is generally increased relative to the natural state. The mass increase rate without the freeze-thaw experiment is 3.9% ~ 5.9%. It is considered that this is the comprehensive effect of soluble component dissolution and water absorption in the sample. The mass increase rate of sample immersed in pH 2.8 solution is 3.9%, and that of sample immersed in distilled water of pH 7.0 is 5.9%. The difference between the mass increase rates is mainly because the pores