Research on the Creep Damage Characteristics of Acid-leached Sandstone

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Abstract. The dissolution of rock masses in acidic environments can lead to the degradation of pore structures and a reduction in mechanical strength, consequently making the rock mass more susceptible to creep instability. To analyze the creep damage characteristics of acid-leached sandstone under acidic conditions, a seepage erosion device was utilized to prepare acid-leached sandstone specimens. Subsequently, uniaxial creep tests were conducted on the leached specimens, and a damage variable was defined from an energy perspective based on thermodynamic principles. The results indicate that after 9 days of acid leaching, the porosity of the specimens increased by 6.0%, while the creep failure strength decreased with prolonged acid leaching time, leading to an earlier onset of the accelerated creep stage. Compared to traditional models, the newly defined damage variable simplifies the resolution of creep model parameters. The findings provide theoretical support for the long-term stability assessment of rock masses subjected to erosion in acidic environments.

Keywords: sandstone; acidic dissolution; creep; damage variable

1 Introduction

The accumulation of mine tailings generates significant amounts of acidic mine drainage (AMD)[1]. The hydrochemical interactions between AMD and groundwater can erode rock pore structures, affecting their physical and mechanical properties[2]. Sandstone, a common medium in geotechnical engineering, has numerous fine pores and weak cementation between mineral grains. Prolonged acidic corrosion can lead to pore expansion and interconnection, adversely impacting the macroscopic mechanical characteristics of the rock, resulting in large deformations and creep instability. Therefore, studying the mechanical properties and creep damage mechanisms of acid-leached sandstone is vital for rock engineering practices in acidic environments.

The creep behavior of rocks is closely related to rock engineering design and construction[3]. In the study of rock creep damage under acidic conditions, researchers have primarily focused on chemical damage variables and have proposed creep damage models that effectively describe creep behavior[4-10]. However, the accumulation and dissipation of energy are fundamental characteristics of the physical movement of

W. Nie et al. (eds.), *Proceedings of the 2024 6th International Conference on Hydraulic, Civil and Construction Engineering (HCCE 2024)*, Atlantis Highlights in Engineering 37,
https://doi.org/10.2991/978-94-6463-726-7_51

matter, making the analysis of rock creep behavior from an energy perspective more physically meaningful.

Therefore, this paper conducts seepage corrosion tests on sandstone samples using acidic solutions to simulate the sandstone affected by acidic environmental erosion in actual engineering scenarios. Subsequently, indoor creep loading tests are performed on the acid-eroded sandstone. A numerical model is established by integrating experimental data with the discrete element method to analyze the energy evolution characteristics of the eroded sandstone during creep, leading to the proposal of a damage variable from an energy perspective. On this basis, a nonlinear creep damage constitutive model is constructed.

2 The Study of Creep Characteristics of Sandstone under Acidic Erosion Conditions

2.1 Preparation of Sandstone Samples

To investigate the changes in creep characteristics of sandstone after acidic leaching, this study conducts acid seepage tests on sandstone specimens to simulate the conditions of sandstone in acidic environments encountered in engineering applications. Acidic fluids present in engineering contexts, such as acid mine drainage (AMD), are formed as a result of mining activities and exert prolonged infiltration times on the rock mass. Therefore, this study employs a permeant and a seepage corrosion apparatus to accelerate the leaching effects of the acidic fluid on sandstone. The seepage fluid selected for the experiments is a sulfate solution with a pH of 2.0, and the experimental setup is illustrated in Figure 1.

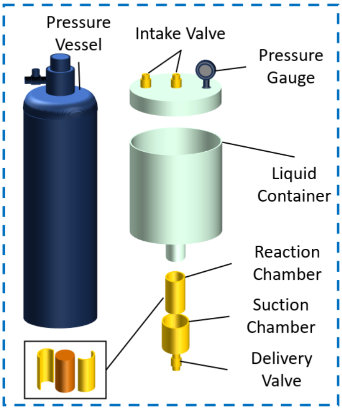


Fig. 1. Seepage corrosion apparatus

The seepage durations for each group of samples were 0 days, 1 day, 3 days, 5 days, 7 days, and 9 days. After the seepage tests, the specimens were soaked in deionized water and then dried in an oven at 105°C for future use.

To analyze the leaching effects of the acidic liquid on the sandstone, the leached specimens were subjected to scanning electron microscopy (SEM) analysis. The structural porosity was measured using ImageJ software, as shown in Figure 2.

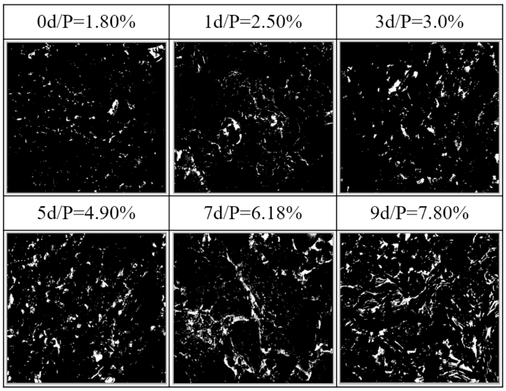


Fig. 2. Pore structure of acid-dissolved sandstone

The changes in porosity of sandstone after acidic leaching are illustrated in Figure 2. As the duration of leaching increased, the porosity of the samples exhibited a linear increase, with a significant growth in the internal pore volume. Additionally, the interconnectedness of the pores increased, accelerating the damage and deterioration of the rock's pore structure. This phenomenon is primarily attributed to the dissolution of cementing materials between the rock particles caused by the acidic liquid. Compared to the unaltered samples, the porosity of the specimens leached for 9 days increased by 6.0%. Overall, acidic leaching has a significant impact on the pore structure of sandstone.

2.2 Creep Testing and Result Analysis

The uniaxial compression and uniaxial creep tests were conducted using a TAW-2000 rigid pressure testing machine, as shown in Figure 3. The testing method involved single-stage loading, where the loading stress was set at 80% of the peak strength from the uniaxial compression tests of each specimen. The loading was applied at a rate of 0.5 MPa/s until the designated stress level was reached, and then maintained until failure occurred. The creep test curves are illustrated in Figure 4.

From Figure 4, it can be observed that the creep curve of sandstone after acidic dissolution can be divided into two stages: the instantaneous elastic deformation stage and the creep deformation stage. The creep stage consists of three phases: decaying creep, steady-state creep, and accelerating creep.

As the duration of seepage increases, the accelerating creep phase occurs earlier, and creep failure is initiated sooner. This is attributed to the increase in internal porosity of the sandstone caused by acidic dissolution, which accelerates the propagation of internal cracks within the sandstone. Consequently, the specimen experiences failure at an earlier stage. This observation highlights the detrimental effects of acidic corrosion on the mechanical integrity of sandstone, emphasizing the need for careful consideration in engineering applications involving acidic environments.

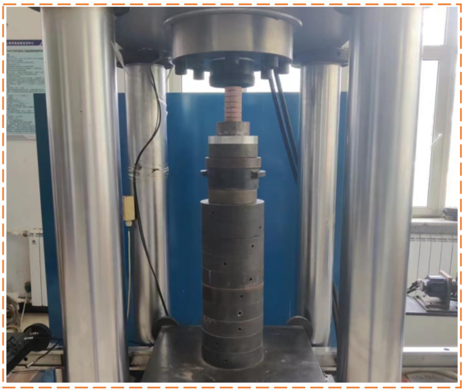


Fig. 3. TAW-2000 rigid pressure testing machine

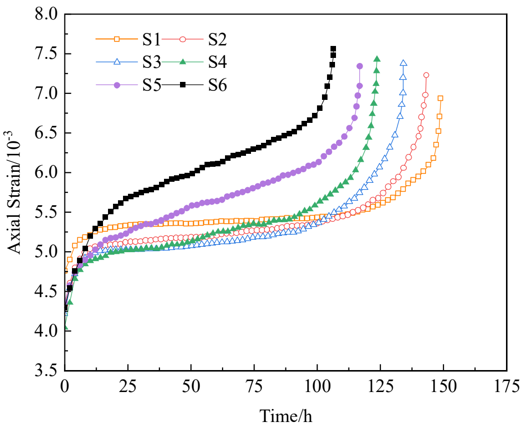


Fig. 4. Sandstone creep test curve

3 Damage Variable From an Energy Perspective

3.1 Evolutionary Characteristics of Creep Energy In Sandstone

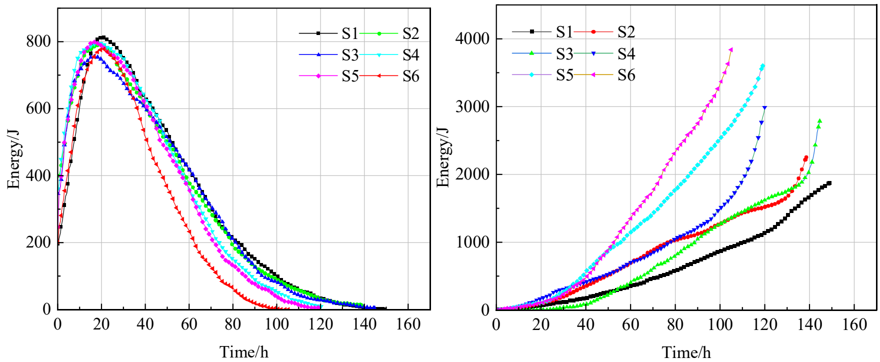
According to the laws of thermodynamics, energy conversion is an essential characteristic of the physical processes of matter[11]. Therefore, analyzing the creep damage patterns of rock masses from an energy perspective allows for a deeper understanding.

Based on the first law of thermodynamics, assuming that there is no heat exchange between the rock and the external environment during the loading process, the following equation can be derived Equation (1):

$$U=U_e+U_d \tag{1}$$

In the equation, U represents the mechanical energy density input from the external load, kJ·m^{-3}. U_e is the elastic potential energy density that can be released by the rock unit, kJ·m^{-3}. U_d is the energy density dissipated by the rock unit, kJ·m^{-3}。

Due to the difficulty in obtaining the energy variation patterns of the specimens during the different creep stages through experiments, this study employs the PFC program combined with FISH language to obtain the microscopic energy values of the rock unit particles. The simulation results are illustrated in Figure 5.



(a) Elastic energy (b) Dissipated energy

Fig. 5. Energy evolution law of creep in acid-eroded sandstone

As shown in Figure 5, during the creep process, elastic potential energy primarily accumulates during the decaying creep phase, and it is gradually released during the steady-state creep and accelerating creep phases. Furthermore, the longer the duration of acidic leaching, the faster the rate of elastic energy release.

The energy during the creep process is mainly dissipated through the cracking and propagation of cracks across the different stages of creep. Additionally, the rate of energy dissipation increases with the extension of the acidic leaching time.

3.2 Damage Variable

During the creep loading process, energy storage and dissipation continuously occur within the rock. Therefore, the damage variable based on the energy perspective is helpful for studying the creep failure process of rock materials. This paper defines the damage variable D_s as the ratio of dissipated energy to the externally input mechanical energy during the loading process of the rock, expressed as follows:

$$D_s=\frac{M_d}{M} \tag{2}$$

Existing research has shown that the damage variable and time have the following relationship based on the Weibull random distribution:

$$D_s = 1 - e^{-\alpha t^{\beta}} \tag{3}$$

In the equation, α and β are damage factors that are related to the material properties and can be determined through fitting the elastic energy and dissipated energy obtained in Section 3.1. This facilitates the parameter determination of the constitutive model.

4 Conclusion

To investigate the effect of acidic dissolution on the creep damage of sandstone, a series of acid corrosion and creep tests were conducted, leading to the following conclusions:

The porosity of sandstone significantly increases with the duration of dissolution, with a 6.0% increase observed after 9 days of corrosion. The deformation during both the decay creep and steady-state creep phases markedly increases, and the time to creep failure decreases with prolonged acid dissolution, while the onset of the accelerated creep phase occurs earlier. This indicates that the effect of acidic dissolution has a significant negative impact on the creep strength and long-term mechanical properties of sandstone. The damage variable *Ds* can be derived through simulations, allowing for the determination of creep damage parameters α and β, thereby facilitating the parameter identification of the creep damage model.

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