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Research paper

Experimental study on fatigue mechanical properties of sandstone after dry and wet cycle

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Abstract: At present, many studies have been carried out on the fatigue mechanical properties of conventional rocks, but there are few studies on the mechanical properties of rocks after water rock interaction. The aim is to better study the fatigue mechanical characteristics of sandstone after dry wet cycle and the research object we take was sandstone samples after a certain number of drying and wetting cycles. The WAW-2000 electro-hydraulic servo pressure system was used to carry out uniaxial fatigue cyclic loading and unloading tests with different amplitudes and different upper limit stresses. The test found that: when the sample is damaged under fatigue load, the stress-strain curve shows a sharp downward trend and a sudden instability failure occurred in the sample. With the increase of the upper limit stress and amplitude, the life of the sample decreases gradually which also conforms to the change of power function. Then the relationship between fatigue life and stress is obtained. The fatigue stress-strain curve is characterized by sparse-dense-sparse. With the increase of cycle time, the axial strain of the sample shows an inverted "S" shape. The strain change can be divided into three stages: initial stage, constant velocity stage and acceleration stage.

Keywords: cyclic loading, dry-wet cycle, fatigue characteristics, rock mechanics

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1. Introduction

Fatigue failure of rock is a process in which cracks occur or complete fracture occurs suddenly after a certain number of cycles with rock material under the action of cyclic stress and strain, in one or more places gradually produce local permanent cumulative damage. Studying the fatigue mechanical characteristics of rock under periodic load is of practical significance for evaluating the stability of related projects [1], such as the stability of underground roadway under seismic load and excavation load. Further, as water rock interaction is active in all parts of the project, water will have a series of effects on rocks in geotechnical engineering, resulting in physical, chemical and mechanical changes of rock mass. Under the action of water, different degrees of deterioration occurs in rocks, which seriously affects the safety of kinds of projects. Therefore, the study on the fatigue mechanical properties of rock under dry wet cycle is conducive to these studys on rock properties under water rock action.

Scholz [2] and Zoback [3] proposed a simple model for the hysteresis loop in the stress-strain curve in fatigue failure and showed two kinds of axial cracks, which quantitatively explained the mechanism of fatigue failure. Cerfontaine [4] research shows that under cyclic load, the stress-strain curve of the sample shows an on-off-on mode. The opening at the initial stage is due to the initiation of cracks and then gradually shows stability with the cycle's operation.When the curve is in off mode, the crack hardly extends because of the obvious friction effect. For the sample is close to damage, the crack spreads on a large scale, resulting in the aggravation of later period lag. This phenomenon is also explained in the literature [5]. Many scholars have found that the fatigue failure of samples has a lot to do with the waveform, frequency and amplitude of testing. Ge Xiurun [6–9] team conducted a series of studies on uniaxial fatigue tests of sandstone, marble and granite and found that the fatigue failure of rock is closely related to these testing parameters such as waveform, frequency and amplitude, etc. Lu Gaoming et al. [10] had fatigue tests with different upper limit stress and different amplitude. It was found that the failure mode of fatigue test sample was different from that of uniaxial test: before the failure of the sample, "initial failure"comes to it first. Feng Chunlin et al. [11] found that the fatigue failure of white sandstone during fatigue test is mainly caused by the upper limit stress and amplitude determined in the test. Badge [12, 13] et al. studied the influence of load waveform and amplitude on rock mechanical properties under uniaxial cyclic load. The results show that the fatigue behavior is a function of load cycle energy and waveform shape. Under the waveform of high energy demand, the damage accumulation speed is the fastest. The slope waveform is the minimum failure force considered. The load waveform strongly influence the damage accumulation under cyclic loading and the amplitude and load frequency under cyclic loading affect the fatigue strength and deformation characteristics of rock. As the amplitude up, the fatigue strength of rock down, while the rock modulus down as the load frequency up. Momeni [14] et al. Studied the uniaxial fatigue behavior of granite, in which the effect of stress level and frequency on the sample is greater than that of amplitude. Meanwhile, the fatigue failure process are better reflected by these damage parameters such as transverse and axial strain and so on. He [15] carried out fatigue test on rock salt and analyzed the law of deformation, which is divided into three stages: cyclic hardening, saturation and cyclic softening. The cumulative dissipated energy of rock salt with different stress amplitude, load rate and load frequency is calculated according to the three plastic deformation stages. In addition to the above research on the influence behavior, Li Shuchun [16] conducted uniaxial cyclic load mechanical test on sandstone and limestone to compare the macro deformation characteristics under cyclic load. Li et al. [17] studied the deformation of samples through multistage uniaxial cyclic loading and unloading experiments. Yang Yongjie et al. [18] conducted multi-stage cyclic load test on coal under uniaxial state. The fatigue failure, circumferential and volumetric strain changes of coal samples are more sensitive than axial stress's. What's more, the crack propagation of rock is much concerned with the peak stress of cyclic load. When the peak stress of cyclic load is higher than the fatigue strength, the rock cracks proliferate until it is destroyed. At present, there are few studies on material fatigue characteristics after dry wet cycle. Mario [19] had conducted cyclic loading and unloading test on mudstone to study the change law of rock mechanical properties under dry wet cycle. By conducting low cycle fatigue tests on epoxy materials added with DBP, Wang et al. [20] found that stress ratio and stress level are two key factors of material fatigue life which increase as the stress ratio increases.Mastor et al [21] studied the fatigue mechanical properties of hollow steel columns filled with rubber concrete.

A series of studies have been carried out on the fatigue mechanical properties of conventional rocks. Compared with most studies focusing on conventional rocks, there are few studies on the fatigue mechanical properties of rocks under environmental conditions such as water-rock interaction. Therefore, it is necessary to study the fatigue mechanical properties of samples after wetting and drying cycles. In this paper, the common rock sandstone in engineering is taken as the object and the fatigue mechanical tests with different upper limit stress and different amplitude are carried out to reveal the fatigue mechanical characteristics of sandstone after dry-wet cycle, so as to provide practical reference for related projects.

2. Test scheme

The sandstone samples used in the test are from Sichuan province, China, from the same rock mass, with a size of $h \times d$ = 100 mm × 50 mm. Before the test, sound wave test was carried out to select the sample which has the close sound wave value to ensure the regularity of the test results. Firstly, sandstone samples after different dry and wet cycles are obtained. The specific operation of one dry and wet cycle is to soak the sandstone in purified water for 24 hours and dry it for 24 hours until the quality of the sample does not change. After getting the sample under dry-wet cycle, the WAW-2000 electro-hydraulic servo press is used to carry out the uniaxial compression test of sandstone under different dry-wet cycle. The maximum stress of the testing machine is 2000 kN, the accuracy of displacement measurement is ±1% and the accuracy of deformation measurement is ±1%.

The uniaxial compression test is loaded through stress control. Preloaded first and then loaded at the rate of 1 kN/s until the sample is damaged. The test scheme and results are shown in Table 1.

Table 1. Uniaxial compression test scheme

Sample number	Number of dry and wet cycles	Loading mode	Loading rate	Peak stress (MPa)
1–1	0	Stress control	1 kN/s	112.16
2–1	8			68.55
3–1	16			92.27
4–1	24			91.89

According to the uniaxial test results, the sandstone samples after 16 dry-wet cycles are selected for fatigue test. In order to better analyze the data, the stress ratio parameter is introduced to describe the influence of different parameters on the test results. The equation are to be referred to as Eq. (2.1).

$$n = \frac{\sigma_0}{\sigma_c} \tag{2.1}$$

where: n is the stress ratio; σ_0 is the upper limit stress and lower limit stress; σ_c is uniaxial compressive strength.

The mechanical loading process of fatigue cycle test is divided into two stages: firstly, loading in the way of stress loading until to the upper up limit stress and then following the periodic load to the sample repeatedly to final sample damage. The loading waveform of the fatigue test is cosine wave, and the frequency f is 0.1 Hz. The loading waveform diagram is shown in Fig. 1. In the diagram: σ_{max} and σ_{min} respectively represent the upper limit stress and the lower limit stress. The difference between the upper limit stress and the lower limit stress is $\Delta\sigma$, T is the cycle, $f = 1/T$. The specific test scheme parameters are shown in Table 2.

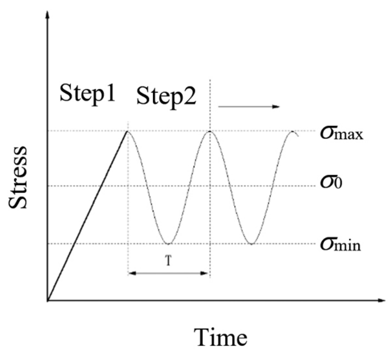

Fig. 1. Loading parameters

Table 2. Fatigue loading test scheme

Sample number	Number of dry and wet cycles	Upper limit stress ratio	Lower limit Stress ratio	Stress amplitude ratio	*f*	Wave form
3–3	16	0.9	0.3	0.6	0.1 Hz	Cosine wave
3–5		0.9	0.5	0.4		
3–6		0.9	0.6	0.3		
3–7		0.85	0.25	0.6		
3–8		0.8	0.2	0.6		

3. Test results and analysis

3.1. Stress-strain curve in the whole process of fatigue failure

According to the analysis of the experimental results in the previous stage, the uniaxial compressive strength of sandstone samples after 16 dry-wet cycles is 92.27 MPa. The samples after dry-wet cycles are subjected to different amplitude and upper limit stress fatigue loading tests. The stress-strain curve of the samples is shown in Fig. 2 (take sample 3–7 as an example).

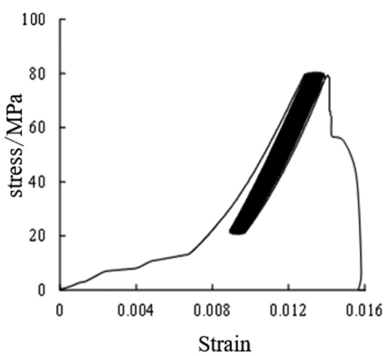

Fig. 2. Stress-strain curve of sample 3–7

It can be seen from Fig. 2 that in the initial stage of stress loading, the deformation of the sample changes greatly but its stress changes slightly. When it comes to the upper limit stress, the cyclic loading starts. When the sample cyclic loading and unloading happens, the stress-strain curve of the sample overlaps obviously. It indicates that the plastic strain produced by each cycle of the sample is small and the deformation slowly increases. After a certain time's cycle, the sample shows sudden loss of stability and breakageand. The stress-strain curve shows a dramatic decline.

3.2. Fatigue life analysis

According to the stress-strain curve of sandstone fatigue test, the fatigue life under different amplitude and different upper limit stress is obtained, as shown in Table 3.

Table 3. Fatigue life

Sample number	Number of dry and wet cycles	Upper limit stress ratio	Lower limit stress ratio	Stress amplitude ratio	Fatigue life
3–5	16	0.9	0.5	0.4	19
3–6	16	0.9	0.6	0.3	34
3–3	16	0.9	0.3	0.6	9
3–7	16	0.85	0.25	0.6	262
3–8	16	0.8	0.2	0.6	894

From Table 3: When the cyclic stress amplitude ratio is 0.3, the sample is damaged after 34 cycles; When the stress amplitude ratio is 0.4, the damage happens after 19; When the stress amplitude ratio is 0.6, the sample is destroyed after 9 cycles. It can be further seen from the Table 3 that when the upper limit stress ratio is 0.8, the sample damage happens after 894; when the upper limit stress ratio is 0.85, it turns to be 262; when the upper limit stress ratio is 0.9, it damages after 9. With the increase of cyclic amplitude and upper limit stress, the fatigue life of the sample decreases gradually. When the upper limit stress of the sample is high and the number of cycles is small, the sample will be damaged.

Under cyclic loading, when the upper limit stress of the sample is higher than the rock fatigue limit, the sample accumulates certain damage under each cycle which will lead to a final sample breakdown to some extent. Therefore, the failure of the sample under different amplitudes and upper limit stress is highly associated with the number of cycles. According to the data in Table 3, the relationship between fatigue life with amplitude and upper limit stress is studied and then the fitting curves between different amplitude and upper limit stress and cycle times are obtained, as shown in Fig. 3 and Fig. 4.

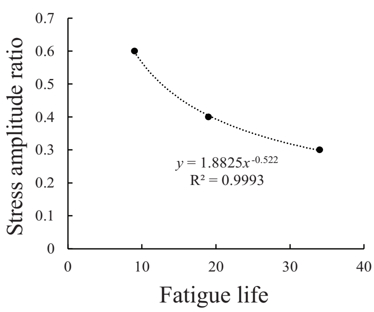

Fig. 3. Relationship curve between different amplitude and fatigue life

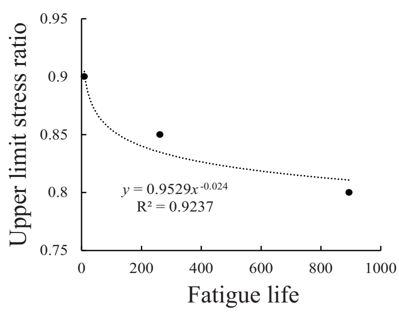

Fig. 4. Relationship curve betweendifferent upper limit stress and fatigue life

According to the fitting curve, the relationship between fatigue life and stress can be obtained. The equation are to be referred to as Eq. (3.1):

$$N = aA^b \tag{3.1}$$

where: N is the fatigue life of the sample; A is the amplitude or upper limit stress of the sample; a; b is the material constant. The relevant parameters of the Eq. (3.1) are shown in the Table 4. According to equation (3.1), the sample life under different amplitude and upper limit stress can be obtained, which plays a guiding role in predicting rock fatigue failure.

Table 4. Equation (3.1) fitting parameters

	a	b	R^2
Stress amplitude ratio	1.8825	0.522	0.9993
Upper limit stress ratio	0.9529	0.024	0.9237

3.3. Evolution law of hysteresis loop

In the fatigue test, the change of hysteresis loop can well reflect the process of fatigue failure. To better study the hysteresis change of the sample during the fatigue test, the hysteresis of the fatigue failure sample (cyclic stress ratio 0.6–0.9) at different cycle stages is taken as an example in this paper, as shown in Fig. 5.

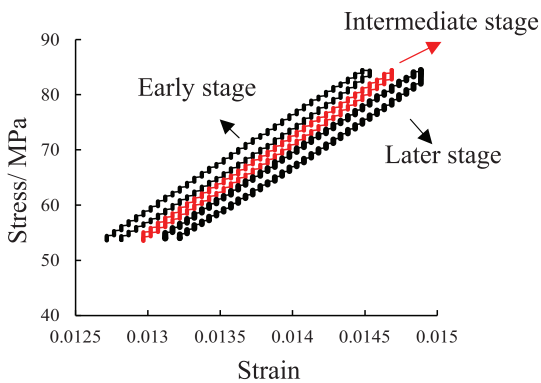

Fig. 5. Evolution law of hysteresis loop in different stages

Fig. 5 shows the change law of hysteresis loop of the damaged sample in fatigue test under different cycle times. It is that in the initial stage, opening is large; in the middle, it is small; in the later, it becomes large again. The hysteresis loop change of fatigue failure sample corresponds to the change characteristics of sparse-dense-sparse stress-strain curve.

There are natural pores and voids in natural rock particles. As the internal particles of the sample are compressed by the pressure, the plastic strain changes greatly. That's why the curve spacing of the sample is large at the initial stage. When in the middle stage, the pores and voids of the sample have been so completely compressed that dense connections are formed between the particles and the damage caused by periodic loading and unloading keeps stable and accumulates step by step. However, the plastic strain changes little, which shows that the sample curve is dense. Further, in the later stage of the test, the sample is to be destroyed after the damage is accumulated to a certain extent. At this time, the spacing of hysteretic curve increases, the plastic strain of the specimen changes greatly. After several cycles, the sample is damaged.

3.4. Fatigue failure deformation analysis

Fig. 6 is the relationship curve between axial strain and time development of typical fatigue failure sample from which the strain of the sample mainly shows three-stage phenomenon under fatigue load. It is common to see that the strain of sample varies with the cycle, as it is a typical fatigue failure test. And the variation trend of typical peak strain is inverted 'S' shape, which is similar to the results studied by most scholars. As for his kind of strain change, it can be divided into three stages: initial stage, constant velocity stage and acceleration stage. In the initial stage, the peak strain of the sample has a fast development with the increasing number of cycles. After a certain cycle, the peak strain of the sample tends to be stable as it increases. During this period, the increasing rate keeps the same but when sample appears to failure, the peak strain accelerates its increase. In these three stages, the constant velocity stage occupies most of the fatigue test time and is the main part of the fatigue failure curve. The initial stage and acceleration stage take less time and have a large amount of strain accumulation.

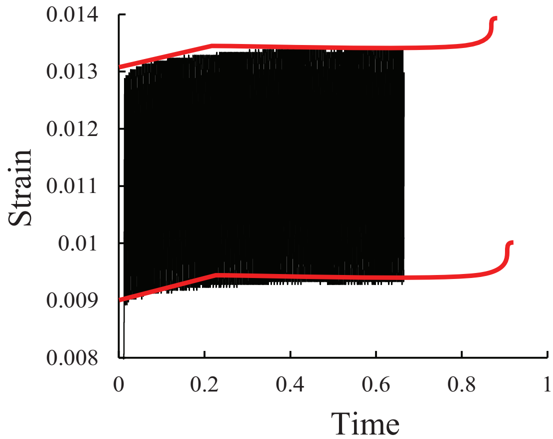

Fig. 6. Development law of axial strain

4. Discussion

It is a complex process for different wetting and drying cycles and there will be some effects on rock mass after water rock interaction. Under the action of dry wet cycle, the degree of cementation between the structure and particles of rocks will change, which will affect the properties of rocks. During the process, the adhesion between the internal particles will change with the continuous impact of water on the rock, resulting in the varition of particle gap in the rock. What's more, some particles in the rock will dissolve in water, which will also increase the gap between particles. The change of cementation structure between particles will cause the corresponding change of sample strength to a certain extent The process is shown in Fig. 7.

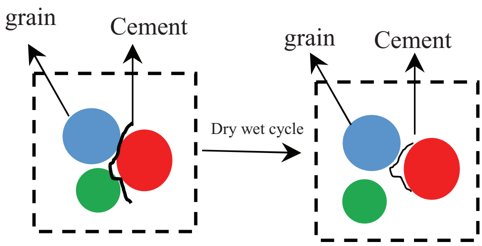

Fig. 7. Particle change after dry wet cycle

After the dry wet cycle, the strain variation of the sample under loading appears a typical inverted "S" shape. It can be seen that before the fatigue failure limit of the sample is reached, the changing strain of the sample increases gradually, but it does not cause sample damage. When the sample reaches the fatigue failure limit, the strain of the sample increases rapidly and a strong failure happends in the sample. Therefore, attention should be paid to this kind of situation in practical engineering.

The influence of fatigue load waveform and frequency is not considered in this paper. We would like to continue something relevant in the future. The fruits of this paper is for future related research reference.

5. Conclusions

In this paper, through the test of sandstone fatigue characteristics after dry wet cycle, the evolution law of sandstone fatigue characteristics under different amplitude and upper limit stress is studied. The following conclusions can be drawn:

1. When the yellow sandstone sample is fatigue damaged, the stress-strain curve appears a rapid decline and sudden instability failure occurs. With the increase of amplitude and upper limit stress, the sample life is gradually shortened and it conforms to the change of power function. According to the fitting curve, getting the relationship between fatigue life and stress, the fatigue life of the sample under different amplitude

and upper limit stress can be obtained, which plays a guiding role in predicting rock fatigue failure.

2. Under the action of fatigue load, the hysteresis loop opening of the sample shows the phenomenon of large in the early and late stage and small in the middle stage. The hysteresis loop change of the sample with fatigue failure corresponds to the sparse-dense-sparse change characteristics of the stress-strain curve.
3. The axial strain of the sample with fatigue failure shows an inverted "S" shape as time changes. With the progress of loading, the change of strain can be divided into three stages: initial stage, constant velocity stage and acceleration stage.

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