Characterisation of Energy Evolution in Freeze-thawed Sandstone under Cyclic Loading and Unloading

Dongyang Han*, Yongjun Song, Shuanglong Wang

School of Architecture and Civil Engineering, Xi 'an University of Science and Technology, Xi 'an, 710054, China

*hdy1914940726@163.com

Abstract. In order to study the energy evolution law of rock under the combined action of freeze-thaw cycle and loading and unloading, the freeze-thaw cycle and graded cyclic loading and unloading tests were carried out on coarse-grained sandstone, and the mechanical properties and energy evolution characteristics of sandstone with different freeze-thaw cycles under cyclic loading were analyzed. The results showed that the peak strength of sandstone under cyclic loading decreased from 16.5 MPa at 0 times of freezing and thawing to 5.9 MPa at 30 times of freezing and thawing, which was negatively correlated with the number of times of freezing and thawing in a linear relationship. The freeze-thaw cycles promoted the deformation, and the maximum strain increased from 1.43% to 2.60%, which enhanced the ductility of the sandstone. The total and dissipated energy densities showed a U-shaped change under loading and unloading at each stress level, and the elastic energy density showed a horizontal stepwise increase, and the elastic energy was accelerated to be released before the destruction of the rock. The cumulative elasticity, dissipated energy density and cumulative total energy density of sandstones with different numbers of freezing and thawing were all linearly related, and the fit R^2 was greater than 0.99. The energy storage coefficient decreased from 0.68 at 0 times of freezing and thawing to 0.57 at 30 times of freezing and thawing, and the energy consumption coefficient increased from 0.32 to 0.43. The energy storage level of the sandstone decreased with the increase in the number of freezing and thawing cycles, whereas the energy consumption level was positively correlated with the number of freezing and thawing cycles.

Keywords: Freeze-thaw Cycle, Cyclic Loading and Unloading, Energy Evolution.

1 Introduction

In recent years, with the depletion of mineral resources in the Middle East and the in-depth implementation of the strategy of western development, mineral mining and engineering construction in the western region is increasing [1]. And most of China's western region is in the cold zone, engineering rock body is susceptible to freeze-thaw cycle, the repeated freezing and melting of water inside the pores of the rock body leads

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to damage inside the rock body, so that the mechanical properties of the rock body greatly weakened, increasing the risk of engineering disasters [2]. On the other hand, in actual engineering activities, the rock body is often subjected to cyclic loading, such as excavation and support of slopes in open pit coal mines, and mineral mining disturbance. The primary defects inside the rock body are compacted, the newborn cracks develop continuously, the damage accumulates, and the bearing capacity is reduced, thus inducing safety accidents [3]. It can be seen that under the joint action of freeze-thaw and cyclic loading, the safety and stability of the rock mass is seriously threatened. Therefore, it is of great practical significance to carry out the research on the mechanical properties and energy evolution of rocks under the joint action of freeze-thaw cycle and loading/unloading for the prevention and control of rock body engineering disasters in cold regions.

In cold regions, water in rock mass undergoes water-ice phase transformation in the diurnal temperature difference and seasonal alternations, resulting in frost heist force, which leads to deterioration of rock mass mechanical properties [4], and then induces rockfall, landslide and other geotechnical engineering disasters. At present, many scholars have conducted relevant research on freeze-thaw or cyclic loaded rocks and achieved good results. For example, Zhao JJ et al [5] conducted uniaxial compression tests on freeze-thaw rock materials and investigated the mechanical characteristic parameters and damage modes; Momeni A et al [6] investigated the mechanical properties of granite under cyclic loading; Wei MX et al [7] investigated the uniaxial compression mechanical properties of rocks of different lithologies after freeze-thaw cycling; Petros V et al [8] and Wang RX et al [9] analysed the deformation and damage characteristics of rocks under dynamic loading and cyclic loading and unloading. However, the existing results lack the study of mechanical properties of freeze-thawed rocks under complex loading and ignore the essential driving force behind the macroscopic damage. Therefore, the causes of damage under cyclic loading of freeze-thawed rocks still need to be deeply investigated.

In summary, in order to properly understand the rupture behaviour of open pit mining slopes in cold regions under complex cyclic loading, energy-driven rock damage damage research is pending. Based on this, this paper carries out freeze-thaw cycle and graded cycle loading and unloading tests on coarse-grained sandstone to study the mechanical properties and energy evolution characteristics of sandstone under the joint action of the two.

2 Pilot Programme

2.1 Preparation of Rock Samples

The raw rock used in this test were taken from the same rock layer of a coal mine in northern Shaanxi Province, and according to the international rock mechanics test protocol, the core of the rock block drilling was processed into cylindrical rock samples with a diameter of 50mm and a height of 100mm, and the rock samples with obvious differences in appearance were excluded. According to the principle of similarity of physical parameters, the rock samples were divided into 4 groups of 6 each, and they were frozen and thawed 0 times (Group F), 7 times (Group C), 15 times (Group D) and 30 times (Group H), respectively, and the freezing and thawing temperatures were set to -20°C and 20°C, respectively, according to the Standard for Testing Methods of Engineering Rocks, and the temperature was kept for 8h when the temperature reached the lowest and the highest to ensure that the rock samples were fully frozen and thawed.

2.2 Graded Cyclic Loading and Unloading Test

The TAW-1000 microcomputer controlled test system was used for loading and unloading test. In order to determine the stress level of graded loading and unloading, three rock samples of each group were selected for uniaxial compression test after freezing and thawing, and their uniaxial compressive strength was obtained as shown in Table 1. The loading stress levels of the hierarchical loading and unloading were set to 20%, 50%, and 80% of the average peak strength, respectively, and each stress level consisted of five loading and unloading processes, with the last stage loading the rock sample to failure. Both loading and unloading during the test were controlled by deformation at a rate of 0.06mm/min.

Table 1. Uniaxial compressive strength of rock samples.

Number of freeze-thaw cycles	Rock sample number	Peak intensity (MPa)	Mean peak intensity(MPa)
0	F-2	15.52	15.82
	F-11	15.73	
	F-14	16.21	
7	C-1	13.10	13.04
	C-8	13.02	
	C-30	13.01	
15	D-5	9.17	9.22
	D-9	9.22	
	D-12	9.28	
30	H-17	6.38	6.54
	H-24	6.50	
	H-39	6.73	

3 Stress-strain Curve

Limited to the length of the article, one representative rock sample is taken from each group of rock samples to be analysed. The stress-strain curves of the rock samples during the whole process of graded cyclic loading and unloading are shown in Fig. 1. The peak strengths of the rock samples at 0 and 7 times of freezing and thawing were 16.5 MPa and 13.2 MPa, which were slightly higher than the peak strengths of uniaxial compression with the same number of times of freezing and thawing, and the peak strengths of the rock samples at 15 and 30 times of freezing and thawing were 9.1 MPa and 5.9

MPa, which were slightly decreased compared with that of the peak strengths of uniaxial compression. This is due to the fact that when the number of freezing and thawing is less, the cyclic loading and unloading can compact the microfissures produced by freezing and thawing, so that the integrity of the rock samples can be improved; when applying the repeated loading to the rock samples with more freezing and thawing, the more internal fissures are compacted and expanded at the same time, and the damage degree of the rock samples is larger, which leads to the reduction of the peak strength of the rock samples. Since each cyclic loading will cause damage to the rock sample and produce irreversible plastic strain, the loading and unloading curves of the rock sample do not completely coincide, resulting in a hysteresis loop curve. The hysteresis loop curves are tighter at low stress levels of cyclic loading and looser at high stress levels. The maximum strain increases with the number of freezes and thaws, from 1.43% to 2.60%, and the ductility of the sandstone is enhanced. In addition, the peak strength of cyclic loading and unloading of the rock samples decreased gradually with the increase of the number of freeze-thawing, from 16.5 MPa for 0 times of freeze-thawing to 5.9 MPa for 30 times of freeze-thawing, and it was found that the peak strength was linear with the curve of the number of freeze-thawing through the fitting and the degree of fit R^2 was 0.9543.The stress fitting equation was:

$$\sigma=15.7485-0.3518N \tag{1}$$

Where: σ is the stress and N is the number of freeze-thaw cycles.

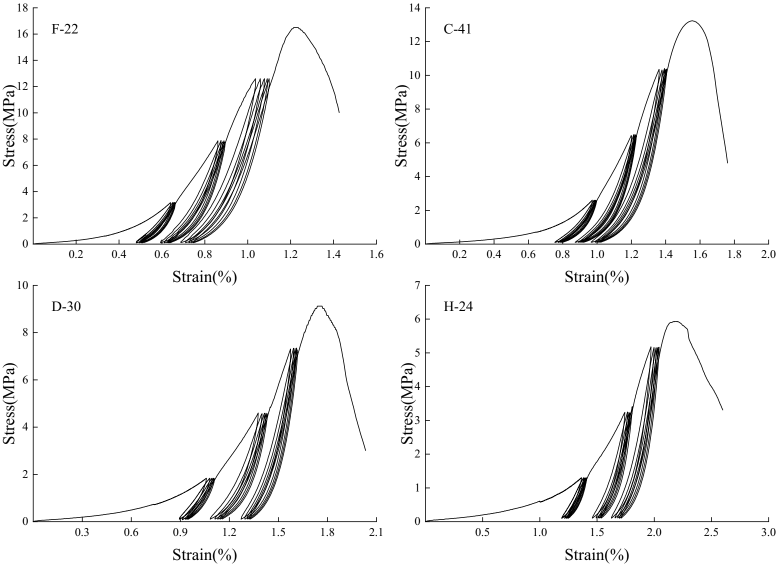

Fig. 1. Stress-strain curves of sandstones with different freeze-thaw numbers during the whole process of graded loading and unloading

4 Characteristics of Energy Evolution

4.1 Energy Distribution and Calculation

Rock deformation and destruction is actually a dynamic process of energy conversion, assuming that there is no heat exchange between the rock and the outside world during loading and unloading, i.e., part of the work done by the testing machine on the rock is stored as elastic energy and released during unloading; the other part is dissipated in the rock damage process. Then according to the law of conservation of energy can be obtained:

$$u = u_{\mathrm{e}} + u_{\mathrm{d}} \tag{2}$$

Where: u is the total energy density of external input; u_e is the elastic energy density; u_d is the dissipated energy density.

The area enclosed below the loaded stress-strain curve represents the total work done by the testing machine on the rock, and the area enclosed below the unloaded stress-strain curve represents the density of elastic energy released by the rock, the area enclosed between the two curves represents the dissipated energy density that leads to rock damage, and in this paper, the area enclosed by the curves is integrated to obtain each energy density.

In particular, during the last stage of loading damage of the rock, since there is no unloading phase, the following formula is usually used to calculate the elastic energy density during a single compression:

$$u_{\mathrm{e}} = \frac{1}{2E}\sigma_{\max}^{2} \tag{3}$$

Where: E is the modulus of elasticity during final loading; σ_{max} is the maximum stress in the final loading damage stage.

4.2 Laws of Energy Evolution

Through the above calculation method, the total energy density u, elastic energy density u_e and dissipated energy density u_d of the rock under each cyclic loading can be obtained respectively. the energy density evolution law of the freeze-thawed sandstone during the graded cyclic loading and unloading process is shown in Fig. 2.

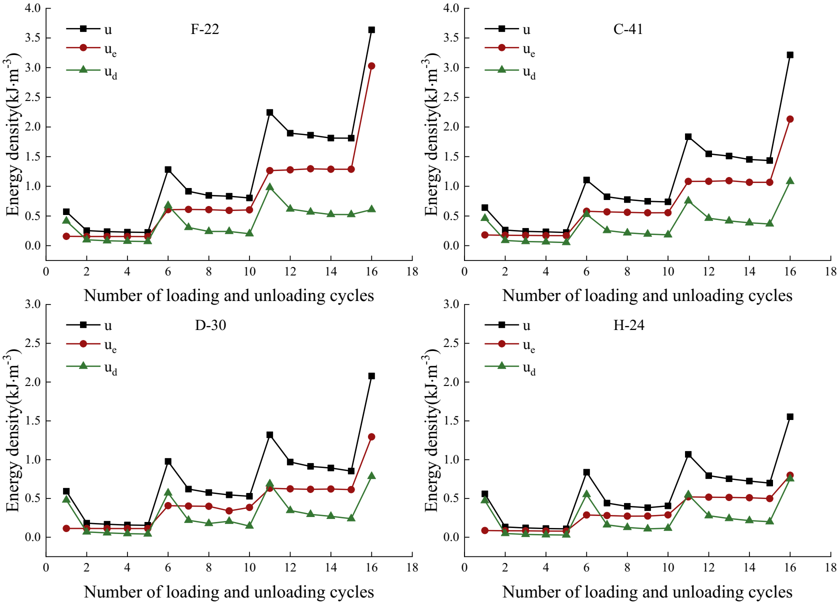

Fig. 2. Evolution of energy density with number of loading and unloading cycles

As can be seen from the figure, u and u_d have a similar law of change, in each level of load level under the "U" type change. Each level of stress after the first loading and unloading first rapid decline, and then in the same stress level with the increase in the number of cycles of energy density curve slightly decreased, but remain relatively stable. When the stress level is increased, the energy density suddenly increases, which exceeds the deformation resistance of the rock samples, and the cracks expand violently, and is the maximum value under the cyclic loading of the stress level. u_e is a horizontal step change, the curve stays relatively level under the cyclic loading of each stress level, and the stored elastic energy density is approximately the same. It is easy to see from the figure that the difference between u and u_d is small at the beginning of loading, and this gap gradually increases as loading continues. This is because most of the total energy input during the first loading is used to compact the internal defects of the rock samples, and only a small portion is converted into elastic energy storage. Continuing to load, many pores and cracks inside the rock samples are further compacted to make the internal structure denser, and the storage of elastic energy is gradually more than the dissipation of energy. However, with the increase of stress level, the cracks inside the rock samples continue to sprout and develop, the irreversible deformation gradually accumulates, and the dissipated energy gradually increases. In the final loading damage stage, the elastic energy density increases sharply, the elastic energy is released at an accelerated rate, and the gap between the elastic and dissipated energy densities decreases gradually with the increase in the number of freezing and thawing times, from 2.35 kJ·m^{-3} to 0.05 kJ·m^{-3}.

4.3 Effects of Freeze-thaw Cycles on Energy Storage and Consumption

In order to further explore the relationship between the elastic properties, dissipated energy and total energy during loading and unloading of freeze-thawed sandstone, due to the similarity of the change rule of each energy density under cyclic loading of each stress level, the energy densities of five cyclic loads of each stress level were summed up and accumulated sequentially with the stress level, and then fitted, and the results of the fitting were shown in Fig. 3. The results show that, although the sandstone experienced different numbers of freezing and thawing, the change curves of cumulative u_e and u_d with the cumulative total energy density all showed good linear relationship, and the curve fit R^2 were all greater than 0.99.

From the fitted functional equation in Fig. 3, it is found that the slope of the elastic energy fitted curve decreases with the increase in the number of freeze-thaw cycles, and the opposite is true for the slope of the dissipative energy fitted curve. This indicates that freeze-thaw cycles have a significant effect on the energy storage and dissipation levels of sandstone.

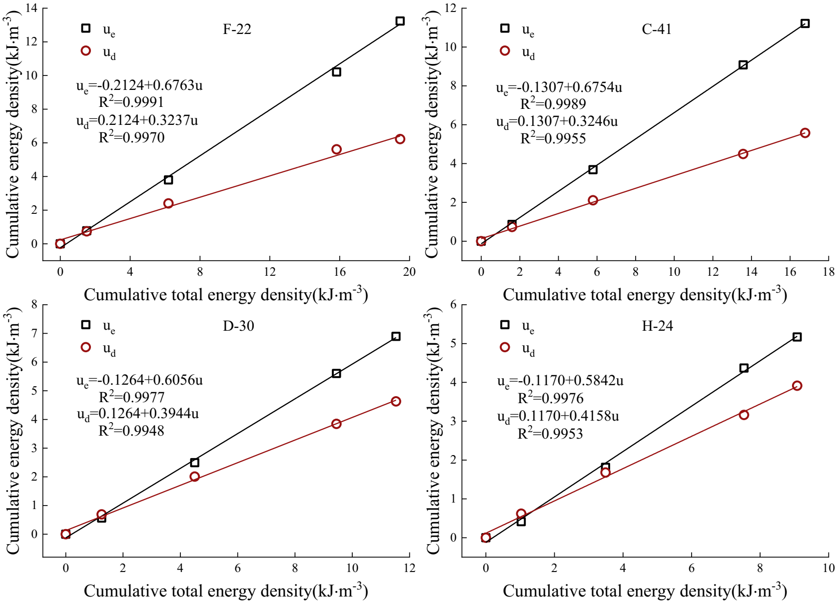

Fig. 3. Relationship between cumulative elasticity, dissipated energy density and cumulative total energy density

Define energy storage coefficients k_e and energy depletion coefficients k_d to quantitatively characterise the effect of freeze-thaw cycles on energy storage and depletion in sandstones:

$$k_{\mathrm{e}}=\frac{u_{\mathrm{ez}}}{u_{\mathrm{z}}} \tag{4}$$

$$k_{\mathrm{d}}=\frac{u_{\mathrm{dz}}}{u_{\mathrm{z}}} \tag{5}$$

Where: u_z enters the cumulative total energy density; u_{ez} is the cumulative total elastic energy density; u_{dz} is the cumulative total dissipated energy density.

The energy storage and energy consumption coefficients were obtained through calculation, and Fig. 4 shows the change rule of the two coefficients with the number of freeze-thaw cycles. With the increase of the number of freeze-thaw cycles, the energy storage coefficient decreases continuously, the energy storage coefficient decreases from 0.68 in the unfrozen and thawed to 0.57 in the 30 times of freeze-thaw cycles, while the energy dissipation coefficient increases continuously from 0.32 in the unfrozen and thawed to 0.43. It shows that the more the number of freeze-thaw cycles is, the rock samples have a weakened capacity of energy storage and an enhanced capacity of energy dissipation. This can be explained by the fact that the freeze-thaw cycle leads to the generation of more secondary defects in the rock samples, and more energy needs to be dissipated when the secondary defects gather and develop into cracks when the rock samples are loaded and damaged, and the stored elastic energy decreases.

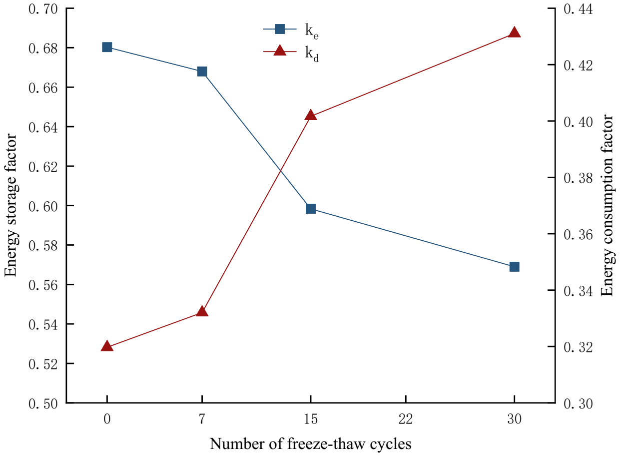

Fig. 4. Changes in energy storage and dissipation coefficients with the number of freeze-thaw cycles

5 Conclusion

In summary, the current research on the energy evolution law of freeze-thawed rocks under cyclic loading is relatively rare, but the energy evolution law of freeze-thawed rocks under uniaxial compression has been studied by scholars [10], and it is found that the total and elastic energy densities of the rocks before destruction gradually decrease with the increase of the number of freeze-thaw times. Comparison with the energy density changes in Fig. 2 of this paper shows that the total energy density of freeze-thawed sandstone under cyclic loading decreases from 3.64 kJ·m^{-3} for 0 times of freeze-thaw to 1.55 kJ·m^{-3} for 30 times of freeze-thaw, and the elastic energy density decreases from 3.03 kJ·m^{-3} to 0.80 kJ·m^{-3}, also has a similar trend of change, thus reflecting the reliability of the results of this test. In this paper, the energy evolution characteristics of freeze-thawed rocks under cyclic loading are further comprehensively analysed, and the results of the study can provide certain reference for the stability analysis of rock engineering in cold regions. The main research conclusions are as follows:

(1) Compared with uniaxial compression, cyclic unloading increased the sandstone load-bearing capacity at a lower number of freeze-thaw cycles and decreased it at a higher number of freeze-thaw cycles, and the peak strength of cyclic unloading decreased linearly with the number of freeze-thaw cycles. The maximum strain increased from 1.43% at 0 to 2.60% at 30 cycles of freeze-thaw, and the freeze-thaw cycles contributed to the development of deformation and increased the ductility of the sandstone.

(2) The variation curves of total energy density and dissipated energy density at each level of loading show a "U" shape, and the elastic energy density increases in a horizontal step. The difference between the total energy density and the dissipated energy density is small when loading for the first time, but the difference gradually becomes larger with the increase of loading and unloading cycles. The overall trend of dissipated energy is increasing. Before the final loading damage, the elastic energy is accelerated to be released, and the difference between the elastic and dissipated energy densities decreases from 2.35 kJ·m^{-3} to 0.05 kJ·m^{-3} with the increase of the number of freeze-thaw cycles.

(3) There was a good linear relationship between cumulative elasticity, dissipated energy density and cumulative total energy density, with the slope of the fitted curve for elastic energy decreasing with the increase in the number of freeze-thaw cycles and the opposite for dissipated energy. Freeze-thaw cycles significantly affected the energy storage and energy dissipation levels of sandstone, with the increase of freeze-thaw times, the energy storage coefficient decreased from 0.68 to 0.57, and the energy dissipation coefficient increased from 0.32 to 0.43, the energy storage capacity was weakened, and the energy dissipation capacity was enhanced.

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