Research Article

Strength and Microscopic Damage Mechanism of Yellow Sandstone with Holes under Freezing and Thawing

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In order to study the damage characteristics of the yellow sandstone containing pores under the freeze-thaw cycle, the uniaxial compression test of saturated water-stained yellow sandstones with different freeze-thaw cycles was carried out by rock servo press, the microstructure was qualitatively analyzed by Zeiss 508 stereo microscope, and the microdamage mechanism was quantitatively studied by using specific surface area and pore size analyzer. The mechanism of weakening mechanical properties of single-hole yellow sandstone was expounded from the perspective of microstructure. The results show the following. (1) The number of freeze-thaw cycles and single-pore diameter have significant effects on the strength and elastic modulus of the yellow sandstone; the more the freeze-thaw cycles and the larger the pore size, the lower the strength of the yellow sandstone. (2) The damage modes of the yellow sandstone containing pores under the freeze-thaw cycle are divided into five types, and the yellow sandstone with pores is divided into two areas: the periphery of the hole and the distance from the hole; as the number of freeze-thaw cycles increases, different regions show different microscopic damage patterns. (3) The damage degree of yellow sandstone is different with freeze-thaw cycle and pore size. Freeze-thaw not only affects the mechanical properties of yellow sandstone but also accelerates the damage process of pores. (4) The damage of the yellow sandstone by freeze-thaw is logarithmic function, and the damage of the yellow sandstone is a power function. The damage equation of the yellow sandstone with pores under the freezing and thawing is a log-power function nonlinear change law and presents a good correlation.

1. Introduction

With the gradual implementation of the strategy of developing the western region, the cold area needs a lot of engineering construction [1] and more and more rocks and rock damage problems under the conditions of alternating low temperature and temperature; the rock itself is a relative water content. The higher materials, combined with the temperature difference between day and night, make the freeze-thaw cycle appear, accompanied by the generation and disappearance of the frost heaving force, which causes cumulative damage to the rock mass structure. Therefore, with the deepening of the development of the western region, it is of great theoretical and practical significance to

study the mechanism of rock mechanical deterioration under the action of freeze-thaw cycles.

At present, scholars at home and abroad have made corresponding research on the performance of rocks under freeze-thaw cycles. Hall et al. [1, 2] studied the mechanical properties of rocks under freezing and thawing; Yamabe et al. [3–5] studied damage degradation of different types of rocks under freeze-thaw cycles; Yang et al. [6, 7] used CT scanning technique to study the mesoscopic damage propagation mechanism inside rocks with different freezing and thawing temperatures; DelRoa et al. [8] analyzed the damage degradation mechanism of different types of granite under the freeze-thaw cycle by ultrasonic wave monitoring technology through ultrasonic monitoring technology; using

CT scanning technology, CT image, scanning electron microscope by Wang et al. [9–11], the mechanical properties and internal damage of rocks with different saturated states under freeze-thaw cycles were studied. Zhang et al. [12–17] found that the mechanical properties of sandstone deteriorated under the combined action of freezing and thawing and load. The speed is accelerated; Huseyin [18] analyzed the deterioration of hardness, wave velocity, and compressive strength of andesite after freeze-thaw cycles; Li et al. [19], taking the rock mass under the action of freeze-thaw cycles as research object, based on the mesoscopic damage theory and macroscopic damage model, established a single-fracture sandstone damage model under freeze-thaw-load coupling. Zhou et al. [20] used NMR experiments to study the compressive strength of sandstone under freeze-thaw cycles. Reasons for the decrease are as follows: Tian and Xu [21], based on the pore characteristics inside the rock after freezing and thawing, established the relationship between the mechanical properties of the rock and the porosity during the freeze-thaw cycle.

Most scholars have studied the physical and microscopic properties of rocks after freezing and thawing. There are few studies on the properties of rock with pores and the apparent damage characteristics after freezing and thawing by microscope. This paper takes the construction of rock mass in cold area as the background. The saturated single-hole yellow sandstone with pores is studied. The mechanical properties of saturated yellow sandstone with pores under freezing and thawing are obtained by uniaxial compression test. The pores and yellows are described by stereo microscope and pore size analyzer. The microscopic damage mechanism of sandstone provides a reference for the construction of rock mass engineering in cold regions.

2. Test Overview

2.1. Sample Preparation and Working Conditions. The origin of the yellow sandstone in this experiment is Sichuan. The main mineral components of the sandstone are quartz, feldspar, muscovite, clay, and silty materials. The apparent crumbs are densely compacted and the cement is tightly connected. According to the rock test standards and specifications, a rectangular parallelepiped sample of 30 mm × 60 mm × 120 mm was prepared. The selected test conditions were as follows: single-hole yellow sandstone samples with pore diameters of 0 mm (control group), 6 mm, 8 mm, 10 mm, and 12 mm. The freeze-thaw cycle test was carried out at 0, 5, 10, 20, and 40 times. At the early stage, 5 samples were selected for each working condition. At the later stage, 2 samples with relatively high dispersion (mechanical properties were taken as the main reference) were removed, and 3 samples with relatively small dispersion were listed for analysis.

The list of compressive strength and average value of each sample was added, and samples close to the average value were listed for microscopic analysis in this paper.

2.2. Test Methods and Principles. Freeze-thaw cycle test method: using the freeze-thaw cycle test machine to simulate

the cold-thaw environment of the cold zone, set the freeze-thaw cycle temperature to $-20^{\circ}\text{C}\sim 20^{\circ}\text{C}$, the temperature from 20°C to -20°C , and then the constant temperature for 4 hours. After rising to 20°C , the temperature is kept constant for 4 hours. By default, this process is one cycle.

German Zeiss 508 stereo microscope principle: the microscope can clearly observe the surface and pore variation characteristics of yellow sandstone before and after freezing and thawing by high magnification amplification principle. One surface of yellow sandstone is selected as the observation surface, and the observation surface is divided into A and B. Two areas (B area is a square with a side length of 10 mm) and several points are uniformly selected in different areas for observation, as shown in Figure 1; in order to reduce the test error, two observations before and after the freeze-thaw test ensure that the room is in a dark environment, the only source of light is the instrument's own light, using the same light intensity, and the eyepieces use the same magnification, to ensure that the two test conditions are exactly the same.

The principle of specific surface area and pore size analyzer: its essence is nitrogen adsorption method, nitrogen has good reversible adsorption characteristics, and nitrogen molecules are used as measuring tools. Under constant temperature and pressure, the surface of the sample forms monomolecular nitrogen due to van der Waals force between molecules. In the adsorption layer, when the pressure of the adsorption gas is changed, the curve of the adsorption/desorption amount of the sample surface with the pressure can be obtained, and the specific surface area and the pore size distribution of the sample are calculated by the BET method and the BJH method.

The test is based on saturated yellow sandstone as follows: ① The prepared yellow sandstone is immersed in water for 48 hours and then dried and weighed. ② The saturated sample is placed in a German Zeiss 508 stereo microscope (as shown in Figure 2). The apparent particle and pore structure are observed under the microscope. ③ The saturated sample observed by the microscope is placed in the freeze-thaw cycle test machine in turn. ④ The frozen sample after freezing and thawing is taken out, weighed, placed under the microscope again and observed and compared with the apparent granules and pore structure of the unfrozen and thawed samples. ⑤ After the freeze-thaw test, take a small number of samples under different freeze-thaw cycles, using the specific surface area and pore size analyzer (Figure 3). The specific surface area and the change of the pore diameter are detected. ⑥ The sample after the freeze-thaw and the microscopic observation is subjected to uniaxial compression test to test the mechanical properties.

3. Mechanical Properties of Yellow Sandstone before and after Freezing and Thawing Cycles

3.1. Peak Strength of Different Diameter Yellow Sandstone after Freeze-Thaw Cycle. Tables 1 and 2 in Appendix are lists of

FIGURE 1: Single-hole yellow sandstone observation area.

FIGURE 2: German Zeiss 508 stereo microscope.

FIGURE 3: Specific surface area and pore size analyzer.

test samples for compressive strength and microscopic analysis. The average compressive strength is used for mechanical properties analysis below.

Figure 4 is a graph showing the compressive strength of different diameter yellow sandstones with the number of

freeze-thaw cycles. It can be seen from the figure that as the number of freeze-thaw cycles increases, the compressive strength of five groups of different diameter yellow sandstones gradually decreases. When the freeze-thaw cycle is 0 times, the compressive strength of the yellow sandstone with different pore sizes is the largest. When the freeze-thaw cycle is 40 times, the compressive strength of the yellow sandstone with different pore sizes is the smallest. The case of the complete 12 mm yellow sandstone with different freeze-thaw cycles is taken as an example. Description: the compressive strength of intact yellow sandstone is 60.07 MPa when the freeze-thaw cycle is 0 times, and the compressive strength is 54.89 MPa, 51.38 MPa, 48.07 MPa, and 41.3 MPa when the freeze-thaw cycle is 5, 10, 20, and 40 times. Compared with freezing and thawing, the intensity decreased by 8.62%, 14.47%, 19.98%, and 31.25%, respectively. The compressive strength of the 12 mm yellow sandstone was 37.86 MPa when frozen and thawed, and the freeze-thaw cycle was 5, 10, 20, and 40 times. When the compressive strength is 37.59 MPa, 30.55 MPa, 27.07 MPa, and 19.05 MPa, respectively, the strength is reduced by 0.71%, 19.3%, 28.5%, and 49.68%, respectively.

It is found that the compressive strength of the yellow sandstone with the same pore diameter increases with the increase of the number of freeze-thaw cycles, indicating that the freezing and thawing effect is an important factor affecting the compressive strength of the yellow sandstone.

In addition, the compressive strength of different diameter yellow sandstones also showed different changes under the same number of freeze-thaw cycles. When the freeze-thaw cycle was 0 times, the compressive strength of intact yellow sandstone was 60.07 MPa, and with the increase of the pore diameter, the strengths are 51.33 MPa, 49.95 MPa, 45.34 MPa, and 37.86 MPa, respectively. The strength is reduced compared with the intact yellow sandstone. When the freeze-thaw cycle is 40 times, the compressive strength of the intact yellow sandstone is 41.3 MPa. With the increase of the pore size, the compressive strengths are 38.64 MPa, 34.83 MPa, 29.79 MPa, and 19.05 MPa, respectively, and the strengths are reduced by 6.4%, 15.67%, 27.43%, and 53.87%, respectively, compared with the intact yellow sandstone, indicating that the pores reduce the compressive strength of the yellow sandstone. And the larger the aperture, the larger the reduction.

3.2. Elastic Modulus of Yellow Sandstone with Different Pore Sizes after Freeze-Thaw Cycles. The elastic modulus is the physical parameter that characterizes the yellow sandstone resisting the external elastic deformation. Figure 5 is the curve of the elastic modulus of the yellow sandstone with different pore sizes as a function of the number of freeze-thaw cycles. The elastic modulus of the yellow sandstone after different freeze-thaw cycles can be seen from the figure. Similar to the compressive strength, the overall trend is gradually decreasing. Under different freezing and thawing cycles, the elastic modulus of intact yellow sandstone is 9.653 GPa, 8.645 GPa, 8.31 GPa, 6.499 GPa, and 6.32 GPa, respectively, compared with freezing and thawing 0 times. The reductions are 10.44%, 13.91%, 32.67%, and 34.53%,

TABLE 1: Microdamage mode table.

Microscopic damage mode	(1) Particle flaking	(2) Pore is granules filling	(3) Pore expansion	(4) Pore shrinkage	(5) Pore connectivity
Microscopic under the microscope damage before
Microscopic under the microscope damage after

respectively. The elastic modulus of the 12 mm yellow sandstone is 8.16 GPa, 6.303 GPa, 5.975 GPa, 4.59 GPa, and 3.658 GPa, which is lower than that of freezing and thawing 0 times. They are 22.76%, 26.781%, 43.75%, and 55.17%, respectively; with the increase of the number of freeze-thaw cycles and the elastic modulus of yellow sandstone, the amount is decreasing and the decline is increasing. The elastic modulus of different diameter yellow sandstones with the same number of freeze-thaw cycles is analyzed. It can be seen that the elastic modulus of yellow sandstone with different pore sizes is the largest when the freeze-thaw cycle is 0 times, which are 9.653 GPa, 11.06 GPa, 7.581 GPa, 8.78 GPa, and 8.16 GPa, respectively. The elastic modulus of the 6 mm yellow sandstone is the largest under the number of freeze-thaw cycles, and the elastic modulus of the 8 mm yellow sandstone is the smallest, which indicates that the yellow sandstone has no significant change with the hole. However, as the number of freeze-thaw cycles increases, at the freeze-thaw cycle 5, 10, 20, and 40, the yellow sandstones with different pore sizes show that the elastic modulus decreases with the increase of the pores.

Comparing the mechanical properties of different diameter yellow sandstones under different freeze-thaw cycles, it is found that the damage of yellow sandstone caused by freezing and thawing will increase the damage of yellow sandstone.

4. Microscopic Characteristics of Different Diameter Yellow Sandstones after Freeze-Thaw Cycles

4.1. Microscopic Damage Pattern Analysis. The microscopic pores and particle changes of different diameter yellow sandstones under different freeze-thaw cycles observed by microscope were summarized, and the five microscopic damage modes shown in Table 1 were summarized.

4.2. Microscopic Qualitative Analysis. In order to more clearly characterize the effects of freezing and thawing and pore action on the granules and pores of the yellow sandstone, the micropictures of the yellow sandstones with

different freeze-thaw cycles and different pore sizes were pretreated, and the particles were separated from the pores. The treatment effect is shown in Figure 6, showing that the black areas represent pores and the white areas represent particles.

The freezing and thawing cycles cause different degrees of damage inside the yellow sandstone. The existence of the pores divides the damage of the yellow sandstone into the A and B regions as shown in Figure 1. With the increase of the diameter of the holes, the A and B regions of the yellow sandstone have the following characteristics. The range is different, but the damage mode remains unchanged. This paper focuses on the analysis of the difference of damage patterns in the A and B regions under different freeze-thaw cycles.

Combined with Figures 7 and 8 and microscope observations, the following has been found: ① When the freeze-thaw cycle is 5 times, the main damage mode of the yellow sandstone in the A region is pore shrinkage, the pores are filled by particles, and the main damage mode in the B region is pore expansion, the number of freeze-thaw cycles. Under the joint action of frost heaving force and hole effect, the B area is seriously damaged and the pores become large. The A area suffers from the frost heaving force on one hand, and the fine ice crystal particles fill the pores. On the other hand, the B area has different effects on the A area. The degree of extrusion causes the pores in zone A to become smaller. ② When the freeze-thaw cycle is 10 times, the main damage modes of the yellow sandstones in the A and B regions are particle spalling. Under this cycle, the surface of the yellow sandstone in the A and B regions falls off and is exposed. The internal particles and pores are more serious. ③ When the freeze-thaw cycle is 20 times, the main damage mode of the yellow sandstone in the A area is pore expansion, and the main damage mode in the B area is pore communication. Under the cycle number, the yellow sandstone particles are affected by the frost heaving force. The intergelation is reduced, the continuous damage in zone A leads to the increase of pores, the effect of pores in zone B accelerates the failure of the rock sample around the hole, and the surface of the yellow sandstone is

TABLE 2: List of test samples for compressive strength and microscopic analysis.

	Standard yellow sandstone			The hole diameter 6 mm			The hole diameter 8 mm			The hole diameter 10 mm			The hole diameter 12 mm		
	Compression strength (MPa)	Average value (MPa)		Compression strength (MPa)	Average value (MPa)		Compression strength (MPa)	Average value (MPa)		Compression strength (MPa)	Average value (MPa)		Compression strength (MPa)	Average value (MPa)	
0 times	61.75			53.46			46.32			46.62			41.96		
0 times	60.20▲	60.07		51.13▲	51.33		48.62▲	49.95		46.19▲	45.34		36.38▲	37.86	
0 times	58.26			49.32			54.92			43.23			35.23		
5 times	56.22			50.23			49.82			45.07			40.72		
5 times	55.73▲	54.89		48.62▲	48.60		47.06▲	47.48		42.87▲	43.20		36.17▲	37.59	
5 times	52.73			46.96			45.56			41.65			35.88		
10 times	52.67			51.08			43.02			41.06			32.51		
10 times	50.89▲	51.38		46.62▲	47.68		41.16▲	41.46		39.37▲	38.90		31.12▲	30.55	
10 times	50.59			45.33			40.21			36.23			28.03		
20 times	51.54			46.26			41.55			32.58			29.23		
20 times	46.56▲	48.07		45.27▲	44.88		39.01▲	39.26		31.29▲	31.03		27.86▲	27.07	
20 times	46.12			43.12			37.23			29.23			24.13		
40 times	43.23			39.26			36.71			31.15			20.09		
40 times	42.35▲	41.3		39.03▲	38.64		34.03▲	34.83		30.01▲	29.79		20.03▲	19.04	
40 times	38.32			37.63			33.75			28.21			17.02		

▲, samples selected for microscopic analysis.

FIGURE 4: Compressive strength curve of yellow sandstone under freeze-thaw cycles.

FIGURE 5: Elastic modulus curve of yellow sandstone under freeze-thaw cycles.

accompanied by pores. The phenomenon of the pass: ④ When the freeze-thaw cycle is 40 times, the main damage modes of the yellow sandstones in the A and B regions are pore expansion and accompanied by particle spalling, indicating that, under the cycle number, the high-order circulation freeze-thaw causes the rock sample to have larger pores. At the same time, micropores are continuously generated inside. On the other hand, due to serious damage, the pores inside the rock mass penetrate, resulting in larger pores in the A and B regions.

4.3. Microscopic Quantitative Study. In Figures 9 and 10, (a), (b) and (c) are the pore volume sizes of the A and B regions of the yellow sandstone containing pores measured by nitrogen adsorption, and from (d), (e), and (f) for the relative change of pore volume of different pore sizes (compared with the previous freeze-thaw cycle), the relative change amplitude is used to characterize the response of different types of microscopic pores to freeze-thaw.

As can be seen from (a), (b), and (c), that, as the number of freezing-thawing cycles increased, the pore volumes of

FIGURE 6: Pore extraction.

FIGURE 7: Microporosity change diagram of A zone in yellow sandstone under freeze-thaw cycles. (a) Freeze-thaw 0 times. (b) Freeze-thaw 5 times. (c) Freeze-thaw 10 times. (d) Freeze-thaw 20 times. (e) Freeze-thaw 40 times.

FIGURE 8: Microporosity change diagram of B zone in yellow sandstone under freeze-thaw cycles. (a) Freeze-thaw 0 times. (b) Freeze-thaw 5 times. (c) Freeze-thaw 10 times. (d) Freeze-thaw 20 times. (e) Freeze-thaw 40 times.

small holes, medium holes, and large holes in area A (0~2 nm is micropores, 2~50 nm is medium holes, and holes more than 50 nm are large holes according to the international IUPAC definition) increased on the whole. Only the mesopore volume decreased in the freeze-thaw cycle 5 times, and the volume of small, medium, and large pores in the B region increased overall. Analysis of (d), (e), and (f) combined with microscopic observations shows that the response of A and B regions of yellow sandstone to freezing and thawing is different. ① When the freezing and thawing cycle is 5 times, the pore volume in the A region has the following characteristics. The relative decrease is -36.67%, the relative volume of large pore volume is 0%, and the

relative increase of medium and large pore volume in B area is 83.3% and 41.18%, respectively. Under the cycle number, free mineral particles are produced on the surface of yellow sandstone. In the A region, the pore volume is reduced due to the shrinkage of the mesopores or by the filling of mineral particles. The expansion of the pores and the pores in the B region leads to an increase in the volume of the mesopores and macropores. ② When the freeze-thaw cycle is 10 times, the A region is small. The relative increases in volume of pores, mesopores, and macropores were 100%, 54.89%, and 16.67%, respectively. The relative volume increases of small, medium, and large pores in B region were 80%, 36.36%, and 4.17%. Under the number of times, the connection between

FIGURE 9: Pore volume and relative change amplitude of A in yellow sandstone under freeze-thaw cycles. (a) Micropore volume. (b) Mesoporous volume. (c) Macropores volume. (d) Relative change in micropore volume. (e) Relative change in mesoporous volume. (f) Relative change in macropores volume.

FIGURE 10: Pore volume and relative change amplitude of B in yellow sandstone under freeze-thaw cycles. (a) Micropore volume. (b) Mesoporous volume. (c) Macropores volume. (d) Relative change in micropore volume. (e) Relative change in mesoporous volume. (f) Relative change in macropores volume.

the aggregates of the yellow sandstone aggregates is loose, and the pores in the A region increase. At the same time, due to the spalling of the particles, the mesopores and macropores are continuously generated. The small pores in the B region increase, while the mesopores and macropores do not change significantly. ③ When the freeze-thaw cycle is 20 times, the pore volume in the A region has the following characteristics. The relative increase is 46.67%, the relative increase of macropore volume is 33.33%, the relative increase of pore volume in B region is 6.66%, and the relative increase of macropore volume is 16%. The volume of mesopores and macropores increases in A region due to pore expansion. Severely, the volume of pores communicating with mesopores and large pores increased slightly in the B region due to particle spalling. ④ When the freeze-thaw cycle was 40 times, the relative increases in the volume of small pores, mesopores, and macropores in the A region were 110%, 4.54%, and 42.8%, respectively. The relative increase of the volume of small holes, mesopores, and macropores in B area was 177.78%, 21.87%, and 44.82%. The A and B areas were seriously damaged by freezing and thawing, and the internal cracks were generated by new cracks. The decrease in force causes the particles to peel off continuously, and the volume of small holes, mesopores, and large pores increases.

In summary, the freezing and thawing cause the pores in the yellow sandstone to increase continuously, the cohesive force decreases, and the strength is continuously reduced, but the single hole also causes damage. In zone A, freezing and thawing 10 times are the threshold for the generation of small holes, mesopores, and macropores in yellow sandstone. In the B region, the freezing and thawing 5 times are the thresholds for the mesopores and macropores, and the freezing and thawing 10 times are the thresholds for the pores. Compared with the pores in the A and B regions, the mesopores and macropores in the B region are significantly better than the A regions. The production time is earlier and the quantity is more, which indicates that, under the action of freezing and thawing and pores, the freezing and thawing will damage the interior of the yellow sandstone, and the pores will further accelerate the degradation of the yellow sandstone, and then the mechanical properties will be accelerated.

5. Yellow Sandstone Damage Function under Freeze-Thaw Cycles

By studying the strength and microscopic properties of the yellow sandstone containing pores after freezing and thawing, it is known that both freezing and thawing and pore effects cause significant damage to the rock. Figure 11 shows the damage process of the yellow sandstone containing pores after freezing and thawing. The volume of the intact yellow sandstone is assumed to be V . The effective volume of the yellow sandstone in the hole is V_1 . The effective volume of the yellow sandstone containing pores under the freezing and thawing is V_2 , so the damage value of the yellow sandstone in the hole is D_1 . The damage value of the frozen-thawed yellow sandstone is D_2 , and the damage value of the

FIGURE 11: Damage process of yellow sandstone with pores under freezing and thawing.

frozen-thawed yellow sandstone is the D_t . The damage of the yellow sandstone in different states is characterized by the change of bulk density:

$$\begin{aligned} 1 - D_1 &= \frac{V_1}{V} \\ 1 - D_2 &= \frac{V_2}{V_1} \\ 1 - D_t &= \frac{V_2}{V} \end{aligned} \quad (1)$$

Among them,

$$\begin{aligned} V\alpha(e) \\ V_1\alpha(d, e_1) \\ V_2\alpha(d, e_2), \end{aligned} \quad (2)$$

where e is the pore volume of the intact yellow sandstone, e_1 is the pore volume of the yellow sandstone containing the pore, e_2 is the pore volume of the yellow sandstone containing the pore after freezing and thawing, and d is the diameter of the pore of the yellow sandstone.

According to the above formula, the total damage formula of the yellow sandstone containing pores under freezing and thawing is

$$D_t = D_1 + D_2 - D_1 D_2. \quad (3)$$

The rate of change of compressive strength of the yellow sandstone containing pores after freezing and thawing is taken as the measure of the damage degree of the yellow sandstone, which is expressed as D . Then

$$D = \frac{\sigma_0 - \sigma_i}{\sigma_0}. \quad (4)$$

Among them, σ_0 and σ_i are the compressive strength of yellow sandstone in the initial state (freezing and thawing 0 times, hole diameter is 0 mm); the degree of damage D of the yellow sandstone containing pores after freezing and thawing is shown in Table 3.

The yellow sandstone with a pore size of 0 mm and the damage curve of the yellow sandstone with zero-degree freeze-thaw under the action of freezing and thawing alone were fitted, and the graphs shown in Figures 12 and 13 were obtained.

TABLE 3: Damage degree of yellow sandstone with pores under freezing and thawing.

Freezing and thawing times	Hole diameter (mm)				
	0	6	8	10	12
0	0.000	0.145	0.168	0.245	0.370
5	0.086	0.191	0.210	0.281	0.374
10	0.145	0.206	0.310	0.353	0.491
20	0.200	0.253	0.346	0.483	0.549
40	0.312	0.357	0.42	0.504	0.683

FIGURE 12: Yellow sandstone damage curve under freezing and thawing.

FIGURE 13: Yellow sandstone damage curve under the action of holes.

It can be seen from the figure that the damage law of the frozen-thawed yellow sandstone accords with the logistic function:

$$D_2 = \ln(1.03 + 0.009n), \quad (5)$$

where n is the number of freeze-thaw cycles.

The damage of yellow sandstone with a pore diameter of 0 mm under the action of freezing and thawing is defined as D_2 , and the damage of yellow sandstone with zero freezing and thawing under the action of pore is defined as D_1 . It can be seen from the figure that the damage curve of frozen-thawed yellow sandstone accords with the logistic function. One has

$$D_1 = 0.012 \times d^{1.35}, \quad (6)$$

where d is the diameter of the hole.

Taking formulas (5) and (6) into (3), the nonlinear equation for the number of freeze-thaw cycles n and the diameter d of the hole is

$$D_t = a(0.012d^{1.35}) + b \ln(1.03 + 0.009n) - c(0.012d^{1.35}) \times \ln(1.03 + 0.009n), \quad (7)$$

where a , b , and c are the influence factors, respectively.

The following is a fitting of the rock damage with pores under the freeze-thaw cycle. Figure 14 shows the damage curve of yellow sandstone under different freeze-thaw cycles when the aperture is 6 mm. Figure 15 shows the yellow sandstone under different pore sizes when the number of freeze-thaw cycles is 5. The damage curve and the fitting result are shown in Table 4. The damage value of the yellow sandstone containing pores under freezing and thawing is represented by the equation. The fitting curve returns the scattered points into a function with certain physical meaning and has good correlation.

Through the analysis of the fitting curve, it is found that the effects of freezing and thawing and pores have obvious effects on the yellow sandstone. This equation can better reflect the damage degree of the yellow sandstone under the freezing and thawing.

Li et al. [22] and Yuan et al. [23] studied the rock under the combined action of freezing-thawing and crack (joint) and showed that the total damage of rock sample increased under the combined action of freezing-thawing times and crack. The damage is related to freezing-thawing times, crack length, and inclination angle. The macroscopic damage and its coupling effect determine the obvious anisotropy of the joint to the macroscopic damage of rock. With the increase of the number of freeze-thaw cycles, the macroscopic anisotropy of the jointed rock samples is weakened, and the degree of weakening is related to the joint properties and freeze-thaw degree. The anisotropy of rock samples aggravated was verified.

According to the results of hole and freezing-thawing test, this paper shows that, after 5 cycles of freezing-thawing, large hole and middle hole begin to appear around the hole, but far away from the hole area, it has not yet occurred (or the production is few and cannot be monitored). After 10

FIGURE 14: Yellow sandstone damage curve of different freeze-thaw cycles (aperture 6 mm).

FIGURE 15: Damage curves of different diameter yellow sandstones (5 freeze-thaw cycles).

TABLE 4: Fitting curve related parameters.

Test piece condition	Combined function			
	$D_t = a(0.012d^{1.35}) + b \ln(1.03 + 0.009n) - c(0.012d^{1.35}) \times \ln(1.03 + 0.009n)$			
	a	b	c	R^2
Hole diameter $d = 6$ mm	0.038	1.05	0.59	0.91
Hole diameter $d = 8$ mm	0.85	1.01	0.94	0.8
Hole diameter $d = 10$ mm	0.88	1.09	0.65	0.73
Hole diameter $d = 12$ mm	0.98	1.2	0.37	0.92
Freezing and thawing times $n = 5$	0.94	1.06	1.86	0.94
Freezing and thawing times $n = 10$	1.05	1.01	0.55	0.87
Freezing and thawing times $n = 20$	1.13	0.84	0.28	0.85
Freezing and thawing times $n = 40$	1.18	0.79	0.45	0.71

cycles of freezing-thawing, small holes begin to form around the hole, and then large holes, middle holes, and small holes begin to form when they are far away from the hole area. Therefore, the macroscopic anisotropy of rock samples changed by pore action can be divided into two stages: when the number of freezing-thawing cycles is 0–10 times, the pore patterns around the hole and away from the hole area are different, and the change law is opposite. The macroscopic anisotropy of the sample was enhanced by pore action. When the freezing-thawing cycle was repeated for 10–40 times, the pore patterns around the hole and far away from the hole area were the same, the variation law was the same, and the macroscopic anisotropy of the sample gradually weakened.

6. Conclusion

- (1) With the increase of freezing and thawing times and pore size, the compressive strength and elastic modulus of yellow sandstone gradually decrease.
- (2) The rock sample with pores after freezing and thawing is divided into two damage areas: the periphery of the hole and the distance from the hole; five kinds of microdamage modes of the yellow sandstone after freezing and thawing are as follows: (1) particle peeling, (2) pores filled by particles, (3) holes extended, (4) pore shrinkage, and (5) pore communication.
- (3) As the number of freeze-thaw cycles increases, the damage pattern at the farther hole is different from the damage pattern around the hole. The damage mode at the far hole is filled by pores and the pores are filled with particles (5 times), particle peeling (10 times), pore expansion (20 times), and pore expansion and particle spalling transition (40 times); damage pattern around the hole by pore expansion (5 times), particle spalling (10 times), pore connectivity (20 times), and pore expansion and particles peeling transition (40 times), and the mesopores and macropores around the pore are farther than the pores. The time of occurrence is earlier and the damage is more serious, indicating that the freezing and thawing damage the yellow sandstone, and the hole promotes the damage of the yellow sandstone.
- (4) Under the combined action of hole and freeze-thaw, the sample anisotropy caused by hole is divided into two stages: freezing-thawing cycle 0–10 times, the macroscopic anisotropy of the sample was enhanced by pore action; freezing and thawing times 10–40 times, the sample macroscopic anisotropy gradually weakened.
- (5) Under the same freezing and thawing frequency, the total damage of rock sample increases with the increase of hole diameter. With the same hole diameter, the total damage of rock sample increases with the increase of freezing-thawing times. The damage

degree of yellow sandstone is closely related to the number of freezing-thawing cycles and the pore size. The damage equation of the yellow sandstone with pores under freezing and thawing is nonlinear. The equation can better reflect the damage of rock with pores under freezing and thawing and provide reference for the long-term stability of damaged rock.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

- [1] K. Hall, "A laboratory simulation of rock breakdown due to freeze-thaw in a maritime Antarctic environment," *Earth Surface Processes and Landforms*, vol. 13, no. 4, pp. 369–382, 1998.
- [2] N. Matsuoka, "Microgelivation versus macrogelivation: towards bridging the gap between laboratory and field frost weathering," *Permafrost and Periglacial Processes*, vol. 12, no. 3, pp. 299–313, 2001.
- [3] T. Yamabe and K. M. Neaupane, "Determination of some thermo-mechanical properties of Sirahama sandstone under subzero temperature condition," *International Journal of Rock Mechanics and Mining Sciences*, vol. 38, no. 7, pp. 1029–1034, 2001.
- [4] X. Tan, W. Chen, J. Yang, and J. Cao, "Laboratory investigations on the mechanical properties degradation of granite under freeze-thaw cycles," *Cold Regions Science and Technology*, vol. 68, no. 3, pp. 130–138, 2011.
- [5] B. Fatih, "Predicting mechanical strength loss of natural stones after freeze-thaw in cold regions," *Cold Regions Science and Technology*, vol. 83–84, pp. 98–102, 2012.
- [6] G. Yang, Q. Zhang, and Y. Pu, "Study on the influence of freezing temperature on microscopic damage expansion characteristics of rock," *Rock and Soil Mechanics*, vol. 25, no. 9, pp. 1409–1412, 2004.
- [7] G. Yang, Q. Zhang, J. Ren et al., "Study on the variation of CT number of Tongchuan sandstone damage caused by freezing speed," *Chinese Journal of Rock Mechanics and Engineering*, vol. 23, no. 24, pp. 4099–4014, 2004.
- [8] L. M. Del Roa, F. Lopez, F. J. Esteban et al., "Ultrasonic study of alteration processes in granites caused by freezing and thawing," in *Proceedings of the IEEE Ultrasonics Symposium, 2005*, Rotterdam, The Netherlands, September 2005.
- [9] L. Wang and C. H. Yang, "Study on the difference of freezing and thawing damage of red sandstone in different initial

- saturated states,” *Rock and Soil Mechanics*, vol. 27, no. 10, pp. 1772–1776, 2006.
- [10] L. Lang, H. Jia, and Y. Guo, “Study on the mechanism of freeze-thaw damage and mechanical properties of freeze-thaw in sandstone,” *International Journal Hydroelectric Energy*, vol. 30, no. 11, pp. 118–121, 2012.
 - [11] J. Park, C.-U. Hyun, and H.-D. Park, “Changes in micro-structure and physical properties of rocks caused by artificial freeze-thaw action,” *Bulletin of Engineering Geology and the Environment*, vol. 74, no. 2, pp. 555–565, 2015.
 - [12] H. Zhang and G. Yang, “Experimental and damage propagation characteristics of rock freeze-thaw,” *Journal of China University of Mining & Technology*, vol. 40, no. 1, pp. 140–145, 2011.
 - [13] H.-M. Zhang and G.-S. Yang, “Experimental study on damage and mechanical properties of freeze-thawed rock,” *Journal of China Coal Society*, vol. 38, no. 10, pp. 1756–1762, 2013.
 - [14] H. Zhang and G. Yang, “Effects of water and freeze-thaw cycles on physical and mechanical properties of red sandstone,” *Journal of Experimental Mechanics*, vol. 28, no. 5, pp. 635–641, 2013.
 - [15] H. Zhang and G. Yang, “Mechanical properties test and damage analysis of red sandstone under freezing and thawing environment,” *Mechanics and Engineering*, vol. 35, no. 3, pp. 57–61, 2013.
 - [16] H. Zhang, M. Zhang, X. Xie et al., “Experimental study on physical and mechanical properties of red sandstone under freeze-thaw cycles,” *Journal of Taiyuan University of Technology*, vol. 46, no. 1, pp. 69–74, 2015.
 - [17] H. Zhang, H. Xia, G. Yang et al., “Experimental study on the effects of freeze-thaw cycles and confining pressure on physical and mechanical properties of rocks,” *Journal of China Coal Society*, vol. 43, no. 2, pp. 441–448, 2018.
 - [18] Y. Huseyin, “Effect of freeze-thaw and thermal shock weathering on the physical and mechanical properties of an andesite stone,” *Bulletin of Engineering Geology and the Environment*, vol. 70, no. 2, pp. 187–192, 2011.
 - [19] X. Li, Y. Lu, and Y. Wang, “Study on damage model of single-fractured rock mass under the coupling of freeze-thaw load,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 32, no. 11, pp. 2307–2315, 2013.
 - [20] K.-P. Zhou, B. Li, J.-L. Li, H.-W. Deng, and F. Bin, “Microscopic damage and dynamic mechanical properties of rock under freeze-thaw environment,” *Transactions of Nonferrous Metals Society of China*, vol. 25, no. 4, pp. 1254–1261, 2015.
 - [21] Y. Tian and S. Xu, “Correlation analysis of rock physical and mechanical indexes under freeze-thaw cycles,” *Mining Safety & Environmental Protection*, vol. 44, no. 4, pp. 24–27, 2017.
 - [22] X. Li, Y. Lu, and Y. Weng, “Research on damage model of single jointed rock masses under coupling action of freeze-thaw and loading,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 32, no. 11, pp. 2307–2315, 2013.
 - [23] X. Yuan, H. Liu, and J. Liu, “A damaging model of jointed rock under coupled action of freezing and thawing,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 34, no. 8, pp. 1602–1611, 2015.