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Microscopic damage and dynamic mechanical properties of rock under freeze−thaw environment

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Abstract: For understanding the rock microscopic damage and dynamic mechanical properties subjected to recurrent freeze−thaw cycles, experiments for five groups of homogeneous sandstone under different freeze−thaw cycles were conducted. After freeze−thaw, nuclear magnetic resonance (NMR) tests and impact loading tests were carried out, from which microscopic damage characteristics of sandstone and dynamic mechanical parameters were obtained. The results indicate that the porosity increases with the increase of cycle number, the rate of porosity growth descends at the beginning of freeze−thaw, yet accelerates after a certain number of cycles. The proportion of pores with different sizes changes dynamically and the multi-scale distribution of pores tends to develop on pore structure with the continuing impact of freeze−thaw and thawing. Dynamic compressive stress−strain curve of sandstone undergoing freeze−thaw can be divided into four phases, and the phase of compaction is inconspicuous compared with the static curve. Elastic modulus and dynamic peak intensity of sandstone gradually decrease with freeze−thaw cycles, while peak strain increases. The higher the porosity is, the more serious the degradation of dynamic intensity is. The porosity is of a polynomial relationship with the dynamic peak intensity.

Key words: rock; freeze−thaw cycle; nuclear magnetic resonance (NMR); pore structure; dynamic mechanical property; dynamic compression; stress−strain curve

1 Introduction

Rock is a complex mechanical medium which contains joints, cracks, pores, gas, water and other fluids. When temperature is below freezing point, the volume of pore water inside rock expands by 9% with transforming from liquid to solid, which results in the change of pore structure; when temperature is above freezing point, the freezing water thaws and migrates between pores so that cohesion between rock particles reduces. Recurrent freeze–thaw cycles gradually cause the accumulation of damage inside rock and further weakening of mechanical properties. As the rocks in cold regions are in the mechanical environment of dynamic disturbance such as blasting, crushing, piling, earthquakes and landslides, the mechanic and engineering phenomena of rock are developing progressively under the joint action of freeze−thaw and external disturbances. Therefore, the study on the dynamic mechanical characteristics of the rock under freeze−thaw action provides important theoretical and practical value for directing construction and freezing disaster prevention in cold regions.

With deep study on rock mechanics, many researchers have investigated the effects of freeze−thaw on the properties of rocks from different aspects. JAVIER et al [1] investigated the evolutionary process of the physical properties of rocks under freeze−thaw weathering. DENG et al [2] analyzed physical mechanics properties of sandstones in various chemical solutions subjected to recurrent freeze−thaw cycles. CHEN et al [3] studied the effect of water saturation on uniaxial compressive strength, P wave velocity and porosity due to freeze−thaw action. LIU et al [4] carried out an investigation on the damage of jointed rock mass due to cyclic freeze−thaw. TAN et al [5] examined the

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mechanical property degradation of granite, covering the changes of strength, deformation characteristics, elastic modulus, cohesive strength and internal frictional angle, etc, through freeze−thaw tests and triaxial compression tests.

Many scholars have carried out research on dynamic behaviour of rocks. The split Hopkinson pressure bar (SHPB) system, developed by KOLSKY [6], was used to test dynamic strength characteristics of 10 different carbonate rocks by YAVUZ et al [7], and the relationship between dynamic compressive strength and physical and mechanical properties of rock was analyzed by multiple linear regression analysis method. Dynamic properties of sandstone subjected to cyclic loading were studied by BAGDE et al [8] and the influencing factors of dynamics were summed up. YIN et al [9] compared and analyzed the differences between static and dynamic mechanical properties at different high temperatures. HONG et al [10] determined the relationship among energy consumption density of rock and its strain rate, dynamic strength and fragment distribution. JIA et al [11] investigated the mechanical behavior of jointed rock mass under dynamic load by using a numerical code called RFPA-dynamics.

By summarizing the research achievements of predecessors, it can be found that researches, in terms of freeze−thaw rock mechanics characteristics, are mainly focused on static mechanical properties and physical characteristics of rock but in shortage of dynamic mechanical properties. In the aspect of rock dynamics, the temperature factors, including high temperature and room temperature, have been taken into account, while freeze−thaw factor is rarely considered. In this work, sandstones under different freeze−thaw cycles were tested on SHPB equipment to investigate deterioration of dynamic mechanical properties of the rock subjected to recurrent freeze−thaw cycles, and nuclear magnetic resonance (NMR) technique was used to detect microscopic damage of sandstone [12,13], and the influence of freeze−thaw action on dynamic damage characteristics of sandstone was analyzed from the microscopic perspective.

2 Specimen preparation

The specimens used in tests were sandstones of integrity and homogeneity and cored from the same sandstone block. The length-to-diameter ratio (L/D) was controlled to be about 1.0 and the diameter was (50±1) mm. Two ends of specimens were polished carefully, and the accuracy met the requirements of freeze−thaw test according to conventional mechanics performance of rock. 25 pieces of specimens were divided into five groups based on freeze−thaw cycles and the specimens are shown in Fig. 1.

Fig. 1 Sandstone specimens

3 Experimental

The main experimental equipments, shown in Fig. 2, included freeze−thaw cycle test machine, vacuum saturation device, NMR test system and SHPB equipment. All specimens were tested according to the experimental procedures described as follows.

1) Specimens were saturated by vacuum saturation device for 12 h and then placed in the freeze−thaw cycle test machine under the condition of freezing temperature of −30 °C and thawing temperature of 20 °C with reference to the weather condition of sampling sites. According to the standard operating procedure [14], each complete cycle of freeze−thaw lasted for 8 h, comprising 4 h for freezing and 4 h for thawing. For each group of rock, different cycles were applied.

2) Rock samples were removed out of freeze−thaw cycle test machine after the planned freeze−thaw cycles were finished, and then wiped up surface water on specimens and recorded the variations of appearance. Porosity and T_2 distribution were obtained by means of NMR technology.

3) Impact loading tests were carried out at gas pressure of 0.5 MPa after NMR tests were finished. Before that, gas pressure was selected according to the broken pieces, between 2−4 pieces, of standby sample in impulse tests.

4 Results and discussion

4.1 Variation of porosity

The pores inside rock have important influence on physical and mechanical properties of rock, which means that quantitative description of the variation of internal pore structure is the foundation and the key to study the characteristics of micro-damage due to freeze−thaw. The measured values of porosity are listed in Table 1.

It can be seen from Table 1 that the porosity of sandstones increases with the increase of freeze−thaw cycle and the average porosity increases by 55.153% after 140 cycles. The reasons are as follows. On one hand, the volume of pore water inside water-saturated rock expands when it freezes. While for limited pore space, the volume of pore is prompted to increase by frost heave force produced by frozen water. What's more, greater pressure will be posed when the pores are saturated again, which leads to the sustained growth of porosity. On the other hand, different deformation characteristics of the mineral compositions of sandstone, caused by temperature variation under freeze−thaw, exacerbate the effect of freeze−thaw to some extent.

The variation curve of average porosity of sandstone samples with freeze−thaw cycles is given in Fig. 3. Porosity increases by 11.445% at the end of the 20th freeze−thaw cycle, accounting for 19.841% of the overall growth. This indicates that the cohesiveness between crystal particles is far less than the frost heave force at the beginning of freeze−thaw, which causes a large increase in porosity. After that the rate of porosity growth descends during 20−100 freeze−thaw cycles. The reasons are as follows: on one hand, sandstone materials are compacted because of the accumulation of the incremental pore volume with freeze−thaw cycles, accordingly, the cohesive action is strengthened gradually so as to partially offset the effect of frost heave force and make the expansion of pore restricted; on the

Fig. 2 Main experimental equipments: (a) freeze−thaw cycle test machine; (b) Vacuum saturation device; (c) NMR test system; (d) SHPB equipment

Table 1 Porosities of sandstones after different freeze−thaw cycles

Sample No.	Saturated rock porosity after different freeze−thaw cycles /%								Percentage increase in porosity/%
	0 cycle	20 cycles	40 cycles	60 cycles	80 cycles	100 cycles	120 cycles	140 cycles	
B21	8.033	8.825	9.460	9.998	10.330	10.389	11.130	11.732	46.048
B22	7.407	8.560	9.012	9.564	9.699	10.121	10.401	11.484	55.042
B23	7.207	8.018	8.759	9.362	9.632	10.060	10.278	11.400	58.180
B24	7.312	8.268	8.786	9.242	9.267	9.243	10.139	11.465	56.797
B25	7.866	8.483	9.385	9.717	9.874	9.906	10.644	12.562	59.700
Average value	7.565	8.431	9.080	9.577	9.760	9.944	10.518	11.729	55.153

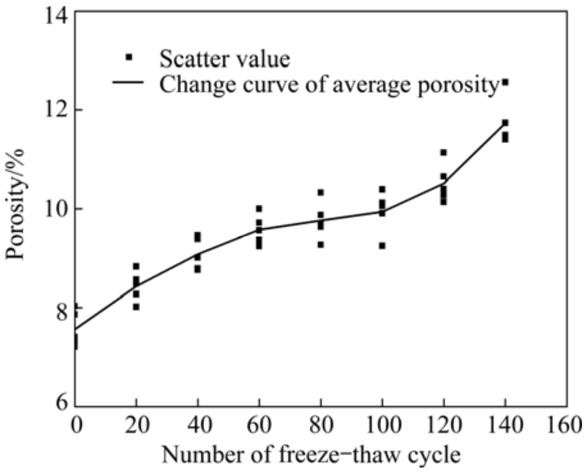

Fig. 3 Change curve of average porosity of sandstone samples after different freeze−thaw cycles

other hand, the development of pores and cracks are restricted by squeezing action of adjacent pores due to the static pressure of water.

The rate of porosity growth is accelerated after 100 freeze−thaw cycles. The reasons are as follows: on one hand, cohesiveness presents fatigue subjected to recurrent frost heave action and cohesion is further weakened with migration of pore water; on the other hand, frost heave force increases remarkably when pores saturate again, which results from the volume of pores expanding continuously under frost heave action and micro cracks are generated. Consequently, the effect of frost heave force is considerably greater than the cohesive force between the particles, causing a sharp increase in porosity and significant expansion of micro cracks. This implies that there is a critical value of freeze−thaw cycle for rock damage. When the cycles reach the critical value, the pores and cracks, reflecting the damage of rock, will develop rapidly.

The NMR imaging was conducted on the saturated specimens to intuitively show the change of pore sizes and pore structures after different freeze−thaw cycles. As a result, two cross-sectional images along the axial direction of specimens were described, as shown in Fig. 4. The bright spots in Fig. 4 indicate pores with fluid, and the spot size is proportional to pore volume.

As expressed in Fig. 4, the number of bright spots and brightness gradually increase with the increase of cycle, which reveals that the pores inside sandstones continuously develop under freeze−thaw environment. After 100 freeze−thaw cycles, part of bright spots are concentrated and bright stripes are gradually formed. This states that the pores expand and penetrate continuously, and then the weak structural planes are formed in the sandstone. Besides, the border is obviously

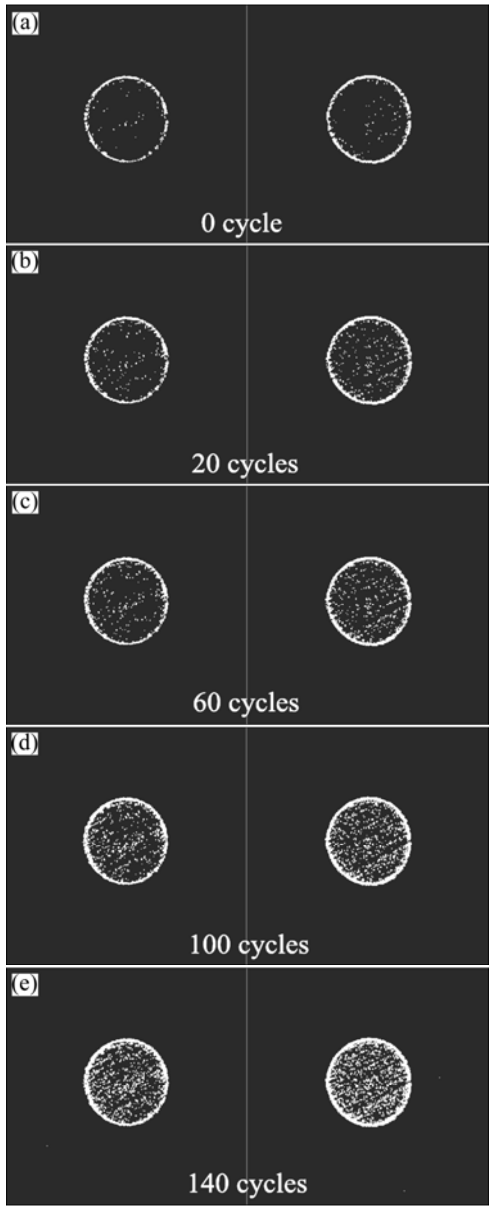

Fig. 4 NMR images of some typical samples under different freeze−thaw cycles

brighter than the center and a bright ring is formed. This is mainly because the inner moisture evaporates under the influence of room temperature and attaches to the thin film that wraps specimens in the imaging process. Thus, the NMR signals significantly increase around the border.

4.2 T_2 distribution under different freeze−thaw cycles

Pore size inside rock samples is proportional to transverse relaxation time (T_2) of pore fluid [15]. Therefore, T_2 distribution can reflect characteristics of pore structure of rock. In this work, the evolutionary process of rock microscopic damage was investigated by analyzing the variation of T_2 distribution after different freeze−thaw cycles, as shown in Fig. 5.

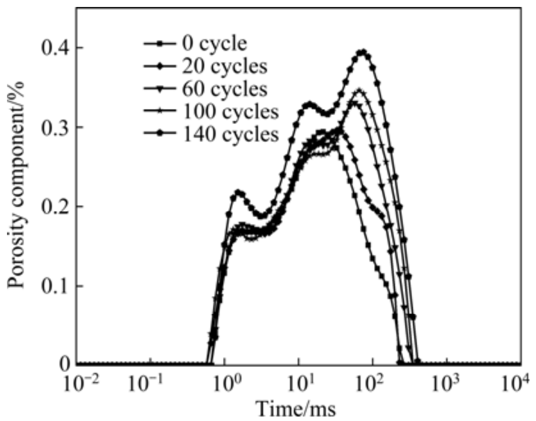

Fig. 5 Typical T_2 distribution under different freeze−thaw cycles

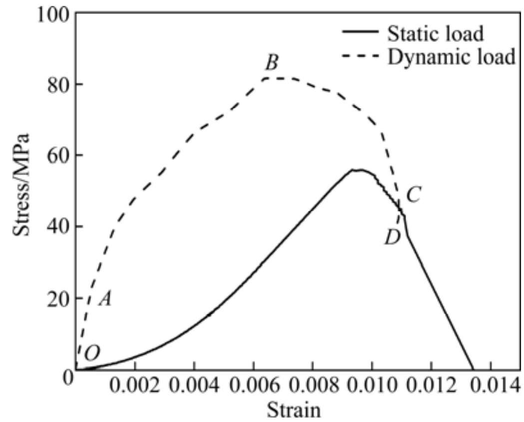

Fig. 6 Comparison of static and dynamic stress−strain curves

As can be seen from Fig. 5, two peaks are shown in T_2 distribution at 0−20 freeze−thaw cycles, while T_2 distribution continues to evolve with increasing freeze−thaw cycle and three peaks develop after 60 freeze−thaw cycles. This states that the pore proportion of each size changes dynamically with the continuing impact of freeze−thaw, and multi-scale distribution, namely the homogenization of the pore proportion of each size, tends to develop on pore structure. The overall shape of T_2 distribution shifts rightward and NMR signal of large pores is enhanced, showing the variation from small size to large size and gradual accumulation of internal damage. The starting time of T_2 distribution shifts leftward after 20 cycles, which means that micro-pore generates inside sandstone subjected to recurrent freeze−thaw cycles. The change of T_2 distribution is slight during 60−100 cycles, indicating that the rate of change of pore structure and damage due to freeze−thaw cycles is blocked by the cohesion in this process.

4.3 Comparison of stress−strain curves

In order to investigate the similarities and differences between dynamic and static stress−strain curves of sandstone under the same freeze−thaw cycles, the comparison results are given in Fig. 6. The displacement rate of 0.005 mm/s was selected to control the speed of axial loading in static load test, while speed control in dynamic load test was realized by using constant gas pressure of 0.5 MPa.

As shown in Fig. 6, the dynamic compression stress−strain curve of sandstone, subjected to freeze−thaw, can be divided into four phases. The first phase *OA*, different from concave of static stress−strain curve, approximately reveals a trend of straight line, which means that the compaction phase for dynamic curve is unobvious. This is due to late closure of pore or micro crack undergoing impact load. Phase *AB* deviates from straight line and compression modulus decreases gradually, the reason for which is that low intensity materials inside sandstone become broken and the cracks develop and expand continuously under the effect of impact load [16]. After reaching peak point *B*, transverse strain significantly increases and inner micro cracks penetrate and macro damage is generated, followed by phase *BC*. The strain rebounds at the end of dynamic stress−strain curve (phase *CD*). When few freeze−thaw cycles are conducted, specimens are not completely crushed and the fragmentations are comparatively large, leading to loading stress less than inner elastic force in loading stage. As a consequence, deformation rebounds in small range and the total strain decreases, which agrees with dynamic mechanical properties of sandstone at normal temperature [17].

Based on the impact loading test results, typical dynamic compression stress−strain curves of sandstones under different freeze−thaw cycles are contrasted in Fig. 7 for understanding the variation of mechanical properties of rock.

With reference to Fig. 7, we can see that the length of phase *OA* of stress−strain curve increases with the increase of freeze−thaw cycle, showing obvious elastic

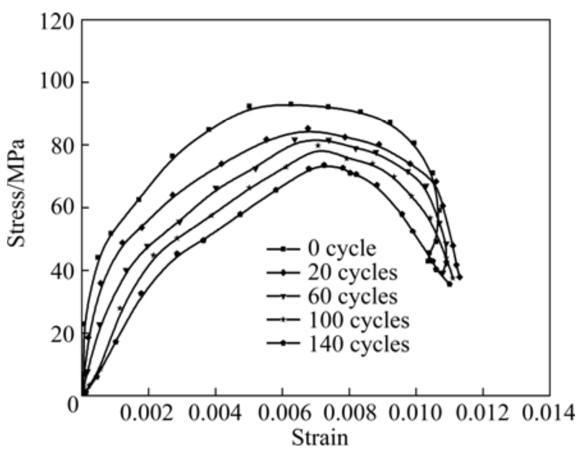

Fig. 7 Typical dynamic compression stress−strain curves of sandstones under different freeze−thaw cycles

characteristic. This states that the effect of freeze−thaw cycles on pore structure is a cumulative process of damage and part of plastic deformation cannot be recovered with cycles, which leads to more apparent elastic characteristic of rock. The decrease of straight slope implies the reduction in initial modulus, which results from gradual accumulation of inner damage under recurrent freeze−thaw cycles. The peak strain significantly increases in the process of 0−20 cycles, while the change is unobvious after 20 cycles, indicating that the 20th cycle is a critical value for great change of rock deformation characteristic. Combined the analysis of porosity and T_2 distribution, it can be inferred that a large number of new micro-porosities are generated after 20 freeze−thaw cycles, and the original pores expand rapidly due to frost heave force, causing a significant increase in peak strain of rock under impact loading. The phase *CD* of stress−strain curve disappears after 100 cycles. This is because the rocks crush into small pieces under impact load and nearly lose carrying capacity for intensified expansion of inner pores and cracks. Thus, the phenomenon of continuous increase of total strain occurs.

4.4 Relationship between dynamic peak intensity and freeze−thaw cycles

The change in the peak intensity as a function of the freeze−thaw cycles is presented in Fig. 8.

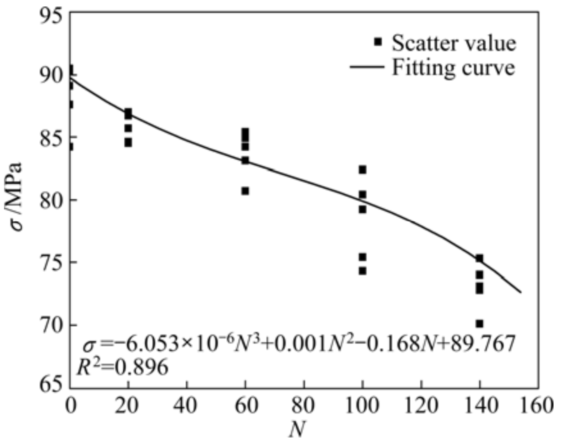

Fig. 8 Relationship between dynamic peak intensity (σ) and freeze−thaw cycle (N)

Figure 8 shows that dynamic intensity of specimens gradually decreases with increasing freeze−thaw cycle. It can be specifically represented from following data: the average peak intensity reduces from 88.34 to 85.70 MPa after 20 cycles, falling by 2.99%. While the average peak intensity descends from 85.70 to 83.66 MPa in the process of 20−60 cycles, only falling by 2.38%, because the cohesiveness between crystal particles is enhanced and frost heave force is partially offset, retarding inner damage and reducing influence of freeze−thaw cycle on dynamic intensity. The average peak intensity drops from 83.66 to 78.34 MPa in the process of 60−100 cycles, falling by 6.36%. This states that dynamic strength declines sharply in this stage, yet the increasing rate of porosity gradually slows down as analyzed before, all of which prove that macro dynamic intensity is not only influenced by porosity but also other factors. According to the analysis on T_2 distribution, it can be known that multi-scale distribution of pore structure develops, which is favorable for the penetration of crack under impact load. Consequently, the dynamic peak intensity declines by a large margin. The average peak intensity decreases from 78.34 MPa to 73.06 MPa in the process of 100−140 cycles, falling by 6.74%, more than the falling range in 60−100 cycles. This is because the proportion of large size pores increases rapidly after 100 cycles, and pores and cracks expand or penetrate quickly.

To study on relationship between pore structure characteristics and dynamic peak intensity, the porosity and its corresponding dynamic peak intensity are summarized in Fig. 9.

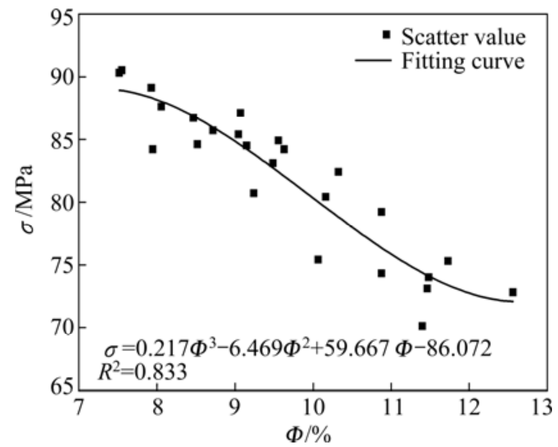

Fig. 9 Relationship between dynamic peak intensity (σ) and porosity (Φ)

According to Fig. 9, the results disperse widely for anisotropy of rock structure. However, it can be found that the dynamic peak intensity decreases with increasing porosity as a whole and the relationship between them is non-linear.

The peak intensity values range from 84 to 91 MPa when porosities are less than 9% yet range from 74 to 87 MPa when porosities are 9%−11%, showing change by a large margin. But the peak intensity values range from 70 to 76 MPa and change slightly as the porosities are more than 11%. These indicate that two critical values, which reveal the rate of damage undergoing freeze−thaw, can be found around the porosity of 9% and 11%, respectively. When porosity values of sandstones are in the scope of two critical values, the inner micro cracks expand rapidly and deterioration of macro dynamic mechanical properties accelerates. But if the porosities are less than 9% or more than 11%, the rates of crack expansion and deterioration are retarded.

The fitting correlation coefficient, R^2, between dynamic peak intensity and porosity value is 0.833, which indicates that fitting curve and formula can provide theoretical reference to some extent for engineering practice on one hand. On the other hand, it is proved that dynamic peak intensity of rock obtained from test is influenced by many factors, such as mineral composition, pore structure property, moisture content, strain rate and test environment. The unique porosity value cannot reveal actual damage of rock.

5 Conclusions

1) Porosity of sandstone increases with the increase of freeze−thaw cycle, and there is a critical value of freeze−thaw cycle for rock damage. The rate of porosity growth descends at the beginning, yet accelerates after reaching the critical value.

2) The volume of pores enlarges and the proportion of pores of each size changes dynamically with the continuing impact of freeze−thaw, and a trend of multi-scale distribution develops on pore structure ultimately.

3) Dynamic compressive stress−strain curve of sandstone undergoing freeze−thaw can be divided into four phases and the phase of compaction is inconspicuous compared with the static curve. Elastic modulus and dynamic peak intensity gradually reduce with the increase of freeze−thaw cycle, while the peak strain increases.

4) The higher the porosity is, the more serious the degradation of dynamic strength is. The porosity is of a polynomial relationship with the dynamic peak intensity. And the actual damage cannot be characterized by single porosity value.

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冻融作用下岩石的微观损伤及动态力学特性

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摘 要：为研究冻融循环作用下岩石的微观损伤及动态力学特性，对 5 组均质砂岩进行不同冻融循环次数的冻融试验，并对冻融后的砂岩进行核磁共振测试以及冲击荷载试验，获得冻融作用下砂岩的微观损伤特征及动态力学参数。结果表明：孔隙度随冻融循环次数的增加而增大，冻融初期的孔隙度增长率趋缓，在达到一定冻融循环次数后孔隙扩展加快；不同尺寸的孔隙比例随冻融循环次数呈动态变化，且孔隙结构总体趋向多尺寸分布发展；冻融砂岩的动态压缩应力−应变曲线可以分为 4 个阶段，相比静态曲线其压密阶段不明显；随着冻融次数的增加，砂岩的弹性模量和动态峰值强度逐渐减小，而峰值应变则有所增大；砂岩孔隙度越大，动态峰值强度越小，且拟合曲线呈多项式分布。

关键词：岩石；冻融循环；核磁共振；孔隙结构；动态力学特性；动态压缩；应力−应变曲线

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