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Association Rules between the Microstructure and Physical Mechanical Properties of Rock-mass under Coupled Effect of Freeze-thaw Cycles and Large Temperature Difference

(Peraturan Kaitan antara Mikrostruktur dan Sifat Mekanik Fizikal Jisim Batu di bawah Kesan Berganding Kitar Beku-Cair dan Perbezaan Suhu yang Besar)

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ABSTRACT

The mechanical properties of fractured rock mass are largely dependent on the fracture structure under the coupling of freeze-thaw cycles and large temperature difference. Based on the traditional macroscopic continuum theory, the thermal and mechanical model and the corresponding theories ignore the material internal structure characteristics, which add difficulty in describing the mesoscopic thermal and mechanical behavior of the fractured rock mass among different phases. In order to uncover the inherent relationship and laws among the internal crack development, structural change and the physical and mechanical properties of rock under strong cold and frost weathering in cold area, typical granite and sandstone in cold region were analyzed in laboratory tests. The SEM scanning technology was introduced to record the microstructural change of rock samples subject to freeze-thaw cycles and large temperature difference. Association rules between the microstructure and the physical mechanical properties of rock mass were analyzed. The results indicated that, with the increase of the cyclic number, the macroscopic physical and mechanical indexes and the microscopic fracture index of granite and sandstone continuously and gradually deteriorate. The width of original micro crack continues to expand and extend and new local micro cracks are generated and continue to expand. The fracture area and width of the rock increase and the strength of the rock is continuously damaged. In particular, the strength and elastic modulus of granite decrease by 20.2% and 33.36%, respectively; the strength and elastic modulus of sandstone decrease by 33.4% and 36.43%, respectively.

Keywords: Association rules; fractured rock mass; freeze-thaw cycle; large temperature difference; mechanical properties; microstructure

ABSTRAK

Sifat mekanik jisim batuan retak bergantung kepada struktur retak di bawah gandingan kitar-beku-cair dan perbezaan suhu yang besar. Berdasarkan teori tradisi kontinum makroskopi, model terma dan mekanik serta teori berkaitan mengabaikan ciri struktur bahan dalaman yang menambah kesukaran dalam menerangkan terma mesoskopi dan tingkah laku mekanik jisim batuan retak dalam fasa berbeza. Untuk menunjukkan wujud hubungan inheren serta hukum antara pembangunan retak dalaman, perubahan struktur serta sifat fizikal dan mekanik batuan dalam cuaca sejuk kuat dan fros di kawasan sejuk, granit dan batu pasir tipikal di rantau sejuk dianalisis dalam ujian makmal. Teknologi imbasan SEM digunakan untuk merakam perubahan mikrostruktur sampel batuan tertakluk kepada kitar-beku-cair dan perbezaan suhu yang besar. Peraturan kaitan antara sifat mikrostruktur dan fizikal mekanik jisim batu dianalisis. Keputusan menunjukkan dengan peningkatan bilangan kitaran, indeks fizikal dan mekanik makroskopi serta indeks granit mikroskopi retak dan batu pasir secara berterusan beransur-ansur merosot. Lebar retak mikro asal terus melebar dan meningkat dan keretakan mikro baru dihasilkan dan terus melebar. Kawasan retak dan kelebaran batuan meningkat dan kekuatan batuan berterusan rosak. Secara khususnya, modulus kekuatan dan elastik granit masing-masing menurun sebanyak 20.2% dan 33.36%; modulus kekuatan dan elastik batu pasir masing-masing menurun sebanyak 33.4% dan 36.43%,.

Kata kunci: Jisim batu retak; kitar-beku-cair; mikrostruktur; perbezaan suhu yang besar; sifat mekanik; peraturan kaitan

INTRODUCTION

In the field of underground rock mass engineering in cold regions, research has been focused on the physical and mechanical characteristics of fractured rock mass, the damage and deterioration mechanism and the expansion of the mesoscopic fracture structure characteristics under the coupled effect between freeze-thaw cycles and large temperature difference (Atiqah et al. 2017; Liu et al. 2012b; Ma & Wang 2012). Frozen cracked rock is a discontinuous geo-engineering material and its mechanical properties under the action of the external environment and loads are determined by the complex internal structures (Deng et al. 2013). Therefore, primarily depending on the characteristics of the fracture structure inside the rock, the mechanical properties of frozen cracked rock are quite different from those of homogeneous rock. Engineering practices show that (Kang et al. 2013; Neaupane et al. 1999), the mesoscopic thermal and mechanical behaviors of fractured rock mass of various groups are ignored by traditional macroscopic continuum theory which does not take into account the multiphase and discontinuity of frozen cracked rock. Therefore, the expansion characteristics of rock mass microstructure have become a key factor for the damage of fractured rock mass under the coupled effect of freeze-thaw cycles and large temperature difference. The damage rule based on the real meso-structure of frozen rock helps to uncover the causes of freeze-thaw damage of fractured rock mass. This provides new research ideas and methods to reveal the frost heave mechanism of fractured rock and mesoscopic frost heave mechanism of rock.

Yamabe and Neupane (2001) performed uniaxial and triaxial compression tests of sand stones under different temperatures. The results proved that uniaxial compressive strength of rock decreased with the increase of freezing and thawing cycles, while triaxial compressive strength increased with the increment of cell pressure. Freeze-thaw cycle test was conducted for different types of granite at the temperature range of -12-20°C by Del Roa et al. (2005). The ultrasonic wave velocity test of the granite after freezing and thawing showed that, the increase of the pore and micro cracks of the rock resulted in the change of ultrasonic velocity. Sondergld and Rai (2007) studied the change of the physical parameters of sandstone in a certain region subject to freeze-thaw cycle. Under the confining pressure of 6.9 MPa and temperature of -4~6°C, the coefficient of compressibility, the shear rate and the resistance coefficient changed noticeably. Yavuz tested andesite samples subject to various freeze-thaw cycles (Syazwanee et al. 2016; Yavuz 2011), analyzed the damage degradation mechanism of andesite, and summarized the variation laws of wave velocity, compressive strength, hardness and porosity of the rock. Fatih (2012) researched the strength loss of natural rock in cold regions and established the prediction equations of uniaxial compressive strength for a particular limestone subject to freezing and thawing cycle. The ultrasound wave velocity attenuation, strength loss and porosity variation of carbonate rock sample after 100 cycles of freezing and thawing were analyzed by Martínez-Martínez et al. (2013). Liu et al. (2012a) carried out freeze-thaw cycle test and ultrasonic measurement of granite and andesite. The two kinds of rocks showed micro cracks after many cycles and the influence of the freeze-thaw cycles on the rock weathering and the variation trend of the physical and mechanical parameters of the rock subject to these cycles. Tan et al. (2011) carried out the test of granite subject to 150 freeze-thaw cycles at the temperature of -40°C~40°C, and studied the axial strain, compressive strength and confining pressure as functions of cycle count. The mechanical properties of rock under low temperature and freeze-thaw environment were studied systematically (Chen et al. 2011). Akagawa and Fukuda (1991) proved by experiment that the frost heave cracks were critical to the strength characteristics of rock mass. Using the theory of interface mechanics and thermodynamics, the phase equilibrium equation of fractured rock mass media in closed system was established by Wettlaufer and Worster (2006). In rock fracture, the increased fissure water pressure due to the increase of ice facilitates the expansion of rock fracture and accelerates the frost cracking of fractured rock mass.

Strong freeze-thaw cycles with large temperature difference in cold regions leads to the attenuation of rock strength. The rock mass strength is also decreased by the propagation of original crack and the continuous generation of new fracture. Coupled by the frost wedging of crack water, the reiterative harmomegathus stress and strain of the rock mass produced by the large temperature difference between day and night destroyed the rock structure, reduced the rock compactness and the connections between particles, led to a decline in rock macroscopic strength and rigidity and eventually resulted in massive destruction of rock mass (Konrad & Morgenstern 1982; Lai et al. 2009; Shuib et al. 2017). Therefore, different representative types of rock samples were selected to study the coupled influence of freeze-thaw cycles and large temperature difference on the physical mechanical property of rock and the micro structure of rock mass is particularly important in the assessment of rock mechanics system. Based on the conventional rock mechanics test index, this paper presented freeze-thaw test and explored the mechanical characteristics of the rock mass under the coupled effect between freeze-thaw cycle and large temperature difference in cold regions. The present work lays a theoretical foundation for the research of disaster mechanism and dynamic evolution law of underground rock engineering in cold regions.

Materials and Methods

TEST PROCEDURE OF ROCK MASS MICROSTRUCTURE

Representative rock samples from an underground engineering site in Xinjiang were used for the experiment, in which granite was selected as hard rock sample and sandstone was selected as medium-hard rock sample. The physical and mechanical qualities of granite and sandstone are summarized in Table 1.

TABLE 1. The physical and mechanical qualities of the granite and sandstone

Rock samples	Natural moisture content/%	Saturated water absorption/%	Porosity/%
granite	0.23	0.33	0.87
sandstone	1.08	1.19	3.02

The granite and sandstone are made into 1250 × 100 mm cylinder samples, then divided into six groups (3 specimens in one group). As shown in Figure 1, the samples underwent 0, 10, 20, 30, 40 and 50 freeze-thaw cycles with large temperature difference to simulate the frost and weathering conditions of the rock at the spot. At the same time, superposition simulation, which considered the typical large temperature difference and the local historical data in the region, was done for the frost weathering circulation in the temperature range of -30~+50°C. SEM micro scanning was performed to study the decay law of the rock samples in cold regions under intense frost weathering effects. Moreover, the test uncovered the law of crack development, the internal structure characteristics and the physical mechanics parameter index for different types of rocks in strong frost weathering alpine regions. These laid the foundation for the future research of Cavern stability mechanism and evolvement rule.

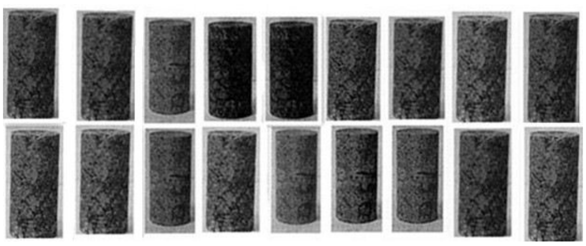

FIGURE 1. Rock samples in each group

The microscopic structures of each sample were analyzed after different numbers of cycles, using SEM with magnification of 60, 100, 300 and 1000×. From the analysis, we will know the mechanism of internal microstructure change and the characteristics of different typical rocks in the cold area under different frost weathering. Combined with the microscopic physical mechanical index rule, it is possible to establish the comprehensive macro-micro decay mechanism and the evolution characteristics of rocks subject to strong freeze-thaw cycles and large temperature difference.

TEST PROCESS OF ROCK MASS MICROSTRUCTURE

The process of laboratory experiment was explained as follows. First of all, the microstructure characteristics of rocks subject to freeze-thaw cycles with large temperature difference were studied by SEM scanning, by uncovering the microstructure development law and by analyzing the micro cracks area and width features. Secondly, the physical-mechanical properties of rocks subject to the mentioned conditions earlier were investigated in uniaxial compression test by using SANS/CMT5105 type material testing machine. Lastly, the relation between the physical/mechanical properties and the law of internal microstructure development was analyzed.

Firstly, the specimen was put into DW-25W198 freezing and thawing box at -30°C and taken out after 12 h. It was then kept in a YH-40B curing box at constant temperature of 50°C and constant humidity for 12 h. This marks a complete freeze-thaw cycle. Freezers and curing box was opened in advance to ensure that the temperature conformed to the test requirements when the specimen was put in. Upon reaching the predetermined number of freeze-thaw cycle, the specimen was placed at room temperature for 2 days and then scanned for SEM microstructure by SANS / CMT5105 material testing machine to select qualified samples for uniaxial compression test. Finally, the physical and mechanical properties of samples were measured.

ANALYSIS OF EXPERIMENTAL RESULTS

The microstructural changes of granite rock sample subject to 0, 10, 20, 30, 40 and 50 cycles are shown in Figure 2.

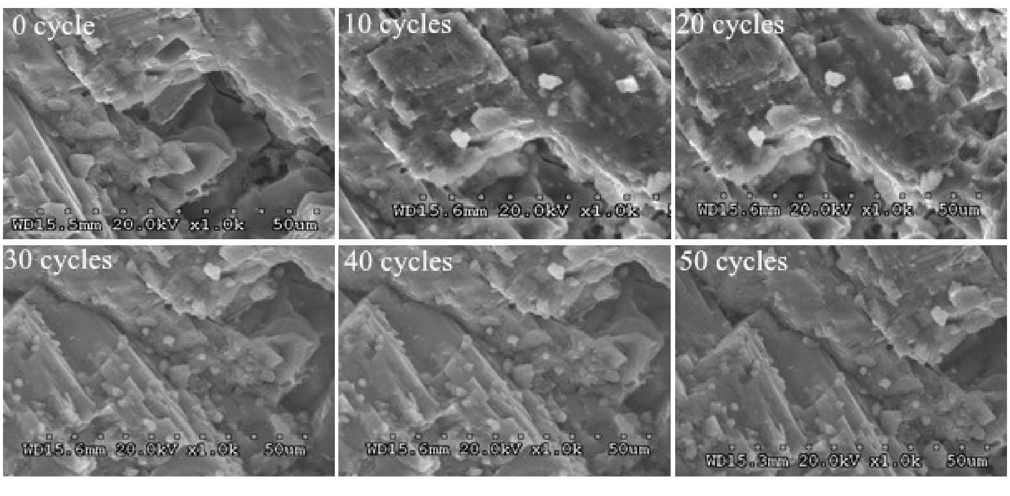

FIGURE 2. SEM scans of granite sample after certain number of freeze-thaw cycles with large temperature difference

As seen from Figure 2, after few number of cycles, the internal structure of granite changed tremendously, with growing crack width and particle gap. Due to the repeated impact of water frost heave and swell-shrink stress under large temperature difference, there were extrusion and relative displacement between the particles in the granite. The increase in the relative displacement and pore between the particles caused gradual permeating of water into the rocky body, leading to greater damage. After 20 cycles, the original micro crack width of granite interior extended significantly and new micro cracks appeared. From 20 to 30 cycles, the width of original micro crack continued to grow with the generation of new micro cracks. After 40 to 50 cycles, the width of original micro crack further developed and extended and new micro cracks were formed.

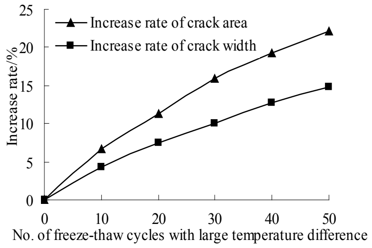

FIGURE 3. The change trend of micro crack area and crack width of granite subject to coupled effects of freeze-thaw cycles and large temperature difference

Figure 3 shows the change trend of granite micro crack area and crack width subject to coupled effects of freeze-thaw cycles and large temperature difference. It can be seen that the growth rates of internal micro cracks area and width increase with the increase of cycles and the growth rate of the fracture area is significantly higher than the growth rate of crack width.

The microstructural changes of sandstone rock subject to 0, 10, 20, 30, 40 and 50 cycles are shown in Figure 4.

Figure 4 shows the internal structure of sandstone changed substantially after different numbers of freeze-thaw cycles with large temperature difference, as reflected by the larger crack width and particle gap. Due to the repeated impact of water frost heave and swell-shrink stress under large temperature difference, there were extrusion and relative displacement between the particles in the sandstone. The increase of the relative displacement and pore between the particles caused gradual permeating of water into the rock body, leading to greater damage. After 20 cycles, the width of original micro crack of sandstone interior extended significantly and new micro cracks appeared. From 20 to 30 cycles, the width of original micro crack of sandstone interior had certain extension, with the formation of new micro cracks. After 40 to 50 cycles, the width of original micro crack continued to develop and extend, and new micro cracks continued to expand.

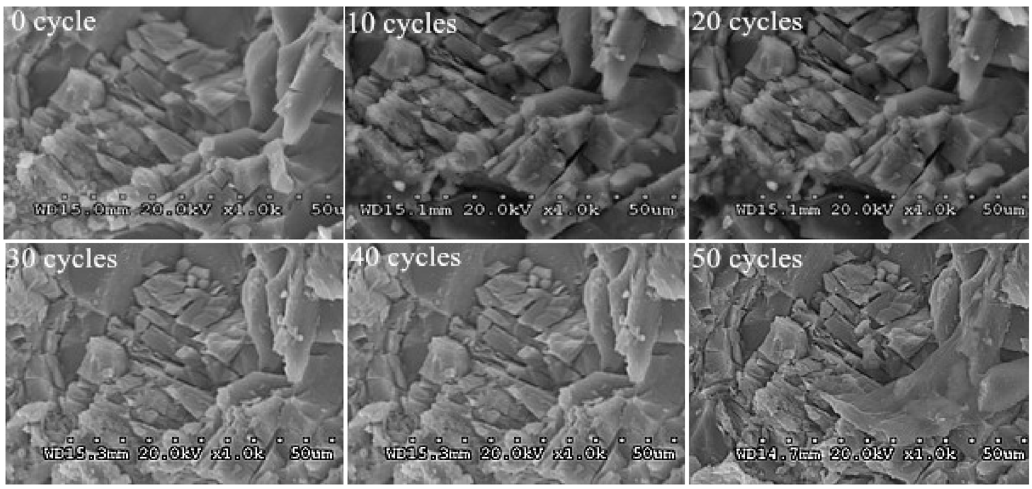

FIGURE 4. SEM scans of sandstone sample after certain number of freeze-thaw cycles with large temperature difference

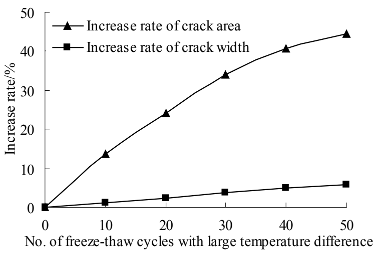

FIGURE 5. The change trend of micro crack area and crack width of sandstone subject to coupled effects of freeze-thaw cycles and large temperature difference

Figure 5 shows the change trend of micro crack area and crack width of sandstone subject to coupled effects of freeze-thaw cycles and large temperature difference. It can be seen that the growth rate of sandstone internal micro cracks area and the growth rate of crack width increase with the increase of cycles. The crack area grows rapidly in the first 30 cycles and then the change slows down. In addition, the growth rate of the fracture area is significantly higher than the growth rate of crack width.

Discussion

MACROSCOPIC PHYSICAL AND MECHANICAL PROPERTIES OF THE ROCK SAMPLES

The rock samples subject to 0, 10, 20, 30, 40 and 50 cycles were tested for macroscopic physical and mechanical properties, including mass loss rate, pore rate, elastic modulus, uniaxial compressive strength and Poisson's ratio of the rock mass in the freezing and thawing process. The attenuation law of the physical and mechanical indexes of rock samples was analyzed for the coupled effect of freeze-thaw cycles and large temperature difference. The internal relations and rules of underground engineering of granite and sandstone in cold area were uncovered. The internal relations and rules reflect the characteristics of the internal crack development, the change of the internal structure, the physical and mechanical parameters of the rock under the strong cold and frost weathering.

Under the influence of the freeze-thaw cycle, the mass loss rate of rock samples was measured by portable rock mechanics parameter test instrument. The modulus of elasticity, uniaxial compressive strength and Poisson's ratio were determined by SANS/CMT5105 type material testing machine together with corresponding calculation. Table 2 shows the variation of physical and mechanical parameters of granite after different freeze-thaw cycles with large temperature difference.

TABLE 2. The physical and mechanical properties of granite after various freeze-thaw cycles with large temperature difference

Number of freeze-thaw cycles with large temperature difference	Mass loss rate/%	Growth rate of crack area/%	Elastic modulus/Gpa	Uniaxial compressive strength/Mpa	Poisson's ratio
0	-	-	12.32	72.8	0.262
10	0.02	6.7	12.07	67.4	0.283
20	0.02	11.3	11.24	65.1	0.257
30	0.02	15.9	10.32	63.8	0.228
40	0.015	19.3	9.67	62.3	0.234
50	0.01	22.1	8.21	58.1	0.215

It can be concluded from Table 2 that the compressive strength and elastic modulus of granite without freeze-thaw cycles were 72.8 MPa and 12.32 Gpa, respectively. With the increase of cycle number, the strength and elastic modulus of granite decreased continuously. The compressive strength and elastic modulus were 58.1 MPa and 8.21 GPa, respectively, after 50 freeze-thaw cycles, which decreased by 20.2% and 33.36%, respectively. However, the variation of Poisson's ratio shows certain dispersion with the overall trend of decline. The results indicate a positive correlation between the loss of strength and modulus of granite subject to the coupled effects of freeze-thaw cycles and large temperature difference. It means more damage increases with freeze-thaw cycle. Table 3 presents the physical and mechanical property change of sandstones subject to various coupled effects of freeze-thaw cycles and large temperature difference.

TABLE 3. The physical and mechanical properties of sandstones subject to the coupled effects of freeze-thaw cycles and large temperature difference

Number of freeze-thaw cycles with large temperature difference	Mass loss rate/%	Growth rate of crack area/%	Elastic modulus/GPa	Uniaxial compressive strength/MPa	Poisson's ratio
0	-	-	9.14	51.8	0.263
10	0.01	13.6	8.26	46.3	0.271
20	0.015	24.1	7.82	42.7	0.257
30	0.02	34.1	7.05	38.1	0.237
40	0.02	40.8	6.29	36.2	0.231
50	0.01	44.6	5.81	34.5	0.213

As can be noted from Table 3, the compressive strength and elastic modulus of sandstone without freeze-thaw cycles were 51.8 MPa and 9.14 Gpa, respectively. With the increase of cycle number, the strength and elastic modulus of sandstone decreased continuously. The compressive strength and elastic modulus were 34.5 MPa and 5.81 GPa, respectively, after 50 freeze-thaw cycles, which decreased by 33.4% and 36.43%, respectively. However, the variation of Poisson's ratio shows certain dispersion with the overall trend of decline. The results indicate a positive correlation between the loss of strength and elastic modulus of sandstone subject to the coupled effects of freeze-thaw cycles and large temperature difference. It means that the increase of freeze-thaw cycles leads to more damage in the rock.

CORRELATION ANALYSES BETWEEN MACROSCOPIC MECHANICAL PROPERTIES AND MICROSTRUCTURE OF ROCK MASS

The microstructural changes of fractured rock mass have an important impact on the physical and mechanical properties. The freezing and thawing evolution and expansion of the fracture contain lots of microstructural characteristic information of the rock. Through in-depth analysis of the development and evolution law of rock microstructure under specific conditions, the failure and deformation mechanism of rock can be uncovered in essence.

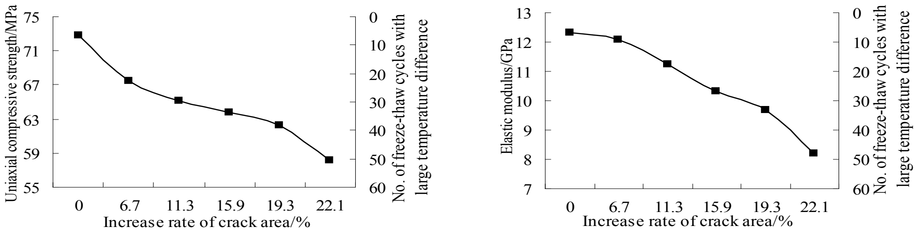

FIGURE 6. The strength and modulus of elasticity attenuation of the growth rate of granite micro fracture

CORRELATION ANALYSIS BETWEEN MICRO STRUCTURE AND MACRO PHYSICAL MECHANICS INDEXES OF GRANITE

With the increase of freeze-thaw cycles, the macroscopic physical mechanics index and the microscopic fracture index of granite deteriorate in similar overall trend, as shown in Figure 6. With the increase in cycles, the relationship between the strength attenuation and the expansion of internal micro cracks of granite is regular, while the strength and elastic modulus of rock mass gradually deteriorate. However, the major factor leading to the intensity damage of the rock mass is the crack area and the crack width, which increase continuously as the number of cycle grows. This causes the water to seep into the interior of the rock and leads to more damage.

CORRELATION ANALYSIS BETWEEN MICRO STRUCTURE AND MACRO PHYSICAL MECHANICS INDEXES OF SANDSTONE

With the increase of freeze-thaw cycles, the macroscopic physical mechanics index and the microscopic fracture index of sandstone deteriorate with similar overall trend, as shown in Figure 7. With the increase in cycles, the relationship between the strength attenuates and the expansion of internal micro cracks of sandstone is regular, while the strength and elastic modulus of rock mass gradually deteriorate. However, the major factors leading to the intensity damage of the rock mass are the change of porosity and water absorption. The intensity damage of the rock mass is not directly related to the expansion rate of internal micro cracks.

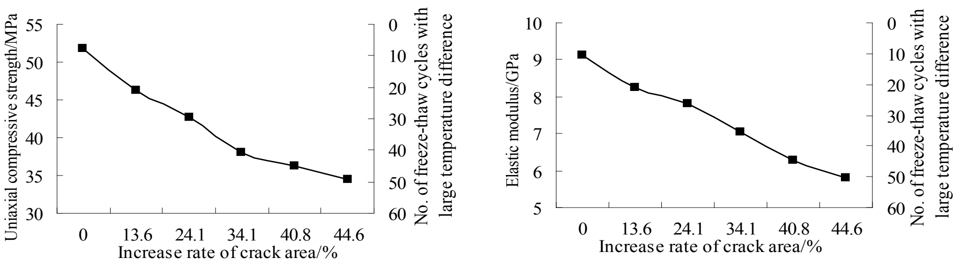

FIGURE 7. The strength and modulus of elasticity attenuation of the growth rate of sandstone micro fracture

CONCLUSION

With the increase of freeze-thaw cycles coupled by large temperature difference in alpine regions, the macroscopic physical mechanics index and the microscopic fracture index of sandstone and granite gradually deteriorate in similar overall trend. Under different cycles, through SEM microscopic scanning analysis of rock, it is found that the original micro crack width of granite and sandstone evidently extended under the repeated impact of freezing and thawing ice splitting force and large temperature difference, with the generation of new micro cracks. With the increase in the cycle number, the original micro crack width continues to expand and extend, and new micro cracks continue to expand as well.

During the freeze-thaw cycles coupled by large temperature difference, the increase of internal crack in rocks continuously leads to the increase of moisture content, and the frost wedging is more intense in the interior of fracture rock after freezing. In terms of the macro performance of the rock, the mass loss rate decreases, while the crack area and the width increase, leading to the strength damage of the rock mass.

During the freezing process, the water freezes in the rock and produces expansion force, which forms frost wedging in the rock and causes the increase of cracks. During the freezing and thawing process, the fracture rate of the rock increases and the water transfer occurs in the rock, which results in the increase in water content of the rock. Frost wedging is produced by water freeze in the rock crack, which leads to the strength damage of rock mass.

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