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Macro-micro behaviors and failure mechanism of frozen weakly cemented mudstone

Xianzhou Lyu^a, Jijie Du^a, Hao Fu^a, Dawei Lyu^{a,*}, Weiming Wang^b^a College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao, 266590, China^b College of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao, 266590, China

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ABSTRACT

Understanding the mechanical properties and multiscale failure mechanism of frozen soft rock is an important prerequisite for the construction safety of tunnels, artificially frozen ground and other infrastructure in cold regions. In this study, the triaxial compression test are performed on mudstone in the weakly cemented soft rock strata in the mining area of western China, and the mechanical characteristics and failure mechanism of weakly cemented mudstone are systematically investigated under the combined action of freezing and loading. Furthermore, the quantitative relationship between the microstructural parameters and the macroscopic strength and deformation parameters is established based on fractal theory. Thus, the failure mechanism of frozen weakly cemented mudstone is revealed on both micro- and macro-scales. The results show that temperature and confining pressure significantly affects the elastic modulus and peak strength of weakly cemented mudstone. With decreasing temperature, the compressive strength increases, while the corresponding peak strain decreases gradually. On the deformation curve, the plastic deformation stage is shortened, and the brittle fracture feature at the post-peak stage is more prominent, and the elastic modulus correspondingly increases with decreasing temperature. Under low-temperature conditions, most of the weakly cemented mudstone undergoes microscopic shear failure along the main fracture surface. The micro-fracture morphology characteristics of weakly cemented mudstone under different temperatures are quantified via the fractal dimension, and an approximately exponential relationship can be obtained among the fractal dimension and the temperature, compressive strength and elastic modulus.

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1. Introduction

As a typical soft rock, the weakly cemented soft rocks widely distribute in western China, with the characteristics of dense structure, low strength, poor cementation, easy softening, easily undergoes weathering and extremely unstable mechanical properties (Zhao et al., 2021, 2023; Wang et al., 2022a). With the development in western China and the Belt and Road strategy, engineering construction and mining inevitably have to pass through frozen weakly cemented soft rock strata (Li et al., 2021; Kang et al., 2021). However, due to the unique physical and mechanical properties of weakly cemented soft rock (Rahimi et al., 2018; Li et al., 2020; Zhao et al., 2022), the frozen rocks are generally in a particularly complex

stress state, and the deformation and failure mechanism are influenced by the interactions of multiphase media. Since the macro-failure of rocks is essentially caused by the expansion and penetration of micro- and meso-scale cracks (Zhou et al., 2020), the mechanical effects and deformation mechanism of frozen weakly cemented soft rock are studied from multiple perspectives. It is of great significance to understand the special mechanical properties of frozen soft rocks to guarantee the construction safety of engineering projects under frozen conditions.

In recent years, a series of experimental studies has been conducted on frozen soft rocks. The research showed that the elastic modulus, peak strength and residual strength of weakly cemented soft rocks improved to varying degrees after freezing, and the macro-failure mode was also different under freezing conditions. Freezing action made the brittleness of rock increase with decreasing temperature, and the plastic characteristics became obvious with increasing confining pressure. The crack initiation stress and damage stress of rocks also increased with decreasing

* Corresponding author.

E-mail address: lydawei95@sdust.edu.cn (D. Lyu).

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temperature (Liu et al., 2019a; Yang et al., 2019; Bai et al., 2020). To further explore the macroscopic failure process of frozen rocks, the acoustic emission (AE) tests have also been performed, and the AE response of frozen rock during loading can be divided into three stages, i.e. slow growth, rapid growth and basic stability. The lower the temperature is, the stronger the response of AE is, and the failure mechanism of frozen soft rocks can be from the aspects of AE response and energy evolution (Dong et al., 2022; Yang et al., 2022). According to the macroscopic failure mode of frozen rocks, the failure characteristics are mainly shear failure, but there are some differences at various temperatures.

The failure mechanism and mechanical properties of rocks are not only related to the stress state but also closely related to its micro-structure (Hou et al., 2022; Hu et al., 2022), and thus the micro-failure mechanism of frozen rocks has been investigated. For example, Ma et al. (2020) used nuclear magnetic resonance (NMR) and found that pores were filled with ice during the freezing process, and the sizes of the pores decreased rapidly and then decreased slowly (Dong et al., 2022). Via scanning electron microscope (SEM), Shen et al. (2018) reported that the concave and convex contacts between frozen soft rock particles were embedded with each other, and the micro-structure was quite different from that at room temperature. Due to the frost heaving and external forces, some pores were filled and compacted or even degraded. Some scholars have studied the meso-structure of frozen soft rock by computer tomography (CT). Water inside rocks expanded due to freezing, which induced particle stripping, crack generation and expansion inside rocks. The porosity increased slightly, mainly because the number of small pores increased (Liu et al., 2019b, 2020). Thus, the internal deterioration of frozen rock was mainly dominated by changes in pores. The transformation from the liquid phase to the solid phase caused the expansion and connection of primary pores with a disordered distribution, finally formed large pores. In fact, mainly secondary micro-pores formed, accompanied by dislocation, slip and fracture of the micro-structure (Jia et al., 2019a, b).

Qualitative analysis is the most commonly used method to explore the macro-micro failure mechanism of rocks. To reveal the failure essence of frozen soft rocks, it is of great significance to establish the quantitative relationships between micro-failure characteristics and macro-mechanical properties. Fractal theory is able to meet such requirements. Huang et al. (2019) studied the relationship between uniformity, mechanical properties and fractal dimensions of four types of rocks (i.e. mudstone, sandstone, limestone and basalt). Gao et al. (2020) established the relationship between the fractal dimension and mechanical parameters of typical sandstone based on images of the micro-structure and fractal theory combined with MATLAB, and they analyzed the correlation between the meso-structure strength and deformation characteristics of sandstone. Jiang et al. (2022) calculated the fractal dimension of granite and sandstone after high-temperature treatment, and the relationship between macro- and micro-damage mechanisms was established. Fractal theory has unique advantages in establishing quantitative relationships between micro-structure parameters and macroscopic strength, deformation and other characteristics of rocks (Liu et al., 2022a; Ye et al., 2022).

In this study, the triaxial compression tests are conducted on frozen weakly cemented mudstones, and the multiscale failure characteristics and mechanism are revealed combined with SEM. The evolution of strength parameters, deformation parameters and macroscopic failure characteristics of weakly cemented mudstones under different temperatures and confining pressures are analyzed. The quantitative relationships between the fractal dimension of the fracture micro-structure characteristics and the macroscopic rock strength and deformation parameters are established by fractal theory. The correlation mechanism between the micro-structure

damage and the macroscopic failure is revealed in detail. The findings of this study can provide theoretical guidance for the prevention and control of underground engineering disasters in the artificial or natural frozen weakly cemented soft rock strata in western China.

2. Experimental methodology

2.1. Samples

Mudstone samples used in this study were collected from the weakly cemented soft rock strata in a mining area in western China, and they were made into standard samples with 50 mm in diameter and 100 mm in height. The weakly cemented mudstone contained a large amount of clay minerals (He et al., 2016; Niu et al., 2021). The mineral composition of the weakly cemented mudstone was obtained by X-ray diffraction, as shown in Table 1. It can be observed that the weakly cemented mudstones were mainly composed of clay minerals such as quartz, kaolinite and illite. Since there are no high expansion minerals, the expansion performance of tested rocks was rather limited.

2.2. Test procedure

The compression experiments were performed at different temperatures according to the following procedure:

- (1) Before the test, the mudstone samples were frozen for 48 h in a DWX low-temperature freezing test box, and the test temperature was selected as 10 °C (control group), −5 °C, −10 °C, −20 °C and −30 °C, respectively.
- (2) The compression test of frozen mudstone is conducted by a TAW-2000 constant temperature triaxial test system, as shown in Fig. 1. The maximum axial pressure of the test system is 2000 kN, the maximum confining pressure is 100 MPa, and the test temperature control ranges from −40 °C to 200 °C. In our tests, the confining pressure of the compression test is set as 0 MPa (uniaxial), 3 MPa, 6 MPa and 10 MPa, and a constant rate of 0.05 MPa/s is selected. Finally, the axial loading is applied using displacement control with a loading rate of 0.02 mm/min, until the sample is destroyed. During the test, the stress–strain data under different confining pressures are recorded, and the constant temperature circulation system is open during the whole test.

3. Experimental results

3.1. Macro-mechanical characteristics of frozen weakly cemented mudstone at different temperatures

3.1.1. Characteristics of stress–strain curve

According to the results of the low-temperature triaxial compression test, the deviatoric stress–strain curves of the weakly

Table 1
Mineral composition of weakly cemented mudstones.

Mineral	Percentage (%)
Kaolinite	33.67
Quartz	27.33
Tillite	11
Mixed-layer illite	10.67
Feldspar	9.33
Chlorite	4.67
Miscellaneous	3.33

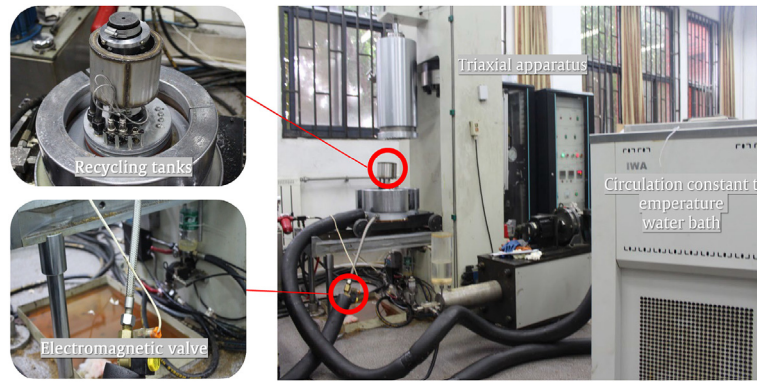


Fig. 1. TAW-2000 low temperature triaxial test system.

cemented mudstone samples at different temperatures are shown in Fig. 2. σ_1 is the axial stress, σ_2 is the lateral stress, i.e. the confining pressure, and ϵ_1 is the axial strain. It can be observed that the stress–strain curve of unfrozen mudstone (10 °C) be divided into four stages, i.e. the compaction stage, elastic stage, plastic stage and softening stage when the confining pressure $\sigma_3 \leq 3$ MPa. In other cases, due to the low-temperature freezing, high confining pressure or the combined action, the pores and cracks of the sample are filled or closed, and thus there is no compaction stage in stress–strain curves. Under the same confining pressure, the pores and cracks of the sample are filled with ice as the temperature decreased, which enhanced cementation between the particles. Therefore, the peak strength and residual strength increased, but the corresponding strain decreased. In particular, when $\sigma_3 = 0$ MPa, the plastic stage and strain softening stage of the curve becomes shorter with decreasing temperature, and the brittleness is enhanced. The strength of tested sample is featured by a brittle drop after the peak. It was thus clear that the low temperature has a great influence on the residual strength. However, this effect tended to decrease with increasing confining pressure, for instance, the temperature had little effect on the residual strength when $\sigma_3 = 10$ MPa. This indicates that the confining pressure is the primary controlling factor for residual strength. When the confining pressure increases to a certain degree, the residual bearing capacity of frozen weakly cemented mudstone will no longer be affected by temperature.

However, under the same temperature, the elastic stage of the curve is longer to different degrees with increasing confining pressure, while both the plastic stage and the softening stage are shorter. The peak strength and the corresponding strain increase with increasing confining pressure, and the strain softening after the peak is significant. In addition, the residual strength of frozen mudstone increases with increasing confining pressure. Thus, the brittleness of the frozen rock decreases and the ductility increases, indicating that the residual bearing capacity could be enhanced due to the restriction from confining pressure. For example, the peak strength of frozen mudstone at temperatures of –10 °C is 11.9 MPa and 35.7 MPa when $\sigma_3 = 0$ MPa and $\sigma_3 = 10$ MPa, respectively, increasing by approximately 200%. The peak strength of frozen mudstone under $\sigma_3 = 6$ MPa is 22.6 MPa and 33.4 MPa at temperature of 10 °C and –30 °C, respectively, increasing by approximately 47.79%.

3.1.2. Relationship of peak strength with temperature and confining pressure

According to the test results, the relationship between temperature and peak strength of weakly cemented mudstone under

different confining pressures can be obtained in Fig. 3, in which an exponential fitting function can be observed. The following fitting relationship could be described as

$$\sigma_p = G + H \exp(-T / I) \quad (1)$$

where σ_p is the peak strength (unit: MPa); T is the test temperature (unit: °C); and G , H and I are the undetermined parameters related to the test.

With decreasing temperature, the peak strength increased, that is, the lower the temperature is, the greater the increase in the peak strength. Taking $\sigma_3 = 6$ MPa as an example, the increase in the peak strength is 3.0 MPa when the temperature decreases from –10 °C to –20 °C, while it is 3.7 MPa when the temperature decreases from –20 °C to –30 °C. In the same temperature interval, the higher the confining pressure is, the greater the increase in the peak strength. From –20 °C to –30 °C, the increase in the peak strength is 3.6 MPa, 3.7 MPa and 4.2 MPa as σ_3 increases from 3 MPa to 6 MPa–10 MPa, respectively. The combined effect of confining pressure and low-temperature freezing obviously improved the strength of frozen mudstone.

The relationship between the confining pressure and peak strength of weakly cemented mudstone at different temperatures is shown in Fig. 4, from which the following linear fitting relationship can be obtained:

$$\sigma_p = J \sigma_3 + K \quad (2)$$

where σ_3 is the confining pressure (unit: MPa), and J and K are the undetermined parameters related to test.

It can be observed that the peak strength increased with increasing confining pressure. In the same confining pressure interval, the lower the temperature is, the greater the increase in the peak strength. Taking $\sigma_3 = 6$ MPa and $\sigma_3 = 10$ MPa as examples, the increase in peak strength is 8.2 MPa, 8.8 MPa, 9 MPa, 10.2 MPa and 10.7 MPa at temperatures of 10 °C, –5 °C, –10 °C, –20 °C, –30 °C, respectively.

To further obtain the relationship between the peak strength of weakly cemented mudstone and temperature and confining pressure, the relationship between J , K and temperature is extracted in Fig. 4, and the fitted curves is obtained, as shown in Fig. 5.

Substituting the relation between J , K and temperature in Fig. 5 into Eq. (2), the relation between peak strength of weakly cemented mudstone and temperature and confining pressure can be obtained as

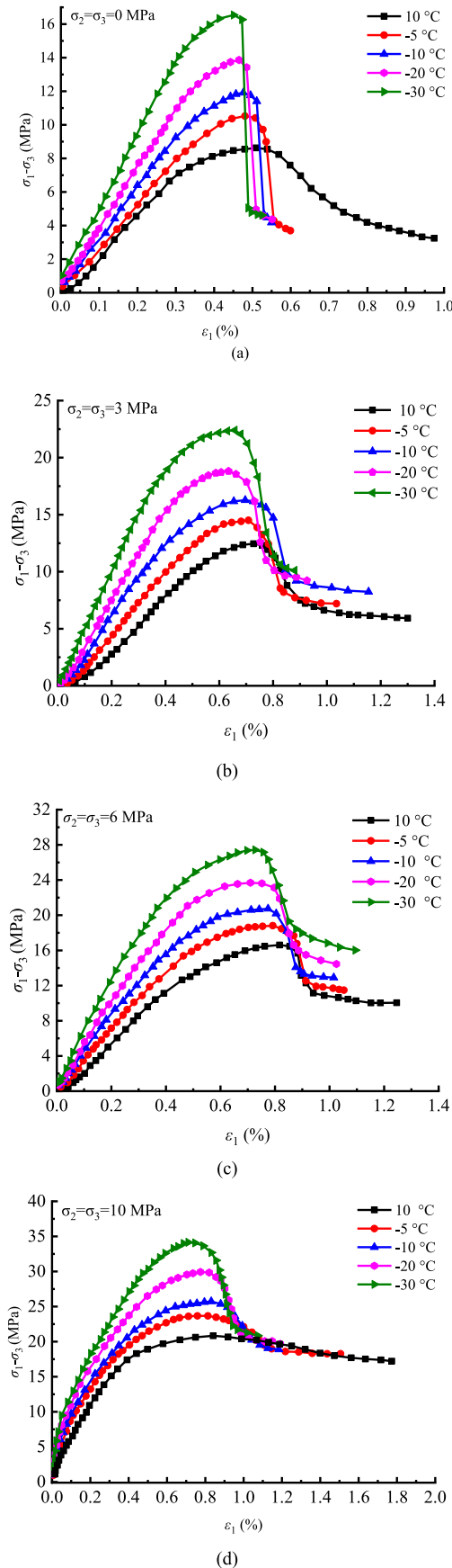


Fig. 2. Deviatoric stress–strain curve of weakly cemented mudstones at different temperatures and confining pressures: (a) $\sigma_3 = 0$ MPa; (b) $\sigma_3 = 3$ MPa; (c) $\sigma_3 = 6$ MPa; and (d) $\sigma_3 = 10$ MPa.

$$\sigma_p = [1.97 + 0.32\exp(-T/33.68)]\sigma_3 + 4.56 + 5.54\exp(-T/37.5) \quad (3)$$

The distribution characteristics of the peak strength of weakly cemented mudstone with different temperatures and confining pressures are shown in Fig. 6. The confining pressure and temperature have significant effects on the peak strength. The lower the confining pressure is, the less the peak strength is affected by temperature. As the confining pressure increases, the effect of temperature on peak strength is more evident, but the significance is relatively limited.

3.1.3. Relationship between the elastic modulus and temperature of surrounding rock

Considering the influence of temperature on the deformation characteristics of weakly cemented mudstone under different confining pressures, of the relationship between temperature and elastic modulus can be obtained in Fig. 7. The fitted relationship between the elastic modulus and temperature can be expressed as

$$E_T = A - BT \quad (4)$$

where E_T is the elastic modulus (unit: GPa), A and B are the test-related parameters.

Fig. 7 shows that under the same confining pressure, the elastic modulus of weakly cemented mudstone is negatively correlated with temperature, that is, the elastic modulus increases with decreasing temperature. Thus, the elastic modulus is significantly affected by the temperature and confining pressure. When the confining pressure increases from 6 MPa to 10 MPa, the elastic modulus increases greatly. Therefore, the greater the confining pressure is, the greater the effect of temperature on the elastic modulus. Taking the temperature of -10 °C as an example, the elastic modulus was 8.163 MPa and 25.446 MPa when $\sigma_3 = 6$ MPa and $\sigma_3 = 10$ MPa, respectively, showing a relative increase of 211.72%.

Considering the influence of confining pressure on the elastic modulus of weakly cemented mudstone at different temperatures, the fitting relationship between the elastic modulus of weakly cemented mudstone and confining pressure at different temperatures is obtained, as shown in Fig. 8, which can be described as

$$E_T = C \exp(\sigma_3 / D) + F \quad (5)$$

where C , D and F are the parameters related to the test.

It can be observed from Fig. 8, the elastic modulus increased with increasing confining pressure. Under low confining pressure (i.e. $\sigma_3 \leq 3$ MPa), the elastic modulus of frozen weakly cemented mudstone increased relatively slowly. However, the elastic modulus increases relatively quickly under high confining pressure (i.e. $\sigma_3 > 3$ MPa), which indicates that high confining pressure conditions has a significant effect on the elastic modulus of frozen weakly cemented mudstone.

To further explore the effect of temperature and confining pressure on the elastic modulus of weakly cemented mudstone, the relationship between A and B and confining pressure are fitted in Fig. 9. Substituting the fitting relation into Eq. (3), the elastic modulus of weakly cemented mudstone with varying temperature and confining pressure can be obtained, as expressed in Eq. (6).

$$E_T = 0.5 \exp(\sigma_3 / 2.7) + 2.07 - (0.05\sigma_3 + 0.05)T \quad (6)$$

Fig. 10 depicts the variation characteristics of the elastic modulus of weakly cemented mudstone under the combined influence of confining pressure and temperature. The lower the

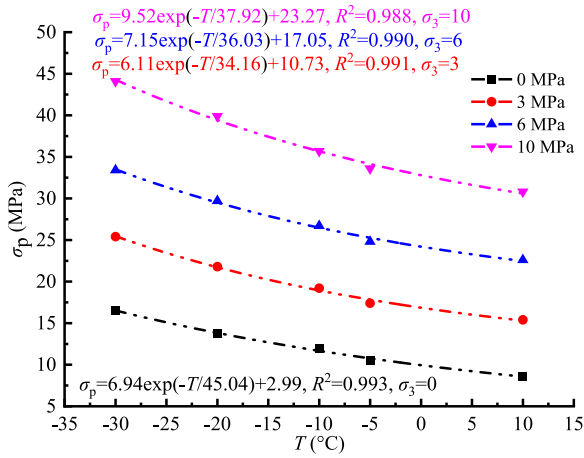


Fig. 3. Relationship between peak strength and temperature of weakly cemented mudstone under different confining pressures.

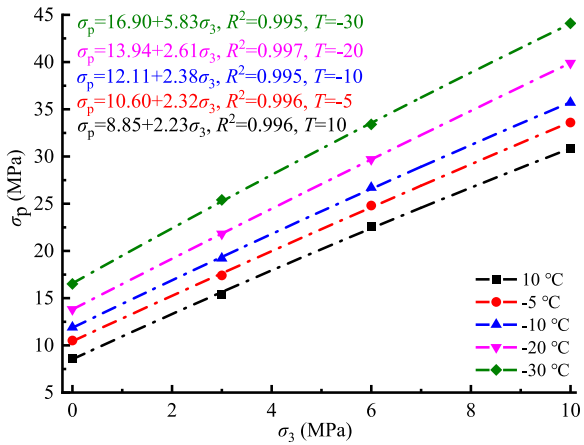


Fig. 4. Relationship between peak strength and confining pressure of weakly cemented mudstone.

confining pressure is, the less the influence of temperature variation on the elastic modulus. With increasing confining pressure, the influence of temperature variation on the elastic modulus is increasingly significant. The elastic modulus of tested rocks under high confining pressure is quite sensitive to temperature variation, indicating that confining pressure is the primary controlling factor of the deformation characteristics of frozen weakly cemented mudstone.

3.2. Characteristics of macro-failure

Taking the macro-failure mode of weakly cemented mudstone samples at -10 $^{\circ}\text{C}$ and 10 $^{\circ}\text{C}$ as examples, the difference between the macro-fracture morphology and fracture mechanism of weakly cemented mudstone under normal temperature and freezing conditions is shown in Fig. 11. Under the condition of 10 $^{\circ}\text{C}$ (see Fig. 11a), when $\sigma_3 = 0$ MPa, the sample is broken in splitting failure mode, and the direction of the main fracture surface is basically the same as the axial loading direction. With the increase of confining pressure, the failure of the sample is mainly shear mode. For instance, the main shear surface penetrates for sample under confining pressure of 3 MPa, and the angle between the main fracture surface and the maximum principal stress is greater for

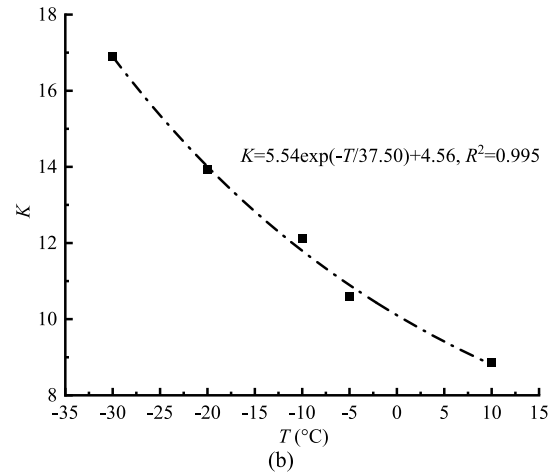
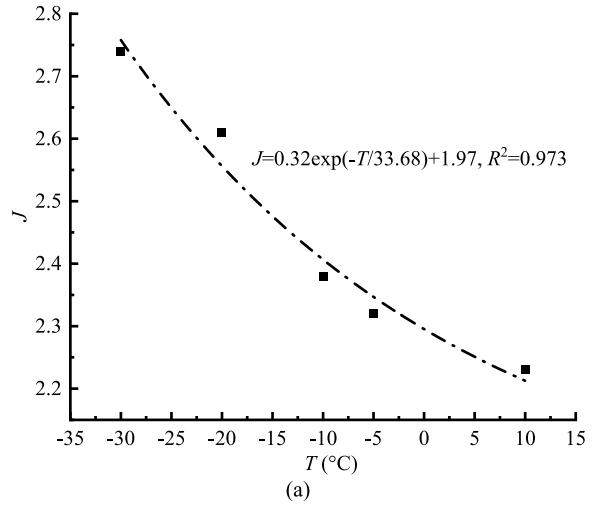


Fig. 5. Relationship between J , K and temperatures.

sample under confining pressure of 6 MPa. When confining pressure is 10 MPa, there are no penetrating cracks on the surface of the sample, and only have a small number of peeling fragments, which indicates that the plastic characteristics is more evident for rocks under higher confining pressure, and that its failure mode changes from shear failure to plastic softening. Under the condition of -10 $^{\circ}\text{C}$ (see Fig. 11b), the failure modes of frozen mudstone are all pure shear failure and unpenetrated cracks appear on the sample surface, while there are a few unpenetrated cracks when $\sigma_3 = 0$ MPa. This is mainly because the decrease of temperature improves the strength and stiffness of the rock. With the increase of confining pressure, the angle between the main fracture surface and the maximum principal stress increases and no longer penetrates the ends of samples. The number of unpenetrated cracks increases, and its direction is consistent with the direction of main fracture surface. On the other hand, the increase of confining pressure enhances the plastic characteristics of the frozen rock. Comparing Fig. 11a and b, it can be seen that under the same confining pressure, the angle between the main fracture surface and the maximum principal stress direction increases with increasing temperature, and more rock powder and classic particles appear on the fracture surface. It is obvious that the brittle failure characteristics of frozen rock are more obvious under lower temperature.

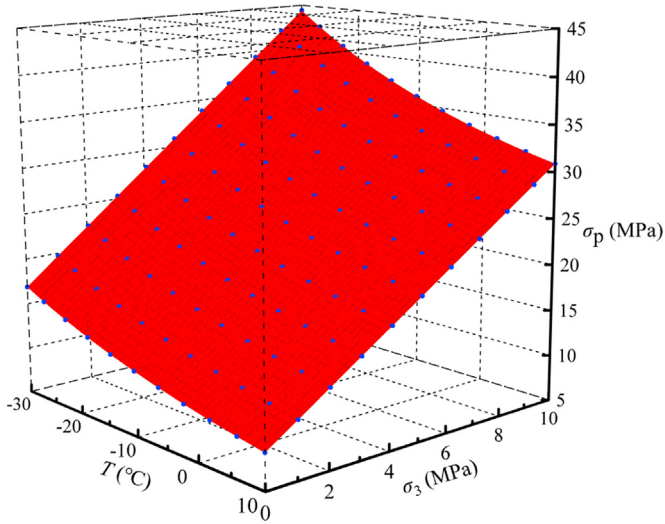


Fig. 6. Peak strength of weakly cemented mudstone at different confining pressures and temperatures.

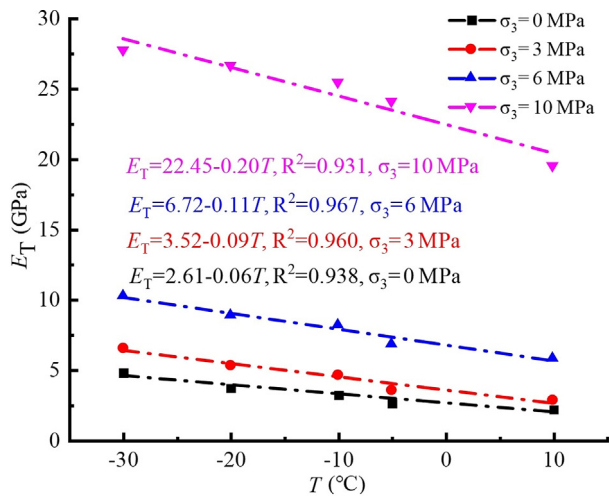


Fig. 7. Elastic modulus of frozen weakly cemented mudstone at different temperatures.

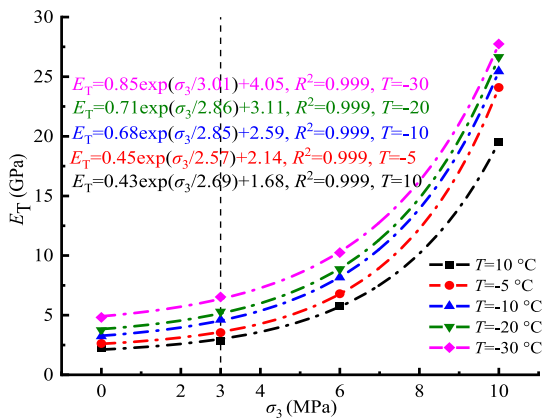


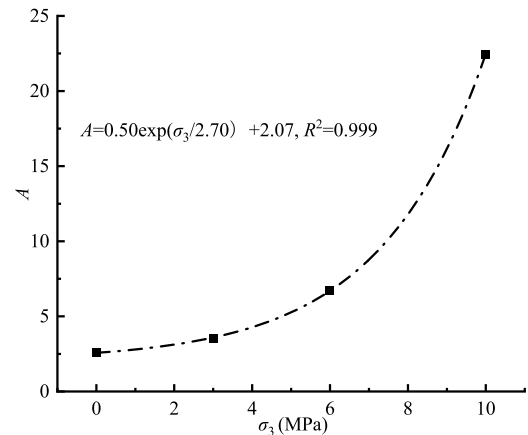
Fig. 8. Elastic modulus of frozen weakly cemented mudstone at different confining pressures.

4. Micro-fracture characteristics and fractal characteristics of frozen weakly cemented mudstone

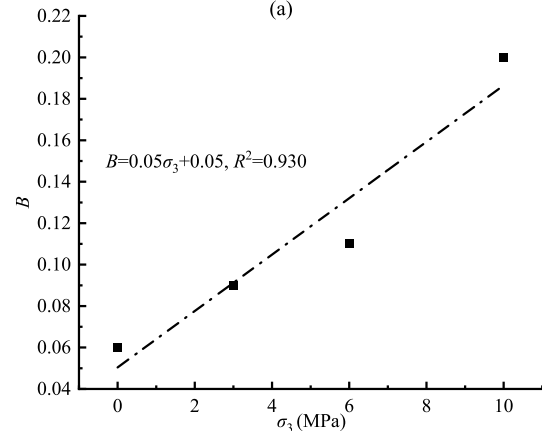
4.1. Micro-fracture mode

On the micro-scale, the crack propagation of weakly cemented soft rock was not entirely along a certain shear plane since the local stress concentration of the micro-scale mineral particle points is generally determined by the particle size, particle morphology, contact mode between particles and degree of cementation and thus micro-cracks tend to pass through mineral particles. Weakly cemented soft rock contains many clay minerals and cements, and thus its fracture shape is relatively complex (Wu et al., 2020; Niu et al., 2021). At low temperature, frozen rocks usually present brittle fracture characteristics, which may produce different fracture morphologies, such as cleavage fracture (i.e. transgranular fracture), quasi-cleavage fracture (i.e. brittle transgranular fracture) and intergranular fracture. Therefore, to analyze the micro-failure mode of weakly cemented mudstone, a FEI Quanta 450 field emission scanning electron microscope (FE-SEM) is used in this study to observe the micro-structure of typical fracture surfaces, as shown in Fig. 12.

Fig. 12a clearly depicts the mineral particles in the micro-fracture at a magnification of 500 times under $\sigma_3 = 0 \text{ MPa}$ and $T = 10^\circ \text{C}$, in which the fracture surface is rough, and abundant primary porosity is produced with many dimples. Nonuniform particles and intergranular cracks are clearly visible at a high magnification of 10,000 times. Under $\sigma_3 = 6 \text{ MPa}$ and $T = 10^\circ \text{C}$ (see



(a)



(b)

Fig. 9. Relationship between (a) A, (b) B and confining pressures.

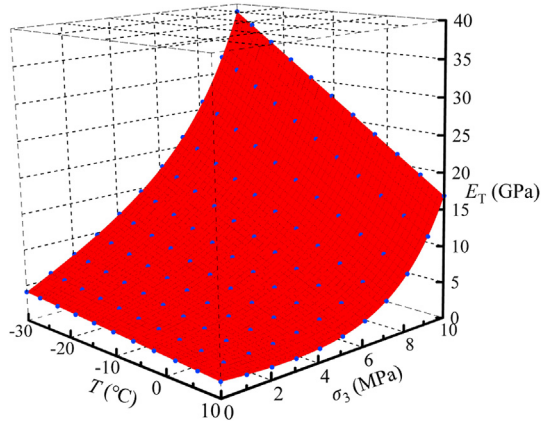


Fig. 10. Elastic modulus of frozen weakly cemented mudstone at different confining pressures and temperatures.

Fig. 12b), there are also some dimples on the fracture surface magnified at 500 times, but the surface is smooth compared to Fig. 12a. Nonuniform particles and river patterns can also be observed in the image magnified 10,000 times. Under $\sigma_3 = 0$ MPa and $T = -5$ °C (see Fig. 12c), the arrangement of particles and dimples can be observed on the image surface at 500 times magnification. Due to the effect of low temperature, the surface is rougher than that in Fig. 12a, with increasing dimple volume. At 10,000 times magnification, the intergranular fractures, step patterns and expanded cracks are also observed. Under $\sigma_3 = 6$ MPa and $T = -5$ °C (see Fig. 12d), the dimple volume on the fracture surface decreases, and the surface becomes relatively smooth due to the effect of low temperature compared to Fig. 12a. However, in the image magnified 10,000 times, its micro-structure is flocculent, and the intergranular expansion of cracks is obviously visible. Under $\sigma_3 = 0$ MPa and $T = -10$ °C (see Fig. 12e), the volume and roughness of the dimples on the fracture surface increases further. The cleavage step and intergranular fracture can be seen in the image magnified 10,000 times. Under $\sigma_3 = 6$ MPa and $T = -10$ °C (see Fig. 12f), the pore volume is 500 times larger than the dimple volume. This is due to grain dislocation and frost heaving, and some dimples further expand and connect into pores. Thus, in the image magnified 10,000 times, there are crystal pieces, intergranular fractures and shear cracks produced by grain dislocation friction on the fracture surface.

4.2. Micro-fractal characteristics of weakly cemented mudstone

4.2.1. Fractal dimension

The fractal dimension of micro-fracture can quantitatively reflect the variation in micro-morphology (Wang et al., 2022b). Therefore, ImageJ image processing software is used in this study to binarize many fine micro-fractures of weakly cemented mudstone, as shown in Fig. 13 ($\sigma_3 = 6$ MPa). In the figure, black color represents the development of fractures and pores in the rock sample, while white color represents relatively intact rock.

The fractal dimension can be calculated by the box dimension (Zhang et al., 2021; Liu et al., 2022b). Using Eq. (6), the fractal dimensions of weakly cemented mudstone under different temperatures and confining pressures are obtained. The average values are shown in Table 2.

$$Q = \left| \lim_{d \rightarrow 0} \frac{\ln N(d)}{\ln d} \right| \quad (7)$$

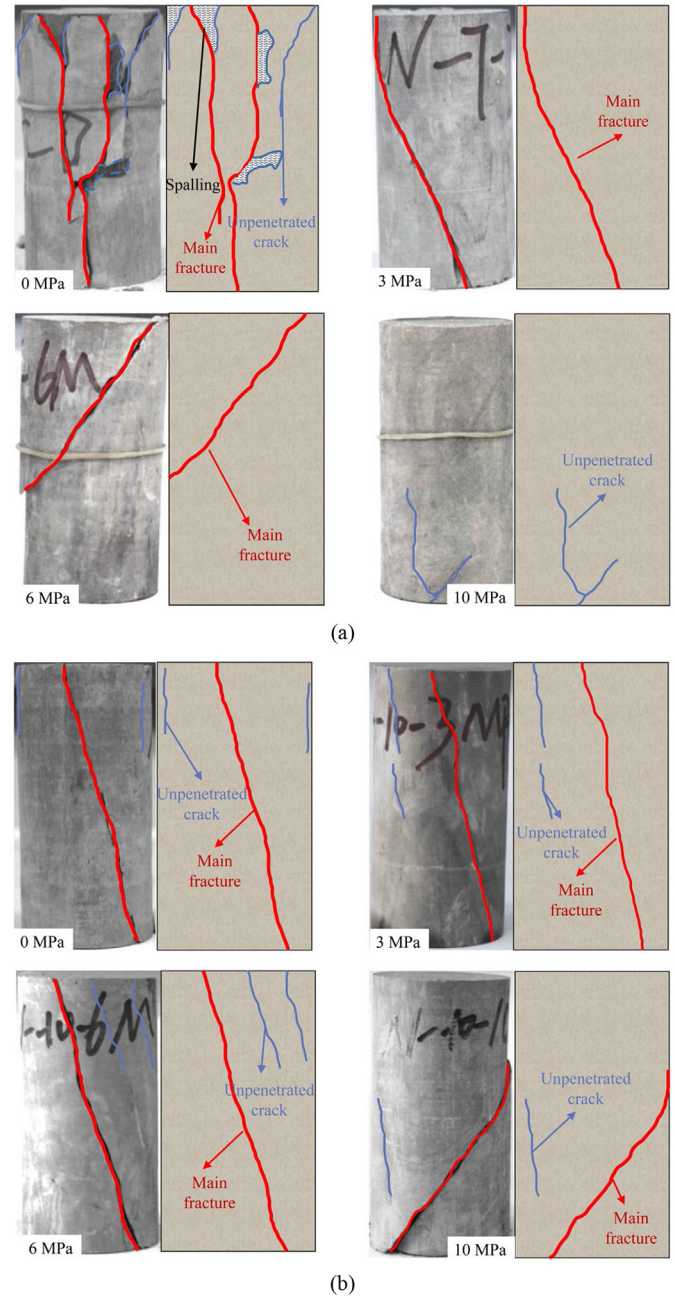


Fig. 11. Macro-failure modes of mudstone at different temperatures and confining pressures: (a) $T = 10$ °C and (b) $T = -10$ °C.

where Q is the box dimension, d is the box size, and $N(d)$ is the number of images covered a box of size d .

The minimum fractal dimension of a fracture is 1.833 for sample under $\sigma_3 = 0$ MPa and $T = 10$ °C. The maximum fractal dimension is 2.013 for sample under $\sigma_3 = 10$ MPa and $T = -30$ °C. Under the same temperature or confining pressure, the fractal dimension of a micro-fracture in weakly cemented mudstone increases with increasing confining pressure or decreasing temperature decrease, respectively, indicating that the variation in temperature and confining pressure affects the fractal dimension. The low-temperature freezing and confining pressure affect the evolution of rock micro-structure, finally resulting in a difference in fractal dimension. When the temperature continues to decrease or the

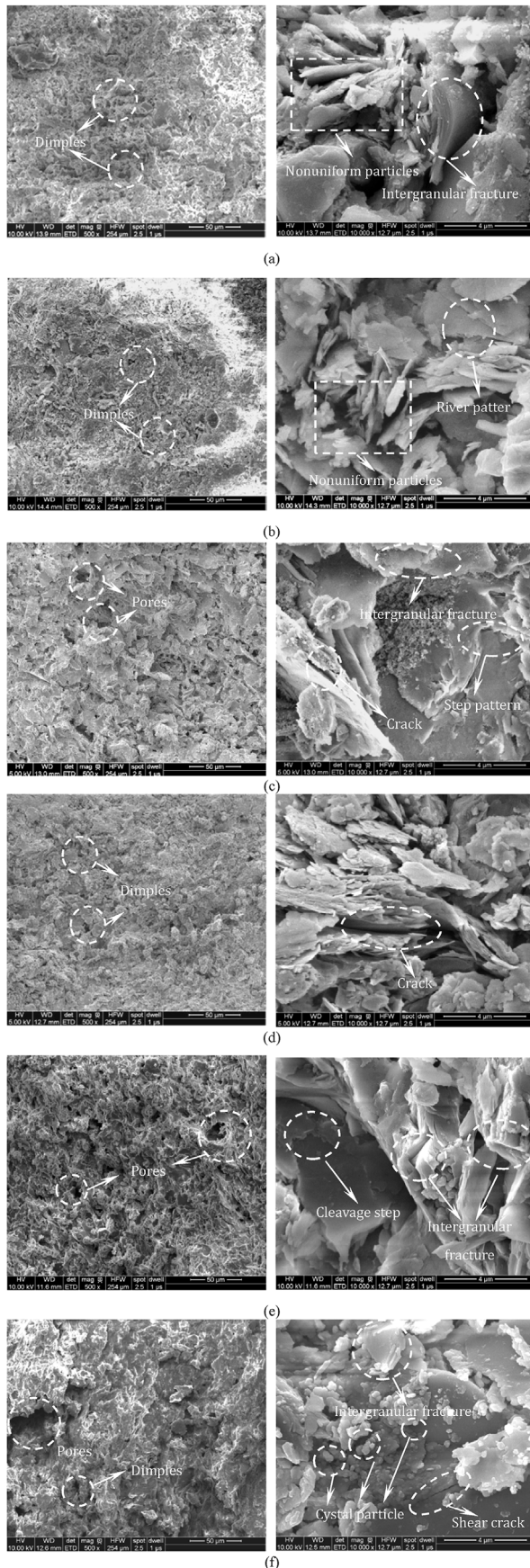


Fig. 12. Micro-failure modes of mudstone under different temperatures and confining pressures: (a) $\sigma_3 = 0$ MPa, $T = 10$ °C; (b) $\sigma_3 = 6$ MPa, $T = 10$ °C; (c) $\sigma_3 = 0$ MPa, $T = -5$ °C; (d) $\sigma_3 = 6$ MPa, $T = -5$ °C; (e) $\sigma_3 = 0$ MPa, $T = -10$ °C; and (f) $\sigma_3 = 6$ MPa, $T = -10$ °C.

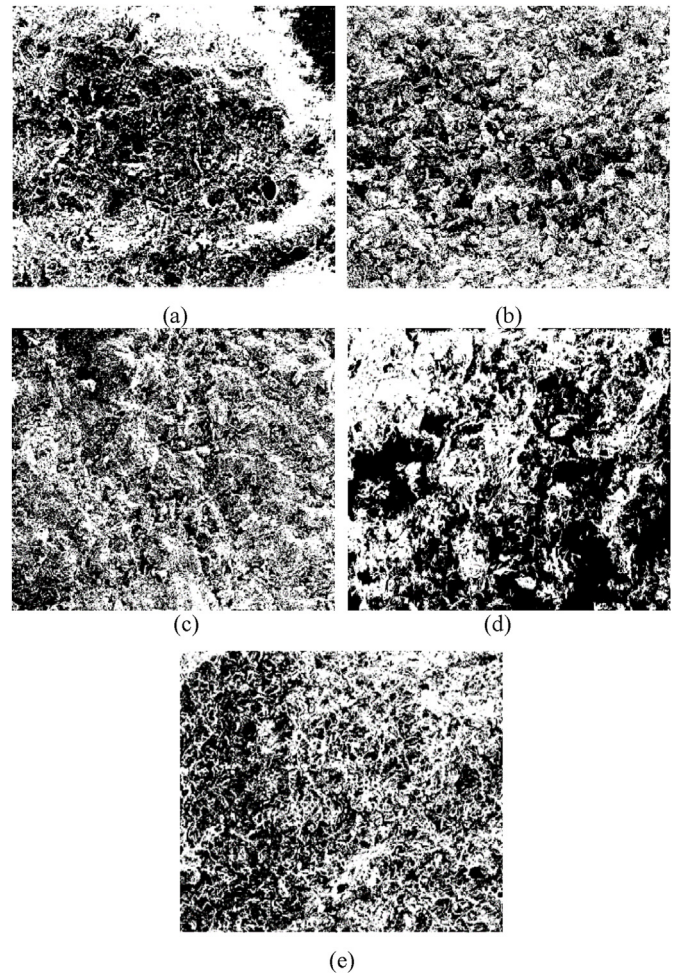


Fig. 13. A binary image of the micro-morphology of triaxial failure of mudstone at temperatures of (a) 10 °C, (b) –5 °C, (c) –10 °C, (d) –20 °C and (e) –30 °C.

confining pressure continues to increase, the fractal dimension is predicted to continue to increase.

4.2.2. Relationship between the fractal dimension, temperature and confining pressure

Based on Table 2, the relationship between the fractal dimension of the micro-fracture and the temperature and confining pressure of weakly cemented mudstone can be further obtained, as shown in Fig. 14. The relationship between the fractal dimension and temperature is fit by an exponential function, and the relationship between the fractal dimension and confining pressure is fit by a linear function. Under the same confining pressure, the fractal dimension increases as the temperature decreases, but the increment of the fractal dimension gradually decreases. When the temperature decreases to a certain degree, the fractal dimension is not increasing. Under the same temperature, the fractal dimension increases as the confining pressure increases, but the increase in the fractal dimension is not affected by confining pressure, indicating that temperature is the primary controlling factor for micro-scale damage of frozen weakly cemented mudstone.

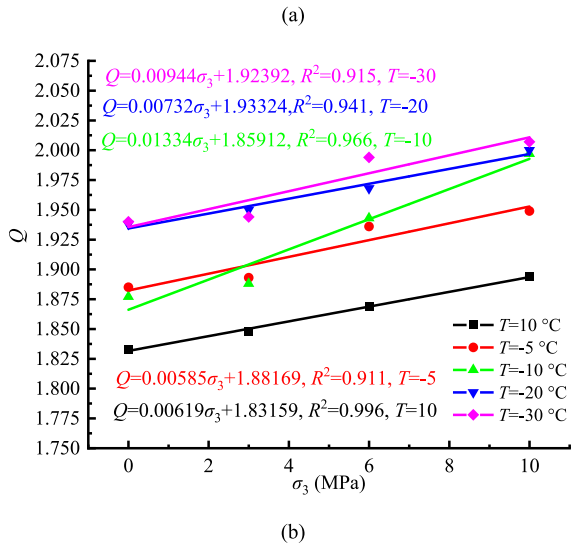
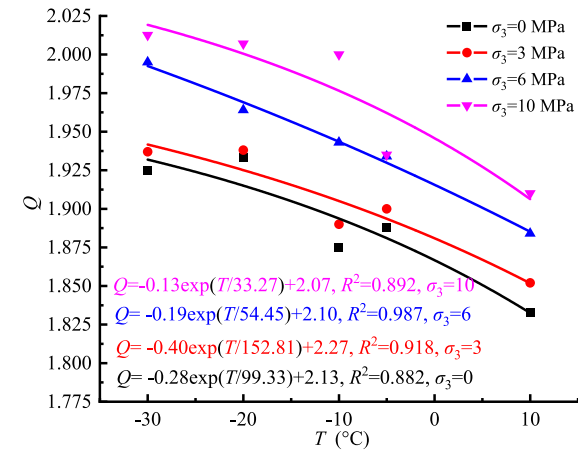
4.2.3. Relationship between the fractal dimension, peak strength and elastic modulus

Based on the above analysis, a model for the relationships between the fractal dimension of the micro-fracture and the peak

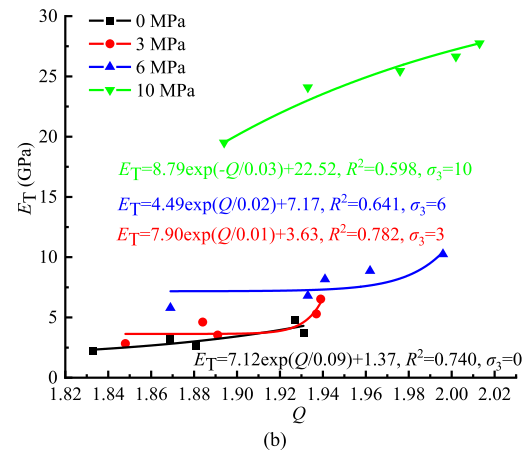
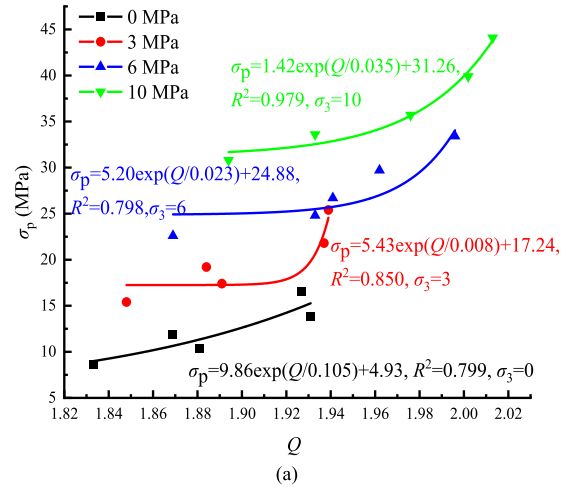
Table 2

Fractal dimension of weakly cemented mudstone at different temperatures and confining pressures.

σ_3 (MPa)	Q				
	$T = 10\text{ }^\circ\text{C}$	$T = -5\text{ }^\circ\text{C}$	$T = -10\text{ }^\circ\text{C}$	$T = -20\text{ }^\circ\text{C}$	$T = -30\text{ }^\circ\text{C}$
0	1.833	1.881	1.869	1.931	1.927
3	1.848	1.891	1.884	1.937	1.939
6	1.869	1.933	1.941	1.962	1.996
10	1.894	1.933	1.996	2.002	2.013

**Fig. 14.** Relationship between the fractal dimension of weakly cemented mudstone and (a) temperature and (b) confining pressure.

strength and elastic modulus of weakly cemented mudstone can be established, as shown in Fig. 15, which is fit by an exponential function. The larger the peak strength of frozen soft rock is, the larger the fractal dimension. The larger the fractal dimension is, the more complex and rougher the fracture surface, and the larger the number of pore cracks inside the soft rock. Similarly, the greater the elastic modulus of frozen soft rock is, the greater the fractal dimension. Therefore, there is a certain quantitative relationship between the macroscopic strength and deformation characteristics and micro-structure of frozen mudstone by the fractal dimension of the fracture.

**Fig. 15.** Relationship between the fractal dimension of weakly cemented mudstone and (a) peak strength and (b) elastic modulus.

4.3. Macro-micro correlation failure mechanism

Rock is a kind of three-phase (i.e. solid, liquid and gas) natural geological material with defects such as pores and cracks. As shown in Fig. 16, under the action of low temperature, the liquid turns into a solid state that fills the pores and cracks inside rocks, and reduces plastic deformation at the compaction stage. The lower the temperature is, the smaller the content of unfrozen water and the greater the ice content, and thus the filling effect of ice on pores and cracks is more evident. The frost heave force generated by water freezing leads to expansion of ice volume, which makes the pores and cracks develop and expand again. In addition, the frost heave force squeezes rock particles, resulting in relative dislocation or even peeling. Some debris and particles are produced at the meso-scale, and the pores and cracks inside rocks further increase in number. Meanwhile, the main failure mode in rocks is intergranular fracture. However, the increasing porosity increases volume occupied by ice and increases the cohesion between rock particles, thus improving the strength of rocks from a macroscopic perspective. Therefore, the freezing effect weakens rock plasticity and enhances brittleness. During the test, the confining pressure inhibits the expansion of internal pores and cracks inside rock samples. The effect of confining pressure is mainly reflected in transgranular fracture and shear slip at the micro-scale, and the dimples

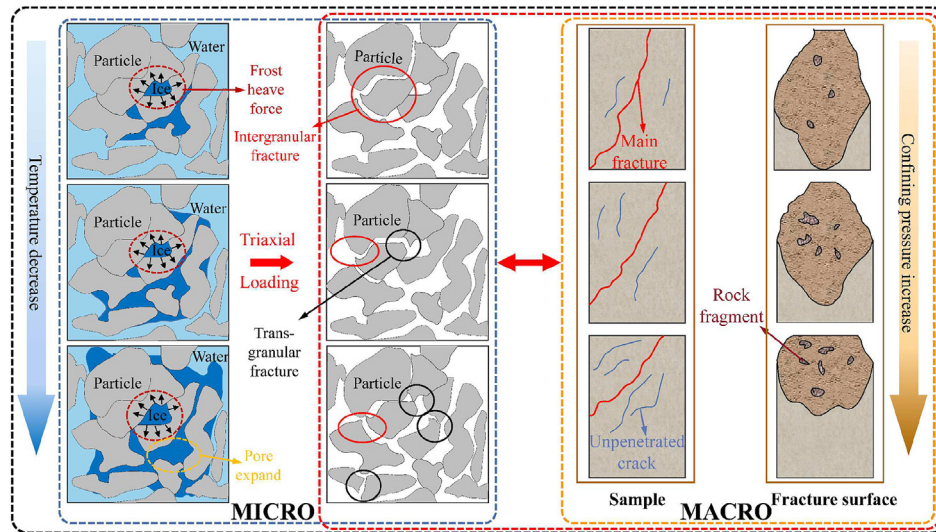


Fig. 16. Macro-micro correlation failure mechanism of frozen weakly cemented mudstone.

decreases in size, which visibly reduces the number of dimples on the micro-fracture, and the section becomes relatively flat (see Fig. 12b and d). However, in fact, the confining pressure leads to the formation of secondary pores and cracks in rocks, which increases the proportion of pores and cracks overall, and the extrusion and shear dislocation of some particles significantly increases the pore size. Therefore, the effect of confining pressure decreases the brittleness and enhances the plasticity of frozen soft rocks.

In our tests, rock samples are first frozen and then compressed. With decreasing temperature, frozen mudstone mainly shows brittle-shear failure. Although the confining pressure inhibits the lateral expansion of rock sample, which correspondingly enhances its plasticity. There are obvious microscopic cuts and particles on the fracture surface, and the lower the temperature is, the greater the confining pressure, and the more cuts and particles. The effects of freezing and confining pressure cause dislocation friction between particles to cause spalling. Under higher confining pressure and lower temperature, there are more rock powder and fragments on the main fracture surface of rock samples.

By analyzing the fracture morphology of weakly cemented mudstone under different temperatures, it can be observed that low temperature has a significant effect on the fracture morphology of rock samples, especially below -10°C . The variation of fracture morphology reflects the difference of macro-failure mechanism of rocks (Li et al., 2018; Liu et al., 2019c). Weakly cemented soft rock is an aggregate composed of mineral particles and cements, and the mineral composition and cementation form determine its macro-mechanical characteristics. Under temperature of 10°C , the strength of mineral particles and cements between pores of weakly cemented soft rock is much lower than that of skeleton particles. Therefore, its failure fracture mostly occurs on clay cements or the junction of clay cements and mineral particles, and a few occurs on mineral particles. Under compressive loading, the internal cracks in the cement of rock samples are continuously bred, expanded and connected, which is reflected in the rough undulation of fracture morphology. Under freezing, the pore water in rock samples gradually condenses into ice, which improves the bonding strength between the frozen mineral particles, cements and mineral particles with cements, and manifested as the improvement of rock strength in macro and brittle fracture in micro. Under freezing, frozen weakly cemented soft rock is an anisotropic heterogeneous

aggregate, which composed of mineral particles, ice medium, cement and so on, and the shrinkage rate of each phase medium is different under compressive loading. Thus, cracks are most likely to occur at the interface of each phase medium. In the presence of shear, the cracks produce friction separation. On the micro-scale, the rock failure fracture appears shear pattern bands such as river pattern and step pattern, while on the macro-scale, it is reflected as shear failure.

5. Conclusions

In this paper, the strength and deformation characteristics of weakly cemented mudstone are deeply investigated under different temperatures and confining pressures, and the micro-failure characteristics of frozen weakly cemented soft rock are further analyzed by SEM and image processing. The fractal geometry is introduced to quantitatively describe the complex characteristics of micro-fracture morphology and establish relationships between microscopic geometric parameters and macro-mechanical parameters. Finally, the macro-micro correlation failure mechanism of frozen weakly cemented mudstone is interpreted. The following conclusions are obtained:

- (1) With decreasing temperature, the plastic yield stage of weakly cemented mudstone gradually becomes shorter, and the brittle characteristic is more evident. The peak strength and elastic modulus exponentially and linearly increased with decreasing temperature, respectively. The peak strength of weakly cemented mudstone linearly increased with increasing confining pressure at different temperatures.
- (2) An exponential function can be observed among the fractal dimension, temperature, compressive strength and elastic modulus. With decreasing temperature, the compressive strength of mudstone increased gradually, and the corresponding fractal dimension increased. The micro-fracture fractal dimension was greater for triaxial compression failure than that of uniaxial compression failure, indicating that with decreasing temperature or increasing confining pressure, the structural plane of rock failure fracture is more complex. The variations in temperature and confining

pressure significantly affect the fractal dimension of rock micro-fractures.

- (3) When the confining pressure is constant, the brittleness of weakly cemented soft rock increases with decreasing temperature, and the plasticity decreases. Rock samples usually show shear failure characteristics along the main fracture surface, and the angle between the fracture surface and the maximum principal stress increases gradually with increasing confining pressure. Although the freezing effect improved the cementation ability, intergranular fracture and transgranular fracture occurred in the compressed rock, which destroyed its original structure. Subsequently, the number of pores in the rock increased, and the cracks expand, and the cement or particles fall off, resulting in shear patterns such as river-like patterns and step-like patterns in the micro-fractures.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Dr. Xianzhou Lyu now works at the College of Earth Science and Engineering in Shandong University of Science and Technology, where he is also deputy secretary general of Professional Committee of Pipe Gallery and Underground Space of China Municipal Engineering Association. His research interests include: (1) Multi-scale deformation mechanism and support control technology of deep soft rock, and (2) stability analysis theory and deformation control technology of surrounding rock of urban subway engineering in composite stratum.