Effect of Frost Heave on Internal Structure and Mechanical Behavior of Rock Mass at Low Temperature

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Abstract

Frost heaving plays an important role in improving the internal structure and mechanical behavior of rock mass, but little effort has been devoted to addressing this concern. In this paper, a series of pore structure, uniaxial compression experiments and mesoscopic numerical analyses were conducted to explore the frost heaving mechanisms and mechanical behaviors of rock mass. In these tests, the compactness, P-wave velocity, compressive strength, elastic modulus and brittleness of frozen sandstone increased significantly; and the permeability and permeability coefficient decreased by several orders of magnitude with temperature dropping. The experimental results indicate that cryogenic freezing can significantly improve the internal structure and strength characteristics of sandstone. In reservoir simulation, it may be instructive for forming complex fracture networks, which helps to provide more channels for oil and gas seepage and migration, thus improving the fracturing performance. In addition, the meso-damage constitutive model were successfully integrated into Abaqus to simulate the damage evolution of rock mass, which has quite promising future for solving the trans-scale progressive failure of rock mass. The study provides a basic reference for the design and maintenance of cold region engineering and cryogenic reservoir stimulation.

Key Words: Rock Mass, Low Temperature, Frost Heaving, Pore Structure, Mechanical Behavior, Mesoscopic Numerical Simulation

1. Introduction

The frost heaving of rock mass is globally observed in cryogenic fracturing and cold regions. Many underground structures and cold region engineering, such as buried pipelines, underground excavation, oil drilling, retaining walls, liquefied natural gas (LNG) storage and cryogenic reservoir stimulation (liquid CO₂ fracturing, liquid nitrogen fracturing), are subject to severe frost heaving due to a complex geological environment and special climatic conditions [1–4]. Frost heaving seriously threatens the serviceability and sustainability of geotechnical engineering and easily leads to engineering hazards, such as frost weathering, frost extrusion, frost splitting, slope instability, borehole sloughing and thaw subsidence [5–9]. But frost heaving also plays a positive role in improving the strength and brittleness of rock mass. In reservoir simulation, increasing the brittleness of tight rock mass may cause it to produce more complex fracture networks, which helps to increase the volume of reservoir stimulation and promote the desorption and diffusion of oil and gas. Consequently, it is of great significance and academic value to study the influence of frost heave on the pore and mechanical characteristics of rock mass for improving the global problems of engineering safety assessment and the effectiveness of reservoir simulation.

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In the past, there are many studies devoted to the freezing and thawing of soils. The various properties of soils have been widely disclosed, such as strength, compressibility, permeability and composition [10–12]. However, with the change of the geological environment, the problems of frost heaving in rock mass are becoming more and more common. For example, many tunnels in China have been excavated in cold regions [13]. Cryogenic reservoir stimulation has also attracted the attention of many scholars, such as liquid CO₂ fracturing and liquid nitrogen fracturing [4,14]. So far, there are few scholars who discuss the effect of frost heave on the properties of rock mass. It is known that there is a great difference between the freezing process of soil and rock. It is also known that the internal structure and mechanical properties of rock mass is susceptible to change due to the freezing of pore water, especially its initial saturation exceeds the critical saturation [15]. These only few studies noted that frost heaving could significantly enhance the fracture toughness and strength of rock mass [1,16–19]. However, the influence mechanism of frost heaving on the internal structure and mechanical properties of rock mass is still not completely understood, and the mechanical responses of different rock masses to frost heaving are different. Moreover, previous studies have seldom focused on the change of permeability characteristics of rock mass during freezing. Especially, no scholars have used the meso-damage constitutive model to evaluate the change in the failure modes of frozen rock. In addition, few studies have discussed the effect of frost heaving on rock compressibility in cryogenic fracturing. Therefore, the current research work in this paper may make up for the shortcomings of previous studies.

The paper aims to investigate the effect of frost heave on the internal structure and mechanical behavior of rock mass during freezing. The interrelation between frost heave, permeability and mechanical behavior of sandstone was analyzed in detailed. The study provides a basic reference for the design and maintenance of cold region engineering and cryogenic reservoir stimulation.

2. Experimental Methodology

2.1 Specimen Preparation

The Ordos Basin in China is rich in oil and gas resources; its natural gas reserves are approximately 13 × 10¹² m³ [20], but exploitation is difficult due to the low porosity and low permeability of sandstone reservoir [21, 22]. To evaluate the strength and compressibility of the sandstone at low temperature, the sandstone blocks used in the paper were acquired from this basin. The average density of the sandstone specimens is 2.27 × 10³ kg/m³. All sandstone samples were cut into cylinders with a diameter of 25 mm and a height of 50 mm from the same sandstone block following the International Society for Rock Mechanics standard [23]. The core direction of all specimens was perpendicular to the direction of rock deposition. To avoid differences in the samples, all drilling samples were tested by ultrasonic waves, and the samples with similar wave velocity were selected as the experimental samples to ensure their uniformity. The height and diameter errors of all specimens were within ±0.5 mm. In this study, the screened qualified samples 1-2 and 1-3 were saturated and freezing treated, samples 1-5 and 1-6 were dried and freezing treated, and the compared samples weren’t freezing treated.

2.2 Experimental Apparatus and Steps

To explore the effect of frost heave on the internal structure and mechanical behavior of rock mass at low temperature, a series of pore structure, uniaxial compression experiments were conducted. The experimental steps are listed as follows:

Step 1: First, all sandstone samples were placed in a dry box at a constant temperature of 105 °C for drying more than 24 hours. Then, samples 1-1, 1-2 and 1-3 were vacuumed for 6 hours and immersed in distilled water for 48 h, and the compared samples were untreated.

Step 2: After samples were saturated, all sandstone samples were placed in constant refrigeration for full freezing at -5 °C and -30 °C, respectively. During freezing, the gas permeability and ultrasonic wave tests were carried out for sample 1-3 at 25 °C--30 °C. From permeability tests, the confining pressure was 1.5 MPa, and the inlet and outlet pressure of the sample were monitored until the inlet pressure remained constant for at least 30 min. Moreover, during these tests, the internal temperature of the sample was uniform at the
required temperature. Step 3: After specimens were completely frozen, all sandstone samples were subjected to uniaxial compression tests in the refrigeration house at the corresponding temperature levels following the International Society for Rock Mechanics standard [23]. During these tests, the stress-strain curves of all samples were recorded by axial and radial strain gauges installed on the sample surfaces. In these experiments, the axial load was controlled by the axial displacement, and the loading rate was 0.02 mm/min.

Figure 1 shows a computer-controlled refrigeration house. This refrigeration system is mainly composed of refrigeration house, compressor and temperature induction system. In this control system, the temperature point can be detected using a temperature sensor with a switching output. When the temperature of the refrigeration house is higher than the setting temperature (i.e., -5 °C, -30 °C), the compression will automatically start, whereas when the temperature is lower than the setting temperature, the compression will automatically stop. Figure 2 shows a TAW-100 servo-controlled triaxial testing system and assembled rock sample. The TAW-100 servo-controlled triaxial testing system was located in the refrigeration house. For the purpose of this study, six groups of uniaxial compression tests were performed at three temperature levels in the refrigeration house. During the experiments, the samples were placed inside the heat-shrink rubber, and local axial and circumferential strains were recorded simultaneously by the axial and lateral strain gauges attached to the sample surface (see Figure 2).

3. Mesoscopic Numerical Simulation Methods

3.1 Meso-damage Constitutive Model of Frozen Rock

Frozen rock is a typical macroscopic heterogeneous natural geological material. Based on the theory of micro-damage mechanics, it can be divided into a large number of representative volume elements (RVE). These volume elements are large enough for meso-scale, and contain enough information about the micro-structure of frozen rock, such as micro-holes, micro-cracks, and so forth. The initial defects of frozen rock are generalized into these RVE by the method of statistical homogenization. Elastic modulus, Poisson’s ratio and strength can fully reflect the mechanical properties of volume element. Therefore, the mechanical analysis of volume element can be carried out by continuum mechanics to study the change of the meso-characteristics of frozen rock. Previous researches have confirmed that the mechanical parameters of the mesoscopic elements of heterogeneous rocks satisfy the Weibull distribution [24–27]. In this paper, it is also assumed that the mechanical parameters of frozen rock also obey the Weibull distribution. The distribution function can be written as

\[
f(u) = \frac{m}{u_0} \left( \frac{u}{u_0} \right)^{m-1} \exp \left[ - \left( \frac{u}{u_0} \right)^m \right]
\]  

(1)

Figure 1. Computer-controlled refrigeration house.

Figure 2. TAW-100 servo-controlled triaxial testing system and assembled rock sample.
where \( u \) is the mechanical parameter of the mesoscopic elements (such as elastic modulus or strength); \( u_0 \) is the mean of mechanical parameter; \( m \) is the shape parameter for describing the spatial concentration and discrete degree of \( u \). As shown in Figure 3, the curves reflect the relationship between the distribution density of elastic modulus of mesoscopic elements and the homogeneity index \( m \). From the figure, it can be found that the mechanical parameters of frozen rock are more uniform with the increase of the homogeneity index \( m \).

According to the theory of elastic damage mechanics, the damage of mesoscopic element can be expressed by damage variable. Based on the hypothesis of Lemaitre equivalent strain, the elastic modulus of a damage element degrades monotonically with the increasing of damage variable. It can be described as

\[
E = (1 - D)E_0
\]  

where \( E \) is the elastic modulus of damaged element; \( E_0 \) is the initial elastic modulus of element; \( D \) is the damage variable of element. The damage variable ranges between 0 and 1 (0 \( \leq D \leq 1 \)). When \( D = 0 \), the element is not damaged, whereas it approaches 1 to indicate complete damage. To ensure the continuity of the value, when the element is completely damaged, its elastic modulus \( (E) \) is given a very small value, such as \( 1.0 \times 10^{-5} \) MPa.

In this study, it was also assumed that the mesoscopic elements were mainly subjected to tensile failure and shear failure. The maximum tensile stress criterion and the modified Mohr-Coulomb criterion can be used to judge the tensile failure and shear failure of mesoscopic elements, respectively \([24–27]\). The maximum tensile stress criterion and the modified Mohr-Coulomb criterion are expressed as:

\[
F_1 = -\sigma_3 - f_t = 0 \quad \text{and} \quad F_2 = \sigma_1 - \sigma_3 \frac{1 + \sin \varphi}{1 - \sin \varphi} - f_c = 0
\]  

where \( F_1 \) and \( F_2 \) are the damage functions, \( \sigma_3 \) is the minimum principal stress, \( \sigma_1 \) is the maximum principal stress, \( f_t \) is the uniaxial tensile strength, \( f_c \) is the uniaxial compressive strength (UCS), \( \varphi \) is the internal friction angle of frozen rock.

When the mesoscopic element is in a uniaxial stress state, the constitutive relation of elements is shown in Figure 4. In the initial loading stage, the elements are in the linear elastic state, and all elements are not damaged. When the stress state of element meets the damage threshold (Eq. 3), the irreversible damage of element begins to happen.

When the maximum tensile stress criterion or the modified Mohr-Coulomb criterion is satisfied under multiaxial stress states, the constitutive evolution equation of damage elements can be expressed as \([24,25]\):

\[
D = \begin{cases} 
0 & F_1 < 0 \quad \text{and} \quad F_2 < 0 \\
1 - \frac{\lambda \varepsilon_0}{\varepsilon_c} & F_1 \geq 0 \\
1 - \frac{\lambda \varepsilon_0}{\varepsilon_t} & F_2 \geq 0 
\end{cases}
\]  

where \( \varepsilon_0 \) is the elastic tensile strain limit of element, \( \varepsilon_c \)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Stochastic distribution of elastic modulus of elements with different homogeneity index.}
\end{figure}
is the maximum principal strain under multiaxial stress states, $e'$ is the equivalent principle strain of damaged element under multiaxial stress states, $e_i$ is the maximum compressive principal strain of damaged element under multiaxial stress states, $\lambda$ is the coefficient of residual strength, $0 < \lambda \leq 0.1$. When the element is completely damaged, it follows that $f_{tr} = \lambda f_{t0}, f_{cr} = \lambda f_{c0}$ (see Figure 4).

In the tensile failure mode of element, $e_{\text{ta}}$ and $e'$ can be respectively defined as:

$$e_{\text{ta}} = \frac{f_{\text{ta}}}{E_0}$$  \hspace{2cm} (5)

$$e' = -\sqrt{\left(\langle -e_1 \rangle \right)^2 + \left(\langle -e_2 \rangle \right)^2 + \left(\langle -e_3 \rangle \right)^2}$$  \hspace{2cm} (6)

where $e_1, e_2, e_3$ are three principal strains of element, and $\langle \rangle$ is a function defined as follows:

$$\langle x \rangle = \begin{cases} x, & x \geq 0 \\ 0, & x < 0 \end{cases}$$  \hspace{2cm} (7)

In the shear failure mode of element, the influence of other principal stresses during damage evaluation should be fully considered [24,25]. Therefore, the maximum principal strain $e_{\text{oa}}$ can be calculated at the peak value of maximum principal stress by the following formula:

$$e_{\text{oa}} = \frac{1}{E_0} \left[ f_{\text{oa}} + \frac{1 + \sin \phi}{1 - \sin \phi} \sigma_1 - v(\sigma_1 + \sigma_2) \right]$$  \hspace{2cm} (8)

where $v$ is Poisson’s ratio of frozen rock, $\sigma_2$ is the intermediate principal stress.

### 3.2 Meso-scale Numerical Model of Frozen Rock

The above mentioned constitutive model was integrated into the traditional commercial finite element software Abaqus to simulate the progressive failure process of frozen sandstone under uniaxial compression. Figure 5 shows the heterogeneous numerical model of frozen sandstone. From the figure, it can be readily noted that the elastic modulus of all elements is randomly distributed. The boundary conditions of the numerical models is displayed in Figure 6. The bottom of the model is considered to have zero displacement along the axial direction, and the top is subjected to a downward displacement.
load according to the quasi-static loading condition and step length.

Moreover, in this study, the randomness of elastic modulus, tensile strength and UCS of all elements are considered. The random distributions of Poisson’s ratio and internal friction angle are not considered. The primary mesoscopic parameters used for the simulations are listed in Table 1.

4. Experimental Results and Analysis

4.1 Change in Permeability Characteristics

Permeability and permeability coefficient were often used to characterize the flow conductivity and penetrability of rock mass, which was mainly related to the size of pores and the physical properties of pore fluid [28,29]. During permeability tests, the calculation formula of permeability and permeability coefficient can be described below:

\[
k = \frac{Qh\Delta L}{A\Delta p}
\]

(9)

\[
K = k \frac{\gamma}{\mu}
\]

(10)

where \(k\) is the permeability of frozen rock sample; \(Q\) is the gas flow of frozen rock sample; \(\mu\) is the fluid viscosity; \(\Delta L\) is the sample length; \(A\) is the sample cross-section area; \(\Delta p\) is the pressure difference between the upstream and downstream of frozen rock sample; \(K\) is the permeability coefficient of frozen rock sample; \(\gamma\) is the specific gravity of fluid.

According to previous studies, there may be still many unfrozen water in the frozen area [2,7]. This phenomenon indicates that the rock pores may still have a certain degree of permeability. However, the permeability of frozen rock has been neglected. In this study, the permeability of frozen sandstone was discussed in detail. Figure 7 shows the variation of the permeability and permeability coefficient of frozen sandstone with temperature. From the figure, it can be observed explicitly that the permeability and permeability coefficient of sandstone are basically unchanged above the freezing point (0 °C). As the temperature decreases, they have significantly reduced below the freezing point. They may decrease by several orders of magnitude at the temperature between 0 °C and -30 °C. In particular, the permeability and permeability coefficient of frozen sandstone in deep freezing state tend to be zero, which indicates that the permeability of frozen sandstone can be ignored at this time. It may be called extremely low permeability [28]. The experimental results reveal that the compactness of sandstone gradually

<table>
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<tr>
<th>Table 1. Weibull distribution parameters of sandstone numerical specimens</th>
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<tr>
<td>Sandstone parameters</td>
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<tr>
<td>Homogeneity index m</td>
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<td>Maroscopic elastic modulus (GPa)</td>
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<td>Mesoscopic mean elastic modulus (GPa)</td>
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<td>Maroscopic tensile strength (MPa)</td>
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<td>Coefficient of residual strength</td>
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<td>Internal friction angle (°)</td>
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<td>Poisson’s ratio</td>
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Figure 7. Variation of permeability and permeability coefficient of frozen sandstone with temperature.
increases with the decrease of freezing temperature. Based on these results, it can be concluded that the formation of pore ice may be the main reason for the decrease of permeability and permeability coefficient of sandstone. The ice lenses gradually fills the micro-pores of sandstone during freezing, which will prevent the diffusion and migration of pore fluids. Meanwhile, the generation of pore ice has changed the pore structure of sandstone, and it may have an impact on many properties of sandstone, as discussed in the later sections.

4.2 Change in the P-wave Velocity

Ultrasound wave test was used to detect the pore structure of frozen sandstone by the propagation velocity of the primary wave (P-wave). It can also predict the change of elastic modulus of frozen sandstone with temperature. The P-wave velocity can be given by:

\[ v_p = \frac{\Delta L}{\Delta t_p} \frac{(1-v)E_0}{(1+v)(1-2v)\rho} \]  

where \( v_p \) is the P-wave velocity of frozen rock sample; \( \Delta t_p \) is the propagation time of the P-wave; \( \rho \) is the density of frozen rock sample.

For the same rock, the P-wave velocity is mainly influenced by the degree of pore development. The more pores inside the rock, the smaller the P-wave velocity will be. From ultrasound wave tests, the variation of P-wave velocity of sample 1-3 with temperature is presented in Figure 8. It can be seen from the figure that the values of the P-wave velocity of the sample has little change above the freezing point (0 °C). Then, it is obviously increased at the temperature between 0 °C and -30 °C. The P-wave velocities increased by 13.51%, 25.29%, 37.08%, respectively. The main reason may be that the pore ice gradually fills the pores of sandstone, which will provide the medium of the P-wave propagation. The experiments further reveal that the compactness of sandstone is obviously increased under freezing, which may create a favorable condition for improving the strength and brittleness of sandstone.

4.3 Change in the Stress-strain Curves

A series of uniaxial compression experiments are conducted to test the change of mechanical properties of sandstone at sub-zero temperature. Figure 9 shows the stress-strain curves of sandstone samples with dry and saturated states at different temperatures. There are clear dif-
ferences in the variation trend of the stress-strain curves. All stress-strain curves can be divided into four different stages [4,30]. The trend of each stage reflects the effect of frost heaving on the internal structure and mechanical properties of sandstone.

Stage I: Crack closure stage. At the initial loading stage, all stress-strain curves are slightly concave upward. The concave feature mainly depends on the compaction degree of sandstone specimens, which is less noticeable for tight rocks. From Figure 9, it can be found that the concavity characteristics of frozen sandstones are not apparent than those of the unfrozen ones. The results illustrate that frozen sandstone samples become more compact than their original state due to the effect of frost heaving and heat shrinkage.

Stage II: Linear elastic deformation stage. At this stage, all stress-strain curves are approximately linear until the yield, and the slopes of the straight lines represent the elastic modulus of sandstone samples. The smaller the space of pore in the sandstone, the larger its elastic modulus will be. Correspondingly, the larger the elastic modulus of sandstone, the stronger its ability to resist deformation will be [4,30]. It can be seen from the figure that the elastic modulus of all frozen samples shows a significant increase compared with the unfrozen ones. As shown in Figure 10, the elastic modulus of the dry and water-saturated samples increased by 9.57%~43.62% and 19.18%~82.19%, respectively. The results indicate that low temperature freezing can effectively increase the ability of sandstone to resist brittle failure.

Stage III: Yield stage. The stress-strain curves of all specimens become nonlinear again and convex upward until the peak stress. At this stage, the compressive deformation of all samples has plastic characteristics, and the deformation cannot be completely restored after releasing the load. It can be observed from Figure 9 that the peak stress of all frozen samples is much higher than those of the unfrozen ones. As shown in Figure 10, the UCS of the dry and water-saturated samples increased by 3.63%~25.64% and 12.16%~74.47%, respectively. The results indicate that low temperature freezing can effectively increase the ability of sandstone to resist brittle failure.

Stage IV: Post-peak stage. At this stage, all sandstone samples show significant macro-shear failure until complete rupture, and the stress suddenly releases. The deformation of all samples after peak stress can be characterized by post-peak stress dropping. A larger value of the post-peak stress dropping indicate that the sandstone is more brittle and is more likely to be broken fully. Therefore, it can be revealed from Figure 9 that the brittleness of all frozen samples is obviously improved compared to the unfrozen ones. These changes indicate that frost heave and heat shrinkage can significantly increase the brittleness of sandstone. The changes in the brittleness of sandstone will be further revealed in detail in the section 4.5.

4.4 Change in Meso-failure Characteristics

In this section, the plane stress model was used to

![Figure 10. Variation of elastic modulus and compressive strength of frozen sandstone with temperature. (EM: elastic modulus)](image-url)
simulate the uniaxial compression failure of sandstone at 25 °C, -5 °C, and -30 °C. Figure 11 shows the comparison of stress and strain curves of the numerical simulations and experiments. From the figure, it can be noted that the equivalent stress and strain curves of the numerical simulations are in good agreement with the experimental curves. Moreover, it can also be observed explicitly that the macro-mechanical responses of frozen sandstone can be divided into four stages, namely crack closure stage, linear elastic deformation stage, yield stage and post-peak stage. From the numerical simulations, the macro-mechanical responses of the samples largely depend on the heterogeneity of the samples itself. The higher the homogeneity index m, the more uniform the distribution of mechanical parameters, and the less the location of stress concentration inside the samples will be. They will directly determine the stress level of all mesoscopic elements, which in turn affects the macro-mechanical responses of the samples. The ability of mesoscopic elements of frozen sandstone to resist failure at low temperature will increase, thereby resulting in a significant increase in the macro-mechanical responses. The numerical simulations reveal the changing mechanism of the mechanical characteristics of sandstone at low temperature.

Figure 12 presents the damage evolution patterns of two numerical samples (Samples 1-1 and 1-2). From the figures, it can be found that the mesoscopic elements of frozen sample (Sample 1-2) has less damage rate and quantity than the unfrozen sample (Sample 1-1). The results indicate that the damage evolution rate of the unfrozen sandstone is more obvious than the frozen one under uniaxial compression. It reveals that these unfrozen elements contain more micro-pores, so that their elastic modulus and compressive strength become lower than these frozen elements. It can be explained that the ice lenses gradually fills the pores of sandstone during freezing, so that the denseness and strength of these frozen elements are greatly increased. The simulation results reveal that the ability of frozen sandstone to resist deformation and failure was significantly improved at low temperature. In addition, by tracing these damage elements, it can also be noted that the meso-elements of the two specimens is mainly tensile failure, and the shear failure is very poor. This phenomenon shows that the failure process of frozen sandstone is mainly caused by a large number of micro-tensile failure. In other words, the macro-shear plane of frozen sandstone can be regarded as the cumulative process of micro-tensile failure. The simulation results are basically consistent with other related reports [26,27]. Moreover, the shear failure modes of the two numerical samples are in good agreement with the physical experiments, which indicates that the proposed numerical methods can accurately predict the complicated failure process of sandstone.

4.5 Change in Brittleness Characteristics

Previous studies rarely discussed the brittleness of rock mass during freezing. However, cryogenic freezing has a great influence on the brittleness of rock mass. In cryogenic reservoir stimulation, the brittleness is considered as the key factor to forming complex fracture networks. In this section, a new brittleness index based on the stress dropping rate after peak stress of stress-strain curve and the ratio of elastic energy release at the point of rock failure to total energy that stored before the peak stress was used to evaluate the brittleness of rock mass reasonably [31]. It can be expressed by the following formulas:

\[
B = B_{\text{pre}} + B_{\text{post}}
\]

\[
B_{\text{pre}} = \frac{S_{\text{ABD}}}{S_{\text{ACO}}} = \frac{(1/2) \times AB \times BD}{(1/2) \times AC \times OC} = \frac{(\sigma_p - \sigma_r)(\epsilon - \epsilon_r)}{\sigma_p \epsilon_p}
\]

\[
B_{\text{post}} = \frac{(\sigma_p - \sigma_r)}{(\epsilon - \epsilon_r)}
\]
where $B$ is the total brittleness index; $B_{pre}$ is the pre-peak brittleness index and its range is 0 to 1 ($0 \leq B_{pre} \leq 1$); $B_{post}$ is the post-peak brittleness index; $S_{ABD}$ is the area of the triangle ABD that represents the elastic energy released by the unstable failure, as shown in Figure 13; $S_{ACO}$ is the area of the triangle ACO that represents the total energy stored before the peak strength; $\sigma_p$ is the peak strength; $\sigma_r$ is the residual strength; $\varepsilon_p$ is the peak strain; $\varepsilon_r$ is the residual strain.

Figure 14 exhibits the variation of brittleness index of frozen sandstone with temperature. From the graph, it can be observed that the brittleness indexes of sandstone always tends to increase with temperature dropping. Ob-
viously, the brittleness indexes of water-saturated samples are greater than the values of dry ones. From 0 °C to -30 °C, the brittleness indexes of water-saturated samples increased by 53.36% and 177.44%, and the brittleness indexes of dry samples increased by 48.35% and 130.14%, respectively. The results indicate that frost heave and low temperature shrinkage can significantly improve the brittleness of sandstone. A larger value of the brittleness index indicates that the rock is more brittle and is more likely to be broken fully. Therefore, it can be concluded that cryogenic fracturing may be able to form more channels for oil and gas seepage and migration than conventional hydraulic fracturing due to the improvement of the brittleness of the reservoir. This may be the main reason for cryogenic fracturing to improve the effectiveness of reservoir simulation.

Based on the above results, the influence of frost heave and low temperature shrinkage on the internal structure and mechanical behavior of rock mass is complex. Therefore, it is necessary to discuss the influence mechanism in detail. For dry sandstone, it will undergo large thermal shrinkage because of the existence of temperature difference, which causes its internal pore volume to decrease or even close. According to the theory of fracture mechanics, the complete closure of internal pores of rock mass may lead to the increase of the required driving force for the shear slip of micro-cracks under uniaxial compression [30]. It may cause a substantial increase in the initiation pressure of rock mass. Therefore, it can be seen that the UCS, elastic modulus and brittleness of dry sandstone increase significantly at sub-zero temperature. For water-saturated sandstone, when the temperature decreases below the freezing point, the pore water gradually freezes into the ice lenses, which will fill the natural micro-cracks inside sandstone. The pore ice can be considered as an adhesive material. It has a certain strength and cementing ability between the solid particles [16], which can change the overall permeability, strength and brittleness of sandstone. With the decrease of the temperatures in the range of 0 °C to -30 °C, the strength and cementing ability of ice lenses in frozen sandstone are higher than those at the temperatures near the freezing point. Therefore, the compactness, strength and brittleness of water-saturated sandstone also increase significantly with temperature decreasing from these experiment tests.

5. Conclusions

The present study reports the effect of frost heave on the internal structure and mechanical behavior of rock mass. A series of pore structure, uniaxial compression experiments and mesosopic numerical analyses were conducted. The changes in the permeability and mechanical characteristics of the sandstone during freezing were analyzed in detail. Based on this study, the following main findings were obtained:

(1) Frost heave and low temperature shrinkage can significantly improve the internal structure of rock mass. In pore structure tests, the permeability and permeability coefficient of frozen sandstone decrease by several orders of magnitude, which indicates that the compactness of sandstone obviously increases with temperature dropping. It reveals that cryogenic freezing may be able to create a favorable conditions for improving the brittleness and strength of sandstone.

(2) Frost heave and low temperature shrinkage have a positive influence on the mechanical properties of rock mass. In uniaxial compression tests, the compressive strength and elastic modulus of water-saturated sandstones increased by 12.16%~74.47% and 19.18%~82.19%, respectively; the compressive strength and elastic modulus of dry sandstones increased by 3.63%~25.64% and 9.57%~43.62%, respectively. Moreover, the brittleness indexes of frozen sandstones always tends to increase with temperature dropping. The results indicate that low temperature freezing can effectively increase the ability of sandstone to resist the deformation and brittle failure, and promote it to fracture more fully.

(3) From the numerical simulations, the macro-mechanical responses of frozen sandstone is mainly affected by the heterogeneity of mechanical parameters and the damage evolution rate of meso-elements. Based on this simulation results, the meso-damage constitutive model were successfully integrated into Abaqus to simulate the damage evolution of rock mass, which has quite promising future for simulating the trans-scale progressive failure of rock mass.

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Call for Papers

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