Research Article

Effect of Moisture Content on Bursting Liability of Sandstone due to Freeze-Thaw Action

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Moisture content (MC) and freeze-thaw (F-T) process have an important influence on the mechanical properties of rock and its rockburst tendency in the cold region. In addition, uniaxial compressive strength (UCS) of rock is of great importance in evaluating weathering durability, frost resistance, and bursting liability of rock. In this study, the UCS of rock and bursting liability index of rock including elastic energy index ($W_{ET}$), impact energy index ($W_{CF}$), elastic strain energy index ($E_S$), and modified values of brittleness index (BIM) were measured by laboratory tests. These tests were implemented in six different MC (0, 0.58, 1.06, 1.82, 2.43, and 2.80%) and 20 F-T cycles. The relationship between rock mechanical properties, bursting liability of rock, and MC after freeze-thaw damage was established, and the control mechanism of moisture content on mechanical properties and rockburst tendency of rocks in cold regions was revealed. Uniaxial compressive test results showed that the UCS of rock decreases significantly with the increase of MC. Under the action of F-T cycles, $W_{ET}$, $W_{CF}$, and $E_S$ decrease with the increase of MC, and BIM of rock increases gradually. This indicates that the rockburst tendency of sandstone decreases with the increase of MC. To calculate $W_{ET}$, $W_{CF}$, $E_S$, and BIM of sandstone samples, new empirical equations were established and put forward under different MC after 20 F-T cycles.

1. Introduction

In the special natural environment of cold regions, one of the hot topics in the field of geotechnical engineering is the influence of freeze-thaw (F-T) cycles on the physical and mechanical properties and bursting liability of rocks [1–3]. F-T cycles are the major reasons for the degradation of physical and mechanical parameters of rocks in many projects such as excavation of tunnels, construction of roads, and dams in cold regions [4, 5]. During the freeze-thaw cycle, the number of F-T cycles, the temperature of freeze-thaw, and the moisture content of rock play an important role in the influencing factors of rock properties [6–8]. Under the influence of low temperature, the water content in the pores and fractures in the rock is frozen, and the volume expansion is about 9%. This causes the rapid increase of micropores, the appearance of new microcracks, and the expansion of existing cracks [9–12].

Uniaxial compressive strength (UCS) is an engineering index to evaluate the durability and bursting liability of rock under freeze-thaw cycles. In recent years, researchers have studied the effect of freeze-thaw cycles on UCS of various saturated rocks [13–15]. Momeni et al. [16] reported the effects of freeze-thaw cycles on the physical and mechanical properties of Arvin granitic rocks in western Iran. They found that, with the increase of freeze-thaw cycles, uniaxial compressive strength, tensile strength, dry density, and $P$-wave velocity decreased while water absorption and porosity increased. Mousavi et al. [17] studied the influence of freeze-thaw cycles on the uniaxial compressive strength of schists. The results show that with the increase of freeze-thaw cycles, the UCS and elastic modulus of rock decrease exponentially, but the Poisson ratio of rock increases. Ke et al. [18] and Rong et al. [19] found that F-T cycles have a major impact on the UCS of sandstone rock. Zhao et al. [20] investigated the effect of freeze-thaw cycles on the uniaxial compressive strength and microstructure of oil shale. They found that the increase of F-T cycles had a significant impact on the uniaxial compressive strength. Additionally, they
reported that microstructure, especially microcracks, is one of the main factors controlling the F-T cycle metamorphism process of oil shale. The researchers found that there is a critical saturation of rock in cold regions, and the UCS of rock decreases significantly only when the water saturation exceeds the critical saturation [8, 21]. Previous studies have shown that the degree of F-T damage of rock is affected by environmental conditions and rock properties, including freezing and thawing temperature and time, mechanical strength, porosity and pore structure, permeability, and water saturation [22–24]. Surprisingly, researchers have focused on the effects of F-T cycles and temperature on the physical and mechanical properties of saturated rocks. However, the water saturation of most natural rocks is not complete and may not reach the critical value of pore frost cracking. Through the analysis of the mechanism of rock failure caused by F-T cycles, it is not difficult to find that the water content in the pores and fractures of rocks plays a decisive role in the physical and mechanical properties of rocks in cold regions.

Bursting liability refers to the sum of all kinds of physical and mechanical properties when the rock can accumulate elastic strain energy and release it suddenly after exceeding its own strength. There are many factors affecting the bursting liability of rockburst, including rock mechanical properties, excavation geometry, discontinuities, stress caused by site and mining, and construction methods [25]. The researchers analyzed the mechanical properties and impact tendency of sedimentary rocks with different water contents. They found that the impact tendency of sedimentary rocks decreased significantly with the increase of moisture content [26, 27]. Additionally, a lot of research has been done on rockburst to understand the mechanism, prediction, and control method of rockburst from both theoretical and experimental aspects [28–30]. The deformation and failure process of rock under uniaxial compression contains rich information about the bursting tendency. Therefore, most of the rockburst tendency indexes based on rock characteristics are proposed based on the mechanical behavior of rock under uniaxial compression. The rock bursting tendency can be measured by one or a group of indexes. At present, impact energy index, elastic energy index, and dynamic failure time are widely used in China. Additionally, in recent years, some scholars have proposed new indexes to correct the shortcomings of the above indexes, such as stiffness ratio index, effective impact energy index, energy storage and consumption index, residual energy index, and brittleness coefficient and elastic deformation index [31–34]. However, in the process of building mines, buildings, dams, and tunnels in cold areas, it is necessary to consider the effect of water content and F-T cycle and use effective and reasonable indicators to comprehensively evaluate rock impact tendency, to ensure people’s life safety.

In this study, the rock of a highway tunnel in North China is taken as the research object. The mechanical properties and impact tendency of sandstone with different water content under F-T cycles are studied by the uniaxial test. The relationship between the rockburst tendency of sandstone and moisture content is established. Specifically, our objectives are (i) to analyze the influence of water content on uniaxial compressive strength of sandstone under F-T cycles through uniaxial compression test and (ii) to explore the influence of different moisture content on sandstone bursting tendency under F-T cycles.

2. Materials and Methods

2.1. Experimental Materials. The rock samples used in this test were taken from sandstone around a highway tunnel in northern China. The average density of the sandstone is 2.32 g/cm³, and the integrity and uniformity of the sandstone are relatively good. The mineral composition of the rock was analyzed using the TD-3500 X-ray diffractometer (Dandong Tongda Technology Co., Ltd., Dandong City, China), and the results are shown in Figure 1 and Table 1. The main minerals characterizing sandstone samples include Quartz, Albite, Chlorite, and Illite. Quartz is predominant, accounting for 60.35% of the total mineral composition, followed by Albite.

2.2. Sample Preparation. In this study, the original rock was cut and polished into 18 cylinders with 50 mm diameter and height of 100 mm (Figure 2(a)) using SCQ type automatic stone cutter (Figure 2(b)), core drilling machine (Figure 2(c)), and double end automatic grinding machine (Figure 2(d)). To ensure the reliability and authenticity of the test results, the test pieces were carefully checked and screened after the test pieces were prepared and processed, and the possibility of adverse effects on the test results caused by obvious cracks, delamination, and other specimens not conforming to the test material specifications was excluded.

Three standard cylinder samples were processed for the water absorption test. Firstly, the samples were dried at 105°C for 24 h; subsequently, they were taken out and put into a dryer to cool to room temperature. Then, the samples were quickly immersed in a container full of distilled water. The samples were taken out every 30 min and weighed by wiping off the surface moisture with a wet cloth. Finally, the moisture content of the samples at each time was calculated. The variation law of moisture content of rock samples with time obtained by immersion test is shown in Figure 3. The moisture content of rock can be divided into four stages. The first stage is the rapid growth stage of moisture content (I); the second stage is the stable growth stage of moisture content (II); the third stage is the deceleration growth stage of moisture content (III); and the fourth stage is the stable moisture content stage (IV). The fitting relationship between water content and time is expressed as the following equation:

\[
\omega = 0.042 + 0.938(1 - e^{-0.03t}) + 1.778(1 - e^{-0.002t}),
\]

\[R^2 = 0.97931,\]

where \(\omega\) is the moisture content of the rock sample, %; \(t\) is the soaking time of the rock sample, min; and \(R^2\) is the goodness of fit of the fitting curve.
According to the water absorption characteristics of sandstone, the rapid growth stage of moisture content (30 min), the stable growth stage of moisture content (60 min), the deceleration growth stage of moisture content (390, 900 min), and the stable moisture content stage (1500 min) are selected as the representative times. To ensure uniform distribution of rock moisture, the moisture content of the sample was changed by the drying method and the water film transfer method, to obtain the samples with different moisture content. The moisture content of samples at different times is shown in Table 2.

2.3. Freeze-Thaw Cycles Implementation. The F-T cycle consists of placing the rock in a freezer at \(-20^\circ\text{C}\) for 4 hours and then placing it in a water bath at \(+20^\circ\text{C}\) for another 4 hours according to ASTM D5312 [35]. Accordingly, each F-T cycle required about 8 h to complete (Figure 4). In this study, we mainly consider the influence of moisture content on the mechanical properties and rockburst tendency of sandstone under F-T cycles. Therefore, according to the engineering rock mass test method standard [36], the number of freeze-thaw cycles was determined to be 20.

2.4. Experiment Equipment. In the present study, a Saw-2000 microcomputer-controlled electrohydraulic servo rock triaxial pressure testing machine (Changchun Kexin Test Instrument Co., Ltd., Changchun city, China) was used to perform the uniaxial compressive test on the sandstone samples, as shown in Figure 5. The standard specimen size of the testing machine is \(\varphi 50 \times 100\text{mm}\), the maximum axial test stress is 2000 kN, and the stiffness of the test instrument is \(2 \times 10^7\text{ kN/m}\).

The tests are divided into two groups. One group is used for the uniaxial compression test to obtain the complete stress-strain curves of rock, and the other group is used for the loading and unloading test. For the uniaxial compression test, the loading of the sample adopts the electrohydraulic servo displacement control method to load the rock sample, and the displacement rate is 0.002 mm/s. Additionally, to obtain the elastic energy index of rock, the loading and unloading test was carried out on the rock. After loading to 80% of the UCS at the speed of 0.5 MPa/s, the rock was unloaded at the same speed to 1% of the UCS, and then the specimen was loaded again at the speed of 0.5 MPa/s until the specimen was destroyed.

2.5. Rockburst Tendency Index. In this study, four rockburst tendency indexes including elastic energy index \(W_{ET}\), impact energy index \(W_{CI}\), elastic strain energy index \(E_S\), and modified values of brittleness index (BIM) are used to analyze the influence of moisture content on rock bursting tendency of sandstone under F-T condition.
Figure 2: Test samples and instruments. (a) Part of sandstone samples, (b) SCQ type automatic stone cutter, (c) core drilling machine, and (d) automatic grinding machine.

Figure 3: The curve of the moisture content of rock sample changes with time variation.
3. Results and Discussion

3.1. Stress-Strain Curves. Figure 6(a) shows the stress-strain curves of sandstone with different moisture content under F-T cycles. It can be seen that the UCS of sandstone decreases from 82.39 MPa to 51.65 MPa with the increase of moisture content under F-T action. The deterioration of UCS is due to the accumulation of long-term fatigue damage under freeze-thaw action. In addition, under the action of F-T cycles, the stress-strain curve of sandstone under uniaxial compression can be roughly divided into four stages: compaction stage, linear elastic stage, weakening stage, and failure stage. The loading and unloading curves of sandstone with different moisture content under F-T cycles action are shown in Figure 6(b). These curves can be used to calculate all kinds of rockburst tendency indexes and make a comparative analysis.

3.2. \( W_{ET} \) versus Moisture Content. The elastic energy index is a kind of index which takes the ratio of elastic energy and permanent deformation dissipation energy as an index to measure the rockburst tendency of rock. In order to obtain \( W_{ET} \) of rock, cyclic loading and unloading tests were carried out. In this section, changes \( W_{ET} \) for different moisture content after 20 F-T cycles are studied. Figure 7 shows \( W_{ET} \) of sandstone with different moisture content after F-T cycles. With reference to Kidybinski’s classification of rockburst tendency [37], all rock samples have a strong rockburst tendency. However, according to the results given in the figure, with the increase of moisture content, \( W_{ET} \) of sandstone decreases from 8.11 to 7.67. In other words, with the increase of moisture content, \( W_{ET} \) of rock decreases relatively while the plastic deformation increases. This indicates that the elastic strain energy accumulated in the process of rock loading decreases gradually, while the permanent deformation energy consumed in plastic deformation increases relatively, which leads to the weakening of rockburst tendency.

In this study, the determination coefficient (\( R^2 \)) was used to select the best relationship between the rockburst index and moisture content. In different relationships (linear, polynomial, and exponential), the polynomial equation presents the highest \( R^2 \) (0.97931) for determining the variation of \( W_{ET} \) versus the increase in moisture content (Table 3). Therefore, the fitting curve shows the quadratic function relationship between \( W_{ET} \) and moisture content, expressed by the following equation:

\[
W_{ET}(\omega) = 0.02475\omega^2 - 0.23178\omega + 8.11404,
\]

where \( \omega \) is the moisture content of the rock sample.

3.3. \( W_{CF} \) versus Moisture Content. The impact energy index is a kind of index to measure the impact tendency of rock mass, which is the ratio of the energy stored before the peak strength of rock and the energy required for stable failure after the peak value. According to the complete stress-strain curves of rock under uniaxial compression, \( W_{CF} \) can be obtained. \( W_{CF} \) of rocks with different moisture content after F-T cycle is shown in Figure 8. According to the classification of rock impact tendency in coal industry standard [38], all the rock samples have a strong rockburst tendency. However, it is worth mentioning that \( W_{CF} \) of rock decreases with the increase of moisture content. This indicates that the existence of water in rock does reduce the rockburst tendency of rock. In order to obtain the relationship between \( W_{CF} \) and moisture content, \( R^2 \) criterion is still used in this section. Based on the best \( R^2 \) obtained, the linear relationship is defined as the optimum equation between \( W_{CF} \) and moisture content (Table 4 and Figure 8). Based on the result provided in Figure 8 and Table 4, a new linear equation is proposed to calculate \( W_{CF} \) of rocks with different moisture content after 20 F-T cycles:

\[
W_{CF}(\omega) = -3.32061\omega + 15.11992,
\]

where \( \omega \) is the moisture content of rock sample.

| Sample name | Immersion time (min) | Moisture content (%) |
|-------------|----------------------|----------------------|
| WT1         | 0                    | 0                    |
| WT2         | 30                   | 0.58                 |
| WT3         | 60                   | 1.06                 |
| WT4         | 390                  | 1.82                 |
| WT5         | 900                  | 2.43                 |
| WT6         | 1500                 | 2.80                 |
3.4. $E_s$ versus Moisture Content. The occurrence of impact and rockburst can be measured by the maximum stored elastic strain energy, that is, the elastic strain energy per unit volume of rock mass. Under uniaxial compression, the elastic strain energy stored in the rock sample before the peak strength is given by the following formula:

$$E_s = \frac{R_C^2}{2E}$$  \hspace{1cm} (4)

where $R_C$ is the uniaxial compression strength MPa and $E$ is the unloading tangential modulus MPa.

Figure 9 shows $E_s$ of rocks with different moisture content under F-T conditions. It can be seen that $E_s$ of rock varies between 127.76 kJ/m$^3$ and 237.85 kJ/m$^3$, and $E_s$ decreases significantly with the increase of moisture content. This shows that the increase of moisture content greatly affects the uniaxial compressive strength and deformation resistance of rock. According to Wang's classification of
rockburst tendency [39], when the moisture content of rock is 0%, the rockburst hazard is very high; when the moisture content of rock is 0.574%, 1.057%, and 1.82%, the rockburst hazard is high; and when the moisture content of rock is 2.428% and 2.803%, the rockburst hazard is moderate. The results indicate that the rockburst tendency of rock changes from a very high rockburst tendency to moderate rockburst tendency with the increase of moisture content under F-T condition. This is consistent with the mechanism of using the water injection method to prevent rockburst during tunnel excavation.

Figure 9 shows the change of $E_S$ with the increase of moisture content. To determine the optimum relationship between $E_S$ and moisture content, the above-mentioned $R^2$ criterion is still used in this section, which is to find the best functional relationship between $E$ and moisture content by comparing $R^2$. Therefore, the exponential function was chosen as the best relationship between $E$ and moisture content (Table 5). According to the relationship between $E_S$ and moisture content, a new empirical equation is proposed to estimate $E_S$ of rocks with different moisture content after 20 F-T cycles:

$$E_S(\omega) = 127.30489 + 109.19648 e^{-0.92721\omega}$$

(5)

where $\omega$ is the moisture content of rock sample.

3.5. BIM versus Moisture Content. The modified value of the brittleness index (BIM) is the ratio of the deformation energy stored before the peak load and the elastic deformation energy stored at the peak value calculated according to the elastic modulus $E_{50}$. It is one of the important indexes to evaluate the rockburst tendency. The BIM of sandstone with different moisture content after 20 F-T cycles is shown in Figure 10. According to the distribution of data points in Figure 10, with the increase of moisture content, the BIM of rock sample gradually increases from 1.05 to 1.29. According to Aubertin’s classification of rockburst tendency [40], in this study, when the moisture content of rock is 0%, 0.574%, 1.057%, and 1.820, the rockburst risk is high; while the rock moisture content is 2.428% and 2.803%, the rockburst risk is moderate. With the increase of moisture content, the rockburst tendency of rocks changes from high rockburst tendency to moderate rockburst tendency. It can be seen that with the increase of moisture content, the brittleness of rock gradually weakens and the plasticity increases gradually. In order to determine the best relationship between BIM and moisture content of rock, $R^2$ criterion is still used in this section. By comparing $R^2$, the exponential function is considered to be the best function between BIM and moisture content (Table 6). Based on the information given in Figure 10 and Table 6, the exponential relationship between BIM and moisture content is given in the following equation:

$$BIM(\omega) = 1.00685 + 0.04388 e^{0.66585\omega}$$

(6)

where $\omega$ is the moisture content of rock sample.

3.6. Comparative Analysis. In this section, we will evaluate the impact propensity of rocks with different moisture content after F-T cycles by integrating the four important indexes mentioned above. By referring to the corresponding specifications, the rockburst tendency of rocks with different moisture content after F-T cycles is given in Table 7. According to $W_{ET}$ and $W_{CF}$, the rock samples have a strong rockburst tendency. Although the increase of moisture content cannot make the rock samples
become moderate rockburst tendency, it is worth noting that $W_{ET}$ and $W_{CF}$ decrease monotonically with the increase of moisture content. This indicates that the existence of water reduces the uniaxial compressive strength and elastic modulus of rock under freezing and thawing, which will lead to the weakening of brittleness and the enhancement of plasticity. In contrast, $E_S$ and BIM of rock confirm that water in rock can effectively reduce its rockburst tendency. According to the classification of rockburst tendency by scholars based on $E_S$ and BIM, the rockburst tendency of sandstone changes from high rockburst tendency to moderate impact tendency with the increase of moisture content under F-T cycles (Table 7).

According to $R^2$ criterion, the relationship between $W_{ET}$ and moisture content is quadratic, $W_{CF}$ is linear, and $E_S$ and BIM are exponential. The difference is that $E_S$ is positively correlated with moisture content, while BIM is negatively correlated with moisture content. Previous studies have found that BIM and $W_{ET}$ have linear relationship with moisture content. The main reason for this conflict is that the rock studied by predecessors has not experienced F-T cycles, and the moisture content of rocks in the test design is less. It should be noted that the relationship between rockburst indexes and moisture content of F-T rock studied in this paper is consistent with the previous research results on the relationship between unfrozen rocks and moisture content.

In this study, it is found that the UCS and impact tendency of rock decrease with the increase of moisture content under freeze-thaw cycles. In practical engineering, the water injection method was used to prevent rockburst. Therefore, groundwater should be considered when evaluating the stability of rock mass in practical projects in cold regions. This is of great significance to the safety of engineering design and the rationality of decision-making in cold regions. In order to quantitatively evaluate the rockburst tendency of rocks, up to now, scholars at home and abroad have put forward more than ten evaluation indexes or methods from different analysis angles according to different conditions [41]. In this study, only the commonly used indexes are used to evaluate the rock impact tendency. Therefore, in future research, we will synthesize more than ten evaluation indexes or methods to comprehensively evaluate the impact tendency of rocks with different moisture content under the action of F-T cycles.

4. Conclusions

In this study, an experimental study was conducted to evaluate the effect of moisture content on the bursting liability of sandstone under freeze-thaw cycles in northern China. For this purpose, 21 core samples were prepared from boreholes and then tested for UCS, cyclic loading and unloading, and F-T testing of sandstone in the laboratory. Therefore, the summary results of this study are presented as follows:

1. By increasing the moisture content at 20 F-T cycles, the UCS of sandstone decreases gradually from 82.39 MPa ($w = 0\%$) to 51.65 MPa ($w = 2.80\%$).
2. Considering the impact tendency indicators comprehensively, the bursting liability of rocks was changed from strong to weak by the increasing moisture content of rock under the condition of F-T cycles.
3. New empirical formulas were presented and suggested to calculate $W_{ET}$, $W_{CF}$, $E_S$ and BIM of sandstone samples with different moisture content at 20 F-T cycles in northern China.
4. In cold regions, the effect of moisture content on the mechanical properties and rockburst tendency of rock is very obvious. To make the engineering design and construction decision more reasonable and reliable, the underground water factor should be fully considered in tunnel excavation and evaluation of underground engineering rock mass stability.
Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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