Static Mechanical Properties and Failure Modes of Layered Sandstones in Freeze-thaw Cycles

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Abstract. Because the underground space in the alpine area is often in the freezing and thawing cycle state, as well as the layered rock is widely found in nature and the mechanical properties are complex, the mechanical properties of the lower rock in the freeze-thaw cycle are directly related to the development and utilization of the underground space in the alpine area. Based on the electro-hydraulic servo pressure tester, the static compression test of freeze-thaw damage specimen was carried out to study the strength, deformation, failure mode and anisotropy characteristics of the layered sandstone in freeze-thaw cycle condition. Also, the influence of freezing and thawing action and layered structure on the static mechanical properties and the mechanism of action were analysed. Finally, we obtained the following conclusions: The stress-strain curves of vertical and parallel bedding sandstones under freezing and thawing conditions can be roughly classified into compaction phase, elastic phase, plastic yielding stage and failure stage, and with the increase of freezing and thawing times, the peak stress and elastic modulus of layered sandstone samples decrease gradually; compared with vertical bedding samples, the mechanical parameters of parallel bedding samples deteriorate faster under freeze-thaw cycles; the deterioration of mechanical parameters of parallel layered specimens is faster under the condition of freeze-thaw cycle; the anisotropy index Re of the intensity increased from 1.07 in 0 freeze-thaw cycle to 1.46 in 40 freeze-thaw cycles, and the intensity anisotropy became more significant as the number of freeze-thaw cycles increased.; when the number of freeze-thaw cycles is less than 10 times, the vertical bedding test specimen breaks the main crack at a certain angle (about 30°), showing shear failure through multiple bedding, while when the number of freeze-thaw cycles increases, the main crack tends to be parallel to the loading direction; parallel bedding samples always exhibit splitting failure along the bedding. The test results can provide theoretical support for the development of special underground space such as alpine and freeze-thaw areas.

1. Introduction
The rock is formed in an open material system and is a cement body of various mineral particles. When different kinds of mineral particles, micropores and cracks are regularly arranged and stacked, a
layered structure is generated, due to the strength of each layer itself. The parameters are different and there are a large number of bedding joints, so the mechanical properties of the bedding rock are more complex than the homogeneous rock compared to isotropic rocks. The existence of bedding has uneven distribution of mechanical property properties. The same rock material has regular distribution of performance advantages and disadvantages. When subjected to load, anisotropic characteristics of failure mode, strength and deformation performance often occur. The mechanical properties of the engineering are more complicated, and the accumulation of damage under the freeze-thaw cycle increases the complexity of the physical and mechanical properties, directly affecting the reliability of the engineering structure, based on the previous isotropic rock in the freeze-thaw environment. It is difficult to provide an accurate reference to production practices.

Mustafa [1] (2015) studied the freeze-thaw degradation law of the physical and mechanical properties of andesite based on the longitudinal wave velocity, porosity and tensile and compressive strength changes. Ghobadi [2] (2016), Kolay [3] (2016), Heidari [4] (2017), İnce [5] (2016) carried out freeze-thaw treatment and mechanical tests on different rocks, and summarized the attenuation law of rock strength parameters with increasing number of freeze-thaw cycles. Sudisman [6] (2016) carried out freeze-thaw and tensile tests on three kinds of rocks, and studied the influence of rock moisture content, porosity and species on the accumulation of freeze-thaw damage. Luo [7] (2011) carried out freeze-thaw tests on four common rocks, and found that the lower the strength of the rock, the more serious the loss of freeze-thaw quality. Wu [8] and Zhang [9] (2013, 2014) studied the correlation between physical parameters such as longitudinal wave velocity and tensile and compressive strength and model under freeze-thaw cycles. Fang [10] (2014) carried out simulation experiments on the freeze-thaw weathering of the Yungang Grottoes sandstone, and obtained the main mechanical properties of the saturated and dry Yungang Grottoes in the freeze-thaw environment.

In this paper, the static compression test of freeze-thaw specimens is carried out based on electro-hydraulic servo pressure tester. The strength, deformation, failure mode and anisotropic characteristics of the layered sandstone under freeze-thaw cycles are studied. The freeze-thaw and layer structure are analyzed. The influence of static mechanical properties and its mechanism of action have paved the way for rock engineering and underground engineering in freeze-thaw areas.

2. Static compression test of layered sandstone in freeze-thaw cycle

The static compression test is the most common one in the material mechanics test. The strength and deformation parameters obtained under the test conditions have a basic reference value for the mechanical properties of the rock under various storage environments and loading conditions. Therefore, based on the electro-hydraulic servo pressure tester, a static compression test was performed on the layered sandstone at a loading mode of 20 kN/min, as shown in Fig. 1.

Figure 1. Uniaxial static compression test

The electro-hydraulic servo pressure test system used in the test consists of a pressure table, a hydraulic pump and a microcomputer control system. The loading limit of the press is 2000 kN. Through the measurement and control software, the complete stress-strain curve of the sample under
pressure can be obtained.

2.1. Test piece preparation
The bedding sandstone used in this experiment is fresh wood grain sandstone taken from an underground defense project in Yunnan. The mineral particles are small and densely arranged. The whole is yellowish in the dry state, and the layered structure and the layered structure can be seen. Directional distribution of pore strips. Structurally, the rock is attributed to a transversely isotropic material. According to GB/T 50266-2013[11], the original rock mass is divided and polished into a cylindrical standard test piece with a height to diameter ratio of 2:1. After processing, the test piece is 100±0.3 high. Mm, diameter 50 ± 0.3 mm. The parallel error of the two end faces is less than 0.05 mm; the vertical error between the end face of the test piece and the axis of the cylinder is less than 0.25°, and the sample is processed as shown in Fig. 2.

Figure 2. Static compression specimens of two bedding angle: (a)Vertical bedding sample; (a) Parallel bedding sample;

A film is coated on the surface of the sample (as shown in Fig. 2) to maintain the overall shape after the sample is destroyed. At the same time, it is used to trace the crack after the compression test as the original data for studying the failure mode.

2.2. Static compression test plan
In order to explore the effects of the number of freeze-thaw cycles and the direction of the bedding structure on the mechanical properties and failure modes of the bedding sandstone, and then analyze its mechanism of action, the static compression test scheme shown in Table 1 was developed.

| Layering direction | Freezing and thawing times | Remarks |
|--------------------|---------------------------|---------|
| Vertical bedding    | 0, 10, 20, 30, 40         | 3 samples for each working condition |
| Parallel layering   | 0, 10, 20, 30, 40         | 3 samples for each working condition |

According to the relevant standard of GB/T 50266-2013[11], in the compression test, the sample of 0 freeze-thaw cycles shall be in a saturated state, and the remaining freeze-thaw samples shall be subjected to mechanical tests in time after completion of the freeze-thaw cycle. If it cannot be performed in time, while it shall be stored in water, and perform mechanical tests in the short term.

3. Freezing and thawing apparent morphology of static pressure specimens
The apparent morphology of rocks in the freeze-thaw environment can reflect the damage development from the macroscopic level. It is the external manifestation of the overall damage degree of rock materials under freezing and thawing conditions. The physical and mechanical properties of
the rock are based on the apparent morphology of the rock. The preliminary judgment is a method often used in engineering practice, which can provide preliminary judgment basis for engineers. At the same time, it can summarize and analyze the changes of the apparent morphology of rock samples under freezing and thawing, and it is also helpful to explore the mechanism of freeze-thaw injury.

3.1. Deterioration of apparent morphology of vertical and parallel samples

According to the apparent damage of the sample during the freeze-thaw cycle, the freeze-thaw cycle node with obvious changes in the apparent morphology of the sample is analyzed. The apparent morphology of the sample is not completed until 16 freeze-thaw cycles are completed. Significant changes occurred. After 16 freeze-thaw cycles, the deterioration of the apparent morphology of the samples gradually appeared. The main process is shown in Fig. 3.

(a) 16 times——When 16 freeze-thaw cycles were completed, the surface layer of the vertical bedding sample began to peel off, and the parallel layered samples did not change significantly.

(b) 24 times——When 24 freeze-thaw cycles were completed, small bulges appeared on the sides of the stratified samples in both directions, and the surface of the bulge distributed fine cracks and scattered a small amount of rock particles.

(c) 30 times——When 30 freeze-thaw cycles were completed, the laterally (substantially along the bedding direction) of the undeveloped fine cracks appeared on the side of the vertical bedding sample, which was about 3 to 4 cm long; the virtual layer due to the layering peeling appeared on the side of the parallel bedding sample. A small amount of surface peeling occurred in some samples.

(d) 36 times——When 36 freeze-thaw cycles were completed, the transverse crack width on the side of the vertical bedding sample increased, and the surface peeling at the end increased. At the same
time, due to the falling of the rock particles, a virtual hole appeared on the side of the sample; A large area of spalling occurred, and at the same time, a small amount of transverse unopened fine cracks appeared in the middle of a small number of parallel bedding samples.

(e) 40 times——When 40 freeze-thaw cycles were completed, the transverse cracks on the side of the vertical bedding sample were further developed, which showed an increase in the number, an increase in the width, and a length extension. At the same time, surface peeling occurred on the side; the side of the parallel bedding sample was severely peeled off while observing. It was found that severe surface spalling occurred around the crack produced after 36 freeze-thaw cycles. At this time, the cylindrical samples of the two bedding directions have been deformed, and the central portion of the sample is swollen.

Figure 3. Superficial sandstone-static pressure specimen-freeze-thrust cycle apparent morphology

3.2. Anisotropic characteristics of apparent morphology freeze-thaw degradation

Although the two directions of the bedding samples are wood grain sandstones, the relationship between the bedding direction and the sample size is different, and the effect of the sample itself on the damage is also different, resulting in the same freeze-thaw cycle conditions. There are significant differences in the development of apparent damage morphology between the two types of bedding samples:

(1) The damage characteristics of the vertical bedding specimens appeared earlier, and the obvious damage characteristics were observed when 16 freeze-thaw cycles were completed. The damage characteristics of the parallel bedding samples appeared later, and the obvious features did not appear until 24 freeze-thaw cycles were completed.

(2) As shown in Fig. 3, the damage characteristics and development order of the two types of stratified samples were different.

(3) As the number of freeze-thaw cycles increases, the parallel layered static compression specimens are more severely exfoliated than the vertical bedding specimens, and the waist bulging is more pronounced; the vertical bedding specimens are more prone to be produced along the bedding. The transverse crack.

4. Static pressure and compression characteristics of layered sandstone in freeze-thaw cycles

During the freeze-thaw cycle, new damages occur in the rock specimens, and the damage accumulation is deepened, which has a significant impact on the mechanical properties of the specimens. The following is an analysis of the specific mechanical parameters of the frozen-thawed bedding sandstones. The effect of freezing and thawing times on the mechanical properties of bedding sandstone.

According to the GB/T50266-2013[11], the static compressive stress-strain curve is extracted, and the mechanical parameters of each test group are obtained. Then the arithmetic mean of each set of mechanical parameters is obtained. The results are shown in Table 2.

Among them, the elastic modulus is calculated as follows:

$$E = \frac{\sigma - \sigma_a}{\varepsilon_b - \varepsilon_a}$$  \hspace{1cm} (1)
where \( \sigma_a, \epsilon_a \) are the stress and strain values at the starting point of the straight line segment on the stress-strain curve; \( \sigma_b, \epsilon_b \) are the end point stress and strain value of the straight line segment; \( E \) is the elastic modulus.

### Table 2. Freezing-thawing cycle bedding sandstone static pressure test results

| Group           | Freeze-thaw cycles | Peak stress (MPa) | Peak strain \((10^{-3})\) | Elastic Modulus (GPa) |
|-----------------|--------------------|-------------------|---------------------------|-----------------------|
| Vertical bedding| 0                  | 64.87             | 19.87                     | 5.78                  |
|                 | 10                 | 64.14             | 19.96                     | 5.33                  |
|                 | 20                 | 55.96             | 22.10                     | 5.14                  |
|                 | 30                 | 49.06             | 24.00                     | 4.13                  |
|                 | 40                 | 46.93             | 25.30                     | 4.04                  |
| Parallel bedding| 0                  | 60.17             | 16.80                     | 6.36                  |
|                 | 10                 | 56.94             | 17.78                     | 5.92                  |
|                 | 20                 | 47.88             | 19.61                     | 4.64                  |
|                 | 30                 | 38.44             | 19.79                     | 3.65                  |
|                 | 40                 | 32.08             | 22.85                     | 3.01                  |

### 4.1. Freeze-thaw degradation analysis of mechanical parameters

Fig. 4 is a graph of the mechanical parameters of the layered sandstone-freeze-thaw times according to Table 2. The analysis shows that as the number of freeze-thaw cycles increases, the peak stress and modulus of the bedding sandstone sample decrease gradually, and the peak strain increases gradually. It can be seen from Fig. 4(a) and Fig. 4(b) that the mechanical parameters of the parallel bedding samples decrease faster under the freeze-thaw cycle conditions than the vertical bedding samples: after 40 freeze-thaw cycles, parallel bedding The peak stress of the sample was reduced by 47% and the modulus of elasticity was reduced by 53%. The peak stress of the vertical bedding sample was reduced by 28% and the modulus of elasticity was reduced by 30%.

Among them, the peak stress \( \sigma \) and the number of freeze-thaw cycles show a clear linear relationship, and the fitting effect is good. The relationship is shown in Fig. 4(a).

As the peak strain increases with the increase of the number of freeze-thaw cycles, on the one hand, the internal porosity defects are further developed due to the freeze-thaw cycle. Once subjected to the crushing load, more strain is generated during the compaction phase; On the one hand, due to the softening effect of water on rock minerals, the deformation ability of the sample under freezing and thawing conditions is enhanced, resulting in an increase in peak strain at the time of sample failure.
Figure 4. Mechanical parameters of sandstone samples under freeze-thaw cycles: (a) Peak stress; (b) Peak strain; (c) Modulus of elasticity

Under normal circumstances, the development of freeze-thaw damage of parallel layered specimens is higher than that of vertical bedding samples. If the damage of materials is higher, its ability to resist deformation will be weaker \cite{12}. However, as shown in Fig. 4(c), before 10 freeze-thaw cycles, the elastic modulus of the parallel bedding sample is larger than that of the vertical bedding sample. The reason for the analysis is the performance of the bedding structure under load.

1. When the parallel layered specimens are subjected to load instability, the internal structural mechanical effects of the rock are similar to the "pressing rod instability" of each layer \cite{13}, The deformation resistance of the material is fully exerted, and the elastic modulus is greater.

2. When the number of freeze-thaw cycles increases, the degree of freeze-thaw damage gradually deepens, so that the cumulative effect of damage gradually weakens the "contribution" of the layered structure to the deformation resistance of the sample. In addition, the parallel layered samples have higher damage development, so after 20 freeze-thaw cycles, the parallel layered samples have lower elastic modulus than the vertical layered samples.

4.2. Evolution Analysis of Anisotropic Index

Because the wood grain sandstone used in the experiment has obvious bedding structure, it shows obvious difference when conducting mechanical tests along different bedding directions. The rock anisotropy index is the physical quantity derived from the difference in properties of materials in different directions.

As shown in Fig. 5, under the same number of freeze-thaw cycles, the peak stress and peak strain of the vertical bedding samples are larger than those of the parallel bedding samples. The peak stress difference between the two types of bedding samples increases with the number of freeze-thaw cycles. The value gradually increases, that is, the difference gradually increases. In order to quantitatively study the anisotropic characteristics of the bedding sandstone under the freeze-thaw cycle conditions, an anisotropic index is measured to measure the rock strength. The closer the value is to 1, the weaker the anisotropy.

\[ R_c = \frac{\sigma_{c(90)}}{\sigma_{c(min)}} \]  

(2)

In the formula, \( \sigma_{c(90)} \) is the peak stress of the vertical bedding sample; \( \sigma_{c(min)} \) is the minimum peak stress at each layer structure angle \( \alpha \). In this paper, the value is taken at \( \alpha = 0^\circ \), that is, the peak stress of the parallel layered sample.

Similarly, the peak strain anisotropy index \( R_l \) is defined by the definition method of the strength anisotropy index \( R_c \):

\[ R_l = \frac{\varepsilon_{c(90)}}{\varepsilon_{c(min)}} \]  

(3)
In the formula, $\varepsilon_{c\epsilon(90)}$ is the peak strain of the vertical bedding sample; $\varepsilon_{c\epsilon(min)}$ is the minimum peak strain at each layer structure angle $\alpha$. In this paper, the value is taken at $\alpha=0^\circ$, that is, the peak stress of the parallel layered sample.

Figure 5. Anisotropy index - number of freeze-thaw cycles

As shown in Fig. 5, $R_c$ is increased from 1.07 at 0 times of freezing and thawing to 1.46 at 40 times of freezing and thawing, that is, the intensity anisotropy characteristic becomes more and more obvious as the number of freeze-thaw cycles increases; and the difference in peak strain is relatively stable. In the 40 freeze-thaw cycles, the average value of the peak stress anisotropy index $R_l$ was 1.15.

5. Freezing-thawing cycle bedding sandstone static pressure failure mode

The failure mode of rock specimens is the visual representation of its load response. The mechanical properties and failure modes of rock are actually two manifestations of their physical and mechanical properties. The relationship between the two is the relationship between the table and the inside, which can explain each other.

The failure mode of rock is not only related to loading conditions and mineral properties, but also closely related to its damage degree and internal structural characteristics. The rock bedding and the pores and micro-cracks along the bedding distribution are all weak structures when they are unstable, and they are more likely to be connected as destructive large cracks. It can be seen by observing the crack morphology of the sample (see Fig. 6), because the bedding direction and load relationship of the two bedding sandstone samples are different and the damage development under freezing and thawing conditions is different. Therefore, under the same number of freeze-thaw cycles, the cracks and morphology formed by the uniaxial static pressure failure of the two layered samples also showed significant anisotropy characteristics. At the same time, it was found from the test results that the freeze-thaw damage accumulation test The mode of destruction has a significant impact.
For vertical bedding samples, when the number of freeze-thaw cycles is 0 or 10 times, the main crack is broken at a certain angle (about 30°), showing a shear failure pattern running through multiple bedding planes, but the number of freeze-thaw cycles When increasing, the main crack is broken and the loading direction is gradually parallel.

For parallel bedding samples, since the original rock defects and freeze-thaw damage are more parallel to the bedding structure distribution, when the load is applied along the axial direction of the sample, the defects further develop, and finally penetrate and expand into fracture cracks along the bedding. Therefore, whether it is 0, 10 freeze-thaw, or 20, 30, 40 freeze-thaw, the failure mode of the sample is crust failure; at the same time, it can be observed that when the number of freeze-thaw cycles increases, the two bedding samples The number of cracks showed an overall increasing trend.

Comparing the failure modes of the two bedding sandstone samples when the number of freeze-thaw cycles is small, the reason why the vertical bedding specimens break the crack at a certain angle may be that the joint of the layer is weak as the degree of freeze-thaw damage is low. The effect is relatively obvious when the crack develops, and the guiding cracking path is shifted toward the bedding direction; However, as the number of freeze-thaw cycles increases, the damage of the rock matrix is deepened, and the influence of the difference in the fracture strength caused by the bedding structure on the development of the fracture path is gradually weakened. Therefore, the fracture cracks gradually show the typical tensile failure mode of the isotropic rock under uniaxial static compression, which leads to the development of the fracture crack along the loading direction. The development law of uniaxial compression cracks in the frozen-thawed bedding sandstone as shown in Fig. 7 can be summarized.

6. Conclusion
Based on the electro-hydraulic servo pressure tester, a static compression test was carried out on the bedding sandstone samples subjected to 0, 10, 20, 30, 40 freeze-thaw cycles. The freeze-thaw cycle bedding sandstone was studied under static compression conditions. The main conclusions of strength, deformation, failure mode and anisotropy are as follows:

(1) The stress-strain curves of vertical and parallel bedding sandstones under freeze-thaw conditions can be roughly classified into compaction phase, elastic phase, plastic yielding stage and
failure stage; whether vertical or parallel layered samples, when the number of freeze-thaw cycles increases, the strain range of the compacted section becomes larger, and the slope of the elastic section curve decreases. Under the freeze-thaw cycle conditions, the peak-point deterioration path and the post-peak strain softening curve shape of the vertical-parallel layered sandstone specimen stress-strain curve have obvious to the opposite sex feature.

(2) With the increase of the number of freeze-thaw cycles, the peak stress and elastic modulus of the bedding sandstone samples gradually decrease, and the peak strain gradually becomes larger. Compared with the vertical bedding samples, the mechanical parameters of the parallel bedding samples are in the freeze-thaw cycle conditions. The degradation is faster; the bedding structure has a "pressure bar" effect when the parallel layered sample is loaded, and the elastic modulus of the parallel layered sample is greater than that of the vertical bedding sample before the 10 freeze-thaw cycles. When the number of fusion times increases, the action of the pressure bar is weakened, and the elastic modulus of the vertical bedding sample is larger than that of the parallel bedding sample.

(3) The anisotropy index Re of the intensity increases from 1.07 in the 0 freeze-thaw cycle to 1.46 in the 40 freeze-thaw cycles. When the number of freeze-thaw cycles increases, the intensity anisotropy becomes more significant; and the difference in peak strain is relatively stable. In the 40 freeze-thaw cycle tests, the peak strain anisotropy index Rl averaged 1.15.

(4) When less than 10 freeze-thaw cycles, the vertical bedding specimen breaks the main crack at a certain angle (about 30°), showing shear failure through multiple layers. When the number of freeze-thaw cycles increases, the main crack and loading. The direction tends to be parallel; while the parallel layered specimens always exhibit splitting failure along the bedding; as the accumulation of freeze-thaw damage increases, the number of cracks in both bedding samples increases overall.

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