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Overview of Current Research on Deformation and Mechanical Properties of Fissured Rocks under Freeze-Thaw Cycles

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Abstract

This paper elucidates the practical significance of studying the deformation and mechanical properties of fissured rocks under freeze-thaw cycles. It systematically analyzes that the key research focuses on fissured frozen rocks should revolve around frost heave force, freeze-thaw deformation, compressive strength, tensile strength, and fracture toughness. Additionally, it summarizes recent research progress made by domestic and international scholars in this field. The analysis results indicate that research in this area is gradually converging toward the fundamental influencing factors of frost heave force and deformation. Numerous scholars have already utilized comprehensive, multi-scale physical and mechanical testing methods to analyze and detect the mechanical properties of rocks under freeze-thaw conditions. Furthermore, the paper identifies and summarizes the existing research gaps in this field.

Keywords

Freeze-Thaw Cycles; Rock Fissures; Frost Heave Force; Freeze-Thaw Deformation; Mechanical Properties.

1. Introduction

Since the beginning of the 21st century, the construction of underground rock engineering projects in China has developed rapidly. These projects typically refer to temporary or permanent structures excavated and built within underground rock, such as highway and railway tunnels, mine chambers, and underground hydropower stations [1]. Tunnel engineering, as an important component of infrastructure construction, has seen a significant increase in both scale and number in recent years. With the continuous improvement of the transportation network, the construction of railway and highway tunnels is gradually extending into high-altitude or cold regions with extreme climatic conditions.

Cold-region tunnel engineering, as a typical example of rock underground engineering in cold areas, has always attracted widespread attention due to the stability issues of the surrounding rock. The surrounding rock of tunnels and underground engineering is often filled with numerous pores and fissures, which are usually saturated with groundwater. In cold regions, temperatures often drop below zero, and seasonal alternations cause severe temperature fluctuations. Under these conditions, rocks are subjected to freeze-thaw cycles. During these cycles, water molecules within the rock pores undergo a phase change from water to ice, generating frost heave force. The transition from liquid to solid state results in approximately a 9% volumetric expansion. The surrounding rock of tunnels,

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influenced by cyclic temperature stresses and pore ice frost heave force, undergoes uneven expansion and contraction of the rock matrix particles. This process expands the internal rock pores, leading to macrostructural damage and degradation of mechanical properties, thereby affecting tunnel stability [2]. This dynamic process can cause significant damage to the overall structure of the rock mass. Consequently, the series of issues arising from freeze-thaw cycles in frozen rock cannot be ignored. These problems not only pose numerous challenges for engineering design, construction, and operational management but also often result in substantial economic losses [3]. Therefore, in-depth research on the deformation and mechanical properties of fissured rocks under freeze-thaw cycles is of great significance for disaster prevention and mitigation in cold-region tunnels and underground rock engineering.

2. Key Research Focuses on the Deformation and Mechanical Properties of Fissured Rocks under Freeze-Thaw Cycles

2.1 Frost Heave Force in Rocks under Freeze-Thaw Cycles

Under freeze-thaw cycles, the water within water-saturated rocks continuously undergoes phase transitions between liquid and ice. When water freezes into ice, it expands by approximately 9% in volume. Simultaneously, the surrounding rock matrix particles contract and deform due to the cold. The mutual compression between the solid ice and the rock matrix particles generates frost heave force within the rock. Frost heave force is crucial for studying freeze-thaw damage in fissured rock masses. Due to the natural presence of pores and microcracks in rocks, frost heave force can be divided into pore frost heave force and fissure frost heave force. Pore frost heave force is generated by the solid ice within rock pores compressing the surrounding matrix particles. Given the abundance of natural pores in rocks, the volume of rock pores continually expands under the influence of pore frost heave force. The tensile stress from frost heave force weakens the cohesion among rock matrix particles, damages the cementing materials, and gradually loosens the rock matrix particles. Fissure frost heave force is generated by the solid ice within rock microcracks compressing the surrounding matrix particles. Microcracks often exist as thin, linear features within rocks. Fissure frost heave force leads to stress concentration at the tips of the cracks, causing the cracks to extend, expand, and intersect, forming new microcracks. The development and increase of microcracks significantly weaken the mechanical properties of the rock.

2.2 Freeze-Thaw Deformation in Rocks under Freeze-Thaw Cycles

Under freeze-thaw cycles, the phase transition of water to ice within the rock induces frost heave, which also leads to the contraction effect of the rock matrix. This means that under the tensile stress of low-temperature frost heave force, the rock matrix undergoes expansion deformation. Simultaneously, the rock matrix particles exhibit thermal expansion and contraction in response to temperature changes; they contract when the temperature decreases and expand when the temperature increases. Under the combined effect of these two processes, rocks generally exhibit expansion deformation after repeated freeze-thaw cycles, resulting in residual strain. This process damages the rock cementation, weakens cohesion, and gradually loosens the rock matrix particles. As a result, rock pores and microcracks continuously expand and interconnect, leading to damage in the rock matrix. Frost heave deformation is one of the key characteristics used to measure frost heave force.

2.3 Physical and Mechanical Properties of Rocks after Freeze-Thaw Cycles

2.3.1 Compressive Strength of Rocks

Compressive strength of rock refers to the maximum compressive stress a rock can withstand under an external load before failure. Since rocks in actual engineering applications are often subjected to compressive stresses, compressive strength is a crucial indicator for evaluating the mechanical properties of rocks. Uniaxial compressive strength typically refers to the maximum axial stress a rock specimen can endure under axial pressure without confining pressure at failure. Triaxial compressive strength refers to the maximum axial stress a rock specimen can withstand under three-directional loading conditions at failure.

Frost resistance of rock refers to its ability to resist freeze-thaw damage and is an important indicator for evaluating the frost stability of rocks. It is commonly expressed by the freeze-thaw coefficient, which is the ratio of the uniaxial compressive strength of the rock after multiple freeze-thaw cycles (from -20°C to 20°C) to the saturated uniaxial compressive strength before freeze-thaw cycles. After repeated freeze-thaw cycles, the rock matrix undergoes the previously described damage effects from frost heave force and freeze-thaw deformation, significantly reducing its ability to resist external damage. The more freeze-thaw cycles a rock undergoes, the more phase transitions between water and ice occur. This repetitive process increases the number of pores and cracks within the rock, reduces cohesion between matrix particles, and progressively weakens the rock matrix. Consequently, the rock's ability to resist failure diminishes, leading to a continuous decrease in compressive strength and the freeze-thaw coefficient.

2.3.2 Tensile Strength of Rocks

Tensile strength of rock refers to the maximum tensile stress that a rock specimen can withstand under uniaxial tensile loading before failure. Under the tensile stress induced by frost heave force, the cohesion among rock matrix particles weakens, and the cementing materials are damaged, resulting in frost heave damage during freeze-thaw cycles. Therefore, the tensile strength of rock is a crucial indicator for studying the stability characteristics of rock engineering under freeze-thaw conditions. After undergoing repeated freeze-thaw cycles, the tensile strength of rock gradually decreases due to the repeated effects of frost heave force and freeze-thaw deformation. Since the tensile strength of rock is significantly lower than its compressive strength, the reduction in tensile strength has a greater impact on the stability of rock engineering projects. This issue deserves considerable attention.

2.3.3 Fracture Toughness of Rocks

Fracture toughness characterizes the ability of rock to resist crack propagation. The magnitude of fracture toughness determines the ease of crack extension; the smaller the value, the easier it is for cracks to extend, which is beneficial for hydraulic fracturing. Since the initiation, cracking, and penetration of cracks in rock materials fall within the scope of rock fracture mechanics, the mechanical behavior of rocks under freeze-thaw cycles is closely related to their fracture characteristics. Therefore, the fracture toughness of rocks is an important indicator for evaluating the safety and stability of rock engineering in cold regions. Rocks naturally contain various levels of micro-pores and cracks, which can be regarded as an initial damage field distributed within the rock material. Under freeze-thaw conditions, this damage field continuously enlarges due to the repeated effects of frost heave force and freeze-thaw deformation. Consequently, the fracture toughness of rocks gradually decreases with the increasing number of freeze-thaw cycles.

3. Current Research Status at Home and Abroad

3.1 Research Status on Frost Heave Force in Fissured Rocks under Freeze-Thaw Conditions

Currently, Tian Zhen et al. [4] have conducted experimental studies on the evolution patterns of force, temperature, and strain in water-saturated fissured red sandstone during freeze-thaw processes. The experiments revealed that temperature changes inside the fissures lag behind those on the surface and that a sliding phenomenon occurs during the formation of ice plugs. Qiao Chen et al. [5], through real-time monitoring experiments of freeze-thaw ice wedging, investigated the variation patterns and evolution characteristics of frost heave force in water-saturated fissured granite. The experimental results indicated that frost heave force is influenced by fissure size, freezing temperature, and the number of freeze-thaw cycles. With ongoing freeze-thaw cycles, the peak frost heave force gradually decreases. Winkler [6] observed in freeze-thaw experiments that when pore volume does not expand, pore water generates different expansion pressures at various freezing temperatures. Specifically, at -5°C, -10°C, and -20°C, the phase transition induced expansion pressures were 61.0 MPa, 133.0 MPa, and 211.5 MPa, respectively. These findings reveal the pressure variation of pore water under different conditions.

3.2 Research Status on Freeze-Thaw Deformation Characteristics of Fissured Rocks

Jia Peng et al. [7] conducted freeze-thaw cycle experiments on water-saturated fissured green sandstone, red sandstone, and granite with varying porosities. They analyzed the deformation patterns over time and temperature changes for rocks with different fissure lengths, fissure widths, and lithologies during freeze-thaw cycles. The experiments revealed that as the number of freeze-thaw cycles increased, the frost heave force in the rocks gradually increased, the residual strain also increased, and the maximum strain exhibited fluctuating growth. Kang Yongshui et al. [8] studied the deformation characteristics of rocks in low-temperature environments and the frost heave deformation of tunnels in cold regions. By testing the strain characteristics of dry and water-saturated rock samples in low-temperature environments, they found that water-saturated rock samples exhibited residual strain during the stages of contraction, frost heave, thaw contraction, and thermal expansion, whereas dry rock samples only showed linear elastic characteristics. Matsuoka [9] explored the effects of water supply conditions and cooling rates on rock freeze-thaw strain, using temperature and strain of the rock as variables. The study focused on examining how the rock's temperature and strain, as functions of time, are influenced by water supply conditions and cooling rates.

3.3 Research Status on the Physical and Mechanical Properties of Rocks after Freeze-Thaw Cycles

3.3.1 Research Status on Compressive Strength of Rocks

Bai Yao [10], using the shaft freezing project at the Shilawu Mine in Northwest China as an example, selected typical red sandstone from the water-filled aquifer surrounding the shaft as the research material. A triaxial compression test was conducted on artificially prepared underground ice samples using a frozen soil triaxial tester. The study analyzed the triaxial compressive strength, deformation, and failure characteristics of red sandstone under different sizes and loading rates. Zhang Jizhou et al. [11] investigated the damage degradation mechanisms and mechanical properties of rocks under freeze-thaw conditions through cyclic freeze-thaw tests. The results indicated that the freeze-thaw damage degradation patterns of rocks are influenced by lithology and environmental conditions, with more severe freeze-thaw strength damage observed under acidic conditions. Fu Helin et al. [12] studied the elastic properties and compressive strength of the slate with varying freeze-thaw cycles through indoor freeze-thaw and uniaxial compression tests. The results showed that the elastic modulus and shear modulus of slate decreased exponentially with increasing freeze-thaw cycles while the Poisson's ratio increased linearly. Additionally, it was found that the compressive strength of slate decreased exponentially with the number of freeze-thaw cycles and exhibited a U-shaped curve relationship with the bedding angle. Yavuz [13] conducted freeze-thaw cycle tests on andesite, and the results showed decreases in the P-wave velocity, compressive strength, and hardness of the rock while the porosity and water absorption rate increased.

3.3.2 Research Status on Tensile Strength of Rocks

Zhang Huimei and Yang Gengshe [14] studied the effects of moisture and freeze-thaw cycles on the mechanical properties of red sandstone and shale. The experimental results showed that freeze-thaw cycles lead to a decrease in the tensile strength of the rocks and cause different damage patterns. There are differences in the freeze-thaw damage characteristics between red sandstone and shale, which may be related to their structures and mineral compositions. The study emphasizes the importance of considering the stress state in rock freeze-thaw damage in cold region rock engineering. Inada and Yokota [16] conducted studies on granite and andesite under dry and water-saturated conditions using uniaxial tensile and compression tests. The results showed that within the temperature range from -160°C to 20°C, the tensile and compressive strengths of the rocks increased as the temperature decreased. Additionally, they tested the compressive and tensile strengths of the rocks at room temperature after one and three freeze-thaw cycles.

3.3.3 Research Status on Fracture Toughness of Rocks

Griffith [17] proposed a quantitative correlation between material strength and crack size, which led to the development of the Griffith criterion for quantitatively assessing brittle fracture behavior in solids. Wang Changsong [18], through indoor experiments, microstructural analysis, and theoretical derivation, studied the fracture characteristics and damage mechanisms of fissured rock masses under freeze-thaw cycles. The experiments showed that freeze-thaw cycles significantly affect the fracture characteristics of rocks, with differences in fracture toughness observed under different fracture modes. He Jingjing and Shi Junping [19] investigated the changes in the three-point bending fracture performance of sandstone through freeze-thaw cycle tests. The study indicated that freeze-thaw cycles have varying degrees of deterioration effects on the fracture performance of sandstone, which increase with the initial notch height ratio. Additionally, the roughness coefficient of the sandstone fracture surface increased with the number of freeze-thaw cycles.

4. Conclusion and Outlook

Based on the current research status, it can be summarized that domestic and international scholars are gradually focusing their studies on frost heave force and deformation as the fundamental influencing factors in frozen rock issues. Numerous scholars have already utilized comprehensive, multi-scale physical and mechanical experiments and testing methods to analyze and detect the mechanical properties of rocks under freeze-thaw conditions. However, the following issues still require in-depth research:

(1) The monitoring methods for frost heave force are relatively limited, predominantly relying on single-point monitoring. Most monitoring points are positioned at the center of the monitoring surface, with few scholars conducting multi-point or full-surface frost heave force monitoring.

(2) The rock fissure surface, being a weak failure plane, is highly prone to shear failure under external loads, significantly affecting the safety and stability of tunnels and rock engineering in cold regions. However, the shear strength testing of fissured rocks is often overlooked. There is a need to thoroughly investigate the relationship between the maximum shear strength of fissured rocks, the number of freeze-thaw cycles, and the maximum normal stress.

(3) The geological and climatic conditions of tunnels and underground engineering in high-altitude or cold regions are complex and variable, with significant differences across different regions. A notable climatic feature in parts of northern China is the cold and dry climate during the autumn and winter seasons, with large diurnal temperature variations. Many areas have low annual rainfall and prolonged low-temperature periods in winter, preventing rocks from fully replenishing or absorbing external water during freeze-thaw cycles, resulting in a long-term partially saturated state. Currently, there is limited research on the freeze-thaw damage characteristics of fissured rocks in the context of northern China's arid, low-temperature, and low-humidity conditions. The deformation and mechanical properties of rocks under conditions of insufficient water replenishment and repeated freeze-thaw cycles also require further investigation.

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