International Journal of Materials Science and Technology Studies
ISSN: 3006-7693 (Print), ISSN: 3006-3744 (Online) | Volume 4, Number 1, Year 2025
DOI: https://doi.org/10.62051/ijmsts.v4n1.01
Journal homepage: https://wepub.org/index.php/IJMSTS/index

Analysis of the Failure Mechanism of Rock Freeze-Thaw Cycles

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ABSTRACT

The freeze-thaw conditions have a great influence on the mechanical properties of rock mass, and the freeze-thaw failure of rock mass physical properties is one of the main diseases commonly encountered in rock engineering in cold areas. This paper systematically analyzes the freezing-thawing of rocks affected by freeze-thaw cycles, which provides a reliable theoretical basis for the future study of rock freeze-thaw damage and freeze-thaw fractures. In addition, the thermal, hydraulic and mechanical characteristics of rock mass under freeze-thaw cycle conditions have very important guiding significance for the study of the failure mechanism of engineering freeze-thaw cycle and the design of cold protection and thermal insulation in cold areas.

KEYWORDS

Rock mechanics; Freeze-thaw cycle

1. INTRODUCTION

According to statistics, permafrost, seasonal frozen soil, and transient frozen soil zones cover approximately 50% of the Earth’s land area, primarily distributed in Russia, Canada, China, Alaska (USA), and Northern Europe. Permafrost alone accounts for 25% of the global land area. In China, permafrost and seasonal frozen soil regions occupy over 70% of the national territory, mainly in western and northern areas. The deterioration of rock mechanical properties induced by freeze-thaw cycles is a major cause of geological hazards in cold regions. As a heterogeneous material, rocks contain various minerals and numerous micro-fractures. Under alternating temperatures, differential thermal deformation among minerals weakens the bonding between internal particles, leading to mesostructural degradation. Concurrently, water within micro-fractures undergoes cyclic freezing and thawing, generating periodic frost heave pressures that propagate micro-cracks. Eventually, interconnected cracks cause rock strength failure. Freeze-thaw-induced damage in cold-region rocks triggers engineering geological issues, such as frost cracking in tunnel surrounding rock, instability of support structures [1], weathering and erosion of rock slopes [2], destabilization of high-steep rock masses, and safety risks in liquefied natural gas storage caverns [3].

With extensive cold-region areas in China (over 70% of the territory), these issues are particularly severe. Moreover, extreme cold waves and snow disasters over the past two decades have caused significant casualties and economic losses. For example, the 2008 extreme ice-snow disaster in southern China affected over 100 million people and resulted in direct economic losses exceeding 150 billion yuan. A critical factor exacerbating such disasters is that their impact extends beyond traditional "cold regions" to areas with abundant rainfall but lacking typical low-temperature conditions.

As cold-region geotechnical engineering activities increase, challenges related to frozen rock mechanics—studying the physical and mechanical behavior of rocks with natural defects (e.g., fractures and joints) under freezing, thawing, and cyclic conditions—have become prominent. This field aims to elucidate the evolution of rock damage under varying temperature histories and water/ice states, providing theoretical guidance for engineering design and construction in cold regions.

2. RESEARCH STATUS

2.1. Prospect Analysis

2.1.1. Research on Physical and Mechanical Properties of Frozen-Thawed Rocks

Studies on the mechanical properties of frozen-thawed rocks under different water contents show that the frost heaving force varies with water content. Experiments indicate that whether the rock is saturated during the freeze-thaw process significantly influences damage structure expansion. First, under saturated conditions, the effect of freeze-thaw on internal damage structure expansion differs for rock materials with varying initial damages. For soft rocks with high porosity, water content, and low density/strength, the number of freeze-thaw cycles obviously promotes damage structure expansion. In contrast, for hard rocks with low porosity, water content, and high density/strength, the number of cycles has minimal initial effect on damage structure expansion due to low water content. Thus, the initial damage state, initial water content, and freeze-thaw cycles are inseparably linked to damage structure expansion in rock materials.

2.1.2. Research on Freeze-Thaw Mechanical Properties under Freezing Temperature, Freezing Rate and Freeze-Thaw Cycle Conditions

The influence of freeze-thaw action on rock damage propagation is inherently complex. Different freezing temperatures and rates exert distinct effects on the mechanical properties of various rock materials, while the number of freeze-thaw cycles represents a primary factor in rock freeze-thaw damage propagation. Integrating damage mechanics theory to couple these factors into damage variables and constitutive equations remains a topic warranting in-depth exploration. Notably, even if temperature-related factors could be coupled into such models, the results would be specific to certain rock types—coupling outcomes inherently vary across different rock materials.

2.1.3. Research on Mechanical Properties of Freeze-Thawed Rocks under High Confining Pressure

Current studies predominantly focus on the mechanics of freeze-thawed rocks under uniaxial stress, while actual rocks in-situ are subjected to triaxial stress states. In recent years, numerous coal mine freezing projects have encountered deep rock formations—particularly water-saturated strata—beneath thick alluvial layers. For instance, during the construction of coal mines by Shaanxi Binchang Coal Industry Co, Ltd., the main shaft was designed at 539 m depth and the auxiliary shaft at 568.3 m, with only 11.85 m of overburden soil. The rock strata exceed 500 m in thickness. Owing to multiple aquifers, high shaft water inflow, low rock strength, high confining pressure, and significant strength degradation of unstable rocks upon water exposure, full-depth freezing of the shafts was designed. As there is currently no domestic experience in freezing vertical shafts through entirely bedrock, researching the mechanical properties of freeze-thawed rocks under high confining pressure holds significant theoretical and practical importance for both frozen rock mechanics theory and engineering applications.

2.1.4. Experimental Research on Hydrothermal Migration during Rock Freeze-Thaw Processes

Experimental studies form the foundation of frozen rock physics research. Regarding hydrothermal migration in frozen soil mechanics, scholars at home and abroad have conducted systematic experimental investigations on hydrothermal migration in soil under various low-temperature environments, and published a series of monographs. However, experimental research on hydrothermal migration during rock freeze-thaw processes remains scarce, and extensive work is still needed in this field. Due to the small geometric dimensions of standard rock specimens, the moisture migration path during hydrothermal coupling is short, leading to indistinct experimental results.

Actual rock engineering projects are situated in specific geostress, hydrological, and thermal environments, which are open systems where the water environment, stress field, and temperature field form a dynamically balanced coupling relationship. Therefore, when studying the influence of freeze-thaw environments on the hydrothermal migration characteristics of rock masses, the effect of the stress field must be considered—that is, the coupling relationship among the moisture field, temperature field, and stress field. Although certain progress has been made in numerical studies on tri-field coupling, experimental research achievements remain limited. Thus, innovating experimental methods to deeply explore hydrothermal migration during freeze-thaw processes represents a necessary direction for future efforts.

2.2. Physical and Mechanical Properties of Freeze-Thaw Rock Mass

In practical engineering, rock masses often contain joints and fractures. However, in the existing research on the characteristics of rocks under freeze-thaw conditions, due to the limitation of experimental scale, the freeze-thaw expansion effect generated by the freezing of these defects (joints and fractures) in the presence of water is rarely considered. The freezing expansion effect is greater, and the influence of the rock mass fracture network on the stability of freeze-thawed rock masses should be considered. In the laboratory, indoor freeze-thaw mechanical experiments on rock masses with single or multiple fractures can be carried out. Based on the experiments, a coupling model of freeze-thawed rock masses considering macro-structural planes and real fracture networks can be derived for numerical simulation calculations.

2.3. Numerical Simulation and Virtual Testing Under Freeze-Thaw Conditions

Numerical simulation calculations and simulation tests serve as crucial foundations for engineering computational design. Currently, there have been certain research achievements in the numerical simulation and simulation tests of rock mechanics under freeze-thaw conditions. For rock mass engineering in freeze-thaw environments, since rock masses in practical projects often contain joints and fractures, which are difficult to consider in laboratory rock samples, numerical simulation calculations and simulation tests can play a significant role in this regard. Coupled numerical simulation calculations among the moisture field, temperature field, and stress field should be fully considered to reflect the moisture migration process of rock masses in freeze-thaw environments through numerical simulation calculations.

3. INFLUENCING FACTORS OF FREEZE-THAW DAMAGE AND DETERIORATION IN ROCKS

3.1. Lithology

Lithology exerts the most significant influence on the degree of freeze-thaw damage and deterioration in rocks [10]. To date, all studies on the damage properties of rocks under freeze-thaw cycles have addressed this aspect. The impact of lithology on freeze-thaw damage and deterioration in rocks is primarily reflected in mineral particle size and composition, mineral composition, cement strength, rock strength and stiffness, development of joints and fractures, characteristics of joint distribution, porosity, rock density, etc. Studies have found that rocks with higher strength and stiffness, denser mineral particles, higher cement strength, less developed joints and fractures, and lower porosity are less affected by freeze-thaw cycles; conversely, they are more significantly affected by freeze-thaw cycles.

3.2. Porosity, Water Content and Saturation of Rocks

Rock porosity and water content are the main factors influencing freeze-thaw damage and deterioration. As shown in the above analysis, the freeze-thaw damage process in rocks is caused by the freezing and thawing of water in internal pores—without water, there would be no freeze-thaw damage.

Studies have found significant differences in the effects of freeze-thaw cycles on dry and saturated rocks. Dry rocks are almost unaffected by freeze-thaw cycles (assuming the temperature range is not extreme), while water-saturated rocks exhibit varying degrees of damage, with some even experiencing complete failure [12]. Freeze-thaw cycles have minimal or no effect on high-strength dense rocks like granite and fine sandstone [13], but severely impact low-strength rocks such as medium-coarse sandstone, limestone, mudstone, and siltstone—some of which disintegrate after fewer than 15 freeze-thaw cycles[10].

Water content and saturation also significantly influence freeze-thaw damage. For different lithologies, rocks with higher water content are more susceptible to freeze-thaw cycles, while those with lower water content are less affected. For the same rock type, saturation is the key determinant: research shows that within a freeze-thaw temperature range of -18°C to 14°C (3.5-hour cycle: 2h freezing, 1.5h thawing), saturation below 60% has little impact on damage, but exceeding 70% significantly accelerates deterioration [14].

3.3. Number of Freeze-Thaw Cycles and Freeze-Thaw Period

The number of freeze-thaw cycles and freeze-thaw period significantly influence rock freeze-thaw damage and deterioration, primarily due to the varying durability of different rock types. The more frequent the freeze-thaw cycles and the shorter the freeze-thaw period, the more pronounced the impact on rocks. Reference [10] conducted freeze-thaw cycle tests on 10 rock types with different lithologies, revealing that their freeze-thaw durability varies. For the same rock type, the general trend is a gradual strength reduction with increasing cycle numbers, though high-strength rocks like argillaceous limestone and magnetite showed stable mechanical properties after 75 cycles. This study’s uniaxial compression tests on red sandstone and shale samples at room temperature after different freeze-thaw cycles also confirmed this trend.

While no reports currently address the influence of different freeze-thaw periods (or frequencies) on rock damage, similar conclusions can be drawn from concrete studies: shorter freeze-thaw periods (i.e., higher freeze-thaw frequencies or rates) intensify the impact of freeze-thaw cycles on rocks.

3.4. Unfrozen Water and Salt Solution

Studies on porous media such as concrete and rock have found that even below 0°C, not all water in soil freezes. This is primarily due to the presence of crystalline water in the soil and the lowering of the freezing point caused by certain salts in the water. Additionally, the smaller the micro-pore size in the rock and the more salts dissolved in the water, the lower the freezing point of the pore water in the rock [15] (this method can, to some extent, reduce the impact of freeze-thaw cycles on the damage and deterioration of rock masses). Water that remains unfrozen below 0°C in geotechnical materials is called supercooled water [14]. Under freeze-thaw cycles, pore water affects rock freeze-thaw damage mainly through three mechanisms [14]:

(1) Volume expansion occurs when water turns into ice. When the saturation of pore water exceeds 90%, this expansion exerts significant compressive stress on the pore walls;

(2) Formation of ice lenses or ice prisms, which has a substantial impact on rock freeze-thaw cracking;

(3) Pore water pressure: When the temperature drops and water freezes and expands in pores or original defects, supercooled water (unfrozen water) is displaced from the pores by these ice bodies, creating a certain pore water pressure within the rock.

3.5. Freeze-Thaw Temperature Range

The freeze-thaw temperature range has a significant impact on the freeze-thaw damage and deterioration of rocks. In experiments, it is manifested that the larger the freeze-thaw temperature range (the lower the freezing temperature limit), the greater the impact of freeze-thaw cycles on rocks. In engineering, this is reflected in the fact that the freeze-thaw effect in severe cold regions is more significant than that in general seasonal cold regions. Studies on concrete have found that under the same other conditions, when the freeze-thaw temperature ranges are -17°C to 5°C and -5°C to 5°C, respectively, and their compressive strengths are both reduced by 40%, the concrete in the former temperature range can only withstand 7 freeze-thaw cycles, while that in the latter temperature range can withstand 133 cycles, illustrating a huge difference. The same problem exists in rocks. The larger the freeze-thaw temperature range, the more fully water converts into ice, and the greater the difference in thermal expansion properties among the rock's phase components. This leads to higher internal freeze-thaw pressures in the rock after freeze-thaw cycles, causing faster freeze-thaw damage and deterioration of the rock.

4. THEORETICAL MODEL OF SANDSTONE FREEZE-THAW DAMAGE

4.1. Volume Expansion Theory

During the freezing process, water undergoes approximately 9% volume expansion. If it freezes in a rigidly constrained enclosed space, the restriction on volume increase will inevitably lead to an increase in ice pressure. Two rather strict conditions are required to generate significant ice pressure: the space must be enclosed and provide sufficient constraints; the initial saturation of the space must exceed 91%. However, these two conditions are rarely fully met or only partially satisfied in natural rocks [17]. Due to the above limitations of this theory, particularly the contradiction between water absorption in rock pores and pore space constraints (i.e., if rock pores absorb water, they cannot be completely enclosed), some scholars have even directly questioned the validity of this theory[19]. The author argues that considering rock pores consist of different pore sizes, pore water in pores of varying sizes freezes at different temperatures, and water in larger pores freezes first. After the water in large pores freezes, it can seal connected small pores, forming an enclosed space, which provides a basis for the volume expansion mechanism (a detailed description of this process is provided below). This process does not depend on the freezing rate and can partially expand the applicability of the volume expansion theory. In addition to directly causing rock failure through "ice wedging," the growth of ice crystals during water freezing can also induce hydrofracturing effects by squeezing unfrozen water, leading to rock damage.

4.2. Hydrostatic Pressure Theory

This theory was first proposed by T.C. Powers [20] in the 1940s while studying the freeze-thaw damage of concrete, and it was subsequently widely used to explain the freeze-thaw damage of concrete. When a specimen (concrete or rock) is exposed to water for a period (without immersion) before freezing, its surface is likely to approach saturation, while the interior remains relatively dry. When the surface freezes, the remaining unfrozen water is trapped inside. As freezing progresses, the unfrozen water is driven into the interior of the specimen by the ice. If the specimen has a low permeability coefficient, this can lead to an increase in water pressure. If the freezing rate is sufficiently fast or the permeability coefficient of the pores is sufficiently low, the pressure from the unfrozen water caused by frost heave can still damage the rock even in connected pores [21].

Freeze-thaw damage theories based on the volume expansion property of water during freezing have relatively clear physical meanings and were therefore long used to explain rock freeze-thaw damage phenomena. However, with advancements in testing methods, some new phenomena cannot be explained by the above theories. The most difficult to explain is that when the pore fluid is replaced with benzene (benzene has a smaller volume after crystallization: density of benzene is 0.8765 g/cm³ at 25°C and 1.031 g/cm³ at -15°C), significant expansion is still observed in porous materials during freezing [22].

4.3. Segregation Ice Theory

Relatively speaking, the conditions for the occurrence of segregation ice are less stringent than those for frost heave. It mainly requires three conditions: (1) a slow freezing rate and a long freezing time, with the ideal condition being a stable temperature between −2°C and −6°C; (2) sufficient unfrozen water or supercooled water as the material source for segregation ice; (3) frost-susceptible rocks, primarily referring to rocks with small mineral particle sizes or large specific surface areas. The earliest discussion of the segregation ice theory originated from S. Taber's [23] work on soil frost heave in the 1930s. Later, he extended this theory to explain the frost heave damage of limestone along lake shores. Subsequently, increasing laboratory evidence has demonstrated the effectiveness of this theory in explaining rock freeze-thaw damage.

The basis of the segregation ice phenomenon is the migration of unfrozen water toward ice lenses. To achieve this process, it is necessary to ensure that unfrozen water remains near the ice lenses when they form, and to provide the driving force and pathway for the migration of unfrozen water toward ice crystals. Unfrozen water exists in two forms: one is in the micro-pores within the frozen area (where capillary forces lower the freezing point), and the other is in the unfrozen area (where the water temperature has not yet dropped to the freezing point). For small rock blocks (such as laboratory specimens with a diameter of 5 cm and a height of 10 cm), the time required for complete freezing is short, so the unfrozen water during freezing mainly exists as water in micro-pores.

It has been confirmed that unfrozen water can migrate along the unfrozen water film between ice crystals and mineral particles, which solves the problem of its migration path. The driving forces for its migration mainly include pressure potential, temperature potential, and gravitational potential. For small rock blocks, water migration during freezing is dominated by the movement of unfrozen water from micro-pores to ice crystals in macro-pores (except when the freezing rate is very low), and the main driving force for this migration is pressure potential. This process is the capillary theory discussed below. For large rock blocks, water migration during freezing is mainly from internal unfrozen water to the external frozen area, with the main driving force being temperature potential. For bedrock, the influence of gravitational potential on unfrozen water migration must also be considered. When unfrozen water migrates from deep to the surface (where surface rocks freeze first), gravitational potential will slow down the migration rate; when unfrozen water migrates inward (where the surface thaws first or there is a permafrost zone inside), gravitational potential will accelerate the migration rate.

4.4. Capillary Theory

D. H. Everett [24] proposed this theory based on the thermodynamic equilibrium of water and ice in pores, arguing that the additional pressure caused by ice in macro-pores entering micro-pores is a crucial factor inducing freeze-thaw damage in porous materials. The principle is shown in Figure 1: two cylinders with pistons are connected by a capillary tube, where A is filled with liquid water and B contains ice. Initially, the water-ice system in the pores is in phase equilibrium, i.e., u_i=u_w((where u is the chemical potential of the substance), Ti=Tw, and Pi=Pw (where P is the pressure and T is the temperature of the substance)). When the temperature of B decreases while the pressure remains constant, the phase transition proceeds toward water freezing, causing water in A to migrate to B (Figure 1). There are two possible ways for water to freeze in B: (1) If the piston in B can move and Pi remains constant, water migrates to ice, freezing at the lower surface of B and continuously pushing the piston upward. If the temperature of B remains constant, freezing continues until the water in A is completely drawn out; (2) If the piston in B is fixed, water in A first migrates to B and freezes at the lower surface of B. However, as ice accumulates, the pressure in B gradually increases. When the pressure in B meets the threshold, ice will enter the capillary tube and continue to grow. The pressure difference caused by ice entering the capillary, Pc= Pi-Pw, if exceeding the tensile strength of the material, will induce freeze-thaw damage. According to the theory's principle, the conditions for freeze-thaw damage include suitable temperature in B, sufficient unfrozen water in A, and constrained ice in B.

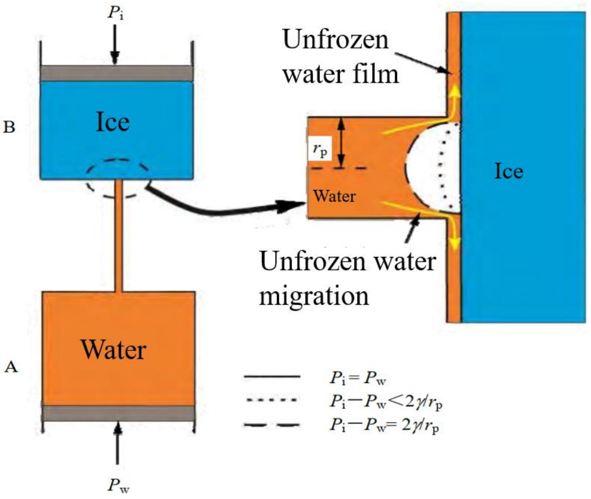

Figure 1. Schematic diagram of Everett's capillary theory

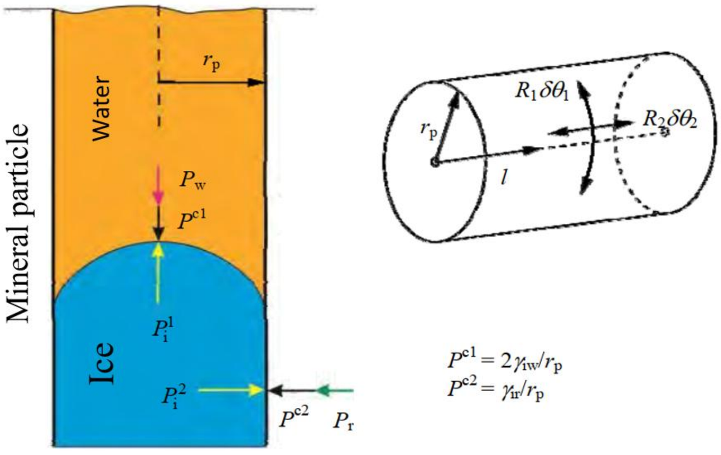

Figure 2. Force state of ice inside the capillary tube

4.5. Theories of Freeze-Thaw Damage

The above two categories of freeze-thaw damage theories each have their rationality and applicable conditions. A common premise for the second category of freeze-thaw damage theories is the presence of a large number of micro-pores within the rock. One of the main roles of micro-pores is to lower the freezing point of internal pore water, meaning that when water in connected macro-pores freezes, the water in micro-pores remains liquid. For the capillary theory and crystallization pressure theory, the capillary forces within micro-pores form the basis for the generation of frost heave forces.

The first category of freeze-thaw damage theories operates under the premise that there are relatively enclosed spaces within the pores, or that ice growth during freezing can create pore closures, which is not directly related to the presence of numerous micro-pores. Therefore, for rocks with very few internal micro-pores, their damage under freeze-thaw action can be considered primarily derived from the first category of mechanisms (freeze-thaw damage theories). For rocks with more micro-pores, their frost heave damage may stem from both categories of mechanisms, with the specific dominant mechanism depending on environmental conditions.

In addition to the widely applied theories mentioned above, there are also the osmotic pressure theory, micro-ice crystal theory, pore medium mechanical models, etc. Furthermore, there is a class of theories that do not involve the micro-mechanisms of sandstone freeze-thaw damage but instead equate freeze-thaw action to tensile stress within the rock and freeze-thaw cycles to fatigue stress, using relevant theories of fatigue damage mechanics to evaluate the degradation laws of sandstone mechanical properties after multiple freeze-thaw cycles. These models are not elaborated on in this paper.

5. CONCLUSION

Based on a systematic introduction of existing freeze-thaw damage theories, this paper analyzes the freeze-thaw damage mechanisms of sandstone under different freezing conditions using fundamental thermodynamic principles, and verifies these mechanisms through freeze-thaw experiments on sandstone.

From theoretical and experimental perspectives, this study analyzes and validates the damage mechanisms of sandstone during freezing, emphasizing the controlling effects of freezing conditions and sandstone pore structure on its freeze-thaw damage mechanisms. The dominant mechanisms under different freezing conditions are identified, providing theoretical support for follow-up research. However, this study is only conducted on layered porous rocks and qualitatively discusses the freeze-thaw damage characteristics at the laboratory scale, leaving room for further research.

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