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Research on Frost Damage Prevention Technologies and Monitoring Systems for Cold Region Tunnels

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Abstract. Due to the increasing development efforts in China's transportation sector, the coverage of highway tunnels has expanded extensively. Consequently, the number of cold region tunnels has grown significantly, and frost damage issues in these tunnels have gradually emerged. This paper focuses on existing frost damage prevention technologies for cold region tunnels and prospects for future intelligent monitoring systems. It aims to analyze the shortcomings of current systems and propose improvements using advanced scientific and technological methods. The technical analysis concludes that enhancing material properties through biological and chemical means, coupled with refining intelligent monitoring systems via digital models, neural networks, and interdisciplinary approaches, can effectively improve the efficiency of frost damage prevention in cold region tunnels. Digital models and computational power can be enhanced to improve monitoring technology: establishing a comprehensive digital model that includes geological, structural, and environmental factors can enable real-time simulation of frost damage evolution. Combining blockchain technology can also help build a credible data storage system for monitoring.

Keywords: Frost Damage Prevention Technologies, Monitoring System, Cold Region Tunnels

1. Introduction

Recent extensive field investigations and literature reviews reveal that frost damage in cold region highway tunnels is prominent and adversely affects tunnel structures and operational safety [1]. A key reason for frequent frost damage is the significant proportion of permafrost areas. Globally, permafrost covers 25% of the total land area, with cold regions being widely distributed. In China, permafrost accounts for 22.3% of the total territory, while seasonally frozen ground covers 53.5% [2]. Frost damage primarily manifests as lining cracks, drainage system icing, and surrounding rock frost heave deformation. The core causes are freeze thaw cycles, water seepage and freezing, and frost heave pressure. Although traditional prevention technologies—such as insulated ditches and coldproof doors—can partially mitigate these issues, they suffer from high costs, poor adaptability, and difficult maintenance.

Early cold region tunnels were predominantly constructed in permafrost zones, where annual temperature fluctuations are minimal and physicomechanical properties remain relatively stable [3].

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In recent years, novel antifreeze materials and intelligent monitoring technologies have provided new directions for precise prevention. Intelligent detection technologies are now widely adopted in many regions, and the integrated application of intelligent detection and frost damage prevention has become a new research focus. This paper systematically analyzes frost damage mechanisms, prevention technologies, intelligent detection, and prospects. It reviews research advances in the characteristics of frost damage, prevention technologies, and monitoring systems for cold region tunnels, aiming to provide theoretical references for engineering practice and highlight the critical role of modern intelligent detection systems in tunnel frost damage prevention.

2. Mechanisms and characteristics of frost damage

Cold region tunnels refer to tunnel engineering projects constructed in areas with cold climates, long winters, and seasonal or perennial permafrost. Their core characteristic is addressing special geotechnical hydrothermal mechanical challenges, including low temperatures, frost heave, ice pressure, and thaw settlement.

Frost damage in cold region tunnels primarily stems from tunnel excavation disrupting the original thermohydromechanical equilibrium, significantly intensifying multiphysical field interactions [4]. Tunnel excavation destroys the original balanced system. After excavation and support, the temperature within the tunnel redistributes, forming a new steady-state system. Within a certain range (the lining and surrounding rock to a specific depth), interactions between the old and new systems cause fatigue or degradation, inducing frost damage. Long-term observation data from 25 tunnels on the Qinghai Tibet Plateau show an annual average of 90–150 freeze thaw cycles, with temperature fluctuations exceeding 40°C in tunnels above 4,500 meters elevation. Such periodic temperature changes generate significant thermal stress gradients in the surrounding rock and lining structures. For example, the daily temperature variation at the vault of Fenghuoshan Tunnel reaches 28°C, causing microcracks in concrete to propagate at a rate of 0.05 mm/year.

Additionally, unfrozen water film effects unique to permafrost zones drive water migration toward freezing fronts. Laboratory simulations indicate that under a temperature gradient of 3°C/m, sandy surrounding rock exhibits a water migration flux of 1.2×10^{-6} $m^3/(m^2\cdot s)$, forming ice lenses up to 15 cm thick. The volume expansion from this phase change process generates frost heave pressures of 8–12 MPa in closed systems, far exceeding the tensile strength of ordinary concrete.

The most common form of frost damage is structural cracking and deformation. Survey data from 37 operational tunnels in Northeast China show a 63% occurrence rate of circumferential lining cracks, 70% concentrated within a 120° arc at the vault. Crack width follows an exponential relationship with freezethaw cycles, reaching an average width of 2.8 mm after 500 cycles.

Frost damage also causes drainage system failures: Monitoring in Xinjiang's Tianshan tunnel group shows that 85% of traditional drainage channels freeze at 15°C, leading to base water accumulation exceeding 30 cm. Ice plug pressure peaks at 0.6 MPa, causing invert deformation.

Material degradation is inevitable. Concrete mass loss during freezethaw cycles exhibits a threephase pattern: initial 200 cycles at 0.8%/100 cycles, 200–400 cycles at 1.5%/100 cycles, and post400 cycles sharply rising to 3.2%/100 cycles. Compressive strength attenuation correlates strongly with air content: increasing air content from 4% to 6% raises the strength retention rate of F300 frostresistant concrete from 78% to 85%.

Unlike Northeast China, Qinghai Tibet permafrost tunnels face triple challenges of "high altitude, strong radiation, perennial permafrost." For antifreeze design in high-altitude tunnels in Western Sichuan, methods such as field measurements and numerical simulations are used to analyze intunnel temperatures during operation [5]. Kunlun Mountain Tunnel, for instance, has a permafrost

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table depth of 1.8 m and a summer thaw depth of 3.2 m, causing annual cyclical thaw settlement deformation of 12 mm. Northeast cold region tunnels exhibit "deep freezing, intense heaving" characteristics, with freezing depths reaching 2.5 m in Harbin metro tunnels and maximum heave ratios of 7.3%. These regional differences necessitate locationspecific adaptations in prevention technologies.

3. Current development of frost damage prevention technology systems

Existing frost damage prevention technologies focus on material improvements and structural design, with key advancements in environmental control, structural frost resistance, and drainage system innovations.

3.1 Environmental control technologies

China's current frost prevention and drainage measures for cold region tunnels are diverse. Research on specialized measures should consider unique temperature and hydrogeological conditions [6]. Environmental control technologies are categorized into passive and active temperature control:

Passive Temperature Control reduces heat exchange between tunnel interiors and exteriors through material properties, structural design, or natural conditions without external energy input. Newgeneration composite insulation layers adopt a "aerogel (5 mm) + vacuum insulation panel (20 mm) + waterproof breathable membrane" sandwich structure. Field tests show an equivalent thermal conductivity as low as 0.015 W/(m·K), 40% more energy efficient than traditional polyurethane. Applied at the portal section of Zangmu Tunnel on the LhasaNyingchi Railway, freezing depth decreased from 2.1 m to 0.8 m.

Active Temperature Control requires continuous external energy to actively regulate surrounding rock temperature fields via artificial heating/cooling systems. Breakthroughs include ground source heat pumps at Wushaoling Tunnel on the LanzhouXinjiang Railway, using vertical buried tube heat exchangers (120 m depth). The system achieves a heating COP of 4.2 in winter, saving 68% energy compared to resistive heating. Its intelligent control system automatically adjusts output based on real-time temperatures, stabilizing lining surface temperatures within ±1°C.

3.2 Structural frost resistance technologies

Basalt fiberreinforced concrete independently developed by Jilin University demonstrates significant advantages in frost resistance, substantially improving concrete's mechanical properties and durability [7]. Orthogonal tests determined an optimal dosage of 0.45% (volumetric ratio), increasing flexural strength by 32% and retaining 91% dynamic modulus after 300 freeze thaw cycles. Nanomodification breakthroughs show that adding 1.5% SiO_2 nanoparticles reduces cement stone porosity by 46% and chloride diffusion coefficients to 0.8×10^{-12} m^2/s. Studies confirm basalt fibers effectively mitigate concrete mass loss and declines in relative dynamic elastic modulus, compressive strength, and tensile strength [8].

In structural design, prestressed lining systems mark a milestone in Zheduoshan Tunnel on the SichuanTibet Highway. Preapplying 3 MPa compressive stress limits frost heave displacement to <2 mm. Novel "slip joints" allow 10 mm free deformation, combined with EPDM rubber waterstops, reducing construction joint leakage to 0.3 locations/km.

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3.3 Drainage system innovations

3D drainage systems are a major innovation, holistically addressing drainage issues in interchange systems to intercept highelevation rainwater and discharge lowelevation runoff [9]. ChengduLanzhou Railway's Ping'an Tunnel employs a "circular Ωpipe + longitudinal electric heattraced ditch + central deepburied drain" system. PIDcontrolled electric heattracing maintains drain temperatures at 3–5°C, reducing energy consumption by 25% versus constantpower modes. The deep drain includes twostage sedimentation tanks, lowering sediment content from 12 g/L to 0.5 g/L.

Surrounding rock improvement is another key innovation. Ultrafine cementsodium silicate grouting in a QinghaiTibet tunnel reduced permeability from 10^{-3} cm/s to 10^{-7} cm/s at 1.2–1.5 MPa injection pressure and 3.8 m grout spread radius. Postgrouting frost heave pressure decreased by 62%, though stress redistribution requires attention.

4. Advances in intelligent monitoring technologies

Rapid technological advancements—including AI, IoT, and big data analytics—have improved construction quality and efficiency in highway engineering [10]. As critical highway components, tunnels face growing safety and energy efficiency challenges as mountainous and long tunnels increase [11].

Brillouin optical time domain reflectometry (BOTDR) achieves 0.3 m spatial resolution and ±15 μεstrain accuracy, detecting 0.05 mm heave displacements in Northeast China tunnels. MEMS sensors (Φ20 mm × 5 mm) integrate temperature/humidity/stress monitoring with 5year battery life.

LoRa+5G heterogeneous networks achieve 99.9% connectivity in a 15 km Xinjiang tunnel. Lightweight algorithms reduce data processing latency to <200 ms. Attentionenhanced GRU neural networks improve frost risk prediction accuracy to 93%.

BIMGIS platforms enable 3D visualization of frost damage evolution. A QinghaiTibet Railway tunnel system with 1,200 sensors classifies damage into: Type A (structural cracking); Type B (drainage blockage);Type C (base heave);Operational data show 88% accuracy for 7day early warnings, reducing emergency repair costs by 37%.

5. Future prospects

5.1 Development directions

Currently, the technical bottlenecks in frost damage prevention can be categorized into three main areas: Firstly, there are issues with the durability of materials. The performance degradation of existing insulation materials under wet and hot cycles has not been fully understood, and the thermal conductivity of polyurethane materials increases by 28% after 100 freeze-thaw cycles. Additionally, the accuracy of multi-field coupling models is not satisfactory; current numerical simulations still have an error rate of 20% in depicting the water phase transition process, necessitating the development of constitutive models that consider ice crystal growth kinetics. Moreover, the cost of intelligent operation and maintenance (O&M) is potentially too high; the construction cost of existing monitoring systems per kilometer is 800,000 yuan, which limits their widespread application in ordinary railway tunnels. To address these challenges, a potential direction is to improve material durability through the joint development of intelligent materials and biotechnology. Phase change energy storage concrete (PCM-Concrete) can achieve automatic

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thermal regulation within a 5-15℃ range using wax microcapsule technology. Self-healing concrete, utilizing microbial mineralization technology, can autonomously repair cracks when the width is less than 0.3mm. Furthermore, digital models and computational power can be enhanced to improve monitoring technology: establishing a comprehensive digital model that includes geological, structural, and environmental factors can enable real-time simulation of frost damage evolution. Combining blockchain technology can also help build a credible data storage system for monitoring.

5.2 Technical system outlook

To establish a comprehensive technical specification system that encompasses material properties, design methods, construction techniques, and operation and maintenance standards, ensuring efficient construction through the effective operation of this system. Key areas include: setting evaluation standards for the long-term performance of frost-resistant concrete, with a recommended freeze-thaw cycle of at least 500 times; improving the method for determining frost heave force design values, with recommendations to determine relevant coefficients based on frost depth zones; establishing an access index system for intelligent monitoring systems, which includes 12 indicators such as accuracy, reliability, and cost-effectiveness.

6. Conclusion

This study investigates frost damage mechanisms and regionspecific prevention strategies in cold region tunnels. By comparing Northeastern and SichuanTibet regions and analyzing existing technologies, we propose integrating intelligent detection with prevention measures. This interdisciplinary approach can establish an economical, efficient, and advanced frost damage prevention system, contributing to China's highway development.

Advancements require multidisciplinary collaboration, theoretical innovation, and technical breakthroughs. Through the threedimensional linkage of theory, technology, and practice, modern intelligent monitoring systems will be perfected. By setting technological anchors and mastering systemic navigation, China will develop a distinctive technical framework for cold region tunnel construction.

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