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A Review on the Impact of Saline Soil Environments on Thermal Insulation Layers in Cold-Region Tunnels in China

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Abstract: With the advancement of the "Belt and Road" Initiative and the Western Development Strategy, the demand for tunnel construction in cold, high-altitude, and high-latitude regions of China has increased significantly. Frost damage poses a serious threat to tunnel structural safety in these areas, where installing thermal insulation layers is a key measure for prevention. Organic insulation materials such as polyurethane (PU) and expanded polystyrene (EPS) are widely used due to their excellent performance. This paper systematically reviews research progress on temperature field theory, experimental studies, and numerical simulations related to cold-region tunnels, with a focus on the impact mechanisms of saline soil environments on insulation layer performance. Studies indicate a significant positive correlation between Cl^- and Na^+ content in seasonal frozen soil within western China, and water seepage containing salts affects the thermal conductivity of insulation materials by altering their pore structure and moisture content. These effects vary spatially due to regional differences in salinity. While new approaches such as machine learning are increasingly applied to predict material performance and optimize design, systematic research on the long-term impact of seepage water salinity on insulation layers remains limited, representing an important direction for future studies.

Keywords: Cold-region Tunnels; Saline Soils; Thermal Insulation Layers; Frost Damage; Seepage Water Salinity.

1. Introduction

Driven by the Belt and Road Initiative and the Western Development Strategy, the demand for tunnel construction in high-altitude and high-latitude cold regions of western China continues to grow. These areas are characterized by harsh climatic conditions, including low oxygen levels, extremely low temperatures, significant diurnal temperature variations, and active tectonic activities. Coupled with complex geological challenges such as permafrost and freeze-thaw hazards, these factors pose substantial threats to tunnel structural safety and long-term operational stability[1]. Frost damage represents the most critical risk for tunnels in cold regions, often leading to lining cracks, ice formation, water leakage, and other defects that severely compromise operational safety. Currently, the installation of thermal insulation layers is a key engineering measure to prevent frost damage. These layers help mitigate the impact of construction activities and environmental temperature fluctuations on the surrounding rock temperature field by inhibiting heat transfer through conduction, convection, and radiation. Thanks to their excellent thermal insulation properties and ease of installation, organic insulating materials such as polyurethane (PU) and expanded polystyrene (EPS) have become the primary choice for insulation in cold-region tunnel projects[2].

2. Research Status of Cold Region Tunnels

2.1. Theoretical Advances in Temperature Field Analysis of Cold-Region Tunnels

Bonacina et al. [3] made a significant contribution to the study of temperature fields in frozen soil by systematically accounting for the influence of phase change latent heat—a critical factor often oversimplified in earlier models. They employed a stable and convergent implicit finite difference method, which allowed for the derivation of an analytical solution for the nonlinear temperature field under small temperature difference conditions. This solution effectively incorporates the effects of latent heat during the phase transition process, thereby providing a more accurate representation of the thermal behavior in cold-region tunnels. Their work has been recognized in the field for enhancing the theoretical foundation of temperature prediction in frozen geomaterials.

Building upon the analytical framework established for circular tunnels, Zhao et al. [4] extended the research by developing a temperature field distribution solution tailored for elliptical cross-section tunnels. This advancement is particularly valuable for practical engineering applications, as the elliptical profile more closely approximates the actual shapes commonly used in modern tunnel construction compared to the idealized circular section. The proposed solution not only improves the applicability of theoretical models to real-world tunnel geometries but also provides designers with a more practical tool for thermal analysis and insulation design in cold regions. The methodology adopted by Zhao et al. has been regarded as an important step toward bridging the gap between theoretical models and practical tunnel designs.The sequential developments by Bonacina et al. and Zhao et al. together form a progressive enhancement in the analytical modeling of temperature fields in cold-region tunnels, moving from fundamental theoretical solutions to more geometrically adaptable and practically relevant applications.

2.2. Advances in Experimental and Numerical Simulation Studies

Through systematic freeze-thaw cycle experiments, Jiang et al. [4] quantitatively investigated the degradation mechanism of extruded polystyrene (XPS) insulation materials. Their experimental results demonstrated a clear linear relationship between the number of freeze-thaw cycles and the deterioration of material properties: both thermal conductivity and volumetric water absorption showed a progressive increase with accumulating cycles. This finding provides crucial experimental evidence for predicting the long-term performance of insulation materials in cold regions and highlights the importance of considering material degradation in the design of tunnel insulation systems.

In a more theoretical approach, Ma et al. [5] developed an advanced numerical model that incorporates both phase change latent heat and hydro-thermal coupling effects. Their comprehensive model enabled the proposal of an optimization methodology for insulation layer parameters specifically tailored for tunnels in seasonal frozen soil regions. The significance of this work lies in its ability to simulate complex environmental interactions that affect tunnel performance in cold regions.

Advancing the integration of multiple factors, Xia et al. [6] conducted a sophisticated multi-parameter coupling analysis that incorporated annual average temperature, initial surrounding rock temperature, and wind speed. Based on this analysis, they introduced an innovative collaborative design framework that synergistically combines insulation layer optimization with active ventilation strategies for enhanced frost prevention. This integrated approach represents a significant step forward in holistic thermal management design for cold-region tunnels.

In a more application-oriented study, Li et al. [7] formulated a heat-mass coupling model and implemented it in the context of the FengHuoshan Tunnel project. Their research systematically examined the thermal insulation effectiveness of aerogel blanket insulation layers with varying installation thicknesses, providing practical guidance for material selection and design optimization in real engineering applications.

Addressing a fundamental design consideration, Lu et al. [8] challenged conventional practices by advocating for thermal resistance parameter, rather than mere thickness, as the primary indicator for evaluating the anti-freezing performance of insulation layers. This perspective shift offers a more scientifically grounded approach to insulation system evaluation and design.

At the microscopic level, Shrestha et al. [9] made a substantial theoretical contribution by developing a quantitative model that distinguishes the individual contributions of gas, solid, and radiative heat transfer in porous insulation materials. Their work establishes a comprehensive theoretical foundation for understanding the fundamental heat conduction mechanisms in insulating materials, enabling more precise material characterization and performance prediction.

Collectively, these studies demonstrate the multidisciplinary nature of current research in cold-region tunnel insulation, spanning experimental investigation, numerical modeling, practical application, and theoretical development, while addressing both macroscopic performance requirements and microscopic material behavior.2.3Impact of Saline Soil Environments on Thermal Insulation Layers

In western China, characterized by low precipitation and high evaporation, a significant positive correlation exists between Cl^- and Na^+ content in seasonal frozen soil [10]. When the tunnel waterproofing system is compromised, salt-containing groundwater infiltrates and saturates the insulation layer. The presence of saline solutions and crystals within the material's pores subsequently affects its moisture status and thermal conductivity [11]. Notably, the ionic composition of seasonal frozen soils in China exhibits distinct spatial variability, following a "low in the northeast, high in the northwest" trend. This geographic disparity leads to significant variations in the salinity of seepage water across different regions, consequently exerting differing degrees of influence on the thermal performance of the insulation layers. Current research on tunnel insulation in cold regions predominantly focuses on the materials themselves, installation techniques, and the impacts of freeze-thaw cycles. In contrast, systematic studies investigating the specific effects of seepage water salinity on insulation layer performance remain relatively limited [12].

2.3. Application of Machine Learning in Cold-Region Tunnel Research

In recent years, machine learning methods have been progressively integrated into thermal insulation research for cold-region tunnels, demonstrating significant potential in enhancing prediction accuracy and optimization efficiency. Javier et al. [13] pioneered the application of machine learning by employing material type, cold vacuum pressure, and layer density as key input parameters to predict the thermal conductivity of insulation materials under low-temperature conditions. Their work established a valuable data-driven approach for rapid material performance assessment, reducing reliance on time-consuming experimental measurements.

Building on this foundation, Wang et al. [14] adopted a more sophisticated methodology by combining the Lattice Boltzmann Method (LBM) with deep learning techniques. They first utilized LBM to accurately simulate the temperature field and thermal conductivity of polyurethane (PU), then leveraged the generated high-fidelity dataset to train a Convolutional Neural Network (CNN) model. This hybrid approach successfully bridged numerical simulation with artificial intelligence, enabling efficient prediction of material behavior while maintaining physical consistency.

Further advancing the field, Peng et al. [15] focused on solving complex geometric challenges in temperature field prediction. By training a CNN model on steady-state temperature field data generated through Finite Element Method (FEM) simulations, they developed a powerful tool for efficient prediction under various geometric configurations. This methodology significantly reduced computational costs while maintaining prediction accuracy, offering practical solutions for real-world engineering applications with complex tunnel profiles.

In a broader contextual application, Mohammad et al. [16] extended machine learning techniques to sustainable building design, utilizing these methods to predict optimal insulation thickness and layout configurations for green buildings across different climate zones. Their research highlighted the transferability of machine learning approaches from specialized tunnel engineering to general building energy efficiency optimization, demonstrating the versatility and scalability of these data-driven methods.

Collectively, these studies illustrate an evolutionary trajectory in machine learning applications—from fundamental parameter prediction to integrated multi-physics modeling, and from specific tunnel engineering problems to broader building thermal performance optimization. The integration of physical simulations with data-driven approaches presents a promising paradigm for future research in cold-region infrastructure development, potentially revolutionizing traditional design and optimization processes through enhanced computational efficiency and prediction accuracy.

3. Next Research Direction

3.1. Development of Coupled Models

Indeed, there exists a pressing requirement to advance the development of sophisticated hydro-thermal-chemical (H-T-C) or thermo-hydro-mechanical-chemical (THMC) multiphysics coupling models. Such advanced computational frameworks must be capable of quantitatively characterizing the complex interdependencies among critical factors, including salt solution concentration dynamics, cumulative freeze-thaw cycle effects, and multiphase moisture migration patterns, and their synergistic impacts on the progressive degradation of thermal performance in insulation materials. These models should incorporate precise constitutive relationships that account for phase change phenomena, ion transport mechanisms, and microstructural evolution, thereby enabling accurate prediction of long-term material behavior under realistic environmental conditions. The development of such comprehensive modeling capabilities will provide invaluable insights for optimizing material selection, designing durable insulation systems, and establishing reliable service life predictions for infrastructure in cold regions.

3.2. Long-Term Performance and Standards

A systematic and comprehensive program of experimental investigation is imperative to elucidate the long-term evolution of critical material parameters—such as thermal conductivity, compressive and tensile strength, and deformation characteristics—under the synergistic influence of combined environmental and mechanical stressors. These stressors include exposure to saline solutions of varying concentration, repeated freeze-thaw cycles, and sustained or cyclic mechanical loading.

Such experiments should be designed to simulate real-world service conditions over extended periods, enabling the quantification of degradation kinetics and the identification of failure mechanisms. The experimental data generated will be fundamental for developing accurate, physics-based constitutive models that describe material behavior under these complex multi-physical interactions.

Building upon this foundational understanding, it is essential to formulate modified design equations, performance-based specifications, and comprehensive guidelines. These updated frameworks will provide engineers with the necessary tools for the scientifically-grounded selection and optimized design of insulation layers specifically for saline environments. This will ensure long-term structural safety, functional performance, and durability of infrastructure constructed in cold regions affected by salt.

3.3. Leveraging Machine Learning

Indeed, the application of machine learning methodologies should be significantly expanded beyond the current focus on thermal conductivity prediction. Future research should prioritize the development of sophisticated AI-driven models that holistically integrate multi-source data encompassing geological conditions, climatic parameters, material properties, and long-term monitoring data. These advanced models could effectively predict insulation system failure risks by analyzing complex patterns in environmental stressor interactions and material response mechanisms.

Furthermore, such AI frameworks should be developed to optimize maintenance schedules through predictive analytics, enabling proactive intervention before significant performance degradation occurs. Ultimately, this research direction should contribute to the creation of intelligent health monitoring systems for cold-region tunnels in saline environments. These systems would leverage distributed sensor networks coupled with machine learning algorithms to enable real-time assessment of insulation layer condition, facilitate data-driven maintenance decisions, and support the development of digital twins for tunnel infrastructure management. The integration of these capabilities will transform the current practice from schedule-based maintenance to a condition-based predictive paradigm, significantly enhancing the safety, service life, and cost-effectiveness of tunnel operations in challenging cold and saline environments.

4. Conclusion

Theoretical, experimental, and numerical studies have established a fundamental framework for understanding the temperature fields in cold-region tunnels and the performance of insulation layers. However, the presence of saline groundwater, a common issue in western China, introduces a critical complicating factor. The infiltration of salt-laden water alters the moisture content and thermal conductivity of insulation materials like XPS and PU. The significant spatial variation in soil salinity across different regions implies that the impact on insulation layers is not uniform, presenting a location-specific challenge. While machine learning offers promising tools for prediction and optimization, the current body of research lacks systematic, quantitative models that explicitly account for the effects of seepage water salinity on the long-term thermal and mechanical performance of insulation layers.

References

[1] Cui G, Ma J, Wang L, et al. A new off-wall insulation liner for high-speed railway tunnels in cold regions [J]. Case Studies in Thermal Engineering, 2021, 28: 101652.

[2] Sun K, Jia J, Xiong Z, et al. Investigation of hydro-thermal variations and mechanical properties in cold region tunnels under long-term freeze-thaw cycles [J]. Tunnelling and Underground Space Technology, 2024, 143: 105469.

[3] Bonacina C, Comini G, Fasano A, et al. Numerical solution of phase-change problems [J]. International Journal of Heat and Mass Transfer, 1973, 16(10): 1825-1832.

[4] Zhao Y, Zhang J, Li L, et al. Analytical solution for the temperature field of an elliptical tunnel in cold regions [J]. Cold Regions Science and Technology, 2023, 208: 103793.

[5] Ma Q, Luo X, Lai Y, et al. Numerical investigation on thermal insulation layer of a tunnel in seasonally frozen regions [J]. Applied Thermal Engineering, 2018, 138: 280-291.

[6] Xia C, Wang S, Ying Y, et al. Advances in indicators for defining cold levels within tunnels: Current state and future

perspectives [J]. Cold Regions Science and Technology, 2025: 104477.

[7] Li S, Li G, Wang C, et al. Optimal reinforcement for improving the thermal performance of a permafrost tunnel based on coupled heat-mass transfer [J]. Tunnelling and Underground Space Technology, 2022, 121: 104331.

[8] Lu T, Zhang G, Liu S, et al. Numerical investigation of the temperature field and thermal insulation design of cold-region tunnels considering airflow effect [J]. Applied Thermal Engineering, 2021, 191: 116923.

[9] Shrestha S S, Tiwari J, Rai A, et al. Solid and gas thermal conductivity models improvement and validation in various porous insulation materials [J]. International Journal of Thermal Sciences, 2023, 187: 108164.

[10] Bu X, Hao L, Mou Z, et al. Mass fractions of water-soluble ions and characteristics of soil salinization in seasonal frozen soil of Northeast and Northwest China [J]. Journal of Lanzhou University (Natural Sciences), 2023, 59(03): 314-321.

[11] Elchishcheva T F, Erofeev V. The influence of salts' presence in the materials on their moisture and thermal conductivity [C]// Materials Science Forum, 2020.

[12] Ding J, Wang F. Environmental modeling of large-scale soil salinity information in arid areas: A case study of the low-middle altitude alluvial plains on the north and south sides of the Tianshan Mountains, Xinjiang [J]. Acta Geographica Sinica, 2017, 72(01): 64-78.

[13] Rahman A A, Wang B, Yu J, et al. Machine learning approaches for the prediction of thermal performance of multilayer insulation materials at low temperatures [J]. Applied Thermal Engineering, 2025, 264: 125527.

[14] Wang M, Wang H, Yin Y, et al. Temperature field prediction for various porous media considering variable boundary conditions using deep learning method [J]. International Communications in Heat and Mass Transfer, 2022, 132: 105916.

[15] Peng J, Liu X, Aubry N, et al. Data-driven modeling of geometry-adaptive steady heat conduction based on convolutional neural networks [J]. Case Studies in Thermal Engineering, 2021, 28: 101651.

[16] Ghalandari M, Mukhtar A, Yasir A S H M, et al. Thermal conductivity improvement in a green building with Nano insulations using machine learning methods [J]. Energy Reports, 2023, 9: 4781-4788.