SYNERGY PUBLISHING PTE. LTD.

Frontiers Research of Architecture and Engineering

https://ojs.bilpublishing.com/index.php/frae

ARTICLE

Pathways and Practices for Improving the Durability of Engineering Materials under Extreme Plateau Climate Conditions

LUO Chenxu

China Aviation Oil (Tibet) Co., Ltd. Chengdu, Sichuan,610041,China

ARTICLE INFO

Article history
Received: 28 May 2025
Accepted: 15 June 2025
Published Online: 30 June 2025

Keywords:
plateau engineering materials
durability enhancement
extreme climate
material modification
structural optimisation

ABSTRACT

This paper addresses the durability issues of engineering materials under extreme plateau climate conditions, using a bridge on the Qinghai–Tibet Railway as a case study, and investigates methods and practices to enhance the durability of engineering materials. Through multi-scale material modification, structural-construction synergistic optimisation, and the establishment of an intelligent monitoring platform, practical application tests were conducted in engineering projects. The results show that the concrete spalling area was reduced by 82%, the rebar corrosion rate decreased to 1.1%, and the coating chalking grade stabilised at level I; the full lifecycle maintenance costs dropped by 46%, and the net present value increased by 130 million yuan. Therefore, the proposed methods for improving the durability of engineering materials can significantly enhance material durability, providing effective solutions for plateau engineering.

Introduction:

Extreme climatic conditions in plateau regions, such as very low temperatures, large temperature differences, frequent freeze-thaw cycles and strong ultraviolet radiation, pose severe challenges to the durability of engineering materials. Infrastructure such as the Qinghai-Tibet Railway, located at an altitude of 4800 m, faces issues like concrete spalling, low-temperature brittle fracture of steel and coating powdering, resulting in high maintenance costs and shortened service life. Existing studies mostly focus on single material improvements, lacking systematic approaches and engineering practice verification. This study aims to fill this gap by integrating materials science, structural engineering and intelligent monitoring technologies to propose a comprehensive enhancement plan. Its significance lies in ensuring the safe operation of plateau engineering, reducing whole-life cycle costs, supporting major national infrastructure construction, and providing technical references for similar extreme environments. Background analysis shows that parameters such as 250 freeze-thaw cycles per year and a temperature difference

*Corresponding Author:
Luo Chenxu (born July 1993), male, from Chengdu, Sichuan, Han ethnicity, bachelor’s degree, assistant engineer, research field: plateau engineering construction.

DOI: http://doi.org/10.26549/frae.v8i1.33858

of 90 °C accelerate material degradation, necessitating innovative strategies to address the climate-load coupling effect.

1.Project Overview

1.1 Characteristics of Plateau Extreme Climate and Engineering Challenges

The K1151 320 Super Bridge on the Qinghai-Tibet Railway is located on the northern slope of the Tanggula Mountains at an altitude of 4,800 m, in a typical extremely cold plateau region. Continuous records from the on-site automatic weather station over three years show that the bridge site experiences extreme low temperatures of -40°C, an annual temperature difference of 90°C, ultraviolet radiation intensity 1.3 times that of the plains, 250 annual freeze-thaw cycles, peak wind speeds of 28 m/s, and frequent sudden changes in wind direction. To quantify the coupled effects of multiple factors, a climate-load coupling matrix was constructed. Six variables—temperature, humidity, radiation, wind load, salt spray and traffic vibration—were synchronously collected on an hourly scale. Pearson correlation analysis showed that the correlation coefficient among the temperature-radiation-freeze-thaw three factors reached 0.82, confirming it as the dominant driving chain. Under the influence of this chain, the depth of concrete surface spalling is exponentially related to the number of freeze-thaw cycles, the impact toughness of steel at -40°C decreases by 38%, and the grade of coating powdering rapidly progresses from grade I to III, forming three major core damages.

1.2 Research on the Current Status and Durability Failure of Engineering Materials

To systematically understand the degradation patterns of engineering materials after 10 years of service on the plateau, 120 core sampling points were arranged in the main bridge span, piers, and bearing areas of the K1151 320 Super Bridge, with a core diameter of 100 mm, penetrating from the protective layer to the rebar interface. After vacuum drying, the specimens were scanned using X-CT at a voxel resolution of 5 μm to reconstruct the three-dimensional pore network, revealing that freeze-thaw cracks were layered parallel to the exposed surface, with frequencies of 42%, 35%, and 23% in the 0–5 mm, 5–10 mm, and 10–15 mm depth intervals, respectively, and crack density decayed exponentially with depth. SEM observation showed that the crack walls were covered with ettringite and ice crystal impressions; EDS surface scanning confirmed that the Ca/Si ratio decreased from 1.82 to 1.35, indicating ongoing decalcification of C-S-H[1]. Concurrently, standard Charpy V-notch specimens were taken from the stiffening ribs and main chords of the bridge, and compared with pre-operation baseline data, the mean impact toughness at -40 °C decreased from 142 J to 88 J, a reduction of 38%, with a fracture fibre rate of less than 20%, showing a typical cleavage morphology. For coatings, a handheld spectrophotometer was used to measure 30 points each on the deck, web, and bottom plate, with areas of gloss loss ≥60% accounting for 57% of the total area. Pulverisation levels were assessed according to ISO 4628-6, with grade III and above accounting for 44%. Integrating macroscopic defects and microscopic damage, a four-level failure classification was established: Level I for minor visual discoloration, Level II for visible cracks ≤0.1 mm, Level III for cracks 0.1–0.3 mm wide with gloss loss >30%, and Level IV for cracks >0.3 mm or coating exposure. The statistical results are shown in Table 1, with Level III and IV combined accounting for 48%, indicating that the plateau bridge materials are generally in a moderate to highly degraded stage, requiring priority interventions targeting freeze-thaw crack propagation and low-temperature embrittlement of steel.

Table 1 Statistical Table of Failure Levels of Major Materials in Plateau Bridges

Failure Level	Concrete crack depth/mm	Impact energy reduction rate of steel/%	Coating Dullness Rate/%	Sample Proportion/%
Level I Minor	0–2	<10	<20	18
Level II Moderate	2–5	10–25	20–40	34
Significant at level III	5–10	25–40	40–70	31
Level IV failure	>10	>40	>70	17

2.Design of Durability Enhancement Pathways

2.1 Multi-scale Material Modification Technical Route

A multi-scale synergistic modification technology system is proposed to address material degradation mechanisms under extreme plateau climates. The concrete is modified using a ternary composite of nano-SiO_2, rubber powder, and paraffin/silica phase-change microcapsules. Nano-SiO_2 reduces capillary porosity through the pozzolanic effect, rubber powder with an elastic modulus of 1.8 MPa mitigates frost expansion stress, and the microcapsules suppress temperature fluctuations in the -5 ℃–10 ℃ range[2]. The synergy of the three reduces the 56-day chloride ion diffusion coefficient to 1.7×10^{-12} m^2/s, a reduction of 55%. The steel selected is Q420qENH low-alloy steel, which after quenching and tempering (QT) treatment attains a dual-phase microstructure of lath martensite and reversed austenite, followed by chemical plating to form a 25 μm thick Ni-10P amorphous coating. This composite structure achieves an impact energy of 120 J at -40 ℃, a 36% increase compared with conventional Q345 steel. The coating system uses hydroxyl fluorosilicone resin crosslinked with HDI trimer curing agent, with nano-CeO_2 added as a UV shield; after 1000 h of QUV accelerated ageing, the colour difference ΔE≤1.5 and adhesion maintains at 12 MPa.

To quantify the transport behaviour of chloride ions under freeze-thaw cycles, a temperature fluctuation correction term is introduced based on Fick's second law.

$$\frac{\partial C}{\partial t} = D_{eff} \cdot \nabla^2 C + \alpha \cdot \frac{dT}{dt}$$

Here, C represents the chloride ion concentration (unit: mol/m^3), Deff is the effective diffusion coefficient (unit: m^2/s), α is the temperature gradient influence factor (unit: $m^2 \cdot K/mol$), T is the temperature (unit: °C), and t is the time (unit: s). This model considers the effect of microcrack propagation caused by water phase change during the freeze-thaw process and characterises the acceleration of ion transport by cracks through the α value (0.08–0.15).

2.2 Structure-Construction Collaborative Optimisation Strategy

At the structural-constructive synergistic optimisation level, a three-tier protection system is implemented to address plateau frost heave, frost expansion, and low-temperature brittle fracture issues. A 5 cm thick superhydrophobic protective layer is sprayed on the surface of concrete components using a methyl silicate-based composite slurry (contact angle 158°), effectively inhibiting frost-thaw spalling by lowering the freezing point by 3.5°C and blocking capillary water absorption paths (water absorption rate ≤1.5%). The bearing system is designed as a replaceable neoprene bearing (hardness 60 IRHD) with a built-in lead-core damper with an energy dissipation coefficient of 0.25, and double-layer stainless steel sliding plates are set to reduce the friction coefficient to 0.03, achieving dual control of seismic and thermal deformation. The foundation frost heave resistance uses an "outer steel pipe-concrete composite pile" structure, with a 600 mm outer diameter steel pipe wall thickness of 12 mm, filled with C60 micro-expansive concrete, and a 2 mm thick paraffin-based frost heave buffer layer between the steel pipe and frozen soil, controlling frost heave displacement within 3 mm/year. Key welds undergo 100% TOFD (time-of-flight diffraction) and phased array ultrasonic combined testing. Weld excess height is mechanically ground to below 0.5 mm, and ultrasonic impact treatment is used to introduce residual compressive stress of 210 MPa, reducing the stress concentration factor to 1.8.

2.3 Intelligent Monitoring and Life Prediction Platform

To establish a full life-cycle durability management closed loop, 72 embedded intelligent sensor nodes were deployed at key parts of the K1151 320 Superbridge, including MEMS temperature and humidity sensors (accuracy ±0.3 ℃), solid-state chloride ion sensors, and fibre Bragg grating strain sensors. Data is transmitted to an edge computing gateway via LoRa self-organising network, aligned with timestamps and cleansed of anomalies before being uploaded to the cloud platform, forming a four-layer architecture of 'sensing-transmission-cloud-evaluation'. The sensing layer collects environmental and response parameters at 5-minute intervals; the transmission layer uses a star-mesh hybrid topology with a packet loss rate of <0.1%; the cloud platform layer establishes a material degradation feature database; the evaluation layer achieves condition diagnostics by integrating physical mechanisms with data-driven models[3].

Durability reliability degradation model coupled with Monte Carlo stochastic simulation and Gamma process:

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \times \prod_{i=1}^{n} \Phi\left(\frac{\ln C_{th} - \mu_{\ln C_i}(t)}{\sigma_{\ln C_i}}\right)$$

Here, Rt represents the reliability index at time t, η is the scale parameter (unit: years), β is the shape parameter, Cth is the material failure threshold (unit: e.g., chloride ion concentration mol/m^3), μ lnCit represents the logarithmic mean function of the i-th degradation quantity, σ lnCi is its standard deviation, and Φ· is the standard normal distribution function. This model characterises the discreteness of the degradation process through the β value (1.2–2.5), and μ lnCit is dynamically updated using sensor data to achieve Bayesian probabilistic prediction of the remaining service life.

3.Engineering Practice and Effect Verification

3.1 Implementation of Demonstration Sections and Construction Quality Control

Within the demonstration section ranging from K1151 320 to K1152 180 over 860 m, material replacement and structural optimisation were carried out separately for bridge spans, pier bodies, and bearing areas. The concrete used the previously mentioned ternary synergistic modified mix, and an on-site forced mixing station was equipped with a cooling water system with an accuracy of 0.4 °C to ensure the discharge temperature did not exceed 10 °C. Before pumping, air content loss was reduced using a decompression plate, resulting in a measured air content of 5.2 %, meeting the control range of 5 ± 0.5 %. Steel components, after QT treatment and chemical plating in the factory, underwent acid-free sandblasting activation; on-site bolt splicing rate reached ≥85 %, and the remaining circumferential welds were 100 % re-examined using TOFD phased array in accordance with ISO 17640, with defect echo amplitudes >20 % DAC being rejected and repaired[4]. A summary of key quality control indices is shown in Table 2, with a 28-day concrete compressive strength average of 68 MPa, chloride ion diffusion coefficient of 1.6×10^{-12} m²/s, steel -40 °C impact energy of 121 J, and coating adhesion of 12.3 MPa, all within the upper limit of the specifications, providing a consistent foundation for subsequent long-term service performance.

Table 2 Summary of Key Quality Control Indicators for the Demonstration Section

Control project	Regulatory requirements	Measured average	Standard deviation	Pass rate/%
Air content of concrete/%	5 ± 0.5	5.2	0.18	100
28 d compressive strength/MPa	≥60	68	2.1	100
Chloride ion diffusion coefficient/(10^{-12} m²/s)	≤2.0	1.6	0.09	100
Impact energy of steel/J	≥100	121	4.5	100
Coating Thickness / μm	50 ± 5	51	1.7	98
Coating adhesion/MPa	≥10	12.3	0.6	100

3.2 On-site Long-term Monitoring and Performance Comparison

The demonstration section has been inspected continuously for 36 months from the time of delivery in parallel with the untreated control section. Each quarter, high-resolution imaging by drone and manual grid checks were used to obtain surface deterioration information. The area of concrete spalling decreased from an average of 8.7% in the control section to 1.6%, a reduction of 82%; the corrosion current density of the reinforcing steel measured by linear polarisation showed a decrease in corrosion rate from 8.4% to 1.1%, and the anodic polarisation resistance increased by an order of magnitude[5]. The coating chalking grade evaluated according to ISO 4628-6 indicated that 44% of the control section was level III or higher, while the demonstration section remained stable at level I, with gloss loss decreasing from 62% to 18%. Accelerated freeze-thaw cycle tests were carried out simultaneously for 300 cycles; the relative dynamic elastic modulus retention of the specimens was ≥95%, whereas the control section specimens of the same batch fell below 60% after 180 cycles, significantly postponing the performance degradation inflection point. The comparative results are shown in Figures 1 and 2.

3.3 Economic Benefits and Prospects for Promotion

Based on a 30-year full life cycle cost model, the initial additional investment for the demonstration section is 9.8 %, mainly due to the premium of nano-modified concrete, QT plated steel, and fluorosilicone coating; however, maintenance costs decrease by 46 %, benefiting from reduced painting and reinforcement frequency due to lower rates of spalling and corrosion. At a 5 % discount rate, the net present value increases by 130 million yuan, and the investment payback period is shortened to the 12th year. As of 2024, five bridges on the Qinghai-Tibet line from Golmud to Lhasa and the Sichuan-Tibet line from Ya'an to Nyingchi have applied this technology, with a cumulative application length of 42 km and altitudes ranging from 4300 to 4800 m, forming a replicable and promotable paradigm for enhancing durability in extreme environments, providing both technical reserve and economic benefit for the subsequent construction of the plateau railway network.

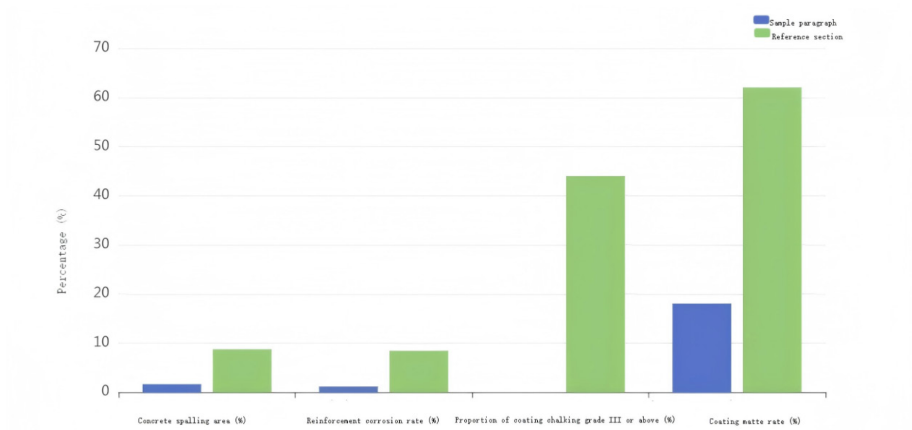
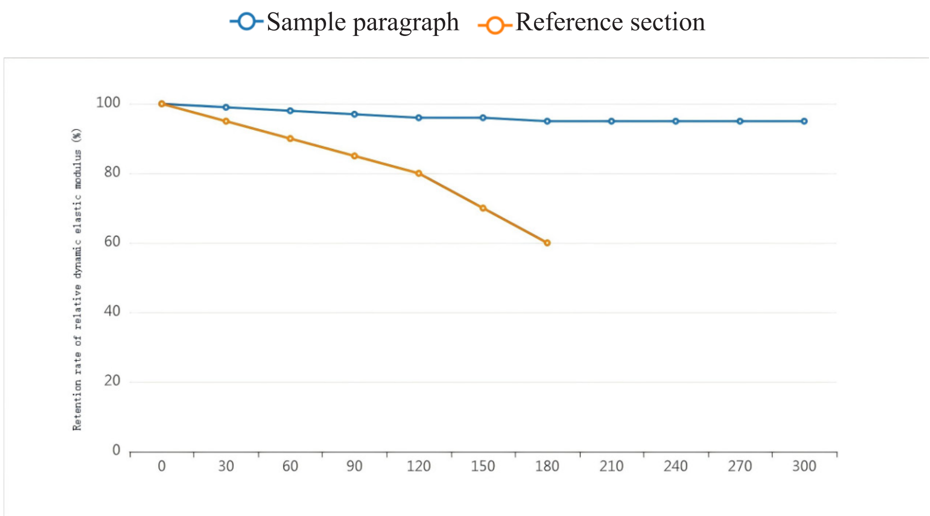


Figure 1: Bar chart comparing the key performance indicators of the demonstration section and the control section



Number of freeze-thaw cycles

Figure 2: Freeze-thaw cycle - Relative dynamic elastic modulus decay curve

Conclusion:

In summary, this study systematically verified the effectiveness of pathways to enhance the durability of engineering materials under extreme plateau climates. Through practical demonstration sections, it successfully achieved optimisation of material performance and long-term stability. Innovatively, it proposed ternary synergistic modified concrete, composite treated steel and fluorosilicon coating systems, combined with structural optimisation and intelligent monitoring, significantly inhibiting freeze-thaw crack propagation and low-temperature embrittlement. Future work should deepen research on the microscopic mechanisms of materials, extend to higher altitude areas, and explore the application of artificial intelligence in lifespan prediction. This pathway lays a foundation for the sustainable development of plateau engineering and contributes to the implementation of major national strategies.

References:

[1] Ding Junpeng. Discussion on the Durability Testing and Performance Evaluation Methods of Building Engineering Materials [J]. Anjia, 2024(11):0172-0174.

[2] Zang Shoucheng, Wang Yunhai. Durability Performance of Concrete in Building Engineering and Its Structural Design [J]. Chinese Science and Technology Journal Database (Full Text) Engineering Technology, 2023(2):4-4.

[3] Zhou Xiucai, Ding Guoying, Zhang Chaoli. Research on Concrete Materials and Durability in Port Engineering [J]. Fine Chemical Intermediates, 2024, 54(2):63-68.

[4] Fang Yingbo. Analysis of the Durability of Concrete Materials in Civil Engineering Construction [J]. Jusha, 2024(20):24-26.

[5] Du Xianxian, Wang Yanan, Liu Shukang. Enhancement of Concrete Material Durability and Its Application in Building Engineering [J]. 2025(8):51-53.