Original Research Article

Study on causes and prevention technologies of hidden cracks in secondary lining concrete of high ground temperature tunnels

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Abstract: In the construction of plateau railway tunnels, high ground temperature environments significantly increase the risk of hidden surface cracks in secondary lining concrete, compromising structural durability and long-term safety. Based on extensive field tests conducted in a plateau railway project, this paper systematically investigates the distribution characteristics, formation mechanisms, and key influencing factors of hidden cracks. A comprehensive prevention technology system centered on "temperature reduction and shrinkage control, enhanced moisture retention, and process solidification" is proposed. Through two-phase comparative field tests, it was demonstrated that an integrated approach—Incorporating 40% fly ash content, optimized water-binder ratio, concrete placing temperature ≤15°C, and the application of 2–3 layers of curing agent combined with mist-spray curing—Remarkably reduces the occurrence of hidden cracks. Test results indicate that this strategy lowered the hidden crack panel ratio from 22.9% to 3.6%, effectively enhancing the crack resistance of secondary lining concrete under high-temperature and low-pressure conditions. This study provides both theoretical insights and practical technical references for tunnel concrete construction in similar geological and climatic environments.

Keywords: high ground temperature tunnel; secondary lining concrete; hidden cracks; curing technology; fly ash content; drying shrinkage; thermal stress; plateau environment

1. Introduction

Tunnel engineering in plateau regions is often confronted with complex and harsh environmental conditions, including high ground temperature, low atmospheric pressure, strong ventilation, and significant diurnal temperature variations. Under such conditions, secondary lining concrete is particularly susceptible to developing surface hidden cracks during its early hardening stage. These cracks, typically invisible when the concrete surface is either completely dry or fully saturated, become apparent only in a semi-dry, semi-wet state. They are predominantly distributed in the arch waist area, posing a potential threat to the concrete's durability, impermeability, and overall structural stability. In recent years, with the rapid advancement of plateau railway construction, hidden cracking has emerged as a critical technical challenge that constrains engineering quality and project longevity.

Existing research on concrete cracking has largely focused on shrinkage behavior and temperature control under standard or moderate climatic conditions. However, systematic experimental studies and in-depth mechanistic analysis of early-age cracking under the coupled influences of "high ground temperature and low atmospheric pressure" remain scarce. The unique environmental synergy in plateau regions accelerates moisture evaporation and alters the concrete's hydration and stress development processes, necessitating specialized investigation. To address this gap, a comprehensive field test program was conducted from January to April 2025 within a plateau railway project, focusing on hidden crack prevention. Through a two-phase comparative experimental design, the primary causes of hidden cracks were identified. Subsequently, a set of tailored measures—Encompassing concrete mix proportion optimization, advanced curing processes, and stringent construction procedure control—Was proposed for high ground temperature tunnels. Grounded in empirical test data and theoretical analysis, this paper systematically elaborates on the formation mechanisms and prevention technologies for hidden cracks, aiming to furnish valuable guidance for similar engineering projects worldwide.

2. Experimental design and methods

2.1. Overview of test sites

The field tests were conducted across 33 high ground temperature working faces along the tunnel alignment. Based on the recorded ambient temperatures at the lining construction sites, the test sections were categorized into four distinct types:

Low-High Temperature (LHT): ≤ 28°C
Medium-High Temperature (MHT): 28 – 37°C
High-High Temperature (HHT): 37 – 50°C
Ultra-High Temperature (UHT): > 50°C

A clear positive correlation was observed between the ambient temperature and the severity of hidden cracking. The average area of hidden crack zones increased significantly with rising temperature, reaching approximately 18 m^2 in the Ultra-High Temperature sections, underscoring the critical influence of thermal environment.

2.2. Investigation of hidden crack characteristics

Hidden cracks typically manifested within 1 to 5 days after formwork removal. They were primarily located above the second window of the secondary lining in the arch waist region and exhibited a developmental pattern aligned with the direction of tunnel ventilation. These cracks display a unique visibility characteristic: they are invisible when the concrete surface is dry or fully wet, only becoming discernible in a semi-dry, semi-wet condition. This behavior classifies them as typical early-age drying shrinkage microcracks, influenced by surface moisture gradients.

2.3. Experimental design

The investigation was structured into two sequential phases to compare and refine prevention strategies:

Phase 1 (Pilot Implementation): Involved 7 working sites with 4 lining panels per site. A unified strategy was applied, featuring a concrete mix with 40% fly ash content and the application of three layers of curing agent post-demolding, followed by standard moist curing.

Phase 2 (Comparative Analysis): Encompassed 12 working sites with 2 panels per site. Two distinct curing schemes were implemented on different panels for direct comparison:

Scheme 1: Segmented application of curing agent based on tunnel height: 1–2 layers for the lower section (0–6 m), and 2–3 layers for the upper section (6–12 m).

Scheme 2: A more conservative approach with no curing agent applied on the lower section (0–6 m) and only 1 layer applied on the upper section (6–12 m), simulating less intensive curing practices.

2.4. Testing and monitoring regime

A multi-parameter monitoring regime was established to capture environmental, material, and performance data:

Environmental Parameters: Continuous logging of ambient temperature, relative humidity, and wind speed at the working faces.

Fresh Concrete Properties: Measurement of slump, flow spread, air content, and monitoring of concrete temperature history from placement through early hardening.

Hidden Crack Documentation: Systematic visual inspection and photographic recording of all test panels after formwork removal. The number of cracked panels and the surface area of cracks were quantified periodically.

Drying Shrinkage Tests: Laboratory comparison of free drying shrinkage values for identical concrete mixes cured under simulated plateau (low-pressure) and low-altitude (standard pressure) conditions.

Moisture Loss Tests: Specimens subjected to different curing conditions (e.g., uncured in tunnel environment, with curing agent, under steam curing cart) were weighed periodically to determine 3-day water loss and calculate moisture retention rates.

3. In-depth analysis of hidden crack formation mechanisms

3.1. Aggravated drying shrinkage under plateau conditions

The primary driver of hidden cracks is significantly accelerated drying shrinkage. In plateau regions, the low atmospheric pressure reduces the boiling point of water and increases the diffusion coefficient of water vapor.

This physical environment leads to a moisture loss rate from concrete that is approximately 1.43 times faster than that observed in plain regions at standard atmospheric pressure. Concurrently, high ground temperature further intensifies evaporation; the evaporation rate increases by 50% to 100% for every 10°C rise in temperature. This rapid surface moisture depletion causes substantial capillary tension and hygroscopic stress within the surface paste, leading to immediate shrinkage. However, the interior of the concrete member retains moisture longer and shrinks at a slower rate. This differential creates a steep moisture gradient and a corresponding shrinkage gradient from the surface to the core. The restrained surface shrinkage generates tensile stresses that can quickly exceed the low early-age tensile strength of the concrete, resulting in the formation of fine, shallow microcracks—The observed hidden cracks.

3.2. Excessive temperature peaks and induced internal thermal stress

The heat of hydration, combined with high ambient temperatures, leads to significantly elevated peak temperatures within the concrete mass. In high-high temperature sections, core temperatures were recorded to exceed 55°C. This temperature rise has two major effects. First, the cement paste and aggregates have different coefficients of thermal expansion. During the heating phase, the paste expands more than the aggregate, creating compressive stress in the paste and tensile stress at the paste-aggregate interface. During subsequent cooling, the paste contracts more, reversing the stress state and often inducing tensile stress in the paste. Second, a steep temperature gradient develops between the warmer interior and the cooler surface (especially after formwork removal or due to ventilation). This gradient causes differential thermal expansion, leading to self-restrained thermal stress. Calculations based on test data indicated that with temperature differentials ranging from 20 to 35°C between the core and surface, the resulting shear stress at the interface could reach 1.0 to 4.2 MPa. This thermal stress synergistically combines with drying shrinkage stress, drastically increasing the propensity for surface microcracking.

3.3. The "Canyon Effect" and accelerated surface drying

The tunnel itself acts as a wind tunnel, creating a "canyon effect" that accelerates air movement across the concrete surface, particularly when formwork is removed and curing is not immediately initiated. This forced convection dramatically increases the evaporation rate from the concrete surface, far exceeding the rates predicted by temperature and humidity alone. The rapid removal of moisture from the surface layer not only exacerbates drying shrinkage but also can lead to a phenomenon known as "skin drying," where a dense, less permeable layer forms on the surface, trapping moisture beneath and potentially creating delamination risks. This effect is a critical environmental factor that makes timely and effective curing absolutely imperative in tunnel environments.

4. Results and discussion

4.1. Comparative analysis of hidden crack incidence

The effectiveness of the implemented measures was evaluated based on crack incidence rates:

Pre-Test Baseline: Out of 931 lining panels inspected before the study, 213 panels exhibited hidden cracks, yielding a high incidence rate of 22.9%.

Phase 1 Results: After implementing the optimized mix (40% fly ash) and 3-layer curing agent strategy, only 1 out of 28 panels developed cracks, reducing the incidence rate to 3.6%. This marked a dramatic improvement.

Phase 2 Results: The comparative phase provided further insights. Out of 29 panels, 4 showed cracks (13.8% incidence). A breakdown revealed:

No curing agent + steam curing: 33% incidence (highest).

1 layer curing agent + steam curing: 6.7% incidence.

2–3 layers curing agent + steam curing: 0% incidence (no cracks observed).

These results statistically validate the necessity of adequate curing agent application and its synergistic use with active moist curing.

4.2. Influence of curing methods on moisture retention

Quantitative moisture loss tests provided concrete evidence supporting the field observations:

Specimens exposed to the tunnel environment without any curing agent lost 162.2 g of water over 3 days, with a very low moisture retention rate of only 3.7%.

In contrast, specimens treated with 3 layers of curing agent and kept under a steam curing cart lost only 25.7

g of water, achieving a high moisture retention rate of 84.8%.

Furthermore, under steam curing cart conditions, the application of curing agent alone reduced moisture loss by approximately 45% compared to cart curing without the agent. This demonstrates that curing agents form an effective semi-permeable barrier that significantly retards evaporation, while the steam cart provides a humid macro-environment.

4.3. Effectiveness of mix proportion and process optimization

The study confirmed the multi-faceted benefits of the proposed material and process controls:

40% Fly Ash Content: The high volume of fly ash served multiple purposes: it diluted the cement content (reducing heat generation), contributed to pore refinement through secondary pozzolanic reactions (lowering permeability), and improved the long-term creep and shrinkage characteristics of the concrete.

Controlled Water-Binder Ratio and Slump: Strict limits (e.g., C30≤0.39, C35≤0.37, C40≤0.36) ensured a dense matrix with reduced capillary porosity, directly mitigating autogenous and drying shrinkage. Controlled slump (side wall ≤200 mm, arch ≤220 mm) minimized segregation and bleeding, leading to a more homogeneous and crack-resistant surface layer.

Low Placing Temperature (≤15°C): Controlling the initial concrete temperature was crucial. Tests showed that each 1°C reduction in placing temperature translated to roughly a 1°C reduction in the subsequent peak hydration temperature. This linear relationship highlights the importance of cooling aggregates and mixing water, and minimizing transport time in hot environments.

5. Integrated prevention technology system

Based on the synthesis of experimental results, a holistic, three-pillar prevention system was established: "Temperature Reduction and Shrinkage Control, Enhanced Moisture Retention, and Process Solidification."

5.1. Pillar I: Temperature reduction and shrinkage control

This pillar focuses on mitigating thermal and shrinkage strains at the material source.

Cement Selection: Use cement with a moderate specific surface area (300–320 m²/kg) and controlled early strength (3-day strength <25 MPa) to reduce the rate and total heat evolution.

Mix Optimization: Increase fly ash content to 40% (by mass of binder) to replace cement. For a C40 concrete, the cement content should be limited to ≤250 kg/m³.

Thermal Control: Enforce a maximum concrete placing temperature of ≤15°C. This is achieved by shading and sprinkling aggregates, using chilled mixing water or ice, and minimizing delays during transport and placement.

5.2. Pillar II: Enhanced moisture retention

This pillar aims to create and maintain a favorable humidity environment around the concrete during the critical early curing period.

Graded Application of Curing Agent: The number of curing agent layers should be tailored to the ambient temperature zone:

Normal/Low-High Temperature: Spray 2 layers on localized, vulnerable areas (e.g., arch waist).

Medium-High Temperature: Spray 2 layers over the entire exposed surface.

High-High/Ultra-High Temperature: Spray 3 layers over the entire exposed surface.

Immediate and Intensive Moist Curing: A steam curing cart must follow immediately after formwork removal and agent application. It should employ a mist-spray system (water temperature 30–40°C) combined with a fine spray (water temperature 25–35°C) to maintain a relative humidity ≥90% inside the enclosure. The interval between demolding and the initiation of cart curing should not exceed 1 hour. The length of the curing cart should be extended by 0.5 m beyond the panel length to ensure full coverage and minimize edge effects.

5.3. Pillar III: Process solidification

This pillar ensures that sound material design and curing are supported by rigorous construction execution.

Formwork Management: Strictly prohibit any early loosening of formwork. The curing cart must be moved into position immediately after formwork removal to eliminate exposure time.

"Zero-Interval" Curing Philosophy: Minimize all idle time between demolding, surface treatment (e.g., curing agent application), and the start of active moist curing.

Standardized Placement Procedures: Concrete must be placed in layers not exceeding 50 cm thick and consolidated adequately with vibration to ensure uniformity and eliminate cold joints or honeycombing, which can become crack initiation points.

Process Acceptance: Formwork removal and the commencement of curing activities should only proceed after a formal inspection and acceptance of the preceding construction steps, ensuring quality gates are enforced.

6. Conclusions and recommendations

Root Cause Identification: Hidden cracks in the secondary lining of high ground temperature tunnels are not caused by a single factor but are the result of a synergistic interplay between aggravated drying shrinkage (due to low pressure and high temperature), significant internal thermal stress (from high hydration heat and ambient temperature), and the accelerating "canyon effect" of tunnel ventilation. Low atmospheric pressure acts as a key exacerbating factor by fundamentally increasing the moisture evaporation potential.

Validated Integrated Solution: The study empirically validates that an integrated technological approach is essential for effective prevention. The combination of "40% fly ash content + low water-binder ratio + low placing temperature (≤15°C) + 2–3 layers of curing agent + immediate mist-spray curing" forms a robust defense system that addresses the thermal, shrinkage, and moisture loss mechanisms simultaneously, reducing hidden crack incidence from 22.9% to 3.6%.

Engineering Recommendations:

Differentiated Curing Protocols: Develop and enforce site-specific curing strategies that are dynamically adjusted based on real-time monitoring of temperature zones (LHT, MHT, HHT, UHT) within the tunnel.

Strengthened Process Coordination: Implement enhanced communication and scheduling protocols to ensure seamless transitions between construction activities, particularly focusing on the demolding-curing sequence.

Promote Combined Curing Methods: Actively promote and standardize the combined use of membrane-forming curing agents and active steam/mist curing carts as a non-negotiable best practice for high ground temperature tunnel linings.

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