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Causes of Cracks in Tunnel Secondary Lining and Application of High-Performance Repair Materials

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Abstract: Cracks in tunnel secondary linings can significantly reduce structural load-bearing capacity and durability, thereby posing risks to operational safety. This paper analyzes the causes of such cracks from four perspectives: material properties, construction practices, design parameters, and environmental and operational conditions. Fluctuations in material quality, deficiencies in construction techniques, unreasonable design parameters, and environmental degradation are all potential contributors to crack formation. On this basis, the performance requirements for high-performance repair materials are discussed, including mechanical compatibility with the original lining, durability under tunnel environmental conditions, and workability and bonding performance conducive to construction. By examining common types of repair materials and construction techniques, and evaluating repair effectiveness in practical scenarios, this study proposes targeted crack prevention and repair strategies. The aim is to provide technical guidance for tunnel maintenance, thereby enhancing structural safety and extending service life.

Keywords: Tunnel secondary lining cracks; high-performance repair materials; cause analysis; repair technology; effectiveness evaluation

Introduction

With rapid development of transportation infrastructure, tunnels account for an increasing share of road networks. The secondary lining, as a key structural component, directly affects operational safety. In recent years, cracks in secondary linings have occurred frequently, not only affecting appearance but also leading to leakage, reinforcement corrosion, and other chain damages that shorten service life [1]. In practice, repair results are often unsatisfactory due to poor material selection or rough workmanship, causing repeated repairs. This paper focuses on the causes of secondary lining cracks, systematically examines performance requirements and application types of high-performance repair materials, and evaluates repair effects with case studies. The aim is to provide practical technical guidance for frontline staff, promote standardized crack repair, and ensure long-term tunnel stability.

1. Analysis of Crack Causes in Tunnel Secondary Lining

1.1 Material Factors

Fluctuations in the quality of concrete raw materials are a key factor inducing crack formation. Improper selection of cement type can lead to mismatches between the rate of hydration heat release and the heat dissipation capacity of the lining structure, thereby generating zones of temperature-induced stress concentration during hardening. When aggregate gradation is poorly designed, oversized particles may cause segregation during placement, creating weak zones of insufficient local density. During the drying shrinkage stage, these areas are prone to premature cracking [2]. Uncontrolled dosage of admixtures can similarly trigger defects. Excessive use of water-reducing agents prolongs the initial setting time of concrete, leading to plastic settlement cracks under self-weight. Substandard quality of mineral admixtures, such as fly ash, can compromise long-term strength, causing the lining structure to develop load-induced cracks prematurely. Inadequate control of slump during construction further increases cracking risks: excessive workability promotes bleeding, and evaporation of surface water results in shrinkage cracks; conversely, insufficient workability leads to poor compaction, producing honeycombing and surface voids that provide pathways for subsequent crack propagation.

1.2 Construction Factors

The installation accuracy of formwork directly affects the stress state of lining structures. Excessive spacing between supports leads to formwork deformation, which in turn induces structural deflection after concrete placement, resulting in through-cracks. Insufficient fixation causes displacement during vibration, producing misalignments at joints; under subsequent loading, cracks are likely to propagate along these offsets. Improper sequencing of concrete casting can trigger segregation between layers: when the lower layer has already initiated setting, disturbance from the upper layer produces cold joints, thereby reducing structural integrity. Deficiencies in vibration operations are a common source of defects. Insufficient vibration results in inadequate compaction and the formation of void clusters, whereas over-vibration causes aggregate settlement and mortar migration, producing a friable surface layer prone to shrinkage-induced network cracking [3]. Delayed curing measures further exacerbate temperature-induced stresses. If concrete surfaces are not promptly covered and moistened after placement, rapid evaporation at the surface combined with higher internal humidity creates a moisture gradient, leading to surface shrinkage cracks. In winter construction, the absence of thermal protection during curing can cause a temperature differential exceeding 25 °C between the interior and exterior of the concrete, thereby generating temperature-induced cracking.

1.3 Design Factors

Insufficient consideration of geological conditions in cross-sectional design can result in inappropriate structural responses. In weak surrounding rock zones, the adoption of uniform-section lining fails to accommodate heterogeneous deformation of the surrounding rock, leading to localized stress concentrations that exceed the tensile strength of concrete and induce cracking. Inadequate reinforcement design further compromises crack resistance: excessive spacing between reinforcing bars causes crack widths to surpass code requirements, while insufficient cover thickness accelerates reinforcement corrosion and subsequent expansion, triggering surface cracking of the concrete. Deficiencies in waterproofing design also facilitate crack propagation. Improper arrangement of waterstops at construction joints can result in leakage, allowing water ingress. Under freeze–thaw cycles, infiltrated water progressively widens and deepens existing cracks [4]. Moreover, inaccuracies in load calculations may leave the lining structure with inadequate bearing capacity. Failure to account for the combined effects of surrounding rock pressure, groundwater pressure, and vehicle-induced dynamic loads during operation places the lining in a long-term overloaded state, eventually leading to stress-induced cracking.

1.4 Environmental and Operational Factors

Geological and hydrogeological variations exert a significant influence on lining structures. Differential settlement of surrounding rock induces additional stresses, often resulting in shear cracks at critical locations such as the haunch and sidewalls. Prolonged groundwater erosion can dissolve the cementitious components of concrete, thereby reducing structural strength and triggering cracking. Temperature-induced stresses are equally critical. In summer, surface temperatures of the lining rise sharply, creating thermal gradients relative to the cooler interior, which generates expansive stresses. Conversely, low winter temperatures cause contraction stresses. Repeated thermal cycling induces fatigue damage in concrete, gradually leading to crack formation. During operation, repetitive vehicular loads further aggravate crack propagation. Vibratory loads from heavy traffic may resonate with the lining structure, concentrating stresses at the tips of pre-existing microcracks and causing them to extend and widen. In addition, chemical aggression accelerates deterioration. In industrially polluted areas, gases such as sulfur dioxide and carbon dioxide react chemically with concrete to form expansive products, resulting in surface crazing. In saline-alkali regions, groundwater infiltration introduces chloride and sulfate ions, which may trigger alkali–aggregate reactions, leading to internal volumetric expansion and subsequent cracking.

2. Performance Requirements of High-Performance Repair Materials

2.1 Mechanical Properties

The mechanical properties of repair materials must match the original lining concrete to avoid secondary stress concentration caused by differences in performance. Compressive strength should not be lower than the design strength of the original structure. Under standard curing conditions, the material should achieve the required strength at the specified age, allowing joint load-bearing with the original lining in areas such as the crown and sidewalls. In particular, the crown must resist vertical rock pressure, while sidewalls must bear lateral loads, ensuring that overall structural capacity is not weakened. Tensile strength is key for crack resistance. The ultimate tensile strength measured by three-point bending tests should meet the stress demands from temperature changes and service loads, effectively preventing crack propagation at tips under repeated vehicle vibration. The elastic modulus of the repair material should be controlled within a range comparable to that of the original lining concrete. An excessively high modulus may cause the repair layer to bear a disproportionate portion of the load, leading to premature failure, whereas an excessively low modulus can result in stress concentration in the original structure, preventing the formation of a fully integrated load-sharing system. This compatibility is particularly critical at the haunches of the lining, where bending deformations occur, as it directly affects the post-repair structural stability.

2.2 Durability

In humid tunnel environments, the impermeability of repair materials is fundamental to ensuring durability. Based on impermeability grade testing, the material must effectively prevent the ingress of groundwater and other harmful substances. In tunnels with water-rich strata, this property prevents moisture from penetrating deep into cracks, thereby avoiding corrosion of internal reinforcement and the underlying concrete. It is particularly important to inhibit water accumulation within cracks, which could lead to frost heave or chemical deterioration. The frost resistance of repair materials must ensure that, under repeated freeze–thaw cycles, there is no significant loss of mass or reduction in compressive strength. In tunnels located in cold regions, the repair layer should withstand the cyclic freezing in winter and thawing in spring, maintaining structural integrity under severe temperature fluctuations. Chemical resistance should be tailored to the specific geological environment. In chloride-rich conditions, the material must effectively block chloride ion penetration to protect the reinforcement from corrosion. In areas prone to sulfate attack, prolonged exposure should not induce excessive expansion due to chemical reactions, preventing the repair layer from becoming friable or delaminating.

2.3 Workability and Bonding Performance

The workability of repair materials must accommodate the confined operational space within tunnels. The initial flowability of the mix should ensure that cracks and surrounding voids are fully filled under manual or small-scale mechanical vibration. For narrow, fine cracks, the material must exhibit sufficient fluidity to achieve complete injection, whereas in larger repair areas, an appropriate consistency should be maintained to prevent segregation. The setting time must be carefully controlled. The initial setting should be sufficiently long to facilitate construction operations, particularly when repairing multiple crack segments consecutively, to prevent premature hardening from compromising workmanship. The final setting time should not be excessively prolonged, so as not to delay subsequent curing procedures, ensuring that the repair layer achieves adequate strength within the specified timeframe to resist external disturbances, such as tunnel traffic vibrations or the removal of temporary supports. Bonding performance with the underlying concrete is critical to repair effectiveness. At standard curing conditions, the bond tensile strength must meet operational requirements, and failure should occur cohesively within either the substrate or the repair material, rather than at the interface. This intimate bond prevents moisture ingress at the interface, avoiding delamination of the repair layer from the original lining.

3. Application Study of High-Performance Repair Materials

3.1 Common Types of High-Performance Repair Materials

Epoxy resin-based repair materials are widely used for tunnel crack remediation. The epoxy groups in their molecular structure react with curing agents to form a three-dimensional network, resulting in high adhesion strength after curing. This allows the material to penetrate cracks and form a tight bond with the concrete substrate. Such materials exhibit excellent performance in dry conditions and are particularly effective for repairing fine cracks without significant water infiltration, preventing further crack propagation. However, in humid environments, the use of specialized modifiers is necessary to enhance adhesion.

Polymer-modified cement-based materials use ordinary Portland cement as the primary binder, combined with polymer emulsions such as acrylate or styrene-butadiene. The polymer molecules fill and bridge the cement hydration products, mitigating the brittleness of conventional cement and enhancing the flexibility and crack resistance of the repair layer. These materials exhibit strong compatibility with the underlying concrete and maintain good adhesion even on damp substrates, making them suitable for repairing wide, active cracks, particularly in areas of tunnels prone to vibration, such as sidewalls and the arch waist.

Sulphoaluminate cement-based rapid repair materials rely on their unique mineral composition to achieve fast hydration rates, attaining high strength within a short time, which is advantageous for emergency tunnel repairs where schedule constraints exist. During hardening, slight expansion compensates for self-shrinkage and fills crack voids, improving bond tightness with the existing lining. Care must be taken to control the ambient temperature during application, as excessively high temperatures can accelerate hydration and induce internal stresses.

3.2 Repair Construction Techniques

Crack preparation is the foundation of effective repair. Treatment methods are chosen based on crack width and depth. Fine surface cracks are milled along the crack path with a diamond-tipped angle grinder to form a V-shaped groove, with width and depth tailored to the crack size to ensure full material filling. For deep through-cracks, specialized drilling equipment creates grouting holes on both sides, with spacing and depth designed according to crack distribution to ensure uniform penetration.

Substrate cleaning directly affects repair quality. After milling or drilling, high-pressure air is used to remove dust and loose particles. If water or oil is present, cotton with anhydrous ethanol is used to wipe the crack repeatedly until clean. In some cases, hot air may be applied to dry the substrate, ensuring tight bonding with repair materials.

The mixing of repair materials must strictly follow the prescribed proportioning requirements. The base material and curing agent should be combined in the specified ratio and placed in a container, then mixed in a single direction using an electric mixer. The mixing duration must ensure a homogeneous blend without clumps. For epoxy resin-based materials, the mixing speed should be carefully controlled to prevent the introduction of excessive air bubbles, which could compromise the density and integrity of the cured material.

The application method—whether injection or troweling—should be selected according to the material's characteristics. For grouting materials, a manual injection pump should be used, beginning at the lowermost injection port. The valve should be closed once adjacent ports show the emergence of grout, and the process should proceed sequentially until all injection points are filled. For troweling-type materials, a spatula should be employed to evenly apply the material to the prepared crack area, with a thickness slightly greater than the design requirement. After initial setting, the surface should be sanded smooth to ensure seamless integration with the surrounding lining.

Curing measures must be implemented throughout the construction process. During the material's setting period, plastic sheeting or similar coverings should be used to prevent rapid moisture loss. In low-temperature environments, additional thermal protection can be applied to promote proper hydration or curing reactions. The duration of curing should be determined based on the material's characteristics, ensuring that the repair layer reaches the designed strength before being subjected to operational loads.

Conclusion

Cracks in tunnel secondary lining result from the combined effects of materials, construction, design, and environment, necessitating targeted prevention. High-performance repair material selection must balance mechanical compatibility, environmental adaptability, and practical constructability. Epoxy resin, polymer-modified cement, and sulfoaluminate cement materials each have suitable applications depending on crack characteristics and tunnel conditions. Repair quality depends on proper crack preparation, substrate cleaning, material mixing, application, and curing. Standardized procedures improve repair layer integrity and durability. Comprehensive evaluation shows that careful material and process selection can effectively control crack propagation and restore structural performance. In practice, crack cause analysis, optimized repair plans, and long-term monitoring are essential for safe and durable tunnel operation.

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