

Research Progress and Performance Comparison of Tunnel Waterproofing Materials

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Abstract. Tunnel waterproofing is vital for ensuring the long-term safety and durability of underground structures, especially under complex stress and environmental conditions. This paper systematically reviews current waterproofing technologies, including sheet materials, spray-applied membranes, and grouting agents. It also introduces recent innovations such as double-bonded systems, energy-absorbing layers, and self-healing hydrogels. Despite the significant progress made in recent years in developing new waterproofing materials and structural systems, several key challenges remain in practical engineering applications. On one hand, the bonding compatibility between different material interfaces is still insufficient, making them prone to delamination or slippage under repeated loading or uneven stress. On the other hand, research on the adaptability and long-term service stability of materials under extreme environments, such as high temperature, high salinity, and freeze-thaw cycles, is still limited. In addition, there is a lack of standardized durability evaluation criteria and complete life-cycle performance testing systems. The article follows a logical structure from traditional materials to new systems, comparing their mechanical, waterproofing, environmental, and construction performances. This study points out the need for smart, flexible materials and integrated systems to support future green and deep-environment tunnel projects.

Keywords: Tunnel waterproofing, Composite waterproofing system, Spray-applied membranes

1. Introduction

As the city infrastructure develops accelerated development, tunnel engineering has been widely utilized in urban transportation, electric power, and water conservancy industries. However, underground construction structures are typically exposed to moist environments, high hydrostatic pressures, and complex stress conditions, which make them highly vulnerable to groundwater seepage and corrosion of poisonous substances [1]. The issues affect the durability and safe operation of the structures. In addition to compromising structural security and environmental stability, leakage also significantly increases maintenance costs during later periods and becomes the core factor that limits tunnel projects' long-term development [2]. Therefore, constructing waterproof systems with high performance, great environmental adaptability, and smooth construction has become a core component of tunnel engineering design.

Nowadays, the most common waterproofing systems are mainly polymer sheet materials, spray-applied membranes, and grouting materials. Sheet materials have excellent impermeability, but delamination and bulging are easily encountered in areas with complicated structure or interfacial change because of low bonding strength. Spray-applied membrane materials have high capabilities of constructing continuous dense waterproof layers with better flexibility, but their film-forming property is significantly affected by construction site conditions. The grouting materials are particularly suited to filling cracks and reinforcing soils, but cement grouts, traditionally, possess limitations such as low permeability and brittleness hardening. Such monolithic systems are inherently of poor durability and poor structural flexibility and are usually incapable of sustaining multiservice conditions with multiple cracks and successive deformations [3].

To address these challenges, scientists have conducted in-depth research on modifying materials and structural design. Currently, the most dominant approaches for waterproofing material optimization are as follows: (1) Microscopic structure control. Through a modification of polymer constituents or through functional fillers, hydrolysis resistance, adhesion, and flexibility of materials are improved. For example, Pan et al. developed a novel sprayable water-proofing material using optimized polyurethane prepolymers. Through the adjustment of polyether polyol composition, they enhanced the interfacial bonding characteristic and environmental adaptability of the material [3]. (2) Composite structure design. Composite structure design. To enhance resistance to dynamic stress and local impact damage, damping layers are incorporated into lining systems. Shi et al. evaluated the application of a polymer material (PMRSE) as a damping layer in underwater tunnels [4]. This material, embedded between concrete linings, dissipates external energy through its porous microstructure and progressive deformation under load. The inclusion of PMRSE significantly reduced stress concentrations and plastic damage zones in numerical simulations, indicating improved impact resistance and service performance in marine environments. (3) Improvement in grouting material permeability and consolidation capacity. To overcome the defects of traditional grouting materials, such as low penetrability in fine pores and low strength, Wang et al. developed a single-component, low-viscosity, and high-strength polyurethane grouting material. It can achieve spherical diffusion in silty clay and form effective filling in medium and large pores, which has excellent reinforcement performance and synergistic permeability-consolidation behavior [5].

Although existing studies have made significant progress in developing various types of waterproofing materials, there lack review papers that systematically compare the performances and applicability of these various types of materials. This paper therefore focuses on the classification and development status of tunnel waterproofing materials. Based on the representative literature, it systematically compares their structural performance, environmental adaptability, and engineering feasibility. Its purpose is to explore their possible application under complex service conditions, and to provide a theoretical foundation and practical reference for the optimization of the design and material of tunnel waterproofing systems in the future.

2. Waterproofing materials

2.1. Traditional waterproofing materials

2.1.1. Sheet-based waterproofing materials

Sheet-based waterproofing materials are currently the most common traditional waterproofing method used in tunnel engineering. They mainly consist of polymer sheets such as ethylene-vinyl acetate (EVA) and high-density polyethylene (HDPE). These materials offer high tensile strength,

good impermeability, and a certain degree of chemical stability. They are suitable for fast installation over large areas and for mechanized construction [2]. In engineering practice, the sheets are typically placed between the primary lining and the secondary lining, serving as the main waterproofing layer to block groundwater infiltration.

To improve the adaptability of sheet materials under complex stress conditions, some studies have attempted to enhance their performance by constructing composite structures or introducing flexible layers. For example, Zhao et al. pointed out in their study of multilayer tunnel waterproofing systems that using sheet materials extensively on the main structural surface can ensure overall water-blocking integrity [6]. However, it is necessary to supplement them with spray-applied materials to strengthen deformation joints and areas with weak adhesion, to achieve a balanced and integrated waterproofing system.

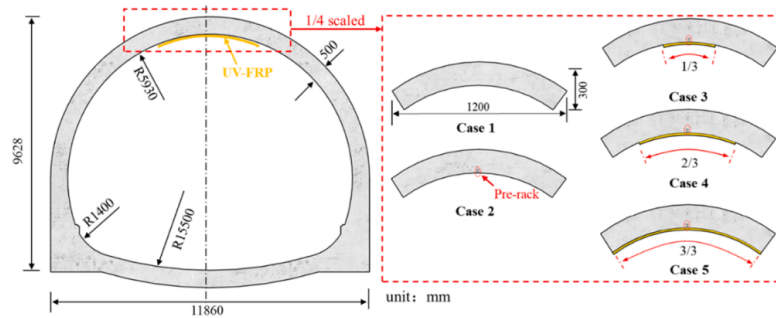


Figure 1. Tunnel lining section and test cases. The left image shows the full tunnel structure where sheet materials are mainly applied. Due to curved shapes and joints, spray materials are added at weak areas. The right image shows five test cases with different UV-FRP reinforcement ranges [6]

2.1.2. Spray-applied waterproofing materials

Spray-applied waterproofing materials form a continuous, smooth, and elastic waterproof membrane on the concrete surface by spraying or brushing. Polyurethane, polyurea, and rubberized asphalt polymer coatings are examples of typical products. Different from sheet materials, spray-applied materials are more able to adapt to intricate interface curvatures and are widely used in tunnel engineering for as-occurred irregular areas such as structural transition zones, pipe wall penetrations, and complex joints. Their flexibility and strong interfacial bonding enable the membrane to remain intact under microcrack movement or minor deformations.

However, spray-applied materials are also subject to many engineering challenges in application. Firstly, their application thickness is likely to be affected by spraying speed, ambient temperature, humidity, and operator skill level [7]. These factors are likely to lead to non-uniform film formation, insufficient thickness, or defects such as pinholes and fisheyes. Moreover, this material is subject to a well-prepared substrate. When the laitance is present in the concrete surface, or there are oil stains, or it is not dry enough, such conditions as blistering or local debonding may be induced by these, greatly degrading the overall compactness and waterproofing performance of the waterproof layer. In addition to that, in high-humidity or alkaline environments, spray-applied materials soften, hydrolyze, or age. Their long-term chemical stability and water pressure resistance over long durations are controversial [2].

Zhou et al. pointed out that spray-applied materials are more suitable for areas with concentrated structural stress, deformation joints, or where sheet installation is difficult, and can serve as an important supplement to sheet-based systems [7]. In composite designs, the spray-applied layer not

only acts as an interface seal but also enhances the system's overall resistance to external disturbance, resulting in a more adaptable flexible sealing structure. Their study suggests that by combining sheet materials with spray-applied coatings, the performance limitations of each single system in different regions can be effectively addressed, providing multiple layers of protection for the long-term service of tunnel waterproofing systems.

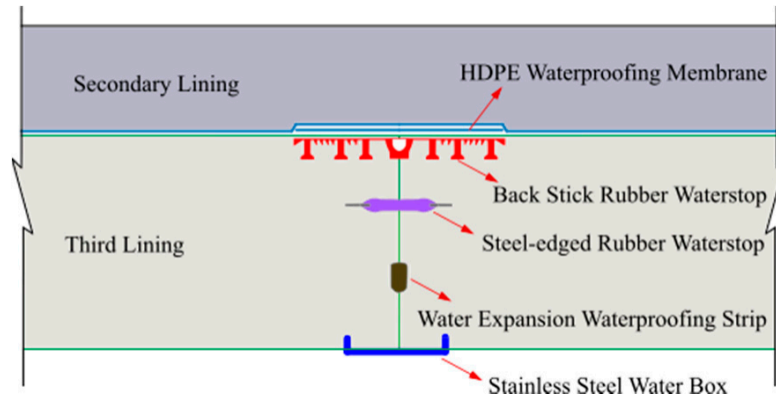


Figure 2. Sectional view of the waterproofing structure at the movement joint, showing the combination of HDPE waterproofing membrane, rubber waterstops, water expansion strip, and stainless-steel water box [7]

2.2. New waterproofing materials

2.2.1. Double-bonded waterproofing system

Double-bonded waterproofing system is a newly proposed structural design innovation for tunnel construction, which has the potential to increase the bonding reliability and impermeability between the waterproof coating and the structure. This system adopts a design configuration comprising a polymer intermediate membrane, an externally bonded drainage layer, and an internally bonded waterproofing layer. It establishes stable dual-interface adhesion with both the primary and secondary linings, thereby forming a continuous and effective sealing pathway between material layers [8]. By multi-interface cooperation, this setup effectively reduces the potential of delamination and water pressure concentration at later stages of service in the waterproofing layer.

Studies have proven that the system works very effectively in regions of tunnel complex structural stress or risk of heavy water infiltration. In effect, it addresses the issue of bonding failure that commonly affects conventional sheet-based systems in deformation zones. On the contrary, by focusing the path of water penetration and reducing the radius, it necessarily enhances the sealing performance and lifespan of the whole waterproofing system [8]. Furthermore, the structure has excellent adaptability and can be mixed with EVA-type polymer films and spray-applied waterproofing materials to form a composite waterproofing system, offering wide application opportunities and promotion opportunities.

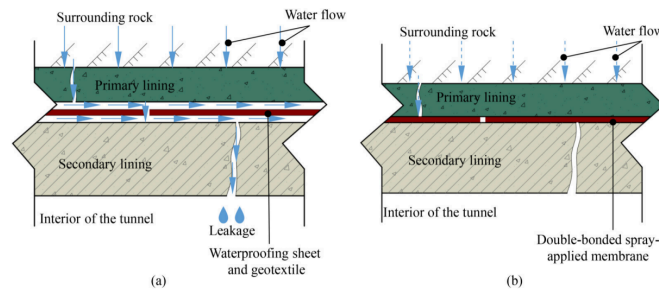


Figure 3. Schematic diagram of waterproofing effect for different lining structures: (a) traditional lining structure; (b) sprayed membrane lining structure [8]

2.2.2. Polymer foam energy-absorbing layer

Exposed to the synergistic effect of high-water pressure and geostress, waterproofing layers within a tunnel generally face intense conditions such as localized stress and impact deformation. Traditional materials would be prone to structural failure or interfacial debonding under these conditions. In addition to improving structural toughness and impact resistance, researchers proposed that a "polymer foam energy-absorbing layer" be implemented within the waterproof system. The polymer material is applied as a dedicated damping layer between the primary and secondary linings in the tunnel structure. In its porous microstructure, foam compresses under load in a controlled way, thus, taking up and dispersing external impact energy and reducing stress concentration [4].

Specifically, this foam material is polyurethane or cross-linked polyolefins, which are blended with masterful techniques to control the foaming ratio and pore structure to form a microscopic network with excellent cushioning property. In Shi et al.'s experimental study, the polymer damping layer (PMRSE) exhibited excellent energy absorption under seismic impact loading [4]. The material also maintained water resistance after seawater erosion, indicating good durability for long-term underwater applications. All these outcomes indicate that the introduction of an energy-absorbing mechanism into the waterproofing system not only helps in overall stability enhancement but also extends the service life of the waterproof layer.

Furthermore, the flexural deformation ability and light weight of the polymer foam layer also enable easy combination with other structural elements such as sheets and spray-applied membranes to form reinforced "rigid-flexible-rigid" or "flexible-rigid-flexible" structural sequences. This further expands its use in complex tunnel waterproofing construction. In the future, this kind of structure will be coupled with smart sensing material so that new developments of stress monitoring and adaptive response function can be realized inside waterproofing layers [9].

2.2.3. Spray-applied EVA waterproof membrane

The spray-applied ethylene-vinyl acetate (EVA) waterproof membrane is a next-generation waterproofing material for use on complex tunnel structures. It can be sprayed in place to form a seamless, continuous waterproof film on the surface of the substrate [10]. This "in-situ film formation" method offers superior coverage and construction versatility in the event of complex curved surfaces, variable cross-sections, or intersecting joints in tunnels. It successfully addresses the disadvantages of conventional sheet materials, like folds and seams, that can form weak points when it is installed.

The key lies in its strong flexibility, ductility, and initial adhesion whereby it strongly adheres to the concrete substrate. Microscopically, this EVA membrane consists of cellular, foods-like pore

structure which provides stress buffer against temperature and humidity fluctuation, structural deflection, or microcrack extension. This enhances bonding stability without allowing delamination or leakage to occur. In their publication, Pelz & Karlovšek indicated that unlike in the traditional EVA sheets, spray-applied EVA membranes not only improve the adhesion on the structural surface but also increase the sensitivity of the membrane to substrate deformation even further, making them suitable for application in irregular cross-sections, curved tunnel sections, and areas with high-level excavation disturbance [11].

In addition, the material composition and the thickness of the spray can be optimized according to different requirements for projects, thereby ensuring customized functionality. Its high-water resistance, thermal stability, and cold temperature flexibility enable it to maintain constant protective performance even over a long service life. Constructively, the spraying process is easy and can be realized through automated systems, significantly improving construction efficiency and minimizing human error. This makes it an optimistic approach for future intelligent tunnel construction. Briefly, the spray-applied waterproof membrane composed of EVA has excellent application value in tunnel waterproofing systems, especially under the situation of complex geological conditions and frequent changes in structure.

2.2.4. Self-healing hydrogels and IPN network materials

To improve the extension resistance of microcracks and service performance of tunnel structures under leakage-induced or damage-motivated damage, researchers have developed numerous new self-healing waterproofing materials in recent years [12]. Among them, hydrogel-based self-healing systems constructed by ionic crosslinking and interpenetrating polymer networks (IPN) have attracted wide attention. They can trigger internal network reconstruction processes in the presence of external stimuli such as moisture intrusion or stress perturbation. This allows them to close and restore cracks or micro-damaged regions, effectively slowing the formation of leakage paths and prolonging the process of material failure [13].

Pan et al. synthesized a multifunctional $\text{Ca}^{2+}/\text{Mg}^{2+}$ ion-crosslinked hydrogel that forms an interpenetrating polymer network (IPN) with polyvinyl alcohol (PVA), and the material possesses superior structural stability and repeated self-healing property in the wet state [3].

The structure is facilitated by the reversibility of the physical crosslinking network. Upon external mechanical damage, the material enables chain segment migration and reformation through hydration, allowing self-healing and micro-level crack closure. This makes it suitable for sealing and repair work under repeated extension of cracks or cyclic loading conditions.

In addition, self-healing hydrogels are very flexible, low-modulus, and hydrophilic, properties which allow them to penetrate the micro-pores of concrete and provide dependable sealing. For this reason, they are particularly suitable for anti-leakage repair at weak points such as around waterstops, construction joints, and deformation joints [14]. The stable network topography of the IPN structure enhances their long-term hydrolysis and fatigue resistance, both theoretically and experimentally supporting the engineering application of high-performance waterproof materials. The materials can be capable of forming composite and synergistic systems with sheets, spray-applied membranes, or grouting materials to enable the development of intelligent waterproofing systems with adaptive and self-healing functions.

2.2.5. One-component polyurethane grouting materials

In microcrack and cracked area grouting generally found in operation or construction of a tunnel, grouting materials are extensively used due to their two-fold functions of quick sealing and structural strength. In recent years, one-component polyurethane (PU) grouting materials have emerged as the main technical option in waterproof grouting systems due to their exceptional ease of use and rich environmental adaptability.

Wang et al. developed a new one-component low-viscosity polyurethane grouting material with strong initial strength and quick reaction-curing behavior [14]. It is simply injected into thin cracks or loose structural sections quickly without requiring mixing with other components, and a dense uniform filling body is formed.

In terms of permeability, it performs exceptionally well. It enables spherical diffusion in highly permeable media such as silty soils and sand-clay mixtures, while forming a stable anchoring-sealing composite interface within the pore structure. Such microscopic structural synergy functions as both reinforcement and anti-leakage, and therefore can be applied to principal zones such as fault zones, rock joint surrounding rocks, secondary lining cracks, and segment joints.

This type of polyurethane is also notable for its corrosion resistance, low shrinkage, and rapid reaction with water to form an elastic, sealed surface. It has a long lifespan and good interfacial bonding strength, and thus serves as a dominant waterproofing and repair material for promoting tunnel operating safety and maintenance efficiency.

3. Comparison of key properties of waterproofing materials

3.1. Mechanical properties

Under dynamic loading conditions, waterproofing systems must be excellent in deformation compatibility and interfacial mechanical stability. The polymer foam energy-absorbing layer is excellent in compressive cushioning and possesses high ductility. Its porous microstructure allows progressive deformation under compression, helping to distribute external loads and reduce local stress concentrations [4].

The spray-applied EVA membrane has excellent modulus stability too. The modulus of this material decreased by less than 12% in two years under natural aging conditions, indicating superior flexibility retention, according to Pelz & Karlovšek [11]. As far as peel strength is concerned, the double-bonded waterproofing structure provides a "dual-interface coupling" between the structure and the substrate, which guarantees significantly higher peel force compared to traditional sheet systems and offers higher interfacial stability [7]. For grouting agents, Wang et al.'s one-component polyurethane grouting agent has stable interfacial shear strength with concrete and can be used for high-stress zone reinforcement and sealing [5].

3.2. Waterproofing and impermeability performance

The fundamental function of a tunnel waterproofing system is to exclude water from the structure. The results of a series of permeability tests showed that double-bonded waterproofing structures have the ability to release concentrated water pressure under hydraulic load, reduce the length of hydraulic channels, and prevail over the expansion of the wetting radius [8], thereby improving the overall anti-seepage performance. In addition, IIR multilayer composite structures with drainage properties—i.e., foam core layers or drainage mesh layers—also enhance system stability and

minimize local failure risk through the creation of redundant flow channels and impermeable interfaces [7].

3.3. Environmental adaptability and durability

Under their service lifespan, waterproofing materials are subjected to complex environmental exposures such as temperature changes, UV irradiation, and chemical corrosion. Due to its hydrated network structure, the self-healing hydrogel system maintains high recoverability and flexibility at low temperatures ($< 0^{\circ}\text{C}$) and can heal repeatedly [3]. The one-component polyurethane product can rapidly react and cure in temperatures of -10°C , and as such is suitable for emergency repairs in low-temperature environments [5].

In aging resistance, EVA membranes also show better UV degradation resistance, and structural performance is stable in exposed conditions [11]. In addition, IPN hydrogel materials also have repeated self-healing capacity, and thus their effective service life is significantly extended. In chemical stability, traditional sheet-based materials exhibit strong acid and alkali corrosion resistance, while spray-applied polymer waterproof layers have excellent resistance to microbial attack [2].

3.4. Construction and maintenance performance

Material installation methods play a critical role in determining the cost and duration of a project. Sheet materials require a well-dried substrate and constitute intricate processes, with great reliance on experience. Spray-applied EVA membranes are, however, highly effective in construction and can form a sealing continuous layer and therefore are usable in tunnels with non-standard or irregular cross-sections [11]. Grouting is more appropriate for speedy repair at advanced construction stages or on sudden leakage, particularly in areas affected by localized water damage or complex crack networks [5].

For maintenance and inspection, some multilayer composite structures have the potential to embed monitoring materials such as conductive films or strain-sensing layers for real-time condition monitoring and timely warning of risk. The permanent sealing performance of polyurethane grouting materials ensures long-term sealing without re-excavation and facilitates future maintenance work [8].

4. Conclusion and outlook

Tunnel engineering is placing increasingly higher performance demands on waterproofing systems, evolving from early applications of single-layer sheet materials to multifunctional, multi-material integrated composite systems. A systematic review shows that current mainstream waterproofing strategies are continuously advancing along the paths of composite structural design and functional material integration. These developments reflect clear trends such as material diversification, structural layering, and intelligent functional responsiveness.

To address the above issues, future research on tunnel waterproofing materials and systems may focus on the following directions: (1) At the material level. Multipurpose waterproofing materials need to be created, which integrate waterproofing, reinforcement, and sensing into a single system. Adaptive material networks with stress-triggered self-healing and temperature-humidity sensing properties need to be researched. For example, by combining temperature-sensing polymers, hydrogel networks, and conducting sensor units, sealing and status sensing functions can be

introduced locally in the areas of stress concentration. (2) At the system design level. It is proposed to create multilayer composite systems which will integrate the functions of buffering, drainage, and waterproofing into a unified structure. (3) At the engineering practice level. As the maturity of information technology increases, integration of BIM models with digital twin technology is a new direction to improve waterproofing management for tunnel operation. In the future, integration of sensing materials into waterproofing construction should be explored to facilitate real-time monitoring and remote early warning of significant performance parameters, further improving the proactivity and predictability of maintenance activities. (4) At the green construction level. Stricter environmental regulations have made the development of renewable, high-solids, and solvent-free waterproofing materials essential. Priority should be given to eco-friendly material systems that feature simplified construction processes, low emissions, and easy disassembly and recycling, to promote the full implementation of green construction practices in tunnel engineering.

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