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Advances in Polymer Spray-Applied Waterproofing Technology and CSL Tunnel Support Structures

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***Abstract* - Leakage through tunnel linings remains a persistent engineering problem. Conventional sheet-membrane systems cannot fully resolve it because they contain numerous seams, are easily damaged, and cannot conform closely to the substrate. Polymer spray-applied waterproofing, represented by acrylate membranes, provides a seamless and highly adhesive alternative. This technology has enabled the development of composite shotcrete-membrane-shotcrete support structures, known as composite shell linings (CSLs). This review summarizes the film-formation mechanisms and performance-control strategies of acrylate spray membranes. It examines the principal factors governing interfacial bonding in CSL systems and their durability under long-term service. Drawing on numerical simulations and engineering applications, it further analyzes interlayer shear behavior and load distribution. The review aims to support wider engineering implementation and the development of improved CSL design theory.**

Keywords - acrylate; CSL support structures; tunnel engineering; bonding performance; waterproofing performance; mechanical performance.

I. INTRODUCTION AND BACKGROUND

Rapid infrastructure development has substantially increased the scale of tunnel construction. However, leakage through tunnel linings remains a major constraint on durability and operational safety. Most conventional waterproofing systems combine polymer sheet membranes with composite linings, but several weaknesses emerge during long-term service. Sheet membranes cannot conform completely to the uneven surface of the primary support, allowing groundwater to migrate behind them. Irregularities and exposed rock-bolt heads can puncture the membrane when the secondary lining is cast. In addition, the numerous joints between membrane sheets form vulnerable points in the waterproofing system[Error! Unknown switch argument.].

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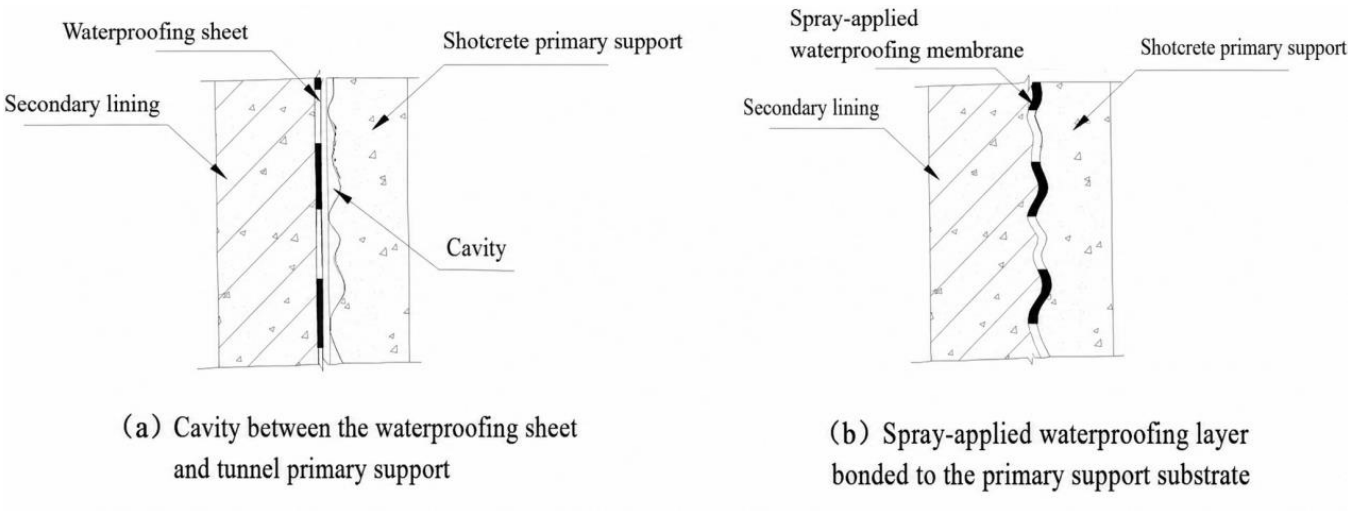

Fig. 1. Comparison of sheet-membrane and spray-applied waterproofing systems in tunnel support structures

Spray-applied waterproofing was developed to overcome the limitations of conventional sheet membranes. Mechanized spraying forms a continuous, seamless waterproofing membrane directly on the substrate (Fig. 1). The membrane conforms to irregular surfaces and eliminates pathways for water migration. More importantly, it bonds effectively to the shotcrete layers on both sides, forming a composite shell lining (CSL). In a CSL system, the membrane provides waterproofing while transferring shear and compressive stresses between the inner and outer linings. This composite action improves load distribution and may permit a thinner inner lining, thereby reducing construction costs[Error! Unknown switch argument.].

II. PROPERTIES OF POLYMER SPRAY-APPLIED WATERPROOFING MATERIALS

A. Material Composition and Film-Formation Mechanism

Among spray-applied waterproofing materials, acrylate membranes are widely used because the technology is mature and the materials are environmentally compatible and non-toxic. Their principal component is an acrylic compound. The monomer is generally prepared by reacting acrylic acid with a metal salt in the presence of water and additives. The monomer is highly water-soluble, whereas the polymerized product is an insoluble elastomer[Error! Unknown switch argument.].

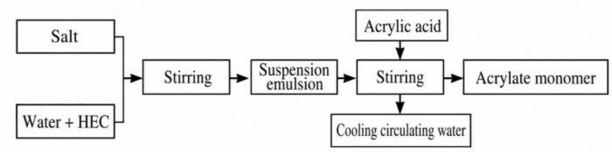

Fig. 2. Preparation process for the acrylate polymer monomer

During application, two liquid components (A and B) are sprayed at high pressure. The streams mix immediately outside the spray nozzle. A water-soluble initiator triggers rapid free-radical chain-addition reactions at the monomer double bonds, producing a dense three-dimensional gel elastomer within 2-6 s[Error! Unknown switch argument.]. Because the reaction releases substantial heat, effective heat dissipation is essential to prevent runaway polymerization.

B. Functions of Key Formulation Components

Several additives must be incorporated precisely to satisfy complex engineering requirements:

Initiator system: A sodium persulfate-sodium sulfite redox system is commonly used. It substantially lowers the activation energy and enables polymerization at temperatures near 0 °C. The initiator concentration directly controls the reaction rate and polymer molecular weight.

Crosslinking agent: An appropriate dosage (2%-5%) substantially improves the elastic stability of the membrane and prevents a gradual transition toward plastic behavior. Excessive dosages, however, sharply increase the viscosity of

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the liquid components and impair spray application[Error! Unknown switch argument.Error! Unknown switch argument.].

Fillers and plasticizers: Inorganic fillers, such as kaolin and carbon black, improve acid and alkali resistance and reduce volumetric shrinkage. Water-retaining plasticizers, such as glycerol at 10%-15%[Error! Unknown switch argument.], enhance membrane flexibility and environmental adaptability.

III. INTERFACIAL BONDING PERFORMANCE OF CSL SUPPORT STRUCTURES

The mechanical advantages of a CSL depend on effective bonding between the inner and outer linings through the waterproofing membrane. Strong interfacial bonding enables composite structural action, suppresses concrete cracking, and is central to integrated waterproofing[Error! Unknown switch argument.].

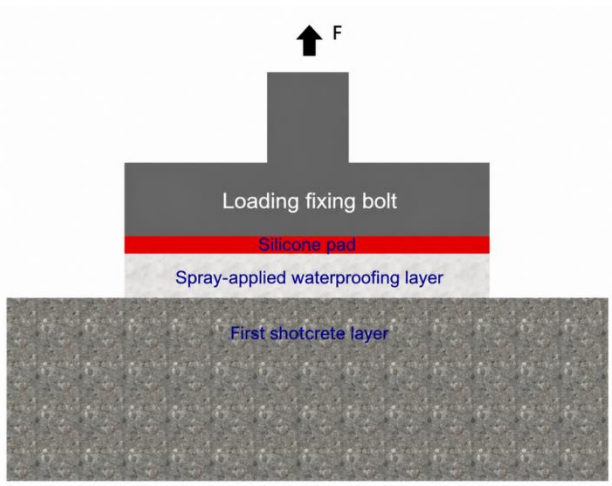

Fig. 3. Schematic of the pull-off test method

A. Principal Influencing Factors

Experimental evidence indicates that interfacial bond strength is governed by several site conditions:

Substrate roughness: A rougher substrate provides stronger mechanical interlocking. Scanning electron microscopy (SEM) shows that the sprayed membrane penetrates pores and depressions in the concrete surface, producing microscale mechanical anchorage. Untreated rough surfaces can provide approximately 35% greater bond strength than smoothed surfaces.

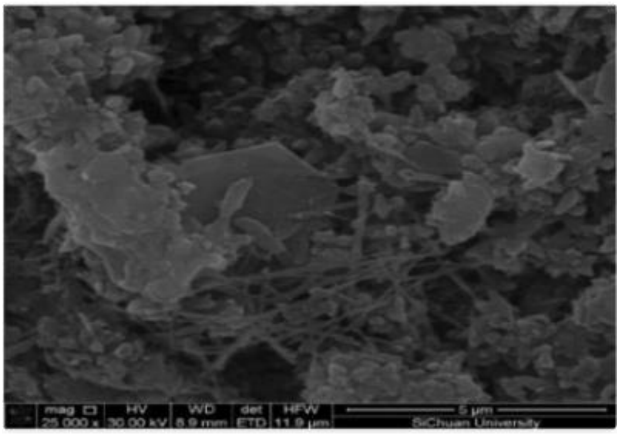

Fig. 4. SEM image of the membrane-concrete interface, showing the membrane filling surface pores

Substrate moisture condition: Contrary to conventional expectations, water-based acrylate membranes can bond slightly more strongly to damp or even water-saturated substrates than to dry substrates, provided that flowing water is absent. Moderate moisture promotes interfacial wetting and penetration by the water-based polymer. This behavior is particularly advantageous in persistently damp underground tunnels.

Membrane thickness: Apparent bond strength decreases as membrane thickness increases. A membrane thicker than 4 mm not only reduces the measured bond strength but also increases rebound of the inner shotcrete because of its high elasticity, thereby reducing interfacial compactness. A thickness of approximately 3 mm provides a practical balance.

IV. LONG-TERM WATERPROOFING PERFORMANCE AND DURABILITY EVOLUTION

After tunnel completion, the waterproofing membrane remains exposed to complex groundwater conditions. Permeability tests simulating service environments indicate that groundwater chemistry strongly influences membrane durability.

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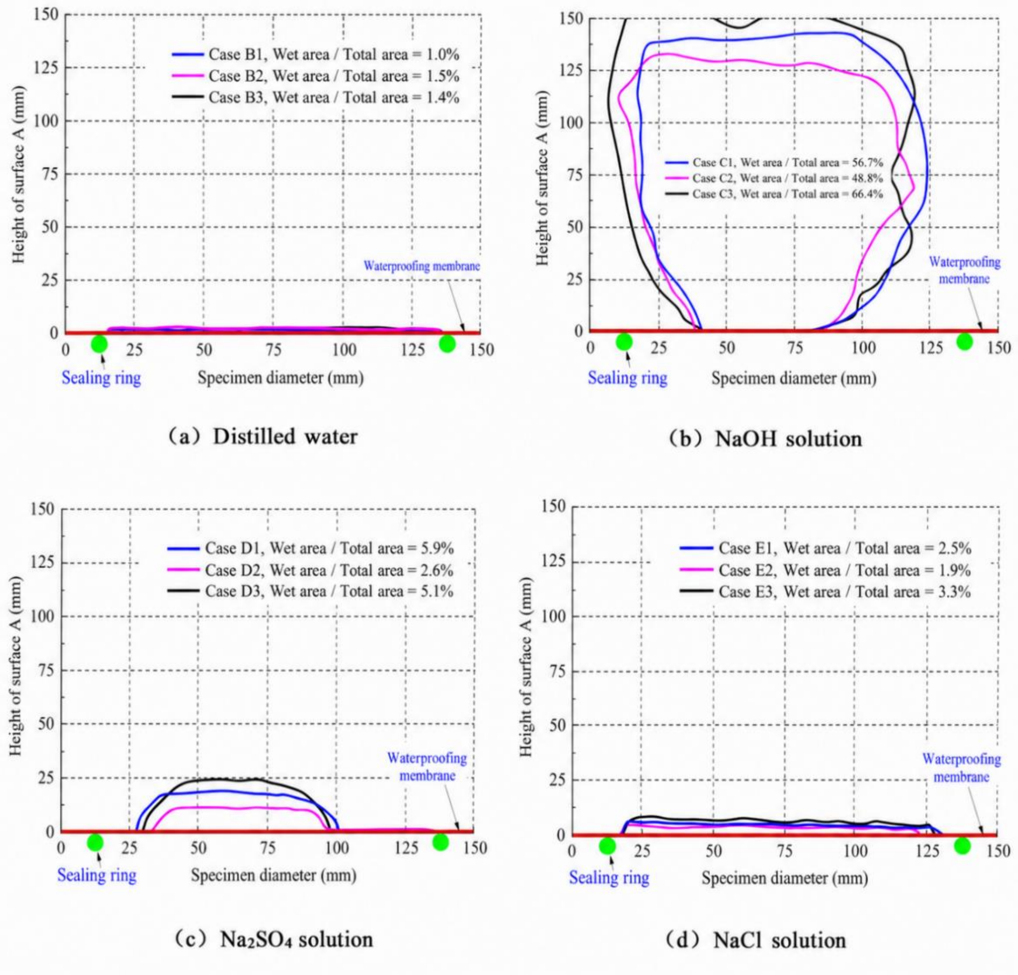

Fig. 5. Water penetration across split concrete specimens under different exposure conditions

The membrane retains strong impermeability in distilled water and common salt solutions, including NaCl and Na_2SO_4, with only slight capillary water uptake. In a strongly alkaline environment (NaOH, pH 12.0), however, substantial chemical degradation occurs. Swelling increases sharply and the crosslinked network deteriorates. X-ray computed tomography (XCT) shows that isolated micropores gradually coalesce into connected macroscopic seepage channels under strong alkaline exposure, ultimately causing waterproofing failure. Applications in strongly alkaline groundwater therefore require project-specific assessment and material modification.

Spray distance is another critical construction parameter. A distance of approximately 50 cm provides effective mixing and polymerization of the two liquid components**Error! Unknown switch argument.**. Under this condition, the membrane develops the densest microstructure and the best long-term mechanical and waterproofing performance.

V. MECHANICAL COMPOSITE ACTION OF CSL STRUCTURES

The principal value of a CSL lies in its composite mechanical action. Numerical simulations reveal how the interlayer interface responds in shear under different conditions:

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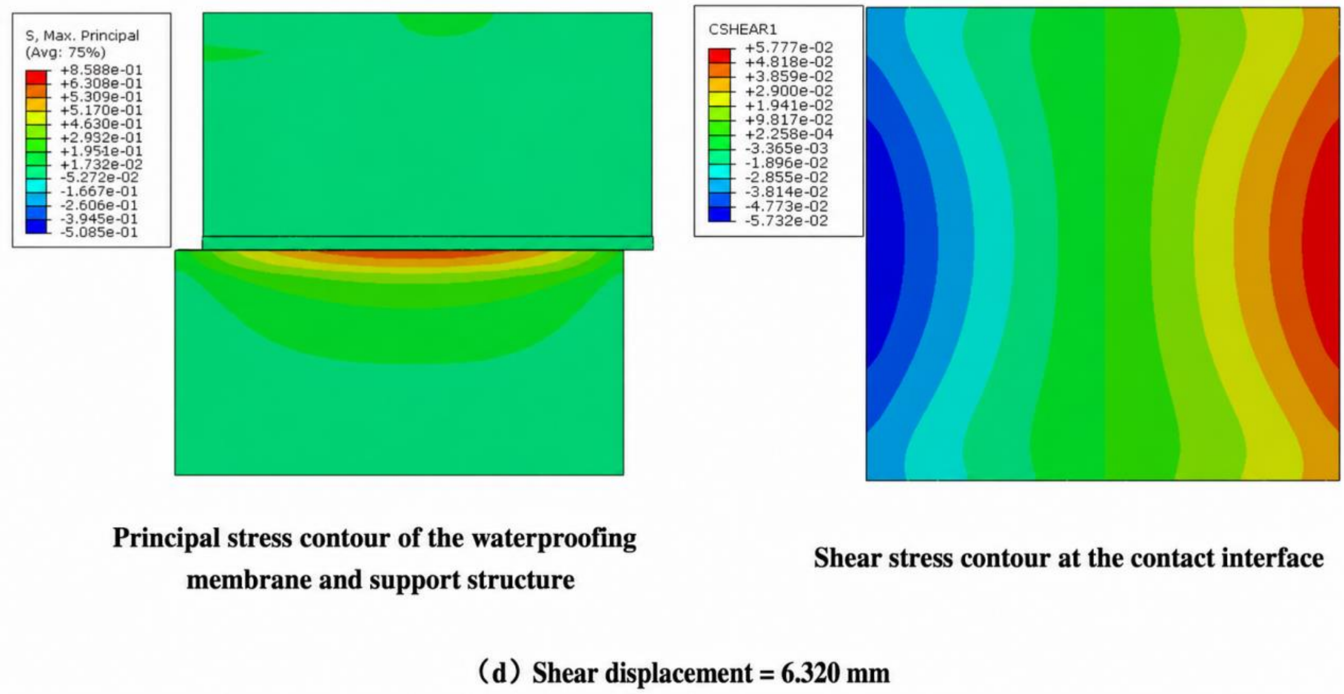

Fig. 6. Calculated shear deformation and shear stress at a compressive stress of 0.5 MPa

For a smooth interface, shear failure progresses through elastic damage, softening, and residual friction. When realistic substrate unevenness is introduced, the governing resistance changes from simple bonding and friction to mechanical interlocking and bearing. A rough interface substantially increases the overall shear stiffness and limits relative slip.

At the structural scale, composite action is strongest when the interface can transfer compressive, tensile, and shear forces, corresponding to a fully bonded state. The inner and outer linings then act together. The inner lining carries greater axial force while its bending moment decreases substantially, producing the desirable combination of high axial force and low bending moment and making effective use of concrete's compressive strength.

VI. ENGINEERING APPLICATIONS AND TECHNO-ECONOMIC ASSESSMENT

Theoretical findings have been validated in trial sections of several railway and metro tunnels. Field applications show that high-pressure airless spraying enables acrylate membranes to bond reliably to rock and concrete substrates while providing high installation efficiency.

Fig. 7. Spray-applied membrane equipment and system

Compared with conventional PE sheet membranes backed with nonwoven fabric, spray-applied waterproofing provides substantial overall benefits:

TABLE I TECHNO-ECONOMIC COMPARISON OF SPRAY-APPLIED WATERPROOFING AND CONVENTIONAL SHEET MEMBRANES

Assessment item	CM-1 spray-applied membrane	PE + nonwoven-fabric sheet membrane
Elongation (%)	514	234
Installation rate (m^2/(worker·d))	60	30

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Assessment item	CM-1 spray-applied membrane	PE + nonwoven-fabric sheet membrane
Material utilization	High (negligible offcuts)	Moderate (cutting/overlap waste)
Technical difficulty	Low (easy to learn)	High (welding-dependent)
Waterproofing integrity	Good (seamless)	Poor (many seams)

Although the initial unit cost of the spray-applied membrane is slightly higher, its installation rate is twice that of manually placed sheet membranes. It also substantially reduces leakage-related maintenance costs**Error! Unknown switch argument.**, providing strong economic benefits over the full life cycle.

VII. CONCLUSIONS AND OUTLOOK

Polymer spray-applied waterproofing addresses key limitations of conventional sheet membranes through close substrate conformity, high elasticity, and efficient installation. The resulting CSL support structure transfers loads between the inner and outer linings through effective interfacial bonding. This composite action creates opportunities for lighter and more economical tunnel support design.

Future research should focus on four priorities. Large-scale in situ shear tests are needed to improve interfacial constitutive models. Standardized design theory and specifications should be developed for CSL structures. Long-term in situ monitoring of completed projects should be expanded. Finally, materials should be modified and optimized for extreme environments, including strongly alkaline groundwater and severe cold.

REFERENCES

[1] Yang Juan. Study of CSL Tunnel Support Structures Based on Acrylate Spray-Applied Waterproofing [D]. Chengdu: Southwest Jiaotong University, 2020.

[2] Fan Kangjia, Li Fan. Application and Performance of Polymer Spray-Applied Waterproofing Materials in Tunnel Engineering [J]. Adhesion, 2023, 50(12): 161-164.

[3] Yang Qixin, Liu Dongmin, Sheng Caoying, et al. Spray-Applied Waterproofing Technology for Tunnels and Underground Engineering [J]. Journal of the China Railway Society, 2002, 24(2): 83-88.

[4] Yang Qixin, Sheng Caoying, Liu Dongmin. Research and Engineering Application of Acrylic Spray-Applied Waterproofing Materials [J]. New Building Materials, 2002, 6: 1-4.

[5] Jiang Yajun, Yang Qixin, Liu Dongmin, et al. Application of Acrylate Spray-Applied Waterproofing in Mined Tunnels [J]. Journal of the China Railway Society, 2019, 41(12): 113-120.

[6] Guan Baoshu. Key Points in Tunnel Engineering Construction [M]. Beijing: China Communications Press, 2011.

[7] Yang Juan. Performance System and Evaluation Method for Acrylate Spray-Applied Waterproofing Layers in Tunnel Engineering [D]. Chengdu: Southwest Jiaotong University, 2013.

[8] Holter K. G. Performance of EVA-Based Membranes for SCL in Hard Rock [J]. Rock Mechanics and Rock Engineering, 2016, 49(4): 1329-1358.

[9] CECS 342:2013 Technical Specification for the Application of Acrylate Spray-Applied Waterproofing [S]. Beijing: China Planning Press, 2013.

[10] ITAtech Activity Group Lining and Waterproofing. ITAtech Design Guidance for Spray-Applied Waterproofing Membranes [R]. International Tunnelling Association, 2013.