

Surface Treatment for Concrete Durability: Progress and Perspective

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Abstract: Concrete structures are widely applied in transportation, municipal and other civil-infrastructure projects. Under long-term service, coupled complex environmental factors such as chloride ingress, carbonation, microbially induced corrosion, freeze-thaw and wet-dry cycles will induce serious deterioration including reinforcement corrosion and concrete cracking, which gradually degrades structural durability. Featuring easy construction, wide adaptability and favorable protective performance, surface treatment serves as a key technique to improve concrete durability and extend service life. This paper systematically summarizes main deterioration mechanisms of concrete structures, and reviews the mechanisms, performance features and global research advances of four typical surface-treatment technologies: surface coating, hydrophobic impregnation, pore-blocking treatment and multifunctional surface treatment. By physically blocking aggressive media ingress, optimizing pore network, building hydrophobic interfaces and realizing multi-mechanism synergy, these treatments restrain corrosive-agent transport and mitigate deterioration of steel reinforcement and cement matrix. Literature review reveals that nano-composite modification, smart self-healing technology, super-hydrophobic functionalization and eco-friendly low-carbon formulations represent major developing trends for advanced concrete surface treatment. Future research shall focus on degradation-failure mechanisms under realistic complex service conditions, long-term durability assessment and synergistic mechanisms of multi-functional systems, so as to provide solid theoretical support and practical guidance for optimized protective design and engineering application of high-durability concrete structures.

Keywords: Concrete structure, Deterioration mechanism, Surface treatment, Durability enhancement, State-of-the-art review.

1. Introduction

Concrete is widely employed in civil infrastructure, including bridges, highways, tunnels, and marine structures, owing to its excellent mechanical properties, superior formability, and low construction costs. However, during long-term service, concrete structures are inevitably subjected to complex environmental factors, such as chloride ingress, carbonation, microbially induced corrosion (MIC), freeze-thaw cycles, and alternating wetting-drying cycles. These aggressive agents trigger a cascade of deterioration processes, including pore network degradation, reinforcement corrosion, and crack propagation, which collectively compromise structural durability and incur substantial maintenance costs. As infrastructure development increasingly expands into coastal, frigid, and other extreme environments, durability has emerged as a critical bottleneck limiting the service life of concrete structures.

To address this challenge, surface treatment has long been widely adopted in the engineering field as a core technology for enhancing concrete durability. This protective system effectively delays structural degradation by obstructing the transport of aggressive agents, optimizing the surface pore structure, and modifying interfacial properties. Among the available methodologies, surface coating, hydrophobic impregnation, and pore-blocking surface treatment have been extensively investigated and widely implemented in engineering practice. Furthermore, recent breakthroughs in nanomaterials, organic-inorganic hybrids, and smart functional materials have propelled the evolution of surface treatment toward higher performance, multifunctionality, and eco-friendly, low-carbon formulations.

In light of these developments, this paper systematically

reviews the principal deterioration mechanisms of concrete structures and the latest global advancements in advanced surface treatment. It comparatively analyzes the performance characteristics of various protective treatments and outlines future developmental trends. Ultimately, this review aims to provide a comprehensive reference and robust theoretical framework for the optimized protective design and practical engineering application of highly durable concrete structures.

2. Major Type and Mechanism of Deterioration in Concrete Structure

During their service life, reinforced concrete structures are continuously exposed to environmental factors, such as chloride ingress, carbonation, microbially induced corrosion (MIC), alternating wetting-drying cycles, and freeze-thaw action. These aggressive agents are considered the primary drivers of structural durability degradation. Corrosive media migrate into the structural interior through interconnected concrete pores and microcracks, triggering the chemical degradation of the cementitious matrix and electrochemical corrosion of the embedded steel reinforcement. This transport process eventually manifests as macroscopic defects, including concrete cracking, spalling, and damage to the concrete cover. Once the protective passivation film on the surface of the reinforcing steel is disrupted, corrosion products accumulate continuously, inducing a significant volume expansion that accelerates both concrete cracking and the further penetration of corrosive substances, thereby establishing a self-accelerating vicious cycle. Concurrently, reinforcement corrosion drastically reduces the effective cross-sectional area and compromises the mechanical properties of the steel rebar, while severely weakening the bond at the steel-concrete interface. This chain of deterioration ultimately leads to a critical decline in the load-

bearing capacity, stiffness, and long-term serviceability of the structural members, posing a severe threat to the structural safety and operational lifespan of engineering infrastructure [1–3, 6–9, 14].

2.1 Chloride-induced Corrosion

Chloride-induced corrosion represents a critical deterioration mechanism that primarily accelerates the degradation of the steel reinforcement embedded within concrete. Hydroxide ions derived from calcium hydroxide ($\text{Ca}(\text{OH})_2$) in the concrete pore solution establish a strongly alkaline environment, inducing the formation of a dense, thermodynamically stable passive film on the rebar surface (as shown in Figure 1). However, when external chloride ions penetrate the concrete matrix and accumulate to a critical

threshold concentration at the reinforcement depth, this localized passivation film destabilizes and breaks down, triggering active electrochemical corrosion. The resulting rust products exhibit a highly expansive nature, with their volumes expanding significantly relative to the original iron matrix. This volumetric transition generates immense internal expansion stresses at the steel–concrete interface, exceeding the tensile strength of the surrounding matrix and subsequently causing macroscopic cracking and spalling of the concrete cover. Concurrently, these newly propagated cracks serve as preferential macro-pathways for the accelerated ingress of additional chloride ions, moisture, and oxygen, further driving the autocatalytic corrosion process of the reinforcement and exacerbating the degradation rate of structural durability [1,2,7–9,17].

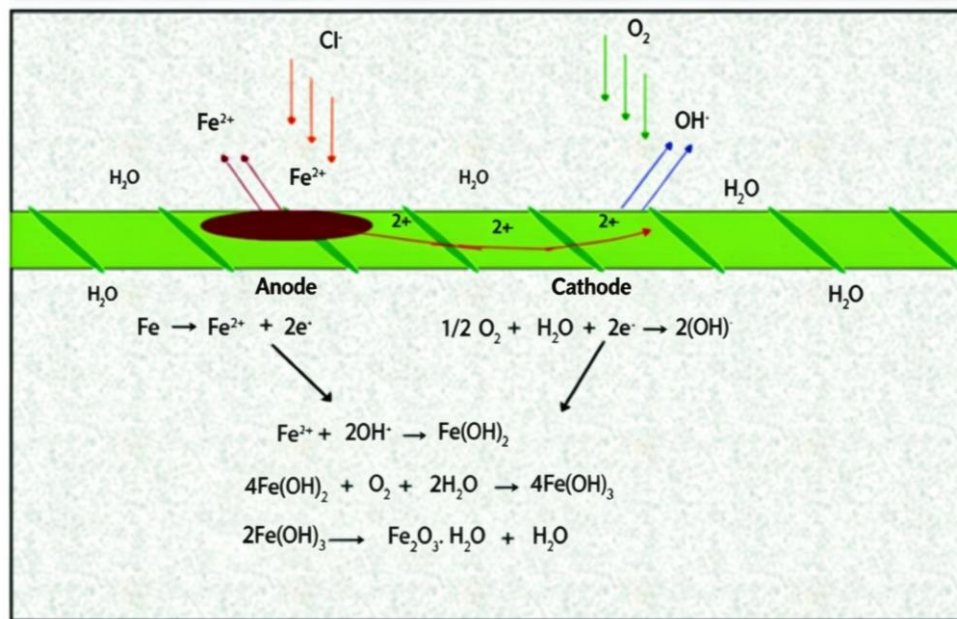


Figure 1: Electrochemical reaction mechanism of chloride-induced corrosion (Adapted from Refs. [1,8,9])

2.2 Carbonation Corrosion

Carbonation represents a typical chemical neutralization process driven by the atmospheric propagation of acidic gases (primarily CO_2). External carbon dioxide penetrates the non-saturated concrete matrix via gaseous diffusion, subsequently dissolving in the concrete pore solution to form carbonic acid (H_2CO_3). This acidic substance undergoes a neutralization reaction with the alkaline hydration products—primarily calcium hydroxide ($\text{Ca}(\text{OH})_2$) and calcium silicate hydrate (C-S-H) gel—to form calcium carbonate (CaCO_3), thereby continuously driving down the internal matrix alkalinity from an initial $\text{pH} > 12.5$ to a critical threshold below 9.0.

Crucially, carbonation and chloride ingress exhibit a pronounced synergistic degradation effect; the severe macro-alkalinity collapse destroys the thermodynamic stability of the passive film, substantially lowering the critical chloride threshold concentration required for rebar de-passivation. Once the cumulative chloride concentration at the steel–concrete interface exceeds this reduced threshold, the localized electrochemical passivation film is thoroughly destroyed, triggering severe pitting corrosion. These corrosion pits continuously expand under active galvanic couples, leading to a drastic loss of the effective cross-sectional area

and a critical reduction in the load-bearing capacity of the steel reinforcement, which ultimately accelerates the progressive durability failure of the reinforced concrete infrastructure [8,9].

2.3 Microbial Corrosion

Microbial-induced corrosion (MIC) is a widespread degradation phenomenon in wastewater treatment facilities and drainage networks [3]. After microorganisms form biofilms on material surfaces, they promote corrosion reactions by consuming oxygen, altering local pH, and producing metabolic byproducts such as sulfuric acid, sulfides, and organic acids. In concrete structures, SRBs and SOBAs act synergistically to form a bio-sulfate corrosion system [3,6,10], leading to the accumulation of corrosion products such as gypsum and ettringite, which trigger cracking, spalling, and structural performance degradation. Concurrently, the oxygen concentration gradient and local electrochemical heterogeneity created by biofilms can induce localized corrosion behaviors such as pitting corrosion (as shown in Figure 2). In recent years, technologies such as self-healing coatings, antimicrobial-modified materials, and biofilm regulation have been proven to effectively suppress the MIC process [10,28,29], thereby enhancing the long-term

durability of concrete structures in sewage environments.

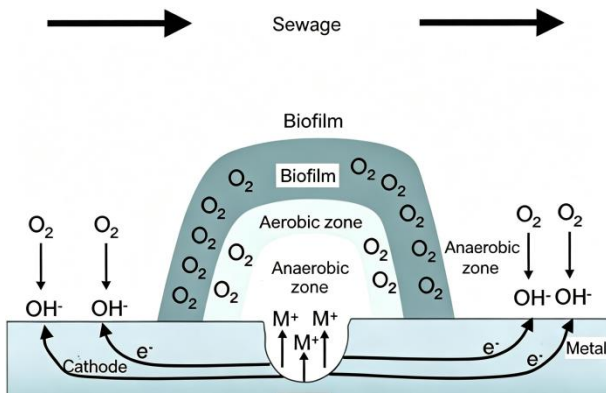


Figure 2: Schematic diagram of the mechanism of concrete corrosion caused by concentration gradients within biofilms. (Adapted from Refs. [3,6])

2.4 Freeze-Thaw Corrosion

Freeze-thaw cycles are a significant environmental factor contributing to the durability degradation of reinforced concrete structures in cold regions [16,18]. In cold regions such as Northwest and Northeast China, ambient temperatures frequently fluctuate below freezing, causing concrete to

undergo repeated freezing and thawing over extended periods. The hydraulic pressure and crystallization pressure generated by the freezing of pore water induce the initiation and propagation of microcracks, increasing porosity and pore connectivity. This facilitates the transport of corrosive agents, such as chloride ions, into the concrete interior and accelerates the corrosion process of the reinforcing steel. Research by REN et al. [16] indicates that freeze-thaw action can exacerbate the salt efflorescence effect caused by sulfate attack, enlarging pore sizes and accelerating internal damage to the material. At the same time, the study further elucidated the mechanism of freeze-thaw damage in a chloride-rich environment: the dissolution and migration of CH, NaCl concentration, and the formation and decomposition of Friedel salts collectively drive the evolution of the pore structure; when the temperature drops below freezing, ice crystals and Friedel salts synergistically generate expansion pressure, promoting crack propagation (as shown in Figure 3).

Therefore, freeze-thaw cycles not only directly cause internal damage to concrete but also accelerate the diffusion of corrosive media such as chlorides and sulfates by altering the pore structure and transport properties, thereby further promoting reinforcement corrosion and structural durability degradation.

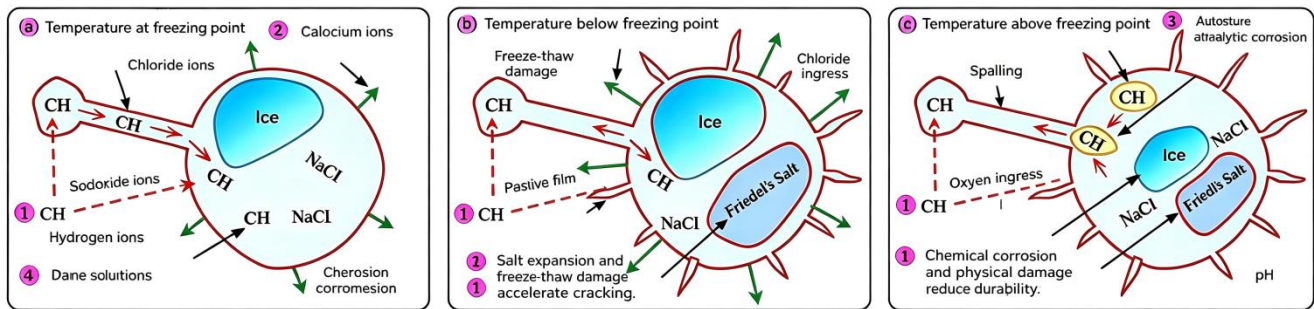


Figure 3: Schematic diagram of concrete corrosion mechanisms in severely cold regions (Adapted from Ref. [16])

2.5 Wet-Dry Cycling Corrosion

Reinforced concrete structures are widely used in highway, tunnel, and bridge engineering. In regions with frequent rainfall, corrosion caused by alternating wet and dry cycles is particularly pronounced. During the wetting cycle, corrosion products generated by chemical corrosion consume calcium silicate hydrate, reducing the density of the concrete matrix; during the drying cycle, as the moisture content of the concrete gradually decreases, the corrosion products migrate toward the pore walls, causing physical damage. OTIENO et al. [19] investigated the influence of concrete surface resistivity on the corrosion rate of reinforcing bars under wet-dry cycling conditions and found that denser micro-concrete with high resistivity exhibited resistivity-controlled corrosion, thereby reducing the corrosion rate of the reinforcing bars. WANG et al. [16] investigated the effect of sulfate wet-dry cycling on the pore structure characteristics of concrete by setting different wet-dry cycling cycles. The results indicated that porosity is positively correlated with the wet-to-dry ratio, and the volume of pores with diameters of 50–200 nm in concrete significantly decreased under sulfate attack.

In summary, the mechanism of wet-dry cycling corrosion is closely related to porosity and resistivity; however, differences in wet-dry cycling cycles in saline-alkali soil

regions and high-temperature arid regions cannot be ignored. Wet-dry cycling corrosion in different service environments is a key focus in the application of concrete structures.

3. Protective Coatings for Concrete Structures

Corrosion protection coating technology for concrete structures is a critical measure for enhancing structural durability. Its mechanism of action primarily involves blocking the transmission of external corrosive media into the concrete, slowing the diffusion of harmful ions and the migration of moisture, thereby reducing the risk of reinforcement corrosion and concrete deterioration. Based on the interaction between the coating and the substrate, as well as differences in protective mechanisms, existing anti-corrosion systems can be classified into four categories: surface film-forming, pore-sealing, hydrophobic impregnation, and multifunctional surface treatment [5, 15, 17].

3.1 Surface-Film-Forming Protective Coatings

As a key method for restricting the transmission of external media [5, 15, 17], surface film-forming protective coatings have long dominated the field of concrete engineering protection. The core mechanism of this type of coating

involves creating a continuous and dense physical barrier on the concrete surface, completely isolating the substrate from the harsh external corrosive environment, thereby significantly reducing the migration rate of corrosive media such as moisture, oxygen, chloride ions, and sulfates into the structure (as shown in Figure 4). Since their protective function relies primarily on macroscopic physical barriers at the surface without altering the microscopic pore structure within the concrete, this technology is characterized by simple application, broad coverage, and significant shielding effects. When the coating remains intact and is well bonded to the substrate, it effectively blocks the penetration of harmful media, thereby delaying steel reinforcement corrosion, concrete carbonation, and freeze-thaw damage at the source. It demonstrates broad applicability in various complex service environments, including marine, freeze-thaw, saline soil, and industrial corrosion settings.

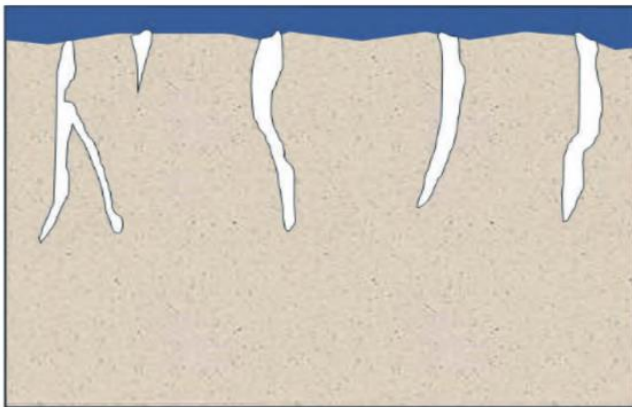


Figure 4: Schematic diagram of surface film-forming protection mechanism (Adapted from Ref. [5])

Based on their chemical composition, commonly used surface film-forming coatings are primarily classified into three categories: inorganic coatings, organic coatings, and composite coatings:

- 1) Inorganic coatings [5,13] (e.g., cement-based and geopolymer coatings). These offer excellent heat resistance, chemical corrosion resistance, and interfacial compatibility with the concrete substrate, with exceptional long-term service stability;
- 2) Organic coatings [21,27] (e.g., epoxy, acrylic, or polyurethane coatings). Exhibit greater flexibility, substrate adhesion, and adaptability to complex and variable construction environments;
- 3) Composite coatings [21, 26, 27]. These combine the respective advantages of inorganic and organic materials. Through interfacial modification and synergistic effects between the two, they balance the coating's long-term durability with mechanical toughness.

Future research priorities and key challenges for surface film-forming coatings lie not only in further advancing the coatings' inherent low permeability and high barrier properties, but also in intensively focusing on enhancing their interfacial bonding capacity, crack resistance, and long-term stability under complex service conditions. In the future, through the refined optimization of material formulations, precise control of microscopic film-forming mechanisms, and the active

adoption of advanced composite modification technologies, it is expected that the material toughness and environmental resistance of coatings can be significantly enhanced while maintaining their high physical density. This will provide long-term, stable, and effective green protection for concrete structures in complex and variable extreme service environments [5,21,26,27].

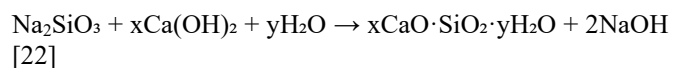
3.2 Pore-Sealing Protective Coatings

The durability of concrete is largely influenced by its pore structure and pore connectivity, as interconnected pores provide migration pathways for water, chloride ions, sulfates, and other corrosive agents. Pore-sealing coatings effectively reduce pore connectivity by generating insoluble products within the pores, thereby impeding the penetration of aggressive media and enhancing concrete durability (as shown in Figure 5). Unlike surface-film-forming coatings, which primarily rely on external barrier effects, pore-sealing materials can penetrate into the surface pores and microcracks of concrete. Through chemical reactions or deposition, they improve the pore structure and form a more stable protective system within the matrix. Consequently, these materials not only increase the density of the concrete surface layer but also enhance its resistance to water penetration, carbonation, and chemical erosion. They are widely used in underground engineering, tunnel linings, hydraulic structures, and concrete structures exposed to long-term damp environments [5,22].



Figure 5: Pore-sealing protection mechanism (Adapted from Ref. [5])

Currently, the most widely used pore-sealing materials are primarily silicate-based systems [22], including sodium silicate, lithium silicate, and calcium silicate, among which sodium silicate (water glass) has been the most extensively studied. After silicate solutions penetrate the concrete, they react with the cement hydration product Ca(OH)_2 to form calcium silicate hydrate (C-S-H) gel. The reaction process can be represented as:



The resulting C-S-H gel deposits on the walls of pores and the surfaces of microcracks, filling some of the capillary pores, thereby reducing porosity and pore connectivity, and consequently improving the surface density and impermeability of the concrete. Studies have shown that after silicate treatment, the surface hardness, impermeability, and resistance to chloride ion penetration of concrete are all improved to varying degrees. The mechanism behind this lies in the optimization of the pore structure and the blocking of

medium transport pathways. Since the formed gel products exhibit good compatibility with the concrete matrix, the protective layer is unlikely to peel off due to interfacial failure and generally offers better long-term stability compared to purely surface-coating protection systems [5,21,26].

However, the protective effectiveness of pore-sealing materials remains limited by penetration depth and pore structure characteristics. The generated gel products cannot completely fill all interconnected pores, resulting in limited repair capabilities for wider cracks and defective areas; simultaneously, single-silicate systems have a weak effect on improving concrete surface wettability, and their long-term protective performance remains limited under conditions of severe sulfate erosion or multi-factor coupled effects. In recent years, researchers have modified silicate systems through composite modification by introducing organic components such as styrene-acrylic emulsions, epoxy resins, and nanomaterials. This approach further enhances the material's toughness, crack resistance, and interfacial stability while maintaining its pore-sealing function. Through the synergistic action of chemical sealing and physical barrier effects, composite pore-sealing materials are expected to achieve more durable protective effects, making them a key research direction in the field of concrete durability protection.

3.3 Hydrophobic Impregnation Protection Systems

Capillary pores and microcracks naturally exist within the concrete matrix, providing key pathways for the transport of water and corrosive ions. Therefore, reducing capillary water absorption is considered one of the effective methods for improving concrete durability. Hydrophobic impregnation technology alters the wetting properties of pore surfaces by penetrating active substances into the surface pores of concrete and forming a stable hydrophobic layer on the pore walls. Unlike surface-film-forming and pore-sealing protection systems, hydrophobic impregnation does not form a continuous covering film nor significantly block the pore structure. Instead, it reduces the surface energy of the pore walls, increases the contact angle, and weakens the capillary water absorption driving force—all while maintaining the open state of the pores and their vapor diffusion capacity—thereby inhibiting the migration of liquid water into the concrete interior [23,24].

Currently, the most widely used hydrophobic impregnation materials primarily include silanes, siloxanes, and their composite systems. Typically, because their molecular size is much smaller than the capillary pore diameter of concrete, silane-based materials can penetrate the near-surface layer of concrete to a depth of several millimeters to over ten millimeters through capillary adsorption, achieving comprehensive protection of the near-surface region. Their mechanism of action primarily involves three stages. Hydrolysis, condensation, and interfacial bonding: First, the alkoxy groups in silane molecules react with water in the pores to generate active silanol groups; subsequently, condensation reactions occur between the silanol groups, forming a polysiloxane network with Si–O–Si bonds as the backbone; finally, the residual silanol groups react with hydroxyl groups on the surface of cement hydration products, chemically bonding to the pore walls to form a stable hydrophobic

network structure. The hydrophobic alkyl chains are oriented toward the interior of the pores, transforming the pore walls from a hydrophilic state to a significantly hydrophobic state. This reduces capillary water absorption [23,24], inhibits the migration of corrosive media such as chloride ions into the interior via capillary adsorption and liquid-phase transport, and enhances the concrete's resistance to chloride and sulfate corrosion as well as freeze-thaw damage.

The aforementioned traditional single-component silane and siloxane impregnation systems also have certain shortcomings, commonly including insufficient penetration depth in high-density concrete, poor structural stability of the hydrophobic layer, and susceptibility to aging and failure during long-term service. To address these shortcomings, in recent years, the academic community has employed technical approaches such as optimizing pressure impregnation processes, modifying with nano-functional materials, and blending multifunctional organosilicon compounds. These methods have effectively enhanced the penetration capacity of hydrophobic active components within highly dense concrete matrices, while simultaneously improving the structural integrity, weather resistance, and long-term service stability of the hydrophobic network on pore walls, thereby significantly improving the comprehensive protective performance of traditional hydrophobic impregnation systems [23,24].

Furthermore, the protective effect of hydrophobic impregnation primarily relies on inhibiting liquid water transport rather than sealing the pore structure; consequently, its ability to block gas diffusion is relatively limited. In carbonation environments dominated by CO₂ diffusion, its protective efficacy is typically inferior to that of surface-film-forming materials; under long-term hydrostatic pressure, corrosive media may still penetrate into the concrete through open pores. At the same time, UV radiation, temperature-humidity cycling, highly alkaline environments, and the formation of cracks can all lead to a decline in the performance of the hydrophobic layer, thereby reducing long-term protective effectiveness. Therefore, the development of a multi-scale synergistic protection system that combines surface barrier, pore-wall hydrophobicity, and micro-densification functions to achieve synergistic enhancement of multiple protective mechanisms represents an important direction for the development of concrete durability protection materials [23–25].

3.4 Multifunctional Surface Treatment Technologies

Traditional concrete surface protection technologies typically rely on a single mechanism to provide protection. For example, surface film-forming coatings primarily act as physical barriers to block corrosive media, pore-sealing materials focus on enhancing surface density, and hydrophobic impregnating agents inhibit water migration by regulating interfacial wettability. However, concrete deterioration in marine, salt-frost, and wet-dry cycling environments typically involves the coupled effects of multiple processes, including water transport, ion diffusion, interfacial damage, and crack propagation. A single protective mechanism often addresses only a specific type of deterioration factor, making it difficult to meet the long-term durability requirements of complex

service environments. Consequently, surface treatment technologies that integrate multiple protective functions have gradually emerged as a key research direction in concrete durability [5,26].

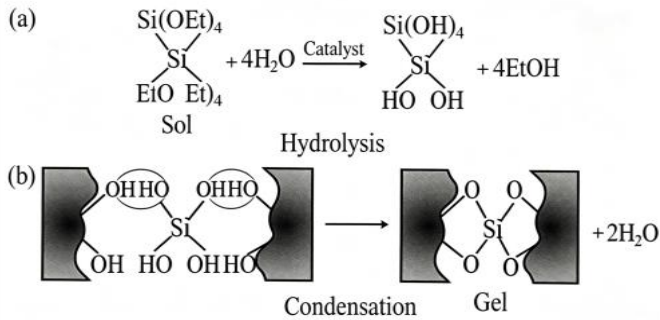


Figure 6: Reaction of tetraethyl orthosilicate (TEOS) on a concrete surface: (a) hydrolysis reaction; (b) condensation reaction. (Adapted from Ref. [5])

Based on their primary mechanisms of action, multifunctional surface treatment technologies are primarily categorized into three types: densification and strengthening, interfacial hydrophobicity, and damage response. Among these, the TEOS [5] (ethyl orthosilicate) treatment system is a typical representative of densification and strengthening technologies. TEOS penetrates the pores in the concrete surface layer, where it undergoes hydrolysis and condensation reactions to form SiO₂ gels and a siloxane network structure, thereby reducing pore connectivity and enhancing surface density.

Studies have shown that such materials can effectively reduce water absorption and chloride ion diffusion coefficients, thereby improving the concrete's impermeability and resistance to carbonation. However, due to factors such as gel shrinkage and environmental sensitivity, there is still room for improvement in their long-term stability.

Interface hydrophobic technologies are primarily represented by superhydrophobic coatings [25]. By creating micro- and nano-scale rough surfaces and low-surface-energy interfaces, these materials significantly reduce the contact area between liquid water and the concrete surface, thereby limiting the ingress of moisture and corrosive agents. Additionally, superhydrophobic surfaces typically possess self-cleaning and anti-fouling properties, which help maintain long-term protective effects. However, their performance is highly dependent on the integrity of the micro- and nano-scale surface structures, and they are prone to performance degradation under the effects of abrasion, UV radiation, and environmental aging.

Damage-responsive technologies are best exemplified by self-healing coatings. By incorporating repair units such as microcapsules, microtubular networks, or functional repair agents, these coatings can release repair components to restore local integrity, thereby delaying the diffusion of corrosive agents into the interior. In recent years, microcapsule self-healing technology has developed rapidly and shown great potential for extending the service life of protective layers. However, it still faces challenges such as limited repair agent reserves, insufficient repeatable repair capabilities, and relatively high costs.

Overall, densification and reinforcement technologies primarily improve the pore structure of the concrete surface, interfacial hydrophobic technologies focus on inhibiting the ingress of water and ions, while self-healing technologies can mitigate protective failure caused by crack propagation. These three categories of technologies enhance concrete durability at different levels—pore structure optimization, interfacial regulation, and damage repair, respectively—but none can independently address the multi-factor coupled deterioration in complex environments. Consequently, current research is gradually shifting toward multifunctional synergistic protection. By integrating mechanisms such as densification, hydrophilization, and self-healing, these approaches aim to comprehensively regulate the transport of corrosive media and the evolution of damage. In the future, integrated protection systems that combine long-term stability, environmental adaptability, and intelligent responsiveness are expected to become a key development direction for concrete surface protection technologies.

4. Trends in Concrete Structure Protective Coatings

At present, various single-type concrete protective coatings all have performance shortcomings and application limitations, making it difficult to meet the long-term protection requirements in complex coupled corrosion environments such as marine environments, saline soils, alternating wet and dry conditions, and high-low temperature cycles. With continuous innovations in materials science, nanotechnology, and intelligent protection concepts, concrete protective coatings are gradually overcoming traditional shortcomings such as single-function protection, limited performance, and insufficient durability. They are evolving toward diversified, high-performance directions characterized by nano-modified reinforcement, multifunctional synergistic protection, intelligent self-healing, super hydrophobicity with high durability, and green, low-carbon environmental sustainability, thereby continuously driving the development of concrete protection technology toward long-term, intelligent, and eco-friendly engineering applications. Combining current research trends with engineering needs, the main development trends of concrete protective coatings can be summarized in the following five aspects.

1) Nano-composite Modification

Nanomaterials such as nano-SiO₂, TiO₂, and graphene are being widely incorporated into protective coatings. By filling pores, enhancing interfacial adhesion, and improving barrier properties, these materials significantly boost the coatings' impermeability, abrasion resistance, and corrosion resistance. Nanocomposite modification has become a key development direction for enhancing the comprehensive performance of concrete protective coatings.

2) Multifunctional Synergistic Protection

Single protective mechanisms struggle to meet the demands of complex environments, and multifunctional coatings that combine barrier, hydrophobic, self-healing, and antibacterial properties are gradually becoming a research focus. Through

the synergistic action of multiple protective mechanisms, these coatings achieve comprehensive suppression of water migration, ion diffusion, and crack propagation.

3) Smart Self-Healing and Long-Term Durability

Technologies such as microcapsules, shape-memory materials, and responsive polymers are being applied to protective coatings, endowing them with damage-sensing and self-healing capabilities. These smart coatings can delay crack propagation, restore the protective barrier function, and extend the long-term service life of structures.

4) Practical Application of Highly Durable Superhydrophobic Coatings

Superhydrophobic coatings effectively reduce concrete water absorption and chloride ion ingress by creating micro- and nano-scale rough surfaces and low-surface-energy interfaces. Future research will focus on improving their wear resistance, aging resistance, and long-term stability to meet the demands of engineering applications in complex environments.

5) Green and Low-Carbon Industrialization

With the advancement of sustainable development concepts, low-VOC, bio-based, and inorganic eco-friendly protective coatings have garnered widespread attention. Green protective materials reduce environmental impact and resource consumption while ensuring corrosion resistance, making them a key development direction for concrete protective coatings.

5. Conclusions

Concrete structures operate in complex service environments, and their durability degradation is typically not caused by a single factor but rather results from the combined effects of multiple factors, including chloride ion attack, carbonation, microbial corrosion, freeze-thaw cycles, and alternating wet and dry conditions. These environmental factors alter the pore structure and transport properties of concrete, facilitating the migration of corrosive media into the interior, ultimately leading to reinforcement corrosion, concrete cracking and spalling, and a decline in structural performance. To address these issues, protective technologies such as surface film formation, pore sealing, hydrophobic impregnation, and multifunctional surface treatments have been extensively studied, achieving significant results in reducing medium penetration, delaying reinforcement corrosion, and improving structural durability. However, different protective systems all have certain limitations, and a single protective mechanism often fails to meet durability requirements under complex environmental conditions and long-term service conditions.

In recent years, the development of concrete protective coatings has gradually shifted from single-function barrier systems toward multifunctional synergistic protection. The introduction of nanomaterials has enhanced coating density and interfacial stability, while multifunctional composite systems have enabled the synergistic optimization of barrier, hydrophobic, and reinforcement properties. Self-healing technologies, meanwhile, offer new solutions for the

autonomous repair of damage during the long-term service life of coatings. Concurrently, with the emergence of the full-life-cycle design philosophy for infrastructure and the “dual carbon” goals, green protective materials that combine high durability, environmental friendliness, and resource sustainability are receiving increasing attention. Overall, nanocomposite integration, multifunctional synergy, intelligent self-healing, super hydrophobicity, and green low-carbon characteristics have become key development directions for concrete protective coatings.

Future research should further investigate the failure mechanisms of coatings and the evolution of interfaces in complex corrosion environments, establishing a correlation between laboratory accelerated tests and actual in-service performance. Concurrently, emphasis should be placed on the synergistic design and long-term stability evaluation of multifunctional protective systems, promoting the transition of novel protective materials from laboratory research to engineering applications, thereby supporting the enhancement of concrete structure durability and the assurance of performance throughout the entire life cycle.

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