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Performance of surface treatments of concrete - A review

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ABSTRACT

Concrete structures are often exposed to aggressive environments, making surface treatments essential for their protection and extended service life. This paper presents a comprehensive review of the effects of various surface treatments on the mechanical properties and durability of concrete, as well as the durability of the treatment materials themselves. Common surface treatments such as acrylic coatings, polyurethane coatings, epoxy coatings, silanes, siloxanes, sodium silicate, and nano-SiO_2 are examined. These treatments exhibit different influences on physical and mechanical properties, water permeability, chloride migration, carbonation resistance, sulphate attack, and freeze–thaw durability. The strengths and weaknesses of each treatment type must be carefully considered when selecting an appropriate surface protection method. Although numerous tests have been conducted to evaluate the barrier properties of these treatments, prediction models for the long-term service life of treated concrete remain limited. Furthermore, many surface treatments—particularly organic ones—are prone to aging and weathering, which can reduce their long-term effectiveness. Therefore, both the immediate protective effect and the long-term durability of surface treatments should be incorporated into service-life modelling and maintenance planning.

Keywords—Concrete, Surface treatment, silanes, nano-SiO_2, Permeability, Durability

1. INTRODUCTION

The reliability and service life of concrete structures are largely influenced by durability-related issues such as carbonation, corrosion of steel reinforcement, and sulphate attack [1,2]. The surface layer of concrete typically the uppermost 30 mm beneath the exposed face serves as both physical and chemical barrier against the ingress of aggressive agents [3–5]. Because most deleterious substances are transported through water or air, the permeability characteristics of this surface layer are critical to the overall durability of the concrete element [5–8]. Among various protection methods, surface treatment has emerged as an economical and effective technique for improving the quality and performance of the surface zone. Compared with other approaches, such as reducing the water-to-cement ratio or incorporating mineral admixtures, surface treatments provide a more practical and efficient means of enhancing durability and extending the service life of concrete structures, the ongoing environmental degradation. Consequently, there is an urgent search for materials and manufacturing techniques that are environmentally friendly and energy .A wide range of surface treatments can be applied to protect concrete structures from environmental deterioration. Based on the chemical composition of the treatment agents, surface treatments are generally classified into two main groups: organic and inorganic [9–11]. Organic surface treatments exhibit excellent barrier properties; however, their limited service life and susceptibility to aging have raised significant concerns. In contrast, inorganic surface treatments are more stable and resistant to aging, though relatively few studies have explored their practical applications. Surface treatments can also be categorized according to their primary function:(a) Surface coatings form a continuous polymer film that acts as a physical barrier to the ingress of aggressive substances [12–14]. Common coating materials include acrylics, butadiene copolymers, chlorinated rubber, epoxy resins, oleoresins, polyester resins, polyethylene copolymers, polyurethanes, vinyl polymers, coal tar, and polymer-modified mortars [15]. These coatings are widely used in structures such as foundations, marine quays, and bridges.(b) Hydrophobic impregnations are typically based on silane or siloxane water-repellent agents [13,16]. They create a hydrophobic surface within the near-surface zone of concrete while keeping the pores open for vapor diffusion [15,17].(c) Pore-blocking treatments function by partially or completely filling the capillary pores, thereby reducing the porosity of the surface layer. Silicate-based compounds are the most common pore-blocking agents. Recently, advanced materials such as nano-SiO_2 and calcium carbonate precipitation systems have attracted growing attention due to their superior performance. These materials are increasingly used in the protection of buildings and highway bridge decks [17–19].Multifunctional surface treatments combine two or more protective mechanisms. Examples include ethyl silicate and modified clay nanocomposites, which not only block capillary pores but also create a hydrophobic layer on the concrete surface [11,16,20].

This review discusses ,summarizes and compares the effects on concrete properties and evaluates the durability of various surface treatments. The purpose of this review is to promote the effective application of surface treatments in practice and to highlight areas requiring further research.

2. EFFECT OF SURFACE TREATMENTS ON CONCRETE'S MECHANICAL AND PHYSICAL PROPERTIES

The effects of surface treatments on the strength of concrete have not been extensively investigated. It is widely recognized that most surface treatments cannot directly increase the intrinsic strength of concrete, as they do not significantly alter the internal quality or porosity of the bulk material. However, surface treatments can play an important role in preventing strength degradation under adverse conditions, such as elevated temperatures.

According to the study by Li [22], the compressive strength of concrete coated with a silicate-based material increased by 3.8%, 3.7%, 11.0%, 17.3%, and 6.1% compared with uncoated specimens after exposure to temperatures of 150°C, 300°C, 450°C, 600°C, and 750°C, respectively. Similarly, Yuan et al. [23] reported that silicate surface treatments effectively enhanced the residual compressive strength and elastic modulus of concrete exposed to temperatures ranging from 200°C to 700°C.

Abrasion resistance is another key indicator of the long-term performance of surface-treated concrete, especially under repetitive traffic loads. Numerous studies have demonstrated that surface treatments can improve the abrasion resistance of concrete [24–26]. Dang et al. [27] found that most organic coatings enhanced abrasion resistance, with epoxy coatings performing best, while high-molecular-weight methacrylate showed negligible improvement. Silane-treated surfaces also exhibited slightly higher abrasion resistance, primarily due to the reduction in surface friction coefficient [16,27].

Franzoni et al. [11] compared the effects of several inorganic treatments on abrasion resistance and reported the following order of performance: sodium silicate > ethyl silicate > nano-silica. Sodium silicate provided the greatest improvement, attributed to the formation of a relatively thick and dense protective layer. However, since different studies used varied concrete matrices and testing methods, direct comparison of results remains difficult. Therefore, additional research is needed to identify the most effective surface treatment for abrasion resistance.Surface treatments can also influence the shrinkage behavior of concrete by altering moisture transport and evaporation rates. Although limited research has been conducted in this area, Shi et al. [28] observed that polymer coatings significantly reduced drying shrinkage in mortar specimens. The reduction was greater when thicker coatings were applied or when coatings were applied earlier during curing, as a compact polymer film could seal open capillaries, limit moisture loss, and thus suppress shrinkage. Conversely, coatings applied later were less effective due to the already developed pore structure and reduced residual moisture content. To date, there has been little investigation into the effects of hydrophobic and pore-blocking treatments on shrinkage behavior, indicating a need for further study in this field.

3. SURFACE TREATMENTS AFFECT ON CONCRETE DURABILITY

The protection provided by surface treatments varies depending on their physical and chemical properties [25,29]. To effectively extend the service life of concrete structures, these treatments must satisfy several performance requirements, including resistance to environmental exposure, chemical attack, and mechanical degradation [30,31]. This section reviews and discusses the influence of different surface treatments on various aspects of concrete durability, including water permeability, chloride penetration, carbonation resistance, sulphate attack, and freeze thaw performance.

3.1. Permeability to water

Since water plays a crucial role in most forms of concrete deterioration, achieving high resistance to water penetration is a key criterion for evaluating the effectiveness of surface treatments [32,33]. According to NCHRP Report 244, a suitable surface treatment should reduce water absorption by at least 75% [34]. Similarly, the German Committee for Reinforced Concrete specifies that treated concrete should exhibit a limiting water absorption of 2.5% by mass and at least a 50% reduction compared to untreated concrete, although the basis for these limits remains unclear [8].

A variety of surface coatings have proven effective in minimizing water ingress through treated concrete. Epoxy coatings, silane coatings with an acrylic top layer, methyl methacrylate, alkyl alkoxysilane (applied in two coats), and oligomeric siloxane are among the most efficient materials for reducing water uptake [35]. Almusallam et al. [30] reported that uncoated cement mortars absorbed water rapidly, reaching approximately 5% by weight after 56 hours. In contrast, mortars coated with polymer emulsion, acrylic, chlorinated rubber, polyurethane, and epoxy coatings showed markedly lower water absorption values of 3.3–3.4%, 0.23–1.46%, 0.76–1.04%, 0.21–1.83%, and 0.27–1.3% respectively.

In the case of hydrophobic impregnations, Medeiros et al. [13,36] demonstrated that silane and siloxane based treatments could significantly inhibit water penetration when the applied water pressure was below 120 kgf/m². These findings indicate that hydrophobic surface treatments are most effective under controlled exposure conditions. When hydrostatic pressure is present, the pressure level must be carefully considered, and alternative treatment methods are generally recommended [35]. Furthermore, Franzoni et al. [37] found that ethyl silicate provided greater efficiency in reducing water permeability compared to sodium silicate and nano-silica treatments.

Comparing the effects of various surface treatments on the permeability of concrete is challenging due to differences in concrete mix designs, curing conditions, and testing methodologies used across studies. To address this, the relative water absorption values of concretes treated with different surface coatings have been normalized with respect to untreated concrete (set as 1). Based on available data, the relative effectiveness of surface treatments in reducing water absorption follows the general order: chlorinated rubber ≈ acrylic ≈ epoxy resin ≈ polyurethane ≈ silane/siloxane > fluorinated polymer > ethyl silicate > modified cementitious mortar coating > sodium silicate ≈ magnesium fluosilicate ≈ polymer emulsion coating > nano-silica.

Significant variations in performance were observed among coatings of the same generic type obtained from different manufacturers. Therefore, it is recommended that the selection of coatings for moisture resistance should not rely solely on general classifications but should be verified experimentally for each specific product prior to application. Furthermore, limited research has focused on the permeability characteristics of high-performance concrete (HPC) treated with surface coatings, despite its increasing use in modern infrastructure. Weisheit et al. [42] reported that siloxane copolymer treatments only slightly reduced the water absorption of HPC and failed to prevent water ingress after weathering exposure. In contrast, previous research [25] on inorganic surface treatments indicated that such materials provide effective resistance to water penetration. Specifically, sodium silicate treatments showed enhanced performance when preceded by sodium fluosilicate pretreatment, while magnesium fluosilicate exhibited similar effectiveness. Both magnesium and sodium fluosilicate treatments demonstrate promising potential for field applications.

3.2. Permeability to chlorides

Chloride ions can penetrate concrete through several mechanisms, including diffusion under concentration gradients, capillary absorption, and migration under an electrical field [6,43,44]. Among these, diffusion is the dominant transport mechanism when the concrete is unsaturated and the internal relative humidity stabilizes between 60–70% [6,45]. In general, surface treatments play a vital role in mitigating chloride ingress by creating physical or chemical barriers at the concrete surface. However, comparing the chloride resistance of different surface treatments is challenging because of variations in testing methods and experimental conditions. Despite these inconsistencies, it is widely recognized that polymer-based coatings provide the most effective chloride resistance. Almusallam et al. [30] reported that polyurethane and acrylic coatings were approximately ten times more effective in resisting chloride diffusion compared to uncoated concrete. Chlorinated rubber coatings were found to be half as effective as epoxy coatings, while polymer emulsion coatings reduced chloride concentrations in concrete to about 60–70% of those in untreated specimens [30].

Research findings on silane and silicate based treatments have been less consistent. Buenfeld et al. [44] observed that silane, polymer-modified cementitious coatings, and polyurethane sealers reduced chloride diffusion coefficients by one to three orders of magnitude compared to untreated mortars. Similarly, Dhir [48] reported that silane was more effective than acrylic coatings in reducing chloride ingress. In contrast, other studies suggested that while silane did not completely prevent chloride diffusion, it could significantly delay the onset of steady-state diffusion [8].

The effectiveness of silicate-based treatments also varies. Ibrahim et al. [46] found the impact of sodium silicate to be negligible, whereas Franzoni [11] observed a 30–50% reduction in chloride migration depth following sodium silicate application. Moon [18] demonstrated that calcium silicate treatments could reduce chloride diffusion, although their performance depended on the number of applied layers. These variations are likely influenced by differences in curing conditions and the interaction time between silicate solutions and the cementitious substrate, as silicate treatments require sufficient reaction time to form durable protective products.

Recent studies have also examined emerging treatment technologies, such as ethyl silicate, nano-silica, nanocomposite coatings, and bio-deposited calcium carbonate. Nanocomposite coatings generally outperform traditional polymer coatings in chloride resistance [14]. According to Muynck et al. [49], bio-deposition exhibited chloride resistance comparable to that of acrylic coatings and silane/silicone repellents, and even superior to silane siloxane mixtures.

The protective capacity of surface treatments is strongly influenced by both treatment category and environmental conditions. Dhir [48] reported that the chloride resistance of organic coatings decreased at elevated temperatures due to the thermal degradation of polymer chains, while silane performed optimally at around 35 °C [8]. Pritzl et al. [50] further observed that the relative reduction in chloride diffusion coefficients was more significant in concretes with initially higher permeability. Yang et al. [51] investigated concretes with varying water-to-cement (w/c) ratios and silane dosages, finding that chloride content increased with higher w/c ratios but decreased with increased silane coverage.

Characterizing chloride diffusion resistance in surface-treated concrete is challenging, primarily because chloride ingress is a complex and time-dependent process [52]. Moreover, the natural diffusion of chlorides through treated concrete is extremely slow, further complicating its accurate assessment [43]. Generally, two experimental approaches are employed to evaluate chloride diffusion: the steady-state and unsteady state methods [53].

The steady-state method (also known as the diffusion cell method) involves placing a thin specimen between two half-cells one containing a chloride solution and the other chloride free and monitoring the change in chloride concentration over time in the initially chloride-free solution to determine an effective diffusion coefficient [43]. Although this method has been widely used for cementitious materials, it is relatively uncommon in evaluating the effects of surface treatments.

Conversely, the unsteady-state method, or chloride profile method, is more frequently used for surface-treated concretes. In this approach, specimens are immersed in a chloride solution for several months or years, after which the chloride concentration profiles are determined through chemical analysis. For untreated specimens, the data can be expressed in terms of an apparent diffusion coefficient and surface chloride content, obtained by fitting the experimental results to Fick's Second Law using an error function solution [54].

Building on Fick's Second Law, Moradllo et al. [55] developed a model to describe the time dependent performance of various surface treatments on concrete exposed to the tidal zones of the Persian Gulf region. Later, Petcherdchoo [56] proposed a pseudo-coating model that improved upon Moradllo's approach, achieving better agreement with experimental data. However, the unsteady-state method has limitations when applied to surface-treated concrete, as it assumes a constant boundary condition at the interface between the surface layer and substrate [57]. Zhang et al. [57] observed that the interfacial chloride concentration increased over time, indicating that the chloride profile does not comply with Fick's law under a constant boundary condition. Consequently, applying Fick's law in such cases can lead to an underestimation of the actual diffusion coefficient.

Schueremans et al. [46,58–60] reported a sharp increase in chloride concentration around a depth of 15 mm in surface-treated concrete, a phenomenon not observed in untreated specimens. To more accurately model this behavior, the refined surface chloride profile method was introduced, which considers both the initial surface chloride concentration and the square-root dependency of chloride ingress over time [61].

Overall, more detailed investigations are required to understand the mechanisms of chloride diffusion through surface-treated concrete. Future improvements to service life prediction models for reinforced concrete should incorporate the time-dependent effects of surface treatments, interfacial transport mechanisms, and environmental exposure conditions to more accurately simulate field performance.

3.3 Carbonation

Only a limited number of models are currently available to describe the carbonation behavior of surface-treated concrete. Park [71] developed a diffusion reaction model using the finite element method (FEM) to estimate carbonation depth in coated concrete. This model also accounted for the degradation of surface coatings over time, allowing for a more realistic simulation of long-term performance. However, it is not applicable to penetrative surface treatments, such as silicate or silane based systems, since their mechanisms differ fundamentally from film-forming coatings.

Modeling carbonation in concretes treated with sodium silicate or ethyl silicate is inherently more complex due to the chemical interactions between the treatment agents and the cementitious substrate, which modify the pore structure, pH, and interfacial resistance [59,72]. In the absence of detailed experimental data on the porosity and permeability coefficients of treated surfaces, it remains difficult to construct accurate and comprehensive models for predicting carbonation behavior in such systems.

3.4. Sulphate attack

Sulphate attack in concrete can generally be classified into three types: physical, chemical, and microbiological attacks [73,74]. These mechanisms are responsible for billions of dollars in damage to concrete wastewater systems and related infrastructure worldwide. The application of suitable surface treatment systems has proven effective in improving concrete's resistance to various forms of sulphate attack.

3.4.1 Chemical Sulphate Attack

The effect of surface treatments on chemical sulphate resistance has been studied for several decades. In the 1990s, Redner et al. [75,76] evaluated more than 20 coating systems in a 10% sulfuric acid solution and reported no coating failures after one year of immersion. In contrast, Aguiar et al. [29] observed that concrete protected by a silicon-based agent performed poorly under sulphate attack compared to that coated with a water-based acrylic. Ibrahim et al. [60] investigated six surface treatments and found that concrete treated with silane/siloxane combined with an acrylic topcoat exhibited only 0.3% reduction in compressive strength after two months of sulphate exposure, and 8.3% reduction after 330 days. Concrete coated with sodium silicate or silicone resin experienced even smaller losses in strength. Their results suggested the following order of resistance:

Silane/siloxane with acrylic topcoat > Two-component acrylic > Silane/siloxane > Silicone resin > Sodium silicate.

Vipulanandan and Liu [77] reported that glass-fiber mat–reinforced epoxy coatings extended concrete service life by over 70 times under 3% sulfuric acid exposure. Nia et al. [78] found polyurethane coatings to be both more effective and economical than epoxy, increasing service life by approximately 14.5 years per 1000 µm thickness, compared to 11 years for epoxy. Recently, Song et al. [79] introduced a super-absorbent resin (SAR) treatment that effectively blocked sulphate ingress channels within the concrete matrix. Overall, organic coatings show greater sulphate resistance than silane-based or silicate treatments, with polyurethane being the most effective among them. However, limited data exist on the performance of newer surface treatments under high hydrogen sulfide (H_2S) conditions, where traditional coatings often fail prematurely. Furthermore, the influence of gas volume and pressure on sulphate attack has not yet been thoroughly investigated.

3.4.2 Physical Sulphate Attack

Suleiman et al. [80] examined the effects of various coatings on physical sulphate attack. Bitumen coatings provided comparable protection to epoxy coatings for dense concrete, but tended to delaminate from substrates with higher water–cement ratios due to entrapped moisture during early-age application. In contrast, epoxy coatings showed stronger adhesion and better overall performance [81]. Acrylic coatings, being more brittle, were less capable of withstanding stresses from salt crystallization [82]. The relative performance ranking for resistance was reported as:

Epoxy > Silane > Bitumen > Water-based acrylic.

3.4.3 Microbiological Sulphate Attack (BSA)

Berndt [73] and Muynck [83] reported that epoxy coatings and polyurea linings provided superior resistance against biogenic sulfuric acid (BSA) corrosion compared to hydrous silicates or antimicrobial cementitious coatings. Cementitious coatings were generally inadequate against such attacks. Despite their effectiveness, epoxy and polyurea systems pose challenges related to surface preparation, uneven layer thickness, and adhesion inconsistencies, which can lead to premature coating failure [84].

3.4.4 Modeling and Influencing Factors

Vipulanandan and Liu [85–87] developed a predictive model to estimate weight changes in coated concrete under sulphate exposure, emphasizing the significance of coating thickness and interfacial properties in limiting ion penetration. The key factors influencing sulphate resistance in surface-treated concrete include [84,85,88]:

1. Calcium hydroxide content – higher levels promote gypsum formation and expansion;
2. Moisture content of the substrate;
3. Adhesion strength between coating and substrate;
4. Distribution of pinholes, which significantly increases sulphate ion ingress.

3.5. Freeze- thaw resistance

Although surface treatments cannot replace air-entraining agents in protecting concrete against freeze thaw cycles, they can provide additional protection, particularly in severe cold environments [27]. Dang et al. [27] reported that surface treatments delay the ingress of moisture during freeze–thaw conditions, thereby increasing the time required to reach the critical moisture content for damage initiation. Similarly, Basheer et al. [89] observed that silane treatments could double the number of freeze thaw cycles before cracking occurred in freshwater exposure tests.

However, conflicting findings exist regarding silane's performance. Some studies suggested that silane-treated concrete deteriorates more rapidly than untreated concrete under laboratory-accelerated freeze thaw tests [90], while others found no such degradation in real structures [89,91]. The overall effectiveness of silane depends on two main factors:

1. Initial moisture content of concrete - When concrete is initially dry, silane treatment significantly enhances freeze thaw resistance by reducing water ingress. However, if the concrete is saturated prior to treatment, silane cannot prevent the expansion of freezing capillary water, thus offering little protection [8].
2. Hydraulic pressure during freezing and thawing – Silane's protective effect diminishes when the internal water pressure generated exceeds the repulsive force provided by the hydrophobic layer.

3.5.1 Salt Frost Deterioration

Freeze thaw damage is often aggravated by the use of de-icing salts on pavements and bridge decks during winter, leading to salt frost scaling [9]. Numerous studies have shown that hydrophobic surface treatments, particularly those based on silane, can significantly reduce salt scaling, mainly by limiting salt solution penetration [27,92–94].

Mamaghani et al. [92] demonstrated that both epoxy-based sealers and silane-based water repellents exhibit superior performance compared to other polymer coatings in resisting salt-induced deterioration. Liu and Hansen [94] reported that silane treatment eliminated over 90% of surface scaling in highly deicer-susceptible concrete, although it did not completely prevent bulk moisture absorption. This was attributed to silane's ability to block cryogenic suction during salt scaling [94]. Furthermore, the initial rate of scaling was significantly slower for silane-treated concrete; however, the number of freeze thaw cycles that concrete could withstand largely depended on the penetration depth of silane into the substrate.

3.6. Corrosion of steel

The permeability and thickness of the concrete cover play a crucial role in determining the time to corrosion initiation and thus the service life of reinforced concrete structures [56]. Generally, surface treatments can provide a certain degree of protection against reinforcement corrosion by limiting the ingress of moisture and aggressive ions. Cleland and Basheer [8] reported that surface treatments could significantly increase the initiation time for steel reinforcement corrosion. Ibrahim et al. [46,60] investigated the influence of various surface treatment methods on the corrosion behavior of steel bars (summarized in Table 4). Among the commonly studied treatments, silane has received particular attention; however, results across different studies remain inconsistent. Basheer and Ibrahim [8,46,60] found that silane treatment reduced the corrosion current by more than 50%, and the amount of corrosion by-products decreased by a similar margin. Sivasankar et al. [95] further demonstrated that silane could extend the time to corrosion initiation by nearly four times, and this effectiveness was influenced by the molecular size of the hydrophobic agent. Likewise, Vassie et al. [96] observed that alkyl alkoxy silane treatment reduced the corrosion rate by approximately 37%, although complete prevention of corrosion was not achieved.

Contradictory findings were reported by Tittarelli and Moriconi [97], who noted that while silane treatments substantially reduced corrosion in uncracked concrete, they accelerated corrosion in cracked specimens. This effect was attributed to the enhanced oxygen diffusion through dry capillaries created by the hydrophobic treatment compared to water-filled pores. Similarly, the silicone resin solution showed only minor reductions in corrosion current density, while sodium silicate treatments were largely ineffective in preventing steel corrosion [46,60]. Batias [98] also confirmed the limited anti-corrosion performance of silicate-based inorganic surface treatments.

In recent developments, graphite-modified coatings such as graphite blended acrylic, chlorinated rubber, and epoxy coatings have been applied to provide cathodic protection for reinforced concrete [99,100]. These conductive coatings have been successfully tested in both pilot-scale and full-scale applications on highway bridges, car parks, and building structures, offering an effective alternative to traditional cathodic protection systems [100].

It is important to note that in the presence of cracks, hydrophobic agents may inadvertently increase corrosion currents, as oxygen diffusion occurs more rapidly through the unsaturated pore networks induced by these treatments [101–103]. Nevertheless, only limited research has evaluated the anti-corrosion performance of surface treatments specifically in cracked concrete conditions [17].

4. SURFACE TREATMENT DURABILITY

The durability of surface treatments plays a crucial role in determining the long-term performance and service life of surface-treated concrete structures. Since these treatments act as the primary barrier between the concrete and its environment, their degradation directly affects the overall durability of the system. The performance of surface treatments is influenced by several environmental factors such as temperature variations, wet–dry cycles, and radiation exposure [8,104–106]. Additionally, effective surface treatments must adapt to a wide range of service conditions, including pH variations, humidity changes, and substrate temperatures ranging typically from 15°C to 45°C. This section summarizes the existing research on the durability of various surface treatment systems.

4.1. Effects of Temperature and Radiation

Environmental exposure, particularly temperature and ultraviolet (UV) radiation, has a significant impact on the long-term effectiveness of surface treatments. Vries [107] examined the resistance of hydrophobic surface treatments (e.g., silane and siloxane) under elevated temperatures. The study reported a dramatic increase in water absorption after just 30 minutes of exposure in a 160°C chamber, indicating severe loss of hydrophobicity. Similarly, Dhir [48] found that while silane provided excellent resistance to chloride ion penetration at 20°C, its performance declined sharply when the temperature increased to 45°C. The deterioration was attributed to the thermal damage of the hydrophobic capillary layer formed by silane, which compromised its waterproofing capacity.

Levi et al. [41] further reported that after UV aging, the water absorption resistance of silane, silicone, and fluorinated polymer coatings decreased by 50%, 90%, and 50%, respectively. Aging studies on polymer coatings have revealed chemical bond degradation, such as the breaking of O–C–H and C–N bonds in acrylic coatings and changes in the C–O–C, C=O, and COO groups in epoxy coatings [108–111]. Similarly, polyurethane coatings experienced reductions in C–H and C–O groups after aging. However, limited research exists on the combined effects of temperature and UV radiation on the protective performance of acrylic, epoxy, and polyurethane coatings, especially under real environmental conditions.

4.2 Long-Term Field Performance

Several studies [55,58,112] have evaluated the long-term performance of surface treatments under natural exposure. However, the findings are often inconsistent due to differences in exposure environments, testing methods, and properties of the base concrete. For instance, Schueremans et al. [58] analyzed silane-treated reinforced concrete specimens extracted from a quay wall after 12 years of exposure and found that the long-term effectiveness of silane could not be guaranteed. Seneviratne et al. [112] also observed that the waterproofing ability of organic coatings decreased over time, mainly due to reductions in elasticity and viscosity under fluctuating temperatures.

Moradllo et al. [55] reported that while surface coatings initially reduced chloride ion diffusion during the first 9 months, their effectiveness declined progressively, with diffusion coefficients increasing significantly after 35 months. After 5 years, the chloride resistance of acrylic modified cementitious coatings became even lower than that of untreated concrete, consistent with Rodrigues et al. [113]. According to Moradllo's study, the durability ranking of surface coatings against chloride penetration followed this order:

fat acrylic < epoxy-modified polyurethane < cement-based coating < styrene-acrylic ester.

Li et al. [105] estimated the service life of several organic coatings through accelerated aging tests (Table 5). The results indicated that silane-based water repellents exhibited approximately twice the service life of cement-based coatings and nearly twenty times that of epoxy and polyurethane coatings. Nonetheless, other researchers reported that silane maintained long-term effectiveness under real exposure. Polder and De Vries [29] observed residual protection after 5 years, while Christodoulou et al. [114] confirmed that silane retained measurable protective effects even after 20 years of outdoor exposure. Although these long-term results were promising, data variability and the lack of detailed meteorological records prevented precise correlation between environmental conditions and coating performance.

4.3 Implications of Coating Degradation

Once a coating deteriorates, the chloride diffusion rate through the treated surface can exceed that of untreated concrete. This phenomenon can be attributed to two key factors:

1. Chloride accumulation near the surface prior to coating failure.
2. Sustained high moisture content beneath the coating, which maintains a favorable environment for chloride transport even after partial degradation.

Therefore, more comprehensive studies are needed to understand the aging mechanisms of coatings on concrete structures. To achieve this, future research should focus on realistic, multi factor weathering simulations that account for combined effects of temperature, moisture, UV exposure, and pollutant interactions, to better predict the service life of surface-treated concrete.

5. SUMMARIZATION

The protection of concrete through surface treatment is a complex issue that involves multiple physical and chemical mechanisms. Based on the findings reviewed in this study, the following major conclusions can be drawn:

1. Effect on Mechanical Properties: The influence of organic coatings and hydrophobic impregnations on the mechanical properties of concrete has received limited attention. However, existing studies have demonstrated that silica-based treatments can prevent the loss of compressive

strength in concrete exposed to elevated temperatures. Among organic surface treatments, epoxy coatings exhibit the best abrasion resistance, while silane treatments show negligible effect. Certain inorganic treatments have also been reported to improve abrasion resistance, following the order: sodium silicate > ethyl silicate > nano-silica**.** To date, no direct comparison has been made between the mechanical performance of organic and inorganic surface treatments.

2. Effect on Permeability and Water Absorption Most surface treatments significantly reduce water permeability in concrete. Among them, polymer coatings demonstrate the greatest effect in lowering water absorption. Hydrophobic impregnations such as silane and siloxane effectively prevent water ingress in the absence of hydrostatic pressure. In addition, ethyl silicate and paper sludge ash coatings recently developed materials have also shown promising water-resisting capabilities.
3. Resistance to Aggressive Substances In general, surface treatments hinder the ingress of aggressive agents, such as chloride ions, CO_2, and sulphates.
    - Polymer coatings are widely regarded as the most effective for chloride ion resistance, and the incorporation of nanocomposites further enhances their performance.
    - Reports on the effects of sodium silicate and silane treatments remain inconsistent.
    - For carbonation resistance, polymer coatings again outperform other methods, while silicate-based treatments provide moderate protection. In contrast, silane and siloxane offer minimal CO_2 resistance.
    - Regarding sulphate attack, polyurethane coatings have proven to be both effective and economical, and sulphate-alumina-resisting (SAR) coatings also reduce sulphate ion penetration. Overall, organic coatings exhibit better chemical resistance than silane-based hydrophobic agents or sodium silicate, although acrylic coatings are unsuitable for environments with physical sulphate attack due to their brittleness.
4. Resistance to Freeze Thaw and Corrosion Current studies mainly focus on the freeze thaw performance of silane-treated concrete, but consensus has not been reached. Both epoxy-based sealers and silane-based water repellents have shown improved salt-scaling resistance. Silane treatment can delay the onset of reinforcement corrosion and reduce corrosion current density in uncracked concrete; however, sodium silicate has shown little to no effect on corrosion resistance.

The following observations based on surface treatment durability of concrete were made:

1. Research shows that temperature and ultraviolet (UV) radiation greatly influence the efficiency of concrete surface treatments. Vries [107] found that hydrophobic treatments such as silane and siloxane lost their effectiveness after just 30 minutes at 160°C, resulting in a sharp increase in water absorption. Similarly, Dhir [48] reported that although silane provides good resistance to chloride penetration at 20 °C, its performance drops significantly at 45 °C because high temperatures damage the hydrophobic capillary layer.
2. UV aging also reduces performance: Levi et al. [41] observed that water absorption resistance of silane, silicone, and fluorinated polymers decreased by 50%, 90%, and 50%, respectively. Studies [108–111] showed that aging can break chemical bonds in acrylic coatings and alter functional groups in epoxy and polyurethane coatings. However, the combined effects of temperature and radiation on acrylic, epoxy, and polyurethane coatings are still not well understood.
3. Long-term field studies [55, 58, 112] have produced inconsistent results due to variations in exposure conditions and concrete properties. For example, Schueremans et al. [58] found that silane treated concrete from a quay wall after 12 years did not show reliable long-term protection. Other researchers noted that organic coatings lose waterproofing ability over time as elasticity and viscosity decrease. Moradllo et al. [55] observed that coatings reduced chloride diffusion during the first 9 months, but this benefit diminished over time, and some coatings eventually performed worse than untreated concrete.
4. Service life estimates [105] suggest that silane based repellents last about twice as long as cement-based coatings and far longer than epoxy or polyurethane. Yet other studies show silane can provide long-term protection, lasting 5 to 20 years [29, 114], although some variations remain unexplained.
5. Once coatings degrade, chloride diffusion may become even higher than in untreated concrete because chloride accumulates at the surface and the treated concrete often stays wetter. Therefore, more research is needed on coating aging mechanisms and more realistic weathering tests should be developed.

6. FUTURE RESEARCH DIRECTIONS

To achieve a more comprehensive understanding of surface treatment technologies, future research should address the following aspects:

1. Conduct systematic studies to evaluate the mechanical performance and durability recovery of fire-damaged concretes treated with surface coatings after air cooling.
2. Develop standardized acceptance criteria to facilitate comparison of performance among different surface treatments, as current methodologies are inconsistent.
3. Investigate the durability and field applicability of inorganic treatments and novel coating systems, such as polymer/clay nanocomposites and modified epoxy resins.

4. Formulate predictive models incorporating the aging and durability characteristics of surface treatments to estimate the service life of treated concrete.
5. Explore in greater depth the anti-corrosion performance of surface treatments on cracked concrete**,** as existing studies remain inconclusive.

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