Review Article

Journal of Environmental Nanotechnology

Integral and Surface Treatment Method of Waterproofing: A Review and Comparative Analysis

Aniket Bansal[1*], Balwinder Lallotra[1] and Aman Sehgal[2]
[1]Department of Civil Engineering, Chandigarh University, Mohali, PB, India
[2]Ultratech Cement, HR, India
Received: 26.07.2024 Accepted: 20.09.2024 Published: 30.09.2024
*aniketbansal3655@gmail.com

ABSTRACT

Water seepage into concrete can cause deterioration and other aesthetic issues that limit the life of concrete constructions. This paper examines and contrasts the various kinds of waterproofing techniques. There are essentially two types: surface treatment method and integral method. Water repellents, crystalline admixtures, and densifiers are examples of integral methods. Surface treatment methods encompass pore-blocking, hydrophobic impregnation, surface coating, and multifunctional surface treatment. The processes of various approaches are examined in this article, followed by a comparison of their durability and mechanical properties. We discuss several properties, such as sulfate attack, chloride penetration, carbonation, reinforcement corrosion, water absorption and permeability, compressive, flexural, and tensile strength. The findings indicate that each has merits and demerits of their own. The inclusion of an integral admixture to concrete offers a number of advantages over surface protection, including convenience of application, the removal of the need for ongoing maintenance, and minimal to no deterioration over time. While surface treatment methods significantly reduce water permeability and porosity. In conclusion, we give a succinct summary of certain issues regarding the present state of research and future directions for the hydrophobic modification of concrete.

Keywords: Waterproofing; Hydrophobic; Seepage; Integral; Surface coating; Admixture.

1. INTRODUCTION

Water seepage into concrete can cause deterioration and other aesthetic issues that limit the lifespan of concrete constructions. To create waterproofing additives that prolong the useful life of concrete components, numerous experiments have been conducted. As a result, significant expenses for upkeep and repairs could be avoided (Muhammad *et al.* 2015; Wong *et al*. 2015). Waterproof concrete should absorb water at a relatively slow rate. Many tactics have been used to lessen concrete's absorption of water. Concrete cracking is traditionally controlled by reducing the water-to-cement (w/c) ratio, adding supplemental cementitious materials (SCMs) to the concrete mixture, and adding more reinforcing (Jahandari *et al*. 2023). Broadly waterproofing is classified into two methods i.e. integral method and surface treatment methods. Compared to other popular waterproofing techniques, the application of integral waterproofing additives is a feasible substitute (Muhammad *et al*. 2015). The intention behind adding integral waterproofing additives to concrete is to directly form a water barrier. As Concrete's permeability and rate of water absorption both sharply increase after damage (Zhou and Xu, 2009; Dong *et al*. 2022). Conversely, exterior membranes or surface coatings only shield the upper or lower surfaces of the concrete. Thus, integral waterproof concrete doesn't need to be maintained often and can be used in constructions where it presents difficulties to add an additional layer of defense (Tittarelli and Moriconi, 2010). In batching plants, concrete can be mixed with liquid or powdered integral waterproofing admixtures. These admixtures fall into three groups: crystalline admixtures, water repellents (hydrophobers), and densifiers (Jahandari *et al*. 2023). Densifiers smooth out the cement matrix and the concrete's pore size distribution, while water-repellent admixtures increase the liquid contact angle by altering the surface tension of pores and fissures, this prevents absorption (Hossain *et al*. 2016; Mehdizadeh *et al.* 2021). However, it has been observed that crystalline admixtures strengthen concrete's resistance to water penetration under pressure by obstructing pores caused by solids deposition through chemical reactions (Xue *et al*. 2021).

Nonetheless, over several decades, a substantial amount of research has been done on the use of surface treatments in concrete. The use of surface treatment technology in concrete structures has grown in importance, particularly in preventing degradation and damage in very aggressive conditions and in further prolonging service life (Pan *et al*. 2017). Pan et al. also examines and contrasts surface treatment effects and durability performance (Pan *et al*., 2017). Concrete can be protected using a number of different surface treatments. The two types of surface treatments are inorganic and organic, based on the chemical makeup of the chemicals used in the treatments (Delucchi, Barbucci and Cerisola, 1997; Hansson, Mammoliti and Hope, 1998; Franzoni, Pigino and Pistolesi, 2013). The other three forms of surface treatments are hydrophobic impregnation, impregnation, and coating, categorized based on their functions (Elsener, 2008; Medeiros and Helene, 2009; Dai *et al*. 2010). However, after adding new techniques the four forms are hydrophobhic impregnation, pore blocking, multifunctional surface treatment and coating (Pan et al., 2017).

A continuous polymer film created by surface coating serves as a tangible obstacle to stop corrosive materials from soaking into cementitious substrate (Medeiros and Helene, 2008; Pacheco-Torgal and Jalali, 2009; Diamanti *et al*. 2013). There are numerous surface coatings, such as acrylic, chlorinated rubber, butadiene copolymer, epoxy resin, polyester resin, polyurethane, and polymer modified mortar, have been used in foundations and quays (Elsener, 2008). Water repellent chemicals based on silane or siloxane are typically used for hydrophobic impregnation (Medeiros and Helene, 2008; Woo *et al*., 2008a). In the zone near the surface, they leave the pores open and form a water-repellent pore surface (Elsener, 2008; Woo *et al*. 2008b; Dai *et al.* 2010). Treatments that block pores can either fully or partially fill the capillary pores, which lowers the surface layer's porosity. In this category, pore blockers based on silicate are the most widely used products. Certain new generation pore-blocking agents, such nano-SiO_2 and $CaCO_3$ precipitation, raised a lot of issues. Pore-blocking treatment compounds have gained popularity recently as a means of preserving structures like highway bridges (Moon *et al*., 2007; Pan *et al*., 2016).

Table 1 summarizes recent reviews that have been published on waterproof concrete in order to show why this review study is necessary. The majority of the prior review studies, as this table illustrates, concentrated on a particular type of waterproofing technique i.e. integral method or surface treatment technology and how it affected concrete's long-term durability and mechanical properties. The waterproofing techniques used on concrete behavior are not jointly reviewed. As a result, the goals of this work are met. We will first go over the mechanism of the several integral waterproofing and surface treatment methods. Second, a rigorous analysis will be conducted to determine how integral waterproofing and surface treatment affect the mechanical and durability qualities of the concrete. Lastly, important conclusions and suggestions for additional study will be provided.

Table 1. Reviews on recent works on waterproof concrete

Method applied	Topics discussed	Reference
Integral waterproof concrete	• Impact of integrated waterproofing methods on the durability and overall performance of concrete.	(Jahandari *et al.* 2023)
Superhydrophobic modification	• Superhydrophobic concrete fabrication: bulk and surface modification. • Superhydrophobic concrete's durability, including its ability to withstand water intrusion, corrosion, ice, freeze-thaw, and UV rays.	(Wu *et al.* 2022)
Hydrophobic modification	• Hydrophobic alteration using internal, coating, and template techniques. • Durability of hydrophobic layer on concrete surfaces • Effects of hydrophobic alteration on cement-based. Materials' carbonation, strength, waterproofing, penetrated chloride ions, and hydration.	(Zhao *et al.* 2022)
Surface coating	• Quality of the hydrophobic agent and the characteristics of the concrete substrate are related. • Impact of w/c ratio and hydrophobic agent on the concrete substrate's ability to withstand carbonation and chloride.	(Courard *et al.* 2021)
Nano-engineered coating	• Surface microstructure's impact on hydrophobic efficiency. • Extended efficacy of hydrophobic surface coating at the nanoscale.	(Chen *et al.* 2018a)
Hydrophobic admixture	• Impact of hydrophobic additive on concrete's decreased water absorption. • The hydrophobic process' mechanism.	(Ebrahimi *et al.* 2018)
Pore blocking, surface coating impregnation and multifunctional surface treatment	• Impact of hydrophobic systems, including bonding strength, air permeability and crack resistance on the surface protection of concrete.	(Pan *et al.* 2017)

2.2. TYPES AND MECHANISM OF INTEGRAL AND SURFACE COATING METHOD OF WATERPROOFING

2.1. Integral Waterproofing

2.1.1 Densifier

Among the densifiers used most frequently in concrete are supplementary cementitious materials and a few nanomaterials (nano-silica, nano-aluminium oxide, and nano-ferric oxide). Several investigations have been carried out on the impact of these compounds on durability, freshness, and mechanical qualities of concrete (Oltulu and Şahin, 2011; Hossain *et al.* 2016; Yang *et al.* 2021). Through ingestion of the liberated calcium hydroxide and creating more calcium silicate hydrates, it is generally accepted that the pozzolanic reactions of SCMs alter the hydration products' chemistry and the concrete's microstructure. As a result, there is an improvement in durability due to decreased porosity and strengthening (Chindaprasirt and Rukzon, 2008). According to reports, adding nano-silica to regular concrete produced a microstructure that was more homogeneous and compacted (Ji, 2005). Because of its high activity and low specific surface area, nano-silica might respond with calcium hydroxide crystal rapidly to form C-S-H gel, which fills in the gaps and increases the density of the binding paste matrix and the interfacial transition zone (ITZ). In concrete with nano-silica, a significant amount of C-S-H gel has developed, which is not visible in the paste without nano-silica. As a result, the hydration product structure's stability and integration are improved, improving the concrete's long-term mechanical qualities and durability (Oltulu and Şahin, 2011).

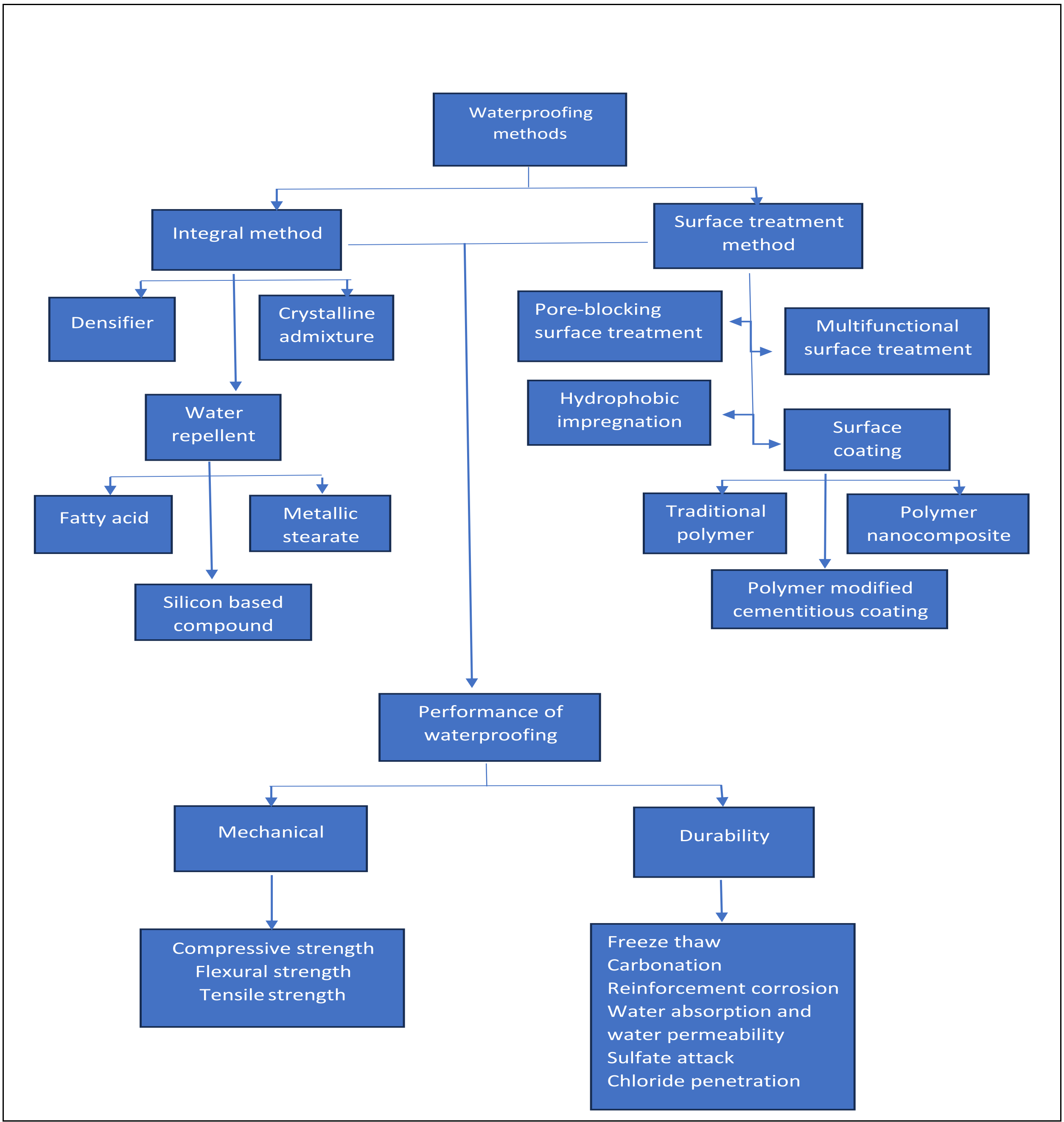

Fig. 1: An overview of study

2.1.2 Water Repellent

Concrete's surface tension is changed by water repellents, sometimes referred to as hydrophobic admixtures, which make the material naturally non-absorptive and water-repellent. In order to stop water from penetrating the pores, the angle of contact for the pore walls might be raised to 90° or higher (Jahandari *et al.* 2023). If hydrophobic admixtures are not utilized in conjunction with other admixtures, they may not be able to withstand water penetration under hydrostatic pressure. Additionally, hydrophobic polymers can affect how cement hydrates or hardens, enhancing the general characteristics of cement-based products (Sakai *et al.* 1995). It was discovered that Concrete's durability and mechanical qualities were enhanced with hydrophobic polymers, as demonstrated by studies(Qu *et al.* 2021; Wathiq Hammodat *et al.* 2021). The following are some varieties of water repellents.

2.1.2.1 Silicon Based Compound

Oligomeric siloxane and silane are employed as essential agents that repel water. Although silanes hinder cement's early hydration, the poly-condensation product of silanes reacts with portlandite to raise the cement's ultimate hydration degree (Falchi *et al.* 2015; Feng *et al.* 2016; Chen *et al.* 2020). Our options for using silanes to lessen their blocking impact are oligomers and nanoparticles (Feng *et al.* 2016). Additional investigation also demonstrated that silanes had varying retarding effects on hydration. Whereas tetraethoxysilane merely decreased the exothermic peak rate by around 20% without extending the induction duration, aminosilane extended the cement's hydration induction period (Kong *et al.* 2015). A water-repellent compound (YREC) was recently developed by Zhu *et al.* (2020a) to increase the crack resistance of concrete under dry curing circumstances. When added to concrete, silicate gel condenses and covers the concrete's capillary pores (Sandrolini *et al.* 2012). Adding silicone oil to mortar improved its quality as well (Luan *et al.* 2023). After five years of being exposed to the outside, concrete treated with hydrophobic alteration with silanes retained its protective qualities, and this effect persisted even after twenty years(Christodoulou *et al.* 2013).

Additionally, Fajun Wang et al. demonstrated that cement mortars treated with polydimethylsiloxane (PDMS) had pore volumes reduced by 7.9% and water absorption reduced by 92.51% (Wang *et al.* 2020). Researchers also utilized silicon rubber to improve the hydrophobic qualities concrete (Li *et al.* 2021).

2.1.2.2 Fatty Acid

Caprylic, oleic, and capric acids are examples of liquid fatty acids that added to a concrete mixture as hydrophobic admixtures, either diluted or undiluted (Zhao *et al.* 2023). In order to aid in stearic acid's dispersion throughout the mixture, inert fillers such as talc, silica, or an emulsion in water can also be premixed. It can also be utilized as a modifying additive to create waste-based, hydrophobic sand that can replace natural sand in mortar and concrete (Song *et al.* 2022; Wang *et al.* 2022). In order to create superhydrophobic oyster shell powder, Song et al. (Song *et al.* 2022) recently employed stearic acid as a modifier. The mortar exhibiting a 95.2° water contact angle was made using 30% superhydrophobic oyster shell powder replacement.

A different study (Wang *et al.* 2022) found that the ideal amount of stearic acid to modify iron ore tailings was 1.5%. To obtain the hydrophobic state, a mortar was filled with thirty percent hydrophobic iron ore powder. Additionally, Shi *et al.* (2022) created a hydrophobically altered steel slag by chemically treating it with 1% stearic acid. This resulted in an increase in the treated mortar's water contact angle to 91.5°.

2.1.2.3 Metallic Stearates

Because stearates like calcium, aluminum, and zinc stearate coat capillary pores hydrophobically, they prevent water from transferring through them in non-hydrostatic concrete (Quraishi *et al.* 2011). Waste utilization was first conceptualized by Wong et al. and applied to the production of hydrophobic agents. The fundamental idea is to alter the surface using the self-assembled hydrophobic calcium stearate monolayer and the coarse structure that the particle produces as it grinds (Maryoto *et al.* 2015). In a research by mixing sand and cement mixture with stearic acid, a strong superhydrophobic cement block was created (Zhu *et al.* 2020b). The majority of stearates, including calcium stearates, adversely affect the mechanical qualities and workability of concrete. Superplasticizers and SCMs, among other admixtures, could be added to lessen these adverse effects (Jahandari *et al.* 2023).

2.1.2 Crystalline Admixtures

Following contact with water, the active ingredients in the cementitious capillary crystalline waterproofing material seep into the concrete using water as a carrier. This causes the formation of acicular crystals that are insoluble in water along with cement hydration products, which fill capillary pores and micro-cracks (Li *et al.* 2019). When concrete was treated with multi-crystallization enhancer (MCE), its porosity and permeability decreased (Al-Rashed *et al.* 2021). A frequent crystalline additive is sodium acetate. The crystalline-based systems are generally available as dry powders and are hydrophilic, or capable of absorbing water. Crystalline technologies, as opposed to water repellents, are said to allow for self-sealing once a break has created since leaking water can cause new crystal formation to bind the fracture (Teng *et al.* 2014). A popular crystalline ingredient that is advised to extend the life and durability of concrete without sacrificing its strength is sodium acetate (Al-Kheetan *et al.* 2018; Al-Kheetan *et al.* 2019).

2.2 Surface Treatment

2.2.1 Hydrophobic Impregnation

By expanding the contact angle, hydrophobic impregnation works by entering the pores of the concrete. At contact angles greater than 90°, the surface turns hydrophobic (Pan *et al.* 2017). Cement-based products become more compact due to surface impregnation (Xue *et al.* 2017). The most widely utilized hydrophobic impregnation materials are silane, siloxane, and combinations of these two (Pan *et al.* 2017). There are many alkoxy groups as well as an alkyl group in both silane and siloxane (Batis *et al.* 2003). The impregnation with silicate proved successful in enhancing the resistance to abrasion and water penetration (Dai *et al.* 2010; Matziaris *et al.* 2011; Baltazar *et al.* 2014). After the concrete was treated with an isobutyltriethoxysilane composite emulsion, its surface changed from hydrophilic to hydrophobic (Zhang *et al.* 2019). A study found that 94% less water was absorbed when polybutadiene was used as an impregnation (Szymańska *et al.* 2022). Water cannot enter the substrate's porous structure through a superhydrophilic coating using a hydrophobic impregnation technique (Carrascosa *et al.* 2020). After five years of exposure to the outside, concrete treated with hydrophobic alteration with silanes retained its protective qualities, and this effect persisted even after twenty years (Christodoulou *et al.* 2013).

2.2.2 Pore-blocking Surface Treatment

For many years, highway bridges and buildings have been treated with pore-blocking surface treatments (Dai *et al.* 2010). They can obstruct the capillary holes in the concrete surface, increasing the layer's hardness and impermeability. It has been demonstrated that silicate-based solutions (such as sodium, calcium, and lithium silicates) and fluosilicate are efficient at obstructing capillary holes in concrete surfaces (Elsener *et al.* 2008). As demonstrated by Jiang *et al.* (2015) and Jia *et al.* (2016), the performance of sodium silicate can also be enhanced by pretreatment with sodium fluosilicate. Cardenas and Struble (2008) attempt to increase concrete's durability with EN treatment was unsuccessful. They discovered that the application of an electrokinetic approach can amp up the impact of nanoparticle therapy on the concrete cover's quality. According to Wu *et al.* (2016) the electrokinetic approach can improve the binding strength of the rebar-concrete interface by causing nano-alumina particles to migrate into the pores of concrete and improve the distribution of porosity. Nano-silica as a siliceous material has been thoroughly investigated (Singh *et al.* 2013; Abdou *et al.* 2016). According to recent research by Hou *et al.* (2014 and 2015) treating hardened cement pastes with nano-silica can increase their impermeability by reducing a pore network's threshold value and the pores volume bigger than 50 nm. Numerous studies have employed Precipitation of calcium carbonate as a surface treatment for concrete due to the material's excellent durability (Faatz *et al.* 2005; Amidi *et al.* 2015).

2.2.3 Multifunctional Surface Treatment

Some recently developed Surface modifications are not a part of the current classification. These include hydrophobic paper sludge ash coating, ethyl silicate, and silane/clay nanocomposites (Pan *et al.* 2017). In addition to having a hydrophobic impact, silane clay nano-composites alter the microstructure of concrete covers, Russo *et al.* (2006) and Woo *et al.* (2008a) reported that a 5% clay percentage produced the lowest permeability. However, they also noted that, in contrast to clean silane, the silane–clay nanocomposite treatment's resistance to chloride diffusion reduces (Leung *et al.* 2008). Another study (Pigino *et al.* 2012; Sandrolini *et al.* 2012) discovered that using tetraethylorthosilicate (TEOS) by brushing or immersing can significantly improve the condition of concrete surfaces. Although TEOS lacks the ability to bind, it can hydrolyze to create a silica gel that fills the pore network. Its hydrophobic properties as an alkoxysilane can endure for longer than six months (Scherer *et al.* 2009) and as a result, it might shield the substrate from corrosive substances before hydrolysis is finished. Calcium silicate hydrate is created when it combines with calcium hydroxide in the concrete substrate. Because of its small molecular size and low viscosity, TEOS may profoundly penetrate concrete substrates (Mosquera *et al.* 2009). Its sluggish reaction rate and susceptibility to cracking during drying and shrinkage are some of its disadvantages, though. The use of chemicals, nanoparticles, and a catalyst could help with these shortcomings (Miliani *et al.* 2007; Maravelaki-Kalaitzaki *et al.* 2008; Kim *et al.* 2009).

2.2.4 Surface Coating

An uninterrupted polymer layer created by surface coating serves as a physical defense to stop corrosive materials from soaking into cementitious substrate(Elsener *et al.* 2008; Diamanti *et al.* 2013). Surface coatings come in several forms, such as cementitious coatings, polymer nanocomposite coatings, and conventional polymer coatings. On the concrete surface, conventional polymer coating and polymer nanocomposite coatings produce a thick polymeric layer that is between 0.1 and 1 mm thick, whereas cementitious coating functions by creating a low permeability layer that is between 2 and 10 mm thick (Pan *et al.* 2017).

2.2.4.1 Traditional Polymer Coatings

Traditional protective coatings including polyurethane, acrylic (Fig. 2) and epoxy resins have been utilized for many years in the building sector. Due to its greatest strength and lowest rate of corrosion, polyurethane was the ideal coating (Afshar *et al.* 2020).

Fig. 2: Acrylic coating

The polymer coating's barrier effect is primarily responsible for the coated concrete's water resistance. For polymer coatings, Fick's law often describes the kinetics of moisture transport (Shen *et al.* 1976; Drozdov *et al.* 2003; Kim *et al.* 2005). Polymer coating's water transport is intricate, though. Diffusion of water in epoxy coatings deviates from Fick's rule, according to experimental results by Maggana *et al.* (1999), particularly at temperatures below 20 °C. Applying polymer coatings to concrete therefore requires assessing their diffusion properties at various temperatures. Van Landingham *et al.* (1999) state that the water diffusion of polymer coatings is dependent upon the water affinity and molecular-sized hole availability in the polymer. Fick's law is limited to describing the first phase of water diffusion due to the influence of polymer-water affinity, and it is not applicable throughout the entire process (Maggana *et al.* 1999; Pérez *et al.* 1999).

Four different forms of failure patterns have been found in polymer coating/concrete systems: blistering, cracking, holes, and peeling (Yang *et al.* 2002; Hinder *et al.* 2005; Vipulanandan *et al.* 2005; Perrin *et al.* 2009; Sørensen *et al.* 2009). Coatings used in modern building are typically composed of multiple layers for optimal protection. Additionally, a lot of work has been done by researchers to enhance their qualities by including different nanofillers (Moloney *et al.* 1987; Chruściel *et al.* 2015).

2.2.4.2 Polymer Nanocomposite Coatings

Because of its exceptional qualities above virgin polymers, polymer nanocomposite coatings have recently sparked a lot of attention in both academic study and application in engineering. Heat resistance, abrasion resistance, tensile modulus, strength, and thermal stability are all typically higher in polymer nano-composite coatings. Nanoparticles may be added to lessen flammability and gas permeability, among other effects (Fischer *et al.* 2003; Hu *et al.* 2005; Pavlidou *et al.* 2008; Woo *et al.* 2008b; Choudalakis *et al.* 2009). By raising the diffusion path, the addition of a nanocomposite that is not organic can enhance barrier qualities and delay the breakdown of polymers (Kumar *et al.* 2009). Diffusion path lengthening is proportional to tortuosity, which rises with nanocomposites' concentration and characteristics like aspect ratio and volume fraction (Sinha Ray *et al.* 2003; Leung *et al.* 2008; Scarfato *et al.* 2012). But there hasn't been much study done on polymer nanocomposite coatings' use in concrete constructions (Sinha Ray *et al.* 2003; Manoudis *et al.* 2007; Carmona-Quiroga *et al.* 2010; Scarfato *et al.* 2012). Few studies have looked into the characteristics of coatings made of polymer/clay nanocomposite on cementitious materials (Kojima *et al.* 1993; Hackman *et al.* 2006; Woo *et al.* 2007; Woo *et al.* 2008b). Although the performances of polymer/Al_2O_3 and polymer/SiO_2 exhibit potential benefits in producing a barrier effect, they have not been assessed. Because they are inexpensive, Organic polymers such as starch can be employed to create nanocomposite materials (Fischer *et al.* 2003).

2.2.4.3 Polymer Modified Cementitious Coatings

PMCCs are composed of aggregates (usually very fine aggregate), cement, and polymers (primarily epoxy, polyurethane, or acrylate). The qualities of cement paste that are significantly enhanced by the inclusion of polymer include strength, resilience, adhesion, chemical resistance, and impermeability (Reddy and Sykes, 2005). Specifically, PCCs are a great option for repairing cracked concrete since they are typically thought to be breathable and have a higher capacity to bridge fractures than polymer coatings because of their lower elastic modulus (Diamanti *et al.*, 2013). Due to its exceptional endurance even in extremely hostile settings, geopolymer is employed as a layer of defense for marine concrete (Zhang, Yao and Zhu, 2010; Pacheco-Torgal *et al.* 2012; Zhang, Yao and Wang, 2012). It has been suggested that superhydrophobic coatings with the capacity for self-repairing might be created by combining Portland cement, PDMS, and foundry dust using the straightforward brush-coating technique (Wang *et al.* 2020).

Furthermore, one efficient way to use and dispose of solid waste is to incorporate certain types of readily available and reasonably priced organic materials into PCCs, such as diatomaceous earth (DE) and solid waste (such fly ash and foundry waste dust) (Sawai *et al.* 2016; Bhardwaj and Kumar, 2017; Siddique, Singh and Singh, 2018; Ahmed *et al.* 2021) . Additionally, it has been observed that colorful superhydrophobic concrete satisfies a number of conditions for building exterior wall decorating (Xu *et al.* 2021). Fig. 3 shows polymer modified cementitious coating.

Fig. 3: Polymer modified cementitious coating

3. DURABILIY PROPERTIES

3.1 Freeze and Thaw

Adding small, irregular air bubbles to the concrete or decreasing the porosity to increase the density of the concrete are two popular ways to increase the freeze-thaw resistance of concrete. Additionally, cement-based materials' ability to withstand freeze-thaw can be greatly enhanced by hydrophobic alteration. Yellow River Engineered Consulting (YREC), a hydrophobic agent, was created by Zhang *et al.* (2021b) using mica powder as the substrate that had been prepared with a silane coupling agent. At a dosage of two to four percent by weight of cement, YREC was added to concrete. After 35 freeze-thaw cycles, it was discovered that the reference concrete, which had a w/c ratio of 0.5, had failed. While surface treatment cannot completely replace air-entraining agent in preventing freeze-thaw cycles in concrete, it can offer supplementary protection, particularly in extremely cold climates (Dang *et al.* 2014). The mechanism is that the hydrophobic surface's reduced area of contact with water lowers the ice's adhesion force and blocks water and hostile ions from entering the pores directly (Liu *et al.* 2016). According to Dang *et al.* (2014), surface treatments lengthened the time it took to reach the threshold moisture level by delaying the entrance of moisture during the freeze-thaw condition. Additionally, Basheer *et al.* (2006) research shown that the application of silane might increase the quantity of freeze-thaw cycles required for concrete to start cracking in a fresh water test. The silane's resistance to freezing and thawing is highly significant when the concrete is first dry, since silane has the ability to lessen water intrusion into concrete.

3.2 Carbonation

Concrete carbonation, or a drop in pH, was caused by carbon dioxide (CO_2) seeping into the porous concrete. This could hasten the steel reinforcement's corrosion caused by chloride (Papadakis *et al.* 2000; Glasser *et al.* 2008). Carbonation is a chemical process that produces Calcium carbonate and silica-rich C-S-H by reacting Calcium hydroxide, calcium-silicate-hydrate (C-S-H), and Carbon dioxide (Johannesson *et al.* 2001) and eliminate the implanted reinforcement bars' passivity (Chang *et al.* 2006). The rate of carbonation of concrete using recycled aggregate (RAC) handled with integrated silane emulsion was investigated by Zhu *et al.* (2013). The findings indicate that the RAC's carbonation depth was around 20 mm, twice as deep as the corresponding natural aggregate concrete. The RAC's carbonation depth was successfully lowered to 14 mm after 112 days of applying 0.5% silane emulsion. Regarding surface treatment techniques, variations in coating techniques also affect cement-based products' ability to withstand carbonation. According to some researchers, film-forming coatings have a higher carbonization resistance than porous coatings. The primary explanation is that the dense protective layer created by the film-forming coating procedure will keep carbon dioxide gas out of the concrete void. The carbonation depth of concrete surfaces was found to be 48.4% lower after applying 99% silane (Courard *et al.* 2021). According to Xu et al., concrete treated with isobutyltriethoxysilane had a decreased carbonation depth, which may have resulted from hydrophobic coatings clogging pores (Xu *et al.* 2016). It was discovered that, even in cured concrete, the water-to-cement ratio was crucial. In comparison to concretes treated with siloxane and acrylic and having a w/c of 0.7, the unprotected concrete with a 0.6 exhibited a reduced carbonation rate (Otsuki *et al.* 2003; Zheng *et al.* 2012; Aguiar *et al.* 2013).

3.3 Reinforcement Corrosion

The thicker and less porous the concrete cover, The rusting process takes longer to complete., so the reinforced concrete structure's service life is extended (Petcherdchoo *et al.* 2016). According to Basheer *et al.* (1997) Surface treatments lengthened the initial period of reinforcement corrosion. Numerous investigations have documented the impact of hydrophobic additives on the corrosion of reinforcement in concrete. The impacts of silane-based products have been the main focus of most of these studies. Sivasankar *et al.* (2013) shown that silane may nearly quadruple the reinforcement corrosion time; however, this effect depended on the hydrophobic treatment agent's molecule size. According to Tittarelli *et al.* (2010), the passivation of the galvanized steel reinforcement was aided by the hydrophobic concrete's quicker oxygen diffusion. Galvanized steel reinforcement was more shielded from chloride-induced corrosion by hydrophobic concrete with silane emulsion than by surface hydrophobic treatment (Tittarelli *et al.* 2011). In a different investigation, graphite was included in coatings made of acrylic, chlorinated rubber, or epoxide to protect reinforced concrete cathodically (Orlikowski *et al.* 2004). It has also been discovered that stearic acid emulsion significantly increases the corrosion resistance of steel reinforcement (Feng *et al.* 2019).

3.4 Water Absorption and Water Permeability

Previous research indicates that water plays a significant role in the majority of concrete degradation processes, including chemical attack, carbonation, alkali-silica reactivity, and freeze-thaw damage (Tibbetts *et al.* 2020; Cantero *et al.* 2021), Thus, the most essential requirement is the high water-repellent property. Three hydrophobic polymers (SBR, PAE, and VAE) were combined with cement mortar by Ramli et al., who then observed a substantial decrease in the water absorption of the polymer-modified cement mortar (Ramli *et al.* 2013). Moisture penetration and capillary suction are greatly reduced when silane emulsion is added to concrete and mortar (Zhang *et al.* 2022). According to Zhu *et al.* (2013), recycled aggregate concrete's capillary water absorption was 81% lower using a silane-based hydrophobic additive than with reference concrete. It was discovered that calcium stearate decreased the permeability and rate at which typical concrete absorbed water (Maryoto *et al.* 2020). The effects of adding styrene butadiene rubber (SBR) latex and recycled plastic fiber (RPF) simultaneously to concrete were assessed by researchers. According to the results, the 1% RPF and 15% SBR dosages dramatically decreased water absorption by 60% (Bhogayata *et al.* 2018). Numerous surface treatments have the ability to lessen the amount of water that enters the treated matrix. In comparison to sodium silicate and nano-silica, Franzoni *et al.* (2014) research revealed that ethyl silicate's efficiency was more noteworthy. Nowadays, it has been demonstrated that a number of polymeric coatings, such as epoxy (Chi *et al.* 2020; Zheng *et al.* 2020), acrylate (Bader *et al.* 2020), polyurethane (Toutanji *et al.* 2013; Chen *et al.* 2018b), and silane or oligomeric siloxane (Bader *et al.* 2019; Namoulniara *et al.* 2019), are effective at reducing the amount of water that enters the concrete matrix. According to Zhao et al, adding PCC (made with 4% silica) decreased concrete's absorption of water by 62.5% (Zhao *et al.* 2020). Waterproof geopolymer composites were creatively created by Ruan et al. by combining PDMS, hydrophobic quartz particles, and hydrophobic metakaolin (Ruan *et al.* 2022). The results indicate that hydrophobic particles' inhibitory effect on water absorption was not as strong as that of PDMS, and that the combination of the two was most efficient (Ruan *et al.* 2022). According to Yin *et al.* (2020), the combined action of the hydrophobic silane layer and mineralized layer produced superhydrophobic concrete's enhanced water permeability.

3.5 Sulfate Attack

When concrete is exposed to excessive amounts of sulfate from the external environment or from within (e.g., sulphate contained in the aggregates or binder), a complex damaging event known as sulfate assault results. Concrete strength can deteriorate due to sulfate's reaction combining hydrated calcium silicate (C-S-H) and calcium hydroxide (CH) to create gypsum and expanded ettringite (Arbi *et al.* 2016). In Wang *et al.* (2015) study, 1% of the cement weight was put to mortar containing commercially available polydimethylsiloxane (PDMS). The sulphate resistance improved, according to the results, and because less water and sodium sulfate entered the PDMS-modified mortar, it was more resistant to sulfate attacks. Additionally, surface treatment methods can strengthen concrete's defenses against sulfate attacks. concrete treated with a glass-fiber mat-reinforced epoxy coating and submerged in 3% sulfuric acid had a lifespan increase of more than 70 times (Vipulanandan *et al.* 2002). Using the super-absorbent resin (SAR) precursor solution for concrete surface treatment, Song *et al.* (2008) showed that the SAR would successfully block the external aggressive sulphate's penetration channel. According to Suleiman *et al.* (2014) evaluation of the impacts of several surface treatments under physical sulfate attack, the resistance of these treatments rose in the following order: water-based solid acrylic, bitumen, silane, and epoxy. Compared to hydrous silicates or antimicrobial chemicals, epoxy coating and polyurea lining have been shown to be more efficient at preventing corrosion caused by biogenic sulfuric acid (BSA) (De Muynck *et al.* 2009; Berndt *et al.* 2011). The resistance of sulfate attack on surface-treated concrete is influenced by a few key parameters (Liu *et al.* 2001; Vipulanandan *et al.* 2005; Vaidya *et al.* 2010):

- The higher Calcium hydroxide content will cause more expansion and gypsum to form;
- Adhesion between the coating and substrate
- The substrate's moisture content.

3.6 Chloride Penetration

Concrete tainted with chloride tends to corrode steel reinforcement. In a demanding climate, reinforced concrete structures may have a longer service life if chloride penetration in integrated waterproof concrete is postponed (Jahandari *et al.* 2023). To lessen the infiltration of chloride ions, it was suggested that calcium stearate be added to concrete mixes at a dose of 1 kg/m^3 (Nemati Chari *et al.* 2019). Additionally successful in preventing chloride intrusion into concrete are crystalline admixtures. Al-Kheetan and associates (Al-Kheetan *et al.* 2020) made several concrete mixtures with 2% to 4% anhydrous sodium acetate. According to reports, the depth range of 20 to 50 mm resulted in a 90% reduction in chloride diffusion. It is generally acknowledged that polymer coatings provide greater chloride resistance than alternative treatment techniques (Courard *et al.* 2021). In comparison to the uncoated concrete, Almusallam *et al.* (2003) found that the polyurethane and acrylic coatings were roughly ten times more effective at preventing the diffusion of chloride ions. According to Jones *et al.* (1995) silane prevented chloride ions more successfully than acrylic coating. Studies have shown that the primary factor influencing the enhancement of resistance to chloride ion penetration on hydrophobic alteration is interference with the entry of chloride ions. For instance, the use of graphene oxide (GO) nanocomposite coatings can reduce the transit capacity of chloride ions and hence greatly delay the contact time between the ions and the passivation surface of the reinforcement (Mohammed *et al.* 2015).

4. MECHANICAL PROPERTIES

Studies have indicated that the application of hydrophobic modifiers externally did not alter the cement concrete's microstructure, hence negating its effect on cement-based materials' strength. As a result, our primary research focus is on how integral waterproofing affects the mechanical characteristics of concrete.

4.1 Compressive Strength

The strength of cement-based materials was slightly reduced by the addition of silicone polymer. Conversely, silane condensation can react with portlandite when applied in its fresh state to generate C–S–H. The extra C-S-H fills the pores and boosts the cement-based materials' flexural and compressive strengths (Chen *et al.* 2020). However, when the additive was introduced at a low dosage (≤2%), the reported reduction was typically within 20% (Hover *et al.* 2011; Wong *et al.* 2015). Additionally, a high calcium stearate dosage has been suggested to enhance compressive strength in later life (Quraishi *et al.* 2011; Maryoto *et al.* 2015). For instance, when the curing duration was extended from 28 to 60 days, the compressive strength of concrete containing 3% calcium stearate rose from 22.3 MPa to 37.1 MPa (Quraishi *et al.* 2011). A sufficient quantity of SCMs and calcium stearate can be included in the mixing of concrete. to make up for any strength loss (Maryoto *et al.* 2020). Researchers also discovered that after 28 days, the high-volume fly ash mortar containing a 2% mass fraction of nano-SiO2 had a 33%–48% improvement in compressive strength (Shaikh *et al.* 2014).

4.2 Flexural Strength

The ability of the concrete to tolerate bending is indicated by its flexural strength, sometimes referred to as its modulus of rupture. Researchers investigated the consequences of curing time and waterproofing agent doses on the flexural strength of concrete (Geetha *et al.* 2012). After seven days, the flexural strengths of concrete containing admixtures based on polymers, naphthalene, and melamine increased by 13–33%, 24–42%, and 20–40%, respectively, in contrast to the concrete control sample. According to Birenboim et al., the optimal dosage of graphene oxide for enhancing the flexural strength of cement-based composites was 0.025% (Birenboim *et al.* 2019). Madduru et al. have reported on the flexural strength of self-compacted concrete incorporating liquid paraffin wax (Madduru *et al.* 2020). It has been discovered that paraffin wax enhanced flexural strength by holding onto moisture and encouraging the development of C-S-H gel.

4.3 Tensile Strength

The impact of waterproofing additives on concrete's tensile strength has not been the subject of much investigation. When SCC with liquid paraffin wax was compared to reference concrete, the split tensile strength increased by 25–40% (Tian *et al.* 2022). The application of Yellow River Engineering Consulting (YREC), a hydrophobic additive, increased the tensile strength of concrete by 30% in a different research (Zhang *et al.* 2021a). The optimal proportion of 4% for the YREC addition stimulated the cement's hydration reaction and demonstrated a filling impact on the pores.

5. CONCLUDING REMARKS

In this paper, the concrete waterproofing techniques of integral and surface treatment have been examined and compared. First, the mechanisms underlying several kinds of waterproofing admixtures were examined. Next, a summary was given of how waterproofing admixtures affected the durability and mechanical properties of the concrete. Finally, the challenges and possible paths for the advancement of integral and surface treatment techniques for concrete waterproofing were examined. From this investigation, the following findings can be made:

- Two techniques were employed to produce waterproof concrete: integrated mixing and surface treatment.
- It was discovered that the most popular test in this field of study was water absorption.
- Concrete structures can function better and last longer if surface treatments are used to stop hostile substances from penetrating. The mechanism divides agents for surface treatment into four categories: hydrophobic impregnation, pore-blocking surface treatments, surface coating, and multifunctional surface treatments.
- Even though the silane/siloxane and organic coating mechanisms are understood, more experimental research on the coating of polymer nanocomposite and pore blocking treatment is required.

- Concrete's water permeability can be decreased by most surface treatments. The impact of polymer coatings was the most notable among all surface treatments whose effects on water absorption have been assessed. Without the need for hydrostatic pressure, hydrophobic impregnations like silane and siloxane can stop water intrusion.

- The addition of nanocomposites may enhance the chloride resistance-promoting properties of conventional polymer coatings. Furthermore, there is contradictory reporting on the effects of silane and sodium silicate. Polymer coatings remained more effective than previous treatment methods for carbonation retardation.

- Concrete strength is typically decreased by water repellents; this is particularly true of products containing silane or siloxane. A sufficient quantity of densifiers, such as additional cementitious ingredients, can be included in the mixing of concrete to make up for the strength loss.

- Waterproofing additives have been shown to reduce concrete's water absorption by up to 80%, according to research findings. They also mentioned that integral waterproof concrete had less chloride penetration.

- The inclusion of waterproofing admixtures can increase its resistance to freeze-thaw cycles and carbonation.

The distinctions between integral and surface waterproofing methods for concrete and their effects on various concrete properties have not been extensively studied by previous researchers. This review demonstrates how concrete structures and infrastructure may be made more durable and have a longer service life by using integral waterproofing admixtures and surface treatments. To put recently developed surface treatments, such as polymer/clay nanocomposite coating, and epoxy resin modification, into practice, further research is needed to fully understand how well they operate. Further investigation is necessary to create affordable and efficient waterproofing admixtures. In the interim, appropriate protocols for sample preparation and waterproofing admixture efficacy assessment must be established. It's critical to investigate the environmental consequences and toxicity of waterproofing admixtures. Given the large range of waterproofing admixtures available and their benefits based on life cycle evaluation. Further, the study is necessary to completely comprehend the impact of various admixtures on tensile strength and flexural strength of concrete. Therefore, more investigation is needed to evaluate, using life cycle assessment, the extended advantages of employing integral and surface waterproof concrete.

FUNDING

This research received no specific grant from any funding agency in the public, commercial or not-for profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

COPYRIGHT

REFERENCES

Abdou, M. I., Abuseda, H., Upgrading offshore pipelines concrete coated by silica fume additive against aggressive mechanical laying and environmental impact, *Egypt. J. Pet.* 25(2), 193–199 (2016). https://doi.org/10.1016/j.ejpe.2015.04.004

Afshar, A., Jahandari, S., Rasekh, H., Shariati, M., Afshar, A., Shokrgozar, A., Corrosion resistance evaluation of rebars with various primers and coatings in concrete modified with different additives, *Constr. Build. Mater.* 262, 120034 (2020). https://doi.org/10.1016/j.conbuildmat.2020.120034

Aguiar, J. B., Júnior, C., Carbonation of surface protected concrete, *Constr. Build. Mater.* 49, 478–483 (2013). https://doi.org/10.1016/j.conbuildmat.2013.08.058

Al-Kheetan, M. J., Rahman, M. M., Integration of Anhydrous Sodium Acetate (ASAc) into Concrete Pavement for Protection against Harmful Impact of Deicing Salt, *Jom* 71(12), 4899–4909 (2019). https://doi.org/10.1007/s11837-019-03624-3

Al-Kheetan, M. J., Rahman, M. M., Chamberlain, D. A., Development of hydrophobic concrete by adding dual-crystalline admixture at mixing stage, *Struct. Concr.* 19(5), 1504–1511 (2018). https://doi.org/10.1002/suco.201700254

Al-Kheetan, M. J., Rahman, M. M., Ghaffar, S. H., Al-Tarawneh, M., Jweihan, Y. S., Comprehensive investigation of the long-term performance of internally integrated concrete pavement with sodium acetate, *Results Eng.* 6(January), 100110 (2020). https://doi.org/10.1016/j.rineng.2020.100110

Al-Rashed, R., Al-Jabari, M., Multi-crystallization enhancer for concrete waterproofing by pore blocking, *Constr. Build. Mater.* 272, 121668 (2021). https://doi.org/10.1016/j.conbuildmat.2020.121668

Almusallam, A. A., Khan, F. M., Dulaijan, S. U., Al-Amoudi, O. S. B., Effectiveness of surface coatings in improving concrete durability, *Cem. Concr. Compos.* 25(4-5 SPEC), 473–481 (2003). https://doi.org/10.1016/S0958-9465(02)00087-2

Amidi, S., Wang, J., Surface treatment of concrete bricks using calcium carbonate precipitation, *Constr. Build. Mater.* 80, 273–278 (2015). https://doi.org/10.1016/j.conbuildmat.2015.02.001

Arbi, K., Nedeljković, M., Zuo, Y., Ye, G., A Review on the Durability of Alkali-Activated Fly Ash/Slag Systems: Advances, Issues, and Perspectives, *Ind. Eng. Chem. Res.* 55(19), 5439–5453 (2016). https://doi.org/10.1021/acs.iecr.6b00559

Bader, T., Lackner, R., Acrylic surface treatment applied to architectural High-Performance Concrete (HPC): Identification of potential pitfalls on the way to long-lasting protection, *Constr. Build. Mater.* 237, 117415 (2020). https://doi.org/10.1016/j.conbuildmat.2019.117415

Bader, T., Waldner, B. J., Unterberger, S. H., Lackner, R., On the performance of film formers versus penetrants as water-repellent treatment of High-Performance Concrete (HPC) surfaces, *Constr. Build. Mater.* 203, 481–490 (2019). https://doi.org/10.1016/j.conbuildmat.2019.01.089

Baltazar, L., Santana, J., Lopes, B., Paula Rodrigues, M., Correia, J. R., Surface skin protection of concrete with silicate-based impregnations: Influence of the substrate roughness and moisture, *Constr. Build. Mater.* 70, 191–200 (2014). https://doi.org/10.1016/j.conbuildmat.2014.07.071

Basheer, L., Cleland, D. J., Freeze-thaw resistance of concretes treated with pore liners, *Constr. Build. Mater.* 20(10), 990–998 (2006). https://doi.org/10.1016/j.conbuildmat.2005.06.010

Basheer, P. A. M., Basheer, L., Cleland, D. J., Long, A. E., Surface treatments for concrete: Assessment methods and reported performance, *Constr. Build. Mater.* 11(7–8), 413–429 (1997). https://doi.org/10.1016/S0950-0618(97)00019-6

Batis, G., Pantazopoulou, P., Routoulas, A., Corrosion protection investigation of reinforcement by inorganic coating in the presence of alkanolamine-based inhibitor, *Cem. Concr. Compos.* 25(3), 371–377 (2003). https://doi.org/10.1016/S0958-9465(02)00061-6

Berndt, M. L., Evaluation of coatings, mortars and mix design for protection of concrete against sulphur oxidising bacteria, *Constr. Build. Mater.* 25(10), 3893–3902 (2011). https://doi.org/10.1016/j.conbuildmat.2011.04.014

Bhogayata, A. C., Arora, N. K., Workability, strength, and durability of concrete containing recycled plastic fibers and styrene-butadiene rubber latex, *Constr. Build. Mater.* 180, 382–395 (2018). https://doi.org/10.1016/j.conbuildmat.2018.05.175

Birenboim, M., Nadiv, R., Alatawna, A., Buzaglo, M., Schahar, G., Lee, J., Kim, G., Peled, A., Regev, O., Reinforcement and workability aspects of graphene-oxide-reinforced cement nanocomposites, *Compos. Part B Eng.* 161(October 2018), 68–76 (2019). https://doi.org/10.1016/j.compositesb.2018.10.030

Cantero, B., Bravo, M., de Brito, J., Sáez del Bosque, I. F., Medina, C., Water transport and shrinkage in concrete made with ground recycled concrete-additioned cement and mixed recycled aggregate, Cem Concr Compos. https://doi.org/10.1016/j.cemconcomp.2021.103957

Cardenas, H. E., Nanomaterials in Concrete: Advances in Protection, Repair, and Upgrade, , 176 (2012).

Cardenas, H. E., Struble, L. J., Modeling Electrokinetic Nanoparticle Penetration for Permeability Reduction of Hardened Cement Paste, *J. Mater. Civ. Eng.* 20(11), 683–691 (2008). https://doi.org/10.1061/(asce)0899-1561(2008)20:11(683)

Carmona-Quiroga, P. M., Martínez-Ramírez, S., Sobrados, I., Blanco-Varela, M. T., Interaction between two anti-graffiti treatments and cement mortar (paste), *Cem. Concr. Res.* 40(5), 723–730 (2010). https://doi.org/10.1016/j.cemconres.2010.01.002

Carrascosa, L. A. M., Zarzuela, R., Badreldin, N., Mosquera, M. J., A Simple, Long-Lasting Treatment for Concrete by Combining Hydrophobic Performance with a Photoinduced Superhydrophilic Surface for Easy Removal of Oil Pollutants, *ACS Appl. Mater. Interfaces* 12(17), 19974–19987 (2020). https://doi.org/10.1021/acsami.0c03576

Chang, C. F., Chen, J. W., The experimental investigation of concrete carbonation depth, *Cem. Concr. Res.* 36(9), 1760–1767 (2006). https://doi.org/10.1016/j.cemconres.2004.07.025

Chen, B., Shao, H., Li, B., Li, Z., Influence of silane on hydration characteristics and mechanical properties of cement paste, Cem Concr Compos. https://doi.org/10.1016/j.cemconcomp.2020.103743

Chen, H., Wu, Y., Xia, H., Jing, B., Zhang, Q., Review of ice-pavement adhesion study and development of hydrophobic surface in pavement deicing, *J. Traffic Transp. Eng. (English Ed.* 5(3), 224–238 (2018a). https://doi.org/10.1016/j.jtte.2018.03.002

Chen, J., Ma, X., Wang, H., Xie, P., Huang, W., Experimental study on anti-icing and deicing performance of polyurethane concrete as road surface layer, *Constr. Build. Mater.* 161, 598–605 (2018b). https://doi.org/10.1016/j.conbuildmat.2017.11.170

Chi, J., Zhang, G., Xie, Q., Ma, C., Zhang, G., High performance epoxy coating with cross-linkable solvent via Diels-Alder reaction for anti-corrosion of concrete, *Prog. Org. Coatings* 139(September 2019), 105473 (2020). https://doi.org/10.1016/j.porgcoat.2019.105473

Choudalakis, G., Gotsis, A. D., Permeability of polymer/clay nanocomposites: A review, *Eur. Polym. J.* 45(4), 967–984 (2009). https://doi.org/10.1016/j.eurpolymj.2009.01.027

Christodoulou, C., Goodier, C. I., Austin, S. A., Webb, J., Glass, G. K., Long-term performance of surface impregnation of reinforced concrete structures with silane, *Constr. Build. Mater.* 48, 708–716 (2013). https://doi.org/10.1016/j.conbuildmat.2013.07.038

Chruściel, J. J., Leśniak, E., Modification of epoxy resins with functional silanes, polysiloxanes, silsesquioxanes, silica and silicates, *Prog. Polym. Sci.* 14, 67–121 (2015). https://doi.org/10.1016/j.progpolymsci.2014.08.001

Courard, L., Zhao, Z., Michel, F., Influence of hydrophobic product nature and concentration on carbonation resistance of cultural heritage concrete buildings, *Cem. Concr. Compos.* 115(July 2020), 1–11 (2021). https://doi.org/10.1016/j.cemconcomp.2020.103860

Dai, J. G., Akira, Y., Wittmann, F. H., Yokota, H., Zhang, P., Water repellent surface impregnation for extension of service life of reinforced concrete structures in marine environments: The role of cracks, *Cem. Concr. Compos.* 32(2), 101–109 (2010). https://doi.org/10.1016/j.cemconcomp.2009.11.001

Dang, Y., Xie, N., Kessel, A., McVey, E., Pace, A., Shi, X., Accelerated laboratory evaluation of surface treatments for protecting concrete bridge decks from salt scaling, *Constr. Build. Mater.* 55, 128–135 (2014). https://doi.org/10.1016/j.conbuildmat.2014.01.014

De Muynck, W., De Belie, N., Verstraete, W., Effectiveness of admixtures, surface treatments and antimicrobial compounds against biogenic sulfuric acid corrosion of concrete, *Cem. Concr. Compos.* 31(3), 163–170 (2009). https://doi.org/10.1016/j.cemconcomp.2008.12.004

Diamanti, M. V., Brenna, A., Bolzoni, F., Berra, M., Pastore, T., Ormellese, M., Effect of polymer modified cementitious coatings on water and chloride permeability in concrete, *Constr. Build. Mater.* 49(November 2017), 720–728 (2013). https://doi.org/10.1016/j.conbuildmat.2013.08.050

Drozdov, A. D., De, J., Gupta, R. K., Shah, A. P., Model for anomalous moisture diffusion through a polymer-clay nanocomposite, *J. Polym. Sci. Part B Polym. Phys.* 41(5), 476–492 (2003). https://doi.org/10.1002/polb.10393

Ebrahimi, K., Daiezadeh, M. J., Zakertabrizi, M., Zahmatkesh, F., Habibnejad Korayem, A., A review of the impact of micro- and nanoparticles on freeze-thaw durability of hardened concrete: Mechanism perspective, *Constr. Build. Mater.* 186, 1105–1113 (2018). https://doi.org/10.1016/j.conbuildmat.2018.08.029

Elsener, B., Corrosion of Steel in Concrete, *Mater. Sci. Technol. A Compr. Treat.* 1–2(April 2008), 389–436 (2008). https://doi.org/10.1002/9783527619306.ch17

Faatz, M., Gröhn, F., Wegner, G., Mineralization of calcium carbonate by controlled release of carbonate in aqueous solution, *Mater. Sci. Eng. C* 25(2), 153–159 (2005). https://doi.org/10.1016/j.msec.2005.01.005

Falchi, L., Zendri, E., Müller, U., Fontana, P., The influence of water-repellent admixtures on the behaviour and the effectiveness of Portland limestone cement mortars, *Cem. Concr. Compos.* 59, 107–118 (2015). https://doi.org/10.1016/j.cemconcomp.2015.02.004

Feng, H., Le, H. T. N., Wang, S., Zhang, M. H., Effects of silanes and silane derivatives on cement hydration and mechanical properties of mortars, *Constr. Build. Mater.* 129, 48–60 (2016). https://doi.org/10.1016/j.conbuildmat.2016.11.004

Feng, Z., Wang, F., Xie, T., Ou, J., Xue, M., Li, W., Integral hydrophobic concrete without using silane, *Constr. Build. Mater.* 227, 116678 (2019). https://doi.org/10.1016/j.conbuildmat.2019.116678

Fischer, H., Polymer nanocomposites: From fundamental research to specific applications, *Mater. Sci. Eng. C* 23(6–8), 763–772 (2003). https://doi.org/10.1016/j.msec.2003.09.148

Franzoni, E., Varum, H., Natali, M. E., Bignozzi, M. C., Melo, J., Rocha, L., Pereira, E., Improvement of historic reinforced concrete/mortars by impregnation and electrochemical methods, *Cem. Concr. Compos.* 49, 50–58 (2014). https://doi.org/10.1016/j.cemconcomp.2013.12.013

Geetha, A., Perumal, P., Effect of Waterproofing Admixtures on the Flexural Strength and Corrosion Resistance of Concrete, *J. Inst. Eng. Ser. A* 93(1), 73–78 (2012). https://doi.org/10.1007/s40030-012-0009-4

Glasser, F. P., Marchand, J., Samson, E., Durability of concrete - Degradation phenomena involving detrimental chemical reactions, *Cem. Concr. Res.* 38(2), 226–246 (2008). https://doi.org/10.1016/j.cemconres.2007.09.015

Hackman, I., Hollaway, L., Epoxy-layered silicate nanocomposites in civil engineering, *Compos. Part A Appl. Sci. Manuf.* 37(8), 1161–1170 (2006). https://doi.org/10.1016/j.compositesa.2005.05.027

Hinder, S. J., Lowe, C., Maxted, J. T., Perruchot, C., Watts, J. F., Intercoat adhesion failure in a multilayer organic coating system: An X-ray photoelectron spectroscopy study, *Prog. Org. Coatings* 54(1), 20–27 (2005). https://doi.org/10.1016/j.porgcoat.2005.03.012

Hou, P., Cheng, X., Qian, J., Shah, S. P., Effects and mechanisms of surface treatment of hardened cement-based materials with colloidal nanoSiO2 and its precursor, *Constr. Build. Mater.* 53, 66–73 (2014). https://doi.org/10.1016/j.conbuildmat.2013.11.062

Hou, P., Cheng, X., Qian, J., Zhang, R., Cao, W., Shah, S. P., Characteristics of surface-treatment of nano-SiO2 on the transport properties of hardened cement pastes with different water-to-cement ratios, *Cem. Concr. Compos.* 55, 26–33 (2015). https://doi.org/10.1016/j.cemconcomp.2014.07.022

Hover, K. C., The influence of water on the performance of concrete, *Constr. Build. Mater.* 25(7), 3003–3013 (2011). https://doi.org/10.1016/j.conbuildmat.2011.01.010

Hu, C., Kim, J. K., Epoxy-organoclay nanocomposites: Morphology, moisture absorption behavior and thermo-mechanical properties, *Compos. Interfaces* 12(3–4), 271–289 (2005). https://doi.org/10.1163/1568554053971597

Jahandari, S., Tao, Z., Alim, M. A., Li, W., Integral waterproof concrete: A comprehensproof concreteive review, *J. Build. Eng.* 78(September), 107718 (2023). https://doi.org/10.1016/j.jobe.2023.107718

Jia, L., Shi, C., Pan, X., Zhang, J., Wu, L., Effects of inorganic surface treatment on water permeability of cement-based materials, *Cem. Concr. Compos.* 67, 85–92 (2016). https://doi.org/10.1016/j.cemconcomp.2016.01.002

Jiang, L., Xue, X., Zhang, W., Yang, J., Zhang, H., Li, Y., Zhang, R., Zhang, Z., Xu, L., Qu, J., Song, J., Qin, J., The investigation of factors affecting the water impermeability of inorganic sodium silicate-based concrete sealers, *Constr. Build. Mater.* 93, 729–736 (2015). https://doi.org/10.1016/j.conbuildmat.2015.06.001

Johannesson, B., Utgenannt, P., Microstructural changes caused by carbonation of cement mortar, *Cem. Concr. Res.* 31(6), 925–931 (2001). https://doi.org/10.1016/S0008-8846(01)00498-7

Jones, M. R., Dhir, R. K., Gill, J. P., Concrete surface treatment: Effect of exposure temperature on chloride diffusion resistance, *Cem. Concr. Res.* 25(1), 197–208 (1995). https://doi.org/10.1016/0008-8846(94)00127-K

Kim, E. K., Won, J., Do, J. young, Kim, S. D., Kang, Y. S., Effects of silica nanoparticle and GPTMS addition on TEOS-based stone consolidants, *J. Cult. Herit.* 10(2), 214–221 (2009). https://doi.org/10.1016/j.culher.2008.07.008

Kim, J., HU, C., WOO, R., SHAM, M., Moisture barrier characteristics of organoclay?epoxy nanocomposites, *Compos. Sci. Technol.* 65(5), 805–813 (2005). https://doi.org/10.1016/j.compscitech.2004.10.014

Kojima, Y., Usuki, A., Kawasumi, M., Okada, A., Fukushima, Y., Kurauchi, T., Kamigaito, O., Mechanical properties of nylon 6-clay hybrid, *J. Mater. Res.* 8(5), 1185–1189 (1993). https://doi.org/10.1557/JMR.1993.1185

Kong, X. M., Liu, H., Lu, Z. B., Wang, D. M., The influence of silanes on hydration and strength development of cementitious systems, *Cem. Concr. Res.* 67, 168–178 (2015). https://doi.org/10.1016/j.cemconres.2014.10.008

Kumar, A. P., Depan, D., Singh Tomer, N., Singh, R. P., Nanoscale particles for polymer degradation and stabilization-Trends and future perspectives, *Prog. Polym. Sci.* 34(6), 479–515 (2009). https://doi.org/10.1016/j.progpolymsci.2009.01.002

Leung, C. K. Y., Zhu, H.-G., Kim, J.-K., Woo, R. S. C., Use of Polymer/Organoclay Nanocomposite Surface Treatment as Water/Ion Barrier for Concrete, *J. Mater. Civ. Eng.* 20(7), 484–492 (2008). https://doi.org/10.1061/(asce)0899-1561(2008)20:7(484)

Li, G., Huang, X., Lin, J., Jiang, X., Zhang, X., Activated chemicals of cementitious capillary crystalline waterproofing materials and their self-healing behaviour, *Constr. Build. Mater.* 200, 36–45 (2019). https://doi.org/10.1016/j.conbuildmat.2018.12.093

Li, K., Wang, Y., Zhang, X., Wu, J., Wang, X., Zhang, A., Multifunctional magnesium oxychloride based composite with stable superhydrophobicity, self-luminescence and reusability, Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2021.122978

Liu, J., Vipulanandan, C., Evaluating a polymer concrete coating for protecting non-metallic underground facilities from sulfuric acid attack, *Tunn. Undergr. Sp. Technol.* 16(4), 311–321 (2001). https://doi.org/10.1016/S0886-7798(01)00053-0

Liu, Z., Hansen, W., Effect of hydrophobic surface treatment on freeze-thaw durability of concrete, *Cem. Concr. Compos.* 69, 49–60 (2016). https://doi.org/10.1016/j.cemconcomp.2016.03.001

Luan, Y., Asamoto, S., Experimental study on mortar with the addition of hydrophobic silicone oil for water absorption, strength, and shrinkage, *Constr. Build. Mater.* 367, 130323 (2023). https://doi.org/10.1016/j.conbuildmat.2023.130323

Madduru, S. R. C., Shaik, K. S., Velivela, R., Karri, V. K., Hydrophilic and hydrophobic chemicals as self curing agents in self compacting concrete, *J. Build. Eng.* 28(May 2019), 101008 (2020). https://doi.org/10.1016/j.jobe.2019.101008

Maggana, C., Pissis, P., Water sorption and diffusion studies in an epoxy resin system, *J. Polym. Sci. Part B Polym. Phys.* 37(11), 1165–1182 (1999). https://doi.org/10.1002/(SICI)1099-0488(19990601)37:11<1165::AID-POLB11>3.0.CO;2-E

Manoudis, P., Papadopoulou, S., Karapanagiotis, I., Tsakalof, A., Zuburtikudis, I., Panayiotou, C., Polymer-Silica nanoparticles composite films as protective coatings for stone-based monuments, *J. Phys. Conf. Ser.* 61(1), 1361–1365 (2007). https://doi.org/10.1088/1742-6596/61/1/269

Maravelaki-Kalaitzaki, P., Kallithrakas-Kontos, N., Agioutantis, Z., Maurigiannakis, S., Korakaki, D., A comparative study of porous limestones treated with silicon-based strengthening agents, *Prog. Org. Coatings* 62(1), 49–60 (2008). https://doi.org/10.1016/j.porgcoat.2007.09.020

Maryoto, A., Improving microstructures of concrete using Ca(C18H35O2)2, *Procedia Eng.* 125, 631–637 (2015). https://doi.org/10.1016/j.proeng.2015.11.086

Maryoto, A., Gan, B. S., Hermanto, N. I. S., Setijadi, R., Effect of calcium stearate in the mechanical and physical properties of concrete with pcc and fly ash as binders, Materials (Basel). https://doi.org/10.3390/ma13061394

Matziaris, K., Stefanidou, M., Karagiannis, G., Impregnation and superhydrophobicity of coated porous low-fired clay building materials, *Prog. Org. Coatings* 72(1–2), 181–192 (2011). https://doi.org/10.1016/j.porgcoat.2011.03.012

Miliani, C., Velo-Simpson, M. L., Scherer, G. W., Particle-modified consolidants: A study on the effect of particles on sol-gel properties and consolidation effectiveness, *J. Cult. Herit.* 8(1), 1–6 (2007). https://doi.org/10.1016/j.culher.2006.10.002

Mohammed, A., Sanjayan, J. G., Duan, W. H., Nazari, A., Incorporating graphene oxide in cement composites: A study of transport properties, *Constr. Build. Mater.* 84, 341–347 (2015). https://doi.org/10.1016/j.conbuildmat.2015.01.083

Moloney, A. C., Kausch, H. H., Kaiser, T., Beer, H. R., Parameters determining the strength and toughness of particulate filled epoxide resins, *J. Mater. Sci.* 22(2), 381–393 (1987). https://doi.org/10.1007/BF01160743

Mosquera, M. J., De Los Santos, D. M., Rivas, T., Sanmartín, P., Silva, B., New nanomaterials for protecting and consolidating stone, *J. Nano Res.* 8(11), 1–12 (2009). https://doi.org/10.4028/www.scientific.net/JNanoR.8.1

Namoulniara, K., Mahieux, P. Y., Lux, J., Aït-Mokhtar, A., Turcry, P., Efficiency of water repellent surface treatment: Experiments on low performance concrete and numerical investigation with pore network model, *Constr. Build. Mater.* 227, 116638 (2019). https://doi.org/10.1016/j.conbuildmat.2019.08.019

Nemati Chari, M., Naseroleslami, R., Shekarchi, M., The impact of calcium stearate on characteristics of concrete, *Asian J. Civ. Eng.* 20(7), 1007–1020 (2019). https://doi.org/10.1007/s42107-019-00161-x

Orlikowski, J., Cebulski, S., Darowicki, K., Electrochemical investigations of conductive coatings applied as anodes in cathodic protection of reinforced concrete, *Cem. Concr. Compos.* 26(6), 721–728 (2004). https://doi.org/10.1016/S0958-9465(03)00105-7

Otsuki, N., Miyazato, S., Yodsudjai, W., Influence of Recycled Aggregate on Interfacial Transition Zone, Strength, Chloride Penetration and Carbonation of Concrete, *J. Mater. Civ. Eng.* 15(5), 443–451 (2003). https://doi.org/10.1061/(ASCE)0899-1561(2003)15:5(443)

Pan, X., Shi, C., Jia, L., Zhang, J., and Wu, L., Effect of Inorganic Surface Treatment on Air Permeability of Cement-Based Materials, *Journal of Materials in Civil Engineering*, 28(3), 1–8 (2016). https://doi.org/10.1061/(asce)mt.1943-5533.0001424

Pan, X., Shi, Z., Shi, C., Ling, T. C., Li, N., A review on concrete surface treatment Part I: Types and mechanisms, *Constr. Build. Mater.* 132, 578–590 (2017). https://doi.org/10.1016/j.conbuildmat.2016.12.025

Papadakis, V. G., Effect of supplementary cementing materials on concrete resistance against carbonation and chloride ingress, *Cem. Concr. Res.* 30(2), 291–299 (2000). https://doi.org/10.1016/S0008-8846(99)00249-5

Pavlidou, S., Papaspyrides, C. D., A review on polymer-layered silicate nanocomposites, *Prog. Polym. Sci.* 33(12), 1119–1198 (2008). https://doi.org/10.1016/j.progpolymsci.2008.07.008

Pérez, C., Collazo, A., Izquierdo, M., Merino, P., Nóvoa, X. R., Characterisation of the barrier properties of different paint systems. Part II. Non-ideal diffusion and water uptake kinetics, *Prog. Org. Coatings* 37(3), 169–177 (1999). https://doi.org/10.1016/S0300-9440(99)00073-9

Perrin, F. X., Merlatti, C., Aragon, E., Margaillan, A., Degradation study of polymer coating: Improvement in coating weatherability testing and coating failure prediction, *Prog. Org. Coatings* 64(4), 466–473 (2009). https://doi.org/10.1016/j.porgcoat.2008.08.015

Petcherdchoo, A., Pseudo-coating model for predicting chloride diffusion into surface-coated concrete in tidal zone: Time-dependent approach, *Cem. Concr. Compos.* 74, 88–99 (2016). https://doi.org/10.1016/j.cemconcomp.2016.08.009

Pigino, B., Leemann, A., Franzoni, E., Lura, P., Ethyl silicate for surface treatment of concrete - Part II: Characteristics and performance, *Cem. Concr. Compos.* 34(3), 313–321 (2012). https://doi.org/10.1016/j.cemconcomp.2011.11.021

Qu, Z., Guo, S., Zheng, Y., Giakoumatos, E. C., Yu, Q., Voets, I. K., A simple method to create hydrophobic mortar using bacteria grown in liquid cultures, *Constr. Build. Mater.* 297, 123744 (2021). https://doi.org/10.1016/j.conbuildmat.2021.123744

Quraishi, M. A., Kumar, V., Abhilash, P. P., Singh, B. N., Calcium stearate: A green corrosion inhibitor for steel in concrete environment, *J. Mater. Environ. Sci.* 2(4), 365–372 (2011).

Ramli, M., Tabassi, A. A., Hoe, K. W., Porosity, pore structure and water absorption of polymer-modified mortars: An experimental study under different curing conditions, *Compos. Part B Eng.* 55, 221–233 (2013). https://doi.org/10.1016/j.compositesb.2013.06.022

Ruan, S., Chen, S., Lu, J., Zeng, Q., Liu, Y., Yan, D., Waterproof geopolymer composites modified by hydrophobic particles and polydimethylsiloxane, *Compos. Part B Eng.* 237, 109865 (2022). https://doi.org/10.1016/j.compositesb.2022.109865

Russo, G. M., Simon, G. P., Incarnato, L., Correlation between rheological, mechanical, and barrier properties in new copolyamide-based nanocomposite films, *Macromolecules* 39(11), 3855–3864 (2006). https://doi.org/10.1021/ma052178h

Sakai, E., Sugita, J., Composite mechanism of polymer modified cement, *Cem. Concr. Res.* 25(1), 127–135 (1995). https://doi.org/10.1016/0008-8846(94)00120-N

Sandrolini, F., Franzoni, E., Pigino, B., Ethyl silicate for surface treatment of concrete - Part I: Pozzolanic effect of ethyl silicate, *Cem. Concr. Compos.* 34(3), 306–312 (2012). https://doi.org/10.1016/j.cemconcomp.2011.12.003

Scarfato, P., Di Maio, L., Fariello, M. L., Russo, P., Incarnato, L., Preparation and evaluation of polymer/clay nanocomposite surface treatments for concrete durability enhancement, *Cem. Concr. Compos.* 34(3), 297–305 (2012). https://doi.org/10.1016/j.cemconcomp.2011.11.006

Scherer, G. W., Wheeler, G. S., Silicate consolidants for stone, *Key Eng. Mater.* 391, 1–25 (2009). https://doi.org/10.4028/www.scientific.net/kem.391.1

Shaikh, F. U. A., Supit, S. W. M., Sarker, P. K., A study on the effect of nano silica on compressive strength of high volume fly ash mortars and concretes, *Mater. Des.* 60, 433–442 (2014). https://doi.org/10.1016/j.matdes.2014.04.025

Shen, C. H., Springer, G. S., Moisture Absorption and Desorption of Composite Materials, *J. Compos. Mater.* 10(1), 2–20 (1976). https://doi.org/10.1177/002199837601000101

Shi, Z., Wang, Q., Li, X., Lei, L., Qu, L., Mao, J., Zhang, H., Utilization of super-hydrophobic steel slag in mortar to improve water repellency and corrosion resistance, *J. Clean. Prod.* 341, 130783 (2022). https://doi.org/10.1016/j.jclepro.2022.130783

Singh, L. P., Karade, S. R., Bhattacharyya, S. K., Yousuf, M. M., Ahalawat, S., Beneficial role of nanosilica in cement based materials - A review, *Constr. Build. Mater.* 47, 1069–1077 (2013). https://doi.org/10.1016/j.conbuildmat.2013.05.052

Sinha Ray, S., Okamoto, M., Polymer/layered silicate nanocomposites: A review from preparation to processing, *Prog. Polym. Sci.* 28(11), 1539–1641 (2003). https://doi.org/10.1016/j.progpolymsci.2003.08.002

Sivasankar, A., Arul Xavier Stango, S., Vedalakshmi, R., Quantitative estimation on delaying of onset of corrosion of rebar in surface treated concrete using sealers, *Ain Shams Eng. J.* 4(4), 615–623 (2013). https://doi.org/10.1016/j.asej.2013.01.007

Song, Q., Wang, Q., Xu, S., Mao, J., Li, X., Zhao, Y., Properties of water-repellent concrete mortar containing superhydrophobic oyster shell powder, *Constr. Build. Mater.* 337, 127423 (2022). https://doi.org/10.1016/j.conbuildmat.2022.127423

Song, X. F., Wei, J. F., He, T. S., A novel method to improve sulfate resistance of concrete by surface treatment with superabsorbent resin synthesised in situ, *Mag. Concr. Res.* 60(1), 49–55 (2008). https://doi.org/10.1680/macr.2007.00051

Sørensen, P. A., Kiil, S., Dam-Johansen, K., Weinell, C. E., Anticorrosive coatings: A review, *J. Coatings Technol. Res.* 6(2), 135–176 (2009). https://doi.org/10.1007/s11998-008-9144-2

Suleiman, A. R., Soliman, A. M., Nehdi, M. L., Effect of surface treatment on durability of concrete exposed to physical sulfate attack, *Constr. Build. Mater.* 73, 674–681 (2014). https://doi.org/10.1016/j.conbuildmat.2014.10.006

Szymańska, A., Dutkiewicz, M., Maciejewski, H., Palacz, M., Simple and effective hydrophobic impregnation of concrete with functionalized polybutadienes, *Constr. Build. Mater.* 315, 125624 (2022). https://doi.org/10.1016/j.conbuildmat.2021.125624

Teng, L. W., Huang, R., Chen, J., Cheng, A., Hsu, H. M., A study of crystalline mechanism of penetration sealer materials, *Materials (Basel).* 7(1), 399–412 (2014). https://doi.org/10.3390/ma7010399

Tian, L., Qiu, L. chao, Preparation and properties of integrally hydrophobic self-compacting rubberized concrete, *Constr. Build. Mater.* 338, 127641 (2022). https://doi.org/10.1016/J.CONBUILDMAT.2022.127641

Tibbetts, C. M., Paris, J. M., Ferraro, C. C., Riding, K. A., Townsend, T. G., Relating water permeability to electrical resistivity and chloride penetrability of concrete containing different supplementary cementitious materials, *Cem. Concr. Compos.* 107(April 2019), 103491 (2020). https://doi.org/10.1016/j.cemconcomp.2019.103491

Tittarelli, F., Moriconi, G., The effect of silane-based hydrophobic admixture on corrosion of galvanized reinforcing steel in concrete, *Corros. Sci.* 52(9), 2958–2963 (2010). https://doi.org/10.1016/j.corsci.2010.05.008

Tittarelli, F., Moriconi, G., Comparison between surface and bulk hydrophobic treatment against corrosion of galvanized reinforcing steel in concrete, *Cem. Concr. Res.* 41(6), 609–614 (2011). https://doi.org/10.1016/j.cemconres.2011.03.011

Toutanji, H. A., Choi, H., Wong, D., Gilbert, J. A., Alldredge, D. J., Applying a polyurea coating to high-performance organic cementitious materials, *Constr. Build. Mater.* 38, 1170–1179 (2013). https://doi.org/10.1016/j.conbuildmat.2012.09.041

Vaidya, S., Allouche, E. N., Electrokinetically deposited coating for increasing the service life of partially deteriorated concrete sewers, *Constr. Build. Mater.* 24(11), 2164–2170 (2010). https://doi.org/10.1016/j.conbuildmat.2010.04.042

VanLandingham, M. R., Eduljee, R. F., Gillespie, J. W., Moisture Diffusion in Epoxy Systems, *J. Appl. Polym. Sci.* 71(5), 787–798 (1999). https://doi.org/10.1002/(SICI)1097-4628(19990131)71:5<787::AID-APP12>3.0.CO;2-A

Vipulanandan, C., Liu, J., Performance of polyurethane-coated concrete in sewer environment, *Cem. Concr. Res.* 35(9), 1754–1763 (2005). https://doi.org/10.1016/j.cemconres.2004.10.033

Vipulanandan, C., Liu, J., Glass-fiber mat-reinforced epoxy coating for concrete in sulfuric acid environment, *Cem. Concr. Res.* 32(2), 205–210 (2002). https://doi.org/10.1016/S0008-8846(01)00660-3

Wang, D., Shi, C., Wu, Z., Xiao, J., Huang, Z., Fang, Z., A review on ultra high performance concrete: Part II. Hydration, microstructure and properties, *Constr. Build. Mater.* 96, 368–377 (2015). https://doi.org/10.1016/j.conbuildmat.2015.08.095

Wang, F., Lei, S., Ou, J., Li, W., Effect of PDMS on the waterproofing performance and corrosion resistance of cement mortar, Appl Surf Sci. https://doi.org/10.1016/j.apsusc.2019.145016

Wang, M., Wang, Q., Mao, J., Xu, S., Shi, Z., Study on water-repellent and corrosion-resistant properties of cement mortar using superhydrophobic iron ore tailings, *J. Build. Eng.* 62, 105360 (2022). https://doi.org/10.1016/j.jobe.2022.105360

Wathiq Hammodat, W., Investigate road performance using polymer modified concrete, *Mater. Today Proc.* 42(February), 2089–2094 (2021). https://doi.org/10.1016/j.matpr.2020.12.290

Wong, H. S., Barakat, R., Alhilali, A., Saleh, M., Cheeseman, C. R., Hydrophobic concrete using waste paper sludge ash, *Cem. Concr. Res.* 70, 9–20 (2015). https://doi.org/10.1016/j.cemconres.2015.01.005

Woo, R. S. C., Chen, Y., Zhu, H., Li, J., Kim, J.-K., Leung, C. K. Y., Environmental degradation of epoxy–organoclay nanocomposites due to UV exposure. Part I: Photo-degradation, *Compos. Sci. Technol.* 67(15–16), 3448–3456 (2007). https://doi.org/10.1016/j.compscitech.2007.03.004

Woo, R. S. C., Zhu, H., Chow, M. M. K., Leung, C. K. Y., Kim, J. K., Barrier performance of silane-clay nanocomposite coatings on concrete structure, *Compos. Sci. Technol.* 68(14), 2828–2836 (2008a). https://doi.org/10.1016/j.compscitech.2007.10.028

Woo, R. S. C., Zhu, H., Leung, C. K. Y., Kim, J. K., Environmental degradation of epoxy-organoclay nanocomposites due to UV exposure: Part II residual mechanical properties, *Compos. Sci. Technol.* 68(9), 2149–2155 (2008b). https://doi.org/10.1016/j.compscitech.2008.03.020

Wu, H., Torabian Isfahani, F., Jin, W., Xu, C., Redaelli, E., Bertolini, L., Modification of properties of reinforced concrete through nanoalumina electrokinetic treatment, *Constr. Build. Mater.* 126, 857–867 (2016). https://doi.org/10.1016/j.conbuildmat.2016.09.098

Wu, Y., Dong, L., Shu, X., Yang, Y., She, W., Ran, Q., A review on recent advances in the fabrication and evaluation of superhydrophobic concrete, *Compos. Part B Eng.* 237(March), 109867 (2022). https://doi.org/10.1016/j.compositesb.2022.109867

Xu, Q., Zhan, S., Xu, B., Yang, H., Qian, X., Ding, X., Effect of isobutyl-triethoxy-silane penetrative protective agent on the carbonation resistance of concrete, *J. Wuhan Univ. Technol. Mater. Sci. Ed.* 31(1), 139–145 (2016). https://doi.org/10.1007/s11595-016-1343-6

Xue, X., Li, Y., Yang, Z., He, Z., Dai, J. G., Xu, L., Zhang, W., A systematic investigation of the waterproofing performance and chloride resistance of a self-developed waterborne silane-based hydrophobic agent for mortar and concrete, *Constr. Build. Mater.* 155, 939–946 (2017). https://doi.org/10.1016/j.conbuildmat.2017.08.042

Yang, X. F., Tallman, D. E., Bierwagen, G. P., Croll, S. G., Rohlik, S., Blistering and degradation of polyurethane coatings under different accelerated weathering tests, *Polym. Degrad. Stab.* 77(1), 103–109 (2002). https://doi.org/10.1016/S0141-3910(02)00085-X

Yin, B., Xu, T., Hou, D., Zhao, E., Hua, X., Han, K., Zhang, Y., Zhang, J., Superhydrophobic anticorrosive coating for concrete through in-situ bionic induction and gradient mineralization, *Constr. Build. Mater.* 257, 119510 (2020). https://doi.org/10.1016/j.conbuildmat.2020.119510

Zhang, B., Li, Q., Ma, R., Niu, X., Yang, L., Hu, Y., Zhang, J., The influence of a novel hydrophobic agent on the internal defect and multi-scale pore structure of concrete, *Materials (Basel).* 14(3), 1–17 (2021a). https://doi.org/10.3390/ma14030609

Zhang, B., Li, Q., Niu, X., Yang, L., Hu, Y., Zhang, J., Influence of a novel hydrophobic agent on freeze–thaw resistance and microstructure of concrete, Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2020.121294

Zhang, C., Zhang, S., Yu, J., Kong, X., Water absorption behavior of hydrophobized concrete using silane emulsion as admixture, *Cem. Concr. Res.* 154, 106738 (2022). https://doi.org/10.1016/j.cemconres.2022.106738

Zhang, Y., Li, S., Zhang, W., Chen, X., Hou, D., Zhao, T., Li, X., Preparation and mechanism of graphene oxide/isobutyltriethoxysilane composite emulsion and its effects on waterproof performance of concrete, *Constr. Build. Mater.* 208, 343–349 (2019). https://doi.org/10.1016/j.conbuildmat.2019.03.015

Zhao, J., Gao, X., Chen, S., Lin, H., Li, Z., Lin, X., Hydrophobic or superhydrophobic modification of cement-based materials: A systematic review, *Compos. Part B Eng.* 243(October 2021), 110104 (2022). https://doi.org/10.1016/j.compositesb.2022.110104

Zhao, Y., Lei, L., Wang, Q., Li, X., Study of superhydrophobic concrete with integral superhydrophobicity and anti-corrosion property, *Case Stud. Constr. Mater.* 18(February), e01899 (2023). https://doi.org/10.1016/j.cscm.2023.e01899

Zhao, Z., Qu, X., Li, J., Application of polymer modified cementitious coatings (PCCs) for impermeability enhancement of concrete, *Constr. Build. Mater.* 249, 118769 (2020). https://doi.org/10.1016/j.conbuildmat.2020.118769

Zheng, H., Li, W., Ma, F., Kong, Q., The effect of a surface-applied corrosion inhibitor on the durability of concrete, *Constr. Build. Mater.* 37, 36–40 (2012). https://doi.org/10.1016/j.conbuildmat.2012.07.007

Zheng, W., Chen, W. G., Feng, T., Li, W. Q., Liu, X. T., Dong, L. L., Fu, Y. Q., Enhancing chloride ion penetration resistance into concrete by using graphene oxide reinforced waterborne epoxy coating, Prog Org Coatings. https://doi.org/10.1016/j.porgcoat.2019.105389

Zhu, H., Li, Q., Ma, R., Yang, L., Hu, Y., Zhang, J., Water-repellent additive that increases concrete cracking resistance in dry curing environments, *Constr. Build. Mater.* 249, 1–10 (2020a). https://doi.org/10.1016/j.conbuildmat.2020.118704

Zhu, J., Liao, K., A facile and low-cost method for preparing robust superhydrophobic cement block, *Mater. Chem. Phys.* 250(April), 123064 (2020b). https://doi.org/10.1016/j.matchemphys.2020.123064

Zhu, Y.-G., Kou, S.-C., Poon, C.-S., Dai, J.-G., Li, Q.-Y., Influence of silane-based water repellent on the durability properties of recycled aggregate concrete, *Cem. Concr. Compos.* 35(1), 32–38 (2013). https://doi.org/10.1016/j.cemconcomp.2012.08.008