Review Article

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

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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. The review discusses 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.

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

1. INTRODUCTION

Water seepage into concrete can cause deterioration and other aesthetic issues that limit the lifespan of concrete constructions. To develop waterproofing additives that prolong the useful life of concrete components, numerous experiments have been conducted. As a result, significant expenses for maintenance 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, 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. The permeability and rate of water absorption of concrete 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). They also examined surface treatment effects and durability performance. Concrete can be protected using a number of different surface treatments. The two types of surface

treatments are inorganic and organic, based on 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).

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)

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 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. The mechanism of integral waterproofing and surface treatment methods will be discussed first. 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.

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).

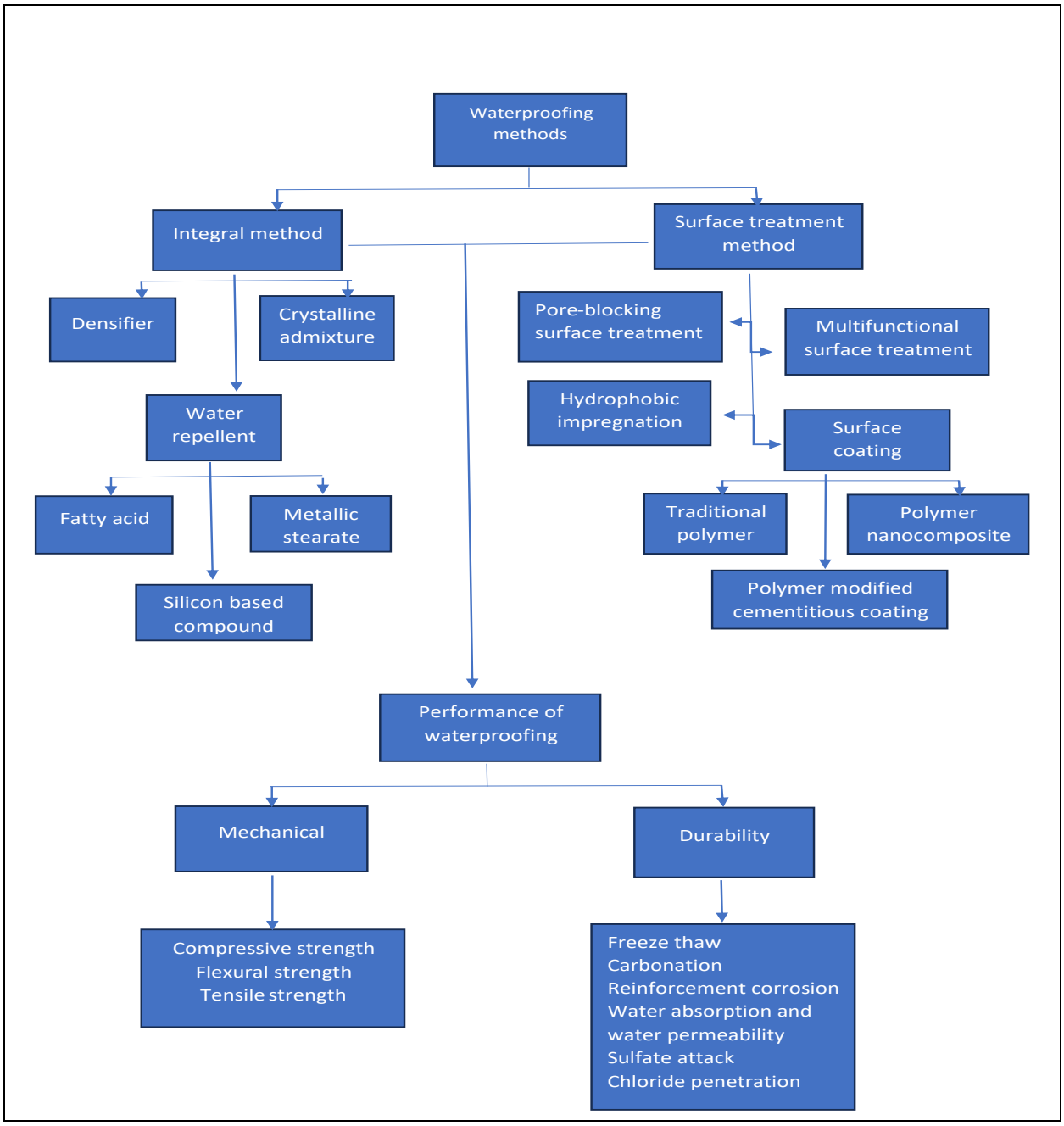


Fig. 1: An overview of waterproofing methods

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 previous 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). The 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. While 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 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, Wang *et al.* (2020) demonstrated that cement mortars treated with polydimethylsiloxane (PDMS) had pore volumes reduced by 7.9% and water absorption reduced by 92.51% (). 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.

Another 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) reported 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

Since 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).

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. The attempt by Cardenas and Struble (2008) 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 formed 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 formed 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).

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 ℃. Applying polymer coatings to concrete therefore requires assessing their diffusion properties at various temperatures. Van Landingham *et al.* (1999) stated 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).



Fig. 2: Acrylic coating

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. Organic polymers such as starch can be employed to create nanocomposite materials as they are inexpensive (Fischer *et al.* 2003).

2.2.4.3 Polymer Modified Cementitious Coatings

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).



Fig. 3: Polymer modified cementitious coating

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 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.

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. 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, it 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 adhesion force of ice 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 to reach the threshold moisture level by delaying the entrance of moisture during the freeze-thaw condition. Additionally, Basheer *et al.* (2006) showed 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 seeping into the porous concrete. This could hasten the corrosion of steel reinforcement 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 passivity of the reinforcement bars (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

A thicker and less porous concrete cover slows down the corrosion process, thereby extending the service life of the reinforced concrete structure (Petcherdchoo *et al.* 2016). According to Basheer *et al.* (1997), surface treatments delay 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) showed 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 another 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.* (2013), who then observed a substantial decrease in the water absorption of the polymer-modified cement mortar 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) revealed that ethyl silicate's efficiency was more noteworthy. 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. Adding PCC (made with 4% silica) decreased concrete's absorption of water by 62.5% (Zhao *et al.* 2020). Waterproof geopolymer composites were developed by combining PDMS, hydrophobic quartz particles, and hydrophobic metakaolin (Ruan *et al.* 2022). The inhibitory effect of hydrophobic particles on water absorption was not as strong as that of PDMS, and that the combination of the two was most efficient. 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-SiO_2 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.* (2019), the optimal dosage of graphene oxide for enhancing the flexural strength of cement-based composites was 0.025%. Madduru *et al.* (2020) reported on the flexural strength of self-compacted concrete incorporating liquid paraffin wax. 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 additive, 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

This review examined and compared integral and surface treatment techniques for concrete waterproofing, focusing on their mechanisms, and their influence on durability and mechanical properties. Waterproof concrete is achieved either through integrated mixing or surface treatment, with water absorption being the most commonly used evaluation method. Surface treatments enhance performance and service life by limiting the ingress of aggressive agents, and include hydrophobic impregnation, pore-blocking treatments, surface coatings, and multifunctional systems. Most surface treatments reduce water permeability, with polymer coatings showing the most significant effect, while hydrophobic agents such as silane and siloxane prevent water ingress without hydrostatic pressure. However, some treatments, particularly water repellents, may reduce concrete strength, which can be compensated by incorporating suitable densifiers.

Waterproofing admixtures can reduce water absorption by up to 80% and improve resistance to chloride penetration, freeze–thaw cycles, and carbonation. Despite these benefits, gaps remain in understanding the comparative performance of integral and surface methods. Emerging treatments such as polymer nanocomposite coatings and epoxy modifications require further validation, along with the development of cost-effective and environmentally safe admixtures. Standardized testing protocols and deeper investigation into long-term performance, including tensile and flexural strength and life cycle impacts, are necessary to fully assess and optimize waterproofing strategies for durable concrete infrastructure.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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