



International Journal of Innovative Research in Science Engineering and Technology (IJIRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)



Impact Factor: 8.699

Volume 14, Issue 5, May 2025

The Application and Progress of Organosilicon Water Repellents in Hydrophobic Treatment of Concrete

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ABSTRACT: With the increasing demand for the durability of concrete structures, organosilicon water repellents have emerged as a new class of waterproofing materials and have been widely used in concrete hydrophobic treatments. This paper reviews the fundamental properties, classifications, and applications of organosilicon water repellents in concrete waterproofing. It focuses on the waterproofing mechanisms of organosilicon compounds such as silanes and siloxanes, and analyzes their performance in enhancing concrete's water resistance, permeability resistance, and freeze-thaw durability. In conjunction with different construction methods, the paper identifies challenges faced in practical applications, including construction techniques and long-term durability. Furthermore, it explores research progress on enhancing waterproofing performance through nanotechnology and composite materials. Finally, it outlines the future development prospects of organosilicon water repellents in the field of concrete waterproofing.

KEYWORDS: Concrete, Organosilicon, Water Repellent, Hydrophobic Treatment

I. INTRODUCTION

Concrete is one of the most widely used construction materials in infrastructure projects such as buildings, roads, and bridges. However, due to its inherent porosity, concrete is highly susceptible to water absorption. Prolonged exposure to moisture or water-rich environments can lead to severe structural deterioration [1]. Firstly, water infiltration can initiate corrosion of the embedded steel reinforcement, thereby compromising both the mechanical strength and long-term durability of the structure [2]. Secondly, the ingress of moisture often results in the formation of microcracks, which not only weakens the structural integrity but also increases maintenance and repair costs. Therefore, improving the waterproofing capacity of concrete structures is critical to ensuring their long-term serviceability and resistance to environmental degradation. Effective waterproofing strategies can create a barrier that significantly minimizes water ingress, thereby reducing risks associated with reinforcement corrosion, crack propagation, and ultimately extending the service life of concrete structures [3]. Additionally, enhanced waterproofing performance contributes to better freeze-thaw resistance by preventing water from freezing and expanding within pores, which is crucial for concrete durability in harsh climatic conditions [4].

Organosilicon materials have garnered significant attention in the construction industry due to their exceptional chemical stability, thermal resistance, UV resistance, and hydrophobicity. Specifically, organosilicon compounds such as silanes and siloxanes have been extensively employed in waterproof coatings, sealants, and protective layers for concrete and masonry [5]. These materials offer promising solutions for enhancing the durability, anti-corrosion properties, and long-term protection of concrete structures [6]. Organosilicon-based water repellents, derived from such compounds, exhibit excellent hydrophobicity. Their waterproofing mechanism lies in the unique structural combination of siloxane backbones and organic functional groups, which enables the formation of a robust hydrophobic film on the concrete surface, effectively preventing water penetration [7–10]. By strongly adhering to the substrate, these water repellents minimize moisture ingress, inhibit reinforcement corrosion, and suppress crack development. Their resistance to UV radiation and aging ensures sustained waterproofing performance even under prolonged exposure to aggressive environmental conditions. Collectively, organosilicon water repellents significantly improve the water resistance and durability of concrete structures.

This review aims to comprehensively assess the application and recent progress of organosilicon water repellents in concrete waterproofing. By evaluating their performance in practical engineering scenarios—including water resistance, durability, and construction techniques—this study further explores emerging trends such as the development of novel composites, performance optimization, and the incorporation of intelligent self-healing technologies.

II. CLASSIFICATION AND FUNDAMENTAL PROPERTIES OF ORGANOSILICON WATER REPELLENTS

Organosilicon water repellents can be broadly categorized based on their chemical structure and functional performance. The most commonly used types in concrete waterproofing applications include silanes, siloxanes, and potassium methylsiliconate. Each class exhibits distinct physicochemical characteristics and waterproofing mechanisms.

2.1 Silane-Based Water Repellents

Silanes, with a general chemical formula of $R-SiH_3$, consist of a silicon atom covalently bonded to organic functional groups such as methyl or ethyl groups. Due to their low molecular weight and high reactivity, silanes can deeply penetrate porous substrates and chemically react with surface hydroxyl groups. This reaction results in the formation of a covalently bonded hydrophobic layer that is both durable and chemically integrated with the substrate. Silanes are particularly effective in enhancing the water resistance and durability of concrete, especially in structures exposed to frequent moisture or aggressive environments.

2.2 Siloxane-Based Water Repellents

Siloxanes are characterized by their $Si-O-Si$ backbone structure, consisting of repeating siloxane units. These compounds exhibit excellent chemical and thermal stability, along with superior resistance to water and ultraviolet (UV) radiation. Unlike silanes, siloxanes typically form a film-like coating on the surface of the substrate, offering long-lasting hydrophobic performance. They are widely applied in the waterproofing of building facades, roofs, and other external surfaces where sustained exposure to weathering occurs.

2.3 Potassium Methylsiliconate-Based Water Repellents

Potassium methylsiliconate (CH_3SiO_3K) is composed of a methyl group ($-CH_3$) and a potassium silicate moiety (SiO_3K). This compound demonstrates good water solubility and substrate penetration, enabling it to significantly enhance the hydrophobicity and corrosion resistance of concrete surfaces. It is commonly used in concrete waterproofing applications to improve surface weatherability, moisture resistance, and overall longevity. Upon application, it reacts with carbon dioxide in the atmosphere to form a water-insoluble hydrophobic film, making it an economical and effective choice for large-scale infrastructure projects.

III. SYNTHESIS METHODS OF ORGANOSILICON WATER REPELLENTS

The synthesis of organosilicon water repellents varies depending on their molecular structure and desired performance characteristics. Commonly used organosilicon water repellents, including silanes, siloxanes, and potassium methylsiliconate, are synthesized through distinct chemical pathways involving hydrolysis, condensation, and functional group modification.

3.1 Synthesis of Silane-Based Water Repellents

Silane-based water repellents are typically synthesized through the functionalization of silanes with organic groups. A common approach involves reacting chlorosilanes with organic alcohols such as methanol to form alkyl-functional silanes. Alternatively, silanization reactions can be employed to introduce functional groups like methyl or ethyl onto the silicon center. During synthesis, chlorosilanes undergo hydrolysis and subsequent condensation in the presence of a solvent, forming oligomeric or polymeric organosilanes. The molecular structure and hydrophobic performance of the resulting products can be precisely tuned by adjusting reaction parameters such as temperature, reaction time, and solvent composition.

3.2 Synthesis of Siloxane-Based Water Repellents

Siloxane water repellents are synthesized via siloxanation reactions, where hydrolyzable silanes react with water or alcohols under acidic or basic catalytic conditions. The hydrolysis of silane precursors leads to the formation of silanol

intermediates, which then undergo condensation to form polysiloxanes with Si–O–Si backbone structures. The resulting organosiloxane polymers exhibit high molecular weight and excellent stability. The use of appropriate catalysts and control over reaction conditions are critical to tailoring the degree of polymerization, cross-linking density, and final hydrophobic performance of the material.

3.3 Synthesis of Potassium Methylsiliconate-Based Water Repellents

Potassium methylsiliconate is typically synthesized by neutralizing methylsilicic acid with a potassium source, such as potassium hydroxide. The process begins with the hydrolysis of methylchlorosilanes (e.g., methyltrichlorosilane) in water or alcohol to yield methylsilicic acid. This intermediate is subsequently reacted with KOH under controlled temperature and pH conditions to produce potassium methylsiliconate. Maintaining optimal reaction parameters is essential to ensure complete neutralization and to obtain a chemically stable product with consistent hydrophobic functionality.

IV. MECHANISMS OF ORGANOSILICON WATER REPELLENTS IN CONCRETE WATERPROOFING

4.1 Interaction Between Water Repellents and Concrete Surfaces

The effectiveness of organosilicon water repellents in concrete waterproofing is fundamentally governed by their interaction with the cementitious matrix. Concrete surfaces are rich in hydroxyl (–OH) and silanol (Si–OH) groups, which serve as reactive sites for the adsorption and chemical bonding of organosilicon molecules. Specifically, the silanol groups in organosilicon compounds undergo condensation reactions with the surface hydroxyls of the cement matrix, resulting in the formation of covalent Si–O–Si bonds. This chemical anchoring enhances the adhesion between the water repellent and the substrate [11]. Concurrently, the repellent forms an insoluble, hydrophobic film on the concrete surface, which acts as a moisture barrier that significantly inhibits water penetration and protects the underlying matrix from degradation [12].

4.2 Water Tightness and Anti-Penetration Mechanisms

Organosilicon water repellents contribute to improved water tightness by modifying the microstructure and surface properties of concrete. By increasing the hydrophobicity of the concrete surface, these agents reduce the adhesion and penetration of water molecules. One of the key effects is an increase in the water contact angle, which alters the wettability of the surface and disrupts capillary absorption pathways. The resultant reduction in surface energy and capillary action, along with the formation of a continuous hydrophobic layer, collectively suppress water ingress through micropores [13,14]. This hydrophobic barrier functions as an effective shield against moisture transport, thereby enhancing the impermeability of concrete, particularly under conditions of high humidity or hydrostatic pressure [15].

4.3 Durability Enhancement and Freeze–Thaw Resistance

Beyond their waterproofing function, organosilicon water repellents significantly enhance the overall durability of concrete, especially its resistance to freeze–thaw cycles [16]. By limiting the ingress of moisture, these treatments reduce the internal water content of the concrete, thereby mitigating the expansive pressure caused by water freezing within pores. Since freezing water can generate stresses that compromise structural integrity, the use of organosilicon repellents markedly improves the freeze–thaw resilience of treated concrete [17–20]. Additionally, reducing moisture ingress helps prevent deleterious reactions such as alkali–aggregate reactions and corrosion of reinforcement, which are commonly triggered by water intrusion. This contributes to long-term structural durability. The hydrophobic surface layer also improves the concrete’s resistance to environmental stressors—including ultraviolet (UV) radiation, acid rain, and chemical attack—thereby delaying surface aging and degradation [21].

V. OVERVIEW OF ORGANOSILICON HYDROPHOBIC TREATMENT METHODS

5.1 Surface Treatment Method

The surface treatment method involves spraying or brushing liquid organosilicon hydrophobic agents onto the surface of concrete, forming a continuous hydrophobic protective film. Its primary advantage lies in its high adaptability during application—it can be directly used in the restoration of existing structures without requiring adjustments to the original concrete mix design. Additionally, small-molecule silanes can rapidly penetrate the surface to form a hydrophobic interface layer within a short period [22, 23]. This method can also be enhanced with functional

composite materials to endow the concrete surface with superhydrophobic or self-cleaning properties, significantly improving resistance to liquid corrosive agents. However, this technique has inherent limitations: The hydrophobic effect is mostly confined to the surface layer and is ineffective in blocking capillary water migration in deeper pores [24]; The organosilicon molecular chains are prone to degradation under prolonged UV exposure [25], leading to a decline in protective performance and necessitating periodic maintenance; Moreover, thorough substrate preparation is required prior to application, as any residual contaminants or microcracks may weaken the interfacial bonding strength between the hydrophobic agent and the concrete matrix.

5.2 Internal Admixture Method

The internal admixture method involves directly incorporating organosilicon hydrophobic agents—either in powder or liquid form—into the concrete mix. Through chemical bonding with cement hydration products, these agents form a uniformly distributed hydrophobic barrier network within the concrete. A key advantage of this method is its deep-penetrating protective mechanism: the hydrophobic agent is evenly distributed throughout the pores and capillaries of the concrete matrix, creating a three-dimensional hydrophobic barrier that significantly inhibits water ingress [26]. When used within a suitable dosage range, the agent is compatible with the mechanical properties of concrete [27, 28], and can further enhance freeze–thaw resistance by reducing pore water saturation [29–31]. Moreover, since its protective function aligns with the lifespan of the concrete, it offers maintenance-free durability over the full service life. However, this technique faces several constraints: Highly active powder-based hydrophobic agents are significantly more expensive than traditional waterproofing materials, posing economic challenges for large-scale application; Even minor deviations in mixing procedures can result in non-uniform dispersion, increasing the risk of localized failure; When overdosed, the agent may encapsulate cement particles, disrupting hydration processes and compromising the workability of the concrete [32].

5.3 Combined Treatment Method

The combined treatment method integrates the internal hydrophobic modification mechanism of the internal admixture method with the surface protective function of the surface treatment method, forming a multi-level synergistic protection system. The internally mixed organosilicon agents establish a continuous hydrophobic network within the concrete, effectively blocking capillary water transport paths. Simultaneously, the superhydrophobic surface coating, applied via spraying, forms a micro-nano textured structure that enhances the surface's resistance to liquid corrosive agents, establishing a graded protective interface from core to surface. The primary strength of this system lies in the spatial coupling of bulk hydrophobicity and surface superhydrophobicity, significantly improving impermeability. Moreover, the material formulations can be customized to withstand extreme conditions such as high salinity marine environments or severe freeze–thaw cycles. Nonetheless, its implementation is limited by multiple technical challenges: The need for material compatibility between the internal admixture and surface coating (e.g., interfacial compatibility between silanes and siloxanes); Increased overall cost due to multi-stage construction; Potential risks such as electrochemical corrosion or ionic migration interference at the interfaces between dissimilar materials. These issues require careful molecular design and process optimization to achieve a balanced and effective protective system.

VI. ADVANCES IN THE APPLICATION OF ORGANOSILICON HYDROPHOBIC AGENTS IN CONCRETE WATERPROOFING

6.1 Applications in the Building Sector

Organosilicon hydrophobic agents are widely employed in building construction to provide waterproof protection for concrete structures, particularly in external walls, roofs, and underground components. Traditional concrete waterproofing methods typically rely on polymer coatings, waterproof membranes, or sealants. In contrast, organosilicon hydrophobic agents penetrate the concrete and form an internal hydrophobic layer, significantly enhancing the impermeability and durability of the material [33–35]. For external wall and roofing protection, these agents form highly weather-resistant hydrophobic coatings that reduce moisture accumulation and slow down the aging of the waterproof layer. In underground structures—such as basements, underground garages, and foundation pits—organosilicon agents infiltrate the concrete's pore structure, creating a stable internal hydrophobic barrier that effectively blocks groundwater infiltration and enhances moisture resistance. Compared to conventional waterproofing materials, organosilicon hydrophobic agents offer superior long-term durability, resisting failure due to temperature fluctuations, UV exposure, or chemical attack. They also maintain the breathability of the concrete, allowing internal moisture to escape and preventing issues such as blistering or peeling of the waterproof layer. Studies have shown that

these agents can significantly reduce water absorption, improve the long-term stability of waterproofing systems, and lower maintenance costs [36].

6.2 Applications in Road and Bridge Engineering

In road and bridge engineering, organosilicon hydrophobic agents are extensively used to prevent moisture intrusion and improve structural durability, particularly in regions with high humidity or complex hydrogeological conditions. Bridge structures are often exposed to rain, high humidity, and chemical agents such as deicing salts, leading to concrete carbonation and reinforcement corrosion. Organosilicon hydrophobic agents, by forming a hydrophobic barrier both on the surface and within the concrete, effectively reduce water penetration, minimize corrosion risk, and delay structural degradation [37]. In tunnel engineering, prolonged exposure to groundwater renders concrete vulnerable to seepage and deterioration. Similarly, in road applications—such as highways and airport runways—concrete pavements are susceptible to freeze–thaw damage and subgrade softening due to rainwater infiltration. Organosilicon hydrophobic agents mitigate these issues by reducing moisture ingress and improving freeze–thaw resistance, thereby extending the service life of roads [38, 39]. In tunnels and other underground works, the agents can penetrate several millimeters to a few centimeters, forming a long-lasting waterproof barrier that reduces maintenance costs and improves operational safety [40, 41]. Overall, the use of organosilicon hydrophobic agents in road and bridge engineering demonstrates excellent water resistance, corrosion protection, and long-term durability, offering reliable protection for infrastructure systems throughout their service life.

VII. CONCLUSION

As a key material for enhancing the waterproofing performance of concrete, organosilicon hydrophobic agents significantly improve concrete's impermeability, durability, and freeze–thaw resistance through the systematic application of surface treatment, internal admixture, and combined treatment methods. The surface treatment method, characterized by its ease of application and rapid effectiveness, is the preferred choice for retrofitting existing structures. However, its protection is limited to shallow depths and may lack long-term stability. The internal admixture method establishes a three-dimensional hydrophobic network within the concrete, providing intrinsic, maintenance-free protection, though its application is constrained by high material costs and sensitivity to mixing procedures. The combined treatment method achieves multi-level waterproofing through a synergistic "bulk–surface" mechanism, and offers customizable solutions for extreme environments, showing promise for multi-scale impermeability and self-healing. However, its comprehensive cost and potential compatibility issues still require optimization. In building, road, and bridge engineering, organosilicon hydrophobic agents effectively suppress moisture intrusion, delay reinforcement corrosion, and significantly reduce maintenance costs, demonstrating strong potential for long-term infrastructure protection.

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