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Research Paper

Review on the Impact of Nanoparticle Additives on Fiber Adhesion in Ultra-High Performance Concrete for Corrosive Traffic Environments

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Abstract

Ultra-high-performance fiber-reinforced concrete (UHPFRC) is a cutting-edge material in traffic and road engineering, combining fibers and cement to deliver exceptional strength and durability. Distinguished by its fine-grained composition, UHPFRC forms microscopic pores that effectively impede the ingress of water, gases, and chlorides. With an optimized mix design, UHPFRC can achieve compressive strengths exceeding 200 MPa and tensile strengths surpassing 20 MPa, along with remarkable tensile performance encompassing both hardening and softening phases. The nanoparticle additives improve the adhesion of fibers. These attributes position UHPFRC as an ideal material for enhancing the stability and longevity of traffic infrastructure components. Despite these advantages, the widespread application of UHPFRC is constrained by the susceptibility of steel fibers to corrosion in wet and aggressive environments. This review article critically evaluates the influence of nanoparticle additives on the adhesion properties of fibers in UHPFRC under corrosive conditions. It addresses the challenges, limitations, and prospective applications of UHPFRC, offering valuable insights for design engineers to accurately estimate the ultimate bearing capacity of UHPFRC structures across diverse environmental settings.

Keywords: Adhesion, High-strength fiber concrete, Nanoparticles, Steel fibers, Corrosive environment

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1. Introduction

In marine environments, the primary factor contributing to the corrosion of reinforced concrete, and the subsequent reduction in its strength and durability, is the infiltration of chloride ions and sulfate attacks on reinforcements. As a result, understanding the mechanisms of corrosion and its detrimental effects on the durability of reinforced concrete structures is of critical importance to researchers, engineers, and concrete technology experts. Extensive studies have been undertaken to investigate corrosion processes and their impacts on the longevity and structural stability of reinforced concrete in harsh environmental conditions.

Given the strategic location of Iran and the presence of the Mazandaran Sea and the Persian Gulf in the north and south of the country, addressing the issue of corrosion and its impact on the durability of reinforced concrete warrants heightened attention and investigation. The placement of vital and strategic structures in marine environments necessitates a comprehensive examination of various aspects related to their durability and stability. The progression of corrosion results in the reduction of the cross-section of reinforcing reinforcements, leading to a decrease in the bond between concrete and reinforcements. Consequently, the stability and safety of the structure are compromised. Raising awareness about the corrosion of reinforced concrete structures and obtaining precise information about the annual budget consumption attributed to damages caused by corrosion prompts government officials, in collaboration with researchers and engineers, to seek solutions for mitigating, delaying, or even preventing this phenomenon. Figure 1 provides illustrative examples of concrete corrosion damage in corrosive environments.

Ultra-high-performance fiber-reinforced concrete (UHPFRC) is a cutting-edge material that has garnered increasing attention in civil engineering, particularly for infrastructure applications exposed to harsh and corrosive environments. Distinguished by its exceptional mechanical properties, including high compressive and tensile strengths, UHPFRC has shown immense potential for improving the durability and longevity of traffic infrastructure, such as bridges, highways, and pavements.

The motivation for this study is rooted in the challenges faced by the widespread adoption of UHPFRC in traffic infrastructure, particularly in environments subjected to aggressive conditions such as high humidity and chloride-rich environments. UHPFRC, despite its exceptional mechanical properties and durability, is hindered by the corrosion susceptibility of steel fibers. Corrosion of these fibers can severely impact the longevity and performance of UHPFRC in critical infrastructure, such as bridges and highways. This study seeks to address these limitations by exploring the role of nanoparticle additives in improving the adhesion properties of fibers in UHPFRC, thereby enhancing its resistance to corrosion. The incorporation of nanoparticles is expected to refine the interfacial bond between fibers and the cementitious matrix, mitigating microstructural defects that contribute to deterioration. By analyzing the mechanical performance, durability, and microstructural characteristics of nanoparticle-enhanced UHPFRC, this research aims to provide a comprehensive understanding of its long-term behavior under aggressive environmental conditions. The insights derived from this study are expected to guide engineers in selecting the most suitable materials and mix designs to optimize the durability of UHPFRC in corrosive traffic environments, ultimately contributing to the development of more resilient and sustainable infrastructure.

Figure 1. Examples of concrete corrosion damage in corrosive environments

2. Recent Advances in Fiber-Reinforced Concrete and Qualitative Comparison with Common Concrete Categories

In recent years, the extensive utilization of UHPFRC has become prevalent, particularly in applications demanding heightened tensile strength and post-cracking ductility. UHPFRC represents a novel concrete class introduced in the last few decades, distinguished by its exceptional strength and durability characteristics. The continuous evolution of UHPFRC has positioned it as one of the most noteworthy concrete materials, featuring unique properties. Figure 2 provides a qualitative juxtaposition of the characteristics of high-strength concrete against other prevalent concrete categories.

A significant advantage of incorporating fibers into UHPFRC is its ability to simplify traditional reinforcement detailing by reducing reinforcement ratios. This is achieved by relying on the fibers' capacity to transfer stresses across cracked surfaces. However, the complex interactions between fibers and concrete mean that the performance of UHPFRC is influenced by various factors, including time-dependent effects such as shrinkage, sustained loading and load history (creep and fatigue), environmental conditions (corrosion), and the interplay of these elements. Despite the potential benefits of fiber-reinforced concrete, particularly in corrosion-prone environments, the lack of comprehensive material models to quantify its long-term performance remains a challenge. Consequently, existing design standards do not yet incorporate the beneficial effects of fibers in addressing long-term durability issues, limiting the full exploitation of this advanced material.

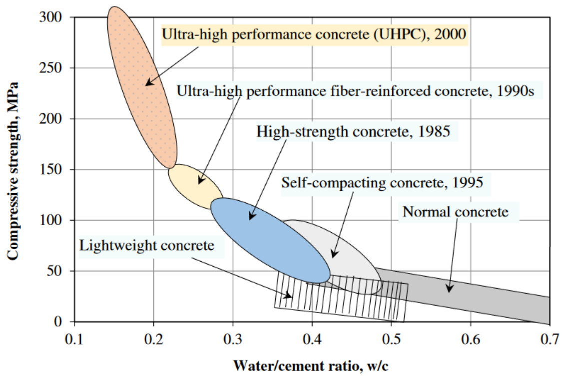


Figure 2. Comparison depicting the compressive strength of UHPFRC in contrast to various grades of concrete

Numerous studies have been undertaken to assess the corrosion resistance of concrete reinforced with steel fibers. For comprehensive guidance in designing experimental work and informing future studies, as well as determining optimal mixing designs for UHPFRC, valuable insights can be gleaned from review studies referenced in [13-15]. A critical observation from these overviews is that tests aimed at quantifying the impact of corrosion have predominantly focused on a relatively narrow range of compressive strengths, typically within the range of 60–70 MPa or exceeding 150 MPa, and with fiber contents up to 2%. Notably, only 29% of the identified tests consider concrete that has experienced cracking before immersion in a corrosive agent. This aspect is of significant importance as the presence of cracks provides a pathway for chloride to ingress more rapidly. Consequently, without pre-existing cracks, there is a risk of obtaining a lower estimate of durability.

Steel fibers are extensively employed in UHPFRC construction owing to their exceptional strength and ductility, enabling UHPFRC to achieve a tensile strength exceeding 10 MPa. Extracting fibers from the matrix involves overcoming chemical friction from concrete hydration products, physical friction between fiber surfaces and the matrix, and mechanical forces between uniquely shaped fibers and the matrix. These factors significantly influence the toughness, dissipation, and energy absorption behaviors of UHPFRC. The adhesion behavior between steel fibers and the concrete matrix has been a subject of extensive research. Shao et al. developed a shear stress model for the fiber pull-out process and presented a mathematical relationship for shear stress between fibers and the matrix. Their model underscores that the friction mechanism predominantly contributes to the energy absorption of fiber elongation during the elastic phase of the load-slip curve. In marine concrete structures, the corrosion of steel fibers and the cracking of concrete substantially reduce the service life. This damage is particularly pronounced in the tidal zone, where wet and dry conditions intensify chloride penetration into the concrete, escalating the corrosion intensity. The corrosion process involves the conversion of metallic iron into oxide, resulting in a volumetric increase of up to 600% depending on the oxidation state. The molecular forces generated by this additional volume lead to cracking and eventual structural degradation. These cracks facilitate increased ingress of water, oxygen, and chlorides, accelerating corrosion. Consequently, a feedback loop is established, with more rust formation creating additional stresses, leading to more cracks until complete concrete destruction occurs.

For this review, the global academic databases Web of Science and Scopus were carefully selected to compile a comprehensive collection of studies. The research focused on publications from 2005 to 2022, using targeted keywords such as "UHPFRC" and "corrosion." Additional keywords, including "fiber concrete," "super-strength concrete," and "super-strength concrete corrosion," were also incorporated to ensure broader coverage. After removing duplicate entries and refining the search results through diverse strategies, a total of 246 articles addressing the performance of UHPFRC in corrosive environments were thoroughly analyzed.

Figure 3 delineates the historical trend, showcasing the number and distribution of studies conducted in the field from 2005 to 2022. Notably, there has been a progressive increase in articles addressing the enhancement of corrosion resistance in UHPFRC over the past 22 years. Particularly noteworthy is the rapid growth, exceeding 64%, observed in the past five years. This surge can be attributed to the swift development and widespread application of UHPFRC, prompting researchers to intensify their focus on investigating its mechanical properties. Figure 4 provides a statistical overview of the studies conducted between 2005 and 2022, focusing on the corrosion behavior of high-strength fiber concrete in diverse environments. The research delves into the impact of different environments—such as water, air, saltwater, salt spray, geothermal water, wet/dry cycles, freeze/thaw cycles, low temperature, and sustained loading—on the mechanical behavior and performance of UHPFRC concrete. This holistic examination sheds light on the varied conditions under which UHPFRC structures operate, contributing to a comprehensive understanding of their corrosion resilience.

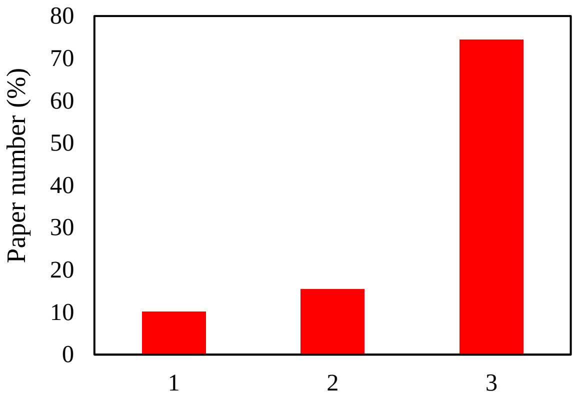


Figure 3. The amount of studies conducted during the years 2005 to 2020 in the field of investigating the mechanical properties of high-strength fiber concrete in non-conventional environments

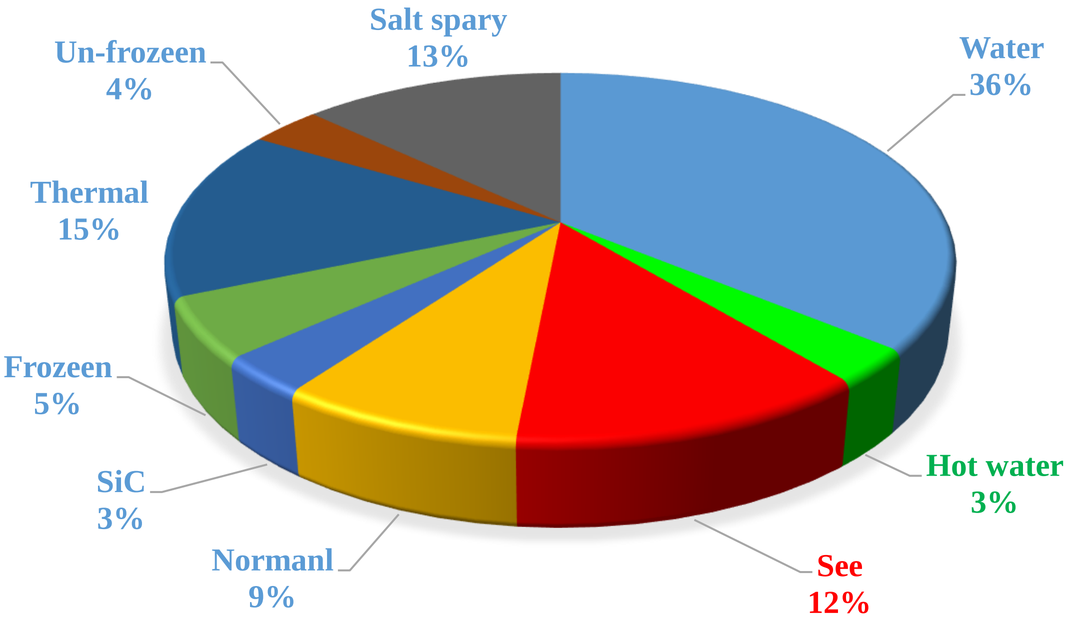


Figure 4. Statistical review of the studies conducted during the years 2005-2022 in the field of corrosion behavior of high-strength fiber concrete in different environments

3. Mechanical Behavior in the Presence of Nano Reinforcements

Nanotechnology, a groundbreaking innovation in science and industry, has found extensive applications across a wide range of sectors. The construction industry is a prominent beneficiary, utilizing nanotechnology to achieve substantial improvements in building performance and efficiency. Key advancements include the incorporation of nanomaterials into concrete construction and the development of nanostructured coatings that enhance water and humidity resistance. The adoption of nanotechnology in construction not only improves building efficiency but also contributes to cost savings and enhanced durability. In recent years, the incorporation of nanomaterials into cement-based composites has become prevalent, aiming to enhance the mechanical and chemical properties of concrete. Diverse nanoparticles, including nano silica, carbon nanotubes, zinc oxide nanoparticles, among others, exhibit a transformative impact on the cement matrix owing to their high reactivity, nucleation capabilities, and filling effects. The utilization of nanoparticles is particularly effective in modifying the cement matrix, leading to enhanced chemical and physical interactions that elevate the fiber-pulling process. This integration of nanoreinforcements presents a promising avenue for advancing the mechanical behavior of construction materials, paving the way for more robust and resilient structures.

In an experimental investigation, Li et al. explored the impact of nano-silica on the pull-out behavior of steel fibers and the mechanical properties of fiber-reinforced concrete. The primary objective of their study was to propose an effective method for enhancing the tensile properties of UHPFRC. The study involved examining the compressive, bending, and tensile behavior of UHPFRC with two types of steel fibers (straight and hook-shaped) and varying mass fractions of nanosilica (SiO_2) (ranging from zero to 5%, by weight of cement mass replacement). The findings revealed that the compressive and bending strength achieved their maximum values at a 3% weight ratio of nanosilica. In contrast, the fiber pullout behavior and tensile properties exhibited superior performance at a 5% weight ratio. This improvement was attributed to the increased attachment of hydration products to the fiber surface and more pronounced scratches post pullout. Notably, the addition of nano-silica to UHPFRC, containing both straight and hooked fibers, resulted in increased tensile strength. This effect was attributed to the reinforcement of the matrix surrounding the steel fibers, contributing to the strain hardening properties of UHPFRC. The study underscores the potential of nano-silica as a strategic additive for enhancing the mechanical behavior of UHPFRC.

Oh et al. conducted a study investigating the impact of substituting nano SiO_2 for silica fume on the performance of the bond between UHPFRC concrete fibers and the matrix surface. In this research, silica fume was replaced with SiO_2 nanoparticles within a weight range of 0 to 50%. The evaluation of the pozzolanic reaction degree of adhesive materials was carried out using thermogravimetric analysis (TGA) and compressive strength measurement. The study also included a steel fiber pull-out test at different placement angles, along with shrinkage measurement, to assess surface bonding. The findings of the study highlighted that the pozzolanic reaction degree of SiO_2 nanoparticles surpassed that of other adhesive materials. The highest compressive strength was achieved when 10% of silica fume was replaced with nano SiO_2, resulting in a 5.9% improvement compared to the base sample. Optimal fiber pull-out performance was observed when 20% of silica fume was replaced with nano-SiO_2, exhibiting an approximately 21% increase in average bond strength and a 68% improvement in pull-out energy. Consequently, the study recommends replacing 10-20% of silica fume with SiO_2 nanoparticles as an optimal proportion, considering the enhanced compressive strength and fiber-matrix bonding performance of UHPFRC.

To enhance the corrosion resistance of UHPFRC in corrosive environments, several actionable recommendations can be made based on the review of nanoparticle additives and fiber types. For nanoparticle additives, incorporating 1-3% silica nanoparticles (SiO_2) by weight of cement improves the bond between fibers and the matrix, enhancing resistance to chloride penetration. Titanium dioxide (TiO_2), at concentrations of 0.5-2%, can aid in self-healing and photocatalytic corrosion resistance, while 0.1-1% zinc oxide (ZnO) nanoparticles form protective coatings on steel fibers, preventing corrosion initiation. In terms of fiber types, galvanized steel fibers or fibers coated with copper or polymers should be considered to mitigate corrosion risks, especially in aggressive environments. Alternatively, non-corrosive fibers such as polypropylene or polyvinyl alcohol (PVA) fibers offer excellent durability, although a hybrid system combining steel and non-metallic fibers can offer a balanced solution, enhancing both mechanical properties and corrosion resistance. Additionally, a low water-to-binder ratio (0.2-0.3) is crucial to ensuring the concrete matrix remains dense and resistant to water and chloride ingress, thus improving the longevity of the fibers embedded in the matrix.

Several studies have investigated the role of nanoparticle additives in improving the adhesion properties of fibers in UHPFRC. While there is a general consensus that nanoparticles can enhance the fiber-matrix bond, the effectiveness varies depending on several factors. Below is a comparison of key studies in this area, along with an analysis of the discrepancies observed and potential reasons for these variations.

3.1. Consistent Findings

Silica Nanoparticles: Multiple studies, report that the incorporation of silica nanoparticles results in improved fiber-matrix adhesion and increased compressive strength. This is attributed to the nanoparticle's ability to fill micro-pores and refine the interfacial transition zone.

Titanium Dioxide (TiO2): Studies show that TiO2 nanoparticles enhance the durability and corrosion resistance of steel fibers, particularly in aggressive environments, owing to their photocatalytic properties which can reduce chloride penetration.

3.2. Discrepancies Across Studies

While many studies have found positive effects of nanoparticles on mechanical properties, some researchers report minimal or no significant improvement. For instance, observed only slight gains in tensile strength when using alumina nanoparticles in chloride-exposed environments, which contrasts with findings by Ref. [14], who documented substantial improvements under similar conditions.

3.3. Reasons for Variations

Nanoparticle Characteristics: Variations in nanoparticle size, shape, and surface area can influence their effectiveness. Nanoparticles with higher surface area tend to provide better adhesion, while those with irregular shapes may hinder uniform dispersion.

Mix Design Differences: The matrix composition, including the type and dosage of fibers, cement content, and water-to-cement ratio, can affect the interaction between nanoparticles and the cement paste, leading to different results.

Testing Conditions: Environmental factors such as exposure to aggressive agents (chlorides, sulfates), temperature, humidity, and curing conditions vary across studies, influencing the observed performance of UHPFRC in real-world applications.

Dispersion Methods: Inconsistent dispersion methods of nanoparticles (e.g., dry mixing vs. pre-dispersion in a liquid) can lead to uneven distribution within the mix, affecting the performance outcomes.

The comparative analysis highlights that while nanoparticle additives generally improve fiber adhesion and durability, their effectiveness is highly dependent on the type of nanoparticle, mix design, and testing conditions. Discrepancies in the results across studies suggest the need for further standardization in experimental protocols, including consistent nanoparticle dispersion methods, material ratios, and exposure environments. These findings provide valuable insights for future research and practical applications in UHPFRC, particularly in corrosive traffic environments.

4. The Effect of Different Types of Fibers

Numerous studies highlight the capillary suction mechanism as the primary pathway for chloride ions entering concrete, particularly in saturated conditions. The thickness of the concrete cover exposed to water surfaces adversely affects capillary suction, with the highest concentrations of chloride ions observed just above the water surface. In chloride-containing water, the cyclic wetting and drying of concrete expedite chloride ingress. To mitigate corrosion on the rebar surface, chloride values must surpass a critical threshold dependent on concrete cover and moisture content. Enhancing chloride resistance in both concrete and the passive film on fibers is crucial to resisting electrochemical reactions and controlling the corrosion process. The kinetic impact of chloride ions on steel corrosion in concrete is emphasized over thermodynamic considerations. Studies underscore the effectiveness of incorporating steel fibers as a primary method for corrosion control, leading to a reduction in chloride ion release. Kakooei et al. highlighted that the presence of fibers in concrete reduces both penetration and cracking. Moreover, the length and properties of fibers significantly influence corrosion control, and the sliding behavior of fibers in concrete undergoes notable changes in their presence. The incorporation of various types of fibers emerges as a key strategy in influencing and optimizing corrosion resistance mechanisms in concrete structures. Preformed fibers can be categorized into end-deformed fibers, hook-shaped fibers, buttons, or hooks. Fibers exhibiting deformations along their length, such as twisted, dented, or polygonal fibers (as illustrated in Table 1), represent various examples within this classification. The bending of fiber ends can intensify stress concentration in the matrix, while deformations along the fibers, like twisting, serve to reduce stress concentration.

Figure 5 compares the force-slip behaviors of straight, hooked, semi-hooked, and twisted fibers. Notably, among the deformed fibers, hook-shaped fibers have garnered significant attention and widespread use in research. In a comprehensive review, Deng et al. delved into studies focusing on the adhesion behavior of fibers with super-strength concrete. Their investigation identified and extensively discussed fiber-matrix bond parameters, encompassing fiber geometry and orientation, surface treatment, matrix composition, and strength. The study concluded with recommendations for future research, emphasizing UHPFRC strengthening methods and testing details based on recent developments.

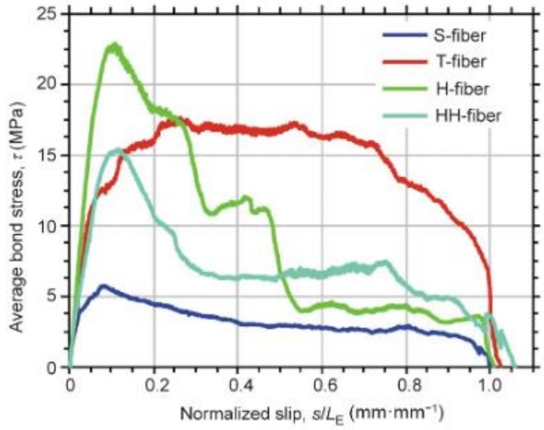


Figure 5. Pullout behaviors of straight (S), twisted (T), hooked (H) and half-hooked (HH) steel fibers from UHPFRC matrix

Du et al. conducted a study investigating the impact of reinforcing the steel fiber-matrix interface on the macromechanical properties of UHPFRC. In their research, two types of steel fibers with a nano SiO2 coating were prepared using the sol-gel method. Figure 6 presents microscopic images illustrating the surface-improved steel fibers employed in their study. Subsequently, fiber pull-out tests, as well as bending and compression tests, were performed on UHPFRC containing varying percentages (1%, 2%, and 3%) of steel fibers. The results revealed that the increase in surface adhesion significantly influenced the macromechanical properties of UHPFRC. However, the presence of granular SiO2 nanoparticles on the surface of the modified steel fibers led to increased roughness, reducing the fluidity of the fresh UHPFRC mixture. Analysis of crack section images indicated that proper vibration could mitigate the impact of steel fiber surface roughness on fiber distribution in UHPFRC. Figure 6 visually depicts the microscopic images of the improved steel fibers utilized in this study.

Xu et al. conducted an extensive series of central pull-out tests to assess the bond performance between steel bars and high-strength concrete modified with three distinct types of nanoparticles—CaCO3, Al2O3, and SiO2. Their study meticulously analyzed the influence of various parameters, including the type and diameter of the steel rebar, bond length, concrete cover thickness, length and content of steel fibers, and the type and content of nanomaterials, on failure modes and the stress-slip relationship. Subsequently, the researchers proposed a structural model based on experimental results to accurately predict the bond stress-slip relationship. To validate the effectiveness of the proposed model, a nanoparticle-reinforced UHPFRC beam underwent testing under uniform lateral loading. The behavior was also numerically simulated using a detailed finite element model incorporating the structural model. Parametric studies were conducted to assess the impact of critical parameters of the structural model on the bending behavior of the UHPFRC beam reinforced with nanoparticles. The experimental results demonstrated superior bond performance between the steel bar and UHPFRC. However, an increase in bond length and ribbed steel rebar diameter negatively affected bond performance. Similarly, reductions in concrete cover thickness, steel fiber length, and fiber content were observed to diminish bond performance. While the inclusion of SiO_2 and $CaCO_3$ nanoparticles enhanced bond behavior, the addition of Al_2O_3 nanoparticles had an adverse effect. Numerical analyses further highlighted the critical influence of bond strength and modulus on the bending behavior of nanoparticle-reinforced UHPFRC beams. Notably, the slope of the descending portion of the bond stress-slip relationship was found to have a negligible impact. Figure 7 provides a visual representation of the effects of various nanoparticles on the interaction between steel fibers and high-strength concrete.

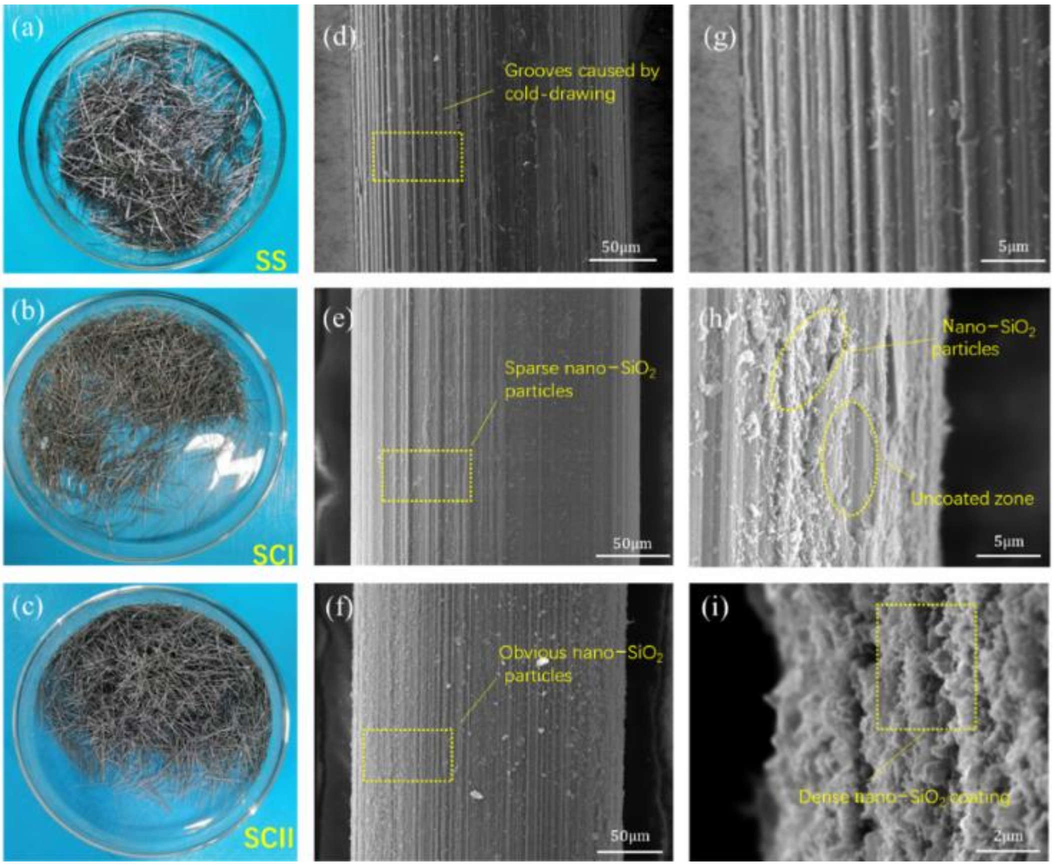
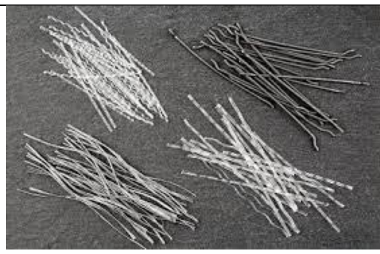


Figure 6. Microscopic images of improved steel fibers

Table 1. Different examples of fibers employed in reinforcing high-strength fiber concrete

Name	Density (kg.m^{-3})	Elastic Modulus (MPa)	Diameter (μm)	Image
Asbestos	2750	500-900	<0.5	
Acrylic	1180	800-950	5-15	
Polyester	1380	650-1200	10-80	
Polyethylene	960	200-300	800-1000	
Glass	2750	1400-3500	8-16	
Wood	1400	50-200	50-400	
Carbon	1750	1800-4000	7-20	
Steel	7850	280-2800	100-1000	

The Interfacial Transition Zone (ITZ) refers to the region within concrete where the aggregates and the cement paste interact. It is typically located at the interface between the coarse aggregates and the surrounding cement matrix. The ITZ plays a crucial role in determining the overall strength, durability, and performance of concrete, as it often exhibits distinct properties compared to the bulk cement paste.

Yu et al. conducted a comprehensive investigation into the impact of graphene oxide (GO) on the microstructure and micromechanical properties of the superstrength concrete matrix, with a particular focus on the interfacial transition zone (ITZ) around the steel fibers. The study aimed to understand how the inclusion of GO affects both the mesoscopic and macroscopic mechanical behaviors of UHPC reinforced with steel fibers, as this is critical for enhancing the material's overall performance, especially in harsh environments. To explore the effects of GO on the microstructure of the concrete matrix, the researchers employed advanced techniques such as Mercury Intrusion Porosimetry (MIP) and Backscattered Electron Microscopy (BSEM). MIP was used to analyze the pore structure, while BSEM provided detailed imaging to observe the interaction between the fibers and the matrix at the micro and nano scales. These techniques allowed for a systematic evaluation of the microstructural changes that occur upon the incorporation of GO, providing insights into the material’s behavior under different conditions. In addition, the researchers employed nano-indentation tests to quantitatively characterize the micro-scale fracture toughness of both the UHPC matrix and the ITZ. This method enabled the team to assess the mechanical properties at a very fine scale, specifically focusing on the hardness and resistance to micro-scale damage at the interface between the steel fibers and the surrounding matrix. The results indicated that the addition of GO to the UHPC mix resulted in a significant improvement in the microstructure. Specifically, the incorporation of GO promoted the formation of more calcium silicate hydrate (C-S-H), a crucial phase that contributes to the strength and durability of concrete. The enhanced C-S-H gel network, particularly around the ITZ, led to a substantial reduction in porosity in the region between the steel fibers and the matrix. This improvement in the ITZ not only reduced the risk of corrosion but also promoted better bonding between the fibers and the matrix, thereby enhancing the overall mechanical properties of the composite material. Furthermore, the reduction in porosity and the improved homogeneity of the microstructure due to GO incorporation resulted in a more durable UHPC. The improved interfacial properties are expected to enhance the material’s resistance to both physical and chemical degradation, making GO-enhanced UHPC a promising candidate for applications in harsh, corrosive environments where the long-term performance of concrete structures is critical.

Owing to the diminished porosity and the bridging effect of GO nanosheets, the fracture toughness at the micro-ITZ scale increased by approximately 24.9%. Specifically, at a critical dose of 0.04% GO—utilized to enhance the joint bonding between straight steel fibers and the matrix—the fracture toughness increased from 0.994 MPa·m to 1.241 MPa·m. Consequently, the macroscopic flexural strength of UHPFRC reinforced with both straight steel fibers and hooked end fibers experienced notable increases of 14.7% and 13.9%, respectively. The study highlights the potential of GO in enhancing the mechanical properties and performance of UHPFRC.

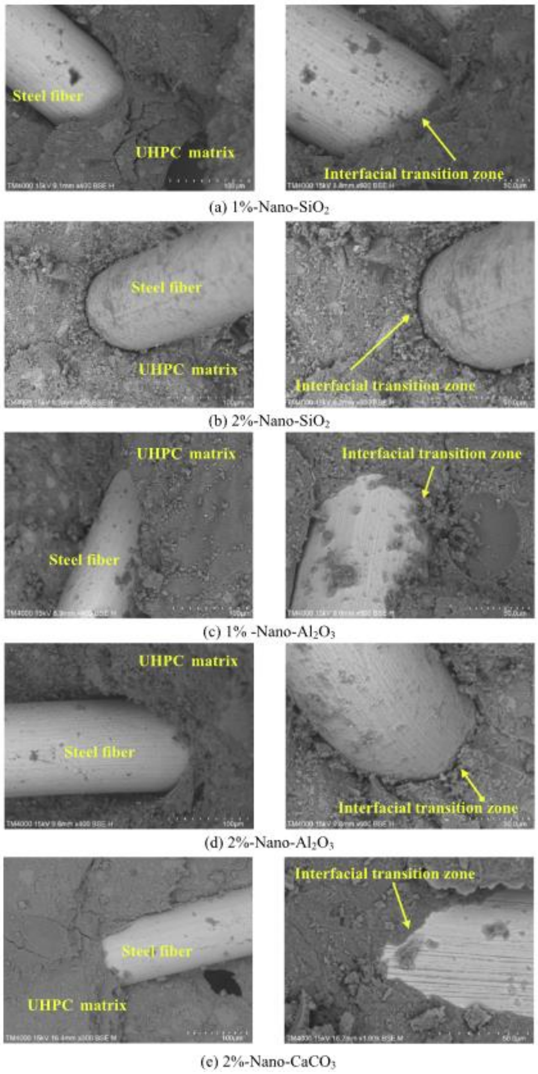


Figure 7. The effect of different nanoparticles on the interaction between steel fibers and high-strength concrete

In a review study, Zhang et al. conducted a comprehensive comparison of various Carbon Nanotube (CNT) dispersion modes and assessed the effectiveness of CNTs on the mechanical behavior of concrete. The study systematically investigated the mechanical properties of concrete reinforced with CNT nanoparticles, encompassing compressive strength, tensile strength, flexural strength, and dynamic performance against impact. Additionally, the durability of CNT-reinforced concrete was examined, considering factors such as chloride penetration resistance, carbonation resistance, sulfate resistance, impermeability, high-temperature resistance, and freezing and thawing resistance. The research delved into the application of CNTs as a conductive filler in concrete and included an analysis of the microscopic mechanisms associated with CNTs. The findings indicated that the addition of carbon nanotubes generally reduces the workability of concrete. However, pre-dispersed liquid CNTs demonstrated a relative increase in the mechanical properties. Carbon nanotubes with OH groups and nickel plating exhibited significant improvements in mechanical properties. Functionalized COOH and shorter CNTs notably enhanced the dynamic impact resistance of ultra-high-performance concrete. Moreover, CNTs were found to optimize the internal pore structure and increase the ITZ, leading to improved durability. Concrete reinforced with CNT nanoparticles demonstrated quality maintenance at high temperatures, with its internal structure undergoing changes to a new shape at 600°C. In summary, CNT-reinforced concrete emerges as a promising new construction material with favorable application prospects.

A review by Lin et al. provides a comprehensive examination of bond properties between fibers and cement matrix. The study explores three distinct bonding mechanisms: electrostatic attraction bonding, chemical reaction bonding, and mechanical locking. Various approaches to enhance fiber-matrix bonding are discussed based on these mechanisms, and the paper summarizes key techniques and models for describing the interfacial transition zone (ITZ) and the bond between fibers and the cement matrix. The failure modes at the fiber-matrix interface are classified into three types based on the location of failure: separation failure, fiber failure, and matrix failure. Figure 8 illustrates different failure modes, including (a) separation failure, (b) fiber failure, and (c) cement matrix failure.

In Figure 9, the pullout behavior of straight and hook-shaped steel fibers is compared. The pullout process for straight fibers is divided into three stages: complete bonding, separation, and frictional sliding. The area enclosed by the curves AB'C' and OAC'F represents separation energy and friction energy. On the other hand, the pullout behavior of hook-shaped fibers involves five stages: elastic and partial separation, first stage of plastic deformation, second stage of plastic deformation, hybrid deformation-slip, and frictional sliding. Peak tensile load is typically reached within the slip range of 0.5 mm to 1.5 mm. Subsequent peaks in the stress-strain curve occur during the second phase of plastic deformation and the DE (deformation and elongation) stage, which are attributed to the steel fiber navigating the final corner or bend within the concrete matrix. This phase reflects the ongoing interaction between the fiber and the concrete as the fiber continues to deform under the applied load.

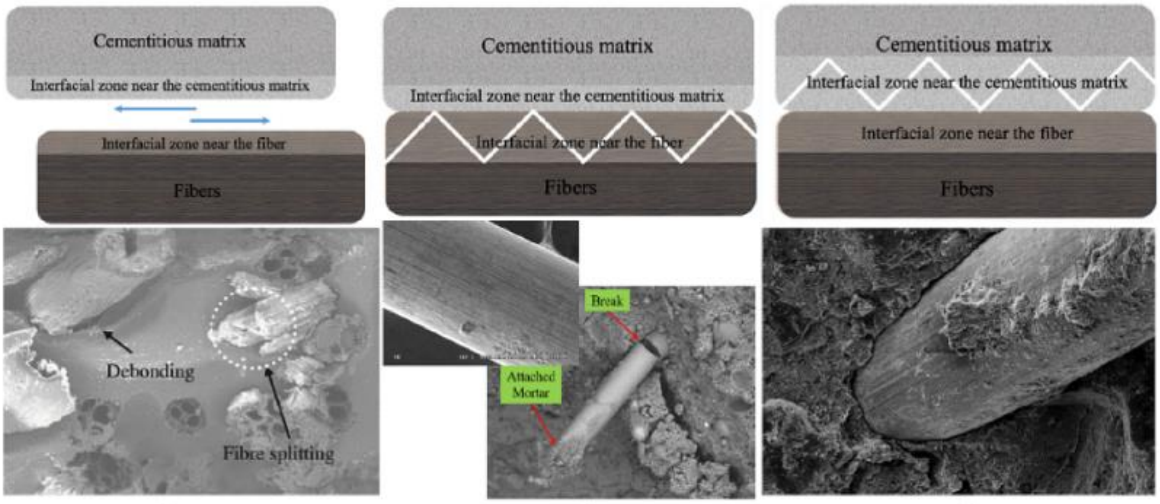


Figure 8. Different failure modes of fiber-concrete matrix interface: (a) separation failure, (b) failure in fibers, (c) failure in cement matrix

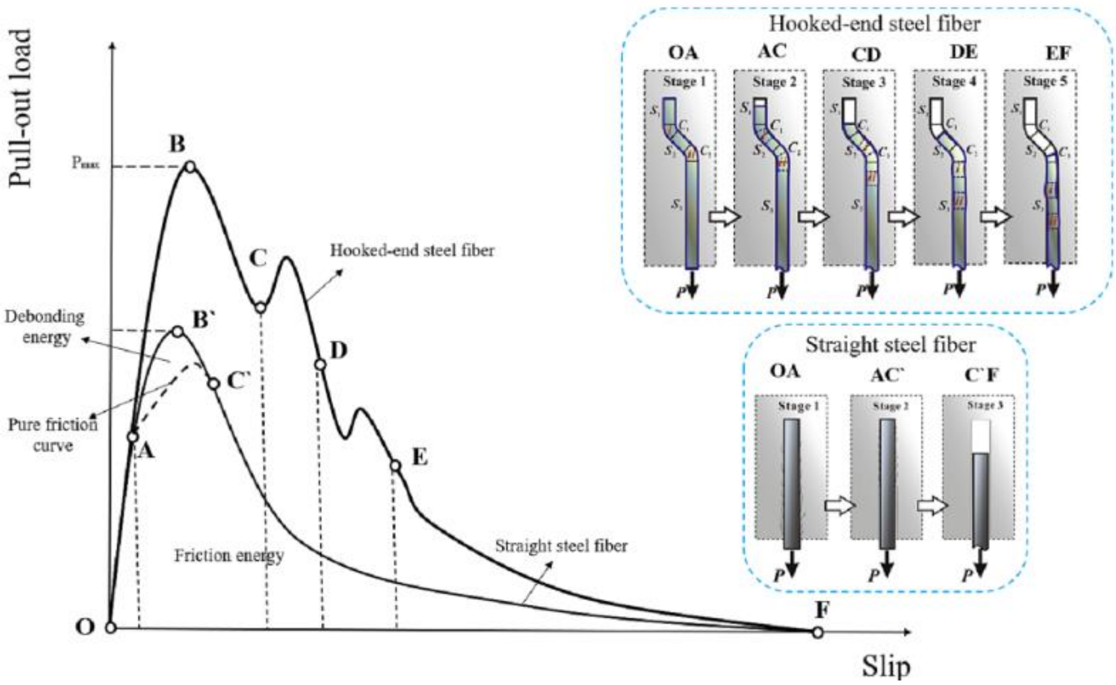


Figure 9. Comparison of the pullout behavior of straight and hook-shaped steel fibers

5. Chloride Ion Penetration Resistance in Concrete: Insights from Recent Research

The corrosion of fibers due to chloride ion penetration poses a significant threat to reinforced concrete structures, especially in acidic environments or salty waters. Even in alkaline environments, steel is susceptible to rusting, emphasizing the critical importance of resistance to chloride ion penetration in concrete durability. In recent studies, researchers have explored the chloride penetration resistance of concrete reinforced with nanoparticles. Kumar et al. employed the weight loss method to calculate the corrosion rate, revealing that concrete reinforced with nanoparticles exhibited a lower corrosion rate than normal concrete under saltwater conditions. Janaki et al. and Gamal et al. measured chloride penetration using electric charge, finding that the addition of a small amount of Carbon Nanotubes (CNT) reduced chloride ion permeability. Carriço et al. and Bogas et al. conducted rapid chloride migration (RCM) experiments, demonstrating that the incorporation of CNTs in various volume fractions decreased the chloride ion migration diffusion coefficient (DCL) compared to reference concrete. For instance, at a water-to-cement ratio (W/C) of 0.55, the DCL of CNTSS concrete was 7% lower than the reference sample. In Figure 10, DCL values for different carbon nanotubes at various water/cement (W/C) ratios are depicted, showing the reduction in chloride ion migration with the addition of CNTs. Moghadam et al. argued that the bridging effect might not be reflected in the chloride ion penetration resistance test of uncracked samples, attributing it to filling and nucleation effects. However, they suggested that, under specific experimental conditions, carbon nanotubes had a limited effect on increasing resistance to chloride penetration. Both studies proposed that CNTs enhance the chloride ion osmotic resistance of concrete. Contrary to some perspectives, Moghadam et al. argued that the bridging effect may not be evident in the chloride ion penetration resistance test of uncracked samples and should be attributed to filling and nucleation effects. However, they suggested that, under the specific experimental conditions used, carbon nanotubes had a limited effect on increasing resistance to chloride penetration. Mak et al. confirmed that carbon nanotubes could enhance chloride penetration resistance in the cracked areas of concrete. Their study investigated cracking and bond strength of rebar in reinforced concrete, employing a novel evaluation approach based on surface cracks. The research, conducted through accelerated corrosion using flow (Figure 11), revealed that surface crack width could serve as a more effective indicator of bond degradation than corrosion levels.

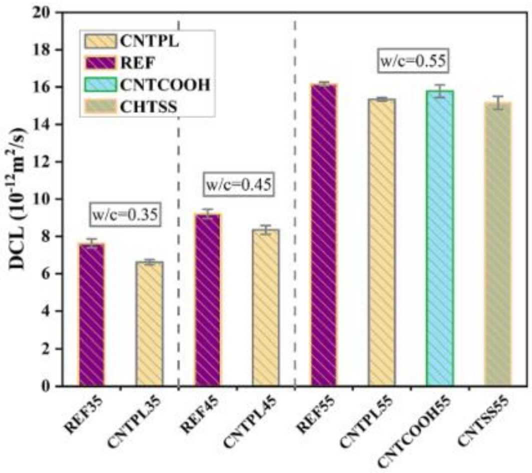


Figure 10. DCL of different carbon nanotubes at different w/c ratios

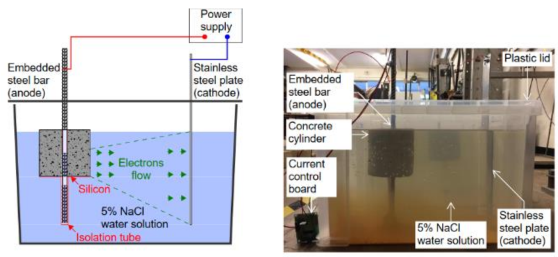


Figure 11. Experimental setup for testing the effect of nanoparticle additives on fiber-matrix adhesion in UHPFRC under corrosive conditions

Although numerous studies have demonstrated the potential of nanoparticle additives in enhancing the corrosion resistance of UHPFRC, conflicting findings regarding the effectiveness of certain nanoparticles remain. For example, while silica nanoparticles (SiO2) have consistently been shown to improve fiber adhesion and corrosion resistance, some studies report varying degrees of effectiveness depending on the specific nanoparticle dosage and the environmental conditions in which UHPFRC is exposed. In contrast, titanium dioxide (TiO2) nanoparticles have exhibited photocatalytic properties that reduce the rate of corrosion, but their performance in aggressive environments such as chloride-laden conditions has been more variable. The differences in the reported effectiveness of nanoparticles can often be attributed to factors such as the type of nanoparticles used, their dispersion within the matrix, the curing process, and the composition of the concrete mix. Further research is necessary to standardize the application of these additives and understand the conditions under which they are most effective.

6. Enhanced Durability against Chloride Ion Erosion in Nanocomposite Concrete

MacLeod et al. employed the chloride apparent diffusion coefficient (Dapp) and observed a significant decrease in the Dapp of cement-based nanocomposites. Vijayabhaskar et al. investigated the weight loss and strength reduction of carbon nanotube-reinforced concrete samples exposed to chloride ion erosion. Figure 12 illustrates the decline in compressive strength of concrete under chloride ion attack at different ages. The addition of Multi-Walled Carbon Nanotubes (MWCNTs) substantially improved the concrete's durability, though an optimal inclusion amount was identified. The research indicates that the incorporation of nanomaterials, such as carbon nanotubes, plays a crucial role in mitigating the impact of chloride ion penetration, leading to enhanced durability and reduced deterioration of concrete structures in aggressive environments.

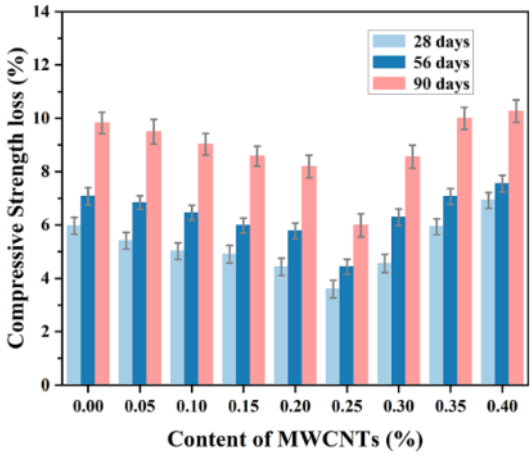


Figure 12. Compressive strength of concrete reinforced with carbon nanotubes for 28, 56 and 90 days of chloride attack environmental conditions

Sulfate erosion poses a significant threat to concrete structures in various environments. Thanmanaselvi et al. conducted compressive strength tests on concrete cubes immersed in 5% Na2SO4 solution for 90 days after a 28-day curing period. Figure 13 illustrates that concrete with 0.25% Multi-Walled Carbon Nanotubes (MWCNT) exhibited the least compressive strength loss, indicating the potential of CNT incorporation in reducing the detrimental effects of sulfate on mechanical properties. In a study by Yang et al., the sulfate resistance of concrete incorporating Silica Fume (SF) and Carbon Nanotubes (CNTs) was investigated under cyclic dry and wet conditions, which simulate real-world exposure to aggressive environments. This finding highlights the potential of CNTs to enhance the durability of concrete, particularly in environments prone to sulfate attack. The presence of CNTs is believed to contribute to the increased resistance by improving the microstructure of the concrete, reducing the permeability of the material, and enhancing the bonding between the matrix and the fibers. Similarly, Mansouri Sarvandani et al. proposed that the incorporation of MWCNTs into cement-based materials significantly enhances sulfate resistance. Over a prolonged exposure of 960 days to a sulfate solution, concrete samples containing MWCNTs exhibited only mild erosion compared to the control samples, which showed considerable degradation. This result suggests that MWCNTs effectively mitigate the impact of sulfate ions on the concrete matrix. The protective effect of MWCNTs is attributed to their ability to fill pores and fractures within the concrete, which reduces the penetration of sulfate ions and helps prevent the formation of expansive products that can damage the matrix. In addition, the MWCNTs act as a structural bridge, reinforcing the matrix network and maintaining the integrity of the concrete in the presence of aggressive sulfate ions. These tests revealed that an optimal MWCNT content of 0.1% to 0.2% by weight enhanced the concrete's resistance to sulfate attack while maintaining its mechanical properties. Among the different dosages tested, 0.2% MWCNT content was found to be the most effective for long-term sulfate exposure, suggesting that this concentration strikes a balance between improving sulfate resistance and maintaining the concrete's strength. The ability of MWCNTs to fill the voids and strengthen the concrete matrix, coupled with their inherent mechanical properties, contributes to the material's improved durability, making it suitable for environments exposed to high concentrations of sulfate solutions.

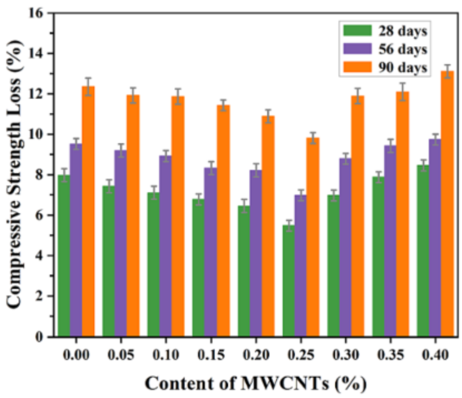


Figure 13. Effect of carbon nanotube content on compressive strength in a sulfate environment at different ages

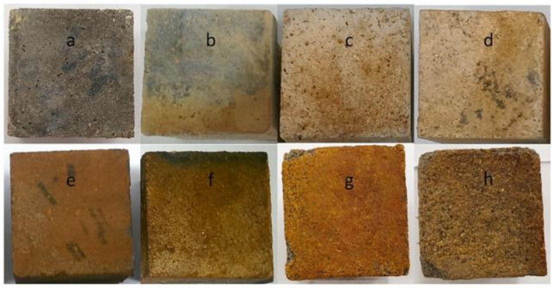


Figure 14. The effect of sulfate on the appearance of concrete reinforced with carbon nanotubes 7, 28, 56, 90, 150, 180 and 360 days

Davolio et al. investigated the mechanical behavior of fiber reinforced concrete under simultaneous action of mechanical loading and exposure to an aggressive environment. In their study, UHPFRC mixtures containing different functional components at the micro and nano scale were investigated to promote self-healing. In order to evaluate the reparability capabilities in different multifunctional scenarios and the evolution of the material's mechanical response over time, a suitable method including non-destructive and destructive tests during exposure times to planned aggressive environments was implemented. Their experimental tests for up to 12 months specifically, an innovative set to reproduce the stable bending loading conditions that a structure is subjected to during its lifetime on as-built specimens. To simulate chloride and sulfate aggressive environments, in addition to one reference, mechanical forces have been performed on three other samples. Several indices were defined to quantify the self-healing efficiency, which were further calibrated against the observation of experimental microscopic cracks as well as cross-correlation with each other, as a further proof of the reliability of the proposed method. The results confirmed the durability of the material, especially in the cracked state, through the capacity to seal the cracks and restore the original properties in short periods and maintain its load capacity. Therefore, a strong argument was made for UHPC as the ideal material suitable for use in aggressive environments.

Figure 15 shows the condition of the steel fibers after twelve months of exposure to the aggressive environment.

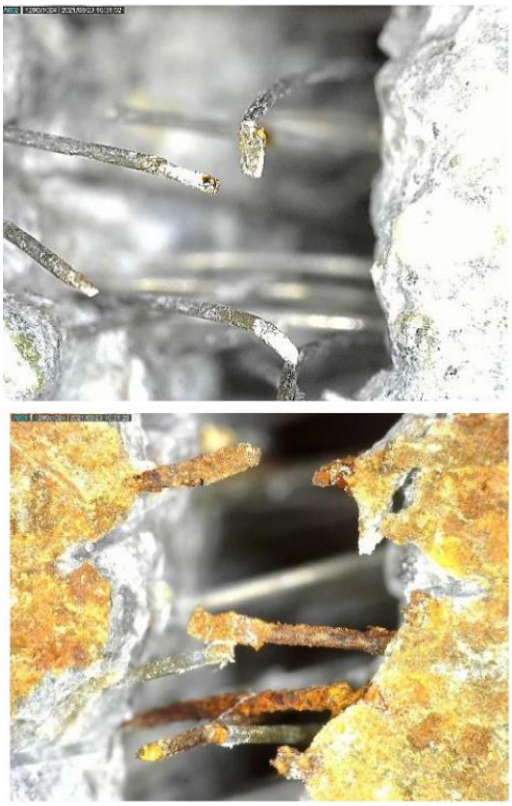


Figure 15. The state of steel fibers after twelve months of exposure to aggressive environment (a) outer layer and b) inner layer

Ma et al. delved into the impact of chloride attack on the mechanical, electrochemical, and microstructural properties of UHPFRC cement composites. Immersing test samples in saturated sodium chloride solution, they assessed compressive, tensile, and bending strength at different curing ages. Electrochemical behaviors were determined through free corrosion potential, AC impedance spectroscopy, and polarization resistance. Microscale investigations using X-ray diffraction (XRD), pore structure characteristics, and scanning electron microscopy (SEM) uncovered internal mechanisms. The chloride-rich environment displayed adverse effects on mechanical properties, notably bond strength, decreasing by an average of 20% in 56 days. The addition of Styrene Butadiene Rubber (SBR) latex, up to an optimal content, enhanced bonding strength but adversely affected compressive strength when overdosed. Moreover, SBR latex delayed corrosion onset in in-system reinforcements. In a study by Frazão et al., the long-term effects of chloride attack on steel fiber-reinforced cement composites were evaluated. Split tensile tests and cylindrical failure tests were conducted, exploring the impact of different chloride immersion periods and steel fiber dispersion on crack surfaces. The study aimed at a simplified prediction of long-term chloride penetration depth into uncracked Reinforced Steel Fiber Concrete under aggressive chloride immersion. Results indicated high sensitivity to surface corrosion under chloride exposure, with post-cracking strength of RSFRC showing minimal impact. The addition of steel fibers had negligible effects on chloride ion diffusion, highlighting RSFRC's resilience, with a critical chloride content surpassing that of conventional reinforced concrete structures.

Liu et al. conducted a groundbreaking study investigating the impact of corrosion on the bond behavior between steel reinforcement and concrete under high-speed dynamic loading. This aspect is crucial as corrosion, which reduces the cross-sectional area and strength of reinforcement bars, poses a significant threat to the bearing capacity of reinforced concrete structures. In their laboratory tests, accelerated corrosion damage was induced on steel bars embedded in concrete specimens. Key findings and observations:

1. Dynamic Bond Parameters: The study focused on dynamic pullout tests to derive crucial bond parameters, including ultimate bond load and bond slip relationships. These were explored in the context of different strain rates and corrosion degrees.

2. Empirical Formulas: Empirical formulas of Dynamic Enhancement Factors (DIFs) were proposed. These factors relate to final bond strength, considering corrosion levels and different strain rates. The DIFs provide insights into how dynamic loading influences the bond behavior under various corrosion conditions.

3. Strain Rate Influence: Results indicated a significant influence of the strain rate on bonding behavior, irrespective of the corrosion level. Notably, the increase in ultimate bond strength with strain rate was more pronounced for heavily corroded reinforcements (corrosion level η = 5%-10%) compared to mildly corroded reinforcements (corrosion level η = 0%-5%).

4. Corrosion Impact at High Strain Rates: The reduction in ultimate tensile strength due to corrosion damage was more pronounced at high strain rates than at low strain rates. This suggests that corrosion's detrimental effects are accentuated under dynamic loading conditions.

5. Crucial Role of Concrete Properties: Corrosion cracking and the tensile strength of concrete played a significant role in influencing both static and dynamic bond behavior. These factors are critical considerations in assessing the structural responses of reinforced concrete under dynamic loads.

The laboratory tests, as depicted in Figure 16, offer visual insights into the accelerated corrosion of rebars in corrosive environments along with the resulting fracture cross-section, providing a comprehensive understanding of the dynamic bond behavior influenced by corrosion levels and strain rates.

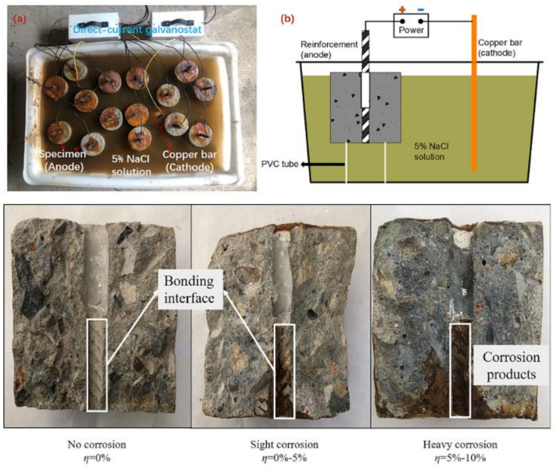


Figure 16. Laboratory tests of accelerated corrosion of rebar in corrosive environments along with the fracture cross-section

Reinforced concrete structures in corrosive areas usually suffer from failure due to reinforcement corrosion, which can be caused by carbonate or chlorine ion penetration. The increase in the volume of corrosion products compared to the original steel causes cracks in the structure, which can lead to the acceleration of the reduction of its useful life. Therefore, the crack formation time is a main parameter in the performance of the structure and it is important to be able to predict it with sufficient accuracy. In order to check the accuracy of analytical models based on modeling the nonlinear behavior of concrete and determine the location of reinforcement corrosion, the finite element model was used in the study of Miri et al. The study delved into investigating the effect of different parameters on concrete cracking. Notably, the protective coating on the reinforcement and the compressive strength of concrete emerged as influential factors. An increase in these parameters correlated with heightened internal pressure induced by corrosion products, pushing the system toward the initiation of cracking. At first, various laboratory samples were made and after initial storage, they were subjected to accelerated corrosion conditions. The location and pattern of model cracks during the test and until the complete failure of the samples are recorded accurately. In the next step, the numerical model of the above samples is made using finite elements and the results obtained from laboratory and numerical methods are compared with each other. After ensuring the correctness of the constructed numerical models, the effect of different parameters on concrete cracking has been investigated. The results indicate that the reinforcement coating and the compressive strength of concrete are effective factors in the initiation of cracking, and with the increase of these two parameters, the internal pressure caused by the products will increase towards the initiation of cracking. The research contributes to enhancing our understanding of the factors influencing the initiation of cracking in reinforced concrete structures subjected to corrosion. The validated finite element models offer a valuable tool for predicting and assessing the progression of cracks, aiding in the development of strategies to mitigate corrosion-induced damage and improve the durability of concrete structures in corrosive environments.

7. Limitations, Research Gaps and Future Research Directions

Several limitations in the reviewed studies need to be addressed for a more comprehensive understanding of nanoparticle additives in UHPFRC. Many studies rely on small sample sizes, which can limit the generalizability of the results and introduce variability. Additionally, most studies focus on short-term testing of mechanical properties without considering the long-term durability of UHPFRC, particularly under harsh environmental conditions like freeze-thaw cycles or chloride exposure. The lack of standardized testing protocols across studies further complicates comparisons, as variations in curing methods, nanoparticle dispersion techniques, and environmental conditions may explain discrepancies in effectiveness. Furthermore, many studies are conducted in controlled laboratory settings, which do not fully replicate the complex conditions of real-world applications, highlighting the need for field studies to validate laboratory findings and assess the material's performance in actual corrosive traffic environments.

While significant progress has been made in enhancing the corrosion resistance of UHPFRC using nanoparticle additives, several important research gaps remain. Future studies should focus on the following key areas to further improve the material's performance and expand its applicability in harsh environments:

1. Exploring Alternative Fibers: While steel fibers are commonly used in UHPFRC, they are vulnerable to corrosion under aggressive environmental conditions. Research into non-metallic fibers, such as polypropylene, polyvinyl alcohol (PVA), and carbon fibers, could provide valuable insights into improving the long-term durability of UHPFRC. These fibers offer the potential for corrosion-free performance, but their mechanical properties, cost-effectiveness, and compatibility with nanoparticle additives require further investigation.

2. Hybrid Fiber Systems: The use of hybrid fiber systems, combining both metallic and non-metallic fibers, represents a promising avenue for enhancing the overall durability and mechanical properties of UHPFRC. Future research should explore the optimal combinations of fibers to achieve superior strength, crack resistance, and corrosion resistance. Investigating the synergy between different fiber types, as well as their interaction with various nanoparticle additives, could lead to the development of more durable and cost-effective UHPFRC formulations.

3. Long-Term Performance and Standardization:
While the effectiveness of nanoparticles in improving corrosion resistance is well-documented in laboratory settings, there is a need for studies that assess the long-term performance of nanoparticle-enhanced UHPFRC under real-world conditions. Additionally, standardized testing methods are necessary to compare the performance of different nanoparticle additives, fiber types, and hybrid systems in a consistent manner.

4. Nanoparticle Optimization and Surface Treatments:
Research into optimizing the concentration, dispersion, and interaction of nanoparticles within the UHPFRC matrix is essential to maximize their corrosion-resistant properties. Additionally, the effectiveness of surface treatments or coatings on fibers, such as polymer coatings, zinc coatings, or copper coatings, should be explored further to protect the fibers from degradation in aggressive environments.

8. Conclusion

In conclusion, the corrosion of metal reinforcements, particularly in marine environments, presents a critical challenge for reinforced concrete structures. This issue arises primarily from the penetration of chloride ions in water, which compromises the protective layer on the reinforcement, leading to corrosion and a consequent reduction in the structure's service life. The economic impact of corrosion is substantial, encompassing significant reconstruction and maintenance costs. As the reliance on reinforced concrete structures continues to expand, addressing and mitigating corrosion-related challenges in such environments remains an urgent priority.

The findings from various studies suggest that the incorporation of steel fibers in UHPFRC can effectively prevent cracks and reduce the width of cracked surfaces. The increase in concrete fiber volume can alter shear failure modes to bending, delaying the time required for crack formation. Fiber-reinforced concrete demonstrates increased impermeability compared to conventional concrete in the cracked state, attributed to the relationship between crack size and permeability.

The experimental data further indicates a significant impact of fibers on the chloride diffusion coefficient in cracked concrete. Fibers play a role in connecting chlorides and impeding their movement within the concrete, thus delaying the onset of corrosion until a certain applied load threshold is reached. However, the type and volume of fibers used can influence the corrosion rate, and further research is needed to investigate the potential galvanic corrosion risk between steel fibers.

In ongoing research, the modification of steel fiber surfaces, the use of stainless steel fibers, various nanoparticles to reduce concrete penetration, and the effects of polymer fibers on the properties of high-strength fiber concrete in corrosive environments are being explored. Additionally, the study highlights the potential benefits of incorporating nanoparticles to fill small pores in hydrated cement, thereby enhancing the strength and durability of ultra-high-strength concrete. This comprehensive review emphasizes the multidimensional aspects of corrosion in reinforced concrete structures and underscores the ongoing efforts to develop effective strategies for corrosion prevention and mitigation. The continuous exploration of innovative materials and technologies is crucial for enhancing the resilience and durability of reinforced concrete structures, especially in challenging environmental conditions.

In conclusion, this study highlights the promising potential of nanoparticle additives in enhancing the corrosion resistance of UHPFRC, particularly in environments exposed to chloride ions and other corrosive agents. However, despite the advances, several challenges remain in optimizing the use of nanoparticles for practical applications. Future research should focus on exploring specific nanoparticle configurations and optimal dosages to maximize their effectiveness in corrosion prevention. For instance, a combination of silica nanoparticles (SiO2) and zinc oxide nanoparticles (ZnO) could provide a synergistic effect, improving both adhesion and corrosion resistance. Additionally, further studies should investigate the impact of surface coatings on steel fibers, such as polymer or copper coatings, which may enhance fiber durability in highly aggressive environments. Finally, research is needed to standardize testing methodologies and assess the long-term performance of nanoparticle-enhanced UHPFRC under real-world exposure conditions. These efforts will be crucial in advancing the application of UHPFRC in infrastructure and ensuring its sustainability in corrosive traffic environments.

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