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A Comprehensive Review of Nanoparticle Incorporation in Construction and Architecture Materials: Impacts on Properties, Performance, and Sustainability

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ABSTRACT: *Over the past two decades, there is a rapid growth of research on nanotechnology in construction materials. This study presents a timely and comprehensive review that focuses on investigating the effects of incorporating various nanoparticles into cementitious, polymeric, and composite materials commonly used in the construction and architecture sectors. The primary objective is to critically analyze the potential benefits and limitations associated with the addition of nanoparticles, particularly in enhancing mechanical performance, durability, functionality, and sustainability. The study methodology involves an extensive analysis of published literature on nanoparticles applied in construction materials. The impact of nanomaterials on properties, including compressive strength, fracture toughness, stiffness, self-sensing capability, resistance to environmental degradation, antimicrobial effects, and recyclability is thoroughly examined. The findings reveal significant progress in demonstrating the capabilities of nanomaterials in tailoring the properties of cementitious composites, coatings, and plastics. However, challenges persist in such areas as dispersion, agglomeration, predicting long-term performance, toxicity evaluation and feasibility assessment. Recommendations are provided, which focus on evaluating durability under in-service conditions, developing sustainable manufacturing methods, and establishing standardized protocols for material preparation and testing. The outcomes emphasize the need for a holistic approach that considers technical, environmental, economic, and social factors to facilitate the widespread adoption of nano-engineered materials. This comprehensive review serves as a valuable reference for researchers, engineers, architects, and construction professionals interested in understanding the current state-of-the-art, limitations, and future outlook on the integration of nanoparticles in construction applications.*

KEYWORDS: *Nanoparticles; Construction materials; Cementitious composites; Mechanical properties; Durability; Sustainability.*

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INTRODUCTION

In recent years, there has been a notable research focus on incorporating nanoparticles into construction materials and architectural structures. Nanoparticles are particles that possess at least one dimension at the nanoscale, typically less than 100 nm [1-6]. A wide range of nanoparticles with diverse physical and chemical properties was investigated for integration into various construction and architecture products, including cementitious materials, composites, coatings, and others [7-12]. Notable categories of nanoparticles that were explored include carbon-based nanoparticles like carbon nanotubes, fullerenes, and graphene, as well as metal and metal oxide-based nanoparticles such as silver, copper, silica, alumina, and titanium dioxide [13-17]. Additionally, polymer-based nanoparticles have also been studied [18-23]. The nanoscale size and high surface area to volume ratio of these particles offer unique properties that can enhance the characteristics and performance of construction materials in various ways [24-30]. Therefore, researchers have examined the incorporation of nanoparticles to improve mechanical properties, enhance durability, introduce functionalities like self-sensing or self-cleaning capabilities, and promote sustainability through reduced resource consumption, increased recyclability, and improved energy efficiency of construction materials and architectural structures [31-37].

Extensive research has been conducted to investigate the potential of nano-silica particles in enhancing the mechanical and durability properties of cementitious materials, such as concrete and mortars. The addition of nano-silica has been observed to expedite cement hydration and refine the pore structure, leading to improvements in compressive strength, fracture toughness, and abrasion resistance [38-42]. Likewise, carbon-based nanoparticles, including carbon nanotubes and graphene, have received considerable attention for their integration into cement composites and fiber-reinforced concrete. The remarkable mechanical properties of carbon nanotubes, such as stiffness and tensile strength, contribute to improvements in flexural strength, fracture toughness, and ductility of cementitious composites even at relatively low nanotube concentrations [43-47]. Additionally, graphene oxide nanosheets have displayed the potential to significantly enhance the compressive and flexural strength of cementitious composites by expediting hydration reactions, reducing porosity, and improving the interfacial bonding between the cement matrix and aggregates [48-52].

Research efforts were directed towards investigating the potential of metal and metal oxide nanoparticles, including copper, zinc oxide, aluminum oxide, and titanium dioxide, for their antimicrobial, photocatalytic, self-cleaning, and anti-corrosion properties in construction materials. Numerous studies were implemented to examine the integration of copper nanoparticles into paints, render, and cement mortar to introduce antibacterial properties that hinder microbial growth, which can lead to degradation and discoloration [53-56]. Titanium dioxide nanoparticles exhibit robust photocatalytic effects when exposed to UV radiation, enabling self-cleaning capabilities in cement composites, while also enhancing compressive strength. Coatings containing zinc oxide nanoparticles can prevent corrosion of steel reinforcement in concrete, thereby improving durability alongside imparting antibacterial effects [57-59]. Moreover, the photocatalytic properties of titanium dioxide nanoparticles have shown promise in air purification applications within the field of architecture and construction. When incorporated into various building facade and construction materials, they facilitate the decomposition of volatile organic compounds and air pollutants [60].

Polymer-based nanoparticles, including latex, epoxy, and polyurethane, have exhibited potential in modifying and improving the performance characteristics of various construction materials, such as concrete, mortars, bricks, composites, and coatings. The addition of styrene butadiene latex nanoparticles during the cement hydration process has been found to accelerate the early development of strength while enhancing workability, adhesion, and durability [61-65]. Epoxy resin nanoparticles have proven an efficiency in enhancing adhesion and tensile strength in cementitious repair mortars [66, 67]. Architectural coatings incorporating polyurethane nanoparticles can provide hydrophobic, self-cleaning, and anti-corrosion properties. Additionally, biopolymer nanoparticles, such as nano-cellulose derived from plant fibers, showed promise as reinforcement in composite materials, contributing to enhanced flexural strength and fracture toughness in a more sustainable and environmentally friendly manner compared to conventional fillers [68-70]. Thus, a diverse array of nanoparticles offer promising capabilities for tailoring and enhancing the multifunctional performance of materials used in construction and architecture.

Some studies have examined the impact of nanoparticles, including nano-silica and nano-titania, on the mechanical and microstructural properties of various materials [71-74]. *Li et al.* [75] investigated the influence of nano-SiO_2 content on compressive strength, pore size distribution, and microstructure in concrete, observing significant enhancements in strength and refinement of pore structure with the addition of nano-silica. Similarly, *Qing et al.* [71] found that the incorporation of nano-titania in high-performance concrete led to strength improvements and a denser microstructure. *Sanchez et al.* [31] conducted a review on nanotechnology advancements in cement and concrete, highlighting the improved performance properties, such as strength enhancement, density, and durability, achieved through the use of various nanoparticles. These studies provide valuable insights into the microscale mechanisms underlying the macroscopic improvements in properties resulting from the incorporation of nanoparticles.

Several investigations have been conducted to explore the potential of different carbon-based nanomaterials, including carbon nanotubes (CNTs), graphene, and carbon nanofibers, in improving the mechanical and multifunctional performance of cementitious materials and different composites [43, 48, 73, 76-79]. *Konsta-Gdoutos et al.* [43] found that the addition of small quantities of CNTs (up to 0.048%) led to a notable increase of more than 25% in the Young's modulus and flexural strength of cement pastes. Similarly, *Nochaiya et al.* [44] observed significant enhancements in fracture toughness and flexural strength when multi-walled CNTs were used to reinforce cement composites. *Lv et al.* [48] reported that the incorporation of graphene oxide nanoflakes at low concentrations (0.03-0.05%) resulted in a remarkable increase of over 40% in compressive strength and over 60% in flexural strength of cement pastes. As a result, the utilization of carbon-based nano-reinforcements shows promise in achieving mechanical enhancements in cementitious materials through synergistic effects at the nano-microscale.

The durability, functionality, and antimicrobial properties of cementitious materials and coatings have been extensively investigated by several researchers, focusing on the effects of various metal and metal oxide nanoparticles [80-84]. Notably, *Cioffi et al.* [53] discovered that the addition of copper nanoparticles in low concentrations (0.5-2% by weight) endowed cement mortars with antibacterial properties, effectively inhibiting the growth of E. coli bacteria on the surface. In another study, *Hüsken et al.* [60] observed that the application of nano-titania coatings on concrete facade panels resulted in air purification and self-cleaning capabilities through the photocatalytic degradation of nitrogen oxides and organic pollutants. Therefore, the utilization of metal and metal oxide nano-additives holds great potential for introducing multifunctional properties into construction materials, leading to enhanced durability, sustainability, and air/self-cleaning ability.

The modification and enhancement of mechanical and working properties of cementitious materials and composites have been the subject of several investigations focusing on the effects of different polymer nanoparticles. *Saxena et al.* [70] reported significant enhancements in flexural strength (up to 90%) and fracture toughness (35%) when cement composites were reinforced with nanocellulose derived from sisal, coconut, and banana fibers compared to plain cement. Hence, the utilization of polymeric nanoparticles holds a promise for their application in construction materials and architectural structures.

Despite the extensive research conducted on the mechanical enhancements achieved by nanoparticles, there has been a relative lack of attention given to exploring their effects on thermal conductivity, electrical properties, and conductivities, all of which hold equal significance in diverse applications within the fields of construction and architecture [85]. *Tugelbayev et al.* [86] observed a remarkable increase in electrical conductivity when 1% multi-walled carbon nanotubes were incorporated into cement paste. *Singh et al.* [87] demonstrated a reduction in electrical resistivity and enhanced electromagnetic interference shielding by incorporating graphene into concrete. *Chandrasekaran et al.* [88] discovered that the addition of 1% boron nitride nanoplatelets to concrete resulted in a significant increase of over 65% in thermal conductivity. These findings indicate that specific nanoparticles offer the potential for substantial customization and enhancement of thermal and electrical properties, which have wide-ranging applications from thermal management to protection against lightning strikes and electromagnetic interference.

However, further research is necessary to fully investigate the effects of nanoparticles on these properties.

The dispersion and distribution of nanoparticles within a cementitious matrix or other materials have been extensively investigated, as they play a crucial role in achieving effective enhancements of material properties [72, 89-92]. *Sobolkina et al*. [89] discovered that ultrasonication proved to be effective in dispersing nano-TiO_2 within cement mixtures, resulting in consistent improvements in strength and density. In another study, *Yazdanbakhsh et al*. [90] reported that the dispersion state of carbon nanotubes had a significant impact on the strength and electrolytic properties of cement composites. Therefore, achieving optimal dispersion of nanoparticles is essential for facilitating desired interactions at the nano and micro-scale within cement-based materials.

The durability properties and long-term behavior of construction materials and structures incorporated with nanoparticles have been the subject of a limited number of studies. Sanchez and Sobolev [31] proposed that the incorporation of nano-engineered cementitious materials could lead to enhanced durability due to reduced porosity and refined microstructure. *Krystek et al*. [93] conducted experimental investigations to evaluate the resistance of graphene-cement nanocomposites against freeze-thaw cycles, seawater exposure, and high temperatures, revealing improved durability compared to plain cement. In a separate study, *Konsta-Gdoutos et al*. [43] observed that properly dispersed carbon nanotubes could potentially delay the onset of corrosion in steel-reinforced cement composites. These findings suggest that certain nanoparticles hold a promise for improving the sustainability and prolonging the service life of construction materials by enhancing their resistance to aggressive environmental factors. However, further long-term field studies are necessary to validate these findings.

Despite the significant potential of nanoparticles in enhancing the performance properties of construction and composite materials, there are still several challenges that require further research. One crucial challenge is the achievement of effective dispersion and optimal distribution of nanoparticles within the base matrix or substrate material [89, 94-97]. The tendency of nanoparticles to agglomerate due to high surface energy and van der Waals forces can impede the complete exposure of the nanoparticle surface area, limiting their interaction with the surrounding matrix [18]. It is important to develop effective dispersion techniques and surface functionalization methods tailored to different nanoparticle-matrix combinations. Gaining a deeper understanding of the mechanisms that influence nanoparticle dispersion and distribution can facilitate improved microstructural engineering. The progress of scientific knowledge across various disciplines has prompted numerous researchers to undertake comprehensive inquiries into material behavior and explore the wide range of potential applications they offer [98-102].

While there have been significant advancements in understanding the incorporation of nanoparticles to enhance the properties of cementitious materials, composites, coatings, and other construction products, there are still several areas that require further research. While many studies have focused on mechanical property improvements [103-105], there is a need to explore functionalities such as self-sensing, energy efficiency, anti-corrosion, and fire-retardance, as these areas have received limited attention. Additionally, the investigation of emerging nanoparticles, including Metal-Organic Frameworks (MOFs) and nanocellulose, which have shown promise in preliminary studies, is necessary. Furthermore, experimental validation of predictive models developed through molecular dynamics simulations will provide a better understanding of the structure-property relationships in nanoparticle-incorporated materials and enable optimal design. Although field-based research, lifecycle assessments, and investigations into exposure risks, aging, and deterioration mechanisms of nano-modified materials are limited, they are crucial for supporting practical applications and facilitating the transition into real-world scenarios.

Some research efforts were directed towards investigating the environmental and health safety aspects of nanoparticles in construction materials. For example, *Diamond et al*. [106] examined the leaching and release kinetics of titanium dioxide nanoparticles from cementitious materials using column tests, demonstrating minimal leaching under realistic exposure conditions. *de Souza et al*. [107] investigated occupational exposure risks associated with handling engineered cementitious composites containing graphene, emphasizing the importance of implementing exposure control strategies [108]. While several studies indicate that nanoparticles can be safely incorporated at optimal dosages, further research is necessary for a comprehensive assessment of the environmental and health impacts involved.

Further research is necessary to address the identified gaps and challenges in the field. It is crucial to conduct comprehensive studies that focus on evaluating the long-term performance and durability of nano-modified concretes, composites, and coatings when exposed to real environmental conditions. Standardized protocols should be developed for material preparation, nano-dispersion, and incorporation methods. Additionally, investigations should be carried out to assess the environmental and health safety aspects throughout the life cycles of nano-modified materials, including leaching studies, life cycle assessments, and exposure monitoring. The modeling efforts should be aimed to see the reinforcing effects and correlations between micro and macro properties in nano-modified cementitious materials. Furthermore, techno-economic studies should be conducted to evaluate the feasibility, cost-benefit analysis, and sustainability implications of adopting these materials in the construction industry. The targeted research efforts in these areas can facilitate the effective translation and adoption of nano-modified materials in sustainable, resilient, and smart construction practices on an industrial scale [109-113].

In conclusion, the review of the literature highlights the wide range of nanoparticles investigated for modifying and enhancing the properties of various construction materials, such as concrete, composites, coatings, tiles, glass and facade elements. Significant progress is reached in demonstrating the potential of nanomaterials to tailor the mechanical, structural, functional and microstructural properties of construction materials. However, knowledge gaps remain regarding real-time performance throughout product lifecycles, environmental impacts, health and safety implications, and the feasibility and sustainability of adopting nano-modified materials on an industrial scale. The targeted research efforts are needed to develop standardized protocols for materials processing and characterization, evaluate long-term field performance, investigate environmental and health impacts through life cycle assessments, establish nanostructure-property relationships through modeling and determine the techno-economic viability through cost-benefit analysis. Addressing these research gaps will unlock the full potential of nanotechnology in enabling smarter, multifunctional, durable, and sustainable construction materials and structures.

This review article is aimed to comprehensively survey the current state of research on incorporating nanoparticles in construction materials, analyzing the achieved effects on various properties and performance enhancements. The significance of this research area lies in the considerable innovation potential of nanotechnology in enabling smarter, multifunctional, and more sustainable construction materials and structures. The objective is to critically review the literature on nano-modified cementitious materials, polymeric composites, and coatings, evaluate the current progress, and identify the challenges and future research needs. The study methodology involves an in-depth literature review of relevant research publications from the past two decades using scientific databases and citation analysis. Both experimental and modeling-based studies focused on nano-modified construction materials are examined. The key areas of focus include mechanical properties, microstructure, durability, functionality, early-age properties, dispersion, orientation, safety, and sustainability. The outcomes and findings of this review can serve as a valuable resource for researchers, engineers, architects, and professionals in the construction industry, providing realistic insights into the prospects and limitations of employing nano-engineered materials. Additionally, the identification of research gaps will assist in charting strategic directions for future studies in this field. Therefore, this review article is targeted to be a comprehensive reference for assessing the current advancements and future potential of nanotechnology in the architecture, engineering, and construction sector.

OVERVIEW OF NANOPARTICLES USED IN CONSTRUCTION MATERIALS

Extensive research has been conducted on a wide range of nanoparticles with diverse chemical compositions for their integration into construction materials. These nanoparticles offer the potential to enhance the performance and introduce multifunctional properties into the materials. Categorically, the nanoparticles can be classified into four main groups based on their chemical composition: carbon-based, metal/metal oxide-based, polymer-based, and other novel or emerging nanoparticles. Each category possesses distinct characteristics that make them suitable for modifying specific properties in construction materials.

Carbon-based nanoparticles, such as CNTs, graphene, carbon nanofibers, and fullerenes, have attracted considerable interest due to their exceptional mechanical, electrical, and thermal properties [31, 114]. CNTs are cylindrical nanostructures known for their ultra-high tensile strength, electrical and thermal conductivities, which make them ideal for multifunctional reinforcement [43]. Graphene consists of single-atom thick sheets of sp2 hybridized carbon atoms arranged in a honeycomb lattice, exhibiting superior mechanical stiffness, fracture strength, electrical conductivity, and surface area [88]. Research indicates that even at low concentrations of 0.02-0.1% by weight, graphene nanoplatelets can significantly enhance the mechanical performance and durability of cementitious composites [48]. Carbon nanofibers possess high tensile strength, electrical conductivity, and surface activity, and they can be utilized to improve cracking resistance and sensing capabilities [18]. Additionally, fullerene nanoparticles exhibit free radical scavenging properties that could provide antioxidant functionality [64].

The integration of metal and metal oxide nanoparticles into construction materials has demonstrated a potential for introducing various functionalities, including catalytic, electrical, thermal, and antimicrobial properties [31, 74, 115]. Nano-titania, for instance, exhibits strong self-cleaning and photocatalytic effects when exposed to UV light, and the properties are utilized in self-cleaning cement composites and coatings [116]. Copper, zinc oxide, and silver nanoparticles possess notable antibacterial properties, causing cellular damage and releasing metal ions to combat common microbes [53, 117-121]. The plasmonic characteristics of silver nanoparticles offer the potential for electrical conductivity, surface-enhanced Raman scattering, and optical effects in materials [54, 119]. Nano-silica is extensively studied for its pozzolanic reactivity with calcium hydroxide in cement, resulting in accelerated hydration, improved pore structure, and enhanced strength and durability properties when used at typical dosages of 1-5% by weight [39].

Polymeric nanoparticles, including latex, epoxy, and polyurethane, have also demonstrated the ability to modify both mechanical and functional properties of construction materials [122]. Latex nanoparticles, through steric stabilization effects, can accelerate cement hydration and provide reinforcement, leading to improved adhesion, workability, and strength [123]. Epoxy nanoparticles contribute to crosslinking reinforcement in repair mortars and adhesives, enhancing tensile strength and bonding effectiveness. Polyurethane nanoparticles form durable and flexible coatings on various surfaces such as concrete, metal, and wood, offering abrasion/corrosion resistance and hydrophobic waterproofing properties [124].

Several emerging categories of nanoparticles show a promise for construction applications, including nanoclays, cellulose nanocrystals, carbon dots and metal organic frameworks (MOFs) [125-127]. Nanoclays, such as montmorillonite, possess high sorption capacity and act as effective barriers against water and chemicals. Cellulose nanocrystals derived from plants exhibit exceptional strength and toughness due to their crystalline structure. Carbon dots and polymer-based MOFs offer customizable porosity, enabling advanced functionalities through surface functionalization.

In construction materials, different types of nanoparticles offer complementary benefits. Carbon-based nanoparticles provide mechanical reinforcement, metal/metal oxide nanoparticles contribute to functional enhancements, polymeric nanoparticles improve adhesion and dispersion and novel nanoparticles offer specific applications. In Table 1, a summary of key nanoparticles, their characteristic properties, and potential applications in construction materials (adapted from the original source) is provided. However, further research is needed to address scalability, cost-effectiveness, and compatibility issues across different nanoparticle-matrix combinations to ensure optimal utilization. Additionally, thorough evaluation of performance benefits and potential risks is crucial to facilitate the construction industry's adoption of nano-engineered materials.

Carbon-based nanoparticles

Carbon-based nanomaterials, such as CNTs, graphene, carbon nanofibers, and fullerenes, have garnered significant attention in the realm of construction materials due to their exceptional mechanical, electrical, and thermal properties.

Table 1: Applications of different nanoparticles in construction materials

Nanoparticle Type	Specific Examples	Key Properties	Potential Applications	Reference
Carbon nanotubes (CNTs)	Multi-walled CNTs, Single-walled CNTs	High tensile strength, electrical conductivity, thermal conductivity	Mechanical reinforcement, self-sensing, energy storage	[43]
Graphene	Graphene nanoplatelets, Graphene oxide	Extremely high stiffness and strength, high electrical and thermal conductivity	Mechanical enhancement, self-sensing, electromagnetic shielding	[88]
Carbon nanofibers	Vapor grown carbon nanofibers	High tensile strength, electrical conductivity	Crack control, self-sensing	[18]
Nano-titania	Titanium dioxide nanoparticles	Photocatalytic activity, self-cleaning	Air purification, antibacterial, self-cleaning coatings	[116]
Nano-silica	Silica nanoparticles, Fumed silica	High pozzolanic reactivity	Strength and durability enhancement in cementitious materials	[39]
Nano-zinc oxide	Zinc oxide nanoparticles	Antibacterial properties	Self-sterilizing coatings, antimicrobial concrete	[128]
Latex	Styrene butadiene latex nanoparticles	High surface area, colloidal stability	Workability enhancement, accelerated hydration	[123]
Epoxy	Epoxy resin nanoparticles	Strong adhesive bonding	Repair of microcracks, adhesive anchors	[124]
Polyurethane	Polyurethane nanoparticles	Tough, flexible, hydrophobic polymer matrix	Abrasion/corrosion resistant coatings	[129]
Nanoclays	Montmorillonite nanoclay	Sorptive capacity, barrier effects	Water/chemical resistance, reduced permeability	[125]

CNTs, characterized by their cylindrical nanostructure composed of rolled graphene sheets, come in single-walled or multi-walled forms. They possess remarkable tensile strength (approximately 150 GPa), electrical conductivity (104-106 S/m), and thermal conductivity (over 3000 W/mK) arising from their sp2 hybridized carbon bonds [130, 131]. These unique properties have propelled extensive research on integrating CNTs into cementitious composites, epoxy resins, and coatings for construction purposes. Direct mixing, sol-gel methods, and spray coating techniques are commonly employed to incorporate CNTs into cement composites, while in situ polymerization is utilized for polymer-based materials [89]. Incorporating CNTs at low concentrations ranging from 0.01 to 0.5 wt% was shown to significantly enhance the mechanical performance of the matrix through crack bridging, filler effects, and nanoscale reinforcement [43, 44]. In cement composites, CNTs expedite hydration reactions and refine the microstructure by providing nucleation sites, resulting in improved compressive strength and elastic modulus [89]. Furthermore, the high aspect ratio and surface area of CNTs enable sensing capabilities by altering electrical resistivity under strain [132]. However, achieving proper dispersion and interfacial bonding of CNTs remains a challenge due to van der Waals interactions. Techniques such as atomic layer deposition and the use of surfactants show a promise in enhancing dispersion [57, 78]

In a recent study conducted by *Parsafar et al.* [133], a novel electrochemical sensor was developed for the purpose of detecting hydrogen sulfide (H2S) gas. This sensor employed carboxylated Multi-Walled Carbon NanoTubes (MWCNTs) and a hydrophobic polytetrafluoroethylene (PTFE) membrane as the working electrode, as shown in Fig. 1. The PTFE membrane, which was coated with MWCNTs, allowed the permeation of H_2S gas while preventing the loss of electrolyte. Scanning electron microscopy (SEM) images displayed a uniform distribution of MWCNTs on the surface of the PTFE membrane (Fig. 1-c, d), facilitating effective interaction between the gas, electrolyte, and MWCNT

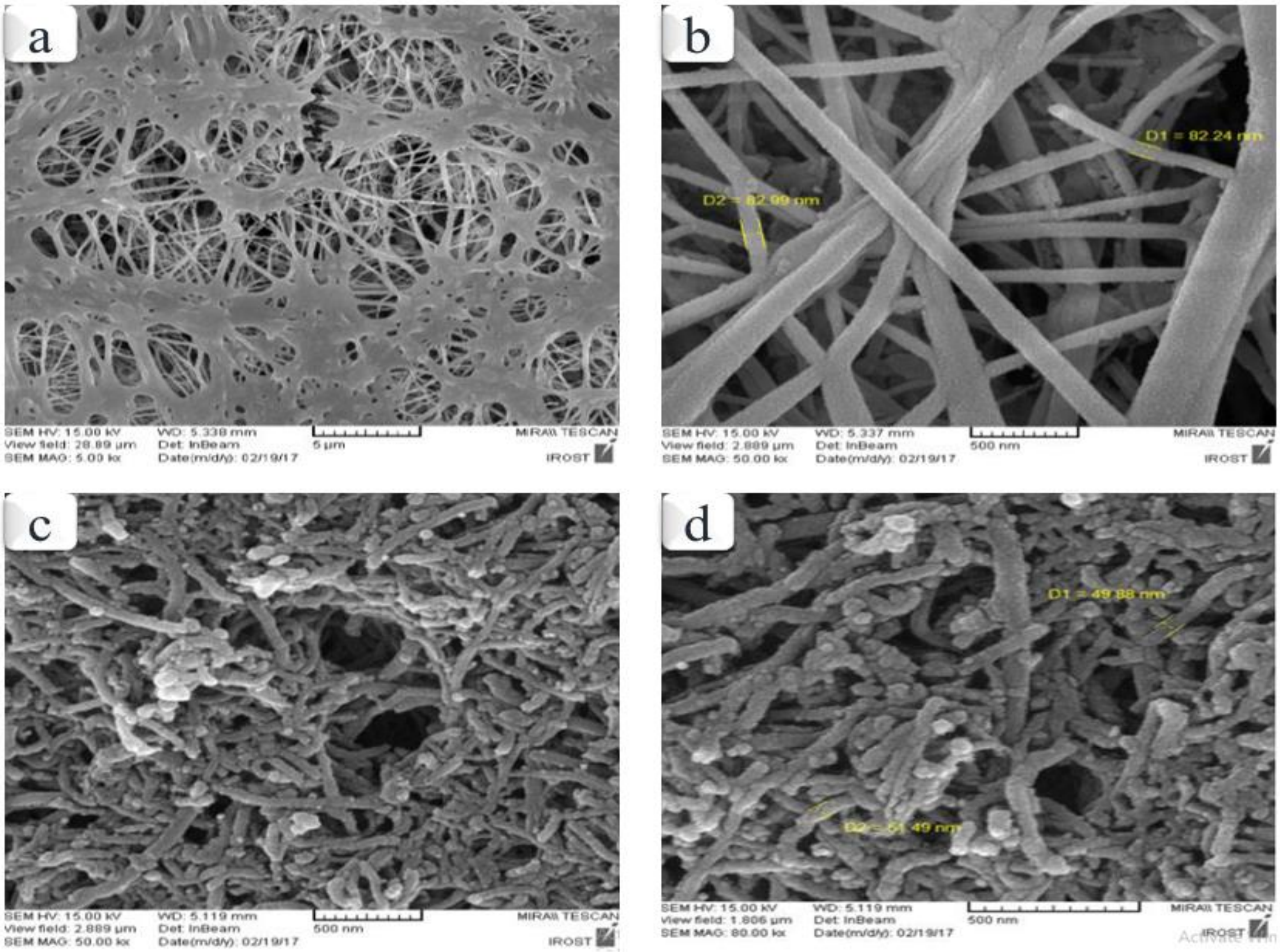


Fig. 1. ***Scanning electron microscopy visualization of (a, b) a hydrophobic PTFE membrane and (c,d) carboxylated carbon nanotubes adhered to the membrane surface; [133]***

electrocatalyst. Furthermore, quantitative energy dispersive X-ray spectroscopy (EDX) analysis confirmed the existence of oxygen-containing functional groups on the MWCNTs, which rendered them hydrophilic and enabled wetting by the sulfuric acid electrolyte. The sensor is characterized by a linear detection range of H2S from 310 ppb to 16 ppm, exhibiting superior performance compared to unmodified MWCNTs. This successful functionalization of MWCNTs for H_2S sensing highlights the potential of carbon nanotubes in the realm of electrochemical gas detection.

Graphene, a two-dimensional lattice structure consisting of single-atom thick sheets of carbon atoms bonded in a honeycomb pattern, exhibits exceptional intrinsic strength (130 GPa), stiffness (1 TPa), electrical conductivity, and thermal conductivity [134]. Graphene Oxide (GO) and reduced graphene oxide (rGO), which contain oxygen functional groups, were extensively investigated for their integration into cementitious materials, polymers and coatings. Various methods, such as Hummer's method and reduction processes using chemical agents or thermal treatment, are commonly employed to synthesize GO/rGO [135]. The high surface area, 2D morphology and inherent mechanical properties of graphene nanoplatelets offer a significant potential for enhancing the strength, fracture toughness and durability of cementitious composites through different mechanisms, such as crack deflection, nucleation and nanoscale filler effects, even at low concentrations ranging from 0.02 to 0.1 wt% [136]. Furthermore, graphene improves the flexural strength and thermal conductivity of fiber-reinforced polymer composites by facilitating efficient

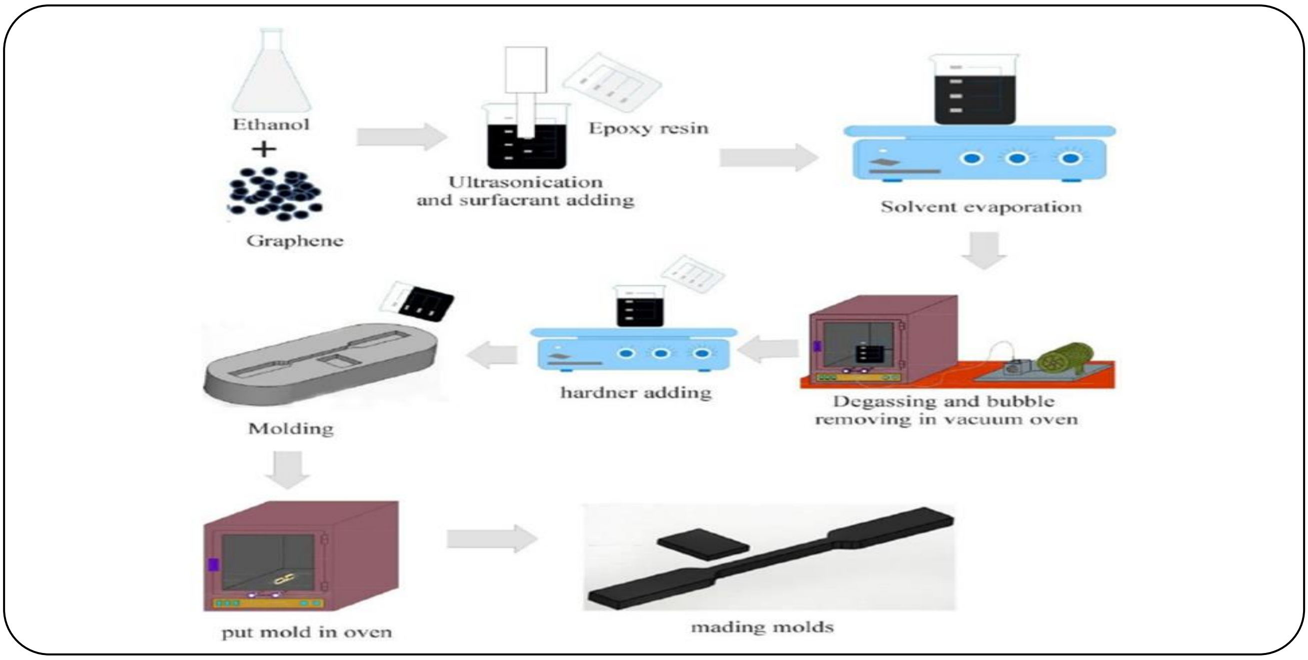


Fig. 2. Preparation process for rGO-epoxy nanocomposite [138]

load transfer [137]. However, the aggregation of graphene due to van der Waals interactions can limit its reinforcement effects. Surface functionalization techniques using surfactants showed a promise in enhancing dispersion.

In a recent study conducted by *Keshavarz et al*. [138], the development of conductive graphene-epoxy nanocomposites using GO and rGO was reported. In Fig. 2, the process of preparing rGO by reducing GO using L-ascorbic acid is illustrated, as confirmed by Fourier transform infrared spectroscopy and X-ray diffraction analysis. Subsequently, the rGO was dispersed in epoxy resin with the assistance of a surfactant to facilitate dispersion. The incorporation of rGO led to a significant enhancement in the electrical conductivity of the nanocomposites, with a maximum value of 3×10-4 S/m achieved at a loading of 2 wt% rGO. This improvement corresponds to an advancement of 8 orders of magnitude in comparison to neat epoxy. The functionalization and reduction of graphene oxide offer the opportunity to fabricate epoxy nanocomposites with remarkably enhanced electrical properties.

Carbon nanofibers, composed of stacked cups of graphite sheets, exhibit high tensile strength (up to 10 GPa), high electrical conductivity and large surface area, which can be harnessed to enhance the toughness, cracking resistance, electromagnetic shielding and self-sensing capabilities of materials, such as polymer composites and concretes [18, 139]. Fullerene nanoparticles, characterized by their spherical, elliptical, or cylindrical arrangements of carbon atoms, have the potential to enhance mechanical properties through efficient load transfer due to their molecular structure. Additionally, fullerenes act as radical scavengers and may impart antioxidant functionality in coatings and cementitious materials. However, the high cost and limited scalability of fullerene synthesis methods currently restrict their widespread application [140].

Therefore, in the realm of construction materials, there has been significant research conducted on the utilization of carbon nanotubes and graphene as reinforcements at the nanoscale. These materials have been investigated for their potential in improving the mechanical, electrical, and thermal properties of cementitious and polymeric composites. The findings of several recent studies pertaining to the incorporation of CNTs and graphene in such construction materials are presented in Table 2.

The remarkable multi-functional properties exhibited by carbon nanomaterials offer significant possibilities for the advancement of high-performance, long-lasting, and intelligent construction materials. Nevertheless, challenges such as cost-effective and scalable synthesis methods, dispersion and interfacial bonding

Table 2: Recent studies on the addition of carbon-based nanoparticles in construction materials

Nanoparticle	Matrix	Concentration	Enhanced Properties	Reference
CNTs	Cement paste	0.048%	25% increase in flexural strength and fracture energy	[43]
Graphene	Cement paste	0.05%	40% increase in compressive strength, 60% increase in flexural strength	[48]
CNTs	Epoxy	1%	30% increase in storage modulus, 45% increase in glass transition temperature	[141]
Graphene	Epoxy	0.5%	130% increase in impact strength	[142]
CNTs	Cement paste	0.2%	50% increase in piezoresistivity, self-sensing capability	[143]
Graphene	Cement	0.03%	85% increase in electrical conductivity	[144]
CNTs	Latex	4%	Formation of percolated network, electrical conductivity	[145]
Graphene	PLA	0.4%	20% increase in Young's modulus	[146]
CNTs	Epoxy	0.1%	Enhanced thermal conductivity	[147]
Graphene	PU Foam	0.05%	Improved mechanical properties, thermal stability	[148]
CNTs	Cement	1%	Reduced chloride permeability, improved corrosion resistance	[149]
Graphene	Concrete	0.02%	Refined pore structure, reduced permeability	[150]
CNTs	Epoxy	0.3%	Increased storage modulus, damping properties	[151]
Graphene	Epoxy	0.1%	Enhanced scratch resistance	[152]

issues, as well as considerations regarding health and environmental risks, need to be carefully addressed through ongoing research to facilitate wider adoption of these materials by the industry.

Metal and metal oxide nanoparticles

Metal and metal oxide nanoparticles have gained significant attention in research for their ability to impart multifunctional properties to construction materials. This category includes various nanomaterials such as nano-silica, nano-titania, nano-zinc oxide, nano-alumina, nano-iron oxide, and nano-copper oxide. These inorganic nanoparticles offer distinct electrical, optical, photocatalytic, antimicrobial, and self-cleaning characteristics that can enhance the performance of cementitious materials, polymer composites, and coatings [31].

Silica nanoparticles were extensively investigated for their integration into cementitious composites. They exhibit high reactivity with calcium hydroxide released during cement hydration, resulting in additional pozzolanic reactions. This leads to a refinement of the pore structure, reduction in porosity, and improvement of interfacial transition zones in concrete [75]. The addition of silica nanoparticles at typical dosages of 1-5 wt% significantly enhances the compressive strength, flexural strength and abrasion resistance of cement composites [38]. Moreover, the durability of these composites against environmental factors, such as freezing-thawing cycles, sulfate attack and chloride penetration is also improved [71].

The photocatalytic properties of titanium dioxide nanoparticles have attracted attention, particularly their ability to degrade organic contaminants and air pollutants such as nitrogen oxides under UV exposure. Incorporating nano-titania into construction materials enables self-cleaning and air purification capabilities, contributing to enhanced sustainability [60]. Furthermore, the addition of 0.5-5 wt% nano-titania accelerates cement hydration, refines the microstructure, and improves the compressive strength and elastic modulus of concrete [153].

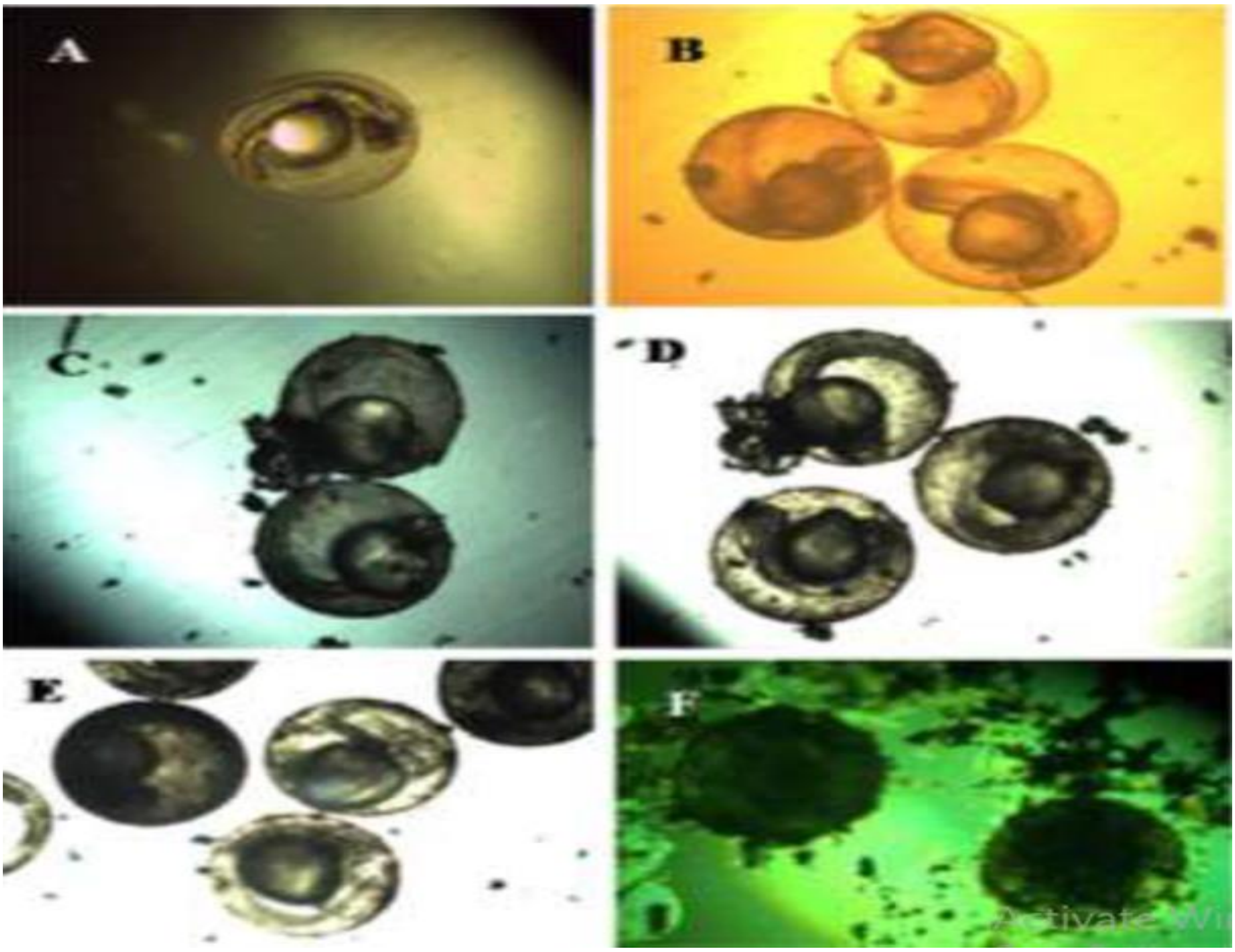


Fig. 3: Representative images of zebrafish embryos exposed to green synthesized ZnO nanoparticles at 72-96 hours post fertilization, demonstrating developmental deformities [155]

Zinc oxide nanoparticles exhibit a wide range of antibacterial properties that are effective against various common microbes [128]. These properties primarily arise from their ability to cause direct cellular damage and release ions. When incorporated into construction materials, nano-ZnO offers sterilization effects that help prevent microbial-induced corrosion and the formation of biofilms on material surfaces, particularly in coatings and paints [154]. Furthermore, the inclusion of nano-ZnO in cement composites imparts hydrophobic characteristics and enhances water repellence. In a recent study conducted by *Subramanian et al*. [155], zinc oxide nanoparticles were synthesized using an environmentally friendly method involving the use of Syzygium cumini seed extract. The resulting biogenic ZnO nanoparticles were subjected to characterization and assessed for their potential developmental toxicity in zebrafish embryos. Fig. 3 is the outcomes of the experiment, where exposure to ZnO nanoparticles at concentrations ranging from 50 to 150 µg/mL led to the aggregation of nanoparticles on the chorion. Furthermore, these concentrations induced deformities such as spinal curvature, yolk sac edema, and pericardial edema in zebrafish embryos at 72-96 hours post fertilization. The toxicity and developmental effects observed in the zebrafish model were found to be dependent on the dosage of the green-synthesized ZnO nanoparticles. This study highlights the usefulness of eco-friendly ZnO nanoparticles in nanotoxicity investigations, particularly in relation to embryonic toxicity assessment.

Copper oxide nanoparticles possess potent antibacterial, antifungal, and antiviral properties, making them suitable for the development of self-sterilizing cementitious materials and coatings that can prevent microbial-induced degradation [53, 156-158]. By directly contacting microbes, nano-CuO induces damage to their cell membranes, and typical dosages of 0.5-2% are sufficient to provide antibacterial effects. The incorporation of alumina nanoparticles refines the pore structure of cement pastes, reducing permeability and improving durability against water and chemical exposures [39]. Iron oxide nanoparticles contribute to enhanced electromagnetic wave absorption, making them suitable for radiation shielding applications [159].

The incorporation of antimicrobial properties in construction materials is of utmost importance for tackling degradation problems arising from microbial activity. Bacterial and fungal biofilm formation not only results in surface discoloration and material decay but also leads to a decline in functional properties [128]. Moreover, microbial activity can directly induce corrosion in metals, concrete, and masonry structures through the generation of acids, which lower the pH and initiate electrochemical reactions. Hence, it is imperative to integrate antimicrobial properties into construction materials to effectively counteract microbial degradation.

In summary, metal/metal oxide nanomaterials offer unique functionalities, such as self-cleaning, sterilization, photocatalysis, conductivity and durability enhancements in construction materials. However, it is important to address concerns related to toxicity, high costs, and stability under harsh exposures through further investigation. A comprehensive evaluation of the balance between performance enhancement, potential risks, and techno-economic feasibility is crucial to facilitate the widespread adoption of metal oxide nano additives in the construction industry.

Polymer-based nanoparticles

Polymer-based nanoparticles, including latex, epoxy, polyurethane and biopolymers, offer a potential for tailoring the properties of construction materials, such as concrete, mortars and coatings. These organic nanoparticles can be synthesized using various techniques, including emulsion polymerization, interfacial polymerization, and controlled radical polymerization [160]. With their colloidal stability, high surface area, and adjustable surface chemistry, polymeric nanoparticles allow for modifications to the microstructure, mechanical performance, and functionality of building materials.

Latex nanoparticles, which consist of nano-sized polymer particle dispersions, were extensively researched for their integration into concrete and cementitious materials [123]. Common polymers, such as styrene-butadiene, polyacrylic and polyvinyl acetate, are used to synthesize latex nano-dispersions [161]. During cement hydration, the latex nanoparticles accelerate the early development of strength by providing nucleation sites. They also refine the pores through steric stabilization effects, improving the bond between concrete and aggregates, and enhancing adhesion, strength, fracture toughness, and abrasion resistance. Typical dosages of latex nanoparticles in concrete are in the range of 5-10 wt%. Additionally, latex modification enhances the flexibility, impermeability, and resistance to freeze-thaw cycles of concrete [162].

Epoxy nanoparticles, synthesized through interfacial or emulsion polymerization techniques, offer excellent adhesion due to their highly crosslinked structure [163]. The addition of 1-5% epoxy nanoparticles to cementitious repair mortars and adhesives significantly enhances tensile strength, flexural strength, and bonding effectiveness by improving compatibility and bonding at the interface between the matrix and particles [164]. Furthermore, epoxy nano-modifications increase resistance to shrinkage and crack propagation.

Polyurethane nanoparticles form durable and flexible coatings that can modify interfacial properties when applied to various construction materials, including concrete, metals, and wood. With their hydrophobic nature, polyurethane nanocoatings provide excellent waterproofing, corrosion resistance, and abrasion protection. These nanocoatings can also exhibit self-cleaning properties and resistance to bacterial adhesion. Typical application methods involve spray coating or incorporation during the mixing process [129].

Biopolymer nanoparticles, specifically nanocellulose derived from plant fibers, have emerged as a promising sustainable reinforcement material for composites and concretes [70]. Nanocellulose possesses high intrinsic strength (up to 10 GPa) and stiffness (up to 140 GPa) due to its crystalline structure composed of rigid rod-shaped nanoparticles. When properly dispersed, nanocellulose can significantly enhance the flexural strength, fracture toughness, and impact resistance of cementitious materials and composites. Therefore, the incorporation of polymeric

Fig. 4: Production process for sugarcane bagasse nanocellulose [165]

nano-additives offers versatile options for tailoring the mechanical properties, functionality, and interfacial characteristics of construction materials through sustainable modifications of the microstructure. However, challenges related to dispersion, interfacial compatibility, and cost-effectiveness need to be addressed to facilitate wider utilization. *Nguyen et al*. [165] investigated the production of nanocellulose from sugarcane bagasse, an abundant agricultural residue from Vietnam's sugar industry. Fig. 4 illustrates the process involved, where the raw sugarcane bagasse underwent alkaline pulping and bleaching to obtain cellulose pulp. Subsequently, the cellulose pulp was subjected to chemical and mechanical processing via limited sulfuric acid hydrolysis to produce nanocellulose. The resulting nanocellulose exhibited a high crystallinity of 80.11% and had a diameter ranging from 20 to 60 nm. When applied as a coating on paper, the nanocellulose significantly enhanced the mechanical strength and barrier properties of the paper sheets. This study showcases the comprehensive utilization of sugarcane bagasse for the production of both paperboard and nanocellulose, thereby highlighting the potential of agricultural residues as valuable sources of nanomaterials.

Other emerging nanoparticles (MOFs, nanocellulose)

In addition to the previously discussed nanoparticle categories, ongoing research is devoted to exploring innovative and emerging nanomaterials that offer new prospects for construction applications. These include MOFs, nanoclays, nanocellulose, carbon dots, and other bio-based nanoparticles.

MOFs are composed of metal ions or clusters coordinated with organic linkers, resulting in the formation of crystalline and porous structures. MOFs exhibit remarkably high surface area, adjustable pore sizes, and the capability to encapsulate functional guest molecules [69, 166]. These characteristics were harnessed in the development of MOF nanoparticles for targeted drug delivery, sensing and advanced construction materials. The MOF nanoparticles synthesized from metals, such as

Table 3: Recent investigations on the incorporation of polymeric nanoparticles in construction materials.

Nanoparticle	Matrix	Concentration	Enhanced Properties	Reference
Latex	Mortar	10%	20% increase in flexural strength	[176]
Epoxy	Mortar	1%	30% increase in bond strength	[177]
PU	Coating	3%	Improved hydrophobicity, ~100% water contact angle	[178]
Cellulose	Cement	2%	80% increase in toughness	[179]
Latex	Concrete	5%	Refined pores, reduced permeability	[180]
Epoxy	Mortar	3%	Higher early strength	[181]
PU	Coating	5%	Enhanced scratch resistance	[182]
Cellulose	Cement	1.5%	20% increase in strength	[183]
Latex	Concrete	8%	Increased resistance to freezing and thawing	[184]
Epoxy	Mortar	2%	Improved resistance to shrinkage cracks	[185]
PU	Coating	4%	Effective corrosion protection	[186]
Cellulose	Composite	0.5%	30% increase in impact strength	[187]
Latex	Concrete	10%	Enhanced workability	[188]
Epoxy	Mortar	5%	85% increase in bond strength	[177]
PU	Coating	2%	Antibacterial effects	[189]
Cellulose	Cement	1%	Refined pore structure	[190]

Zr and Fe, and biomaterials like gallic acid or alginate serve as customizable platforms to reach functionalities like self-healing, self-cleaning and controlled release of corrosion inhibitors in coatings and cementitious materials [167, 168].

Nanoclays, including montmorillonite, kaolinite, and halloysite, have attracted attention as nanofillers in composites and cementitious materials. The considerable surface area and sorption capacity of nanoclays make them effective barriers against fluid and gas permeability. Incorporating nanoclays enhances the durability of concrete and coatings by reducing water absorption, gas permeability, and the diffusion of aggressive chemicals. Moreover, the nanoscale dispersion of clay particles improves strength by optimizing particle packing density. Adding 1-5% nanoclays can refine the pore structure and significantly decrease permeability [169-171].

Luminescent carbon-based nanomaterials known as carbon dots have recently emerged as innovative smart sensors due to their photoluminescence properties. When integrated into structural composites, they enable the detection and monitoring of damage by exhibiting changes in luminescence under stress. The polymer-functionalized carbon dots also demonstrated a potential for controlled release of corrosion inhibitors, healing agents and other chemicals to provide additional functionalities. However, the utilization of carbon dots in construction materials is still in its early stages [172-174].

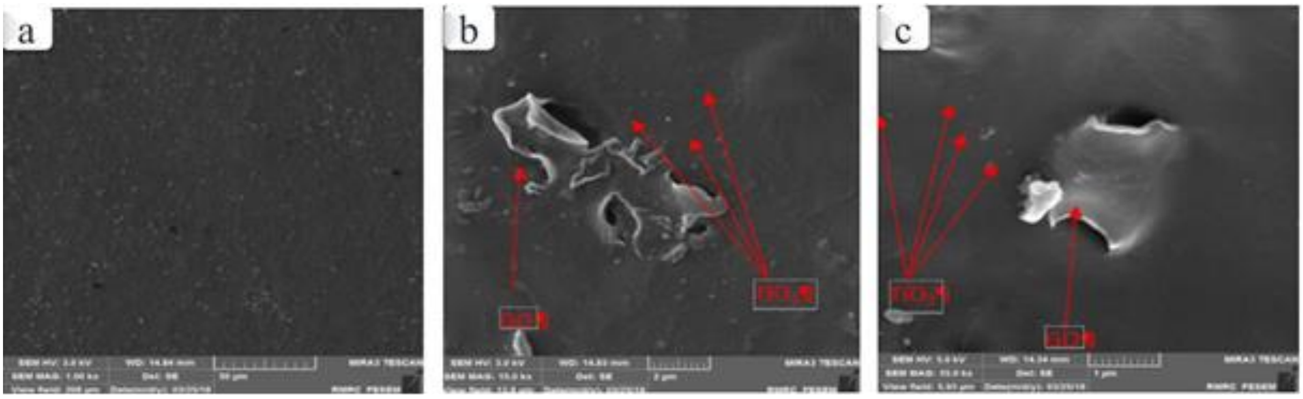


Fig. 5: FE-SEM images showing dispersion of TiO_2 and GO nanoparticles in the PLA matrix with different magnification of a) 1000X, b) 15000X, and c) 35000X, [146]

In general, the introduction of emerging nanomaterials offers vast opportunities for the development of advanced multifunctional composites and coatings in the field of construction. Nevertheless, it is crucial to assess concerns related to toxicity, high costs, scalability challenges, and long-term stability [175]. Furthermore, comprehensive investigations are needed to evaluate the actual performance benefits and potential risks of these novel nanoparticles under real-world conditions, thereby supporting their adoption by the construction industry.

Therefore, polymeric nanoparticles, encompassing latex, epoxy, polyurethane, and biopolymers, present an opportunity to customize the characteristics of construction materials, including concrete, mortars, and coatings. The latest research on the integration of polymeric nano-additives into cementitious composites and coatings is succinctly summarized in Table 3.

The incorporation of polymeric nano-additions provides a versatile approach to customize the mechanical properties, functionality, and interfacial characteristics of construction materials. These modifications can be achieved sustainably by altering the microstructure. However, there are several challenges that must be overcome to enable broader utilization, including the dispersion of nanoparticles, ensuring interfacial compatibility, and optimizing cost-effectiveness.

ENHANCEMENT OF MECHANICAL PROPERTIES

The addition of nanoparticles has demonstrated the potential to significantly enhance crucial mechanical properties of construction materials, such as strength, modulus of elasticity, fracture toughness, and hardness. These improvements directly impact the durability, damage tolerance, and load-bearing capacity of the materials. Therefore, extensive research has focused on investigating the mechanical enhancements induced by various types of nanoparticles in construction materials.

Numerous studies have provided evidence that nanoparticles can impart significant improvements in the compressive and flexural strength of cementitious materials [43, 75]. Nanoparticles contribute to the acceleration of cement hydration and pozzolanic reactions, leading to a refined pore structure with reduced porosity [39]. Additionally, the high surface area of nanoparticles offers nucleation sites for the formation of hydration products, resulting in a denser cement matrix [38]. Nanoparticles fill nano-scale voids within the microstructure and enhance the interfacial bonding between cement paste and aggregates. These modifications in the microstructure collectively contribute to an increase in strength. Multiple studies have reported strength enhancements ranging from 20 to 40% in cementitious materials modified with nanoparticles, such as nano-silica, titania, alumina, carbon nanotubes or graphene oxide, at relatively low concentrations of 0.5-5 wt% [44, 48, 153, 191].

Sharifiana et al. [146] synthesized and characterized hybrid nanocomposites of polylactic acid (PLA) containing graphene oxide (GO) and titanium dioxide (TiO_2) nanoparticles for their mechanical, thermal, and antibacterial properties. In Fig. 5, the uniform dispersion of TiO_2 and GO nanoparticles within the PLA matrix is seen. The incorporation of 0.4 wt% GO resulted in an enhancement of the Young's modulus of PLA from 2850 MPa to 3760 MPa, while the addition of 1 wt% TiO_2 nanoparticles increased the tensile strength from 33.2 MPa to 41.1 MPa. Furthermore,

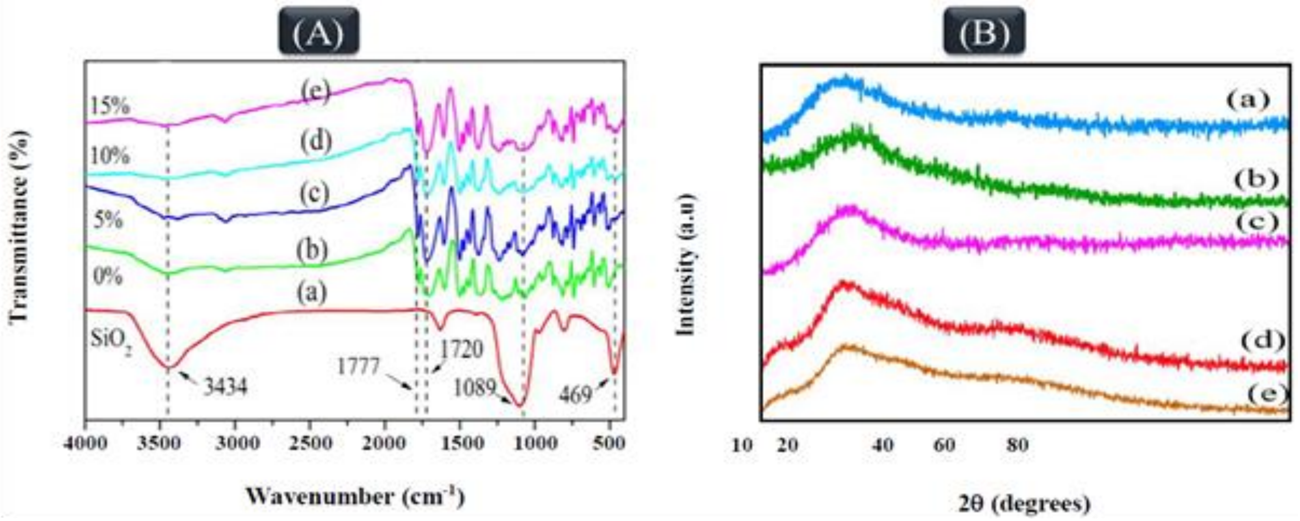


***Fig. 6:** (A) FTIR spectra (In this figure: (a) pure SiO_2, (b) pure PE, (c) PE/SiO_2 NC 5%, (d) PE/SiO_2 NC 10%, and (e) PE/SiO_2 NC 15%.) and (B) XRD patterns showing incorporation of SiO_2 nanoparticles in the PE polymer matrix (In this figure: (a) pure SiO_2, (b) pure PE, and (c, d, e) NC hybrid film with different amounts of SiO_2 nanoparticle.) [192]*

the nanocomposites exhibited improved thermal stability and demonstrated antibacterial activity against Escherichia coli (*E. coli*) and Staphylococcus aureus (S. aureus) with increasing TiO_2 content. The homogeneous dispersion of the nanoparticles and the synergistic effects between them contributed to the overall enhancement in the properties of the PLA-based nanocomposites.

Ahmadizadegan [192] evaluated nanocomposite membranes of polyester (PE) containing silica (SiO_2) nanoparticles and their gas transport and mechanical properties. Fig. 6 is the structural characterization of the nanocomposites using Fourier Transform InfraRed (FT-IR) spectroscopy and X-ray diffraction (XRD), confirming the successful incorporation of SiO_2 nanoparticles within the PE polymer matrix. The nanocomposites displayed improved thermal stability and mechanical properties, including increased tensile strength and Young's modulus, as the SiO_2 content was increased up to 15 wt%. The presence of nanoparticles restricted the segmental motion of the PE chains, primarily through interactions with the hydroxyl groups on the surface of SiO_2. However, higher loadings of SiO_2 resulted in decreased elongation at break due to nanoparticle agglomeration. In this study, the potential of SiO_2 nanoparticles to enhance the strength and heat resistance of PE polymers was indicated.

The addition of nanomaterials was found to significantly improve the fracture toughness and ductility of construction materials. Nanoparticles play a vital role in bridging cracks at the nanoscale and promoting crack deflection mechanisms, leading to increased energy absorption before failure [89]. Notably, CNTs and graphene nanoplatelets shown a remarkable effectiveness in enhancing fracture toughness in composites. The high aspect ratio, strength, and surface area of CNTs enable them to act as anchors across cracks. The fracture energy improvements of over 25-35% were reported in cementitious materials with the addition of CNTs at a concentration of approximately 0.05 wt% [43].

Furthermore, the significant enhancements in the stiffness and elastic modulus of cementitious materials and polymer composites were observed when they were reinforced with nanoparticles, such as nano-alumina, Titania, silica, or CNTs [193-195]. For instance, *Chandrasekaran et al*. [88] observed a stiffness increase of over 65% in epoxy composites with the addition of 1% nano-alumina. The inherent high modulus of nanoparticles, combined with the enhancement of the microstructure, contributes to the improvement in stiffness. However, the magnitude of these improvements can vary depending on such factors as particle geometry, dispersion and interfacial bonding between the nanoparticles and the matrix.

Diverse nanoparticles exhibit varying degrees of improvement in strength, toughness and modulus influenced by such factors as material composition,

Table 4: Enhancement of mechanical properties using nanoparticles

Nanoparticle	Matrix	Improved Mechanical Property	Enhancement Percentage	References
CNTs	Cement paste	Flexural strength	25%	[43]
Graphene	Cement composite	Compressive strength	40%	[48]
Nano-silica	Concrete	Compressive strength	35%	[75]
Nano-titania	Cement paste	Elastic modulus	18%	[153]
Nano-alumina	Epoxy composite	Stiffness	65%	[88]

nanoparticle geometry, and dispersion. To facilitate meaningful comparisons between different nanoparticles, systematic studies are necessary to evaluate a comprehensive range of mechanical properties under standardized conditions. Additionally, long-term investigations are vital for assessing the practical implications of nanoparticle modifications in real-world construction environments. Table 4 presents a concise overview of the mechanical enhancements achieved through the use of selected nanoparticles as demonstrated in specific studies.

To recapitulate, the incorporation of nanoparticles has shown a significant promise in enhancing the strength, toughness, hardness and stiffness of construction materials by leveraging nanoscale reinforcement effects and improving microstructures. However, in order to gain a comprehensive understanding of their long-term practical implications in real field conditions, additional research is required. Advanced characterization techniques that focus on nano-modified microstructures will offer valuable insights for tailoring nanoparticles to reach optimal mechanical enhancements.

Strength

The enhancement of strength, encompassing compressive and flexural strength, is a primary objective in the development of construction materials incorporating nanoparticles. Compressive strength is directly associated with the load-carrying capacity of materials, such as concrete, mortars and composites. Meanwhile, an increase in flexural strength improves the resistance to fractures under bending stresses. Consequently, extensive research has been conducted to explore the positive impact of nanoparticles on the strength of cementitious materials and composites.

Numerous studies have provided an evidence that nanoparticles play a significant role in augmenting the compressive and flexural strength of cementitious materials by refining the microstructure [43, 75]. Nanoparticles such as nano-silica and nano-alumina, characterized by their high surface area and pozzolanic properties, contribute to secondary hydration reactions, which result in the formation of additional calcium-silicate-hydrate gel and densification of the cement matrix [39]. These nanoparticles also serve as nucleation sites, accelerating cement hydration and the precipitation of hydration products, leading to a more refined pore structure with lower porosity [153]. Furthermore, the nano-scale filler incorporation aids in improving particle packing density, thus enhancing the interfacial bonding between the cement paste and aggregates. The combined effect of these microstructural modifications induced by nanoparticles ultimately contributes to the overall improvement in strength.

In numerous studies, the substantial increases in the compressive strength of cementitious materials were documented when nanoparticles are added at low concentrations, typically ranging from 0.5 to 5 wt%. For instance, *Li et al.* [75] observed a 35% enhancement in compressive strength by incorporating 4% nano-silica in concrete compared to plain concrete. *Lv et al.* (2013) achieved a 40% improvement in the compressive strength of cement pastes with the addition of 0.03% graphene oxide nanoplatelets. Another study by *Nazari et al.* [153] reported an increase of over 18% in compressive strength with the incorporation of 0.5% nano-titania. Similar enhancements were observed with other nanoparticles, such as carbon nanotubes, nano-alumina, and nano-iron oxide [44].

The morphology, dispersion, and interfacial bonding of nanoparticles play a crucial role in determining the degree of strength improvements achieved. Platelet and tubular nanoparticles like graphene and carbon nanotubes contribute to crack deflection and bridging effects, thereby enhancing flexural strength and fracture resistance [43]. The uniform dispersion of nanoparticles ensures effective reinforcement throughout the matrix. Weak bonding at the particle-matrix interface can hinder load transfer and reduce the magnitude of strength improvements. Consequently, surface functionalization techniques are often employed to enhance nanoparticle dispersion and bonding.

Further investigation is required to understand the long-term practical implications of nano-modification on the compressive and flexural strength of construction materials in real-world conditions. Most studies are focused on evaluating strength at standard cure times of 7 or 28 days, but it is essential to examine the evolution of strength over extended periods to assess the long-term effects accurately. Additionally, comparative studies using standardized materials and methods are necessary to establish the relative effectiveness of different nanoparticles in enhancing strength conclusively. This will aid in selecting the most suitable nanoparticles for improving strength in specific construction materials.

Therefore, existing studies demonstrate that nanoparticles play a significant role in increasing the compressive and flexural strength of construction materials by improving microstructural characteristics such as reduced porosity, minimized defects, and enhanced interfacial bonding. However, conducting long-term investigations in realistic conditions is crucial to evaluate the practical implications of nano-modification on strength for construction applications.

Modulus of elasticity

The modulus of elasticity, a crucial mechanical property that characterizes the stiffness of construction materials, reflects the ratio of stress to strain within the elastic limit. It signifies the material's ability to resist deformation when subjected to a load and is commonly known as elastic modulus or Young's modulus. A higher modulus of elasticity is desirable for structural materials as it enables them to bear heavier loads without excessive deformation. Consequently, extensive research has been dedicated to exploring the utilization of nanoparticles to enhance the elastic modulus of cementitious materials and composites.

The incorporation of nanoparticles has proven effective in improving the elastic modulus through various mechanisms that modify the microstructure. Nanoparticles such as nano-silica and nano-alumina react with the byproducts of cement hydration, resulting in the formation of additional calcium-silicate-hydrate gel (C-S-H), which enhances the density and stiffness of the cement matrix [196, 197]. Additionally, nanoparticles fill the nano-scale voids, serve as nucleation sites to expedite hydration reactions, and promote improved interfacial bonding between the cement paste and aggregates. These combined effects contribute to the development of a more uniform and refined microstructure, resulting in a higher elastic modulus [39]. Moreover, the inherently high modulus values of nanoparticles directly contribute to the enhanced stiffness upon their incorporation into the material matrix.

The substantial increase in the modulus of elasticity of cementitious materials through the incorporation of nanoparticles was reported in many studies. For instance, *Nazari et al*. [153] found an improvement of over 18% in elastic modulus with the addition of 0.5% nano-titania in cement paste. *Chandrasekaran et al*. [88] observed a 65% increase in stiffness by including 4% nano-alumina in epoxy polymer composites. Similar enhancements were achieved using carbon nanotubes, nano-silica, nano-iron oxide and graphene oxide nanoparticles [198]. However, the degree of improvement can vary depending on such factors as particle geometry, dispersion, interface properties and testing methodologies.

While significant improvements in modulus have been demonstrated, certain challenges still exist. Further investigation is required to understand the long-term evolution of the elastic modulus under sustained loading and its practical implications. The enhancement in modulus is also influenced by different factors like material composition, nanoparticle geometry and dosage. Therefore, comparative studies using standardized parameters are necessary to conclusively evaluate the relative effectiveness of different nanoparticles. Compatibility issues between specific nanoparticles and matrix materials may arise, necessitating tailored surface engineering of nanoparticles. Therefore, optimizing processing methods, interface properties, and microstructural modifications facilitated by nanoparticles can maximize the improvements in the elastic modulus.

Therefore, the existing body of research supports the notion that nanoparticles have a beneficial impact on the elastic modulus of construction materials by modifying the microstructure through increased density, decreased defects, and improved interfacial properties. However, it is necessary to conduct long-term studies under real-world conditions and perform systematic comparative analyses to gain a deeper understanding of the practical implications and relative effectiveness of various nanoparticles in enhancing the modulus. Advancing knowledge in this field will facilitate the informed selection and design of nanoparticles to tailor the stiffness of construction materials.

IMPROVEMENT IN FUNCTIONAL PROPERTIES

In addition to improving mechanical performance, the incorporation of nanoparticles has opened up possibilities for introducing multifunctional capabilities into construction materials. Nanoparticles offer unique properties such as electrical conductivity, self-sensing ability, photocatalytic activity [199], and antibacterial effects, which are highly desirable for advanced functionality and sustainability. Consequently, substantial research efforts were dedicated to exploring the functional properties achieved by adding nanoparticles to cementitious materials, coatings and composites.

The development of self-sensing cementitious materials by leveraging the piezoresistive characteristics of nanoparticles, such as carbon nanotubes and graphene, was investigated in several studies [200]. These nanomaterials can alter their electrical conductivity in response to strain, enabling them to detect damage and sense strains. The self-sensing mechanisms induced by different nanoparticles at the nano-micro scale were examined in in-depth investigations, and models were developed to predict the electrical response. However, challenges still exist in optimizing sensitivity, ensuring reproducible measurements, and achieving long-term reliability.

Extensive research has been conducted on the utilization of titanium dioxide nanoparticles to provide self-cleaning and air purification functionality through their photocatalytic properties when exposed to UV light [60]. By incorporating nano-titania into coatings, glass, and cement composites, it promotes the breakdown of organic contaminants and air pollutants through redox reactions. The photocatalytic performance is influenced by various factors, such as UV intensity, dispersion of nanoparticles, surface area and crystallinity. To advance this field, it would be beneficial to conduct comparative studies that evaluate the efficacy of nano-titania in comparison to other nanomaterials.

Antimicrobial properties play a crucial role in addressing degradation issues caused by microbial activity in construction materials. Copper, zinc oxide and silver nanoparticles, among others, were characterized by antimicrobial activity through direct cell contact and the release of ions [53, 128, 201]. The performance of antimicrobial activity is influenced by factors such as nanoparticle size, shape, dosage, and uniform dispersion. However, careful evaluation is required due to potential concerns regarding toxicity. Future research endeavors should be focused on the development of multifunctional antimicrobial nanocomposites that prioritize enhanced safety.

Nanoparticles have the potential to enhance the corrosion resistance of steel reinforcements and coatings by promoting the formation of passive films, inhibiting ion migration, and decreasing matrix permeability [202]. For example, studies have demonstrated that incorporating nano-silica and nano-alumina can reduce the corrosion rate of steel bars in concrete [203, 204]. Further advancements in this application area can be achieved through comparative assessments of different nanoparticles for long-term corrosion inhibition, as well as optimization of particle size and dosage.

The fire retardant properties of nanoparticles in polymeric composites and surface coatings have received limited attention in research, with nanoclays, carbon nanotubes, and graphene being the most commonly studied materials [205]. The presence of nanoparticles has been found to improve thermal stability and reduce flammability by forming protective char layers during combustion. However, the understanding of fire retardance mechanisms involving nanoparticles is still in its early stages and requires extensive research for practical implementation. Table 5 provides a summary of the various functionalities achieved through the utilization of different nanoparticles in construction materials, along with their typical applications and examples from relevant studies.

Table 5: Functional properties induced by nanoparticles in construction materials

Nanoparticle	Functional Property	Typical Applications	Examples from Studies
Carbon nanotubes, Graphene	Electrical conductivity, Self-sensing	Damage detection in concrete	[200]
Nano-titania	Photocatalysis, Self-cleaning	Air purification coatings, Concrete	[60]
Nano-copper, Nano-zinc oxide, Nano-silver	Antimicrobial activity	Biofilm resistant coatings, Mortar	[53]
Nano-silica, Nano-alumina	Corrosion inhibition	Steel reinforced concrete	[203]
Nanoclays, CNTs	Fire retardancy	Polymer composites, Surface coatings	[205]

Therefore, nanoparticles offer a significant potential for introducing advanced functionalities, such as self-monitoring, pollutant degradation, antimicrobial activity and corrosion inhibition into construction materials. However, further research is necessary to fully comprehend the underlying mechanisms, optimize performance, evaluate environmental impacts, and facilitate integration into practical systems. A multifunctional approach that harnesses the combined benefits of different nanoparticles holds promise for the development of smart and sustainable construction materials in the future.

Self-sensing

The concept of self-sensing in structural materials refers to their inherent ability to detect damage or deformation by monitoring changes in their electrical, thermal, or other properties. This unique characteristic allows for the real-time measurement of strains or cracks without the need for external sensors. The integration of self-sensing capabilities into construction materials is highly desirable as it enables the timely identification of damage, enhances safety, and facilitates automated responses through integration with structural health monitoring systems. As a result, considerable research efforts were dedicated to harnessing the distinct properties of nanoparticles to develop self-sensing cementitious materials and composites.

Carbon-based nanoparticles, such as carbon nanotubes, graphene, carbon nanofibers, and carbon black, have emerged as promising candidates for introducing self-sensing functionality, primarily due to their excellent electrical conductivity. When these nanoparticles are incorporated into the material matrix at concentrations typically ranging over 0.1-1 wt%, they form interconnected networks that facilitate the transport of electrons [200]. As the material undergoes strain, the conductivity of these nanoparticle networks changes proportionally to the mechanical deformation. This piezoresistive behavior enables the sensitive and real-time detection of damage.

In several research studies the mechanisms of self-sensing induced by carbon-based nanoparticles were explored, and the models were developed to understand the relationship between applied strain and electrical resistance changes. The tunneling resistance between adjacent nanoparticles is influenced by the distance between particles, which undergoes alteration under strain [206]. Moreover, the propagation of microcracks modifies the conductive pathways within the nanoparticle networks, resulting in the bulk resistance changes. The effectiveness of the self-sensing effect relies on achieving uniform dispersion and optimal network connectivity through careful selection of nanoparticle geometry, size, and concentration. *D'Alessandro et al*. [207] investigated engineered cementitious composites incorporating multi-walled carbon nanotubes at a loading of 0.1%, resulting in a self-sensing effect with a maximum resistance change of up to 350%. However, challenges remain in terms of the reproducibility and long-term stability of the self-sensing behavior under environmental exposures. Introducing redundancy through the use of hybrid nanoparticles could help address variability. It is essential to conduct comprehensive in-situ validation under service conditions to ensure practical implementation of self-sensing materials.

While the majority of research efforts have focused on incorporating conductive nanoparticle networks into cementitious materials, there have also been endeavors to utilize these networks in polymer composites and coatings to achieve damage detection and strain sensing capabilities. For example, *Gupta et al*. [208] developed concrete containing multi-walled carbon nanotubes and nickel nanoparticles, successfully achieving efficient damage sensing through resistance changes that were sensitive to crack initiation and propagation. However, more research is needed to explore the integration of these networks into coatings for sensing surface strains and defects.

Thus, the incorporation of tailored conductive nanoparticle networks holds a significant potential for attaining self-sensing functionality in structural composites and surface coatings, allowing for real-time damage detection and strain measurements. Nevertheless, further work is necessary to enhance the stability and reproducibility of the sensing effects by optimizing material processing methods. Additionally, comprehensive models need to be developed to understand the relationship between nanoscale network alterations and overall composite resistance changes in response to damage. These advancements would support the adoption of nano-engineered self-sensing materials for automated structural health monitoring and the development of intelligent infrastructure systems.

Self-cleaning/photocatalytic

Self-cleaning in the context of construction materials refers to their inherent ability to remove surface dirt and contaminants without the need for external cleaning efforts. This quality is highly advantageous as it helps maintain the aesthetic appeal of the materials, prevents degradation, and reduces the need for frequent maintenance. Photocatalysis, on the other hand, is a phenomenon where a material with photocatalytic properties facilitates redox reactions upon exposure to light, leading to the decomposition of organic compounds. By incorporating photocatalytic nanoparticles into construction materials, self-cleaning functionality can be induced, as these nanoparticles degrade surface contaminants when exposed to light.

Among the various nanoparticles studied for inducing photocatalytic self-cleaning effects, titanium dioxide (TiO_2) nanoparticles have received significant attention. When TiO_2 nanoparticles are irradiated with ultraviolet (UV) light, they generate electron-hole pairs, which initiate redox reactions with adsorbed water and oxygen. As a result, reactive oxygen species (ROS) are produced. These ROS play a crucial role in degrading and mineralizing organic compounds present on the material surface, converting them into harmless byproducts, such as carbon dioxide (CO_2) and water (H_2O) [60]. This photocatalytic action allows for the continuous breakdown and removal of dirt, grime, and microbial deposits when the material is exposed to UV radiation from sunlight or artificial sources.

The significant self-cleaning capabilities achieved by incorporating nano-TiO_2 into various materials such as coatings, glass, tiles, and cementitious materials were obtained in numerous research studies. For example, *Hüsken et al*. [60] applied nano-TiO_2 coatings on concrete facade panels and observed a self-cleaning effect of up to 25% under the outdoor weathering exposure. *Giannantonio et al*. [209] achieved over 90% degradation of stearic acid contamination by utilizing nano-TiO_2 modified lime mortars under the UV irradiation. The photocatalytic performance of nano-TiO_2 is influenced by factors such as crystal structure, size, surface area, and dispersion uniformity within the matrix [210]. While nano-TiO_2 has been extensively studied, emerging photocatalysts like nano-ZnO, WO_3, and Bi_2O_3 also exhibit a potential for self-cleaning [211].

To further advance this field, comparative studies that evaluate the photocatalytic efficacy of nano-TiO_2 in comparison to other nanomaterials would be beneficial. Additionally, research efforts should be focused on enhancing the longevity of materials against photocorrosion, improving responsiveness to visible light and mitigating potential toxicity risks associated with nano-TiO_2. Exploring the synergistic effects achieved through the combination of nano-TiO_2 with other nanoparticles to achieve self-sensing, antimicrobial properties, mechanical improvements, in addition to self-cleaning abilities, presents promising opportunities [212].

The photocatalytic properties of nano-titania are extensively utilized in the development of self-cleaning construction materials such as coatings, tiles, glass and cementitious composites. However, additional research is required to address the following aspects: 1) the development of nanophotocatalysts responsive to visible light, 2) enhancement of dispersion stability and durability, 3) evaluation of synergies with other multifunctional nanoparticles, and 4) assessment of potential environmental toxicity risks. By addressing these factors, the wider implementation of nano-engineered self-cleaning construction materials with improved sustainability can be facilitated.

Anti-microbial

Microbial activity poses a significant risk to the deterioration and degradation of construction materials, primarily through such processes as biofilm formation, staining and microbial-induced corrosion. The formation of biofilms by bacteria and fungi leads to surface discoloration, material decay, and a decline in functional properties [128]. Furthermore, microbes can directly cause corrosion in metals, concrete, and masonry structures by generating acids that lower pH and initiating electrochemical reactions. Therefore, the incorporation of antimicrobial properties into construction materials is crucial for mitigating microbial degradation.

Nanoparticles composed of specific metals and metal oxides possess remarkable antimicrobial properties, making them promising candidates for the development of self-sterilizing construction materials. Copper, zinc oxide and silver nanoparticles exhibit a broad-spectrum antimicrobial efficacy against common microbes, such as Escherichia coli, Staphylococcus aureus, Pseudomonas aeruginosa, and Aspergillus niger [53]. Even at relatively low concentrations ranging from 0.5 to 5 wt%, these nanoparticles can effectively hinder microbial growth when integrated into materials, such as polymeric coatings, cementitious composites, paints and wood treatments.

Metal nanoparticles exhibit antimicrobial efficacy through various mechanisms. They can directly damage microbial cell membranes through oxidative stress upon contact. Moreover, the release of metal ions from the nanoparticles disrupts enzymatic activity and molecular synthesis in microbes [213]. The reactive oxygen species generated on the nanoparticle surface also contribute to the inactivation of microbes. The antimicrobial performance is influenced by factors, such as nanoparticle size, shape, crystallinity and dosage. Smaller nanoparticles with larger surface areas demonstrate enhanced antimicrobial effects [214].

In their study, *Cioffi et al.* [53] observed more than 80% growth inhibition of E. coli when cement mortars containing 0.5-2% nano copper oxide were used. *Ganesh et al.* [128] investigated paints and render incorporating nano-ZnO and found potent antibacterial, antifungal, and anti-algal properties. However, it is essential to carefully evaluate concerns regarding the potential environmental toxicity associated with these metal nanoparticles.

The integration of metal and metal oxide nanoparticles offers a promising approach to incorporate antimicrobial properties into construction materials, thereby preventing microbial degradation. However, additional research is necessary to develop environmentally friendly synthesis methods for these nanomaterials, enhance their stability under real-world conditions, evaluate potential toxicity concerns, and improve cost-effectiveness. It is also important to establish standardized testing protocols to assess the long-term antimicrobial efficacy of nano-engineered construction materials exposed to weathering conditions. Addressing these factors will facilitate the effective and sustainable integration of antimicrobial properties using nanotechnology.

Anti-corrosion

The durability and service life of reinforced concrete structures are significantly impacted by the corrosion of steel reinforcement. In environments with high humidity and coastal proximity, the penetration of chlorides through the concrete cover can lead to chloride-induced corrosion of steel rebars. This process disrupts the passive oxide film on the steel surface, resulting in active pitting corrosion, cracking, and delamination of the concrete cover [215]. Therefore, preventing steel corrosion is crucial for ensuring the long-term performance and integrity of concrete structures.

The incorporation of nanoparticles into concrete has demonstrated promising outcomes in mitigating steel corrosion. Nanoparticles, such as nano-silica, nano-alumina, nano-titania and nano-clay, are acting as effective barriers that refine the pore structure and reduce the permeability of the concrete matrix [216]. This hinders the ingress of aggressive substances like chlorides, thus delaying the onset of corrosion. Furthermore, certain nanoparticles actively inhibit corrosion by interacting with the steel surface and forming protective passive layers. For example, nano-TiO_2 facilitates the deposition of insoluble compounds on the steel interface, while nano-SiO_2 rebuilds the passive oxide film [126].

In numerous studies, the considerable improvement in the corrosion resistance of steel rebars in concrete was highlighted through the addition of nano-silica at optimal dosages, typically around 2-3%. The nano-silica modified concrete exhibits reduction in corrosion current density exceeding 50-80%, when compared to plain concrete [217]. Similarly, the incorporation of nano-alumina induces a corrosion rate reduction of over 60% and an increase in the time to initiation of active corrosion [218]. The efficiency of corrosion protection is influenced by many factors, such as particle size, concentration and dispersion uniformity. Smaller nanoparticles contribute to greater refinements in the pore structure. However, it is important to avoid excessive dosages that could potentially diminish performance. While nanoparticles have proven effective in enhancing the corrosion resistance of steel rebars in concrete, limited research has been conducted on their protective effects on steel coatings and surfaces. Further investigations are needed to systematically evaluate and compare the performance of various nanoparticles in enhancing the corrosion resistance of steel coatings. Exploring the synergistic effects achieved by using hybrid nanoparticles for corrosion protection could yield promising avenues for development. Moreover, the establishment of standardized accelerated corrosion testing methods is necessary to reliably assess the long-term corrosion mitigation effects of nano-engineered systems.

Hence, the integration of nanoparticles like nano-silica, nano-alumina, and nano-titania shows a promise in improving the corrosion resistance of steel reinforcements in concrete through the refinement of the pore structure and the promotion of passive film formation. However, additional research is needed to investigate their protective effects on steel coatings and surfaces. The development of optimized hybrid nano-systems and the establishment of comprehensive testing protocols would greatly advance this field of application, facilitating the adoption of nano-engineered solutions to enhance the durability of steel structures against corrosion.

Fire retardance

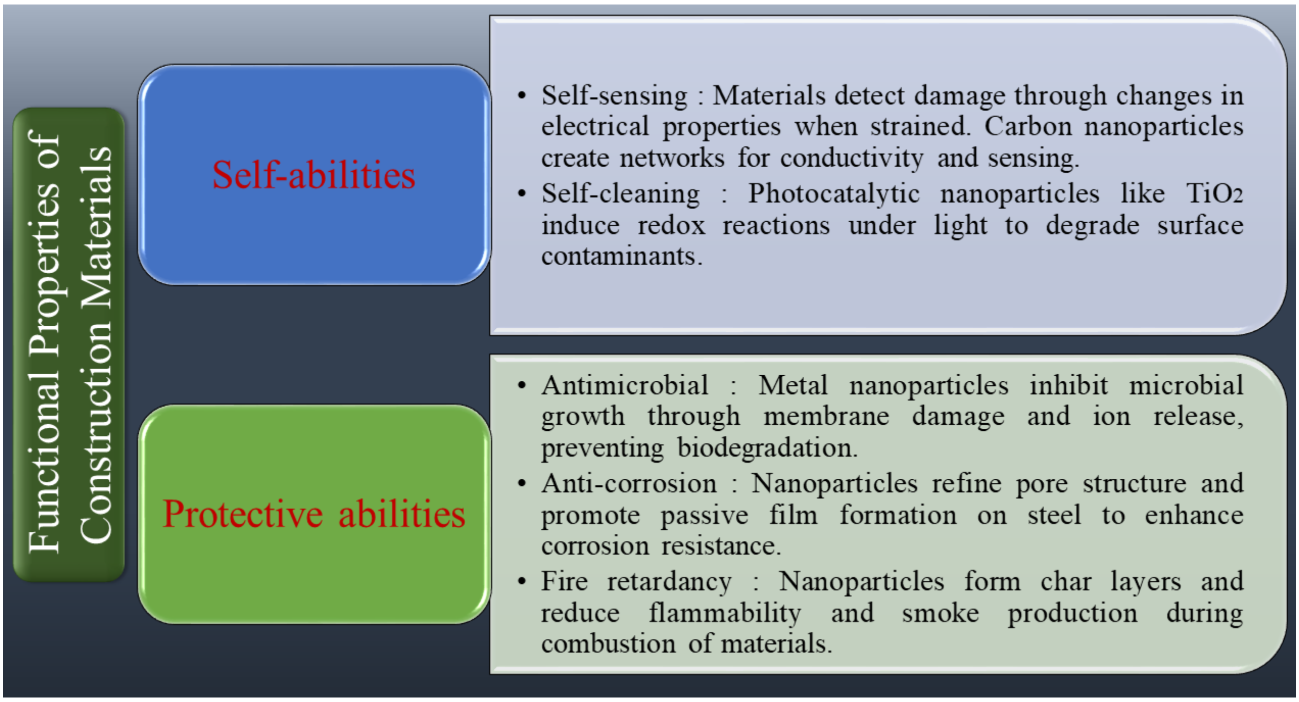
Enhancing the fire performance and flame retardancy of construction materials is of utmost importance for ensuring building safety [219-221]. Polymeric materials, including composites, insulation foams, and surface coatings commonly used in buildings, pose significant fire hazards due to their inherent flammability [222]. Moreover, cementitious materials like concrete exhibit spalling and explosive fragmentation when exposed to high temperatures during fires, which can compromise structural stability [223]. Consequently, extensive research efforts were dedicated to improving the fire response of construction materials through the integration of flame retardant additives.

Nanoparticles were emerged as a promising solution for enhancing the fire retardancy of polymeric composites and cementitious materials. These nanoparticles function as physical barriers and facilitate the formation of char layers, thereby improving the thermal stability and reducing the flammability of materials [224, 225]. Additionally, nanoparticles contribute to a decrease in smoke production and the generation of toxic gases during combustion. Nanoclays, carbon nanotubes, graphene, and metal oxides are among the nanoparticles that have been extensively investigated for their applications in fire retardancy [226].

The fire retardancy of composites can be improved by incorporating nanoclays, which hinder the penetration of oxygen and heat while enhancing char formation [222]. Loading polymeric resins with nanoclays between 1-5% has been shown to increase the limiting oxygen index and reduce the peak heat release rate by over 50%. Carbon nanotubes, on the other hand, create networked char residues that effectively shield against fire in composites and coatings [227]. Adding 2% graphene nanoplatelets to epoxy composites resulted in reductions of more than 35% in peak heat release rate and smoke production [228]. Metal oxides like nano-zinc borates and nano-titania promote the formation of insulating char and reduce flammable volatiles in materials [229]. However, the high cost of these specialized nano-additives limits their widespread use at present.

In the case of concrete and cementitious materials, nanoparticles, such as nano-TiO_2, nano-SiO_2 and nano-alumina, show a promise in mitigating explosive spalling during fires. They densify the matrix, refine hydration, and improve pore structure and interfacial transition zones [223]. However, field-scale validation is necessary to evaluate the practical feasibility of nano-engineered cementitious composites in realistic fire scenarios.

Thus, the incorporation of nanoparticles offers a significant potential for improving the fire safety of polymeric and cementitious materials by enhancing thermal stability, reducing flammability and mitigating spalling fragmentation. However, a deeper understanding



- Self-sensing : Materials detect damage through changes in electrical properties when strained. Carbon nanoparticles create networks for conductivity and sensing.
- Self-cleaning : Photocatalytic nanoparticles like TiO_2 induce redox reactions under light to degrade surface contaminants.
- Antimicrobial : Metal nanoparticles inhibit microbial growth through membrane damage and ion release, preventing biodegradation.
- Anti-corrosion : Nanoparticles refine pore structure and promote passive film formation on steel to enhance corrosion resistance.
- Fire retardancy : Nanoparticles form char layers and reduce flammability and smoke production during combustion of materials.

Fig. 7: Overview of nanoparticle-enabled functional properties for enhanced performance

of the underlying mechanisms and extensive research are required to enable the practical implementation of nanoparticles in fire-resistant construction materials. This includes the development of cost-effective and environmentally friendly nano-additives, assessment of long-term durability under service conditions, and comprehensive toxicity evaluation. Fig. 7 presents a comprehensive overview of the utilization of nanoparticles in conferring functional properties to construction materials.

ENHANCEMENT OF SUSTAINABILITY

The growing concern for environmental issues and the need to minimize the ecological impact of the construction sector have led to a significant focus on sustainability in the development of advanced construction materials. Conventional materials have a life cycle that involves resource consumption and carbon emissions from raw material extraction to disposal. Traditional construction materials also face challenges in terms of maintenance demands, recyclability limitations, and negative health effects, affecting their overall sustainability. To address these challenges, extensive research has been dedicated to improving various sustainability aspects, including resource efficiency, recyclability, durability, eco-friendliness, and long-term functionality. Nanotechnology offers promising opportunities to create next-generation sustainable construction materials by incorporating nanoparticles.

Nanoparticles have the potential to enhance the sustainability of construction materials in multiple ways. The incorporation of nanoscale fillers and reinforcements allows for significant performance improvements using fewer raw materials compared to conventional composites with larger-scale reinforcements [202]. Leveraging the unique characteristics and ultra-high surface area of nanoparticles, it becomes possible to achieve notable enhancements in strength, toughness, and durability without excessive resource consumption. Furthermore, nanoparticles bring additional functionalities like self-sensing, self-cleaning, and antimicrobial capabilities, which reduce maintenance requirements throughout the materials' lifespan [126]. Nanoparticles also facilitate recycling and reuse of materials while minimizing degradation during the processing stage. Moreover, the responsible selection of nano-additives and matrices in nano-engineered materials is aimed to prevent adverse health and environmental impacts.

Numerous experimental studies have provided evidence of the sustainability advantages offered by nanoparticles in cementitious materials and composites. For instance, *Sharma et al*. [230] found that incorporating 2% nano-silica in concrete resulted in a significant threefold reduction in permeability compared to control samples with the same water-cement ratio. This improvement in durability suggests potential cement savings while achieving desired performance specifications. *Gong et al*. [125] obtained impressive enhancements of over 25% in the compressive strength of recycled concrete aggregate composites by incorporating 0.3% graphene nanoplatelets and 0.7% nano-SiO_2.

Several factors influence the sustainability improvements achieved through nano-modification. These factors include the concentration and uniform dispersion of nanoparticles, compatibility between nanoparticles and the base matrix, the techniques used for processing, and finding the right balance between enhanced performance and the energy invested in nanoparticle synthesis [231]. Lower nanoparticle loading typically corresponds to higher resource efficiency, while achieving a stable and uniform distribution of particles optimizes the reinforcing effects. The surface functionalization and geometry of nanoparticles also play a crucial role in ensuring compatibility and the development of composite microstructures, which ultimately determine the resulting properties [18]. Furthermore, it is essential to implement scalable and energy-efficient manufacturing methods. To ensure the effective selection and application of nano-engineered materials, it is vital to evaluate the comprehensive implications of nanoparticles on sustainability using techniques such as life cycle assessment.

Despite the potential advantages of nanoparticles in advancing the sustainability of construction materials, there are certain limitations that need to be addressed. Currently, there is a lack of standards, protocols, and knowledge regarding the safe and responsible use of nanotechnology in construction [202]. It is crucial to conduct extensive in-situ studies to evaluate the long-term behavior and lifecycle impacts of nano-modified materials under real field conditions [31]. The concerns about the potential toxicity risks, particularly related to airborne nanoparticle exposure, require rigorous investigation to develop improved protective strategies and exposure control systems. Moreover, significant research is needed to determine the optimal selection of nanoparticles, surface engineering techniques, and composite processing methods, while minimizing the energy and resource consumption associated with manufacturing. Techno-economic assessments that consider these sustainability factors are essential. Additionally, there is a need for the development of technologies that efficiently recover and recycle nanoparticles from composites after their end-of-life, which requires substantial progress [232].

Therefore, while nanotechnology offers exciting opportunities to advance the sustainability of construction materials, it is crucial to conduct a comprehensive evaluation of sustainability metrics throughout the lifecycle to validate the actual benefits. The systematic selection of appropriate nano-additives and matrices can contribute to the development of next-generation eco-friendly composite materials with lower carbon footprints and energy requirements. Responsible incorporation of nanoparticles has the potential to enhance resource efficiency, recyclability, durability, and functionality of construction materials. However, it is essential to investigate the sustainability implications through thorough technical analyses, lifecycle assessments, and techno-economic studies that focus on safety, human health, and environmental impacts. A balanced approach, supported by standards and exposure control systems, can facilitate the safe, sustainable, and responsible integration of nanotechnology in the construction industry.

Resource and energy efficiency

The incorporation of nanoparticles into construction materials holds a significant potential for improving resource and energy efficiency compared to conventional composites filled with larger microscale reinforcements. By harnessing their nanoscale dimensions and unique properties, nanoparticles enable similar or enhanced performance to be achieved with significantly reduced raw material consumption [223]. This advantage stems from the ultra-high specific surface area of nanoparticles, which promotes enhanced interactions and bonding at the interface between the matrix and particles, effectively reinforcing the material [18]. As a result, the addition of small amounts of nanoparticles can lead to improvements in strength, stiffness, toughness, and durability. The ability of nanoparticles to enhance the mechanical performance and durability properties of construction materials at low dosages was shown in numerous research studies, resulting in notable savings in raw material usage. For instance, *Yang et al*. [195] observed a more than 30% increase in compressive strength in cement mortars with the addition of just 1% nano-alumina, achieving the desired strength level while using significantly less cement.

In another study, *Nazari et al.* [153] achieved an 18% higher elastic modulus in cement paste by incorporating only 0.5% nano-titania. Graphene nanoplatelets show a great potential in enhancing resource efficiency at very low concentrations due to their exceptional intrinsic strength and large specific surface area. *Lv et al.* [48] reported a more than 40% increase in compressive strength and a 60% improvement in flexural strength in cement paste with just 0.03% graphene oxide. *Gong et al.* [125] achieved over 25% enhancement in the compressive strength of recycled concrete composites by adding only 0.3% graphene nanoplatelets and 0.7% nano-silica. These studies highlight the significant mechanical improvements that can be achieved while also promoting the reuse of waste materials through the reinforcement provided by nanoparticles.

Several factors contribute to the resource and energy efficiency offered by nano-engineered construction materials compared to conventional composites. The inherent strength, stiffness, thermal conductivity, and electrical conductivity of nanoparticles allow for targeted property enhancements using smaller quantities of raw materials [223]. The high specific surface area facilitates extensive bonding and interactions between the matrix and reinforcement. Nanoparticles also optimize particle packing density and refine the microstructure [18]. Smaller nanoparticles, with their higher surface area-to-volume ratio, offer greater improvements. However, excessive addition of nanoparticles beyond the optimal concentration can have adverse effects. Furthermore, achieving effective dispersion of nanoparticles ensures their uniform distribution and efficient utilization [31]. Incorporating nanoparticles into recycled composites and utilizing waste materials not only enhances the performance of new materials, but also contributes to sustainability. The significant strength improvements in recycled concrete composites by incorporating nano-additions were reached by *Gong et al.* [125] highlighting the potential to reduce reliance on virgin materials. *Jalal et al.* [126] observed that the addition of nano-silica refined the pore structure and densified the matrix of composites incorporating construction and demolition waste.

The synthesis methods and surface functionalization techniques employed for nanoparticles also have implications for energy consumption and overall resource utilization. Bottom-up approaches based on chemical processes generally require lower temperatures and less energy compared to vapor-phase synthesis methods (*Oluwafemi et al.*, 2019). Effective functionalization tailored to the matrix material ensures better dispersion and compatibility, thereby enabling optimal performance at low nanoparticle loadings [18]. Moreover, the use of plant-derived and sustainable raw materials for synthesizing nanocellulose, nanoclays, or carbon-based nanomaterials contributes to improving the overall sustainability profile.

Additional research is necessary to conduct comprehensive life cycle assessment studies and evaluate the overall sustainability implications of nano-modification in construction materials, despite significant progress made thus far. Several key areas require specific attention in these studies. Firstly, it is crucial to determine the optimal concentrations of nanoparticles that strike a balance between performance enhancements and the embedded energy associated with different nanoparticle-matrix combinations. Secondly, the development of energy-efficient and environmentally friendly synthesis and processing methods for nanoparticles is essential. Furthermore, it is important to investigate the long-term behavior of nano-modified materials under actual in-service conditions. Additionally, the integration of nanoparticles into recycled composites and the reuse of waste materials should be thoroughly assessed through the field performance studies. Advancing knowledge in these areas will enable the selection and design of nano-engineered construction materials that exhibit improved sustainability and energy efficiency.

Lifecycle impacts and recyclability

Assessing the sustainability of construction materials requires a comprehensive evaluation of their lifecycle impacts and recyclability. The lifecycle of a material encompasses various stages, including extraction, processing, manufacturing, transportation, integration, use, and end-of-life disposal or recycling [233]. Each phase contributes to resource consumption, carbon emissions, energy usage, and waste generation. Conventional production methods and materials often have significant ecological footprints due to high embedded energy, greenhouse gas emissions, limited reuse potential, and toxicity concerns. Therefore, it is crucial to analyze the sustainability of nano-modified construction materials from a lifecycle perspective.

Life cycle assessment (LCA) is a valuable methodology for evaluating the environmental impacts of materials throughout their entire lifespan, considering such key indicators as embodied energy, carbon footprint, water usage, solid waste and toxicity potential [234]. Numerous LCA studies have compared nano-modified cementitious materials, composites, and coatings to conventional counterparts. *Hakamy et al.* [235] reported a 35% reduction in embodied energy for nano-modified concrete containing titanium dioxide nanoparticles compared to conventional concrete. *Kansal et al.* [236] achieved a 17% decrease in carbon emissions by partially substituting silica fume with nano-silica in high-performance concrete. These reductions demonstrate improved resource efficiency and reduced binder requirements through the reinforcement effects of nanoparticles.

Peng et al. [202] conducted an LCA study focusing on the fabrication phase of nano-modified cement composites reinforced with nano-iron oxide. The results indicated that the embedded energy was highly dependent on the synthesis technique employed for the nanoparticles, with lower temperatures and simpler procedures leading to reduced environmental impacts. *Mahian et al.* [237] emphasized the importance of optimizing nanoparticle synthesis methods, surface functionalization, dispersion, and dosages to minimize embedded energy while maximizing sustainability benefits.

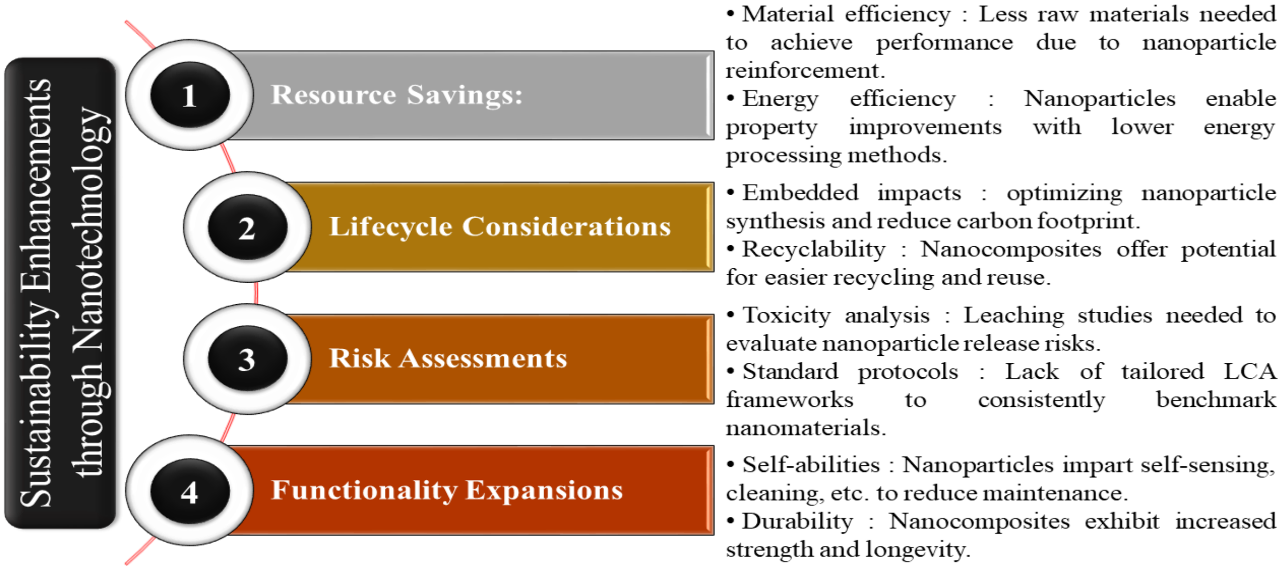
The recyclability and reuse potential of construction materials at the end of their life cycle are crucial considerations for sustainability. Traditional materials often present challenges in terms of recycling due to issues such as composite incompatibility, degradation over time, and complex separation requirements [238]. In contrast, nano-modified materials offer the potential for easier recycling and remanufacturing while maintaining mechanical performance to a greater extent after processing. For example, *Allujami et al.* [239] concluded that incorporating nano-Al_2O_3 and nano-SiO_2 into recycled concrete aggregates resulted in good retention of strength and durability properties during reuse.

Despite the potential of nano-engineered construction materials to improve sustainability, there are some limitations that need to be addressed. Currently, there is a lack of comprehensive and standardized LCA frameworks specifically designed for nano-modified cementitious composites, making consistent comparisons challenging [202]. Additionally, there is a need for long-term and field studies that examine the life cycle impacts of nano-modified materials under real-world conditions [31]. Concerns regarding nanoparticle toxicity require investigation through LCA and leaching studies to develop sustainable synthesis solutions [240]. The optimization of nanoparticle dosage, improved dispersion techniques, and responsible selection of nanoparticles should be guided by sustainability considerations [241]. Furthermore, the development and evaluation of effective and safe recycling methods for recovering nanoparticles from composite matrices are essential.

Addressing these knowledge gaps requires further research in several key areas related to the life cycle impacts and recyclability of nano-modified construction and building materials. Firstly, the establishment of standardized LCA protocols specifically tailored to nano-engineered cementitious composites, coatings, and polymer concretes is necessary to enable consistent comparisons and benchmarking. Secondly, the long-term studies that monitor key LCA indicators for nano-modified materials exposed to real field conditions over extended periods should be conducted. Thirdly, the comprehensive investigation of the recyclability and reuse potential of recycled nano-modified composites through field trials is needed. Fourthly, the development of effective, safe, and sustainable recycling techniques for recovering nanoparticles from end-of-life materials is crucial. Finally, the analysis of toxicity risks and leaching behaviors through LCA and monitoring throughout the product lifespan is important. Advancing research in these areas will contribute to the engineering of next-generation sustainable nano-modified construction materials. Fig. 8 provides a concise summary of various methodologies aimed at enhancing sustainability by integrating nanoparticles into construction materials.

MODELING AND SIMULATION

Computational modeling plays a crucial role in understanding the impact of nanoparticle incorporation on the properties and performance of construction materials, complementing experimental investigations. Advanced simulation techniques at the nano, micro and macro scales provide insights into mechanisms that are challenging to be observed experimentally [18]. Molecular Dynamics (MD) simulations offer atomistic-level understanding of interfacial



- Material efficiency : Less raw materials needed to achieve performance due to nanoparticle reinforcement.
- Energy efficiency : Nanoparticles enable property improvements with lower energy processing methods.
- Embedded impacts : optimizing nanoparticle synthesis and reduce carbon footprint.
- Recyclability : Nanocomposites offer potential for easier recycling and reuse.
- Toxicity analysis : Leaching studies needed to evaluate nanoparticle release risks.
- Standard protocols : Lack of tailored LCA frameworks to consistently benchmark nanomaterials.
- Self-abilities : Nanoparticles impart self-sensing, cleaning, etc. to reduce maintenance.
- Durability : Nanocomposites exhibit increased strength and longevity.

***Fig. 8:** Overview of nanoparticle-enabled functional properties for enhanced performance and protection in construction materials*

interactions, adhesion, and failure processes [45]. Micromechanical modeling captures nanoparticle-matrix interfacial behavior and microstructural characteristics. Macro-scale modeling assesses the overall mechanical response and properties of composite systems. Therefore, a multi-scale computational approach is necessary for effective virtual design and predictive analysis of nano-modified cementitious, polymeric, ceramic, and metallic composites [242-245].

Numerous studies utilized molecular dynamics simulations to examine the interfacial binding between nanoparticles and substrate matrices at the nanoscale. *Mohamed et al*. [246] conducted a comprehensive review on the application of computational methods to investigate the molecular-level mechanisms and interactions of chemical admixtures in cementitious systems. The review primarily is focused on examining the adsorption behaviors and conformations of monomers, oligomers and polymers with molecular weights approximately 10,000 g/mol. The ultimate objective of the study is to identify potential opportunities, address existing challenges, and offer future perspectives regarding the molecular modeling of chemical admixture-cement interactions. *Badjian et al.* [247] conducted MD simulations that demonstrated improved interfacial bonding between epoxy matrices and functionalized carbon nanobuds. However, challenges persist in developing accurate reactive force fields and scaling up simulations to larger system sizes.

In a recent study conducted by *Poorsargol et al*. [248], the MD simulations were employed to examine the adsorption behavior of mixed surfactants on graphene. Fig. 9 is the initial arrangement of surfactant molecules in a perpendicular orientation to the graphene surface, which was done to reduce simulation time. The MD simulations were carried out using the GROMACS software in the isothermal-isobaric ensemble, employing the OPLS-AA force field for the surfactant molecules and the SPC/E water model. By calculating properties, such as the total system energy, Lennard-Jones interaction energy and radial distribution functions, the effects of temperature, electrolyte and alcohol on surfactant adsorption were assessed. The utilization of all-atom MD modeling provided valuable insights into the molecular-level interactions that govern the adsorption of surfactants on graphene under various conditions.

Numerous studies were focused on modeling the mechanical properties, failure mechanisms, and functional properties of nano-modified materials, employing various modeling techniques [75, 249, 250]. *Wang et al.* [251] utilized a micromechanical model considering interfacial debonding to analyze the tensile behavior of polymer composites reinforced with silica nanoparticles, showing good agreement between simulated and measured stress-strain curves. *Xuejun et al.* [252] investigated the shear-lag model to predict the tensile strength and Young's modulus of ultra-high performance concrete. Merah [253] reviewed the use of finite element analysis to gain

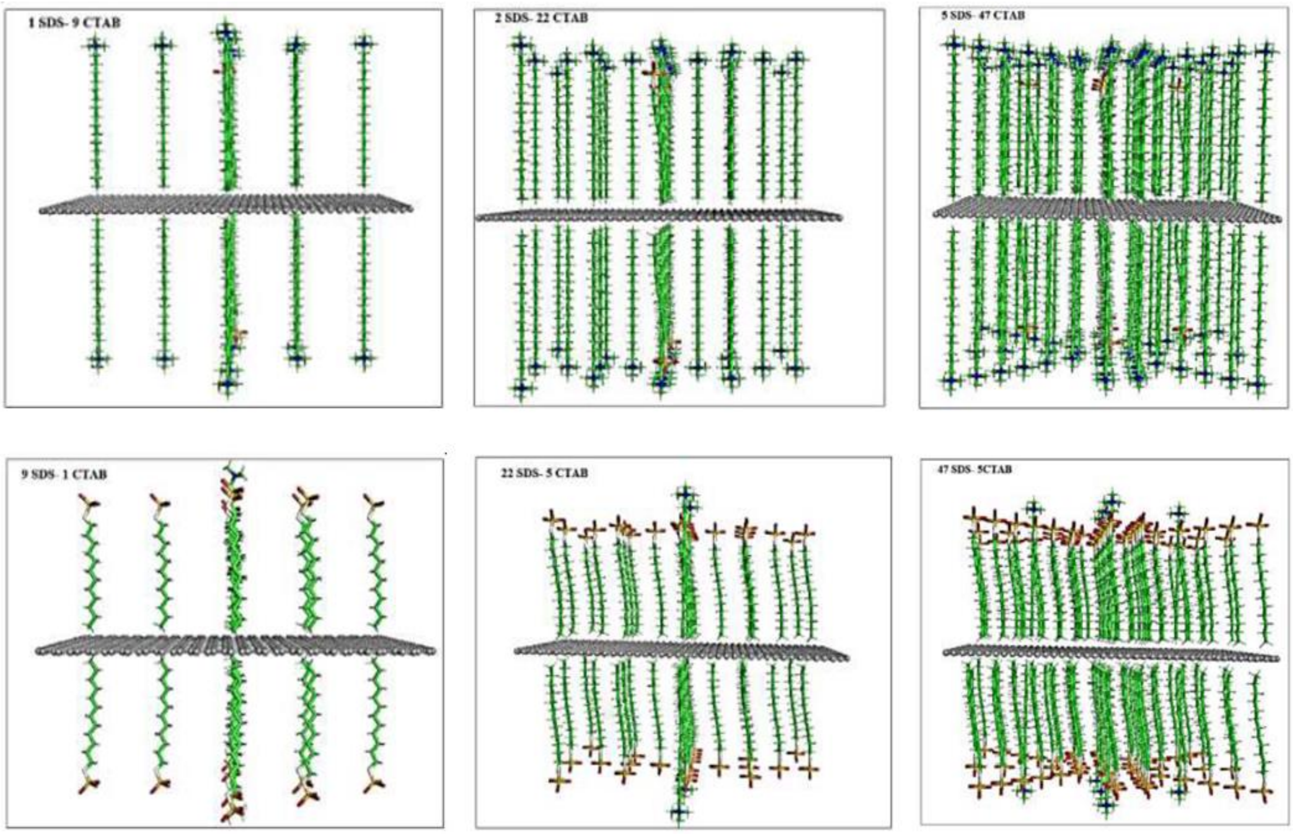


Fig. 9: Initial perpendicular configuration of surfactant molecules on graphene surface in the MD simulations [248]

insights into fracture response in cement paste-epoxy interfaces with different nano-silica contents. However, accurately representing particle aggregation effects remains challenging.

The modeling of functional properties also received some attention. *Châtel et al.* [254] combined molecular simulations and continuum transport modeling to understand the photocatalytic activity of titanium dioxide nanoparticles in concrete, examining the effects of nanoparticle size, dose, distribution, and UV light intensity on self-cleaning efficiency. *Han et al.* [200] developed a three-dimensional resistor network model that successfully captured the relationship between damage progression and electrical resistance changes in carbon nanofiber self-sensing cementitious composites. However, integrating more complex environmental interactions and degradation mechanisms into existing models focused on functional properties is necessary.

In the realm of micromechanics and finite element models, there are limitations in terms of simplified assumptions about particle geometry, spatial distributions, and interfacial properties, which fail to capture the complexity of nano-modified systems [255]. Realistically representing irregular nanoparticle shapes, polydispersity, and agglomeration remains an ongoing challenge [256]. Furthermore, improving the linkage between model length scales through advanced homogenization techniques is necessary. Incorporating material nonlinearities, time-dependent effects like creep, and interfacial debonding mechanisms under coupled environmental loading is crucial for enhancing current micromechanics models. The availability of high-performance computing capabilities will facilitate the development of higher fidelity models that encompass these complexities. Additionally, establishing correlations between model predictions and experimental validations across a comprehensive range of mechanical, physical, thermal, electrical, and durability properties requires further efforts.

To overcome the limitations in current modeling approaches for nano-modified materials in construction applications, several key research areas require attention:

- Enhanced Molecular Dynamics: The development of accurate reactive potentials and the inclusion of environmental interactions in molecular dynamics simulations are essential for realistically representing chemical reactions at interfaces between nanoparticles and construction material matrices.

- Nanoscale Modeling and Simulation: Further advancements are needed in modeling and simulation techniques that focus on critical aspects, such as nanoparticle dispersion, distribution, aggregation effects and time-dependent interfacial bonding phenomena within composites.
- Multiscale Frameworks: Improvement in multiscale frameworks is necessary to integrate molecular, microscale, and macroscale models, achieved through advanced homogenization techniques and optimization of linkages across different model length scales.
- Complex Micromechanics: Current micromechanics models must incorporate complex nonlinear material behaviors, particle polydispersity, intricate defect interactions, and coupled physicochemical effects to capture the true complexity of nano-modified systems.
- Model Validation: Rigorous validation of model predictions against systematic experimental results across a wide range of mechanical, physical, thermal, electrical, and durability properties is essential for establishing the reliability and accuracy of modeling approaches for nano-modified materials.
- Long-Term Degradation and Life Cycle Analysis: The evaluation of long-term degradation processes, environmental interactions, and life cycle implications requires the development of physically representative models that can provide insights into the performance of nano-modified materials over extended periods.
- Computational Efficiency: Utilizing high-performance computing capabilities and state-of-the-art algorithms is crucial to improve computational efficiency and enable more complex simulations for nano-modified materials.
- Multiphysics Modeling: The establishment of multiphysics modeling platforms is necessary to investigate the functional properties, including self-sensing, photocatalysis, and energy transport, in nano-engineered cementitious composites and coatings.

Addressing these research needs through integrated experimental and simulation efforts will lead to the development of robust modeling frameworks that can guide optimal design and predictive analysis for a wide range of nanoparticle-modified construction materials.

CONCLUSIONS AND FUTURE OUTLOOK

This comprehensive review examines the current progress on incorporating nanoparticles into construction materials, assessing the achieved enhancements and challenges. The key findings show that nanoparticles significantly improve the mechanical performance, durability, and functionality of materials like concrete, polymers and coatings. Even at low dosages, nano-reinforcements increase strength, toughness and stiffness. Nanoparticles also introduce advanced capabilities such as self-sensing, photocatalysis, and corrosion inhibition. Moreover, they offer sustainability benefits by enhancing performance with less raw materials and facilitating recycling.

The key findings from this review emphasize the significant enhancements in the mechanical performance, durability and functionality of construction materials achieved through the addition of nanoparticles, even at low dosages of 0.1-5 wt%. Moreover, remarkable enhancements in durability against environmental deterioration were demonstrated. However, some challenges need addressing regarding nanoparticle dispersion, long-term durability, toxicity analysis, and recovery after end-of-life. Targeted research efforts are required to develop cost-effective and eco-friendly synthesis methods, establish standardized protocols, and investigate practical implications through in-situ studies.

Based on the findings of this review, several critical areas require extensive research efforts to overcome the existing limitations and fully harness the potential of nanotechnology in construction materials. Firstly, long-term in-situ studies focusing on the durability of nano-modified materials under real-world environmental exposures are necessary to understand their practical implications. Secondly, standardized protocols should be established to conduct comprehensive evaluations of toxicity, environmental impacts, and life cycle analysis, enabling responsible and sustainable implementation. Thirdly, molecular dynamics modeling should be enhanced through multi-scale techniques, improved force fields, and better representation of environmental interactions. Fourthly, it is essential to develop cost-effective and energy-efficient methods for synthesizing nanoparticles to ensure scalability. Finally, effective recycling techniques and recovery processes for reusing nanoparticles from waste materials require systematic research.

Despite these challenges, the outlook is promising for the potential adoption of nano-modified materials by the construction industry, if these research gaps are systematically addressed. The outlook is promising if a responsible approach is adopted, considering validation, safety, regulations, and techno-economic feasibility. Continued progress in nanoscience can enable tailored, scalable and safe integration of nanoparticles in construction materials. This can potentially revolutionize the sector by enabling smart, durable and sustainable infrastructure solutions. The responsible development guided by life cycle assessments and toxicity analysis will help mitigate environmental risks. The implementation of standard protocols for material preparation, nano-dispersion, and characterization will improve quality control during manufacturing.

In conclusion, this review examines the advancements and limitations of nanotechnology applications in construction materials. While progress is made in enhancing properties, knowledge gaps persist. A collaborative strategy involving all stakeholders is essential to address research needs, facilitate practical adoption, and harness the extensive potential of nano-engineering for superior performance and sustainability.

This review may serve as a valuable reference for informing and guiding future research, development, and adoption endeavors aimed at harnessing the extensive potential of nanotechnology in engineering advanced construction materials with superior performance, multifunctionality, and sustainability.

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