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Effect of Nanomaterials on the Mechanical and Durability Properties of Concrete: A Critical Review

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Abstract (10 PT)

Concrete is the most widely used construction material for these purposes. However, its longevity is frequently compromised by cracking, permeability, chloride penetration, sulfate attack, and associated deterioration processes. Nanomaterials can enhance cementitious composites through pore refinement, accelerated hydration, densification of the interfacial transition zone, and crack-control behavior. The current critical review is focused on the evaluation of the impact of nano-silica (NS), carbon nanotubes and carbon nanofibers (CNTs/CNFs), nano-titanium dioxide (nano-TiO_2), nano-alumina (nano-Al_2O_3), nanoclay, and graphene oxide (GO) on the mechanical and durability performance of concrete. Generally speaking, nano-silica has the highest potential among nanomaterials for providing a consistently high strength increase of about 10-35%, reduction of water absorption, and chloride migration in the range of 20-60%. Meanwhile, carbon-based nanomaterials tend to have a higher potential for improving the tensile and flexural properties of concrete, which is usually observed at 15-50%. Nano-TiO_2 gives rather modest mechanical properties but also provides photocatalytic activity. At the same time, nano-Al_2O_3, nanoclay, and GO have the potential for densifying the matrix, reducing permeability, sulfate resistance, and crack control. It should be noted that all reported values depend on the specific features of the nanoparticles, their dosage, distribution quality, concrete composition, curing regime, and testing procedure. Widespread implementation is restricted by agglomeration, increased demand for water, high prices, lack of field validation, health hazards, and lack of testing standards. Overall, nano-silica shows the best combination of performance and feasibility, whereas carbon-based nanomaterials and GO are applicable only in specialized cases.

Keywords: Nanomaterials, Concrete Compressive Strength, Durability, Nano-Silica, Carbon Nanotubes, Microstructure, C-S-H Gel Permeability, Sustainability.

1. Introduction

Conventional OPC concrete is the predominant construction material globally, with an annual global production surpassing 10 billion tons [1]. This preponderance can be attributed to its flexibility, cost-efficiency, and satisfactory compressive strength; however, there are numerous drawbacks to conventional OPC concrete, such as its vulnerability to cracking, degradation from chemical attack, moisture penetration, and carbonation, which ultimately reduces its structural lifespan [2, 3].

The advent of nanotechnology has generated tremendous potential for manipulating concrete at the molecular and atomic levels. Nanoparticles are materials with one or more dimensions less than 100 nm in size [4, 5]. The highly porous structure of nanoparticles leads to an increased pozzolanic reaction rate, densification of the ITZ, and formation of additional C-S-H gel, all of which lead to improved mechanical strength and durability while also decreasing the binder volume and CO2 emissions [6, 7].

Between 1996 and 2026, considerable research was conducted on the integration of nanomaterials with concrete. Sanchez and Sobolev [8] and Sobolev [9] laid the groundwork for the application of nanotechnology to construction. In contrast, Yang et al. [10] and Shekari and Razzaghi [11] empirically demonstrated that nanoparticles lowered the porosity and increased the tensile strength of a paste matrix. In addition, systematic literature reviews by Huseien [12] have synthesized evidence from many empirical experiments, indicating consistent improvements in compressive strength, chloride resistance, and anti-erosion capacity [12]. However, recent studies have introduced novel nanomaterials, such as graphene oxide, cellulose nanocrystals, and hybrid nanomaterial systems, which are expected to yield synergistic benefits [13, 14, 15, 16, 17].

Nonetheless, several issues persist in the literature. Individual research projects tend to focus on the effects of a single nanomaterial and fail to offer comprehensive comparative analyses of different nanomaterials. Methodological variations such as variations in the water-to-cement ratio, curing process, and testing procedures add further heterogeneity and complexity to the development of practical recommendations for implementation [18, 19]. Moreover, essential topics, including the ultimate environmental impact of nanoparticles and potential health hazards for workers in the construction industry, remain underexplored in existing literature [20, 21].

This critical analytical review aimed to address the identified gaps through a comprehensive synthesis of findings from 75 peer-reviewed papers. The purpose of this study was to: (1) categorize major types of nanomaterials and describe their physiochemical attributes; (2) evaluate their mechanical and durability effects systematically with respect to the underlying mechanisms; (3) outline prevailing difficulties; and (4) delineate promising future research avenues and requirements for successful industrial uptake. The method employed in identifying, screening, and selecting the studies included in this review is provided in the next section.

2. Review Methodology and Study Selection

The present review was conducted following an ordered literature selection procedure that involved finding peer-reviewed papers on nanomaterial-enhanced cement-based composite systems. The literature was searched using Scopus, Web of Science, ScienceDirect, Google Scholar, and publisher databases. Search terms were combined using Boolean operators and included "nanomaterials in concrete," nano-silica concrete, "carbon nanotubes cement," carbon nanofibers concrete, "nano-TiO_2 concrete," nano-alumina concrete, "nanoclay cement," graphene oxide concrete, "mechanical properties," durability, "chloride resistance," sulfate resistance, "permeability," and "freeze-thaw resistance."

Most publications were considered to cover the literature from 2005 to 2026. Nonetheless, seminal articles published before 2005 were retained if they presented a basic mechanism or evidence relevant to nanotechnology in cementitious materials. This review is dedicated to nanomaterials embedded in cement mortar, traditional concrete, high-performance concrete, ultra-high-performance concrete, and geopolymer concrete.

Articles were considered if they (i) were published in peer-reviewed journals or credible conferences, (ii) explored one or several types of nanomaterials within cement-based composites, (iii) included results concerning mechanical properties, durability, microstructure, environmental impact, or implementation, and (iv) included sufficient data for analysis. Articles were omitted if they (i) only referred to a non-cementitious matrix, (ii) did not have experimental procedures and quantitative results described clearly, (iii) were duplicates, (iv) were not available in a full-text version, or (v) had incomplete bibliographical data.

After the selection of articles based on title and abstract screening and full-text review, 75 articles were selected for analysis. These articles were classified based on their nanomaterial type, concentration, dispersion methods, concrete systems, tested properties, exposure, and limitations. Figure 1 shows the literature search and screening process. The diagram outlines the step-by-step approach taken to filter publications based on relevance, eliminate duplication of records, screen the titles and abstracts, check for inclusion criteria at the full-text level, reject ineligible articles, and end up with 75 articles for analysis.

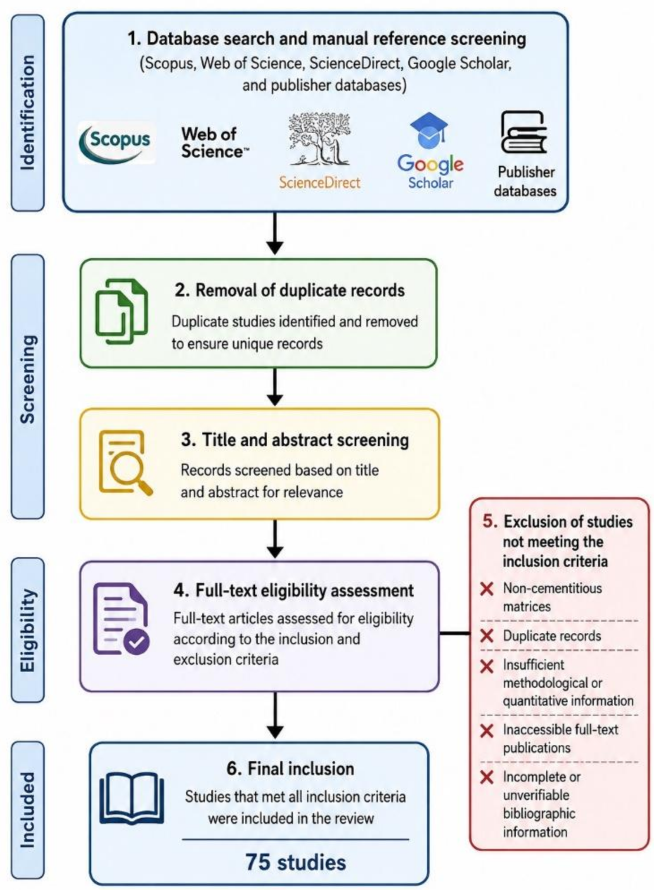

Figure 1. Flowchart of literature search and study selection

These studies were further classified based on the nature of the nanoparticles used, their doses, methods of dispersing them, types of concrete systems being considered, their mechanical and durability characteristics, exposure conditions, and practical constraints discussed by them.

3. Nano-materials used in Concrete

The variety of nanomaterials utilized to modify the properties of concrete is vast and growing. They can be categorized into three major groups: (i) silica- and oxide-based nanomaterials, (ii) carbon-based nanomaterials, and (iii) clay- and bio-based nanomaterials. Their particular physicochemical characteristics govern the interaction between the material and the cementitious matrix [8, 12, 22, 23].

3.1 Nano-silica (NS)

Nano-silica (SiO_2) is the most studied and commercialized nanomaterial for concrete applications. Synthesized either through pyrogenic methods or precipitation, NS particles are usually between 5 and 50 nm in size and have specific surface areas greater than 100 m^2/g [4, 10]. The main mode of action of the material is double-edged: (i) physical pore-filling that results in a density increase in the cement paste and (ii) pozzolonic reaction with portlandite ($Ca(OH)_2$) to form extra C-S-H gel in the ITZ [24, 25].

In experiments with lightweight aggregate concrete, Federowicz et al. [26] found that NS incorporation lowers the total porosity by up to 30% compared with control samples without nanoadditives. Lone et al. [27] reported that the pozzolonic activity indices in NS-modified self-compacting concrete (SCC) were much higher than those in conventional silica fume. Karanth and Kumar [28] found that the presence of NS improves the workability of the fresh state of SCC (in conjunction with proper superplasticizers) and increases the compressive strength of the hardened state. The optimal NS dosage ranges from 1 to 3% by mass of cement [10, 27, 29]. In a study by Rao [30], the compressive strengths of silica fume-incorporated cement pastes increased gradually and then stabilized at much lower values than those of nano-silica, confirming the pozzolonic superiority of the latter [30]. Abd.El.Aleem et al. [31] reported that nano-silica promotes rapid early hydration and reduces the thermal expansion of cement pastes [31]. Dosages above the threshold result in agglomeration, rendering all advantages meaningless [32, 33].

3.2 Carbon Nanotubes (CNTs) and Carbon Nanofibers (CNFs)

Carbon nanotubes are a peculiar type of one-dimensional nanostructure with extremely high tensile strength (more than 100 GPa), high aspect ratio, and conductivity [8, 34]. Multiwalled carbon nanotubes (MWCNTs) are preferred for use in concrete owing to their availability and lower price than single-walled carbon nanotubes [14, 34].

Van et al. [34] demonstrated that adding 1.0% CNTs resulted in the maximum fracture strength and dynamic increase factor of concrete exposed to an impact load. The mechanism behind the observed results was explained by Guo et al. [14], who provided SEM images proving that CNTs are anchored in hydration products and thus provide three-dimensional reinforcement. CNFs have been found to improve flexural toughness and post-crack energy dissipation in ultra-high-performance concrete [35, 36]. One of the crucial problems that should be addressed is uniform dispersion. Ultrasonic treatment, surfactant pretreatment, and acid surface treatment appear to be among the most popular techniques [14, 34, 37].

3.3 Nano-Titanium Dioxide (nano-TiO_2)

What distinguishes nano-titaniuim dioxide from other nanomaterials is its mechanical and photocatalytic properties. Along with the usual mechanical reinforcement by pore-filling and nucleation, the photocatalytic effect of titanium dioxide allows the breakdown of organic compounds on the surface of concrete, leading to self-cleaning behavior under UV radiation [38, 39, 40].

According to Khungar et al. [38], the additions of TiO_2 can mitigate the negative effects of recycled aggregates on concrete properties. In a review of concrete surface treatment techniques performed by Pan et al. [41], photoactive TiO_2 coatings turned out to be the most effective technique to combine improvement in surface durability and purification of surrounding air [41]. Photocatalysis involves the formation of reactive oxygen species (ROS), leading to the oxidation of carbon compounds and nitrogen oxides on the surface [39, 40]. As described by Huseien [12], nano-TiO_2 incorporation improves the resistance to chloride penetration owing to the denser microstructure resulting from nucleation during cement hydration.

3.4 Nano-Alumina (NA)

Nano-Alumina (Al_2O_3) is a kind of nanomaterial with particles of 10–80 nm that react with calcium hydroxide to form an additional Ca-aluminate hydrate along with the usual C-S-H gel, leading to the formation of very dense and durable microstructure [24, 42].

Gao et al. [42] found out that incorporation of NA significantly increased resistance to sodium sulfate solution attack in wet-dry cycle conditions. Al-saffar et al. [24] explained the increase by the nano-filler effect that limits pathways for ionic attack and prevents ettringite formation in the hydrated paste. The optimal amount of NA in concrete was reported to range from 1 to 5% [11, 42, 43].

3.5 Nano-Clays and Layered Silicates

Nanoclay minerals, such as montmorillonite, halloysite nanotubes, and kaolin, are nanomaterials that belong to a group of layered silicates with large aspect ratios and specific surface areas. Their effect on the properties of concrete is linked to the interlayer filling that occurs as clay minerals become incorporated into the cement paste matrix, affecting the rheological properties of the mixture and exhibiting some degree of pozzolonic reactivity [22, 43, 44].

According to Srinivasan et al. [43], using nanosilica and nanoclays in a concrete blend leads to notable mechanical strengthening and improved fluidity. Morsy et al. [45] showed that a combination of carbon nanotubes and nanoclays resulted in a synergistic increase in the compressive and tensile strength [45]. According to Federowicz et al. [26], layered clays reduce alkaline-silica reaction (ASR) susceptibility by consuming alkali. Halloysite nanoclay was used by Farzadnia et al. [44] to improve the mechanical properties and densify the microstructure of cement mortars.

3.6 Graphene oxide (GO) and emerging nanomaterials

Among the recently developed nanomaterials with promising applications in cement matrices are graphene oxide, cellulose nanomaterials, chitin, and iron oxide nanoparticles. Graphene oxide possesses unique features, such as a planar shape, numerous oxygen-containing functional groups, and exceptional mechanical stability (Young's modulus ≈1 TPa). Thus, GO can act as a physical reinforcement for concrete, nucleation template for C-S-H gel, and moisture diffusion hindrance [15, 16].

Kawashima et al. [46] revealed that GO treatment results in significant improvement in flexural strength and stiffness owing to interlocking effect due to wrinkles, as well as lowering the porosity level by up to 18% [46]. Saliani et al. [16] performed tests with Fe_3O_3/SiO_2/GO hybrid nanomaterials that provided synergistic improvement in mechanical properties and durability indices. Cellulose and chitin nanomaterials were reviewed by Zhong et al. [17]. They showed that the reinforcement mechanisms were related to bridging, internal curing, and increased crack tortuosity.

3.7 Critical Comparison of Nanomaterials for Concrete Applications

However, although almost all nanomaterials have the potential to increase the performance of cement-based composite materials, their value cannot be assessed based on the highest gain in compressive strength achieved in certain studies. The practical benefit of using nanomaterials should be considered in terms of the predominant enhancement mechanism, optimal amount of material to be added, dispersity, compatibility with other chemical admixtures, effect on rheological parameters, durability goal, cost, and mass production feasibility.

The current nanomaterial that is the most suitable for structural concrete is nano-silica, because the predominant role of the three mechanisms of action of nano-silica – pore filling, fastening of the hydration process, and consumption of calcium hydroxide due to the pozzolanic reaction – is the provision of high compressive strength, improved porosity, dense interfacial transition zone, and decrease in water and chloride permeability. However, owing to the high specific surface area of the material, its usage leads to increased water demand. Moreover, an excess dosage or improper dispersity will result in agglomeration and loss of workability of concrete. This is why the use of the material is especially beneficial in cases where the improvement of strength development and resistance to durability issues associated with permeability is needed.

In contrast to nano-silica, the use of carbon nanotubes and carbon nanofibers is recommended when there is a need to enhance the tensile-related properties, flexural toughness, fracture resistance, and multiple functionalities of the material. However, their practical applicability is somewhat lower due to the need for proper dispersion in ultrasonic conditions, use of surfactants, and surface functionalization. Therefore, carbon-based nanomaterials are currently more suitable for ultra-high-performance concrete, repair materials, prefabricated elements, and smart concrete.

In turn, nano-TiO_2 is characterized by a completely different set of properties owing to its functional characteristics. In addition to the nucleation and pore-filling effect of nano-TiO_2, the material also provides photocatalytic self-cleaning and pollutant degradation under appropriate illumination. Due to the structural advantages of the material, they are moderate compared to those of nano-silica; however, the material is potentially useful in façade panels, pavements, and surfaces requiring photocatalytic performance. Nanoclays and nano-aluminas improve matrix density and resistance to aggressive environments. Nano-alumina potentially enhances the sulfate resistance of the matrix through microstructural densification and hydration product changes, whereas nanoclay improves the packing and refinement of pores, but is very sensitive to dosage and dispersity issues.

Graphene oxide provides huge possibilities for improvement of matrix due to the high possibility of nucleation of hydration products due to the functional groups and ability to hinder crack propagation and moisture penetration. The usage of the material is not widespread due to its high price, difficulty in reproducing the results, and issues with large-scale dispersion. Therefore, the choice of nanomaterial should be based on the application needs rather than compressive strength improvement.

To facilitate a concise comparison across all nanomaterials, Table 1 provides a brief overview of the primary mode of action, optimal dosage range, key performance benefits, practical considerations, and most appropriate applications for each of the main types of nanomaterials employed in concrete. It is clear from this table that the choice of nanomaterial should depend on the required performance benefit.

Table 1. Critical comparison of the major nanomaterials used in concrete.

Nanomaterial	Dominant mechanism	Typical optimum dosage (% binder)	Main performance contribution	Main practical limitation	Most suitable application
Nano-silica	Pore filling, nucleation, pozzolanic reaction	1–3	Compressive strength, lower permeability, chloride resistance	Increased water demand and agglomeration	General structural and durable concrete
CNT/CNF	Crack bridging and stress transfer	0.05–1.0	Tensile strength, flexural toughness, crack resistance, sensing	High cost and difficult dispersion	UHPC, repair mortars, smart concrete
Nano-TiO_2	Nucleation, filler effect, photocatalysis	1–5	Surface durability and self-cleaning function	UV dependence and modest bulk-strength gain	Façades, pavements, exposed surfaces
Nano-Al_2O_3	Filler effect and hydrate modification	1–3	Matrix densification and sulfate resistance	Workability reduction	Concrete exposed to sulfate environments
Nanoclay	Layered particle packing and pore refinement	1–3	Reduced permeability and improved microstructure	Strong dosage and dispersion sensitivity	Mortars and durability-oriented concrete
Graphene oxide	C–S–H nucleation and crack deflection	0.01–0.1	Crack resistance, stiffness, reduced porosity	Cost, reproducibility, scale-up limitations	High-value multifunctional composites

As can be seen in Table 1, each of the mentioned nanomaterials possesses its own properties and cannot be rated according to only one characteristic. Nano-silica is considered to be the most suitable choice in the case of reinforcing and increasing transportation resistance, while CNTs/CNFs and graphene oxide are better to use in the case of crack resistance and multiple purposes. Nano-TiO_2, on the other hand, can be chosen when it comes to photoreactive surface properties, while nano-alumina and nanoclay are more appropriate in the case of dense matrix and aggressive environment resistance.

Because the observed performance values of concrete reinforced using nanomaterials differ from one study to another, quantification is required to determine the order of magnitude of the enhancement that can be attributed to each nanomaterial. Table 2 illustrates the performance ranges that have been documented in the reviewed literature for optimum addition levels. However, the performance values must be treated with caution because they depend on several factors.

According to Table 2, the use of nano-silica leads to the highest increase in the compressive strength and impermeability towards water and chlorides, thus explaining the higher practical maturity of this material in structural concrete. While CNTs/CNFs and graphene oxide offer better improvements in terms of tensile properties and crack resistance, the performance of such materials is much less stable owing to the critical dependence on the even distribution and interaction between the matrix and filler phases. Nano-TiO_2, nano-alumina, and nanoclay usually provide some mechanical benefits; however, other characteristics can be more significant.

Figure 2 provides an example that indicates that the choice of nanomaterials must depend on the application or exposure conditions, and not just on increasing the compressive strength. Nanomaterials that are readily available for practical use, such as nano-silica, are better for traditional structural concrete, but CNT/CNFs and graphene oxide might be preferred in other cases where there is a need for crack prevention and sensing. From Figure 2, it is clear that the choice of nanoparticles is determined by the intended use and conditions of application, and not just because they improve the compressive strength of concrete. The choice of materials that are highly available includes nano-silica, which is best used in structural concrete, while CNTs/CNFs and graphene oxide could have other uses.

Table 2. Indicative quantitative performance improvements have been reported for nanomaterial-modified concrete.

Nanomaterial	Typical optimum dosage (% binder)	Compressive-strength improvement (%)	Tensile/flexural-strength improvement (%)	Water-absorption reduction (%)	Chloride-transport reduction (%)	Main reason for variation
Nano-silica	1–3	10–35	5–20	20–40	30–60	Water demand, agglomeration, curing regime
CNT/CNF	0.05–1.0	5–25	15–50	10–30	15–40	Dispersion quality and interfacial bonding
Nano-TiO_2	1–5	5–20	5–18	10–25	15–35	Particle size, photocatalytic exposure, dosage
Nano-Al_2O_3	1–3	8–25	5–18	10–30	15–40	Hydrate formation and workability loss
Nanoclay	1–3	5–20	5–15	10–25	10–35	Clay type, dispersion, rheological effects
Graphene oxide	0.01–0.10	10–30	15–45	15–35	20–45	Surface functionalization and dispersion protocol

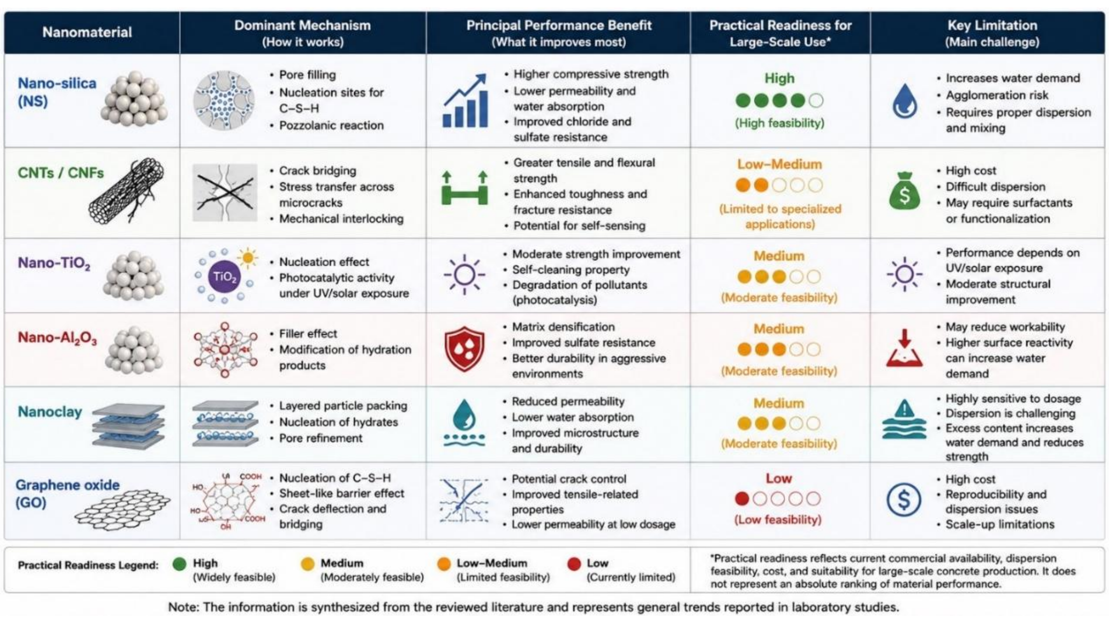

Figure 2. Overview of the most prevalent mechanisms, main benefits, practical availability, and main drawbacks of nanomaterials applied to concrete. Practical availability is the state of commercial availability, dispersibility, cost, and applicability to the mass production of concrete, but it does not necessarily indicate the absolute rating of material properties. Source: Compiled by the authors from relevant literature.

4. Effects on Mechanical Properties of Concrete

Nanomaterials influence the mechanical properties of concrete in three ways: (i) physical pore filling reduces porosity, (ii) pozzolanic and chemical reactions form additional binders, and (iii) crack bridging and energy absorption in fibrous nanomaterials such as CNTs [8, 9, 10, 12]. Each property is discussed in a separate section.

4.1 Compressive Strength

Compressive strength is one of the properties that appears most often when dealing with nanomaterial-modified concrete because it is a good indicator of concrete densification and binder formation. Various studies have reported compressive strength gains of 10–50% compared to conventional concrete, depending on the nanoparticle type and dosage, W/C ratio, and curing conditions [12, 47].

The use of NS yielded the highest and most reproducible gains in compressive strength, ranging from 20% to 35%. This effect was found to hold for various cement types [26, 27, 28]. Li et al. [48] proved that incorporation of both nano-silica and nano-limestone improves flowability and enhances mechanical properties of ultrahigh-performance concrete; compressive strength gains exceed 30% [48]. Qing et al. [49] conducted a comparative analysis of nano-silica and silica fume additives for hardening cement paste and found that the former was associated with stronger pozzolanic action owing to the smaller particles used [49]. The main reason for the improved compressive strength is the conversion of brittle portlandite to a stronger C-S-H gel, which improves the ITZ [24, 25, 26]. The same effect was observed with nano-TiO_2 additives through the nucleation of cement hydrates [38, 39]. The addition of alumina and clay nanoparticles results in a moderate compressive strength gain of 10-25% [42, 43]. Biricik and Sarier [50] performed a comparative analysis of silica fume, nano-silica, and fly ash used in the formulation of cement mortars; the nanomaterials outperformed the others in terms of pozzolanic activity and strength enhancement [50]. Biricik and Sarier [51] further explored the effect of SiO_2 nanoparticles, specifically on the compressive and flexural strengths of high-strength concrete; a compressive strength gain of up to 24% was documented when 3% nano-silica was used [51]. Machine learning models created by Nazar et al. [52] demonstrated better predictive power for nanomodified concrete, indicating promising applications in future data-driven mix designs [52, 53]. Once the threshold for nanoparticle agglomeration is exceeded (generally in the range of 3-5%), compression strengths begin to decrease or level off [32, 33].

4.2 Tensile and Flexural Strength

Tensile strength and flexural strength are important for concrete under tension or dynamic loads; however, these properties remain less studied than compressive strength [9, 37]. Among nanomaterials, fibrous nanoparticles provide the greatest enhancement in tensile strength through crack bridging and pullout resistance [34, 35].

Van et al. [34] showed that UHPFRC containing 1.0% MWCNT yielded the maximum fracture strength and dynamic increase factor at high strains. In the case of particulate nanomaterials, only a moderate improvement (of 10-20%) is possible; this stems from the reduced void size in micropores, but not the crack bridging itself [9, 47]. Sadiq et al. [23] found that ultra-high-performance composites containing functionalized carbon-based nanomaterials exhibited increased toughness, as measured using the area under the load-displacement curves. Yang et al. [38] reported flexural strength improvements of 22% in basalt fiber concrete containing nano-TiC and nano-SiO_2.

4.3 Modulus of Elasticity

The modulus of elasticity governs the behavior of concrete as it influences load transfer and deformation. The addition of nanomaterials typically results in an increased modulus of elasticity, proportional to the increased density and decreased porosity of the material [5, 12].

Federowicz et al. [26] noted that addition of NS resulted in an increase in modulus of elasticity value comparable with that of normal weight concrete, partially offsetting the loss of stiffness of lightweight concrete. Xu et al. [5] observed that the denser ITZ reduces the disparity between paste and aggregate modulus of elasticity. Agglomeration may decrease rather than increase the stiffness of nanocomposites [22, 32, 33].

4.4 Microstructure and Crack Resistance

One of the most important advantages of nanomaterials is their ability to modify their microstructures. SEM studies along with XRD, MIP, and BEI methods have shown that nanomaterial additions (i) reduce the total porosity with an increase in fine pore content, (ii) densify the ITZ, (iii) change the calcium hydroxide crystal habit, and (iv) create additional C-S-H gel filling the pores [5, 24, 54].

As can be seen above, changes in the microstructure result in an increased crack resistance of the concrete [5]. Xu et al. [5] found that the nano-modified ITZs had higher fracture energy due to increased densification and tortuosity of cracks. Guo et al. [14] observed using SEM that cracks in CNT reinforced concrete deviate around CNT aggregates; this leads to an increase in fracture surface area. Mohanty et al. [55] observed a significant decrease in the surface crack density in pavements with nanomaterial addition [55, 56].

4.5 Influence of Curing Condition on Mechanical Properties

The curing condition is a crucial factor in determining the hydration process and, therefore, the ultimate mechanical properties. It was shown that nanomaterial benefits could be greatly magnified if optimal curing conditions were provided (e.g., continuous water cure at 20-23°C); conversely, improper curing may reduce the benefits of nanoparticles added [10, 12].

Huseien [12] showed that addition of nano-SiO_2 led to higher compressive strength of concrete under both air and water curing. Heikal et al. [57] found that NS-incorporated cement paste exhibited superior microstructural stability at higher temperatures, whereas Bastami et al. [58] showed that high-strength concrete with nanomaterials had greater residual compressive strength after exposure to 600°C [57, 58]. Under cold weather conditions, Nilimaa and Zhaka [59] explored the role of smart concrete in achieving the required quality; they found that the addition of nanoparticles accelerated hydration reactions at low temperatures [59, 60].

5. Effects on Durability Properties of Concrete

Durability encompasses the capacity of concrete to resist the deterioration caused by physical, chemical, and biological agents over its intended service life. Nanomaterial incorporation improves durability primarily through pore structure refinement, which reduces ionic and fluid transport, and through chemical modification of hydration products, which increases the resistance to aggressive environments [8, 9, 10, 24].

5.1 Resistance to Chemical Attack

5.1.1 Sulfate Attack

Sulfate attack is one of the most harmful durability problems affecting concrete because of the reaction between external sulfate ions and calcium aluminate hydrate phases to produce expansive ettringite and gypsum [8, 42]. Gao et al. [42] proved that the resistance of NA-modified concrete exposed to wetting-drying sodium sulfate solutions was far greater than that of OPC samples in terms of lower tensile strength and chloride ion penetration depth. This is related to the dense microstructure, which consists of fewer interconnected capillary pores to prevent the penetration of sulfates [24, 54].

5.1.2 Chloride Penetration

Rebar corrosion as a result of chloride penetration is considered the main cause of the early deterioration of reinforced concrete structures [12, 62]. Al-saffar et al. [24] discussed the impact of nanoparticles on the composition of C-S-H gel and its microstructure in a way to decrease chloride diffusion coefficient. Nanosilica has been proven to provide the highest percentage of reduction (40–60%) in chloride ion penetration depth compared to OPC concrete [12, 26, 27]. Moreover, titanium dioxide and other hybrid nanomaterials have been found to exhibit considerable resistance against chlorides [10, 16, 38].

5.2 Permeability and Water Absorption

Water absorption and gas/liquid permeability are gateway properties for practically all types of concrete deterioration processes. Nanomaterial incorporation results in improved resistance to several degradation modes owing to their effect on the pore structure [10, 12, 25].

Federowicz et al. [26] found that nanoparticle-incorporated lightweight concrete showed up to a 40% reduction in water absorption, where the pore size distribution tended to shift towards gel and small capillary pores. This tendency was validated by Mahmud et al. [22], who pointed out that the reduction in permeability depends on the surface area of nanoparticles that are available for secondary hydration. Gamal et al. [13] stated that hybrid nanomaterials are capable of decreasing permeability to a greater extent than those based on a single component [13, 16, 37]

5.3 Freeze-Thaw Resistance

Owing to the volumetric expansion of pore water upon freezing during freeze-thaw cycles, the cement paste becomes gradually damaged in terms of surface scaling and loss of mechanical properties along with the material itself [59, 61]. Consequently, concrete characterized by low connected porosity and fine pore size distribution is less prone to such problems because of the higher temperature required for freezing fine pores and the smaller volume of freezeable water [26, 54, 59].

Nilimaa and Zhaka [59] investigated the application of smart materials in cold weather construction and confirmed that nanomaterials play a role in increasing the resistance of concrete to freezing conditions via pore refinement. Yang et al. [10] found a regularity that proved that nanomaterial-containing concretes had higher frost resistance in comparison with OPC, as reflected in the mass retention and elastic modulus before and after 300 standard cycles of freeze-thaw test (ASTM C666). A study by Imtiaz et al. [61] dedicated to eco-friendly geopolymer concretes incorporating nanomaterials found that the combination of geopolymer binders and nano-SiO_2 was extremely effective owing to the formation of a dense matrix [54,61, 63,].

5.4 Abrasion and Wear Resistance

Resistance to surface abrasion is an important property that should be considered when concrete is exposed to traffic or mechanical loads. This property depends largely on the hardness of the concrete surface and aggregate/paste adhesion strength [12, 55, 56].

Mohanty et al. [55] conducted a review of pavement quality concrete and found that nanoparticle addition yielded better results with respect to abrasion depth and wear index. These results were explained by the effect of nanoparticles on the densification of the concrete surface and the removal of the weak portlandite-rich layer [24, 56]. Moreover, according to the results of Zaid et al. [64], who reviewed geopolymer concretes enhanced with nano-SiO_2 and nano-Al_2O_3, they exhibited better abrasion resistance than conventional geopolymers and OPC-based concretes [64, 65]. In his research on cement mortar containing nanoparticles, Li et al. [65] used SEM and XRD techniques to analyze the microstructure and concluded that this technology resulted in the creation of a more compact and homogeneous matrix with fewer cracks and inter-aggregate porosity [65].

5.5 Long-Term Sustainability and Service Life Implications

The increased durability of nanomaterial-enhanced concrete is beneficial in terms of sustainability because structures that resist deterioration for longer periods require less maintenance, and hence less energy, material usage, and CO_2 emissions [6, 7, 21].

Castro et al. [6] stated that improvement of concrete durability and service life extension resulted in the reduction of lifecycle CO_2 equivalent emissions by 20–40% as compared to conventional concrete with a requirement to rehabilitate it every now and then. Moreover, Rajbahadur et al. [7] concluded that nanomaterial-modified concrete contributes to circular economy because it involves a decrease in material consumption and an increased lifespan of the infrastructure. Nanomaterials have been shown to be able to compensate for the mechanical properties lost by using recycled aggregates, which is a step toward recycling and reusing construction and demolition waste [66]. Nong [67] applied molecular dynamics simulations to study nanomaterial-enhanced concrete durability and chloride diffusion inhibition mechanisms at the atomic level [4, 67].

6. Challenges and Limitations

Although a large body of evidence supports performance improvements from nanomaterial addition, considerable hurdles exist in achieving universal industrial implementation. Such obstacles span multiple fields, including technological, economic, regulatory, and environmental health [9,20, 21].

6.1 Dispersion and Uniformity

Possibly, the most significant challenge to the implementation of nanomaterials in concrete arises from their agglomeration tendencies owing to their high surface energy [12,26,32]. Agglomerated clusters act as defects in the matrix and negatively impact both the mechanical strength and durability compared to well-dispersed forms of nanomaterials or even compared to OPC control mixes in extreme cases.

A variety of dispersion methods have been proposed for nanomaterial-concrete systems: ultrasonic vibration is extremely effective in terms of dispersing CNTs and GO, but power requirements for large-scale implementation make it unfeasible; surfactant pretreatment of NS improves dispersibility but creates air inclusion problems that decrease strength; and shear mixing works for NS but fails with nanoplatelets and nanotubes [14, 34, 43]. Federowicz et al. [26] concluded that no one-size-fits-all approach to dispersion was possible. Collepardi [68] laid out the principles behind the interaction between admixtures and concrete mixtures, providing a basis for the use of superplasticizers as dispersing agents for nanomaterials and noting the importance of matching the surface charges of the particles [68]. Significant rheological modifications resulting from NS addition have been described by Senff et al. [69] and Collepardi et al. [70].

6.2 Cost and Economic Viability

The market prices of most nanomaterials are significantly higher than those of supplementary cementitious materials (SCMs) such as fly ash and GGBFS. While some SCMs can compete in economic value with concrete nanomaterials, CNTs remain several orders of magnitude more costly than most common concrete additives, restricting their use in specialty products [20, 21]. Nano-SiO_2 is relatively cheaper, and as the volume of its production rises, its price falls, but it still costs much more per ton than silica fume [27, 29, 33].

An integrated evaluation of the environmental, human health, and economic implications of concrete nanomaterial usage conducted by Ferreira et al. [20] showed that while environmental and performance indicators strongly support their adoption, economic indicators paint the opposite picture. Economic feasibility would increase considerably for cases involving structures requiring very long lifespans, thus making premature destruction costly [6, 7, 71].

6.3 Environmental and Health Risks

Growing attention is being paid to the health risks related to engineered nanomaterials. Nanoparticles smaller than 100 nm can penetrate biological membranes and avoid phagocytosis, leading to their accumulation in target organs [20, 21]. People engaged in the production and application of concrete containing nanomaterials face direct risks from exposure via inhalation, dermal contact, and ingestion.

The lack of adequate data regarding the toxicity of nanomaterials used in construction was emphasized by Ferreira et al. [20], especially concerning CNTs and nano-TiO_2, and the authors stressed the need for comprehensive exposure assessment studies using realistic construction scenarios. The behavior of nanoparticles released into the environment during the construction or destruction of nano-modified concrete is not fully understood [9, 21]. An appropriate overview of the pros and cons related to the application of nanotechnology in construction by Pacheco-Torgal and Jalali [21] highlights the necessity of risk-benefit analysis before broad industrial deployment.

It is important to assess the potential adverse impacts of nanoparticle-modified concrete not only during the process of nanoparticle production but also throughout the entire life cycle of the material. Exposure might occur during the weighing and handling of dry powders of nanoparticles, mixing and casting of nano-modified cementitious material, spraying of nano-enhanced coatings, and cutting, drilling, grinding, demolishing, recycling, or disposal of hard concrete. The probability and degree of exposure are dependent upon the nanoparticle type, size, surface chemistry, concentration, whether they are in a dry or wet state, and how well they become immobilized in the cement matrix.

However, the possibility of maximum exposure is related to the dust produced during the dry handling of nanoparticles and their mechanical processing. Although the nanoparticles can be well embedded in the cement matrix during its service, there is still a risk of dust containing nanoparticle fragments during the cutting, drilling, grinding, and demolishing of concrete. Nanocarbon materials and nano-titanium dioxide need special attention as the potential biological effects of these materials can depend on their morphology, surface functionalization, concentration, and mode of exposure. Thus, when assessing the exposure, one should consider the nanoparticles themselves and the dust produced from nano-modified concrete.

As it follows from the hierarchy of controls, the risk management of potential exposure to nanoparticles needs to minimize the handling of dry nanopowder with the help of pre-dispersed suspensions, wet mixing, enclosed transport, and automated dosing. Engineering controls, such as local exhaust ventilation and dust collection systems, should be applied during the mixing and mechanical processing of materials. As for personal protective equipment, the choice depends upon the risk of exposure and might consist of respiratory protection, gloves, protective clothing, and eye protection.

Occupational safety frameworks for engineered nanomaterials stress the importance of prevention, monitoring, and risk-based management of exposure, rather than just setting a universal exposure limit. From the perspective of nano-modified concrete, this implies task-specific risk assessment, identification of nanoparticles and their concentration, monitoring of exposure, if necessary, and regular reassessment of control measures. Thus, future research of this type should involve mechanical and durability testing along with the measurement of dust release, leaching and ecotoxicity evaluation, and life cycle analysis.

In this regard, the sustainability of nano-modified concrete must also be evaluated in terms of its capacity to reduce exposure to humans and the environment and at the end of its useful life, rather than just in terms of increasing its strength and durability.

6.4 Lack of Standards and Quality Control

The absence of specific internationally recognized standards for concrete containing nanomaterials poses a serious problem. The current standards for concrete (e.g., ACI 318, Eurocode 2, BS EN 206) do not consider the presence of nanomaterials in concrete formulations [18, 43].

The importance of standardization problems as the primary barrier to the implementation of nano-modified concrete has been highlighted by Srinivasan et al. [43]. ISO/TC 229 (Nanotechnologies) and RILEM Technical Committee 269-IAM are currently actively working on this matter, although their efforts do not keep up with the pace of scientific research [9, 18]. As noted by Shekari and Razzaghi [11], the lack of standardized test procedures for measuring durability leaves the results obtained in different studies incomparable.

6.5 Effect on Workability and Hardening Time

Nanomaterials characterized by high specific surface areas, such as NS and nanoclay, increase water demand and lower the slump of fresh concrete if not compensated by the addition of superplasticizers. High reactivity in the pozzolanic reaction and pore-filling process leads to the acceleration of cement hardening, which decreases the window of opportunity for proper placement and compaction [10, 33, 43].

According to Huseien [12], the careful choice of the superplasticizer type and dose almost completely compensates for any workability loss when NS is added. The rheological properties of NS-modified cement pastes and mortars were thoroughly studied by Senff et al. [69], revealing a considerable increase in yield stress values. A systematic characterization of workability by Said et al. [72] revealed that for NS concentrations above 2%, an additional portion of superplasticizer should be introduced to maintain slump values similar to those of plain cement mortar. Zhang et al. [60] found that the incorporation of nanosilica resulted in a faster setting time of concrete with high amounts of slag.

6.6 Life-Cycle Assessment and Sustainability Implications

Nano-modified concrete needs to be considered from a lifecycle standpoint and not merely the benefits seen in terms of early age strength gain. The overall balance in environmental terms can be measured based on the effects of nanoparticle production, transportation, application dosages, dispersion energy, reduction in cement use, improved durability, maintenance, and disposal at the end of its life cycle. A cradle-to-gate analysis performed for the production of industrially precipitated nanosilica revealed that electricity consumed during water glass production was one of the main drivers for the overall environmental impacts of nanosilica production [76].

Sustainability and economic issues tend to be more significant for carbon-containing nanomaterials owing to the high energy consumption and high cost of the materials used. Du et al. [77] studied the mechanical performance, life cycle cradle-to-gate assessment, and cost analysis of cement mortar with MWCNTs of 0.05-0.45% and nano-silica of 0.2-1.0%. The authors have found that the MWCNT content increases the cost of materials, whereas the use of small amounts of MWCNTs in combination with nano-silica is more advantageous from both environmental and economical perspectives. Multi-parameter optimization proposed the following combination: 0.05% MWCNT and 0.02% nano-silica.

For this reason, it should not be assumed that the only reason nanomaterials can be deemed sustainable is their ability to increase strength or decrease permeability. It is more likely that there could be potential environmental gains from the fact that enhancing durability can decrease maintenance needs and increase lifespan in aggressive environments. Further analysis should be performed on service life-based functional units.

6.7 Scalability and Practical Implementation

Nevertheless, despite encouraging lab-scale results of nanomaterial-modified concrete, several problems still exist that need to be overcome for wide industrial implementation. The majority of papers dealing with the subject contain experiments carried out using small laboratory batches under very specific mixing, curing, and dispersion conditions. Implementing such techniques in ready-mix concrete plants, precast factories, and large construction sites is complicated.

First, it is difficult to ensure the appropriate dispersion of nanoparticles on a large production scale. Lab techniques including ultrasonication, intensive high-shear mixing, and surfactant-based dispersion may become too costly and difficult to implement at an industrial plant. Nonuniform dispersion may lead to the agglomeration of nanoparticles and, consequently, to the reduction of expected properties and formation of weak spots within the cementitious paste. The next aspect that should be considered is the compatibility with traditional admixture systems, as nanoparticles increase water requirements and alter the rheological properties of concrete, which needs some modifications in dosages and techniques of superplasticizer usage.

From an economical point of view, nano-silica has become the most promising solution, as it is already produced commercially and can be introduced to the concrete production process using conventional techniques. At the same time, carbon nanotubes, carbon nanofibers, and graphene oxide are more expensive and normally require some special dispersion technique. That is why, in spite of their great potential, it seems more realistic to use such nanoparticles in ultra-high-performance concrete, repair materials, prefabricated elements, sensoring systems, and other engineering applications where higher performance can cover additional cost.

Finally, it is worth mentioning that, although the number of laboratory studies on the subject is impressive and almost all of them demonstrate improvement in strength, impermeability, durability, etc., there are few field-scale experiments carried out under the influence of environmental factors. Therefore, future research should focus on pilot-scale tests, field monitoring, and service-life analysis. Based on current technological considerations, nano-silica appears to be the most promising material in terms of its performance properties and practicality. Both carbon-based nanomaterials and graphene oxide show great technological promise, but more effort is needed for them to be adopted in mass concrete production because of cost and dispersion issues.

6. Comparative Synthesis and Practical Implications

The studies under review prove that different types of nanomaterials have different influences on the properties of concrete. For example, nano-silica provides the most consistent results in terms of enhancement of compressive strength and transport characteristics owing to its physical filler and pozzolanic reactivity nature. As for carbon-based nanomaterials, they are better in tensile and crack-resistant properties; however, the results vary more because of the dispersion efficiency. Nano-TiO_2 can be used for photocatalysis or self-cleaning purposes while nano-alumina and nanoclay can be chosen for the needs of sulfate resistance or rheology modification.

Table 3. Summary of representative studies on nanomaterials in concrete

Authors (Year)	Nanomaterial	Dosage (%)	Key Findings	Limitations
Sanchez & Sobolev [8] (2010)	Various	—	Foundational framework: nanotechnology in concrete; survey of enhancement mechanisms	Conceptual review; limited primary experimental data
Shekari & Razzaghi [11] (2011)	NS, Al_2O_3, TiO_2, ZrO_2	0.5–2	Nano-particles improve compressive strength and split tensile strength of HPC; TiO_2 most effective for durability	Limited to short-term (28-day) lab testing
Lone et al. [27] (2016)	Nano-SiO_2	1–5	Higher pozzolanic activity in NS-modified mortar/SCC vs. silica fume	Restricted to cementitious lab systems
Federowicz et al. [26] (2021)	NS	0.5–3	Up to 30% porosity reduction in lightweight concrete; density improvement	Results specific to lightweight aggregate
Sadiq et al. [35] (2021)	Functionalised CNTs	0.5–1.5	Enhanced toughness and durability in UHPC; functionalisation critical	High functionalisation cost; lab scale only
Gamal et al. [13] (2021)	Hybrid nano	1–3	Synergistic strength and corrosion resistance; compressive strength up 30%	Limited to hybrid combinations only
Saliani et al. [16] (2021)	Fe_3O_4/SiO_2/GO	0.5–2	Synergistic mechanical and durability gains from ternary nano system	Complex synthesis and cost barrier
Huseien [12] (2023)	Multi-nano	1–4	Consistent mechanical and durability gains across nanoparticle types	Review-based; no new primary data
Al-saffar et al. [24] (2023)	Various	—	C-S-H gel densification and chloride resistance mechanisms elucidated	Variability across study conditions
Nilimaa & Zhaka [59] (2023)	Multi-nano	—	Nanomaterials mitigate freeze-thaw damage in cold-climate construction	Review format; limited primary data
Zaid et al. [64] (2023)	Various in geopolymer	1–4	Geopolymer + nano: enhanced strength, durability, and sustainability	Geopolymer-specific; not directly transferable to OPC
Karanth & Kumar [28] (2024)	Nano-SiO_2	0.5–3	NS enhances SCC workability and mechanical properties significantly	SCC-specific experimental scope
Srinivasan et al. [43] (2024)	NS + Nanoclay	1–3 each	NMC: significant strength and workability improvements; standardisation gap identified	Standardisation framework absent
Mahmud et al. [22] (2024)	Various	1–5	Comprehensive review; nanoparticles improve strength, thermal and durability performance	Heterogeneous study base; variable W/C
Yang et al. [73] (2024)	Nano-TiC + NS	0.5–2 each	Up to 22% flexural strength gain in nano-modified basalt fibre concrete	Single fibre type; limited durability data
Nazar et al. [52] (2022)	ML on nano concrete	—	RFT machine learning model outperforms regression for compressive strength prediction	Data-dependent; requires large curated dataset
Zhong et al. [17] (2022)	Cellulose/chitin	0.5–2	Bio-based nanomaterials improve concrete via bridging and internal curing mechanisms	Durability and long-term data limited
Xu et al. [5] (2022)	Various (ITZ focus)	—	Nano-modified ITZ: higher fracture energy, reduced chloride transport	Review-based; experimental verification needed
Abdalla et al. [39] (2022)	TiO_2, Fe_2O_3, nanoclay, $CaCO_3$	1–3	Multiple nano types enhance cement/geopolymer concrete mechanical and durability properties	Material-specific; variable performance by system
Gao et al. [42] (2025)	Nano-Al_2O_3	1–3	Superior sulfate resistance under wetting-drying cycles	Single chemical exposure condition tested
Khungar et al. [38] (2025)	Nano-TiO_2	1–5	TiO_2 compensates for recycled aggregate deficits; photocatalytic self-cleaning demonstrated	Limited to recycled aggregate concrete systems
Van et al. [34] (2025)	CNTs (MWCNT)	0.5–1.0	Highest fracture strength and dynamic increase factor in UHPFRC	Cost and industrial dispersion barriers
Guo et al. [14] (2025)	CNTs	0.1–1	CNT reinforcing network formation confirmed via SEM; hydration improvement documented	Scale-up challenges remain unresolved
Nong [67] (2025)	Molecular dynamics	—	Atomic-scale Cl^- diffusion inhibition mechanism in nano-enhanced concrete demonstrated computationally	Simulation-based; experimental validation needed

In this respect, it is necessary to carefully consider the results of individual studies. The effectiveness of nanomaterial usage depends on its dosage, size, chemical structure, mixing process, presence of surfactants or superplasticizers, water/binder ratio, additional cementitious materials, curing conditions, testing age, and testing methods. Therefore, the results given in the following table represent a comparative overview of the trends described in the literature only. Table 1 provides a systematic summary of the 25 exemplary articles discussed in the literature, indicating the type of nanomaterial, administered dose, major results, and major constraints.

7. Future Research Directions

The conclusions drawn from the findings of this literature review indicate a very advanced level of understanding concerning the mechanisms behind the improved performance properties of concrete modified with nanomaterials. However, substantial gaps remain in applied and translational research.

7.1 International Standards for Characterization, Quality Control, and Performance Testing of Nanomaterial-Modified Concretes. Establishing internationally agreed-upon standards for the characterization, quality control, and testing of such concrete is essential for the field to move forward. Efforts should be made to agree upon reference test methods, acceptance criteria, and performance expectations with inputs from standard-setting bodies (such as ISO, ASTM, and CEN) [9,18,21,43].

7.2 Studies on Synergies in Mixes with Multiple Types of Nanomaterials. Based on existing work on hybrid nanomaterial concretes [10, 33], it appears that there may be some synergies between the inclusion of different types of nanoparticles in terms of the improved performance of the composite material. Systematic research into the synergistic relationships between two or more nanomaterial mixes based on the modeling of complementary reactions is recommended [12,13,17,73].

7.3 Long-Term Field Performance Analysis. Almost all papers dealing with nanomaterial-concrete have reported experimental results over a period of 28–90 days. Data from long-term field tests over a 5-20-year period must be available to verify the predictions from laboratory experiments and estimate performance decay rates [6, 24, 59, 62].

7.4 Full-Life Cycle Assessments. There is a critical need for lifecycle assessments (LCA) of the use of nanomaterials for concrete in terms of the production phase, construction phase effects, extended lifespan, and eventual nanoparticle release in the environment over the life cycle [9, 20, 21].

7.5 Application of Machine Learning and Digital Twins. Although still in its infancy, ML applications in nanomaterial–concrete have tremendous potential [52]. The collection of an expanded database through data-sharing and linking ML-based analysis with the monitoring of actual concrete structures using digital twins may offer valuable insights and help improve the performance of materials [22,32.35, 41].

8. Conclusions

In this study, 75 scientific articles that investigated the influence of nanomaterials on the mechanical and durability properties of concrete were analyzed. The key findings are as follows.

1. The performance of concrete is enhanced across all major mechanical property areas because of the combined action of physical pore filling, pozzolanic reaction, and crack-bridging properties of the used nanoparticles. The significance of each factor varies depending on the specific type and form of the particle.
2. Moreover, concrete exhibits increased durability, specifically improved resistance to the ingress of harmful agents, freeze-thaw cycles, and chemical attacks. Such performance results in a prolonged lifespan and decreased life-cycle cost and CO_2 footprint of construction materials.
3. At present, nano-silica provides the most optimal balance of mechanical reinforcement, improved durability, availability, and applicability for concrete uses. While carbon nanotubes, carbon nanofibers, and graphene oxide will bring better enhancements in the area of tensile strength and crack resistance, among others, the broader use of these materials is restricted owing to their high cost, necessary dispersion, and limited experience in large-scale operations. In the case of self-cleaning and photocatalytic properties, nano-TiO_2 will be the most appropriate, while nano-alumina and nanoclay will be more effective in environments that need pore refinement and aggression resistance. Thus, the choice of nanomaterial should not be made solely based on the compressive strength enhancement.
4. Simultaneously, issues related to nanoparticle aggregation, high material prices, lack of research concerning the health and environmental impact of nanoparticles, and international regulations hinder the wider implementation of this technology. These issues must be overcome for the successful development of this technology.

5. Some of the most relevant topics for future research include multi-nanomaterial interaction investigations, long-term performance testing under field conditions, comprehensive lifecycle assessment, and applications of AI and digital twins to enhance mix design optimization and structural performance prediction.

Thus, nanomaterials present the most exciting area in the field of construction materials, having the ability to simultaneously improve the mechanical performance and durability of construction materials, their service life, and their environmental footprint.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

A.K. Al-kamal and I.Z. Ahmed: proposed the research problem. A.K. Al-kamal and Z.Y. Hussien: developed the theory and performed the computations. A.K. Al-kamal, I.Z. Ahmed, and Z.Y. Hussien: verified the analytical methods. All authors discussed the results and contributed to the final manuscript.

Data Availability

Data available by request.

AI Declaration Statement

The authors confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.

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