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Review

Comparison of Nanocomposites Groups Performance in Cements: A Review

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Abstract: The performance of cement-based materials is affected by physicochemical processes occurring at the nanoscale. As a result, incorporating nanomaterials into civil engineering applications to develop nano-modified cement-based materials has emerged as a promising research area. Significant efforts in nanotechnology have focused on exploring the unique behaviors and properties of materials at the nanoscale. In past decades, numerous research efforts have aimed to boost the properties of materials based on cement, using various nanomaterials while investigating the mechanisms behind nano-reinforcement. This work offers a detailed review of the newer advancements in nano-engineered cementitious materials. It first examines the fundamental properties and dispersion techniques of commonly used nanomaterials, such as nanotubes and graphene, in cementitious systems. Subsequently, it reviews the evolution of such composites in terms of workability, mechanical performance, and durability. Lastly, the study highlights the existing challenges in this research field and offers insights for future developments.

Keywords: cement nanocomposites; carbon based; nano-silica; nano-alumina; nano-clays; durability; workability

1. Introduction

Since its discovery 175 years ago, cement has grown to be indispensable in construction. Its production has increased 34-fold in the past 65 years, with global demand is expected to rise by 6 billion tons by 2050 [1]. Their widespread use in construction is largely attributed to their low cost and proven reliability [2]. They offer water resistance, can be molded into diverse shapes and dimensions, and are both inexpensive and readily available. In fact, the use of cementitious composites in global infrastructure surpasses the combined usage of all other building materials [3]. Known for their high compressive strength and durability [4], cement-based materials nonetheless face challenges such as low toughness, limited durability, and significant maintenance requirements. In recent years, advancements in construction technologies and growing demands for improved structural performance have driven increasing international interest in formulating enhanced-performance materials [5].

Enhancing the performance of cement-based materials has emerged as a major research focus [6]. Recent progress in nanotechnology and nanomaterials offers promising avenues for tailoring the microstructure at the nanoscale [7]. As nanotechnology has matured, nanocomposite materials have found widespread applications across various research fields, with polymer/nanoparticle composites emerging as a central topic in scientific studies this century [8]. Incorporating nanoparticles has significantly improved the composites' mechanical and thermodynamic properties [9,10]. Numerous studies have demonstrated that polymer/nanoparticle composites exhibit superior properties of all kinds, compared to simple physical blends of polymers and nanoparticles [11,12]. Additionally, nanoparticles can serve as nucleation sites, accelerating the hydration process of cement [4]. This process facilitates the filling of voids with hydration products, thereby producing a denser, more uniform, and compact structure [13].

One of the main challenges in studying nanomaterials is the limited number of review articles that focus on specific groups of nanoparticles, categorized based on their chemical composition or geometric characteristics. This is largely because each group offers unique benefits, such as pozzolanic activity [14,15], or reinforcement properties [16,17]. Additionally, the high cost of commonly used carbon-based nanomaterials in the construction industry restricts their widespread application, whereas alternatives like nano-clay offer a more cost-effective option [17]. This review aims to systematically analyze the broad and fragmented body of literature and extract key insights to enable a robust comparison between different nanoparticle groups, with a particular focus on nano-clays and carbon-based materials. The selection of these specific materials is intended to provide a detailed evaluation of each group, thereby enhancing the reliability of the findings related to individual nanoparticles.

2. Basics of Cements

2.1. Cement Matrix

The properties of this multi-phase material are primarily governed by the cement matrix [18]. Cement-matrix composites encompass concrete, mortar, and cement paste. Additionally, other materials known as admixtures can be incorporated into the mix to enhance the composite's performance. These admixtures are discontinuous phases, allowing them to be easily integrated into the mixture [19].

2.2. Cement Dispersion and Methods to Evaluate Dispersion Quality

Dispersion refers to the process of separating the smallest dispersible units from an agglomerate and uniformly distributing them within the host matrix [20]. One of the key concerns in the field is identifying optimal dispersion methods and agents. This challenge stems from the difficulty in accurately, reliably, and quantitatively evaluating the dispersion state of nanomaterials in aqueous solutions. Proper dispersion significantly impacts the initial hydration and the resulting microstructure. The water-to-surface area ratio in cement mixtures influences hydration heat and particle packing efficiency [21]. Achieving uniform dispersion of additives is important for boosting the workability of cement mixtures and ensuring consistent mechanical strength. Additionally, the mechanical strength of cement paste is strongly governed by the water-to-cement (w/c) ratio of the workable mix.

2.3. Methods to Evaluate the Dispersion Quality of Nanomaterials in Cement Matrix

The complex, multi-phase and porous structure of cement makes it difficult to evaluate how well nanomaterials are dispersed within the matrix [22,23]. Table 1 offers a brief presentation of the methods currently used to evaluate the dispersion of nanomaterials in cement matrices.

Table 1. Approaches for evaluating the dispersion quality of nanomaterials in cement matrices.

Method	Merits	Demerits
UV-vis spectroscopy	UV–Vis spectroscopy, suitable for analyzing any type of suspension, is a reliable and simple technique used to measure the amount of light absorbed or scattered as it passes through a sample compared to a blank reference [24].	This method does not offer insights into agglomerate size or quantify the impact of sonication parameters on tube length and sample polydispersity [24].
Dynamic light scattering	It measures the sizes of nanoparticles in a solution by utilizing elastic Rayleigh scattering. The technique tracks the velocity of particles moving due to Brownian motion by monitoring the intensity of scattered light from the sample [25].	A key constraint of the technique is concentration, since high dilution is necessary to minimize multiple scattering [26].
Zeta potential	The stability of colloidal dispersions is closely linked to their zeta potential [27].	An inappropriate desorbing agent can negatively impact the surface of nanomaterials [28].
SEM observation	A fast, noninvasive method visualizes structure and surface features such as wrinkles, cracks, folds, voids, and impurities through contrast from roughness, edges, and thickness [29].	SEM offers limited capability for quantifying the dispersion of nanomaterials within the cement matrix [30].

3. The Role of Nanomaterials in Cements

The properties of modified cementitious materials depend on factors like strength and nanoparticle type [31]. Nanotechnology improves concrete by reducing cracks, shrinkage, joints, curling, and moisture loss [32]. Nanomaterials are typically 100 nm or smaller in at least one dimension (Figure 1) [33].

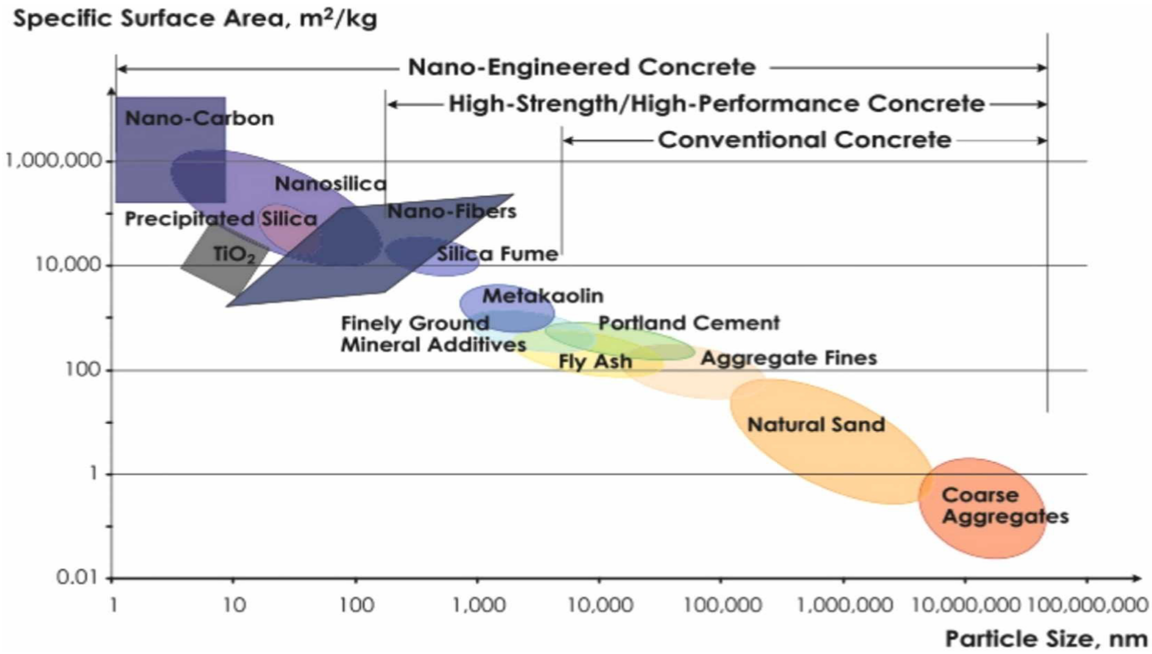

Figure 1. The size range and surface area attributes of concrete incorporating nanomaterials. Reprinted with permission from Ref. [33] Copyright 2025, Elsevier.

Incorporating nanomaterials offers three main advantages: Higher-strength cement composites, reduced cement use lowering costs and environmental impact, and shorter construction times due to faster curing [34].

3.1. Carbon Nanotubes

Carbon nanotubes (CNTs) were first discovered by Iijima in 1991 through arc evaporation of graphite [5]. They are classified as single-walled (SWCNTs) with one graphene cylinder or multiwalled (MWCNTs) with multiple concentric graphene layers [34]. Typically, CNTs have diameters ranging from 1–100 nm and lengths of 1–100 μm, giving them a high aspect ratio that leads to entanglement and challenges in dispersion within water or a cement matrix due to Van der Waals interactions [30]. Two primary challenges are faced when using CNTs in cement: dispersion and bonding. Strong Van der Waals forces cause CNTs to agglomerate, which may result to defects in the composites. Moreover, the minimal interface between CNTs and the cement matrix weakens their bond, leading to detachment under tensile stress [34]. However, incorporating CNTs into building materials enhances mechanical properties, electrical conductivity, and thermal stability, provided that the CNTs form strong contacts and distribute uniformly within the matrix [35]. CNTs are considered a high-quality cement additive due to three main advantages [36]: (1) their exceptional physical and mechanical properties, yet with only one-sixth of the density of steel; (2) their high specific surface area and functional groups enhance cement hydration and promote hydration product growth; (3) their minimal dosage requirement. Carbon nanotubes, used at low dosages, improve pore structure and durability but do not chemically react with cement. Their limited impact at low content and high cost restrict widespread use in cement-based materials [37].

3.2. Graphene

With a hexagonal honeycomb structure, graphene is distinguished by its outstanding mechanical, thermal, and electrical performance [38]. These attributes, including high strength, high modulus, and excellent electrical conductivity, result mainly from the in-plane sp^2 carbon-carbon bonds [39]. Incorporating graphene into cement-based composites offers several advantages: (a) reducing cement usage while maintaining mechanical properties at low graphene dosages; (b) improving resistance to aggressive circumstances; (c) enhancing conductivity; (d) preventing thermal cracking and improving fire resistance due to superior thermal diffusivity; (e) providing excellent electromagnetic interference shielding; and (f) enabling mass production at relatively low costs without compromising its properties. Graphene oxide (GO) enhances cement composites by promoting hydration, modifying the pore network, enhancing microstructural integrity, and improving interfacial adhesion with the matrix [22]. To improve concrete properties with graphene, obtaining even distribution is essential. However, strong van der Waals forces cause graphene sheets to agglomerate, reducing their effectiveness. Preventing this requires creating energy barriers to minimize these forces. Both chemical and mechanical methods have been explored [40]. Covalent methods introduce functional groups like amino, carboxyl, and hydroxyl to bond with graphene, but reactive agents may damage its structure [41]. Non-covalent methods use solvents or polymers for steric or electrostatic stabilization [42], though surfactant-assisted dispersion is challenged by cement's alkaline environment, which can lead to re-agglomeration [43]. Graphene derivatives are used as nano-additives in cement materials. Due to its hydrophilic oxygen groups, graphene oxide disperses well in water and markedly improves the strength and durability of the resulting compound [22]. GO/cement composites offer better water dispersion than other nanocomposites due to hydrophilic groups reducing van der Waals interactions. Studies show that GO reinforcement significantly enhances compressive strength, flexibility, tensile strength, and modulus, while improving durability by limiting the transport of corrosive agents. GO composites exhibit superior mechanical performance, durability, conductivity, and self-sensing capabilities compared to conventional materials and graphene-reinforced composites [28] The schematic illustration depicting the interaction and network formation of GO within cement composites is presented in Figure 2.

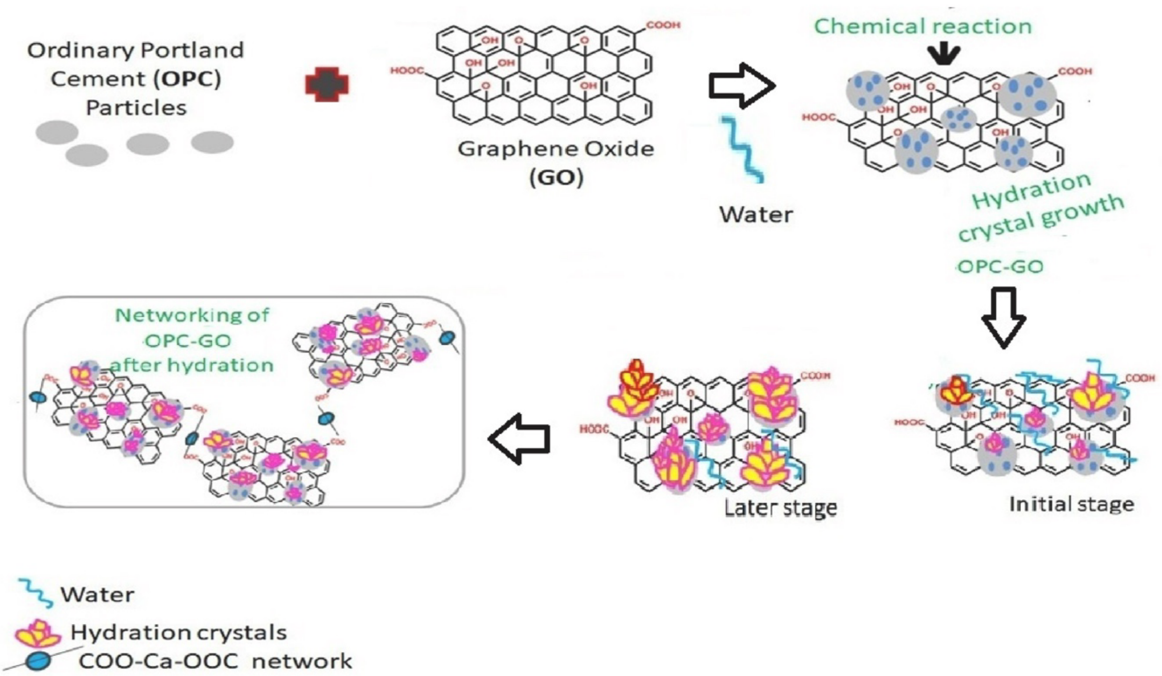

Figure 2. Schematic illustration showing the network formation of GO within cement composites. Reprinted with permission from Ref [28]. Copyright 2025, Elsevier.

3.3. Nano-Silica

Nanosilica is formed by O-Si-O bridges, providing distinct properties for advanced scientific and industrial applications [44]. Nanosilica (NS), with its nano-sized particles, has become a popular additive in cement paste, mortar, and concrete [45]. Also known as silicon dioxide nanoparticles, NS is commonly incorporated to boost the mechanical strength and durability of concrete [46]. Its surface is rich in silanol groups (SiO_2-xH_2O), which interact with both organic and inorganic molecules, determining the hydrophobic or hydrophilic nature of nanosilica based on its bonding capability with aqueous systems [47]. Nanosilica serves as nucleation sites during cement hydration, accelerating calcium silicate hydration and reducing the induction period. Additionally, NS reacts with calcium hydroxide, increasing hydration products, refining the microstructure, and markedly increasing the durability of cement-based materials [37]. The pozzolanic reaction of NS with $Ca(OH)_2$ generates more C–S–H, responsible for strength and density [48].

$$\text{nano-}SiO_2 + H_2O \rightarrow H_2SO_4^{2-}Ca(OH)_2 + H_2O \rightarrow Ca^{2+} + OH^-$$

$$H_2SO_4^{2-} + Ca^{2+} \rightarrow \text{C“–”S“–”H} \quad \text{(Additional C“–”S“–”H)}$$

Replacing cement with nanosilica provides a sustainable and cost-effective way to reduce concrete's carbon footprint. Its superior filler properties and particle size optimize concrete permeability and promote the pozzolanic reaction, forming more calcium-silicate-hydrate gel, making nanosilica a favored additive in research [49,50]. Nanosilica accelerates early cement hydration and transforms $Ca(OH)_2$ into C–S–H gel through its pozzolanic activity, thus enhancing the material properties [51,52]. Its high reactivity is mainly attributed to its ultra-fine particle size [53]. Additionally, nanosilica displays stable thermal and electrical properties, exhibiting low electrical conductivity. These characteristics further support its use as a beneficial additive in cement composites [54]. Studies show that replacing up to 4.0% of cement with nanosilica enhances concrete's strength, performance, and durability, especially under harsh conditions like corrosion and high temperatures [55]. However, the most effective range is between 0.5% and 4.0% replacement, as higher amounts may lead to particle agglomeration and poor dispersion, ultimately reducing workability [56,57].

3.4. Nano-Clay

The influence of clay on cement-based materials has been extensively studied over the years. Nanoclays (NCs), typically sourced from naturally occurring materials, offer advantages such as wide availability, low cost, and safe handling [58]. Clay nanocomposites, part of the smectite family, are valued for their affordability, abundance, and ability to improve gas barrier, mechanical, and thermal properties. Nanoclays like nano-kaolin and nano-montmorillonite, much finer than cement grains, are used as nanofillers in cement materials. Rich in silica and alumina, nanoclay is pozzolanic [59]. When calcined at 600–800 °C, it transforms into nano-metakaolin through particle size reduction and structural changes [60]. They are prized for their biocompatibility, unique layered structure, high surface-to-volume ratio, and excellent loading capacity [61]. Nanoclay, as a nano-pozzolanic additive, improves the cement matrix by refining pore structure, reducing porosity, and enhancing mechanical strength [62]. At 7.5% content, it creates a denser microstructure with nanoclay agglomerations surrounded by C-S-H gels, demonstrating its nucleation effect. The sheet-like structure of nanoclay helps bridge cracks, preventing micro-crack propagation [63].

Research on polymer-nanoclay composites is a growing field aimed at developing advanced materials with enhanced properties, utilizing nanoclays' distinct features to enhance and advance applications in residential construction [64].

3.5. Nano-Alumina

Nano-alumina, a nanometer-scale form of aluminum oxide (1–100 nm), is characterized by a high surface area and porous structure. With a density of 4 g/cm^3, excellent electrical insulation and thermal conductivity of 30 W/m·K it is ideal for protective coatings on construction materials, improving resistance to wear and corrosion [65,66].

Due to its microstructural properties, nano-alumina has been utilized in developing cement mortars for concrete floor overlays. Adding a small amount of nano-alumina strengthens bonding, while reducing mortar porosity. This leads to improved performance characteristics, such as increased tensile strength and reduced abrasion resistance of the subfloor [67]. Nano-alumina expedites hydration in Portland cement [68].

4. Nanocomposite's Performance Indicators

As discussed earlier, nanoparticles can be categorized based on their chemical or geometric properties. Depending on the category, they may be advantageous either due to their pozzolanic activity or their reinforcing capabilities. Pozzolanic activity refers to the rate at which pozzolanic reactions occur, enhancing the bonding force with calcium hydroxide (CH) in the presence of moisture. Pozzolanic activity refers to the reaction between lime and the active components of pozzolans, where Ca^{2+} ions from CH react with siliceous or aluminous materials to form stable cementitious compounds. Using pozzolanic mineral additives in cement mixtures generally enhances the quality of the concrete paste [69]. Examples of nanoparticles beneficial due to their pozzolanic activity include nano-silica, -clay, and alumina, while carbon and graphene oxide are examples that provide reinforcement.

The application of nanotechnology in the production of ultra-high-performance concrete (UHPC) has established itself as a distinct innovation, providing alternatives to conventional materials such as silica fume. Building on the concept of nanoproduction, nanosilica was developed to replicate the beneficial characteristics of silica fume and is now considered one of the most prominent nanomaterials used as its substitute. Leveraging nanosilica, researchers have synthesized various nanoparticles effective in concrete production, including nanoalumina, titanium oxide nanoparticles, carbon nanotubes, and nanopolycarboxylates, marking the beginning of a new nanoconcrete era [70]. Among these, carbon nanotubes are the most extensively applied in cementitious composites, followed by graphene, nanosilica, and nano-titanium dioxide related products [71]. Furthermore, such nanomaterials improve the rheology, stability, flow, and strength of cement-based systems due to their high surface area and reactivity. Their effective use requires deeper insight into their interactions with the cement matrix, enabling tailored rheology for modern construction needs while helping reduce the sustainability impact of high cement use [72].

Numerous approaches have been developed to amplify the performance of cementitious nanomaterials [73,74]. The incorporation of nanomaterials, even in minimal amounts, can markedly improve various attributes such as:

Workability or flowability, is a key parameter in concrete mix design. It is influenced by multiple factors, including cement fineness and type [75]. Owing to their large surface, nanoparticles tend to absorb considerable amounts of water, thereby reducing the water available to maintain workability. In general, the addition of nanoparticles decreases workability and flow values, primarily as a result of nanofiller effects, increased water demand, and stronger interparticle cohesion. Nevertheless, this reduction can be advantageous in certain applications, such as pavement casting and shotcrete, where enhanced cohesiveness helps prevent segregation [76].

Durability is the capacity of a material to resist abrasion, chemical exposure, weathering, and other stresses encountered during service. In concrete, durability is strongly influenced by the ingress of chlorides and sulphates, which can penetrate the matrix through mechanisms such as capillary absorption, permeation, and diffusion [77].

Among performance factors, mechanical properties are generally the most critical in practical applications [78]. It is well established that introducing small amounts of carbon-based nanomaterials (CNMs) into cement significantly enhances mechanical strength, including compressive, flexural, and tensile strengths [30].

4.1. Nano-Silica, Nano-Clay and Nano-Alumina Group

A growing body of research indicates that nanomaterials can be used to upgrade the performance of cement nanocomposites in various ways (Table 2).

4.1.1. Nanoclays

Workability

Previous studies have shown that processing clay into finer particles can intensify certain negative effects on concrete properties, such as a pronounced reduction in flowability [58]. Heical et al. [79] reported that incorporating 9.0% calcined nanoclay into UHPC reduced slump by 10.0%, from 166 mm to 150 mm. Similarly, Alani et al. [80] and Alobaidi et al. [81] observed that substituting cement with nanoclay decreased the workability of self-compacting concrete (SCC). This decline in workability is primarily attributed to the very high surface area of nanoclay, its tendency to form flocculent network structures, its low dispersibility [82] and its ability to absorb significant amounts of free water during wetting [83]. Consistently, Norhasri et al. [84] and more recently Alharbi et al. [85] reported that adding 9.0% nanometakaolin lowered concrete slump by approximately 15.7%.

Durability

Irshidat et al. investigated the effect of nanoclay on the residual strength of mortar and reported a notable improvement, especially at elevated temperatures above 400 °C [86]. Modification of montmorillonite (MMT) with organic surfactants improved its dispersion in cement, with C10-OMMT showing the best performance. It increased 28-day compressive strength by 11.2% and hydration degree by 11.0%, while also reducing water absorption and porosity, as intercalated and partially exfoliated nanosheets created a dense matrix that enhanced durability and sustainability [87]. Field studies confirmed these benefits, with LC3 concrete cubes exposed to seawater for 24 months maintaining low porosity (0.75–1.44%), low chloride migration (0.22–0.83 × 10^{-12} m^2/s), and high resistivity (84.9–93.6 kΩ) [88].

Table 2. Nanomaterials and their impact on the performance of the resulting composites.

Advantageous Nanomaterials Due to Their Pozzolanic Activity	Performance Indicators		
	Workability	Durability	Mechanical Properties
Nano-clays	9.0% calcined nano-clay resulted in a 10.0% reduction slump of UHPC [79].	Significant increase [86].	Improves the compressive strength of nano-clay modified mortar [89]

Table 2. *Cont.*

Advantageous Nanomaterials Due to Their Pozzolanic Activity	Performance Indicators		
	Workability	Durability	Mechanical Properties
Nano-clays	Decreased the concrete slump by 15.7% [85].	C10-OMMT showed the greatest improvement in hydration degree, increasing it by 11.0%, which corresponded to enhanced durability [87].	untreated nano-clay 18.0% increase in compressive strength, 10.0% in tensile strength, and 15.0% in flexural strength. Concrete with 7.5% ultrasonic-treated nano-clay showed: 52.0%, 28.0% and 35.0% in compressive, tensile, and flexural strength respectively [90].
	Reduction in the concrete slump by 15.7% [84]	LC3 with 45.0% replacement showed excellent durability, with very low porosity (0.75–1.44%), low chloride migration (0.22–0.83 × 10^{-12} m^2/s), and high surface resistivity (84.9–93.6 kΩ) [88].	2.0 wt% nano-clay led to a denser microstructure and improved geopolymer gel formation [91].
Nano-silica	76.0% slump reduction [92]	Concrete with 3.0% nanosilica showed a 32.0% higher compressive strength than the control [93].	At a *w/c* ratio of 0.45, nanosilica up to 0.5% increased strength by 13.9%, while 1% replacement led to a 33% gain over the control [94].
	Decreased fluidity by 29.3% [95].	A reduction in the loss of compressive strength [96].	Further improvements included 17.5% and 29.0% gains at 1.5% and 4.5% dosages, respectively, with the highest increase of 43.5% achieved at 3.0% nanosilica [97].
Nano-alumina	NA at 1.0% kept good workability with only ~3.0% slump reduction (~73 mm), while 2% and 3% dosages lowered slump to ~70 mm and ~65 mm, corresponding to ~7.0% and ~13.0% reductions from control [98].	An optimal 1% nano-alumina increased compressive strength by 16% [99].	An optimal 1.0% nano-alumina improved compressive strength by 4.1–20.6% and flexural strength by 7.4–16.9% [100].
	Superplasticizer quantity in UHPC mixtures maintained workability, even with 1.5% and 3.0% nano-alumina [101,102]	Adding nano-alumina to UHPC significantly enhances its durability [100].	Nano-alumina enhanced the microstructure density and boosted compressive strength [103].

Mechanical Properties

Guo et al. demonstrated that ultrasonic dispersion, with treatment times of up to 15 min, significantly enhances the compressive strength of nanoclay-modified mortar [104]. Hamed et al. [90] reported that adding 7.5% untreated nanoclay to concrete improved compressive, tensile, and flexural strength by 18.0%, 10.0%, and 15.0%, respectively, compared to plain concrete. When the same dosage of nanoclay was subjected to ultrasonic treatment, the strength gains were substantially higher—52.0% in compressive strength, 28.0% in tensile strength, and 35.0% in flexural strength. Similarly, Assaedi et al. reported that adding 2.0 wt% nanoclay resulted in a denser microstructure and improved geopolymer gel formation compared to the control specimens [91].

4.1.2. Nanosilica

Workability

Research consistently shows that incorporating nanosilica reduces workability At higher dosages, nano-SiO_2 can increase mixture viscosity and negatively affect flowability [105]. Liu et al. [106] found that when the nanosilica content increased from 0.25% to 3.0% by weight of cementitious materials, concrete slump decreased significantly. To restore workability, the dosage of polycarboxylate superplasticizer had to be adjusted. Another study showed that partially replacing the binder with 0.8% nanocarbon black and 1.2% nanosilica reduced slump by 55.0% and 76.0%, respectively [92]. Aydın, et al. [43] studied 2.0% nanosilica and 40.0% fly ash on concrete fluidity. They found that nanosilica decreased fluidity by 29.3% in mixtures without CNTs and fly ash, primarily because of its higher water demand [95].

Durability

Kumar et al. [93] found that substituting 3.0% of Portland cement with nanosilica greatly enhanced compressive strength and durability, achieving a 32.0% strength increase over the control. Guo et al. [104] studied the effect of nanosilica on C_3S exposed to sulfate attack. Even at low concentrations, nanosilica improved resistance by reducing calcium hydroxide content and modifying the C–S–H gel, thereby lowering susceptibility to sulfate damage after 28–120 days and up to 180 wet-dry cycles. Similarly, Huang et al. [107] showed that incorporating 0–1.5 wt.% nanosilica and 0–1.0 vol.% PVA fibers in fly ash/cement pastes greatly improved sulfate resistance and mechanical performance, with flexural strength increasing by up to 90.0% after 28 days. After 72 days in Na_2SO_4, both compressive and flexural strengths exceeded the 28-day values, while mixes with 1.0–1.5 wt.% nanosilica exhibited excellent sulfate resistance after 100 days in water. Rajput and Pimplikar [108] further highlighted the durability benefits of nanosilica by showing reductions in water absorption for M30 and M40 concretes. In M30 mixes, water absorption decreased by 5.15%, 30.2%, and 35.7% as nanosilica content increased from 1.0% to 3.0%. In M40 concretes, the reductions were 1.5%, 30.4%, and 58.9% for the same dosage range. These findings confirm that nanosilica refines pore structure, lowers water absorption, and enhances the durability of cementitious composites.

Mechanical Properties

Li et al. [94] observed that nanosilica increased compressive strength by 13.9% at 0.5% and by 33.0% at 1.0% replacement (w/c = 0.45). Elkady et al. [97] reported that 4.5% nS increased strength by 13.5% after seven days, while 1.5% and 3.0% dosages raised 28-day strength by 17.5% and 43.5%, respectively, with 4.5% giving a 29.0% gain. Abna and Mazloom [109] explored the combined effects of microsilica, nanosilica, and polypropylene fibers on the fracture strength of concrete. They concluded that polypropylene fibers improved both fracture strength and fracture energy, with the optimal mix being 5.0% microsilica, 0.8% nanosilica, and 0.1% polypropylene.

4.1.3. Nanoalumina

Workability

Jiang et al. [110] observed that nanoalumina (NA) reduced workability; however, the use of superplasticizer (SP) allowed the water-to-binder ratio to remain constant across all mixes. The study assessed nanosilica (1.0–3.0%), nanoalumina (1.0–3.0%), and graphene oxide (0.05–0.15%) using Response Surface Methodology. Nanosilica and GO increased compressive strength by ~25.0%, while GO at 0.1% achieved the highest flexural strength gain (~40.0%). Both also enhanced durability indicators such as RCPT, water absorption, and sulfate resistance, outperforming nanoalumina [98]. Sobolev et al. and Muzenski et al. noted that surfactants used to disperse nanoparticles may reduce workability in UHPC containing nanoalumina fibers, even when superplasticizers are added. In contrast, recent findings suggest that nanoalumina itself does not significantly impact workability. By adjusting the quantity of superplasticizer, UHPC mixtures containing up to 3.0% nanoalumina (by binder mass) were able to maintain workability, highlighting the essential role of SP in sustaining low water-to-cement ratios in UHPC [101,102].

Durability

Farzadnia et al. [99] reported that incorporating nanoalumina improved durability at elevated temperatures. An optimal dosage of 1.0% nanoalumina enhanced compressive strength by 16.0%. Since durability is largely governed by concrete permeability, which depends on pore structure [58], improving microstructure is critical. Chu et al. [100] examined the role of nanoalumina and observed that NA reduced threshold pore size and porosity, thereby refining the microstructure. Their compressive strength tests revealed that an optimal content of 1.0% NA increased compressive strength by 4.1–20.6% and flexural strength by 7.4–16.9%. The study concluded that NA is an effective additive for UHPC, improving both durability and mechanical performance.

Mechanical Properties

Chu et al. [100] further confirmed that nanoalumina enhances UHPC microstructure by reducing pore size and porosity, with the optimal 1.0% content yielding compressive strength gains of 4.1–20.6% and flexural strength gains of 7.4–16.9%. Similarly, Shaikh et al. [103] investigated cement paste with high volumes of blast furnace slag and found that replacing 1.0% of cement with nanoalumina increased microstructural density and compressive strength.

4.2. Carbon Group

Several authors have evaluated the impact of CNTs and GO on the performance of cement as presented in Table 3.

4.2.1. CNTs

Workability

Mosallam et al. [111] reported that adding 0.02% carbon nanotubes (CNTs) to lightweight concrete (LWC) had no notable impact on workability. However, when CNT content exceeded this threshold, workability declined, with a 27.5% reduction observed at 0.3% CNTs. High dosages of multi-walled CNTs (MWCNTs) were also found to reduce workability, compromising material uniformity and compactness [112].

Durability

Ramezanl et al. [113] showed that CNTs improve cement composite durability by reducing ASR damage, with pristine CNTs cutting expansion by 73.0% after 14 days and increasing dynamic elastic modulus by 24.0% after 4 weeks. Malayali et al. [114] combined 5 wt% coconut fiber with 5–15 wt% CNTs, achieving 38.0% higher compressive strength (47 MPa) and a 65.0% reduction in water absorption at 15 wt% CNTs, confirming a strong synergistic effect on strength and durability.

Mechanical Properties

CNTs into concrete has been shown that improves both strength and toughness. Huang et al. [115] found that adding 0.3% carbon nanotubes to UHPC increased compressive strength by 20 MPa, lowered porosity to 2.5%, and produced a denser gel phase. Similarly, Xia et al. [115] observed that concrete containing 0.3% CNTs exhibited a 23.7% increase compared to plain concrete, alongside a 10.0% improvement in impact toughness and a marked strain-rate strengthening effect.

Table 3. The effects of CNTs and GO on the performance of cement nanocomposites.

Advantageous Nanomaterials Due to Their Reinforcing Capabilities	**Performance Indicators**		
	Workability	**Durability**	**Mechanical Properties**
CNTS	The slurry expansion increased by 11.1%, from 152 mm to 168.8 mm, in the amino-functionalized samples (CCNTCF) compared to the ultrasonic-prepared samples (UCNTCF) [116].	Adding 0.05–0.1% CNTs improved concrete mechanical strength by up to 21.0% and durability by up to 25.0%, independent of CNT type and *w*/*c* ratio [117].	MWCNTs at 0.05–0.4% improved flexural strength through enhanced bridging, with compressive and flexural performance verified under different conditions [118].
		Adding 0.05 wt.% CNTs to ultrahigh strength concrete reduced chloride permeability by 24.0%, but increasing CNTs to 0.15 wt.% raised permeability by 14.0% due to foam from excess surfactant [119].	Additionally, 0.5% CNTs combined with 20.0% SiO_2 increased cement mortar compressive strength [120].
GO	Incorporating graphene oxide (GO) into slag- and fly ash-based geopolymers reduced workability, as GO's high surface area absorbed water and led to stickiness [121].	Adding 0.005% GO refined the structure, reducing chloride ion penetration and protecting embedded steel [122].	Adding 0.15 wt% FGO improved flexural strength by 49.0% and compressive strength by 35.0% [123].
	Graphene oxide (GO) adversely affects the workability of cementitious systems [124].	0.1 wt% graphene oxide showed a 31.0% increase in chloride binding capacity, significantly enhancing the durability of cement composites [125].	(RGO) composite that showed significant improvements in compressive strength (~29.0%), flexural strength (~49.0%), and electrical conductivity (~23.0%) [126].
	GO improves hydration in cement, but simultaneously lowers the availability of free water in the slurry, which diminishes its fluidity [127].	Adding fly ash and GO enhances resistance, raising it from 0.78 (ordinary cement) to 1.007 [128].	Introducing 0.08 wt% GO, boosting its tensile strength by 12.0%, compressive strength by 21.0%, and flexural strength by 23.0% [129].

4.2.2. GO

Workability

The influence of graphene oxide (GO) on the rheology of cement-based materials has been widely investigated, with most studies reporting a decline in workability as GO content increases. Liao et al. [128] examined cementitious grouts incorporating GO and industrial waste fly ash (FA). Their findings showed that while GO reduced paste fluidity—by 36.7% at a dosage of 0.15% compared to the control—the addition of FA improved workability without altering the Bingham fluid behavior of the paste. Similarly, Reddy and Prasad [130] confirmed that GO decreased concrete fluidity by 16.7%, whereas fly ash substitution counteracted this effect. Safarkhani and Naderi [131]. found that increasing GO content (0–0.2% bwoc) progressively reduced concrete slump, with the highest dosage yielding a slump of 54 mm, about 20.0% lower than the control. Jiang et al. [132] reported that GO-modified UHPLC showed a slump flow reduction of 10.2%, attributed to the large surface area of GO, which absorbs free water. Fonseka et al. also highlighted GO's significant impact on workability, showing that 0.08% GO reduced slump by 81.0% compared with control mixes. To mitigate these effects, polycarboxylate superplasticizers (PCEs) are considered the most effective solution. Qin et al. [43] demonstrated that PCEs with longer side chains enhance GO dispersion in cement slurries, while FA improves flowability through a ball-bearing effect [128]. Studies modifying GO with materials such as carboxymethyl chitosan [133], and polyacrylamide with sulfonated monomers [134], reported enhanced rheology and flowability [135,136].

Durability

Djenaoucine et al. [122] demonstrated that 0.005% GO refines concrete microstructure, reducing chloride penetration and protecting steel, while 0.1 wt% GO increased chloride binding by 31.0% at lower pH, demonstrating improved durability [122]. Wang et al. [137] found that a low GO dosage (0.03 wt%) improved pore refinement, reduced interconnected voids, and increased matrix density, which in turn inhibited water transport and enhanced freeze–thaw resistance. Similarly, Cui et al. [138] reported that GO reduced mortar porosity by 3.4–11.0%, improving resistance to leaching. Freeze–thaw studies also showed that specimens with 0.03 wt% GO maintained higher dynamic elastic modulus and compressive strength [139]. Consistent with these findings, Zhang et al. [140] observed that concrete containing 0.05% GO exhibited strength gains of 23.3% (initial) and 41.9% (final) under freeze–thaw cycles, with durability improvements linked to enhanced early hydration reactions.

Mechanical Properties

In some cases, GO suspensions were added directly into cement without modification, where improvements in strength may have been due to GO aggregation rather than uniform nanosheet dispersion. At 0.09 wt%, GO boosted geopolymer foam concrete compressive strength by 58.4%, though higher dosages reduced 30-day strength due to poor dispersion. Qiao et al. [141] enhanced fiber–matrix bonding by depositing GO onto carbon fibers, providing additional nucleation sites. Compared with control samples, this approach increased compressive strength by 5.0% and flexural strength by 25.5%.

4.2.3. Economic and Environmental Considerations

Economic Sustainability

The high production costs and environmental impacts of nanomaterials present challenges. Although nanomaterials can markedly enhance the properties of cementitious materials, their elevated cost remains a limiting factor for widespread implementation [142]. Consequently, nanoparticle cost continues to be a subject of significant concern [76]; Table 4 presents economic considerations of the studied nanomaterials

Table 4. Economic considerations.

Nanomaterial	Economic Considerations
CNTs	He limited effectiveness of these materials at low dosages, combined with their high cost, restricts their widespread application in cement-based systems [37].
Graphene oxide	Its cost impacts its large-scale adoption [143].
Nanosilica	Offers a sustainable and cost-efficient strategy for lowering the carbon footprint of concrete [49,50]. However, producing high-purity forms remains associated with significant expenses [143].
Nanoclay	Nanoclays are typically derived from naturally abundant sources and provide several advantages, including broad availability, low cost, and safe handling [58].
Nanoalumina	A more economical alternative for use in UHPC formulations [102].

The price of multi-walled carbon nanotubes is higher than that of other nanoparticles, including nanosilica and nanoclay. For this reason, MWCNTs are often combined with more affordable nanomaterials in geopolymer concretes [144], with special emphasis on low-cost options such as nanoclay [76]. While effective, conventional approaches present drawbacks. For example, mineral admixtures can hinder early-age strength development and workability, whereas high-performance aggregates increase costs and may exhibit variability in thermal expansion [145]. Nanomaterials and polymers are significantly more expensive than traditional cement, and their use often requires multi-step dispersion or grafting processes, which demand greater equipment investment and energy consumption [142]. Similarly, the elevated cost of self-healing concretes compared to conventional OPC-based concretes is largely attributed to their advanced properties, limited expertise regarding their use, and the lower scale of global production. Despite this, nanomaterial-based self-healing concretes should be considered for adoption, given their potential for long-term performance and durability benefits [31].

The adoption of circular economy principles in concrete emphasizes extending service life, where higher initial costs are balanced by long-term savings. Using optimized mixes and supplementary cementitious materials (fly ash, slag, silica fume) improves efficiency, cuts costs, and reduces emissions, creating economic and environmental benefits. Full potential, however, depends on overcoming barriers such as upfront investment, policy support, and industry-wide adoption [146].

Environmental Considerations

Shen et al. [147] emphasized that cleaner production, recycling, and cement substitution represent effective strategies to address current challenges. Cleaner production and recycling primarily involve technological improvements in manufacturing, the comprehensive utilization of waste streams, enhanced resource and energy efficiency, and reductions in greenhouse gas emissions. Cement substitution, on the other hand, refers to replacing part of the cement content with industrial by-products or environmentally friendly alternatives. In recent years, nanomaterials have emerged as a promising substitute, particularly in ultra-high-performance concrete (UHPC), where they can lower CO_2 emissions, enhance mechanical performance, and impart novel functionalities [148]. Nanomodified cementitious systems employ nanotechnology to improve strength, durability, and sustainability, thereby mitigating the environmental impact of ordinary Portland cement. Nanoreinforced composites, which incorporate nanomaterials (<500 nm) as additives or partial cement replacements, show considerable potential in reinforcing interfacial transition zones (ITZs) and creating denser, more durable concretes. A wide range of nanomaterials, such as nano-SiO_2, nano-Al_2O_3, TiO_2, CNTs, GO, and polycarboxylates, have been successfully investigated for these applications [149].

An emerging direction is the integration of smart materials, capable of sensing and responding to environmental stimuli. Embedding nanosensors and responsive nanomaterials like CNTs and graphene within cementitious matrices enables real-time monitoring of parameters such as temperature, moisture, and stress. This approach supports structural health monitoring, thereby improving both safety and service life. Furthermore, eco-friendly binders that either reduce Portland cement content or replace it with alternative systems, such as MgO, phosphate, geopolymers, or gypsum, can be further optimized with nanoparticles like nano-SiO_2 and nano-Al_2O_3. These nanoparticles enhance binder reactivity, minimize environmental impact, and maintain or even improve performance, aligning with sustainable construction practices. Similarly, the incorporation of TiO_2 and limestone nanoparticles and microparticles offers pathways for environmentally responsible nanotechnology in cement-based materials [149]. Sustainability and environmental implications remain central considerations in the design and production of nanomaterials [71]. Green chemistry provides a guiding framework, with evidence suggesting that top-down synthesis methods typically generate more waste than bottom-up approaches [150]. Green nanotechnology, which employs eco-friendly resources such as natural extracts and renewable materials, is advancing in this direction. Nanomaterials synthesized from grape juice or Ficus carica extract show strong photocatalytic potential for degrading hazardous organic pollutants under visible light, highlighting their promise for environmental remediation [146]. However, some bottom-up methods also involve the use or generation of toxic by-products, and others require high energy input, underscoring the importance of optimizing synthesis routes for sustainability [150].

5. Challenges and Future Research

Traditional admixture-modified cementitious materials face pressing challenges, including inadequate dispersion [151]. Unlike conventional admixtures, nanomaterials also tend to agglomerate. In cement-based systems, such agglomeration raises porosity, disrupts hydration, and causes an uneven distribution of hydration products, which significantly reduces durability [38].

Optimizing the dosage of carbon nanotubes (CNTs) in cementitious materials is complex, as both insufficient and excessive amounts can negatively impact workability and mechanical behavior. For CNTs to be effective, they must interact compatibly with the cement paste to improve strength and durability without compromising setting time, hydration, or long-term stability. However, incorporating CNTs is associated with high material and processing costs, making scalable and economically feasible integration methods essential for practical use [152]. Developing new synthesis and processing techniques is necessary to increase yield and ensure consistent quality. CNT performance depends on parameters like diameter, length, dosage, *w/c* ratio, aggregate and fiber types, and treatment methods. However, their high surface area and strong van der Waals forces make stable dispersions difficult, leading to aggregation that harms microstructure and overall performance. Further research on CNT dispersion is needed, as current experimental studies are costly and limited in scale, reducing result robustness [152]. Graphene oxide (GO), with its high surface area and strong interlayer van der Waals forces at reduced interlayer spacing, tends to stack [151]. Nanosilica enhances cement composites. Optimal dosages boost compressive strength, and increase residual high-temperature strength [143]. Clay-based nanomaterials, being hydrophilic, require careful control of water content in clay–cement composites. Ion exchange modifications, where organic cations replace calcium or sodium, reduce interlayer hydrophilicity and thus water demand. A key concern when applying nano-coatings on cultural heritage stones has been their photo-induced superhydrophilicity, which may have adverse effects on stone surfaces [31].

Artificial geopolymers also show considerable promise, as they utilize industrial waste products like fly ash (rich in SiO_2 and Al_2O_3) to form aluminosilicate gels, which provide stronger binding capacity compared to the CaO-based binders of Portland cement [153].

6. Conclusions

This review presents a detailed analysis of recent advancements in the performance characteristics of two primary categories of nanocomposites. It highlights the identification of optimal nanomaterial dosages and underscores the potential benefits of combining micro- and nanoscale materials to enhance overall properties. The incorporation of nanomaterials as additives in cementitious and construction materials offers substantial improvements in efficiency, cost-effectiveness, and long-term sustainability. Nanomaterials contribute multiple functional advantages, such as improved thermal insulation, enhanced mechanical strength, reduced permeability, and surface functionalities including self-cleaning and pollutant degradation. These enhancements can reduce reliance on traditional construction materials, thereby increasing structural safety and environmental compatibility. The mechanical strength gains in cement-based materials are largely attributed to accelerated hydration kinetics and the promoted formation of calcium–silicate–hydrate gel. Nanoparticles function as nucleation centers for C–S–H growth, resulting in microstructures with increased density and cohesion. In addition to initiating hydration, they also occupy void spaces, bridge microstructural gaps, and inhibit microcrack propagation, which collectively enhance the material's integrity and binding performance. Each nanomaterial type presents unique benefits and limitations. For example, nanoclay particles, due to their high surface area and absorption ability, may reduce workability and accelerate setting time. Nevertheless, when optimally dosed and properly dispersed, nanoclay improves durability, mechanical strength, and shrinkage resistance. The method of dispersing nanoclay is a key factor influencing its effectiveness in the cement matrix. Similarly, nano-silica enhances performance by reducing pore size and overall permeability, while reinforcing the C–S–H structure, thus boosting both durability and load-bearing capacity. Metal oxide nanoparticles contribute by filling pores and improving bond strength within the matrix. Carbon nanotubes (CNTs), on the other hand, are especially effective in bridging cracks and gaps, thereby providing critical reinforcement and enhancing fracture resistance.

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