Review Article

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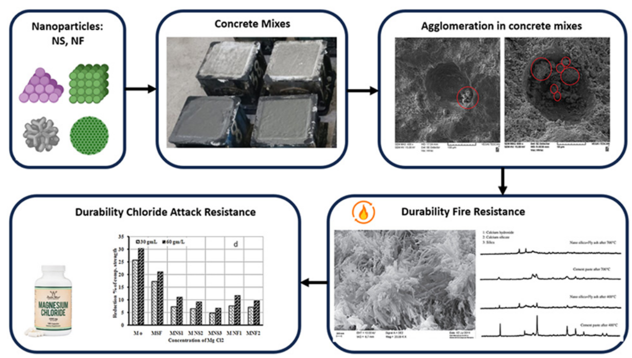
Influence of nano-silica and nano-ferrite particles on mechanical and durability of sustainable concrete: A review

https://doi.org/10.1515/ntrev-2025-0151
received July 9, 2024; accepted February 18, 2025

Abstract: Because cement is the primary component of concrete, the production of concrete results in a significant amount of carbon dioxide emissions. Concrete, thus, has an impact on the environment. Concrete may undergo a change in its nanostructure if it contains even a trace number of nanoparticles (NPs). Constructions made of concrete would be more long-lasting and would have a smaller impact on the environment. Researchers know very little about NPs before they are utilized, and the findings of their investigations have been inconsistent despite the fact that a large number of studies have been conducted. In contrast to the inclusion of metals, NPs, particularly nano-silica (NS) and nano-ferrite (NF), have garnered a lot of attention. Due to the fact that NPs perform more effectively in concrete than metal complexes. To evaluate bids, it is essential to provide background information on the most common methods for the manufacture and fabrication of nanomaterials. The parameters that influence the behavior of NPs in cement-based materials have also been the subject of extensive research. There are also processes for mixing and dispersion, as well as super-plasticizers and nanoparticle agglomeration. The mechanical properties of mixtures containing NPs are also assessed. This encompasses modulus of elasticity, splitting tensile strength, compressive strength, and flexural strength. An assessment is conducted to ascertain the penetration of chloride ions in water, permeability, and fire resistance. This study examines various methods for dispersing NS and NF particles to reduce the probability of agglomeration. The investigation also examines how the buildup of NS particles affects the properties of nano-modified concrete. The study revealed that augmenting the nanoparticle substitution by 3–5% can enhance compressive strength. The hydration process is enhanced by extensively disseminated NPs, which also provide a denser microstructure. The incorporation of NF into concrete enhances tensile strength, permeability, and durability, even at concentrations as minimal as 2%. The graphical abstract encapsulates the research conducted in this article.



Graphical abstract

Keywords: NPs, nano-silica, nano-ferrite, preparation, mechanical properties, durability properties

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Abbreviations

CH	calcium hydroxide
CNFs	carbon nano-fibers

CSH	calcium silicate hydrate
FA	fly ash
FAC	fly ash concrete
GGBFSC	ground granulated blast furnace slag admixtures
HPC	high-performance concrete
HPSCC	high-performance self-compact concrete
HVFAC	high-volume fly-ash concrete
HVSCC	high-volume self-compact concrete
LWC	low-weight concrete
ME	modulus of elasticity
MNF	NF concrete mix
MNS	NS concrete mix
MSF	silica fume concrete mix
NAC	normal aggregate concrete
NF	nano-ferrite
NPs	nanoparticles
NS	nano-silica
NSC	nano-silica concrete
OPC	ordinary Portland cement
PETC	polyethylene terephthalate concrete
PS	precipitated silica
RAC	recycled aggregate concrete
SF	silica fume
SP	super-plasticizer
UHPC	ultrahigh-performance concrete

1 Introduction

Concrete has gained immense popularity as a building material since its inception. It is presently employed in the construction of bridges, highways, buildings, and reservoirs globally. Due to the swift advancement of the 21st century, civil engineers are increasingly using innovative building materials to create structures that are more durable, taller, enduring, and visually appealing [1,2]. The shortcomings of conventional concrete, such as its low tensile strength, poor durability, and weak toughness, were brought to light as a consequence of this trend [3,4]. To address the difficulty, researchers have included nanoparticles (NPs) in concrete mixtures to enhance the qualities of concrete and resolve its challenges [5–13]. It is possible to define nanomaterials as substances that have a diameter that is <100 nm. It is possible for the properties of a material to be affected by its size [2,14–19]. When compared to the larger measurement of the equivalent substance, the physical, chemical, and biological properties of nanoscale materials are typically different. This is the case in most cases [20–22]. This is due, in part, to the nanoscale variation in surface space per unit volume. The fraction of atoms at the surface grows as the number of interior atoms declines as the number of nanoscale particles increases [23,24]. Atoms on the surface tend to behave differently from those on the inside. Surface atoms have a higher energy state, making them more likely to react with particles from nearby substances [25,26]. As a result, chemical reactions between atoms and molecules can occur on surfaces that behave as small chemical reactors [20–22,27,28]. Small particulates and huge specific surface regions characterize nanomaterials [29–32]. The ratio of surface atoms reaches 20%, despite the fact that the particle size can be as small as ten nanometers. Furthermore, the number of atoms that are spread on the layer of the particulates increases at a rapid rate as the particle size comes down. Nanostructures are characterized by a number of distinguishing properties, including surface impact, volumetric influence, filling operation, and others. When particles are 1 nm in size, practically all of their molecules are located on the outer layer [33–35]. When NPs are applied to a core material, they refine the grain to some extent, generating intermolecular or intermolecular structures that improve grain boundaries and material mechanical characteristics [36–38].

Reconstructing a wide range of useful synthetic materials at low dimensions while preserving their essential properties has been made possible by recent advances in nanoscience- and nanotechnology-related production and characterization methods [39–41]. Both bottom-up and top-down methods are used to synthesize nanoscale materials [42]. When picking these approaches, a number of considerations are taken into account, including cost-efficiency, eco-friendliness, the effectiveness of emerging features, and appropriateness. Milling is a versatile top-down process that does not modify the atomic-scale characteristics, and it may be used to construct nanoscale structures that have developing qualities [43–45]. Bottom-up approaches, on the other hand, make it possible to design and regulate matter at the atomic level through the use of chemical reaction pathways [46–49]. The constant packing of cementitious material composition, as shown in Figure 1, is a significant factor in why tiny fragments may be employed effectively in concrete's strength. Nanomaterials serve as nanofillers in cement composites, mitigating the nanoscale proliferation of micro-cracks. Nanomaterials enhanced the interfacial transition zone (ITZ) between aggregates and the matrix, while also purifying the cementitious matrix by occupying pores of nanometer-scale widths [50]. Nano-silica (NS) and carbon nanotubes (CNTs) improve cement-based materials, and people seek to improve them through nanomaterial interaction [51].

Because of its high activity and smaller granularity, silica fume (SF) improves the durability and strength of concrete [53–58]. Because of the growing demand for

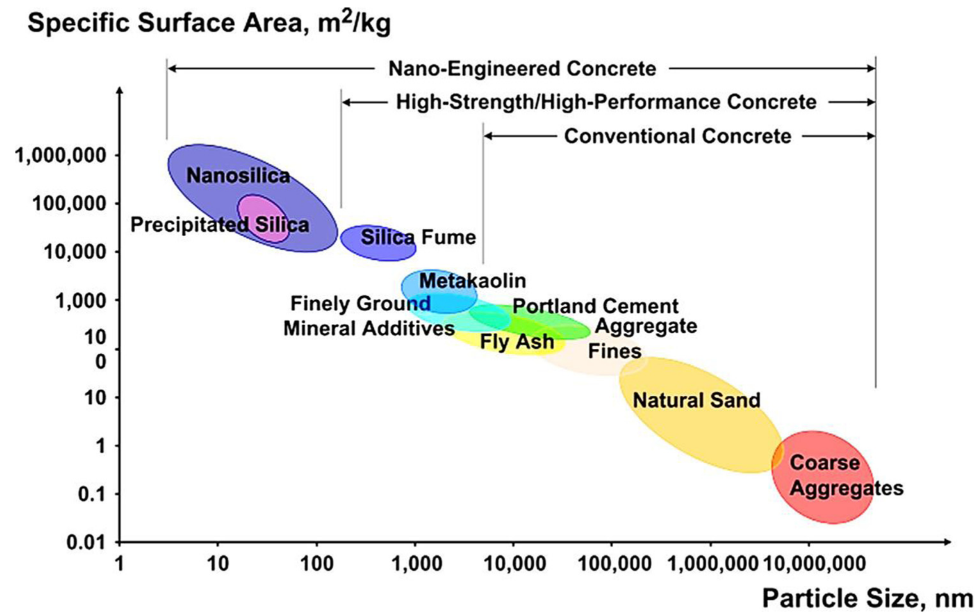


Figure 1: The relation between component size (nm) and the specific surface region (m^2/kg) of concrete materials [52].

high-performance concrete (HPC), nanotechnology has created nanomaterials to substitute SF. Due to their unique nano effects, nanomaterials are frequently utilized in concrete. The findings indicate that adding NPs to concrete increased its workability, durability, hardened characteristics, and microstructure [59–68]. Controlling the cement setting period, nano-alumina addition to concrete may significantly alter concrete qualities [69,70]. The self-cleaning capabilities of nano-TiO_2 enable it to break down a variety of environmental contaminants, including chlorophenols, NO_x, and carbon monoxide [71–76]. The electric conductivity of cement-based mortar is altered by nano-Fe_2O_3. Nano-$CaCO_3$ strengthens the interlayer link and enhances the rheological characteristics needed for shape retention [77–81]. Table 1 compares the performance of ordinary Portland cement (OPC), HPC, ultrahigh-performance concrete (UHPC), and nano-concrete.

Table 1: Summary of the comparisons between various types of concrete

Ref.	Concrete type	Flexural strength (MPa)	Compressive strength (MPa)	Water absorption (%)
[82]	OPC	1–10	10–40	<30
[83]	HPC	11–20	40–100	12–25
[84]	UHPC	20–30	100	<12
[85]	Nano-concrete	12–20	70	<12

The preparation methods and material features of a wide variety of NPs, in particular NS and nano-ferrite (NF), are discussed in this article, which provides an overview of the subject matter. This article provides a wide review of NPs addition, its problems and solutions, and the effect of the addition on the concrete characteristics, especially durability. When it comes to the addition of nanomaterials to concrete, NS and NF are considered to be the most successful forms. Nanoparticle agglomeration, mixing and dispersion techniques, and the utilization of super-plasticizer (SP) are some of the elements that have an impact on the activity of NPs in cement-based materials. A number of NPs, in particular NS and NF, are being researched for their effects on the many kinds of concrete that are currently being used. Additionally, this article will investigate mechanical qualities as well as durability-related characteristics of mixtures that contain NPs. Such an investigation will be carried out by analyzing previous studies that have been conducted in this field.

The integration of NPs into sustainable concrete has demonstrated significant potential to enhance mechanical properties and durability, making it a promising area for advancing eco-friendly construction materials. However, several critical gaps remain in the existing body of research. While NPs are known to improve mechanical strength and durability, the precise mechanisms, particularly at the nano- and micro-scale, through which these enhancements occur are not fully understood. Studies often focus on certain types of NPs (*e.g.*, NS, NF) without systematically comparing their effects. Moreover, there is a lack of consensus on optimal dosages to balance performance enhancements with cost-effectiveness and workability. This article aims to critically assess and summarize the current state of knowledge, identify these gaps, and propose directions for future research to maximize the benefits of NPs in developing sustainable, durable concrete solutions. In particular, a critical analysis is performed on the impact that NS and NF have on the qualities of concrete, which includes hydration characteristic, calcium leaching, porosity, mechanical strengths, and durability. Not only is it anticipated that this article stimulates novel concepts for the purpose of advancing the practical use of NS and NF in construction materials, but it is also anticipated that it will offer some constructive direction for investigations of a similar nature in the future.

2 Methodology

This study was based on a three-step workflow to evaluate the research outputs on the influence of NPs on concrete properties. The review steps, consisting of bibliometric search of the literature using Scopus as the database, sciento metric analysis adopting VOS-viewer as the text-mining tool, and a follow-up qualitative discussion. The importance of NPs in technological progress stems from their versatile properties and superior performance compared to their bulk counterparts. Furthermore, this article will explore NPs, covering their classifications, characteristics, methods of synthesis, applications, and prospects.

3 Factors affecting the behavior of NPs in cement-based materials and their solution

Morphology is defined as the examination of the structure, form, and shape of a thing to ascertain its functions. The similarities in their production methods lead to differences in the structures of nanoparticle sols and nanoparticle gels. Primarily attributed to their condition of aggregation. A restricted number of studies have investigated the influence of shape on the properties of cement composites. It has been hypothesized that NPs in concrete environments are monodisperse particles. This suggests that they have the potential to serve as ultrafine nuclei for the precipitation of calcium silicate hydrate (CSH) and other hydration products, or to occupy the mesopores of concrete. Nevertheless, if it was supposed that NPs like NS gels exist initially as huge agglomerates, then we must further explore these assumptions. It is important to take into account that NPs exhibit various morphologies. Specifically, the powder NPs primarily exist as sizable agglomerates. On one hand, the clusters of pyrogenic NPs have porous structures, whereas, on the other hand, the clusters in the precipitated NPs xerogel are compacted. Unlike powder NPs, NP hydrosols can exist as either monodispersed particles or small-stabilized aggregates. The NS sols are incorrectly identified as colloidal silica in various studies, including those referenced as [86,87]. Colloid dimension, technically speaking, pertains to dimensions that are less than 1,000 nm. Therefore, this word is inaccurate and has the potential to cause confusion. Several research have examined the impact of NS morphology on concrete characteristics. Kong *et al.* [88] demonstrated that the morphology of NS, namely the way in which they agglomerate, has a significant impact on the mechanical characteristics, hydration, and durability of the material. These studies have demonstrated that the structure of NS plays a crucial role in determining the effectiveness of these materials in cement composites. Nevertheless, these investigations have significant limitations and need to be expanded to encompass a wider range of NPs [89]. Morphology is defined as the examination of the structure, form, and shape of an organism to ascertain its functions. For example, the similarities in the way they are produced result in variances in the structure of NPs sol and NPs gel. Primarily ascribed to their state of agglomeration. There is a lack of research that has examined the role of morphology in studying the characteristics of cement composites. In various research studies, it has been postulated that NPs in concrete environments are monodispersed particles. These particles are believed to have the ability to serve as ultrafine nuclei for the precipitation of CSH and other hydration products. Alternatively, they may occupy the mesopores of concrete. Nevertheless, if we suppose that NPs like NS gels exist initially as huge agglomerates, then these assumptions need to be further explored. It is important to take into account that NPs exhibit various morphologies. Specifically, the powder NPs predominantly exist as substantial agglomerates. Nevertheless, the clusters of pyrogenic NPs possess porous structures, whereas the clusters in the precipitated NPs xerogel are compacted aggregates. Unlike powder NPs, NP hydrosols can exist as either monodispersed particles or small-stabilized aggregates. The NS sols are incorrectly identified as colloidal silica in various studies, including those referenced in [86]. Colloid dimension, in technical terms, pertains to dimensions that are less than 1,000 nm. Therefore, this word is inaccurate and has the potential to cause confusion. Several research have examined the impact of NS morphology on concrete characteristics. Kong *et al.* [88]

demonstrated that the morphology of NS, namely the way in which they aggregate, has a significant impact on mechanical characteristics, hydration, and durability. These studies have demonstrated that the structure of NS plays a crucial role in determining the effectiveness of these materials in cement composites. Nevertheless, these investigations have significant limitations and need be expanded to encompass a wider range of NS variants [90].

3.1 NPs agglomeration

With smaller particle sizes, agglomeration should occur more readily because the higher the relative surface and more surface atoms, the less unstable the system. The surface molecules have unsaturated integration, and every molecule has an unfilled linkage site. Then, more bonds are formed between the neighboring surface atoms, and thus, the agglomeration takes place [50,71,88,91–96].

Particle agglomeration occurs for a variety of reasons, and the mechanisms that cause it are constantly being researched. However, researchers from all over the world have postulated the following factors as possible causes of agglomeration reaction: (i) Particle aggregation can be caused by intermolecular forces, hydrogen bonds, and electrostatic interactions; (ii) Particle reactions on the interface are common because of the inter-particle quantum tunneling phenomenon, coupling of interface atoms, and charge transfer; (iii) Due to the large contact interface and high surface energy, NPs are quickly absorbed by gas and medium and react with them, resulting in adhesion and agglomeration; and (iv) The grain development rate is quickened, making particle size management difficult [97–100].

Kong *et al.* [88] studied the influence of NS agglomeration on the characteristics and the microstructure of mechanical cement-based substances, utilizing precipitated silica (PS) agglomerates with extremely large sizes and SF agglomerates with considerably tiny sizes as nanoscale compounds. They demonstrated that adding either SF or PS refines the porous structure of the cured cement paste. According to SEM analysis, the pozzolanic CSH gels from the agglomerates could not operate as binding materials. They also discovered that because of their low strength and modulus of elasticity (ME), massive agglomerates might generate weak zones. In another study, Li *et al.* [101] studied the impact of NS agglomeration on the fresh characteristics of cement pastes employing the same ingredients, namely PS and SF. According to the results of the experiments, precipitated NS had a stronger effect on the rheological characteristics of the paste than fumed NS. This is owing to the extremely large agglomerates of PS, which cannot serve as a filler to generate free water in the empty area and add fluidity. It also absorbs the free water that previously helped the paste's fluidity. On the other hand, they discovered that adding PS with considerably bigger agglomerates greatly increased cement hydration more than SF.

Khaloo *et al.* [93] investigated the effect of using low substitute ratios (0.75 and 1.5% of the binding weight) on the particular surface spaces of nano-SiO_2 particulates. Microstructural studies revealed that a reduction in the effectiveness of NS with a higher surface space at a decrease w/b ratio corresponds with the formation of nanoparticle agglomeration, especially at the maximal replacement level of NS (1.5%) because of the increased particular surface space of nano-SiO_2 particulates. According to X-ray diffraction (XRD) analyses, finer nano-SiO_2 has stronger pozzolanic exertion and accelerates the hydration of cement more than coarser nano-SiO_2.

Kong *et al.* [102] investigated the effect of mono-dispersed NPs with silica solution on the rheological characteristics of cement pastes compared to NS granules agglomerated on the micro-scale. They discovered that adding silica sol with mono-dispersed NPs had a greater acceleration impact on cement hydration than adding NS with micro-scale agglomerates. It was proven that the

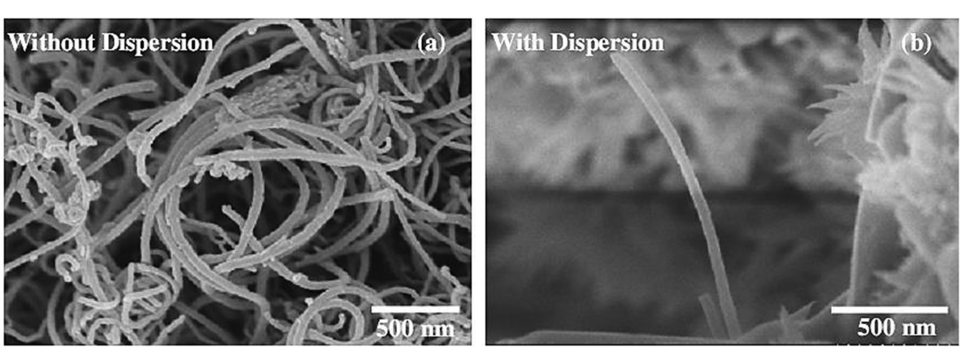


Figure 2: SEM of cementitious material enhanced with NPs [102], (a) without dispersion and (b) with dispersion.

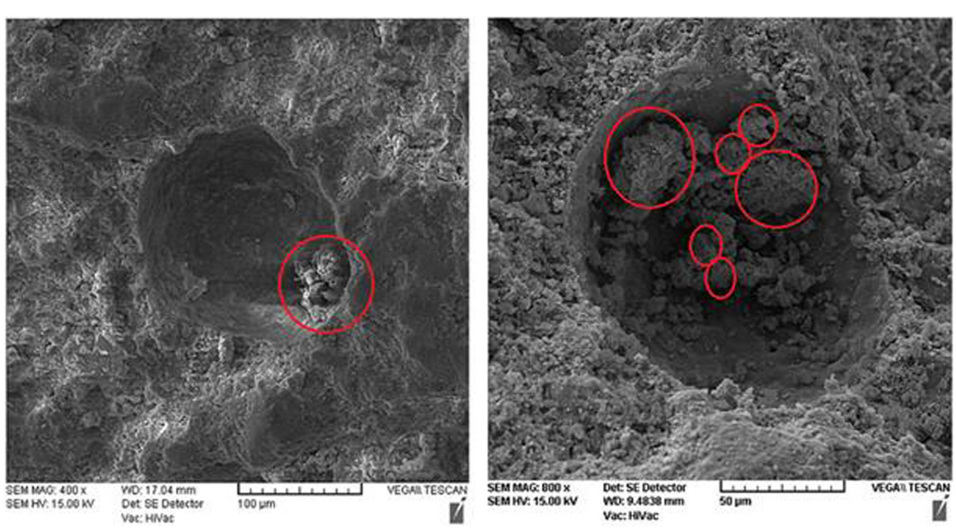
acceleration is not because of the seeding effect but rather because of the quick depletion of calcium ions in the paste [79].

Studies conducted by Kooshafar and Madani [89] made use of NS concentrations as high as 7%. The nanoscale nitrate particles improve the cement system's microstructure. Furthermore, it mitigates calcium leaching *via* its reaction with CH, developing a denser C–S–H gel [103]. Upon incorporation of NS, concrete exhibits exceptional durability and strength.

3.2 Mixing and dispersion method

Kong *et al.* [102], Piro *et al.* [104], and Mohammed *et al.* [105] investigated the influence of CNTs on cementitious substances. To achieve an improved outcome, they distributed NPs in water using detergent and ultrasonic energy. Constant energy (1,900–2,150 J/min) was employed for the NPs dispersions using a 510 W cup-horn high-intensity ultrasonic processor. The analysis indicates that ultrasonic energy and a detergent may be used to efficiently disperse NPs in the cementitious matrix, as shown in Figure 2. To mitigate nanoparticle agglomeration, several innovative methods have been proposed across various studies. These methods focus on altering environmental conditions, utilizing electrical forces, and employing plasma treatments to maintain nanoparticle dispersion. There are many strategies for reducing agglomeration such as pressure reduction, electrical charging, plasma treatment, and magnetic interaction control. Reducing the pressure in nanoparticle systems has been shown to significantly decrease agglomeration. For instance, silver oxide NPs exhibited a four-order magnitude increase in electrical impedance when pressure was lowered to 70 kPa, indicating reduced agglomeration due to increased surface area and diminished twinning volumes [106]. The use of a needle-plate corona charger effectively reduces agglomeration in aerosol NPs. By charging the NPs, the electrostatic repulsion between them is enhanced, preventing collisions that lead to agglomeration. This method is noted for its simplicity and cost-effectiveness [107]. Plasma treatment in colloidal suspensions can also mitigate agglomeration. By interacting with the nanoparticle suspension, plasma alters the physical properties of the solution, promoting long-term stability and dispersion of NPs [108]. For magnetic NPs, mixing them with matrix powder at a temperature above their curie point transforms their magnetic properties, reducing agglomeration caused by magnetic attraction. This method is straightforward and cost-effective [109]. While these methods show promise, challenges remain in scalability and practical application, particularly in maintaining the desired nanoparticle characteristics during treatment. Further research is needed to optimize these techniques for broader industrial use.

Khaloo *et al.* [93] studied the behavior of cement paste incorporating CNTs with dispersion. They carried out the dispersing of NPs in plain distilled water and water with Arabic gum powder to improve the dispersion of the nanotubes. The results highlighted that the specimens with NPs dispersed in water with Arabic gum powder achieved



(a) (b)

Figure 3: SEM image: (a) conglomerate in HPC NS200 porous structure and (b) conglomerate in HPC NS380 porous structure [93].

higher ME and hardness than samples with NPs dispersed in distilled water. Thus, Arabic gum powder appeared to be an effective dispersion reagent for nanotubes, with the further advantage of being suitable for cement-based components. The SEM image is presented in Figure 3.

Kong *et al.* [88] disseminated NPs in epoxy for 1 h with high-speed stirring (2,000 rpm) and found that vigorous stirring is a good method for achieving evenly dispersed NPs in epoxy. Another effective way is to provide adequate compatibility with polymer/NP composites.

To improve the strength of reinforced concrete, Li *et al.* [110] tested the effects of spraying an NS suspension over the surface of recycled aggregate before doing the actual spraying. The pre-spraying technique was determined to be superior to the pre-mixing method.

Najigivi *et al.* [111] investigated the influence of the NS distribution technique within the cement paste as a key aspect influencing the performance of these goods. It was demonstrated that the use of SP, ultra-sonification, and/or high-speed mixing could efficiently spread NS and that the distribution of NS within the cement paste played an important role in governing the overall performance of the cement paste, as shown in Figure 4.

Morsy *et al.* [112] introduced NS to the cement in two forms: colloidal sol and dry powder. This sol was made by swirling it for 5 min. Before adding it to the cement. When the two forms of additions were compared, colloidal dispersions were shown to be far more effective. Li *et al.* [113] used sonification to disseminate the NPs in the mixing water for 28 min. Following that, a polycarboxylate-based SP (1% of the mixture volume) was applied, and the dispersion was significant for a further 2 min. Oertel *et al.* [114] employed SF and a nitric acid surface treatment to aid in the dispersion of carbon nano-fibers (CNFs), which increased the interfacial contact between the CNFs and the cement phase.

3.3 SP

Because of the very small size of NPs, their specific surface area is very high relative to their volume. Therefore, there is a need for higher water content in mixtures with nanomaterials to obtain the same workability as normal mixtures [111]. Stefanidou and Papayianni [115] studied the effect of adding 1% SP to lower the water consumption of NS cement pastes at different levels of NS. It was found that the addition of 1% of SP lessened the w/c ratio by nearly 10% for all the contents of NS. That is, because of its main role in avoiding agglomeration by repulsion between particles, it is used for mixture lubrication and ease of operation without needing to increase the water than the water needed to hydrate the binder only. As known, the increase in water over the water needed for hydration deteriorates the mechanical properties and durability.

Previous research found that when compared to OPC, there was an improvement in the compressive strength of concrete with NPs at early ages but a decline in the improvement rate at later ages [111]. Sobolev *et al.* [116] overcame this challenge by incorporating SP into nanoparticle mortars. The compressive strength of SP mortars containing chosen NS increased by roughly 15–20%. Mechanochemical activation was discovered to be a useful way of enhancing the resilience of cement-based substances. A solid-state reaction between the cement and organic additives is recommended to govern this procedure. During this stage, the cement granules' surfaces bond to the functional

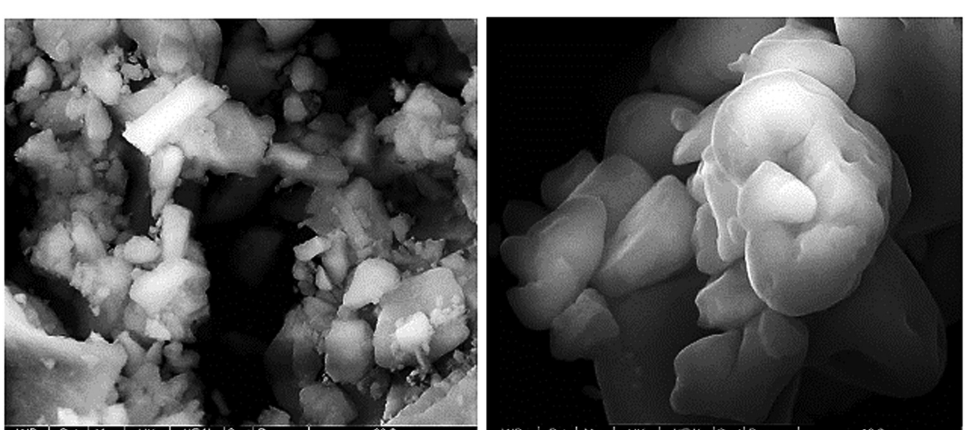


Figure 4: Influence of ultra-sonification on xerogel agglomerates of nano-SiO_2 [111].

structures provided by the modifiers, forming nano-networks or metal-organic nanolayers on the cement surface. Also, Najigivi *et al.* [111] studied the influence of 0.1% SP on NS mortars' flowability, compressive strength, and flexural strength. The results revealed that the addition of SP enhanced flowability by 37% and flexural and compressive strengths by roughly 21 and 7% after 28 days, respectively.

Ghafari *et al.* [117] claimed in their review study that the nucleation impact of NS may effectively compensate for the retardation effect of SP. Furthermore, the introduction of NS elevated the viscosity of ultrahigh-performance (UHP) concrete, resulting in more air collected in the fresh stage and, as a result, an improvement in porosity in the hardened state.

Elkady *et al.* [118] examined the effectiveness of two methods for adding SP to NS concrete. In the first approach, the NS was mixed with SP and water before being de-agglomerated, but in the second way, the NS was de-agglomerated along with a part of the water, and then the SP was mixed with the remaining water before being applied to the dry components. In terms of performance and strength, the findings revealed that sonicating NS with a certain amount of water and then including SP in the remaining water while applying it to the dried elements of the concrete was the best way of adding SP to NS concrete.

4 Utilizing NPs in cement-based materials and concrete

Many nanomaterials are utilized in cement paste and concrete, including NS [93,119], nano-$CaCO_3$ [120], nano-Al_2O_3 [121], nano-Fe_3O_4 [122], nano-TiO_2 [123,124], nano-carbon [125], nano-ZnO_2 [126], nano-LS [127], nano-FA [128], carbon-based nanotubes [129], and nano-MK [130]. The following is a presentation of many previous research studies that have used different types of nanomaterials, whether in concrete or cement paste.

The integration of NPs, such as NS or NF, in the construction industry offers several benefits but also presents certain challenges and hurdles. NPs, particularly NS and NF, are regarded as materials that improve the properties of concrete and other construction components by increasing strength, durability, and environmental resilience. Nevertheless, their application in construction methodologies poses various challenges, including health and environmental risks, regulatory issues, secure storage and disposal, elevated costs, dispersion difficulties, compatibility with other additives, lack of standardization, unclear application protocols, effects on workability, quality control issues, and societal resistance to innovative materials. NPs are extremely tiny and may pose respiratory hazards if inhaled. Personnel must employ appropriate personal protective equipment, such as respirators and gloves when handling the material to prevent exposure to airborne NPs [131]. Current rules governing the safe use and management of nanomaterials, particularly NS, are inadequate, requiring additional safety protocols that are inconsistent across different industries [132]. The secure storage and disposal of NPs require careful management to prevent contamination and reduce environmental harm, as NPs may yield unforeseen ecological effects [133]. NPs typically entail a greater expense than conventional construction materials such as Portland cement. The cost of integrating NS into concrete or other construction materials may present difficulties for construction companies to justify, especially in projects with limited budgets [134]. The use of NPs in the construction process may necessitate specialized equipment or alterations to current mixing procedures. Additionally, workers may need training to handle the material properly, both in terms of mixing ratios and health safety standards, which can add to the overall cost of implementation [134]. A major challenge in employing NS in concrete is achieving uniform dispersion of the NPs inside the mixture. Insufficient dispersion may lead to agglomeration, reducing the effectiveness of the NS and potentially undermining the overall quality of the concrete [50]. NPs may not consistently exhibit compatibility with other chemical admixtures or additives utilized in concrete, thereby influencing the setting time, workability, and curing characteristics of the mixture. NPs may elevate the water demand of concrete mixtures, potentially impacting the final strength or longevity of the material if not adequately compensated for. The addition of NPs to concrete may diminish the mix's workability, complicating handling, placement, or finishing processes. This may elevate labor expenses or necessitate supplementary additives (*e.g.*, SPs) to offset the reduction in workability. Modifications to the mix design may be necessary to sustain the intended performance [135–137].

NPs are relatively novel in the construction industry, and there is a deficiency of standardization concerning their manufacture and quality assurance. Divergences in the quality or characteristics of NS from various vendors may influence the efficacy of the final product. The criteria for integrating NPs into construction materials remain in progress. Consequently, there may be insufficient instructions regarding recommended dosages, mixing protocols, and performance expectations, complicating the effective application of the material by construction teams. Although NS has demonstrated the capacity to enhance short-term performance (including the early strength and durability of concrete), there remains a paucity of long-term data regarding its behavior during decades of utilization in construction materials. The enduring effects on qualities such as shrinkage, cracking, and durability in severe climatic circumstances remain inadequately comprehended [138]. Concerns exist regarding the interaction of NPs with other materials as the structure ages, particularly under environmental influences such as heat, moisture, or UV radiation. The ultrafine nature of NS and its susceptibility to numerous conditions (such as temperature, humidity, and mixing technique) complicate the assurance of uniform quality throughout each batch of concrete or other materials. Inconsistency in the final product may lead to diminished performance and reliability. Novel testing techniques may be necessary to precisely evaluate the impact of NPs on construction materials, potentially resulting in resource intensiveness and delays in product development or project schedules. The construction sector is characteristically hesitant to embrace novel technologies and materials, especially those that lack comprehensive validation. Certain stakeholders may exhibit reluctance to utilize NPS owing to apprehensions regarding uncertainties, nevertheless its prospective advantages [139].

Numerous construction firms, particularly those engaged in large-scale or high-stakes projects, may hesitate to utilize nano-silica due to concerns of potential unforeseen risks or complications in the future. NPs give promising opportunities for boosting the performance of construction materials, particularly regarding strength, durability, and crack resistance; nonetheless, their application entails certain hurdles. This encompasses health and safety hazards, elevated expenses, challenges in handling, compatibility problems with other materials, and ambiguity over long-term efficacy. As research and regulatory standards advance, certain concerns may be resolved; however, meticulous evaluation of the material's benefits and drawbacks is crucial for effective incorporation into construction procedures [139]. Through the ongoing pursuit of rigorous scientific inquiry and comprehensive study in this domain, we will surmount these hurdles and leverage nanotechnology in construction.

4.1 Nano-silica

Stefanidou and Papayianni [115] investigated the hardened characteristics of cement pastes at 7, 14, and 28 days after adding NS at 0, 0.5, 1, 2, and 5 wt%. The paste containing 1% NS had the best compressive strength and densest structure, according to the findings. The flexural strength of specimens comprising 2% NS was increased, but specimens containing 5% NS had declined compressive and flexural strength at all test ages. Figure 5 shows SEM micrographs of 14-day-old cement pastes with various NS contents. Needle-hydrates were found in all of the pastes, but pastes containing NS had a denser structure.

Yu *et al.* [140] investigated the microstructure of cement paste at 28 days after employing NS as a cement substitute. According to the findings, the use of NS enhanced the density of pastes. Additional benefits were obtained by raising the NS concentration till it reached 4%. At 5% NS, the number of pores increased. As illustrated in Figures 6 and 7, the addition of NS considerably increased the viscosity of cementitious mixtures, allowing a large quantity of air to be trapped and enhancing the porosity of cured concrete.

Zhang and Islam [141] studied the impact of 1% NS having a particle size of 12 nm on the rate of cement setting time, hydration, and strength characteristics in mixed cement pastes and mortars, including about 50% fly ash (FA) or slag. The addition of NS to cement pastes containing significant volumes of FA or slag decreased the duration of relatively low heat evolution and increased the rate of slag and cement hydration. The addition of NS to each of these mixed concretes decreased the initial and final setting times by 90 and 100 min, respectively, but it was more active driving the process of hydrating cement. The inclusion of NS improved

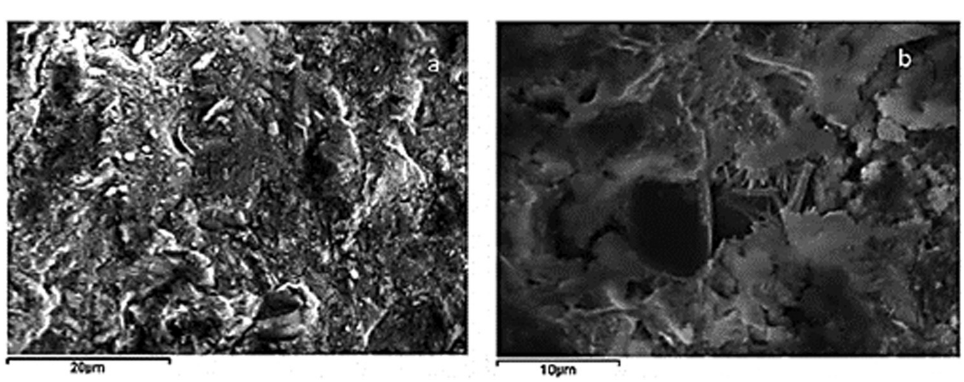


Figure 5: SEM of NS cement pastes at 14 days age [115], (a) NS 0% and (b) NS 0.5%.

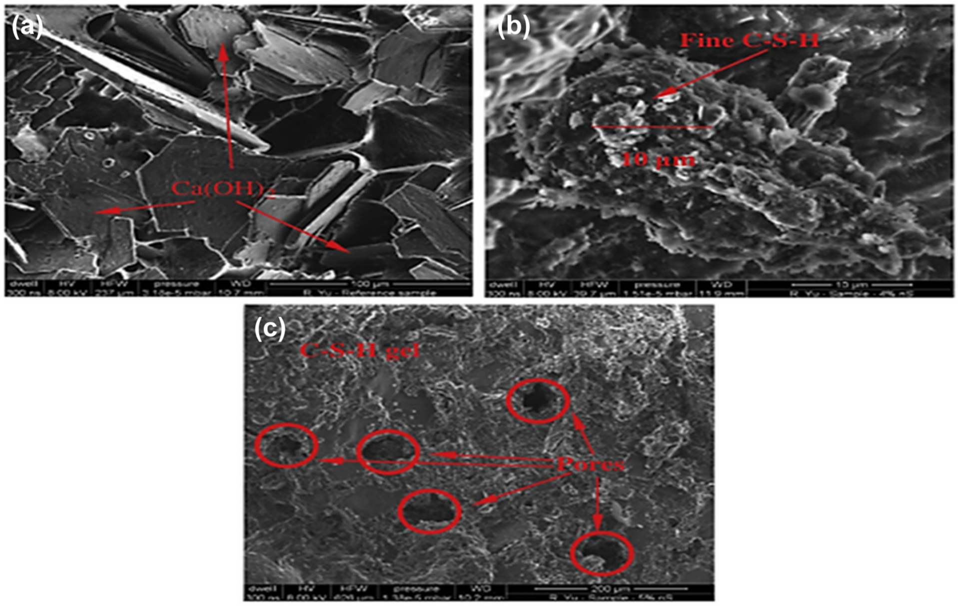


Figure 6: SEM image of cement pastes at different NS percentages: (a) plain concrete, (b) 4% NS, and (c) 5% NS [140].

the early compressive strengths of high-volume FA concrete by 31% compared to the control specimen with 50% FA. A similar trend was observed with high-volume slag concrete.

Sobolev *et al.* [116] studied the mechanical characteristics of mortars with 0.25% NS (5–70 nm particle size) and 0.1% SP. The results depicted that integrating NS into mortars improved their flexural and compressive strengths. The arrangement of NS particles within the cement paste was crucial in determining how well these products performed overall. As a result, it was proposed that SP be added to aid in the spread of NS particles. At 7 and 28 days, the compressive strength of mortars comprising NS and SP rose by 16 and

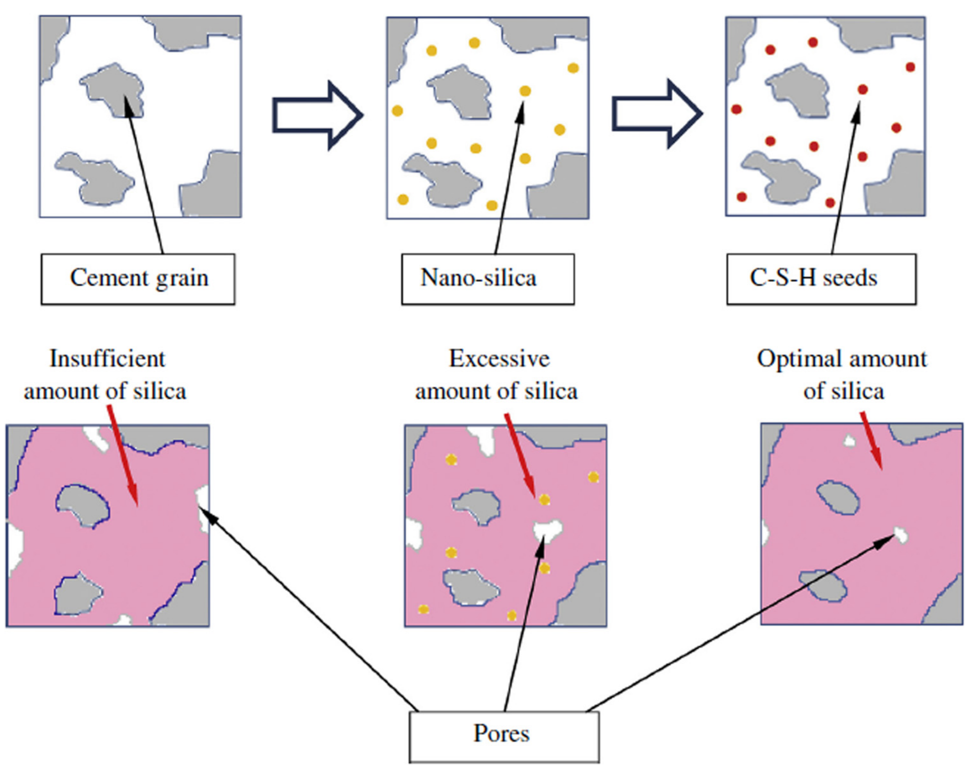


Figure 7: Graphic illustration of the nucleation effect of NS [140].

3.4%, respectively. In addition, using NS and SP increased the 28-day flexural strength of mortars by 18%.

Li [142] investigated the impact of substituting 4% of the cement content with NS in concrete containing 50% FA. They discovered that FA has little starting activity but that after including a tiny dose of NS, the pozzolanic activity increased dramatically. The integration of NS resulted in a boost in both short- and long-term strength; at 3 days, the

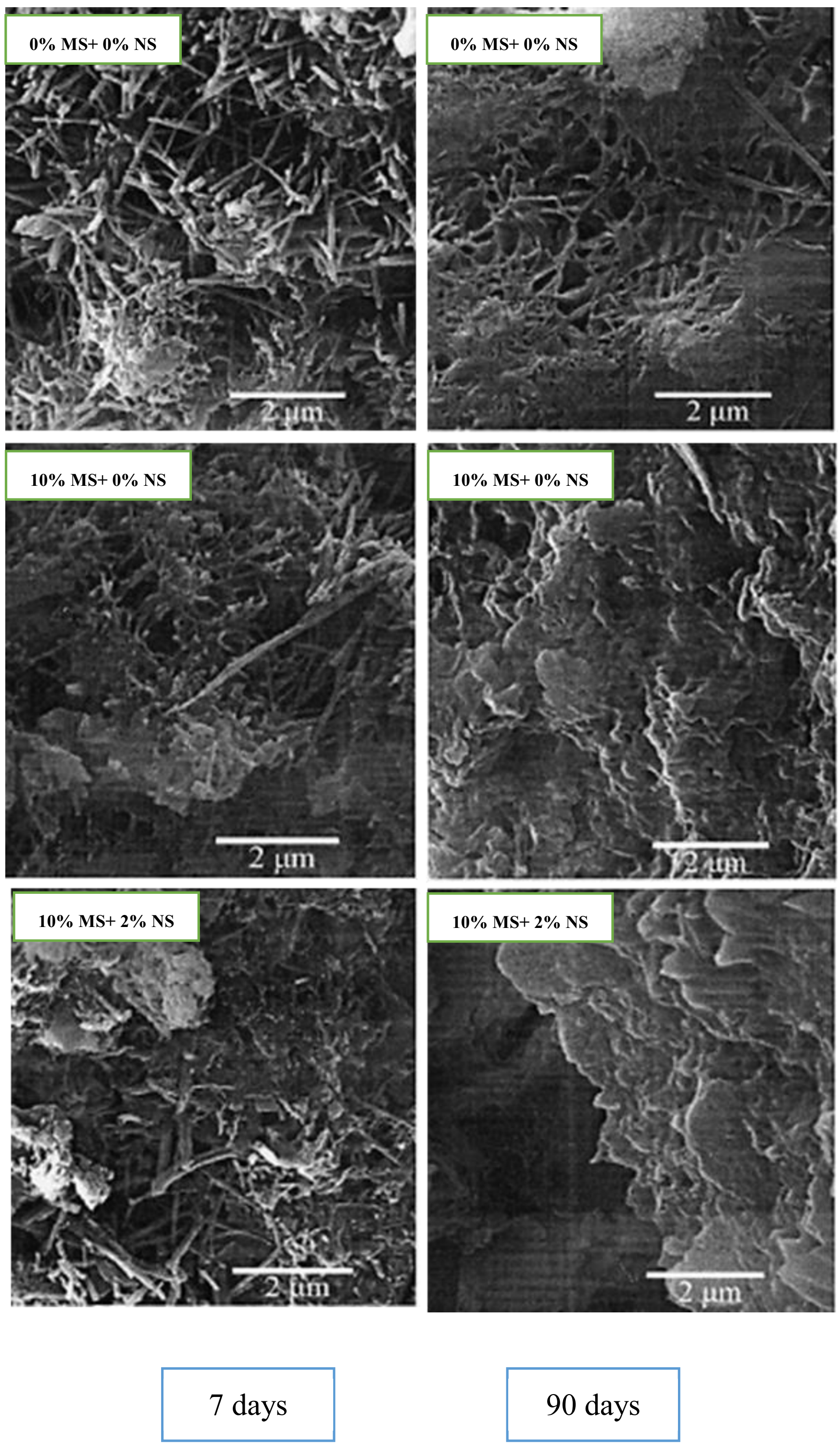


Figure 8: SEM of diverse cement blends of [145].

improvement in strength was around 81%. On the other hand, the 2-year strength of FA concrete was 115.9 MPa, compared to 108 MPa for FA concrete and 104 MPa for plain concrete. In addition, adding FA resulted in increased porosity in the near term, while adding NS acted as an accelerating additive, resulting in more compact structures.

Optimal NS suspension doses of 4 and 6% by mass of aggregate were determined for the NS pre-spraying approach [143]. The interfacial tension between the recycled aggregate and the new mortar was found to be stronger and improved after spraying NS. Li *et al.* [144] found that recycled coarse aggregate (RCA)'s durability and hardened qualities were improved when sprayed with colloidal NS and SF.

Jalal *et al.* [145] studied the microstructure of cement paste, mechanical characteristics, and water absorption of concrete when 10% SF, 2% NS, and 10% SF + 2% NS were substituted for cement at three distinct binder amounts of 400, 450, and 500 kg/m^3. According to the findings, the optimum mechanical qualities and water absorption were found in concrete containing 10% SF and 2% NS. As shown in Figure 8, the cement pastes with NS and SF exhibited a considerable improvement in SEM. In addition to its duty as a filler to enhance the density of concrete, NS might also operate as a kernel in cement paste, making the size of calcium hydroxide (CH) crystals tiny and the tropism more stochastic. This results in a more uniform and dense cement matrix.

Givi *et al.* [146] examined the microstructure and compressive strength of concrete at 7, 28, and 90 days using NS possesses an average dimension of 14 nm and varying ratios of 0.5, 1.0, 1.5, and 2.0%. The analysis indicates that 1% NS was the best addition percentage, improving strength by approximately 21, 22, and 16% at the tested ages. Furthermore, any rise in NS content over 1% had a negative impact on the strength since the overall dosage of NS in the mixture was greater than the amount needed for the lime-silica hydration process.

As a result, excess NS can seep out without further chemical reaction, relegating it to the role of filler and no longer contributing to concrete strength. Furthermore, microstructure examination of the NS-containing paste revealed that the hydration products produced were dense and more compacted, with fewer voids, resulting in higher strength and corroborating the findings obtained in comparison to the control concrete, as shown in Figure 9.

In addition to the aforementioned effects of nanomaterials, Figures 10–13 show the effect of NS ratios on different properties of concrete at 28 days old for different types of concrete. The amount of mechanical strength enhancement may be influenced by the water-to-binder ratio, as stated by Mostafa *et al.* [147]. The enhancement becomes noticeable when the water-to-binder ratio rises. They postulated that the enhanced mechanical strength was due to the dispersing action of NS. Compressive strength may be increased or decreased depending on the degree of NS particle agglomeration, as demonstrated by Vs and Xavier [148] and Stefanidou *et al.* [149]. The dispersion of NS inside the mortar matrix considerably influences its efficacy, as revealed by Wu *et al.* [150].

Mahdikhani *et al.* [151] found that splitting tensile strength improved with age and NS concentration, with a 10% improvement at 28 days and a 24% improvement relative to the control, respectively. Although the maximal tensile capacity of concrete with 1% NS rose by 47% after 91 days compared to control concrete, the strength enhancement was decreased to 26% while 25% FA along

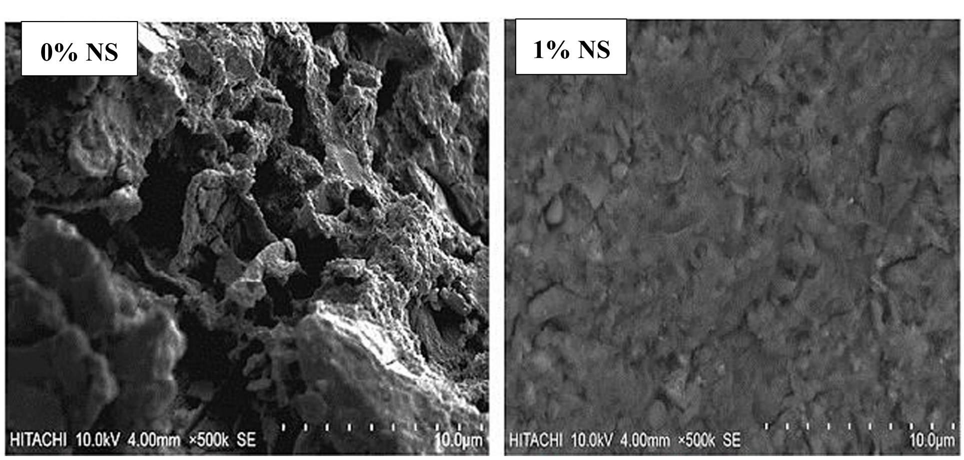


Figure 9: SEM images of NS concrete [146].

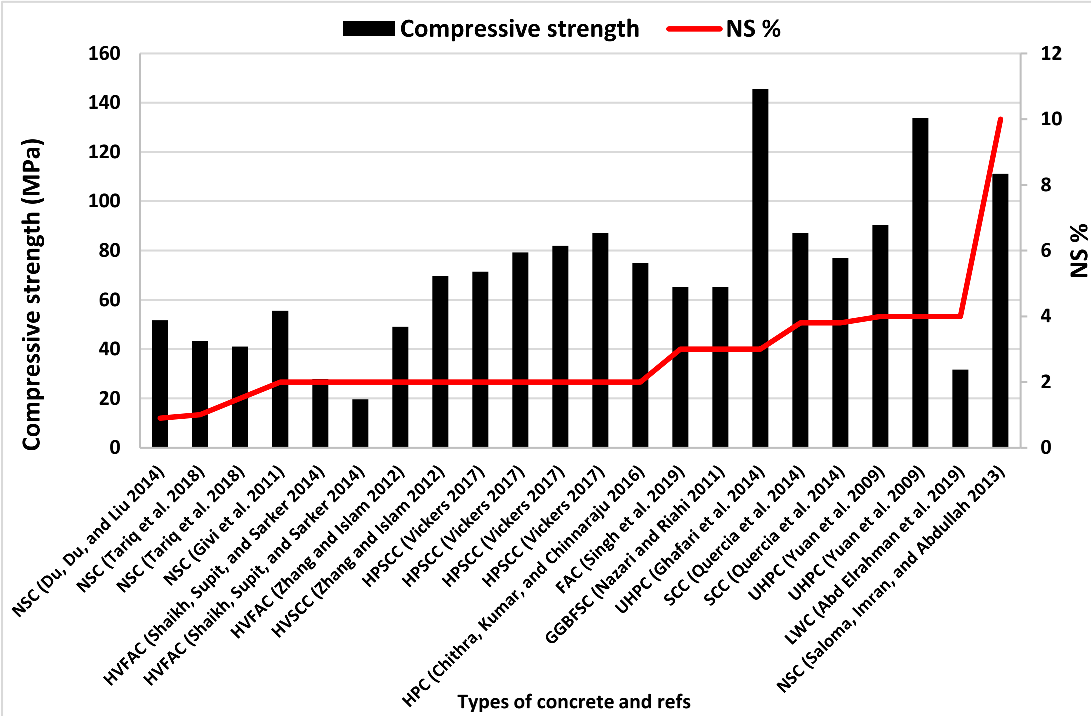


Figure 10: The effect of the NS ratio on the compressive strength of 28 days of age for different types of concrete.

with 1% NS was used [152]. The tensile strength of concrete mixes, which was previously 10% micro-silica, may be increased by 16.68–34.85% by adding NS in the 2.5–10% range, as reported by Puentes *et al.* [153].

In their study, Rong *et al.* [154] found that NS, having an alternative criterion of 3%, might potentially increase the flexural integrity of UHP cement composites. NS particles maintained their tendency to increase flexural

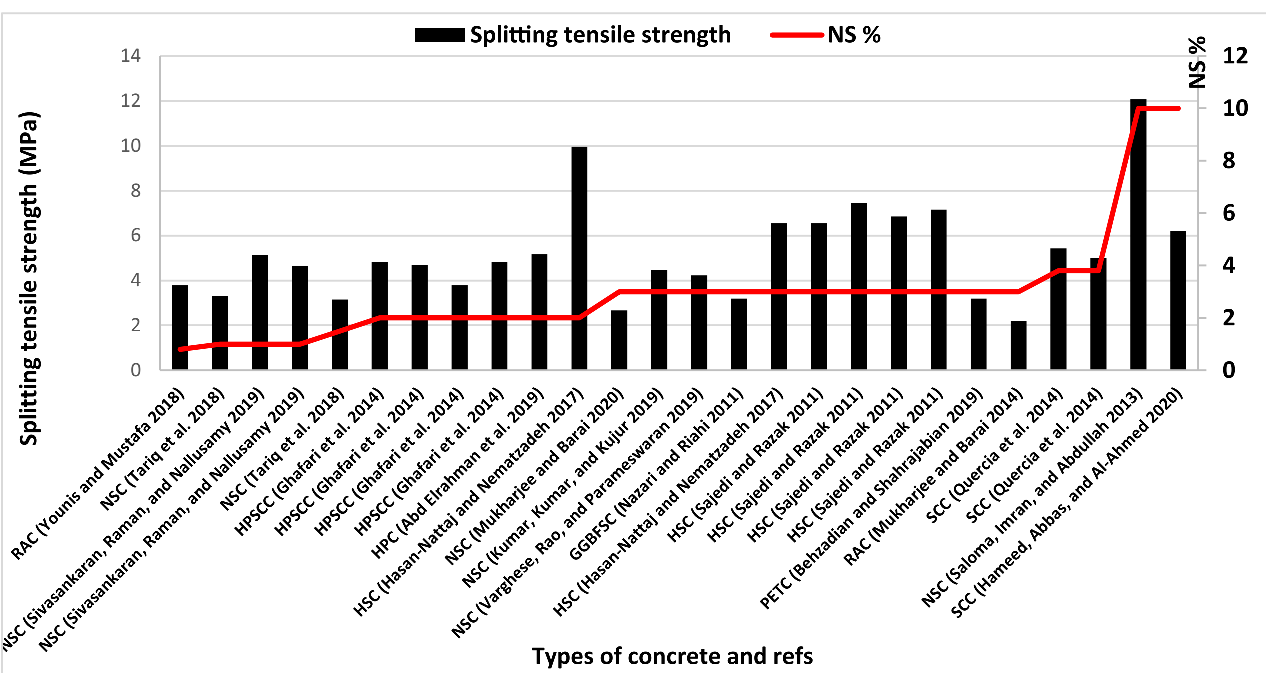


Figure 11: The effect of the NS ratio on the splitting tensile strength of 28 days of age for different types of concrete.

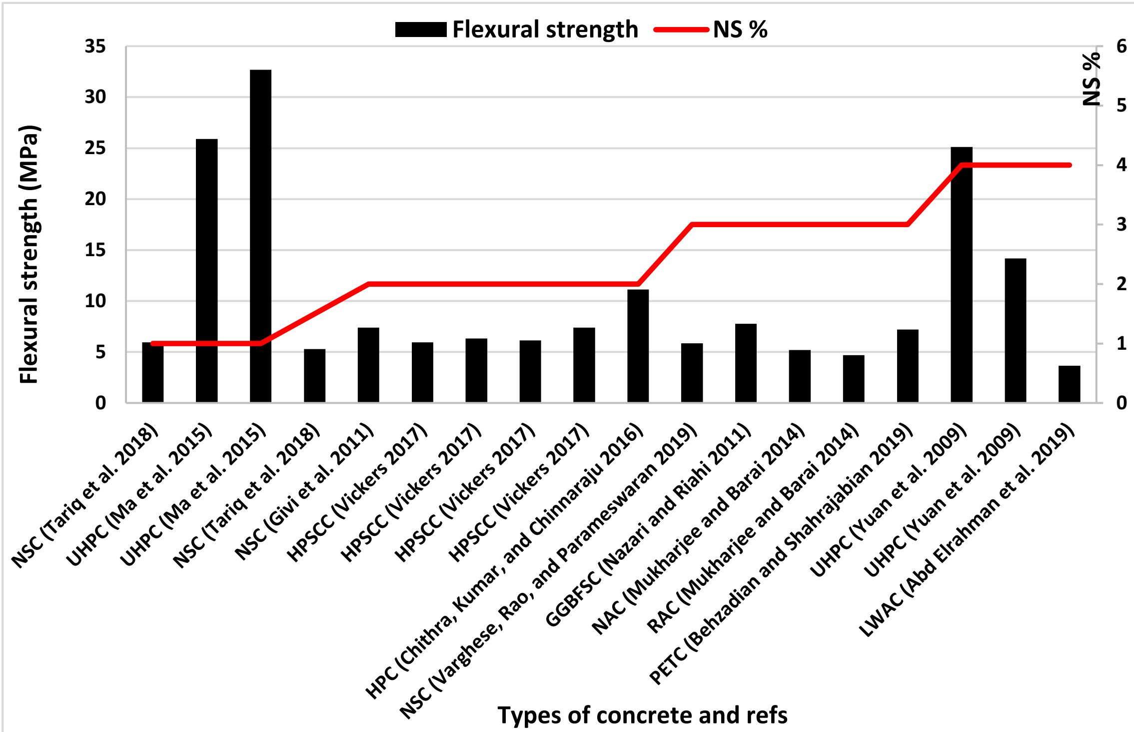


Figure 12: The effect of the NS ratio on the flexural strength of 28 days of age for different types of concrete.

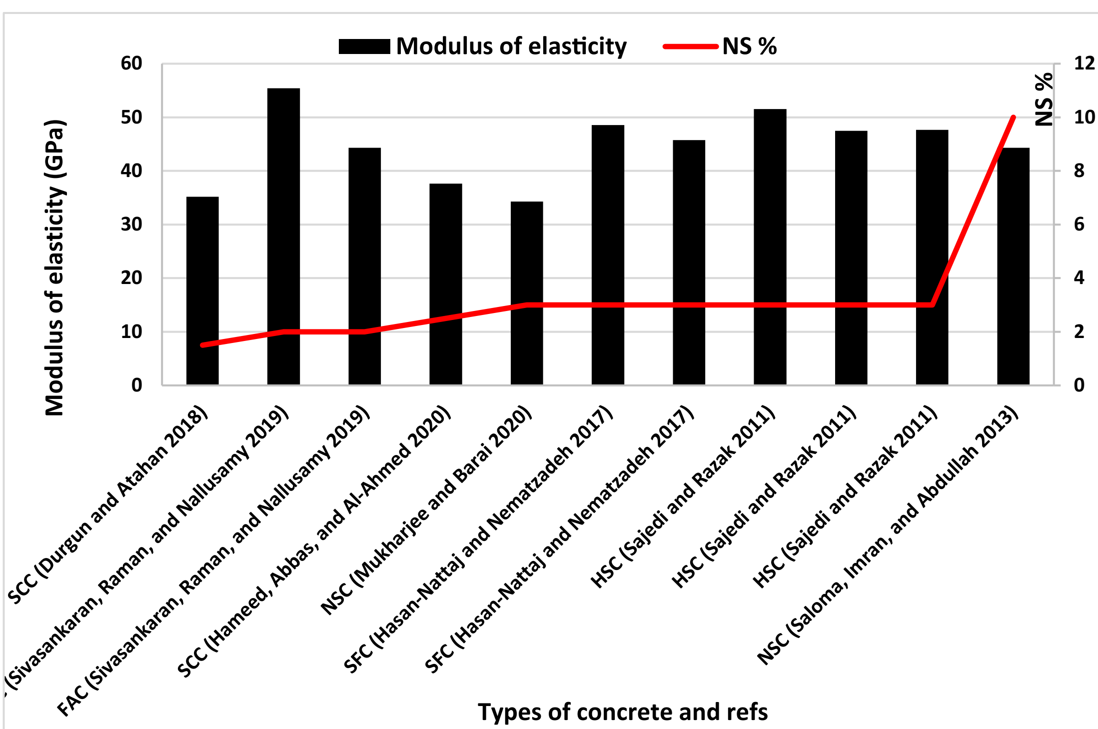


Figure 13: The effect of the NS ratio on the ME of 28 days of age for different types of concrete.

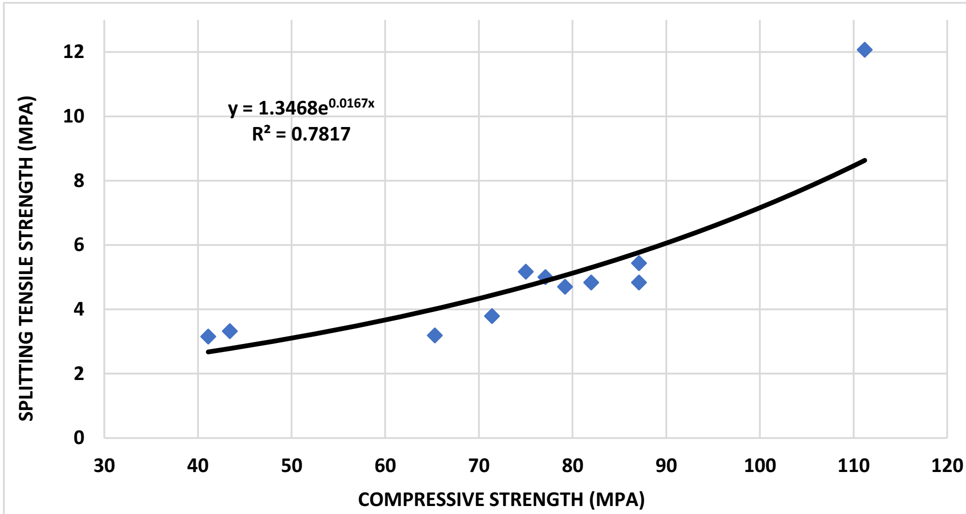


Figure 14: The relationship between compressive strength and tensile strength of NS-containing concrete [86,156–160].

strength even after 90 days of curing, and this trend was unaffected by the duration of curing. The impact of nano-TiO_2 and NS additions on the flexure strength of pavement concrete was studied by Onaizi *et al.* [155].

Besides, a relationship was found between compressive strength and splitting tensile strength, as shown in Figure 14, and compressive strength and flexural strength, as shown in Figure 15.

4.2 NF

Cobalt ferrite ($CoFe_2O_4$) is a well-hard magnetic mineral with modest saturation magnetization and high coercivity. Nano-$CoFe_2O_4$ is a good choice for magnetic recording applications because of these features, as well as its strong anisotropy, outstanding hardness, and great physical and chemical stability [164,165]. NF has attracted attention because of several characteristics, including a huge surface area-to-volume ratio and a high aspect ratio. Many methods have been used to make nano-composites of cobalt ferrite, including hydrothermal synthesis, co-precipitation, auto-combustion, citrate gel, and mechanical alloying.

The inclusion of NPs slowed down the development rate of the $Ca(OH)_2$ crystals, as indicated by Ren *et al.* [166]. This decrease was thought to be caused by the large surface area and high reactivity of the NPs in the concrete mix. Incorporating different NPs into the OPC matrix

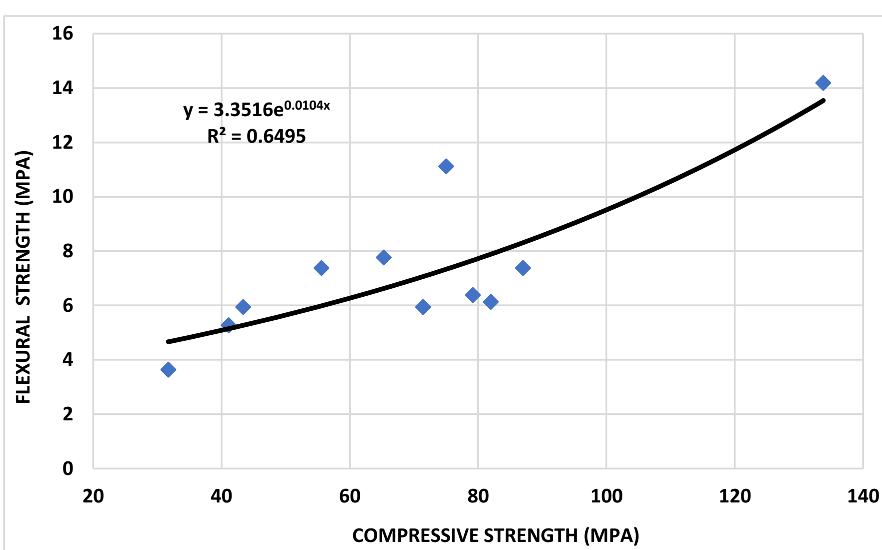


Figure 15: The relationship between compressive strength and flexural strength of NS-containing concrete [86,156–158,161–163].

allowed researchers to slow down the growing rate of CH crystals in the simulated transition zones, which results in more C–S–H gel and acts as a gap-filling agent in the OPC matrix [167].

Khoshakhlagh *et al.* [168] investigated cement paste's microstructure and compressive strength after adding 1–5% NF. They discovered that adding up to 4% NF improved the microstructure and strength of the material. When a small amount of NF is uniformly disseminated in cement paste, the cement hydrate products deposit on the NF because of their high surface energy during hydration and expand to create a conglomerate with the NF as the "nucleus." Because of their high activity, the NF found as a nucleus in the cement paste will promote and expedite cement hydration even more. Because NF will fill gaps to improve strength as SF does, a nice microstructure can be generated with uniformly distributed aggregation in the case of NF uniformly dispersed condition, as shown in Figure 16. They also expected that because NF benefited not only the cement paste but also the contact between the paste and the aggregates, the strengthening effect of NF in concrete would be amplified.

Oltulu and Şahin [169] examined the single, binary, and tertiary impacts of 0.5, 1.25, and 2.5% of three nano-sized powders of primary cement oxides (NS, NF, and NA) on the water absorption and compression strength of cement mortars comprising 5% SF after 3, 7, 28, 56, and 180 days. Powder interactions in binary and ternary blends were revealed to have adverse influences on mortars' physical and mechanical characteristics. The compressive strength values, on the other hand, vary with age. The best compressive strength and vascular permeability results were obtained with 1.25% NA, followed by 1.25% NS. Torabian Isfahani *et al.* [170] also examined the same characteristics as previously but using FA rather than SF. According to the findings, adding any specific type of oxide powder at 1.25% increased the compressive strength of mortars considerably more than the other ratios, with

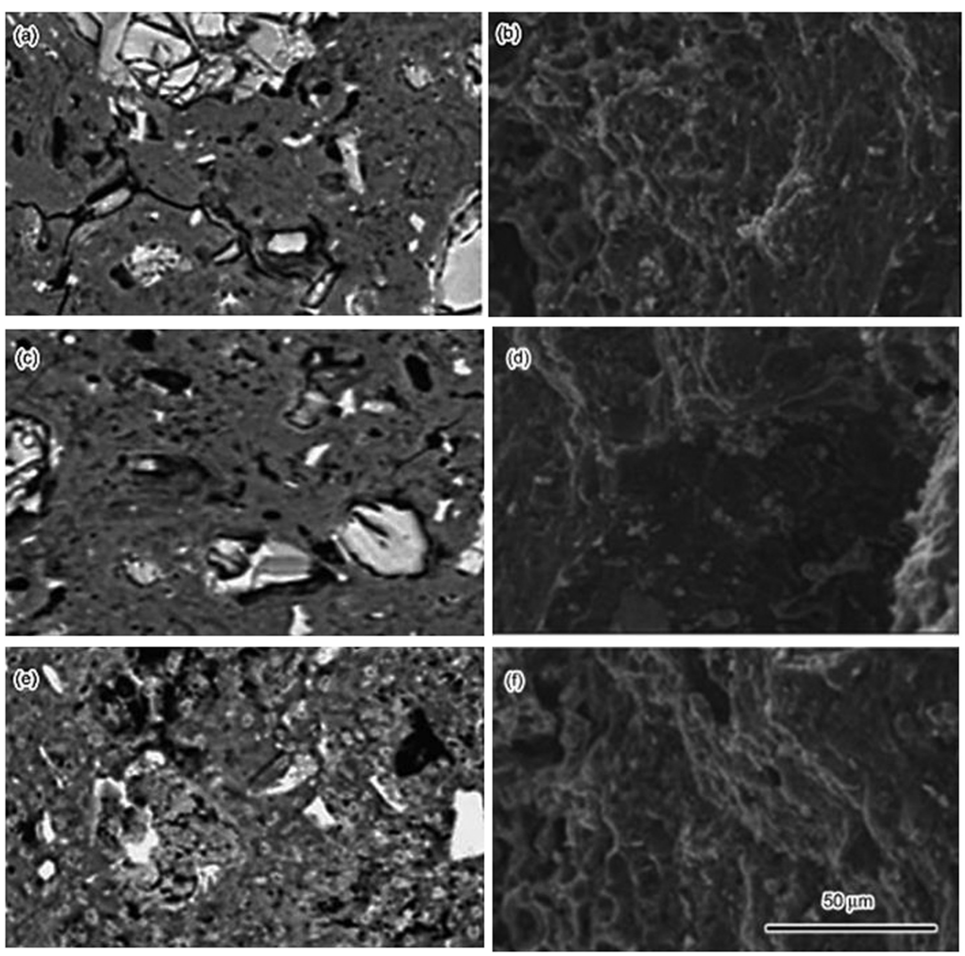


Figure 16: SEM cement pastes with various contents of NF at different ages as (a) and (b) for 2 days, (c) and (d) for 7 days, and (e) and (f) for 28 days [168].

1.25% NS providing the best compressive strength and the lowest permeability coefficient, followed by 0.5% NF.

Ivanchik *et al.* [171] investigated the impact of substituting 1, 2, 3, 4, and 5% of the weight of cementitious materials (SF and cement) with NS and NF on the compressive, splitting, tensile, and flexural strengths of concrete, as well as the ME. Using two types of coarse aggregate, the effect of coarse aggregate form on the mechanical characteristics of concrete incorporating nanomaterials was examined (dolomite and granite). The optimal dosages of NS and NF were 3 and 2%, respectively. Compressive strength and splitting tensile strength improved by 21 and 17%, respectively, while flexural strength and ME rose by 23 and 25%. Trials of concrete containing NS performed better than samples of concrete containing NF at a rate of about 10%. Furthermore, specimens of concrete containing granite outperformed those containing dolomite by a margin of around 10%. To improve workability, SP had to be added to concrete mixtures. The presence of an ITZ between the large responding aggregate or steel and the bulk compound serves as a vulnerable zone because of the minute pores in the cement mortar matrix. Furthermore, a substantial number of CH crystals were produced during the cement–water hydration interaction. CH crystals have a hexagonal structure and can combine to produce an ITZ [90,172–174]. The addition of NF to cement paste could improve its microstructure and strength. A small amount of NF is separated easily in cement paste. The hydrate components of cement, which have high surface energy, deposit on the NF during hydration and develop to create an aggregation with the NF as the "nucleus."

Because of its high activity, the NF found as a nucleus in the cement paste will promote and expedite cement hydration even more. Because NF, like SF, fills gaps to improve strength, a good microstructure can be generated with uniformly dispersed aggregation in the case of NF. Furthermore, because NF enhances the cement paste and the interface between paste and aggregates, the impact of NF in concrete is expected to be strengthened. CSH gel formation could be accelerated if NF acts as a foreign nucleation site [175].

4.3 Other types of NPs

The effect of utilizing 5 and 10% nano-TiO_2 as a partial replacement for cement on the mechanical characteristics of cement mortar was investigated by Meng *et al.* [176]. They discovered that the strength of cement mortar grew dramatically as it aged, whereas the fluidity and strength of the mortar dropped noticeably as it aged. The main explanation for the improvement in strength appeared to be the decline and alteration of the nucleus function's orientation index rather than the increased amount of hydration products. They discovered that enhancing the amount of crystalline CH at the early stage of hydration by up to 3.0% wt nano-titanium (NT) could speed up the development of CSH gels. Wang *et al.* [177] found that when FA and cement paste are mixed with NS, the resulting material is more compact, homogenous, and has a denser microstructure. In the early stages of hydration, this causes a decline in porosity and an enhancement in mechanical strength. To withstand chloride and sulfate assault, Li *et al.* [178] studied the impacts of NS and SF separately and then combined them. As a result, concrete specimens' mechanical characteristics and resistance to water permeability have improved. Chen *et al.* [179] investigated the influence of NT on the microstructure of blended cement pastes as well as mortar compressive strength. The addition of tiny doses of NT to the diet at an early age was found to considerably improve the degree of hydration. The total porosity of NT mixed pastes was reduced, and the pore volume was reduced. Furthermore, using NT increased mortars' microstructure and compression strength at an early age. Li *et al.* [180] investigated the effect of NT on concrete surface smoothness and attempted to create a self-cleaning surface. They discovered that by speeding up the hydration and plugging the nano-pores, adding NT to concrete reduced the surface roughness to 3.5–11 nm and produced an ultra-smooth surface. The incorporation of NT into cementitious materials significantly enhances their strength development and overall performance. Various studies have demonstrated that NT contributes to improved mechanical properties, hydration processes, and microstructural densification. The following sections detail these impacts – enhanced mechanical properties especially compressive strength. The addition of TiO_2 NPs can increase compressive strength by up to 18.5% at 28 days. Similarly, NTs have shown a 12.4% increase in compressive strength when used in hybrid composites [87]. Flexural strength: TiO_2 also improves flexural strength, with significant increases observed in both short- and long-term curing periods [181]. NTs facilitate faster hydration of cement phases, leading to earlier strength gains. For instance, nitrite/nitrate-based accelerators enhance the hydration of tricalcium silicate, improving early strength in cold conditions [182]. The presence of NTs leads to a denser microstructure by providing additional nucleation sites for CSH formation, which is crucial for strength development [181]. The use of NTs is economically feasible, with cost increases remaining below 15% for enhanced performance in applications like pedestrian pavements [183]. While the benefits of NTs in cementitious materials are substantial, it is essential to consider potential drawbacks, such as the risk of cracking due to excessive heat of hydration or adverse effects from high concentrations of NTs. Balancing these factors is crucial for optimizing the use of NTs in construction materials.

Li *et al.* [101] explored the role of adding 3, 5, and 7% nano-Al_2O_3 on cement composite mechanical characteristics. They discovered that NA mostly functions as a superfine aggregate, filling the ITZ of cement and sand as well as some capillaries in the matrix, as shown in Figure 17. The ME and compressive strength of the mortar was enhanced as a result. At 28 days, adding 5% NA raised the ME of the mortar by 143%.

In varying amounts, nanomaterials are utilized to replace cement. Table 2 shows the many types and qualities of nanomaterial particles that have been described in the literature. The mechanical parameters of numerous types of concrete incorporating nanomaterials are outlined in Table 2, including splitting tensile strength, flexural strength, and compressive strength.

5 Durability performance

5.1 Durability performance of nanoparticle concrete

Various attempts to improve the durability of concrete have been made throughout history, with the use of nanomaterials in concrete being one of the most promising areas receiving attention in recent years. Although most nanomaterials used to improve concrete characteristics have been restricted to laboratory settings, further commercial and large-scale applications are projected to develop in the future years. This study looked at the various types of nanomaterials that have already been used in concrete and their effects on its durability.

Hongjian *et al.* [191] studied the durability of concrete with NS at doses of 0.30 and 0.90%. One of the durability tests was a chloride penetration test, which involved submerging a 100 mm cylindrical specimen in 185 g/L liquid for 56 days. The bottom and circumferential surfaces of the cylinders were coated with epoxy to guarantee unidirectional chloride ion movement into concrete *via* the top surface alone. Powder specimens were taken from the test piece at varying depths from the top surface, and the chloride ion concentration was calculated in accordance with NT build 443 [192]. Concrete was shown to be more resistant to chloride inspired by the ion's driving mechanism when 0.3% NS was added. The chloride resistance was not raised further at a 0.9% dose because of the presence of NS agglomerates. As a result, agglomerates appear to have a stronger influence on chloride ion transport in concrete.

According to Li *et al.* [193], the permeability of 5% of NS and 5% of MS was improved by 23 and 13%, respectively. Notably, the combined implications of NS and MS on water absorption rate were often more pronounced than those of either ingredient alone.

El-Feky *et al.* [194] investigated the bond strength of concrete with a high NS content (up to 4.5%) that had been exposed to corrosion. The tensile and bond strengths, as well as the permeability of NS concrete, were all tested. The results showed that using NS to protect metals from corrosion had the best physical, chemical, and physio-chemical characteristics. The addition of 4.5% NS reduced the permeability of concrete to nearly half that of the control mix. It also increased concrete's residual bond strength after being exposed to corrosion and reinforcing bar pullout.

Tobbala *et al.* [195] investigated the bond strength after being subjected to high temperatures of up to 600°C in the

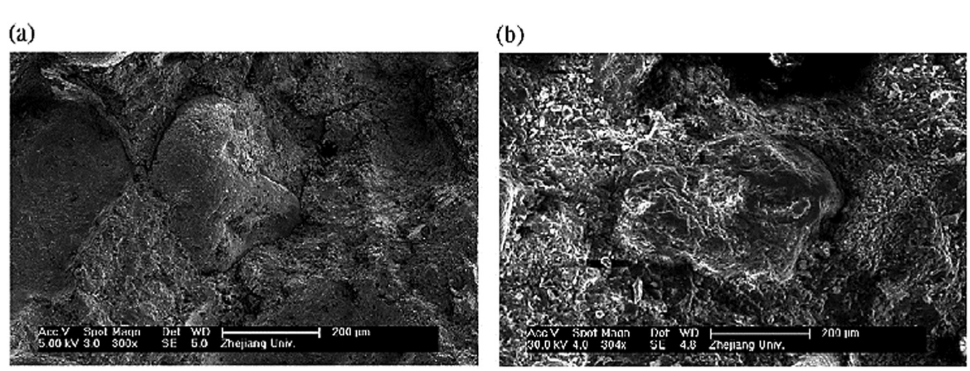


Figure 17: SEM of mortars at 28 days of age with (a) 0% NA and (b) 5% NA [154].

Table 2: Summary of previous research using different types of nanomaterial

Refs	Type of composite	NPs (%)	Compressive strength	Splitting tensile strength	Flexural strength
[170]	OPC	NS substituted cement by 0.5, 1, and 1.5% by mass	Enhanced	—	—
[171]	OPC	NS was employed as a partial substitute for cement at 5–20% by weight	Enhanced	—	—
[176]	OPC	NT and NS substituted cement with 1, 3, and 5% by weight	Enhanced	—	Enhanced
[184]	OPC	NS was repurposed *via* cement-based substances weighing 6 and 12%, respectively	Enhanced	Enhanced	—
[185]	OPC	Nano-clay (NC) and NS substituted cement at diverse contents going from 0.5% up to 10% by weight	Enhanced	—	
[186]	Self-compacting concrete	Cement substituted with 1, 2, 3, 4, and 6% of weight-based nano-TiO_2	Enhanced	—	—
[187]	Concrete pavement	Substitution of NS for 3, 5, and 7% of cement, as well as 1, 2, and 3% of nano-Al_2O_3 by weight	Enhanced	—	—
[188]	Self-compacting concrete	0.25, 0.5, 0.75, and 1% of the cement was replaced with NC	Enhanced	Enhanced	
[180]	Recycled aggregate concrete	Replacement of nano-limestone and NS with cement at 3 and 1% by weight	Enhanced	—	—
[189]	Ultra-high strength concrete	Cement was substituted with 0.50, 1, 1.65, and 2% of NS and 0.15, 3.25, 4.95, and 6.55% of nano-$CaCO_3$ by weight	Enhanced	—	Enhanced
[86]	HPC	NS substituted cement with 0, 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0% by weight	Enhanced	Enhanced	Enhanced
[127]	UHP concrete	NS substituted for 0.5, 1, 1.5, and 2% of the cement weight, while nano-limestone substituted for 1, 2, 3, and 4% of the cement weight	Enhanced	—	Enhanced
[130]	UHP concrete	Nano-metakaolin substituted 1, 3, 5, and 9% of the cement by wt	Enhanced	—	—
[190]	High-volume FAconcrete	Nano-$CaCO_3$ was used at amounts of 1, 2, 3, and 4% by mass of cement	Enhanced	—	—

absence of a hybrid coating of zinc-rich epoxy and NS. The remaining bond strength of coated and zinc-rich epoxy uncoated samples in the combination containing SF was greater than the reference mix without SF at temperatures up to 400°C.

Shekari and Razzaghi [196] investigated the influence of constant NF, NT, and NA concentration on the durability of chloride-penetrated specimens and concrete permeability. The findings revealed that NPs were quite efficient in boosting the concrete's durability. The addition of NF with a 1.5% binder reduced water absorption from 0.09 to 0.5% and chloride penetration by 20%.

According to Tabish *et al.* [143], adding 2% NS decreased capillary water absorption by 58% compared to a control combination. They also found that the depth of absorbed water decreased more noticeably with longer test intervals, such as 72 h. There are fewer capillary holes and better permeability resistance due to NS's reduced water absorption. However, since NS agglomeration increases with increased NS concentration, water penetration depth improves [197].

Florean *et al.* [198] found that when the w/c ratio decreases, the impact of NS on chloride diffusion and permeability rises. They found that in situations when w/c is low, the increasing importance of NS in speeding up cement hydration is the culprit. Substituting 3 and 6% NS for cement particles greatly increased the permeability of concrete, as shown by Said *et al.* [184]. They claim that NS is effective because it enhances the pore structure of the cement matrix.

Maruthapandian *et al.* [199] reported that the possibility of solid-state reference electrodes (SSRE) being stable in an exceedingly alkaline atmosphere for deterioration observed within reinforced concrete structures was examined. The manufactured SSREs were examined in both the presence and lack of chloride ions in a water-soluble sol to confirm its probable stability. The analysis revealed that the produced SSRE exhibited a consistent potential in the alkaline substrate throughout its inclusion of chloride molecules. The constructed SSRE was utilized to evaluate steel rebar corrosion in alkaline sol and actual concrete medium, and the findings were contrasted with a typically saturated calomel electrode (SCE). The outcomes show that, like SCE, the built SSREs can discriminate between the passive and active states of steel rebar.

The density and flow table were calculated during the initial "fresh" phase. At 28 and 56 days, the compression and flexural strengths were tested. After 56 days, we also looked at AAM's ability to absorb water, its sorptivity, and its resistance to chemicals (sulfuric acid, magnesium sulfate, and sodium chloride). NS was added to the AAM mixes with and without polypropylene fiber and cured at room temperature. Alkaline-activated solutions were made by mixing 1.5–2.5 parts sodium silicates with 1.5–2.5 parts sodium hydroxide (NaOH). Using a proportion of 2.5, the results reveal improvements in workability, water absorption, and sorptivity. However, using fiber and NS together had an unfavorable effect. However, a ratio of 1.5 yielded superior toughened performance. Sulfuric acid, magnesium sulfate, and sodium chloride all decreased the flexural and compressive strengths when fiber and NS were used together. In contrast, tests conducted on materials exposed to salt chloride showed an increase in compressive strength.

5.1.1 Fire resistance of NS and NF concrete

The effect of combining colloidal NS with FA as a partial cement substitute on the fire resistance of mortar specimens exposed to temperatures ranging from 400 to 700°C was investigated by Ibrahim *et al.* [200]. The samples were heated at a rate of 9°C/min for 2 h before cooling to ambient temperature at a comparable rate before the compression and flexure testing. The specimens were tested using SEM and XRD, and their porousness was raised by applying the BET approach to analyze the specimen's response after exposition to elevated temperatures. The crystalline nature of the calcium silicate, CH, and silica peaks can be easily seen in XRD graphs; however, amorphous materials such as CSH cannot be detected right away. The compressive and flexural strength findings demonstrate that the mortars had a steady microstructure situation after being subjected to temperatures up to 400°C, while temperatures above 600°C resulted in the hydration products decomposing considerably, resulting in a substantial loss of material strength [201,202]. While the temperature was 400°C, the addition of NS enhanced the compressive strength of the mortar, but it decreased the compressive strength when the temperature was 700°C. They also found that adding NS to the pore size distribution significantly reduced the pore size distribution after exposure to high temperatures. Figures 18 and 19 show the observations of the SEM and XRD for the control and (NS + FA) samples, respectively. CSH and CH were easily distinguishable in the control specimen before being exposed to high temperatures. NS surrounded FA and hydration products in (NS + FA) specimens, contributing to increased CSH levels. The hydration products were bound together with FA by the high reactivity of NS, which served as a nucleating point.

Bastami *et al.* [203] investigated the impact of high temperatures on the compressive and tensile strength of

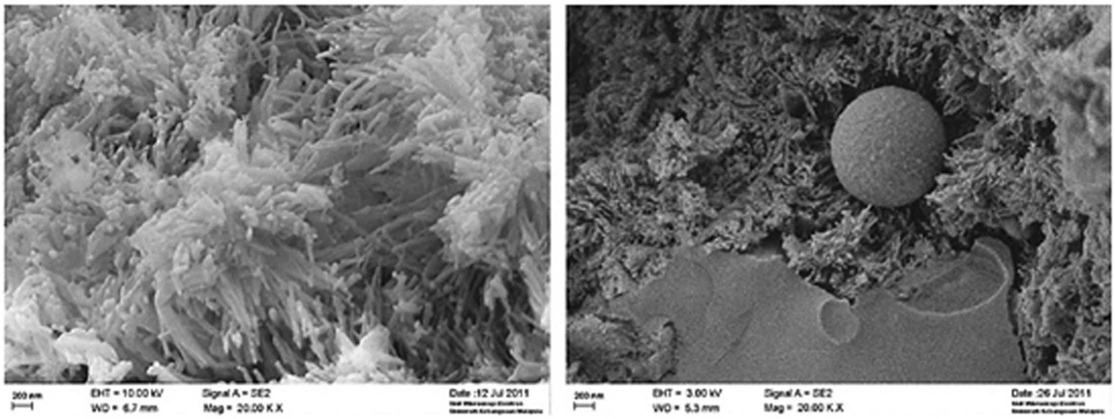


Figure 18: SEM of samples at diverse temperatures [200].

SF concrete, as well as weight loss. Eight 500 kg/m^3 cement blends were modified with 7 and 12% SF in combination with 0, 2, 3, and 4.5% NS as a substitution for each proportion of SF. To assess mechanical characteristics, concrete samples were heated to 450, 600, and 800°C at a rate of 20°C per minute. According to the findings, adding up to 4.55% NS to the mix increased residual compressive and tensile strengths while decreasing bulk. Although water evaporates at higher temperatures, there was no discernible influence on the surface of warmed specimens up to 450°C, and loss of mass was negligible. Significant fractures and partial spalling emerged when the temperature reached 600°C, and when the temperature reached 800°C, the aggregates fragmented and lost their stability. Over 600°C, all heated specimens deteriorated. The compressive strength of NS-containing concrete heated to 600–800°C was reduced even further. NS outperformed SF in terms of enhancing heated samples' residual compressive and tensile strength. The introduction of NS boosted the compressive and tensile strength of concrete. For samples that have been cured for 28 days, Heikal *et al.* [204] investigated the fire resistance of cement-based materials, including 0–6% NS. The specimens were burned at 250, 450, 600, 800, and 1,000°C for 3 h at a rate of 3°C per minute before even being cooled to ambient temperature in the furnace. The compressive strength of the paste of cement was improved with an NS content of up to 4%. The compressive strengths of 4% NS paste were the greatest at all thermally treated temperatures up to 1,000°C, showing that it had the strongest fire resistance of all composite cement pastes. It also had the highest bulk density ratings, which helped to reduce crack development and strength loss. Raising NS to 6% had a detrimental influence, causing the findings to be reversed.

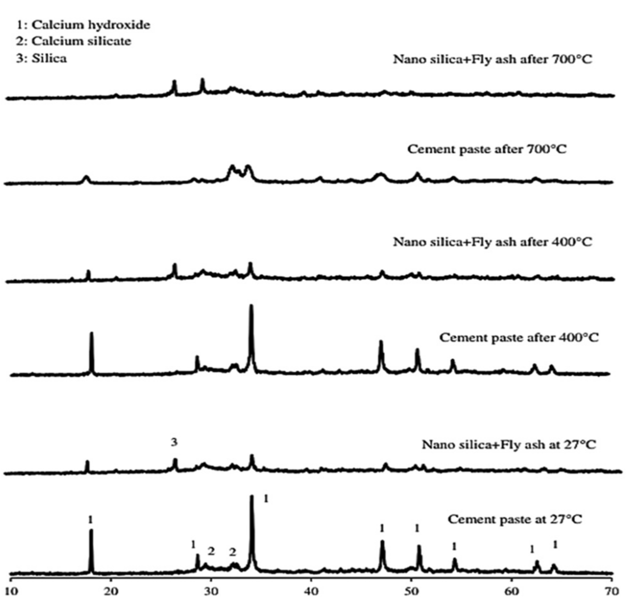


Figure 19: XRD of pastes before and after exposure to fire [200].

The effect of adding 1–4% NF on concrete's resistance to increased temperatures of 200 and 400°C was investigated [205]. Heating resulted in a 20% decline in compressive strength at 200°C and a 30% loss at 400°C. The analysis indicates that the NF had a stronger fire resistance and a lower compressive strength decline of 1%.

Tobbala [138] evaluated the influence of fire on the compressive strength of NS and NF-containing concrete. When 15% SF was introduced to the compressive strength of the control mixture, the reduction reached 6% and then rose to 14.8%. As seen in Figure 20, these declines increased as the NS or NF content rose, reaching 20.4 and 25% at 1 and 2% NS and 18.4 and 39.05% at 1 and 2% NF, respectively. Nevertheless, the compression strength of NF and NS concrete is greater than that of the control specimen and MSF concrete.

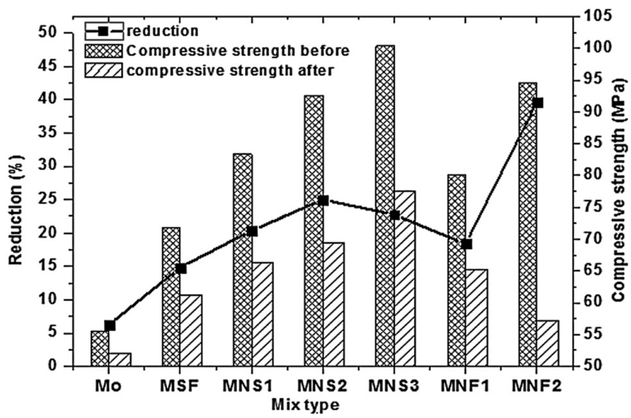


Figure 20: Effectiveness of fire on preparing nano-silica concrete *versus* NF concrete mixture compressive strengths and reduction percentage [138].

5.1.2 Resistance of nanomaterial concrete to chloride and sulfate attack

Negative ion diffusion in saltwater is considered a factor in many of the concretely awful situations observed along the coast. Large sequences of sulfate and chloride ions found in coastal areas have a deleterious impact on concrete's prolonged and immediate durability. The chloride ion is the most significant factor in reinforced concrete corrosion. The formation of chloride around the steel bars influences the propensity for degradation and penetration. The supplementary materials may provide an effective concrete substitute for chloride intrusion resistivity. Numerous additional adhesion chemicals are employed to minimize hydrated temperature on coastal structures, giving them a long lifetime. Inactivation of sulfate ions *via* ingestion and capillary absorption is an extra option in groundwater. A few sulfate ions in saltwater migrate out, decreasing compressive strength. Calcium sulfate reacts with C_3A to generate ettringite and gypsum, which help to reinforce the concrete [206].

Calcium sulfate interacts with C_3A to form ettringite and strengthen the concrete. Sulfate resistance could be achieved by using partial replacement components for cement. The SCM can lower CH and produce more C–S–H by breaking down the detrimental effects of magnesium sulfate [207]. The compression strength of concrete was boosted by 15% of MS with a 26% rise in the 4-week duration [208]. Increased concrete compressive strengths can be achieved by replacing the NS admixtures with a larger proportion. With a decline in the diameter of the mortar porosity, hydration evolvement, and the production of an adverse crystal period, it gains more protection. Sulfate protection against hostile ions could be achieved with a 2% partial substitution of NS [209–211]. Singh *et al.* [212] investigated mortars using 0–10% NS cement substitution. The NS shows decreased sulfate damage during a 154-week immersion in a 5% $MgSO_4$ sol. After a 2-year immersion stage, the control mortar showed a 90 and 95% decline in mortar formation, respectively, with a 5 and 10% replacement of NS. The use of NS to replace concrete has improved its durability and resilience to chlorine attacks [184,213,214]. NPs and pozzolans pave the path for industrial application in salt manufacturing, and NPs improve concrete performance in harsh conditions [215].

Adding NS increased sulfate resistance, which in turn reduced strength loss after a sulfate assault, as stated by Li *et al.* [178]. The effect of NS on C3S's vulnerability to sulfate assault was investigated by Guo *et al.* [216]. Each sample was submerged in a sodium sulfate solution that contained 5% to mimic the circumstances of the municipal water supply. The samples were analyzed at 28, 120, and 180 days after being soaked and dried in Na_2SO_4 at 5% wt. Sulfate attack on C_3S was shown to be retarded, and its resistance to sulfate attack increased throughout modest amounts of NS. A shift in the samples' C–S–H gel, brought about by the lower CH content, is responsible for the increased resistance.

Nasution *et al.* [217] investigated the performance of nanomaterial-concrete resistance to sulfate attack. The resistivity of corrosion of concrete samples, including NS, is substantially superior to that of control specimens after storage in 50 g/L Na_2SO_4 sol for 28, 56, 90, 120, 150, and 180 days. As a result of the cementitious mass expanding, cracking, crumbling, and eventually softening, the strength of the concrete is lost [197]. The majority of previous studies found that adding different NPs to concrete lessens the effects of sulfate and chloride ion attacks [218–220]. This happens because NPs possess an enormous surface space and magnificent reactivity, increasing their reaction with $Ca(OH)_2$, making concrete more resistant to chemical attacks. The reactive SiO_2 in NS can interact with the dissolved $Ca(OH)_2$ in concrete, forming an additional CSH, which increases the concrete's chemical stability and structural hardness while also increasing its impermeability. Furthermore, the nanomaterial might lower the level of Al_2CaO_4 in cementitious substances, resulting in an enhancement in concrete's sulfate resistance. The specimen's mass and strength were both reduced. The resilience of OPC against acid degradation is shown in Figure 21. After 180 days of immersion in sulfuric acid sol, mortar specimens' strength decline was 6.21%, while the strength loss of concrete samples was 9.95%.

Tobbala [138] investigated the chemical resistance of NPs in concrete. The results showed that all the nano-silica

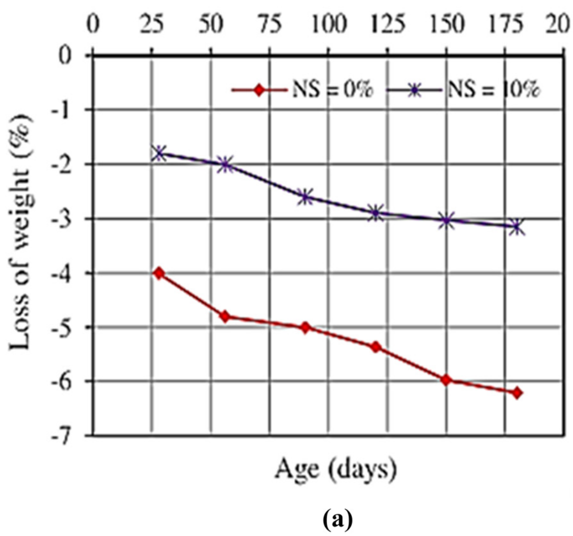


Figure 21: (a) Weight loss and (b) strength loss [217].

concrete and NF mixes improved over time despite exposure to chloride. However, their growth was slightly reduced compared to that of those cured in water because of the chloride effect. As shown in Figure 22, raising the amount of NF or NS with minor concentrations helped minimize chloride's effects.

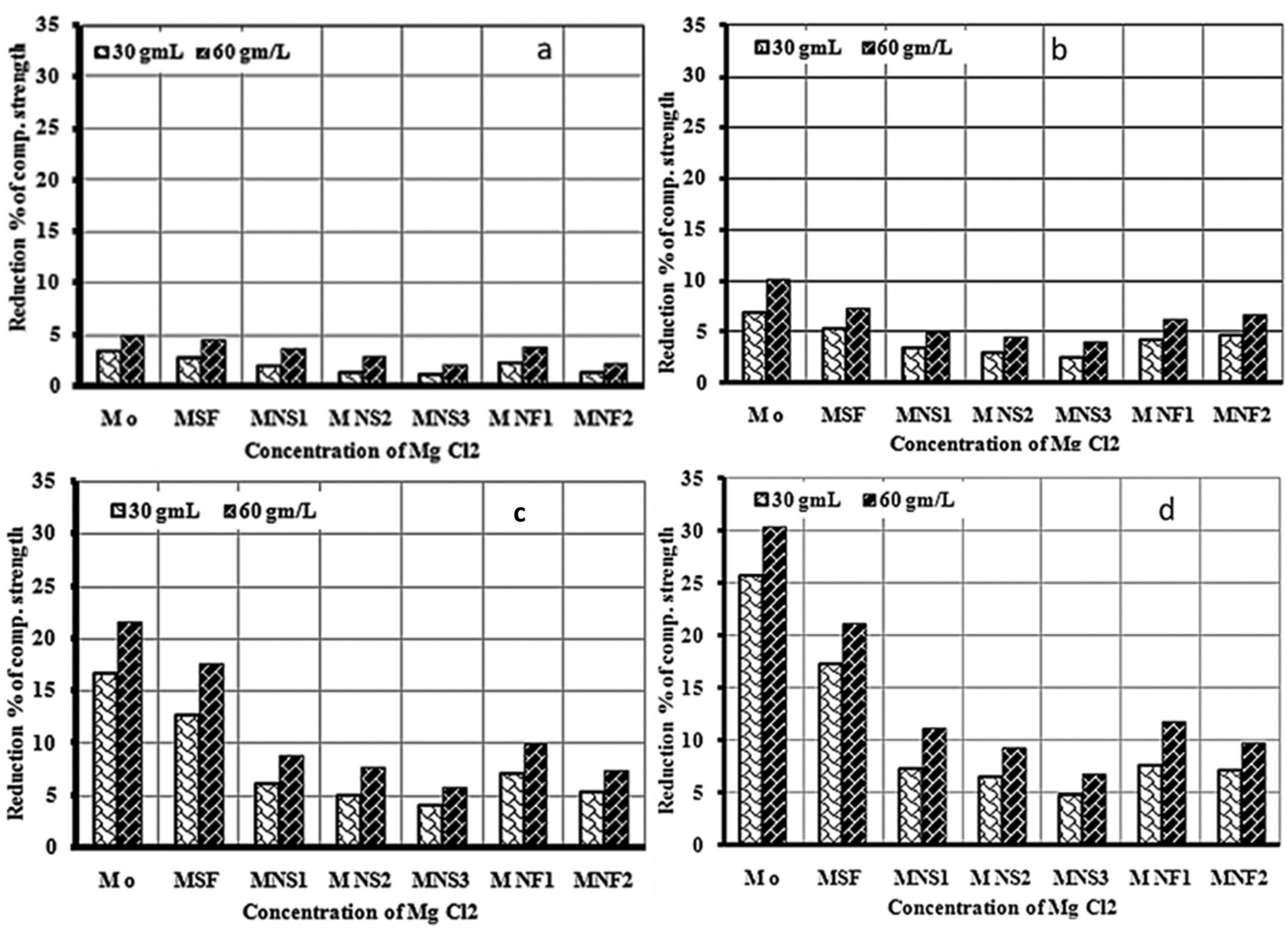


Figure 22: The decline present in fc of nanoparticle mixtures because of curing in hostile $MgCl_2$ solution regarding: (a) 28 days, (b) 56 days, (c) 120 days, and (d) 180 days, relative to their water cure [138].

Feng *et al.* [221] reviewed the effect of nanomaterials on the durability of concrete and concluded that nanomaterials added to concrete increase its resistance to sulfate assault. The use of nanomaterials in concrete increases its resistance to sulfate attack and decreases its permeability to chloride ions while also enhancing its resistance to thawing and freezing and decreasing compressive strength.

5.2 Durability performance of cement-based materials incorporating NPs

The use of NPs increases the durability of cement composites because of their smaller size, which optimizes the composite's nano and microstructure. Additionally, the pozzolanic characteristics of NPs used in cementitious composites result in improved product output and microstructure densification [174,222–226]. The interaction of nanomaterials with $Ca(OH)_2$ in a concrete mixture composite's pore sol resulted in extra $Ca(OH)_2$ formation. In the presence of nanomaterials, the hydration action of Portland cement was also increased, resulting in the formation of extra $Ca(OH)_2$ [227–229].

The durable nature of cement composites is characterized by their willingness to resist damaging pressures in the environment to which they are subjected. The quantity and simplicity with which degrading particles and liquids penetrate concrete composites affect their longevity. In light of their nanoscale definition, nanomaterials may function as pore fillers among cement particles, leading to a more high-density structure and increased resistance to the entrance of any dangerous components [230–232]. Furthermore, most nanomaterials' pozzolanic nature enables particles to interact through $Ca(OH)_2$ inside the pore system of cementitious composites and generate extra CSH, causing the composite's microstructure to density [233–235]. The effect of various forms of nanomaterials used in cementitious composites on their related performance. The incorporation of nanomaterials typically leads to pore refinement and, consequently, decreased permeability. However, there are other benefits to employing these NPs. Also, the incorporation of nanomaterials typically results in pore refinement and, as a result, declining permeability.

Green concrete's (GC) mechanical characteristics and durability are also enhanced by the use of nano-cotton and nano-palm leaves. Therefore, manufacturing eco-friendly, high-strength GC mixtures out of broken granite and agricultural waste NPs is both technically and environmentally viable. Green mixes concrete samples with a whole binder ingredient (BM = 436 km/m^3), in particular (M_{C3P3}), (M_{C5}), and (M_{P5}) that incorporate (3% NP + 3% NC), and (5% NP + 5% NC), are superior to reactive powder mixes with BM = 1,090 km/m^3 in terms of mechanical characteristics and durability. Adding either NC or NP, or both, to an M_{C3P3} mixture at room temperature will increase the fc of M_{SF} by up to 101 MPa after 28 days and 117 MPa after 56 days. Binder concentration increases about 435–1,090 kg/m^3 containing 3% NP or NC did not significantly improve mechanical characteristics but did worsen water permeability, high-temperature resistance, and thermal gravimetric analysis. In addition, the permeability test and an 800°C heat treatment also resulted in specimen fractures. At temperatures as high as 400°C, the introduction of (3% NP + 3% NC) increases compressive strengths by around 106 MPa. When used at 3% NC, compressive strength increased by 158% at 800°C, making it the most effective. In addition, when exposed to 800°C along with the water pressure, the specimens collapsed. The MC3P3 composite possesses the highest hardened properties and thermal resistance, withstanding temperatures of as high as 350°C. Comparable mechanically and thermally to MC_3P_3 and MC_5 mixtures, MC_3 is the most powerful at temperatures exceeding 800°C [236].

6 Economic and environmental effects of using NPs in concrete

The incorporation of NPs in concrete is a burgeoning trend within the construction sector, attributed to their capacity to improve both the economic and environmental efficacy of concrete. NPs, including NS, CNTs, and nano-titanium dioxide, exert diverse impacts on concrete, impacting its durability, strength, sustainability, and cost. There are diverse nanoscale materials and their multifaceted uses in sophisticated technology. Nanotechnology may be pivotal in ushering in a new era of construction, enhancing comprehension of the properties of building materials [155,202]. Due to significant scientific advancements in nanoscience and nanotechnology, including microscopy instruments and materials, it is now feasible to utilize the distinctive characteristics of nanoscale materials to improve the essential properties of traditional materials (such as paints, concrete, glass, wood, metals, and plastics) or to repurpose waste materials like coal byproducts, rice husk ash, waste ceramics, and waste glass. Currently, nanomaterials are utilized across several sectors and applications, including the production of steel, glass, and ceramics, as well as in coatings for windows and roofs, and in the fields of medicine and water treatment [237]. The progression of nanotechnology and nanomaterials facilitates the integration of novel attributes into the essential composition of materials, potentially leading to innovative solutions for concrete durability challenges and the development of future structures that could substantially lower service and maintenance expenses [238]. Reports indicate that numerous items derived from nanotechnology possess unique features that can significantly transform current procedures in the building sector, resulting in enhanced design and planning concepts [239]. Nanostructures of SiO_2, Al_2O_3, TiO_2, Ag, and Cu have various applications in covering building components such as floors, toilets, and roofs for waterproofing, corrosion mitigation, and UV radiation protection. Numerous studies on green building technology indicate that paints including Ag and Cu NPs exhibit enhanced antibacterial characteristics. Furthermore, plastics augmented with CNTs exhibited superior mechanical, thermal, and electrical properties. Additionally, CNTs with isodal or cylindrical nanostructures (exhibiting length-to-diameter ratios of up to 132,000,000:1) possess remarkable properties that render them valuable in nanotechnology, electronic and optical devices, material science, and various other applications [240]. Nanomaterials exhibit self-cleaning and thermal insulation properties when applied to glass window panes (silica aerogel), reducing heat flow in elevated temperatures and regulating heat transfer through the window glass. Through the straightforward modification of material properties utilizing sophisticated nanotechnology, nanoclay can be extensively employed in the construction industry at significantly reduced costs, hence enhancing economic efficiency and sustainability in building practices. The distinctive structure and significant silicate content of morillonite clay render it a suitable material for use as a cement substitute [241]. Moreover, nanostructured composites of steel and ceramics can offer enhanced wear resistance and strength. Furthermore, incorporating NPs into concrete can enhance its qualities and performance. Most research examining the application of nanostructured materials in concrete demonstrated significant improvements in early mechanical strengths and overall bulk properties [82].

6.1 Economic impacts

The incorporation of NPs enhances the longevity of concrete by increasing its resistance to cracking, corrosion, and abrasion. This decreases maintenance and repair expenses throughout the lifecycle of a construction. Ultimately, the economic advantage arises from diminished repair requirements and the extended lifespan of concrete structures [138]. NPs can substantially enhance the mechanical properties of concrete (*e.g.*, compressive strength, flexural strength, and tensile strength) even when utilized in minimal quantities. A modest increase in cost can significantly improve the performance of the concrete [195]. Given that NPs are frequently efficacious in minimal amounts, their expense may be mitigated by the decreased necessity for conventional materials (such as cement). Incorporating NS or other NPs facilitates a decrease in cement content, hence conserving material expenses and mitigating environmental impact [242]. Certain NPs, like nano-clay or CNTs, augment the workability of concrete, facilitating handling, pouring, and molding. This may lead to expedited construction durations and reduced labor expenses. Nanotechnology facilitates the creation of specialized concrete formulations for distinct applications (*e.g.*, self-healing concrete, high-strength concrete for specialized projects, or concrete with improved thermal properties), thereby broadening market prospects and the potential for higher-value products [202].

6.2 Ecological impacts

The manufacture of conventional Portland cement substantially contributes to CO_2 emissions. Substituting a fraction of cement with NPs (*e.g.*, NS) diminishes the cement requirement, hence reducing the overall carbon footprint of concrete manufacturing. Additionally, certain NPs (such as NS) are sourced from waste materials (including rice husk ash), thereby enhancing sustainability [243]. NPs can augment the energy efficiency of concrete by improving its insulating characteristics. Concrete augmented with CNTs exhibits enhanced thermal conductivity, hence increasing the energy efficiency of structures and diminishing the necessity for energy-consuming heating and cooling systems. Certain NPs are sourced from industrial by-products or recycled materials, like FA, SF, or agricultural waste. This not only mitigates the environmental impact of concrete manufacturing but also facilitates the utilization of waste materials that would otherwise be disposed of in landfills [202,244]. Improved performance in NPs enhances concrete's resilience against severe environmental factors, including freeze-thaw cycles, seawater, and corrosive chemicals. This enhanced resilience can prolong the lifespan of concrete in severe conditions, minimizing the necessity for frequent repairs and decreasing overall resource utilization [245]. The superior features conferred by NPs, including augmented strength and durability, facilitate the construction of thinner concrete structures that maintain or exceed existing strength levels, resulting in decreased material consumption. This mitigates the demand for raw materials, so further diminishing the environmental effect of the building sector [246].

6.3 Obstacles and factors to consider

Notwithstanding the enduring economic and environmental advantages, the production and integration of NPs into concrete mixtures might be costly, particularly for extensive construction endeavors. This may restrict their extensive application, particularly in economically constrained areas or initiatives [247]. There are persistent apprehensions regarding the possible environmental and health hazards linked to NPs. Further research is required to understand the long-term consequences of NPs on human health and ecosystems. This may result in regulatory constraints that could affect the implementation of nanotechnology in concrete [132]. The incorporation of NPs in concrete necessitates a high level of precision to guarantee uniform outcomes, particularly in extensive applications. The absence of established methods for integrating NPs into concrete mixtures may hinder wider use [248].

7 Conclusions

The incorporation of NS and NF in sustainable concrete can lead to improved mechanical properties such as strength and durability by enhancing the microstructure and chemical composition of the material. NS, through its pozzolanic reactions and reduction of porosity, bolsters the compressive and flexural strength of concrete while enhancing its resistance to chloride ion penetration and corrosion. NF, acting as a filler material, improves packing density and increases compressive strength and toughness. These advancements not only fortify the structural integrity of concrete but also enhance its durability in harsh environments by mitigating issues like sulfate attack and alkali–silica reaction. Ultimately, these innovations pave the way for the development of more sustainable and long-lasting concrete structures that can withstand the test of time and environmental challenges. Based on a review of the relevant research work mentioned above, the following conclusions were drawn:

1) High-purity NS can be prepared successfully from RS and husk ash. On the other hand, high-purity NF can be prepared successfully using the citrate gel auto-combustion method.
2) The behavior of NPs that have been de-agglomerated is influenced significantly by mixing and dispersion, as well as by the utilization of SP. Consequently, the mixing process is critically important to reduce the agglomeration that happens prior to casting the specimens.
3) Nucleation centers or super-fillers were created by the NS particles that were implanted within the concrete. These particles reacted with $Ca(OH)_2$ to produce an extra C–S–H, which in turn led to a notable improvement in the nano-concrete microstructures.
4) It is possible to enhance the compressive strength of a material by raising the replacement ratio of NPs by as much as three to 5%. The integration of NPs that are finely distributed is responsible for this result. These NPs help to promote hydration and form a microstructure that is more compact. In the first phases, it is possible to assert that the majority of the gain in strength takes place. When the threshold is exceeded by NPs, there is a tendency for high concentrations to decrease.
5) An increase in splitting tensile strength has been seen as a consequence of the incorporation of NPs. It is possible that this is because the incorporation of NPs, which leads to an improvement in the microstructure of the blend, has resulted in a healthier microstructure for the mixture.
6) The ME was produced as a result of the chemical reactions between the NPs and the matrix.
7) Even a very small percentage of NS can be used to reduce the amount of water that penetrates the material when compared to the control mixture. A reduction in the depth of water penetration can be achieved by the process of pore refining and the filler activity of NS.
8) The incorporation of NPs into cementitious mixtures will result in decreased chloride ion penetration values because NPs restrict the permeability of cementitious mixtures to chloride ions.
9) The sulfate resistance of the material is increased by filling voids in the concrete binder and enhancing the permeability with NS particles. Additionally, the sample expansion is reduced due to the lower permeability of the concrete. The ability of NS to improve ITZ results in a reduction in overall porosity, which in turn restricts the amount of sulfate ions that can enter the material.

10) With a little quantity of up to 2%, NF can be successfully utilized to improve all of the mechanical characteristics of various types of concrete, particularly the tensile strength, permeability, and durability of the concrete.
11) The incorporation of NPs in concrete holds much promise for enhancing both economic and environmental results. NPs can enhance material qualities, diminish cement requirements, and increase durability, hence contributing to more sustainable and cost-effective concrete. Nonetheless, the elevated initial expenses and issues pertaining to regulation, safety, and uniformity must be resolved to fully harness their potential in the building sector.

8 Recommendations

1) There is a deficiency in the properties of nano-concrete for high concentration ratios, especially the properties of durability, and this should be covered in future research. Also, a few studies indicated that a spike in the proportion of nanomaterials in concrete for more than 3% negatively affects the mechanical properties and durability, which needs to be investigated further.
2) There are conflicting opinions about the type and size of NPs, methods of scattering, dosage, *etc.* Therefore, extensive research must be conducted in this field to set basic standards for practical applications of these NPs in the future.
3) There are current and future trends to replace traditional concrete with nano-concrete for sustainable development. For this reason, there is an urgent need for a deeper investigation into nano-concrete aspects in terms of sustainable development, environmental impact, economic feasibility, energy storage, and greenhouse gas emissions.

Acknowledgments: The authors acknowledge the support of Prince Sattam bin Abdulaziz University through project number 2024/RV/07.

Funding information: This study was supported by Prince Sattam bin Abdulaziz University through project number 2024/RV/07.

Author contributions: Conceptualization, A.-M.M., and B.-A.T.; methodology, T.-I.A., M.-O.B., and D.-D.T.; validation, B.-A.T.; formal analysis, T.-I.A. and T.-I.A.; investigation, M.-O.B., T.-I.A., and D.-E.T.; resources, A.-M.M. and B.-A.T.; writing – original draft preparation, B.-A.T.; writing – review and editing, A.-M.M., T.-I.A. and D.-E.T.; visualization, T.-I.A. and D.-D.T.; project administration, B.-A.T.; funding acquisition, A.-M.M. All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

[1] Asadollahfardi G, Katebi A, Taherian P, Panahandeh A. Environmental life cycle assessment of concrete with different mixed designs. Int J Constr Manag. 2021;21(7):665–76.
[2] Win T, Raengthon N, Prasittisopin L. Advanced cement composites: Investigating the role of graphene quantum dots in improving thermal and mechanical performance. J Build Eng. 2024;96:110556.
[3] Abouelnour MA, Abd EL-Aziz MA, Osman KM, Fathy IN, Tayeh BA, Elfakharany ME. Recycling of marble and granite waste in concrete by incorporating nano alumina. Constr Build Mater. 2024;411:134456.
[4] Abu el-Hassan K, Hakeem IY, Amin M, Tayeh BA, Zeyad AM, Agwa IS, et al. Effects of nano titanium and nano silica on high-strength concrete properties incorporating heavyweight aggregate. Struct Concr. 2024;25(1):239–64.
[5] Liu C, He X, Deng X, Wu Y, Zheng Z, Liu J, et al. Application of nanomaterials in ultra-high performance concrete: a review. Nanotechnol Rev. 2020;9(1):1427–44.
[6] Cotto-Ramos A, Davila S, Torres-Garcia W, Cáceres-Fernández A. Experimental design of concrete mixtures using recycled plastic, fly ash, and silica nanoparticles, Constr Build Mater. 2020;254:119207.
[7] Alhawat M, Ashour A, El-Khoja A. Properties of concrete incorporating different nano silica particles. Mater Res Innov. 2020;24(3):133–44.
[8] Ghosal M, Chakraborty AK. Engineering the properties of nanomaterials for its use in cement concrete. Mater Today: Proc. 2021;46:7502–6.
[9] Ali RA, Kharofa OH. The impact of nanomaterials on sustainable architectural applications smart concrete as a model. Mater Today: Proc. 2021;42:3010–7.
[10] Al-Tersawy SH, El-Sadany RA, Sallam HEM. Experimental gamma-ray attenuation and theoretical optimization of barite concrete mixtures with nanomaterials against neutrons and gamma rays. Constr Build Mater. 2021;289:123190.
[11] Wang Y, Zeng D, Ueda T, Fan Y, Li C, Li J. Beneficial effect of nanomaterials on the interfacial transition zone (ITZ) of non-dispersible underwater concrete. Constr Build Mater. 2021;293:123472.

[12] Öksüzer N, Anil Ö, Aldemir A, Şahmaran M. Investigation of mechanical properties of high-performance hybrid fiber concretes adding nanomaterials using with coarse aggregate. Structures. 2021;33:2893–902.
[13] Datta SD, Sarkar MM, Rakhe AS, Aditto FS, Sobuz MHR, Shaurdho NMN, et al. Analysis of the characteristics and environmental benefits of rice husk ash as a supplementary cementitious material through experimental and machine learning approaches. Innovative Infrastruct Solut. 2024;9(4):121.
[14] Amin M, Hakamy AA, Zeyad AM, Tayeh BA, Agwa IS. Improving the brittle behavior of high-strength shielding concrete blended with lead oxide, bismuth oxide, and tungsten oxide nanoparticles against gamma ray. Struct Eng Mech. 2023;85(1):29–53.
[15] Tayeh BA, Hakamy AA, Fattouh MS, Mostafa SA. The effect of using nano agriculture wastes on microstructure and electrochemical performance of ultra-high-performance fiber reinforced self-compacting concrete under normal and acceleration conditions. Case Stud Constr Mater. 2023;18:e01721.
[16] Raj A, Yamkasikorn P, Wangtawesap R, Win TT, Ngamkhanong C, Jongvivatsakul P, et al. Effect of Graphene Quantum Dots (GQDs) on the mechanical, dynamic, and durability properties of concrete. Constr Build Mater. 2024;441:137597.
[17] Win TT, Prasittisopin L, Nganglumpoon R, Pinthong P, Watmanee S, Tolek W, et al. Innovative GQDs and supra-GQDs assemblies for developing high strength and conductive cement composites. Constr Build Mater. 2024;421:135693.
[18] Sun Y, Liu H, Yang B, Chen K. Structural strain and crack monitoring based on the fluorescence response of graphene quantum dots. Measurement. 2025;242:115800.
[19] Win TT, Prasittisopin L, Nganglumpoon R, Pinthong P, Watmanee S, Tolek W, et al. Chemo-physical mechanisms of high-strength cement composites with suprastructure of graphene quantum dots. Clean Mater. 2024;11:100229.
[20] Rauwel P, Küünal S, Ferdov S, Rauwel E. A review on the green synthesis of silver nanoparticles and their morphologies studied via TEM. Adv Mater Sci Eng. 2015;2015:682749.
[21] Helmlinger J, Sengstock C, Groß-Heitfeld C, Mayer C, Schildhauer TA, Köller M, et al. Silver nanoparticles with different size and shape: equal cytotoxicity, but different antibacterial effects. RSC Adv. 2016;6(22):18490–501.
[22] Shin S, Liu J, Akbar A, Um S. Nanoscale morphological investigation into surface coverage of platinum catalysts by ionomers on vertically aligned carbon nanotube fuel cell catalyst layers. POWER J Power Sources. 2020;455:227953.
[23] Divya S, Praveenkumar S, Tayeh BA. Performance of modified nano carbon blended with supplementary materials in cement composite–An interpretive review. Constr Build Mater. 2022;346:128452.
[24] Cuenca E, D’Ambrosio L, Lizunov D, Tretjakov A, Volobujeva O, Ferrara L. Mechanical properties and self-healing capacity of Ultra High Performance Fibre Reinforced Concrete with alumina nano-fibres: Tailoring Ultra High Durability Concrete for aggressive exposure scenarios. Cem Concr Compos. 2021;118:103956.
[25] Faried AS, Mostafa SA, Tayeh BA, Tawfik TA. The effect of using nano rice husk ash of different burning degrees on ultra-high-performance concrete properties. Constr Build Mater. 2021;290:123279.
[26] Ghanim AAJ, Amin M, Zeyad AM, Tayeh BA, Agwa IS. Effect of modified nano-titanium and fly ash on ultra-high-performance concrete properties. Struct Concr. 2023;24(5):6815–32.
[27] Çevik A, Alzeebaree R, Humur G, Niş A, Gülşan ME. Corrigendum to “Effect of nano-silica on the chemical durability and mechanical performance of fly ash based geopolymer concrete” [Ceram. Int. 44 (2018) 12253–12264]. Ceram Int. 2019;45(11):14479.
[28] Harihanandh M, Viswanathan KE, Krishnaraja AR. Comparative study on chemical and morphology properties of nano fly ash in concrete. Mater Today: Proc. 2021;45:3132–6.
[29] Li D, Song H, Meng X, Shen T, Sun J, Han W, et al. Effects of Particle Size on the Structure and Photocatalytic Performance by Alkali-Treated TiO_2. Nanomaterials (Basel, Switz). 2020;10(3):7153365.
[30] Nayak V, Munawar SM, Sabjan KB, Singh S, Singh KR. Nanomaterials’ properties, classification, synthesis, and characterization 1. Nanomaterials in Bionanotechnology. Boca Raton, FL: CRC Press; 2021. p. 37–68.
[31] Bindhu MR, Umadevi M, Esmail GA, Al-Dhabi NA, Arasu MV. Green synthesis and characterization of silver nanoparticles from Moringa oleifera flower and assessment of antimicrobial and sensing properties. J Photochem Photobiol, B: Biol. 2020;205:111836.
[32] Sobuz MHR, Al I, Datta SD, Jabin JA, Aditto FS, Sadiqul Hasan NM, et al. Assessing the influence of sugarcane bagasse ash for the production of eco-friendly concrete: Experimental and machine learning approaches. Case Stud Constr Mater. 2024;20:e02839.
[33] Zhang P, Wang L, Wei H, Wang J. A critical review on effect of nanomaterials on workability and mechanical properties of high-performance concrete. Adv Civ Eng. 2021;2021:1–24.
[34] Foltynowicz Z, Czajka B, Maranda A, Wachowski L. Aspects of nanomaterials for civil and military applications. Part 1. Origins, characteristics and fabrication methods. Mater Wysokoenergetyczne. 2020;12(1):5–16.
[35] Singh SB. Emerging sustainable nanomaterials and their applications in catalysis and corrosion control. Curr Nanosci. 2021;17(4):540–53.
[36] Wu Q, Miao WS, Gao HJ, Hui D. Mechanical properties of nanomaterials: A review. Nanotechnol Rev. 2020;9(1):259–73.
[37] Mohammed A, Rafiq S, Mahmood W, Al-Darkazalir H, Noaman R, Qadir W, et al. Artificial Neural Network and NLR techniques to predict the rheological properties and compression strength of cement past modified with nanoclay. Ain Shams Eng J. 2021;12(2):1313–28.
[38] Prabhu K, Charai JPM, Hakeem I, Madenci E, Özkılıç Y. A potential review on the influence of nanomaterials on the mechanical properties of high strength concrete. Steel Compos Struct. 2023;48:649–65.
[39] Costa FN, Ribeiro DV. Reduction in CO_2 emissions during production of cement, with partial replacement of traditional raw materials by civil construction waste (CCW). J Clean Prod. 2020;276:123302.
[40] Lu D, Zhong J. Sustainable nano concrete materials and structures. Sustainable concrete materials and structures. Sawston, Cambridge, UK: Woodhead Publishing, Elsevier; 2024. p. 531–62.
[41] Iranmanesh R, Alameri AA, Jassim GS, Abdulkareem Almashhadani H, Adel Lateef D, Jalil AT, et al. Effect of modified nano-graphene oxide and silicon carbide nanoparticles on the mechanical properties and durability of artificial stone composites from waste. Polycycl Aromatic Compd. 2024;44(4):2244–56.

[42] Shah KW, Huseien GF. Inorganic nanomaterials for fighting surface and airborne pathogens and viruses. Nano Express. 2020;1(3):032003.

[43] Hafez RDA, Tayeh BA, Abdelsamie K. Manufacturing nano novel composites using sugarcane and eggshell as an alternative for producing nano green mortar. Environ Sci Pollut Res. 2022;29(23):34984–5000.

[44] Hakeem IY, Alharthai M, Amin M, Zeyad AM, Tayeh BA, Agwa IS. Properties of sustainable high-strength concrete containing large quantities of industrial wastes, nanosilica and recycled aggregates. J Mater Res Technol. 2023;24:7444–61.

[45] Hamada H, Shi J, Yousif ST, Al Jawahery M, Tayeh B, Jokhio G. Use of nano-silica in cement-based materials–a comprehensive review. J Sustain Cement-Based Mater. 2023;12(10):1286–306.

[46] Huseien GF. A review on concrete composites modified with nanoparticles. J Compos Sci. 2023;7(2):67.

[47] Allujami HM, Abdulkareem M, Jassam TM, Al-Mansob RA, Ng JL, Ibrahim A. Nanomaterials in recycled aggregates concrete applications: Mechanical properties and durability. A review. Cogent Eng. 2022;9(1):2122885.

[48] Matalkah F, Ababneh A, Aqel R. Effects of nanomaterials on mechanical properties, durability characteristics and microstructural features of alkali-activated binders: A comprehensive review. Constr Build Mater. 2022;336:127545.

[49] Reis ED, Resende HF, Christoforo AL, Costa RM, Gatuingt F, Poggiali FSJ, et al. Assessment of physical and mechanical properties of concrete with carbon nanotubes pre-dispersed in cement. J Build Eng. 2024;89:109255.

[50] Win TT, Prasittisopin L, Jongvivatsakul P, Likitlersuang S. Investigating the synergistic effect of graphene nanoplatelets and fly ash on the mechanical properties and microstructure of calcium aluminate cement composites. J Build Eng. 2023;78:107710.

[51] Liu C, Chen F, Wu Y, Zheng Z, Yang J, Yang B, et al. Research progress on individual effect of graphene oxide in cement-based materials and its synergistic effect with other nanomaterials. Nanotechnol Rev. 2021;10(1):1208–35.

[52] Sobolev K, Ferrada Gutierrez M. How nanotechnology can change the concrete world. Am Ceram Soc Bull. 2014;84:113–6.

[53] Hassan AA, Lachemi M, Hossain KM. Effect of metakaolin and silica fume on the durability of self-consolidating concrete. Cem Concr Compos. 2012;34(6):801–7.

[54] Aditto FS, Sobuz MHR, Saha A, Jabin JA, Kabbo MKI, Hasan NMS, et al. Fresh, mechanical and microstructural behaviour of high-strength self-compacting concrete using supplementary cementitious materials. Case Stud Constr Mater. 2023;19:e02395.

[55] Saha A, Tonmoy TM, Sobuz MHR, Aditto FS, Mansour W. Assessment of mechanical, durability and microstructural performance of sulphate-resisting cement concrete over portland cement in the presence of salinity. Constr Build Mater. 2024;420:135527.

[56] Tayeh BA, Akeed MH, Qaidi S, Bakar BA. Influence of microsilica and polypropylene fibers on the fresh and mechanical properties of ultra-high performance geopolymer concrete (UHP-GPC). Case Stud Constr Mater. 2022;17:e01367.

[57] Fattouh MS, Tayeh BA, Agwa IS, Elsayed EK. Improvement in the flexural behaviour of road pavement slab concrete containing steel fibre and silica fume. Case Stud Constr Mater. 2023;18:e01720.

[58] He L, Chen B, Liu Q, Chen H, Li H, Chow WT, et al. A quasi-exponential distribution of interfacial voids and its effect on the interlayer strength of 3D printed concrete. Addit Manuf. 2024;89:104296.

[59] Ghadikolaee MR, Korayem AH, Sharif A, Liu YM. The halloysite nanotube effects on workability, mechanical properties, permeability and microstructure of cementitious mortar. Constr Build Mater. 2021;267:120873.

[60] Rashidi Y, Roudi MRR, Korayem AH, Shamsaei E. Investigation of ultrasonication energy effect on workability, mechanical properties and pore structure of halloysite nanotube reinforced cement mortars. Constr Build Mater. 2021;304:124610.

[61] Seifan M, Mendoza S, Berenjian A. Mechanical properties and durability performance of fly ash based mortar containing nano- and micro-silica additives. Constr Build Mater. 2020;252:119121.

[62] Cui K, Lau D, Zhang Y, Chang J. Mechanical properties and mechanism of nano-CaCO3 enhanced sulphoaluminate cement-based reactive powder concrete. Constr Build Mater. 2021;309:125099.

[63] Zhang X, Li H, Harvey JT, Liang X, Xie N, Jia M. Purification effect on runoff pollution of porous concrete with nano-TiO_2 photocatalytic coating. Transp Res Part D: Transp Environ. 2021;101:103101.

[64] Saleh AN, Attar AA, Ahmed OK, Mustafa SS. Improving the thermal insulation and mechanical properties of concrete using Nano-SiO_2. Results Eng. 2021;12:100303.

[65] Ren J, Luo X, Bai R, Pan C, Zhang J. Pore characteristics of different phase in nano-modified concrete and their influence on the compressive strength. J Build Eng. 2021;46:103784.

[66] Jeon IK, Qudoos A, Woo BH, Yoo DH, Kim HG. Effects of nano-silica and reactive magnesia on the microstructure and durability performance of underwater concrete. Powder Technol. 2021;398:116976.

[67] Luo Z, Li W, Wang K, Shah SP, Sheng D. Nano/micromechanical characterisation and image analysis on the properties and heterogeneity of ITZs in geopolymer concrete. Cem Concr Res. 2022;152:106677.

[68] Tran NP, Nguyen TN, Black JR, Ngo TD. High-temperature stability of ambient-cured one-part alkali-activated materials incorporating graphene nanoplatelets for thermal energy storage. Dev Built Environ. 2024;18:100447.

[69] Divya S, Praveenkumar S, Tayeh BA. Performance of modified nano carbon blended with supplementary materials in cement composite – An interpretive review. Constr Build Mater. 2022;346:128452.

[70] Vipulanandan C, Mohammed AS, Piro NS. Resistivity and piezoelectrical behavior of the smart oil well cement incorporated with aluminum oxide and iron oxide nanoparticles – experimental and analytical study. J Test Eval. 2024;52(4):2643–62.

[71] Chen C, Tang B, Cao X, Gu F, Huang W. Enhanced photocatalytic decomposition of NO on portland cement concrete pavement using nano-TiO_2 suspension. Constr Build Mater. 2021;275:122135.

[72] Orakzai MA. Hybrid effect of nano-alumina and nano-titanium dioxide on Mechanical properties of concrete. Case Stud Constr Mater. 2021;14:e00483.

[73] Bai S, Guan X, Li G. Early-age hydration heat evolution and kinetics of Portland cement containing nano-silica at different temperatures. Constr Build Mater. 2022;334:127363.

[74] Vaid U, Lallotra B. Effect on concrete strength and durability with partial replacement of cement by Nano-titanium dioxide (nano-

TiO_2) and ground granulated blast furnace slag (GGBS): A Review Summary. In IOP Conference Series: Earth and Environmental Science. IOP Publishing; 2024. p. 012046.
[75] Piro NS, Salih A, Hamad SM, Kurda R. Comprehensive multiscale techniques to estimate the compressive strength of concrete incorporated with carbon nanotubes at various curing times and mix proportions. J Mater Res Technol. 2021;15:6506–27.
[76] Jagadesh P, Nagarajan V. Effect of nano titanium di oxide on mechanical properties of fly ash and ground granulated blast furnace slag based geopolymer concrete. J Build Eng. 2022;61:105235.
[77] Chu SH, Li LG, Kwan AKH. Development of extrudable high strength fiber reinforced concrete incorporating nano calcium carbonate. Addit Manuf. 2021;37:101617.
[78] Wu G, Li T, Zhang M, Cui J, Li J. Durability and thermal insulation properties of glazed hollow bead concrete with nanoparticles in marine atmospheric environment. J Build Eng. 2024;94:110071.
[79] Salih A, Rafiq S, Mahmood W, Al-Darkazali H, Noaman R, Ghafor K, et al. Systemic multi-scale approaches to predict the flowability at various temperature and mechanical properties of cement paste modified with nano-calcium carbonate. Constr Build Mater. 2020;262:120777.
[80] Othuman Mydin MA, Jagadesh P, Bahrami A, Dulaimi A, Özkılıç YO, Al Bakri Abdullah MM, et al. Use of calcium carbonate nanoparticles in production of nano-engineered foamed concrete. J Mater Res Technol. 2023;26:4405–22.
[81] Zhao R, Li C, Guan X. Advances in modeling surface chloride concentrations in concrete serving in the marine environment: A mini review. Buildings. 2024;14(6):1879.
[82] Norhasri MM, Hamidah M, Fadzil AM. Applications of using nano material in concrete: A review. Constr Build Mater. 2017;133:91–7.
[83] Ju M, Park K, Oh H. Estimation of compressive strength of high strength concrete using non-destructive technique and concrete core strength. Appl Sci. 2017;7(12):1249.
[84] Marvila MT, de Azevedo ARG, de Matos PR, Monteiro SN, Vieira CMF. Materials for production of high and ultra-high performance concrete: review and perspective of possible novel materials. Materials. 2021;14(15):4304.
[85] Liu X, Sun D, Liu D, Meng K, Ni C, Shao Z, et al. Simulation of ultrasonic propagation in porous cellular concrete materials. Constr Build Mater. 2021;285:122852.
[86] Chithra S, Kumar SS, Chinnaraju K. The effect of Colloidal Nano-silica on workability, mechanical and durability properties of High Performance Concrete with Copper slag as partial fine aggregate. Constr Build Mater. 2016;113:794–804.
[87] Majeed SS, Othuman Mydin MA, Bahrami A, Dulaimi A, Özkılıç YO, Omar R, et al. Development of ultra-lightweight foamed concrete modified with silicon dioxide (SiO2) nanoparticles: Appraisal of transport, mechanical, thermal, and microstructural properties. J Mater Res Technol. 2024;30:3308–27.
[88] Kong D, Du X, Wei S, Zhang H, Yang Y, Shah SP. Influence of nano-silica agglomeration on microstructure and properties of the hardened cement-based materials. Constr Build Mater. 2012;37:707–15.
[89] Kooshafar M, Madani H. An investigation on the influence of nano silica morphology on the characteristics of cement composites. J Build Eng. 2020;30:101293.
[90] Quercia G, Lazaro A, Geus JW, Brouwers HJH. Characterization of morphology and texture of several amorphous nano-silica particles used in concrete. Cem Concr Compos. 2013;44:77–92.
[91] Adamu M, Trabanpruek P, Jongvivatsakul P, Likitlersuang S, Iwanami M. Mechanical performance and optimization of high-volume fly ash concrete containing plastic wastes and graphene nanoplatelets using response surface methodology. Constr Build Mater. 2021;308:125085.
[92] Dong W, Huang Y, Lehane B, Aslani F, Ma G. Mechanical and electrical properties of concrete incorporating an iron-particle contained nano-graphite by-product. Constr Build Mater. 2021;270:121377.
[93] Khaloo A, Mobini MH, Hosseini P. Influence of different types of nano-SiO_2 particles on properties of high-performance concrete. Constr Build Mater. 2016;113:188–201.
[94] Iqbal HW, Hamcumpai K, Nuaklong P, Jongvivatsakul P, Likitlersuang S, Chintanapakdee C, et al. Effect of graphene nanoplatelets on engineering properties of fly ash-based geopolymer concrete containing crumb rubber and its optimization using response surface methodology. J Build Eng. 2023;75:107024.
[95] Adamu M, Trabanpruek P, Limwibul V, Jongvivatsakul P, Iwanami M, Likitlersuang S. Compressive behavior and durability performance of high-volume fly-ash concrete with plastic waste and graphene nanoplatelets by using response-surface methodology. J Mater Civ Eng. 2022;34(9):04022222.
[96] Iqbal HW, Hamcumpai K, Nuaklong P, Jongvivatsakul P, Likitlersuang S, Pothisiri T, et al. Enhancing fire resistance in geopolymer concrete containing crumb rubber with graphene nanoplatelets. Constr Build Mater. 2024;426:136115.
[97] Parashar M, Shukla VK, Singh R. Metal oxides nanoparticles via sol-gel method: a review on synthesis, characterization and applications. J Mater Sci: Mater Electron. 2020;31:3729–49.
[98] Zhao Z, Liu D, Ma J, Chen X. Fluidization of nanoparticle agglomerates assisted by combining vibration and stirring methods. Chem Eng J Chem Eng J. 2020;388:124213.
[99] Kelesidis GA, Kholghy MR, Zuercher J, Robertz J, Allemann M, Duric A, et al. Light scattering from nanoparticle agglomerates. Powder Technol. 2020;365:52–9.
[100] Vipulanandan C, Krishnamoorti R, Mohammed A, Boncan V, Narvaez G, Head B, et al. Iron nanoparticle modified smart cement for real time monitoring of ultra deepwater oil well cementing applications. Offshore Technology Conference; 2015. p. OTC-25842-MS.
[101] Li Z, Wang H, He S, Lu Y, Wang M. Investigations on the preparation and mechanical properties of the nano-alumina reinforced cement composite. Mater Lett. 2006;60(3):356–9.
[102] Kong D, Corr DJ, Hou P, Yang Y, Shah SP. Influence of colloidal silica sol on fresh properties of cement paste as compared to nano-silica powder with agglomerates in micron-scale. Cem Concr Compos. 2015;63:30–41.
[103] Liu H, Li Q, Ni S, Wang L, Yue G, Guo Y. Effect of nano-silica dispersed at different temperatures on the properties of cement-based materials. J Build Eng. 2022;46:103750.
[104] Piro NS, Mohammed AS, Hamad SM. Multiple analytical models to evaluate the impact of carbon nanotubes on the electrical resistivity and compressive strength of the cement paste. Sustainability. 2021;13:12544.
[105] Mohammed A, Rafiq S, Ghafor K, Emad W, Noaman R, Qasim AY, et al. Clay nanosize effects on the rheological behavior at various elevated temperatures and mechanical properties of the cement paste: experimental and modeling. Iran J Sci Technol, Trans Civ Eng. 2022;46(2):819–42.

[106] Abdul-Hafidh EH, Khalafalla MAH, Khalil KD. The reduction of the agglomeration of silver oxide nanosolids under the influence of pressure. Mater Chem Phys. 2024;319:129388.
[107] Efimov A, Patarashvili A, Kornyushin D, Ivanov M, Lizunova A, Nouraldeen M, et al. Efficient charging of aerosol nanoparticles by corona-needle charger with improved design for printing of metallic microstructures. Int J Eng. 2024;37:1926–35.
[108] Richmonds C, Sankaran R. Plasma-liquid electrochemistry: Rapid synthesis of colloidal metal nanoparticles by microplasma reduction of aqueous cations. Appl Phys Lett. 2008;93:131501.
[109] Zhao W, Liu Z, Sun Z, Zhang Q, Wei P, Mu S, et al. Superparamagnetic enhancement of thermoelectric performance. Nature. 2017;549:247–51.
[110] Li L, Xuan D, Chu SH, Lu JX, Poon CS. Efficiency and mechanism of nano-silica pre-spraying treatment in performance enhancement of recycled aggregate concrete. Constr Build Mater. 2021;301:124093.
[111] Najigivi A, Khaloo A, Irajizad A, Abdul Rashid S. Investigating the effects of using different types of SiO_2 nanoparticles on the mechanical properties of binary blended concrete. Compos Part B: Eng. 2013;54:52–8.
[112] Morsy MS, Aglan HA, Abd El Razek MM. Nanostructured zonolite–cementitious surface compounds for thermal insulation. Constr Build Mater. 2009;23(1):515–21.
[113] Li GY, Wang PM, Zhao X. Pressure-sensitive properties and microstructure of carbon nanotube reinforced cement composites. Cem Concr Compos. 2007;29(5):377–82.
[114] Oertel T, Hutter F, Tänzer R, Helbig U, Sextl G. Primary particle size and agglomerate size effects of amorphous silica in ultra-high performance concrete. Cem Concr Compos. 2013;37:61–7.
[115] Stefanidou M, Papayianni I. Influence of nano-SiO_2 on the Portland cement pastes. Compos Part B: Eng. 2012;43(6):2706–10.
[116] Sobolev K, Flores I, Hermosillo R, Torres-Martinez LM. Nanomaterials and nanotechnology for high-performance cement composites. Am Concr Inst, ACI Spec Publ. 2008;254:93–120.
[117] Ghafari E, Costa H, Júlio E. Critical review on eco-efficient ultra high performance concrete enhanced with nano-materials. Constr Build Mater. 2015;101(Part 1):201–8.
[118] Elkady H, Serag M, Elfeky M. Effect of nano silica de-agglomeration, and methods of adding super-plasticizer on the compressive strength, and workability of nano silica concrete. Civ Environ Res. 2013;3(2):21–34.
[119] Ali R, Muayad M, Mohammed AS, Asteris PG. Analysis and prediction of the effect of Nanosilica on the compressive strength of concrete with different mix proportions and specimen sizes using various numerical approaches. Struct Concr. 2023;24(3):4161–84.
[120] Hosan A, Shaikh FUA. Influence of nano-$CaCO_3$ addition on the compressive strength and microstructure of high volume slag and high volume slag-fly ash blended pastes. J Build Eng. 2020;27:100929.
[121] Roychand R, De Silva S, Setunge S, Law D. A quantitative study on the effect of nano SiO_2, nano Al_2O_3 and nano $CaCO_3$ on the physicochemical properties of very high volume fly ash cement composite. Eur J Environ Civ Eng. 2020;24(6):724–39.
[122] Braganca MO, Portella KF, Bonato MM, Alberti E, Marino CE. Performance of Portland cement concretes with 1% nano-Fe_3O_4 addition: Electrochemical stability under chloride and sulfate environments. Constr Build Mater. 2016;117:152–62.
[123] Jafari H, Afshar S. Improved photodegradation of organic contaminants using nano-TiO_2 and TiO_2–SiO_2 deposited on Portland cement concrete blocks. Photochem Photobiol. 2016;92(1):87–101.
[124] Nuaklong P, Boonchoo N, Jongvivatsakul P, Charinpanitkul T, Sukontasukkul P. Hybrid effect of carbon nanotubes and polypropylene fibers on mechanical properties and fire resistance of cement mortar. Constr Build Mater. 2021;275:122189.
[125] Xing G, Xu Y, Huang J, Lu Y, Miao P, Chindasiriphan P, et al. Research on the mechanical properties of steel fibers reinforced carbon nanotubes concrete. Constr Build Mater. 2023;392:131880.
[126] Vazinram F, Jalal M, Foroushani MY. Effect of nano ZnO_2 and lime water curing on strength and water absorption of concrete. Int J Mater Product Technol. 2015;50(3–4):356–65.
[127] Li W, Huang Z, Cao F, Sun Z, Shah SP. Effects of nano-silica and nano-limestone on flowability and mechanical properties of ultra-high-performance concrete matrix. Constr Build Mater. 2015;95:366–74.
[128] Arulraj GP, Carmichael MJ. Effect of nano-flyash on strength of concrete. Int J Civ Struct Eng. 2011;2(2):475–82.
[129] Morsy M, Alsayed S, Aqel M. Hybrid effect of carbon nanotube and nano-clay on physico-mechanical properties of cement mortar. Constr Build Mater. 2011;25(1):145–9.
[130] Norhasri MM, Hamidah M, Fadzil AM, Megawati O. Inclusion of nano metakaolin as additive in ultra high performance concrete (UHPC). Constr Build Mater. 2016;127:167–75.
[131] Shaffer R, Rengasamy S. Respiratory protection against airborne nanoparticles: A review. J Nanopart Res. 2009;11:1661–72.
[132] Yontar AK, Çevik S. Regulatory policies for safety of nanomaterials. Open J Nano. 2020;5:1–16.
[133] Amoabediny GH, Naderi A, Malakootikhah J, Koohi MK, Mortazavi SA, Naderi M, et al. Guidelines for safe handling, use and disposal of nanoparticles. J Phys: Conf Ser. 2009;170(1):012037.
[134] Mohajerani A, Burnett L, Smith JV, Kurmus H, Milas J, Arulrajah A, et al. Nanoparticles in construction materials and other applications, and implications of nanoparticle use. Materials (Basel, Switzerland). 2019;12(19):3052.
[135] Metwally ME, Ahmed MA, Ahmed SA, Sherif MA, Tobbala DE. An investigation into the effect of locally prepared nano-silica on the microstructure and hardened properties of high strength concrete. The International Conference of Engineering Sciences and Applications, Aswan, Egypt, 29-31 January 2016; 2016.
[136] Nigam M, Verma M. Effect of nano-silica on the fresh and mechanical properties of conventional concrete. Forces Mech. 2023;10:100165.
[137] Zhang P, Wang L, Wei H, Wang J. A critical review on effect of nanomaterials on workability and mechanical properties of high-performance concrete. Adv Civ Eng. 2021;2021(1):8827124.
[138] Tobbala DE. Comparative study on the durability of nano-silica and nano-ferrite concrete. East Afr Scholars J Eng Comput Sci. 2021;4(9):124–31.
[139] Koskela L. Application of the new production philosophy to construction. United States: Center for Integrated Facility Engineering, Stanford University; 1992.
[140] Yu R, Spiesz P, Brouwers H. Effect of nano-silica on the hydration and microstructure development of Ultra-High Performance Concrete (UHPC) with a low binder amount. Constr Build Mater. 2014;65:140–50.

[141] Zhang M-H, Islam J. Use of nano-silica to reduce setting time and increase early strength of concretes with high volumes of fly ash or slag. Constr Build Mater. 2012;29:573–80.

[142] Li G. Properties of high-volume fly ash concrete incorporating nano-SiO_2. Cem Concr Res. 2004;34(6):1043–9.

[143] Tabish M, Zaheer MM, Baqi A. Effect of nano-silica on mechanical, microstructural and durability properties of cement-based materials: A review. J Build Eng. 2023;65:105676.

[144] Li L, Xuan D, Chu SH, Poon CS. Modification of recycled aggregate by spraying colloidal nano silica and silica fume. Mater Struct. 2021;54(6):223.

[145] Jalal M, Mansouri E, Sharifipour M, Pouladkhan AR. Mechanical, rheological, durability and microstructural properties of high performance self-compacting concrete containing SiO_2 micro and nanoparticles. Mater Des. 2012;34:389–400.

[146] Givi AN, Rashid SA, Aziz FNA, Salleh MAM. Experimental investigation of the size effects of SiO_2 nano-particles on the mechanical properties of binary blended concrete. Compos Part B: Eng. 2010;41(8):673–7.

[147] Mostafa SA, Faried AS, Farghali AA, El-Deeb MM, Tawfik TA, Majer S, et al. Influence of nanoparticles from waste materials on mechanical properties, durability and microstructure of UHPC. Materials. 2020;13(20):4530.

[148] Sujitha VS, Ramesh B, Xavier JR. Effects of nanomaterials on mechanical properties in cementitious construction materials for high-strength concrete applications: a review. J Adhes Sci Technol. 2024;38(20):3737–68.

[149] Stefanidou M, Tsardaka E-C, Pavlidou E. Influence of nano-silica and nano-alumina in lime-pozzolan and lime-metakaolin binders. Mater Today: Proc. 2017;4(7):6908–22.

[150] Wu Z, Shi C, Khayat KH, Xie L. Effect of SCM and nano-particles on static and dynamic mechanical properties of UHPC. Constr Build Mater. 2018;182:118–25.

[151] Mahdikhani M, Bamshad O, Fallah Shirvani M. Mechanical properties and durability of concrete specimens containing nano silica in sulfuric acid rain condition. Constr Build Mater. 2018;167:929–35.

[152] Sivasankaran U, Raman S, Nallusamy S. Experimental analysis of mechanical properties on concrete with nano silica additive. J Nano Res. 2019;57:93–104.

[153] Puentes J, Barluenga G, Palomar I. Effect of silica-based nano and micro additions on SCC at early age and on hardened porosity and permeability. Constr Build Mater. 2015;81:154–61.

[154] Rong Z, Sun W, Xiao H, Jiang G. Effects of nano-SiO_2 particles on the mechanical and microstructural properties of ultra-high performance cementitious composites. Cem Concr Compos. 2015;56:25–31.

[155] Onaizi AM, Huseien GF, Lim NHAS, Amran M, Samadi M. Effect of nanomaterials inclusion on sustainability of cement-based concretes: A comprehensive review. Constr Build Mater. 2021;306:124850.

[156] Nazari A, Riahi S. The role of SiO_2 nanoparticles and ground granulated blast furnace slag admixtures on physical, thermal and mechanical properties of self compacting concrete. Mater Sci Eng: A. 2011;528(4–5):2149–57.

[157] Vickers NJ. Animal communication: when i'm calling you, will you answer too? Curr Biol. 2017;27(14):R713–5.

[158] Tariq M, Nisar S, Shah A, Akbar S, Khan MA, Khan SZ. Effect of hybrid reinforcement on the performance of filament wound hollow shaft. Compos Struct. 2018;184:378–87.

[159] Saloma A, Imran I, Abdullah M. Experimental investigation on nanomaterial concrete. Int J Civ Env Eng. 2013;13(3):15–20.

[160] Quercia G, Spiesz P, Hüsken G, Brouwers H. SCC modification by use of amorphous nano-silica. Cem Concr Compos. 2014;45:69–81.

[161] Abd Elrahman M, Chung S-Y, Sikora P, Rucinska T, Stephan D. Influence of nanosilica on mechanical properties, sorptivity, and microstructure of lightweight concrete. Materials. 2019;12(19):3078.

[162] Givi AN, Rashid SA, Aziz FNA, Salleh MAM. The effects of lime solution on the properties of SiO_2 nanoparticles binary blended concrete. Compos Part B: Eng. 2011;42(3):562–9.

[163] Sajedi F, Razak HA. Comparison of different methods for activation of ordinary Portland cement-slag mortars. Constr Build Mater. 2011;25(1):30–8.

[164] Nawale A, Kanhe N, Patil K, Reddy V, Gupta A, Kale B, et al. Magnetic properties of nanocrystalline $CoFe_2O_4$ synthesized by thermal plasma in large scale. Mater Chem Phys. 2012;137(2):586–95.

[165] Foroutan R, Peighambardoust SJ, Hemmati S, Khatooni H, Ramavandi B. Preparation of clinoptilolite/starch/$CoFe_2O_4$ magnetic nanocomposite powder and its elimination properties for cationic dyes from water and wastewater. Int J Biol Macromol. 2021;189:432–42.

[166] Ren J, Lai Y, Gao J. Exploring the influence of SiO_2 and TiO_2 nanoparticles on the mechanical properties of concrete. Constr Build Mater. 2018;175:277–85.

[167] Zhang S-L, Qi X-Q, Guo S-Y, Ren J, Chen J-Z, Chi B, et al. Effect of a novel hybrid TiO_2-graphene composite on enhancing mechanical and durability characteristics of alkali-activated slag mortar. Constr Build Mater. 2021;275:122154.

[168] Khoshakhlagh A, Nazari A, Khalaj G. Effects of Fe_2O_3 nanoparticles on water permeability and strength assessments of high strength self-compacting concrete. J Mater Sci Technol. 2012;28(1):73–82.

[169] Oltulu M, Şahin R. Single and combined effects of nano-SiO_2, nano-Al_2O_3 and nano-Fe_2O_3 powders on compressive strength and capillary permeability of cement mortar containing silica fume. Mater Sci Eng: A. 2011;528(22–23):7012–9.

[170] Torabian Isfahani F, Redaelli E, Lollini F, Li W, Bertolini L. Effects of nanosilica on compressive strength and durability properties of concrete with different water to binder ratios. Adv Mater Sci Eng. 2016;2016:8453567.

[171] Ivanchik N, Kondratiev V, Chesnokova A. Use of nanosilica recovered from the finely dispersed by-product of the electrothermal silicon production for concrete modification. Procedia Eng. 2016;150:1567–73.

[172] Olivier G, Combrinck R, Kayondo M, Boshoff WP. Combined effect of nano-silica, super absorbent polymers, and synthetic fibres on plastic shrinkage cracking in concrete. Constr Build Mater. 2018;192:85–98.

[173] Keshavarzian F, Saberian M, Li J. Investigation on mechanical properties of steel fiber reinforced reactive powder concrete containing nano-SiO_2: An experimental and analytical study. J Build Eng. 2021;44:102601.

[174] Herath C, Gunasekara C, Law DW, Setunge S. Long term mechanical performance of nano-engineered high volume fly ash concrete. J Build Eng. 2021;43:103168.

[175] Li H, Xiao H-g, Yuan J, Ou J. Microstructure of cement mortar with nano-particles. Compos part B: Eng. 2004;35(2):185–9.

[176] Meng T, Yu Y, Qian X, Zhan S, Qian K. Effect of nano-TiO_2 on the mechanical properties of cement mortar. Constr Build Mater. 2012;29:241–5.
[177] Wang Y, Xu Z, Wang J, Zhou Z, Du P, Cheng X. Synergistic effect of nano-silica and silica fume on hydration properties of cement-based materials. J Therm Anal Calorim. 2020;140(5):2225–35.
[178] Li LG, Zheng JY, Ng PL, Zhu J, Kwan AKH. Cementing efficiencies and synergistic roles of silica fume and nano-silica in sulphate and chloride resistance of concrete. Constr Build Mater. 2019;223:965–75.
[179] Chen J, Kou SC, Poon CS. Hydration and properties of nano-TiO_2 blended cement composites. Cem Concr Compos. 2012;34(5):642–9.
[180] Li W, Long C, Tam VW, Poon C-S, Duan WH. Effects of nano-particles on failure process and microstructural properties of recycled aggregate concrete. Constr Build Mater. 2017;142:42–50.
[181] Li H, Huang J, Lu F, Liu Y, Song Y, Sun Y, et al. Impacts of carbon dots on rice plants: boosting the growth and improving the disease resistance. ACS Appl Bio Mater. 2018;1(3):663–72.
[182] Higuma T, Yoneyama K, Nakai M, Kaihara T, Sumita Y, Watanabe M, et al. Effects of temperature and humidity on acute myocardial infarction hospitalization in a super-aging society. Sci Rep. 2021;11(1):22832.
[183] Yoneyama T, Komiya T, Fukushima O, Tanaka Y, Tsutsumi Y, Doi H, et al. Nickel-free and corrosion-resistant surface oxide layer on titanium-nickel alloy by electrolytic treatment. 8th World Biomaterials Congress 2008. Vol. 3. p. 91–105.
[184] Said AM, Zeidan MS, Bassuoni M, Tian Y. Properties of concrete incorporating nano-silica. Constr Build Mater. 2012;36:838–44.
[185] Mohamed A. Influence of nano materials on flexural behavior and compressive strength of concrete. HBRC J. 2015;21:212–25.
[186] Jalal M, Ramezanianpour AA, Pool MK. Split tensile strength of binary blended self compacting concrete containing low volume fly ash and TiO_2 nanoparticles. Compos Part B: Eng. 2013;55:324–37.
[187] Salemi N, Behfarnia K. Effect of nano-particles on durability of fiber-reinforced concrete pavement. Constr Build Mater. 2013;48:934–41.
[188] Hosseini P, Afshar A, Vafaei B, Booshehrian A, Molaei Raisi E, Esrafili A. Effects of nano-clay particles on the short-term properties of self-compacting concrete. Eur J Environ Civ Eng. 2017;21(2):127–47.
[189] Wu Z, Shi C, Khayat KH, Wan S. Effects of different nanomaterials on hardening and performance of ultra-high strength concrete (UHSC). Cem Concr Compos. 2016;70:24–34.
[190] Shaikh FUA, Supit SWM. Mechanical and durability properties of high volume fly ash (HVFA) concrete containing calcium carbonate ($CaCO_3$) nanoparticles. Constr Build Mater. 2014;70:309–21.
[191] Hongjian D, Suhuan D, Xuemei L. Durability performances of concrete with nano-silica. Constr Build Mater. 2014;73:705–12.
[192] Elkady H, Serag M, Elfeky M. Effect of nano silica de-agglomeration, and methods of adding super-plasticizer on the compressive strength, and workability of nano silica concrete. Civ Environ Res. 2013;3:2222–863.
[193] Li G, Zhou J, Yue J, Gao X, Wang K. Effects of nano-SiO_2 and secondary water curing on the carbonation and chloride resistance of autoclaved concrete. Constr Build Mater. 2020;235:117465.
[194] El-Feky MS, Serag MI, Yasien AM, Elkady H. Bond strength of nano silica concrete subjected to corrosive environments. ARPN J Eng Appl Sci. 2016;11(23):13909–24.
[195] Tobbala DE, Abdelsalam BA, Agwa IS. Bond performance of a hybrid coating zinc-rich epoxy incorporating nano-ferrite for steel rebars subjected to high temperatures in concrete. J Build Eng. 2020;32:101698.
[196] Shekari AH, Razzaghi MS. Influence of nano particles on durability and mechanical properties of high performance concrete. Procedia Eng. 2011;14:3036–41.
[197] Mansourghanaei M, Biklaryan M, Mardookhpour A. Experimental study of the effects of adding silica nanoparticles on the durability of geopolymer concrete. Aust J Civ Eng. 2024;22(1):81–93.
[198] Florean CT, Vermesan H, Thalmaier G, Neamtu BV, Gabor T, Campian C, et al. The influence of TiO_2 nanoparticles on the physico–mechanical and structural characteristics of cementitious materials. Coatings. 2024;14(2):218.
[199] Maruthapandian V, Muralidharan S, Saraswathy V. Spinel $NiFe_2O_4$ based solid state embeddable reference electrode for corrosion monitoring of reinforced concrete structures. Constr Build Mater. 2016;107:28–37.
[200] Ibrahim RK, Hamid R, Taha MR. Fire resistance of high-volume fly ash mortars with nanosilica addition. Constr Build Mater. 2012;36:779–86.
[201] Jabin JA, Khondoker MTH, Sobuz MHR, Aditto FS. High-temperature effect on the mechanical behavior of recycled fiber-reinforced concrete containing volcanic pumice powder: An experimental assessment combined with machine learning (ML)-based prediction. Constr Build Mater. 2024;418:135362.
[202] Ahmed TI, El-Shafai NM, El-Mehasseb IM, Sharshir SW, Tobbala DE. Recent advances in the heating resistance, thermal gravimetric analysis, and microstructure of green concrete incorporating palm-leaf and cotton-stalk nanoparticles. J Build Eng. 2022;61:105252.
[203] Bastami M, Baghbadrani M, Aslani F. Performance of nano-Silica modified high strength concrete at elevated temperatures. Constr Build Mater. 2014;68:402–8.
[204] Heikal M, Ali AI, Ismail MN, Ibrahim S, Awad NS. Behavior of composite cement pastes containing silica nano-particles at elevated temperature. Constr Build Mater. 2014;70:339–50.
[205] Kamal M, Safan M, Eltabey M, Zaki ES, ABU EHK. Compressive strength of Portland cement pastes and mortars containing Cu-Zn nano-ferrite. Int J Nano Dimens. 2012;3(2):91–100.
[206] Gopalakrishnan R, Kumar SN, Nithiyanantham S. Evaluating resistance of microsilica and colloidal nanosilica in Indian ordinary Portland cement mortar against combined chloride and sulfate attack. Int Nano Lett. 2021;12:91–105.
[207] El-Didamony AH, BAEG S, El-Aleem MSA, Mohamed MN. Chemical and engineering properties of blended cement containing micro- and nano-silica. Am J Chem Eng. 2017;5(5):111–21.
[208] Birgisson B, Mukhopadhyay AK, Geary G, Khan M, Sobolev K. Nanotechnology in concrete materials: a synopsis. Washington, D.C.: Transportation Research Board. Transportation research circular; 2012, no. E-C170.
[209] Moslemi AM, Khosravi A, Izadinia M, Heydari M. Application of nano silica in concrete for enhanced resistance against sulfate attack. Adv Mater Res. 2013;829:874–8.
[210] Atahan HN, Dikme D. Use of mineral admixtures for enhanced resistance against sulfate attack. Constr Build Mater. 2011;25(8):3450–7.

[211] Gopala Krishna Sastry KVS, Sahitya P, Ravitheja A. Influence of nano TiO_2 on strength and durability properties of geopolymer concrete. Mater Today: Proc. 2021;45:1017–25.
[212] Singh L, Karade S, Bhattacharyya S, Yousuf MM, Ahalawat S. Beneficial role of nanosilica in cement based materials–A review. Constr Build Mater. 2013;47:1069–77.
[213] Sobolev K, Gutiérrez MF. How nanotechnology can change the concrete world. Vol. 84, 2005.
[214] Tadayon MKM, Sepehri H, Sepehri M. Influence of nano-silica particles on mechanical properties and permeability of concrete. The 2nd International Conference on Sustainable Construction Materials and Technologies; 2010. p. 1–7.
[215] Al-Akhras NM. Durability of metakaolin concrete to sulfate attack. Cem Concr Res. 2006;36(9):1727–34.
[216] Guo Z, Hou P, Xu Z, Gao J, Zhao Y. Sulfate attack resistance of tricalcium silicate modified with nano-silica and supplementary cementitious materials. Constr Build Mater. 2022;321:126332.
[217] Nasution A, Imran I, Abdullah M. Improvement of concrete durability by nanomaterials. Procedia Eng. 2015;125:608–12.
[218] Jing Y, Lee JC, Moon WC, Ng JL, Yew MK, Chu MY. Mechanical properties, permeability and microstructural characterisation of rice husk ash sustainable concrete with the addition of carbon nanotubes. Heliyon. 2024;10(12):e32780.
[219] Zaid O, Sor NAH, Martínez-García R, de Prado-Gil J, Elhadi KM, Yosri AM. Sustainability evaluation, engineering properties and challenges relevant to geopolymer concrete modified with different nanomaterials: A systematic review. Ain Shams Eng J. 2023;15(2):102373.
[220] Kishore K, Pandey A, Wagri NK, Saxena A, Patel J, Al-Fakih A. Technological challenges in nanoparticle-modified geopolymer concrete: A comprehensive review on nanomaterial dispersion, characterization techniques and its mechanical properties. Case Stud Constr Mater. 2023;19:e02265.
[221] Feng L, Chen X, Ning Y, Wang J, Zhang W. High temperature effect of foamed concrete under equal displacement increment triaxial cyclic compression. Constr Build Mater. 2022;327:126989.
[222] Hou P, Kawashima S, Kong D, Corr DJ, Qian J, Shah SP. Modification effects of colloidal nanoSiO2 on cement hydration and its gel property. Compos Part B: Eng. 2013;45(1):440–8.
[223] Adesina A. Durability enhancement of concrete using nanomaterials: an overview. Mater Sci Forum. 2019;967:221–7.
[224] Alharbi YR, Abadel AA, Mayhoub OA, Kohail M. Effect of using available metakaoline and nano materials on the behavior of reactive powder concrete. Constr Build Mater. 2021;269:121344.
[225] Alan Strauss Rambo D, Umbinger de Oliveira C, Pícolo Salvador R, Dias Toledo Filho R, da Fonseca Martins Gomes O, de Andrade Silva F, et al. Sisal textile reinforced concrete: Improving tensile strength and bonding through peeling and nano-silica treatment. Constr Build Mater. 2021;301:124300.
[226] Abhilash PP, Nayak DK, Sangoju B, Kumar R, Kumar V. Effect of nano-silica in concrete; a review. Constr Build Mater. 2021;278:122347.
[227] Land G, Stephan D. The influence of nano-silica on the hydration of ordinary Portland cement. J Mater Sci. 2012;47:1011–7.
[228] Madani H, Bagheri A, Parhizkar T. The pozzolanic reactivity of monodispersed nanosilica hydrosols and their influence on the hydration characteristics of Portland cement. Cem Concr Res. 2012;42(12):1563–70.
[229] Jo BW, Kim CH, Lim JH. Investigations on the development of powder concrete with nano-SiO2 particles. KSCE J Civ Eng. 2007;11(1):37–42.
[230] Tobbala D, Rashed A, Tayeh BA, Ahmed TI. Performance and microstructure analysis of high-strength concrete incorporated with nanoparticles subjected to high temperatures and actual fires. Arch Civ Mech Eng. 2022;22(2):85.
[231] Hamada HM, Al-Attar AA, Tayeh B, Yahaya FBM. Optimizing the concrete strength of lightweight concrete containing nano palm oil fuel ash and palm oil clinker using response surface method. Case Stud Constr Mater. 2022;16:e01061.
[232] Hakeem IY, Amin M, Zeyad AM, Tayeh BA, Agwa IS, Abu el-hassan K. Properties and durability of self-compacting concrete incorporated with nanosilica, fly ash, and limestone powder. Struct Concr. 2023 Oct;24(5):6738–60.
[233] Adesina A. Nanomaterials in cementitious composites: review of durability performance. J Build Pathol Rehabil. 2020;5:1–9.
[234] Mostafa SA, Ahmed N, Almeshal I, Tayeh BA, Elgamal MS. Experimental study and theoretical prediction of mechanical properties of ultra-high-performance concrete incorporated with nanorice husk ash burning at different temperature treatments. Environ Sci Pollut Res. 2022;29(50):75380–401.
[235] Mostafa SA, Tayeh BA, Almeshal I. Investigation the properties of sustainable ultra-high-performance basalt fibre self-compacting concrete incorporating nano agricultural waste under normal and elevated temperatures. Case Stud Constr Mater. 2022;17:e01453.
[236] Ahmed S. Causes and effects of accident at construction site: a study for the construction industry in Bangladesh. Int J Sustain Constr Eng Technol. 2020;10(2):18–40.
[237] Gajanan K, Tijare S. Applications of nanomaterials. Mater Today: Proc. 2018;5(1):1093–6.
[238] Fulekar M. Nanotechnology: importance and applications. New Delhi: I.K. International Pub. House; 2010.
[239] Pacheco-Torgal F, Jalali S. Nanotechnology: Advantages and drawbacks in the field of construction and building materials. Constr Build Mater. 2011;25(2):582–90.
[240] Jones W, Gibb A, Goodier C, Bust P, Song M, Jin J. Nanomaterials in construction – what is being used, and where? Proc Inst Civ Eng – Constr Mater. 2016;172:1–14.
[241] Lin C-C, Chen W-Y. Effect of paint composition, nano-metal types and substrate on the improvement of biological resistance on paint finished building material. Build Environ. 2017;117:49–59.
[242] Tobbala DE, Khesha GM, Salama RS, Badawy AAM. Reinventing concrete: Sustainable nano-alumina from metallic waste-cans and nano-ferrite for next-generation green magnetite heavyweight concrete. J Build Eng. 2024;93:109829.
[243] Li-ping G, Xiang-peng F, Jian-dong W, Ling-yi Z, Bang-cheng L, Ying C. jie, High ductility cementitious composites incorporating seawater and coral sand (SCS-HDCC) for offshore engineering: Microstructure, mechanical performance and sustainability. Cem Concr Compos. 2024;147.
[244] Ahmed MA, Ahmed SA, Metwally ME, Sherif MA, Tobbala DE. Preparation of nano-silica from rice husk ash using acid chemical treatment and burning. The International Conference of Engineering Sciences and Applications, Aswan, Egypt, 29-31 January 2016; 2016.

[245] Chen Q, Rong H, Tao G, Nimbalkar S, Xie K. Fatigue characteristics of nano-SiO_2 cemented soil under coupled effects of dry-wet cycle and seawater corrosion. Constr Build Mater. 2023;401:132579.
[246] Nilimaa J. Smart materials and technologies for sustainable concrete construction. Dev Built Environ. 2023;15:100177.
[247] Monteiro H, Moura B, Soares N. Advancements in nano-enabled cement and concrete: Innovative properties and environmental implications. J Build Eng. 2022;56:104736.
[248] Hanus MJ, Harris AT. Nanotechnology innovations for the construction industry. Prog Mater Sci. 2013;58(7):1056–102.