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Engineering and Science

Nanomaterials in Concrete: Mechanisms of Action, Benefits, and Future Perspectives – A Theoretical Review

Nanomateriais no Concreto: Mecanismos de Ação, Benefícios e Perspectivas Futuras – Uma Revisão Teórica

[1]Márcio Heron da Silveira Júnior, [2]Renan Zunta Raia

[1]Master in Materials Science and Engineering – UniBrasil Centro Universitário
(marciosilveira@unibrasil.com.br)
[2]PhD in Forest Engineering – UniBrasil Centro Universitário (renanraia@unibrasil.com.br)

ABSTRACT: The incorporation of nanomaterials into concrete represents a significant innovation in civil engineering, capable of enhancing mechanical properties, durability, and functionality of structures. This paper presents a theoretical review of the main nanomaterials used in concrete composition—such as nano-structured silica, titanium dioxide, and carbon nanotubes—their mechanisms of action, benefits, as well as technical, economic, and environmental challenges related to their application. Future perspectives for the consolidation of this technology in construction are also discussed, highlighting its potential for developing more sustainable and intelligent materials. It is concluded that, despite current obstacles, advances in nanotechnology applied to concrete point to an inevitable and promising trend in the field.

Keywords: Nano-silica. Titanium dioxide. Carbon nanotubes. Cementitious composites. Sustainability.

RESUMO: A incorporação de nanomateriais ao concreto representa uma inovação significativa na engenharia civil, capaz de aprimorar propriedades mecânicas, durabilidade e funcionalidade das estruturas. Este artigo apresenta uma revisão teórica sobre os principais nanomateriais utilizados na composição do concreto — como a sílica nanoestruturada, o óxido de titânio e os nanotubos de carbono — seus mecanismos de atuação, benefícios, bem como os desafios técnicos, econômicos e ambientais relacionados à sua aplicação. Discute-se ainda as perspectivas futuras para a consolidação dessa tecnologia na construção civil, evidenciando seu potencial para o desenvolvimento de materiais mais sustentáveis e inteligentes. Conclui-se que, apesar dos obstáculos atuais, os avanços na nanotecnologia aplicada ao concreto apontam para uma tendência inevitável e promissora na área.

Palavras-Chave: Nanossílica. Dióxido de titânio. Nanotubos de carbono. Compósitos cimentícios. Sustentabilidade.

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1. INTRODUCTION

The growing demand for more durable, resistant, and sustainable construction materials has driven the search for technological innovations in the civil engineering sector. Concrete, one of the most widely used materials in the world, presents significant limitations regarding tensile strength, durability in aggressive environments, and the development of cracks over time (MEHTA; MONTEIRO, 2014). In this context, the application of materials science knowledge has proven essential for enhancing the properties of traditional concrete.

In recent years, advances in nanotechnology have enabled the development of materials with nanometric-scale structures, whose physicochemical properties differ significantly from those observed in their conventional forms (SANCHEZ; SOBOLEV, 2010). Among these materials, nano-structured silica (nano-SiO_2), titanium dioxide (TiO_2), and carbon nanotubes (CNTs) stand out, having been incorporated into concrete with the aim of improving its mechanical and functional characteristics (JALAL et al., 2015; KHALEEL et al., 2021).

Several studies indicate that the addition of nanomaterials to concrete can provide benefits such as increased mechanical strength, reduced porosity, refined microstructure, and accelerated hydration of cementitious compounds (QUARCIONI et al., 2018). Furthermore, certain nanomaterials present self-cleaning, photocatalytic, and antimicrobial properties, contributing to the long-term durability and functionality of structures (GHORBANI; SHAFIGH; MALEKI, 2020). However, despite promising advances, significant challenges remain regarding the dispersion of nanomaterials in the cementitious matrix, production costs, the lack of technical standardization, and the potential environmental impacts arising from their use (LEE; KURTIS, 2010).

In this context, the present article aims to present a theoretical review on the use of nanomaterials in concrete, addressing their main mechanisms of action, the benefits associated with their incorporation, and the technical and environmental limitations involved. Based on the analysis of recent studies from national and international literature, this work seeks to contribute to the understanding of the potential of these materials in civil construction, as well as to outline future perspectives for the consolidation of their application on an industrial scale.

2. MATERIALS AND METHODS

This study is a theoretical literature review with a thematic focus, aiming to consolidate and discuss scientific advances related to the application of nanomaterials in concrete, analyzing the main types used, their mechanisms of action, benefits, limitations, and perspectives for use in civil engineering. The approach adopts characteristics of an integrative review, as proposed by Botelho, Cunha, and Macedo (2011), and incorporates elements of the systematic mapping study described by Kitchenham et al. (2009), seeking to provide a broad and structured view of the state of the art.

The search and selection of materials were carried out between May and July 2025, using the following main scientific databases: ScienceDirect, Scopus, SpringerLink, Google Scholar, and Web of Science. The search descriptors used were: “nanomaterials in concrete”, “nano-silica”, “titanium dioxide concrete”, “carbon nanotubes cement composites”, “smart concrete”, “durability”, “microstructure”, “nanotechnology in civil engineering”. The keywords were combined using Boolean operators (“AND”, “OR”) to broaden the research coverage.

The publication period for the articles considered ranged from 2010 to 2024, with an emphasis on peer-reviewed studies and review or experimental articles published in indexed scientific journals. Classic books in the field of materials science and concrete, such as the works of Mehta and Monteiro (2014), which provide a consolidated theoretical foundation, were also included.

Inclusion criteria comprised publications that directly addressed the incorporation of nanomaterials into concrete, focusing on their physicochemical properties, impacts on microstructure, mechanical performance, and durability. Publications that addressed only nanotechnological aspects unrelated to civil engineering, duplicated articles, or those without full-text access were excluded.

The content analysis was conducted qualitatively, with categorization by type of nanomaterial, mechanism of action, advantages, limitations, and future perspectives. The contributions of each publication were interpreted in light of the practical applicability of nanomaterials in civil construction, prioritizing approaches that highlight innovation, sustainability, and technical feasibility.

3. RESULTS AND DISCUSSIONS

Nanotechnology can be defined as the field of science and engineering dedicated to manipulating matter at the nanometric scale, typically between 1 and 100 nanometers (SANCHEZ; SOBOLEV, 2010). At this scale, materials exhibit unique properties compared to their micro- or macro-scale forms, such as high specific surface area, increased chemical reactivity, and distinct optical and mechanical characteristics, among others (JALAL et al., 2015).

In the context of civil engineering, nanomaterials have gained prominence due to their ability to significantly modify the microstructure and, consequently, the performance of cementitious composites. Their incorporation can result in denser, stronger, and more durable concretes, contributing to innovation in construction (LEE; KURTIS, 2010).

The effects of nanomaterials on concrete are strongly linked to their morphology, chemical structure, and ability to interact with cement hydration products. For example, nano-silica (SiO_2) acts as a highly reactive pozzolanic agent, while also filling capillary voids and refining the cement matrix (GHORBANI; SHAFIGH; MALEKI, 2020). Titanium dioxide (TiO_2), in addition to its physical properties, exhibits photocatalytic behavior, enabling additional functions such as self-cleaning surfaces and pollutant degradation (SANCHEZ; SOBOLEV, 2010).

Another relevant aspect of nanomaterials is their ability to act as nucleation sites for hydration products, accelerating chemical reactions within the cementitious matrix (KHALEEL et al., 2021). This property directly influences the kinetics of compounds such as calcium silicate hydrate (C-S-H), the primary contributor to concrete's mechanical strength (MEHTA; MONTEIRO, 2014).

Furthermore, nanomaterials can be classified according to their chemical composition and morphological structure. The main types studied in civil engineering include:

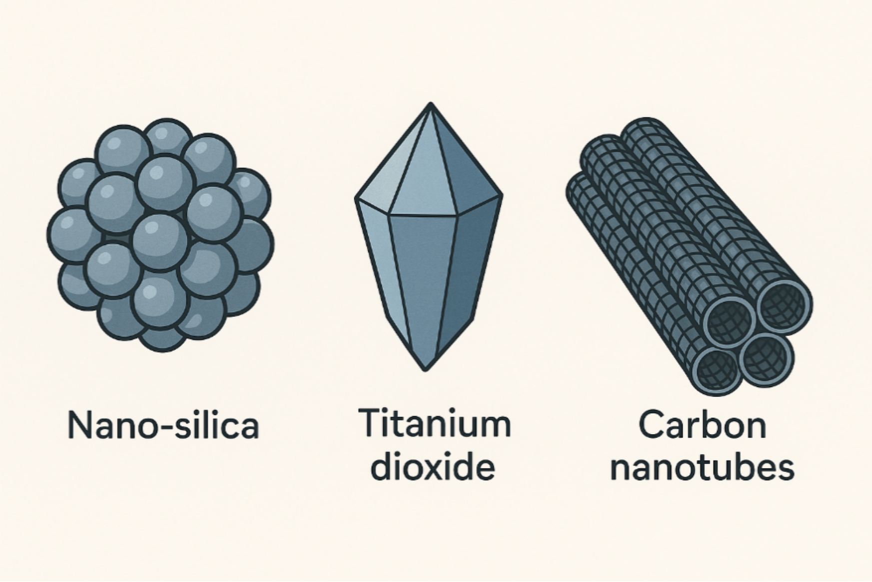
- Inorganic nanoparticles (e.g., nano-SiO_2, TiO_2, Al_2O_3),
- Carbon nanofibers and nanotubes (CNTs),
- Metallic nanoparticles (e.g., Ag, ZnO),
- Hybrid or functional materials, developed with specific properties for advanced applications (QUARCIONI et al., 2018).

Despite their potential benefits, it is important to note that large-scale use of nanomaterials still faces limitations regarding uniform dispersion in cementitious mixtures and variability in synthesis methods, which affects the reproducibility of results in the field (LEE; KURTIS, 2010).

3.1 Main Nanomaterials Used in Concrete

The incorporation of nanomaterials into concrete has been the subject of extensive research in recent decades, primarily due to their ability to improve the mechanical, thermal, chemical, and functional properties of the cementitious matrix. Among the most studied and applied nanomaterials in cement-based systems are nano-structured silica (nano-SiO_2), titanium dioxide (TiO_2), and carbon nanotubes (CNTs). Figure 1 presents a representation of the main nanomaterials used in concrete.

Figure 1 – Representation of the main nanomaterials used in concrete: spherical nano-silica particles, crystalline structures of titanium dioxide, and cylindrical-shaped carbon nanotubes.



These materials act through different mechanisms, such as pore filling, nucleation of hydrated compounds, secondary pozzolanic reactions, and specific functionalizations, contributing to improvements in compressive and tensile strength, durability against aggressive agents, and even the introduction of innovative functionalities, such as photocatalytic properties and intelligent sensing (PACHECO et al., 2021; ABDULLAH et al., 2021; ZHANG et al., 2022). Table 1 presents a comparison of the main nanomaterials used in concrete.

Table 1 – Characteristics, effects, and limitations of the main nanomaterials applied in concrete

Nanomaterial	Typical Structure / Shape	Desired Properties	Recommended Concentration	Main Disadvantages	References
Nano-SiO_2	Spherical, amorphous	Microstructure refinement; strength improvement	1–5%	Agglomeration; reduced workability	(SANCHEZ; SOBOLEV, 2010; PACHECO et al., 2021; LI et al., 2024; JALAL et al., 2015; QUARCIONI et al., 2018)
TiO_2 (anatase)	Crystalline, nanoparticulate	Photocatalysis; self-cleaning	2–5%	Low dispersion; moderate cost	(GHORBANI; SHAFIGH; MALEKI, 2020; LIU et al., 2023; ZHOU et al., 2022; AHMADI et al., 2022; ZHANG et al., 2022)
CNTs (Carbon Nanotubes)	Cylindrical, tubular	Mechanical reinforcement; electrical conductivity	< 0.1%	High cost; difficult dispersion	(KHALEEL et al., 2021; YANG et al., 2024; RAO; SHARMA, 2024; MALEKI et al., 2020; ZHANG et al., 2022)

3.1.1 Nano-Structured Silica (Nano-SiO_2)

Nano-silica is widely regarded as one of the most effective and versatile nanomaterials in cementitious systems. Its high specific surface area (above 200 m^2/g) and highly reactive amorphous structure not only accelerate the initial hydration of cement but also promote pozzolanic reactions with the released calcium hydroxide, generating a greater amount of calcium silicate hydrate (c-s-h), the phase responsible for the mechanical strength of concrete (PACHECO et al., 2021; QUARCIONI et al., 2018).

Studies indicate that the addition of nano-SiO_2 in amounts between 1% and 3% by cement mass can increase compressive strength by up to 30% at early ages and up to 15% at 28 days, while significantly reducing chloride and water permeability (SANCHEZ; SOBOLEV, 2010; MALEKI et al., 2020). This occurs due to the effective filling of capillary pores and the refinement of the matrix microstructure, making it more homogeneous and less susceptible to crack propagation.

Additionally, nano- SiO_2 contributes to the improvement of the interfacial transition zone (itz) between the paste and aggregates, traditionally considered the weakest region of concrete. Its presence densifies this area, enhances adhesion, and reduces the formation of microcracks (ABDULLAH et al., 2021).

However, excessive incorporation of nano-SiO_2 (>5%) may lead to particle agglomeration, impairing workability and, in some cases, creating points of weakness in the matrix. Therefore, it is essential to employ proper dispersion techniques, such as the use of superplasticizers and ultrasonic dispersion (PACHECO et al., 2021). Table 2A presents representative Studies on Nano-Silica (SiO_2) in Concrete.

Table 2A – Representative Studies on Nano-Silica (SiO_2) in Concrete

Reference	Study Type	Main Findings	Conclusion
SANCHEZ; SOBOLEV (2010)	Review	↑ strength (20–30%), ↓ porosity	Effective pozzolanic reaction
PACHECO et al. (2021)	Experimental	Improved ITZ and matrix densification	Higher durability and strength
MARTÍNEZ; ORTIZ (2023)	LCA + Experimental	↓ 15% embodied carbon	Sustainable mechanical gain
SANTOS; OLIVEIRA (2023)	LCA (Brazil)	↓ CO_2 emissions (12%)	Environmentally viable

3.1.2 Titanium Dioxide (TiO_2)

Titanium dioxide (TiO_2) is a remarkable nanomaterial due to its photocatalytic properties, particularly in its anatase crystalline form. When exposed to UV radiation, TiO_2 acts as a catalyst in the degradation of organic compounds and nitrogen oxides (NOx), imparting self-cleaning and air-purifying properties to concrete (SHAFIGH; MALEKI, 2020; ABDULLAH et al., 2021).

This property is especially valuable in urban and environmental applications, such as building facades, sidewalks, pavements, and tunnels, where the accumulation of pollutants can compromise the aesthetic and structural durability of concrete. Furthermore, studies indicate that the incorporation of TiO_2 at levels of 1% to 5% can contribute to microstructure refinement and increased surface abrasion resistance, as well as reduce accelerated aging due to UV exposure and atmospheric agents (QUARCIONI et al., 2018; AHMADI et al., 2022).

Other research demonstrates that TiO_2 can reduce biofilm and fungal growth in humid environments, reinforcing its antimicrobial role in exposed constructions (ZHANG et al., 2022). However, as with nano-silica, proper dispersion of the material remains a challenge, requiring careful control during mixing.

In addition to the pure anatase form, anatase/rutile phase mixtures have been investigated to enhance efficiency under different lighting conditions. Efforts have also been made to functionalize TiO_2 with dopants (e.g., N, Ag, Zn) for activation under visible light (GHORBANI et al., 2020). Table 2B presents representative Studies on Titanium Dioxide (TiO_2) in Concrete.

Table 2B – Representative Studies on Titanium Dioxide (TiO_2) in Concrete

Reference	**Study Type**	**Main Findings**	**Conclusion**
GHORBANI; SHAFIGH; MALEKI (2020)	Review	↑ durability; self-cleaning effect	Suitable for urban environments
ZHOU et al. (2022)	Experimental	↓ 18% NOx concentration	Effective photocatalytic activity
LIU et al. (2023)	LCA + Experimental	↓ 12% embodied CO_2	Dual performance and sustainability
FERNANDES et al. (2023)	Sustainability	Integration with SDG 11	Supports sustainable construction

3.1.3 Carbon Nanotubes (CNTs)

Carbon nanotubes (CNTs) are cylindrical structures formed by rolled graphene sheets, exhibiting exceptional mechanical properties. Their tensile strength can exceed 60 GPa, and their elastic modulus surpasses 1 TPa (KHALEEL et al., 2021). These characteristics make them ideal candidates for structural reinforcement of cementitious matrices, even in very small amounts (typically between 0.01% and 0.1% by cement mass).

CNTs act as micro-reinforcements, connecting cement grains and forming intergranular bridges, which reduces microcrack propagation and increases the toughness, tensile strength, and impact resistance of concrete. Research has shown increases of over 20% in compressive strength and up to 40% in tensile strength when CNTs are properly dispersed (JALAL et al., 2015; ZHANG et al., 2022). Table 2C presents representative Studies on Carbon Nanotubes (CNTs).

Table 2C – Representative Studies on Carbon Nanotubes (CNTs)

Reference	**Study Type**	**Main Findings**	**Conclusion**
KHALEEL et al. (2021)	Review	↑ tensile 40%, ↑ toughness	Excellent reinforcement
YANG et al. (2024)	Experimental	↑ electrical conductivity	Enables smart concrete
RAO; SHARMA (2024)	Review + LCA	High energy footprint	Green synthesis needed
ARAUJO; COSTA (2024)	Experimental	0.05% optimal dosage	Technically viable, moderate cost

Another innovative aspect of CNTs is their electrical and thermal conductivity. This enables the development of smart concretes capable of monitoring deformations, cracks, and structural integrity through variations in electrical resistance — a promising approach for self-diagnosing infrastructure (MALEKI et al., 2020; AHMADI et al., 2022).

However, the use of CNTs still faces considerable challenges: their high production cost, inhalation toxicity risk, and, most importantly, the difficulty of achieving homogeneous dispersion due to their tendency to agglomerate and hydrophobic nature. Strategies such as the use of surfactants, chemical functionalization, and ultrasonic energy application have been adopted to mitigate these issues (ABDULLAH et al., 2021).

3.2 Mechanisms of Action in Concrete

The introduction of nanomaterials into concrete provides significant modifications to its internal structure, acting on multiple scales through various physical, chemical, and functional mechanisms. These mechanisms are responsible for improvements in mechanical strength, durability, and even the incorporation of advanced properties, such as photocatalysis and electrical conductivity. The main mechanisms of action of nanomaterials in cementitious composites are detailed below.

3.2.1 Increased Matrix Density

Nanomaterials possess a high specific surface area and extremely small dimensions, which allows them to occupy the micropores of the cementitious matrix. Thus, they act as physical filling agents, reducing the volume of voids and, consequently, the total porosity of concrete. This action results in a denser, more compact matrix that is more resistant to the penetration of aggressive agents, such as chloride ions, carbon dioxide, and sulfates (ABDULLAH et al., 2021; PACHECO et al., 2021; ZHANG et al., 2022).

For example, in a study conducted by Lin-Ping et al. (2020), the addition of nano-silica to concrete significantly reduced capillary absorption and chloride ion permeability, while simultaneously increasing compressive and tensile strength after aging in an acidic environment.

3.2.2 Microstructure Refinement

Nano-silica and other pozzolanic nanomaterials react with calcium hydroxide ($Ca(OH)_2$) released during cement hydration, promoting the additional formation of calcium silicate hydrate (C-S-H), the phase responsible for providing strength and cohesion to the matrix. This phenomenon reduces the amount of free $Ca(OH)_2$ — a more fragile and soluble substance — and generates a more homogeneous, refined, and resilient microstructure (JALAL et al., 2015; MALEKI et al., 2020).

The increased content of C-S-H decreases pore connectivity, enhancing concrete durability and increasing its compressive strength by up to 25%, as observed by Fallah and Nematzaheh (2017).

3.2.3 Acceleration of Hydration

Nanoparticles also function as nucleation sites for cement hydration products, accelerating the formation of C-S-H gel, ettringite, and portlandite at early ages. This acceleration is particularly beneficial in constructions requiring rapid formwork removal, such as precast elements or concreting in cold climates (QUARCIONI et al., 2018; MA et al., 2025).

For example, the addition of nano-TiO_2 was found to significantly increase the initial hydration rate, especially when combined with mineral additions such as metakaolin or limestone filler (MA et al., 2025).

3.2.4 Enhancement of the Paste-Aggregate Interface

The interfacial transition zone (ITZ), situated between the cementitious paste and the aggregates, is conventionally the most porous region and prone to fissure formation. The incorporation of nanomaterials helps to decrease the porosity in this zone, thereby promoting stronger adhesion between the paste and the aggregate and mitigating the occurrence of mechanical discontinuities (MEHTA; MONTEIRO, 2014; ZHANG et al., 2022).

This refinement of the ITZ leads to a more uniform internal stress distribution, a reduction in microcracking, and a significant enhancement of the concrete's tensile strength and modulus of elasticity (ABDULLAH et al., 2021).

3.2.5 Special Functional Properties

Beyond the structural enhancements promoted by incorporating nanomaterials into concrete, certain nanoparticles confer special functional properties that significantly broaden its scope of application. A prominent example is the photocatalytic activity of titanium dioxide (TiO_2). When exposed to ultraviolet radiation, TiO_2 initiates oxidation reactions that can degrade organic compounds and nitrogen oxides (NOx). This process endows the concrete with self-cleaning and air-purifying capabilities, encouraging its use in building facades, urban tunnels, and pavements exposed to atmospheric pollutants (GHORBANI; SHAFIGH; MALEKI, 2020; QUARCIONI et al., 2018).

Another significant advancement is achieved with carbon nanotubes (CNTs). When adequately dispersed within the cementitious matrix, CNTs form conductive networks that can monitor physical changes in the concrete. By measuring variations in electrical resistivity, these nanomaterials enable the real-time detection of strain, cracking, and other structural anomalies, leading to the development of what is termed "smart concrete" (KHALEEL et al., 2021; MALEKI et al., 2020).

Moreover, recent studies have shown that the presence of CNTs and other nanoparticles can enhance the high-temperature resistance of concrete. These additions mitigate the phenomenon of spalling—the explosive fragmentation of the concrete surface at elevated temperatures—and help preserve structural integrity after severe thermal events, thus improving the material's performance in fire scenarios and industrial settings (ZHANG et al., 2022).

3.2.6 Limitations of the Mechanisms

Despite the promising advancements in the use of nanomaterials in civil engineering, the practical application of these technologies in concrete still faces significant challenges that limit their large-scale adoption. One of the primary obstacles is the difficulty in achieving a homogeneous dispersion of nanoparticles within the cementitious matrix. Due to their high specific surface area and intense surface energy, these particles tend to agglomerate, forming clusters that compromise, rather than improve, the composite's properties. Agglomeration can create regions of structural heterogeneity, stress concentration points, and micro-voids, which act as crack initiators and reduce the efficiency of the desired mechanisms, such as pore-filling and matrix reinforcement (LEE; KURTIS, 2010; ABDULLAH et al., 2021).

Furthermore, inadequate dispersion impairs the pozzolanic and photocatalytic effects, as the active surface of the particles becomes partially unavailable. To achieve an effective distribution, various strategies have been investigated, including the use of high-intensity ultrasonication, the addition of dispersants and surfactants, and the employment of polycarboxylate-based superplasticizers (PACHECO et al., 2021). Although these techniques can enhance incorporation efficiency, many require rigorous process control, specialized equipment, and increased costs—factors that hinder the transition from research to practical application on construction sites.

Another point of concern relates to the dosage of nanomaterials. Studies indicate that contents exceeding the optimal limits—generally between 1% and 5% by cement mass for nano-silica, and below 0.1% for carbon nanotubes—tend to deteriorate the concrete's performance, particularly in its fresh state. High concentrations negatively affect workability, making the mixture more viscous, cohesive, and difficult to compact, which compromises consolidation, finishing, and final strength (SANCHEZ; SOBOLEV, 2010; FALLAH; NEMATZADEH, 2017).

Moreover, the lack of standardization regarding the types, morphologies, sizes, and production methods of nanomaterials complicates the reproducibility of results across different studies. This variability also contributes to the difficulty in establishing technical standards for their use in structural projects, limiting the regulatory support necessary for the approval of works extensively using these technologies (JALAL et al., 2015; GHORBANI; SHAFIGH; MALEKI, 2020).

An additional limiting factor is the cost of the materials. Although the price of nano-silica has become relatively accessible, materials such as CNTs and graphene still have high production costs and require complex purification and functionalization steps, which restricts their economic viability for conventional construction projects. Therefore, the large-scale application of nanomaterials in concrete will depend on advances in both cost reduction and overcoming the aforementioned technical challenges. Table 2 presents the effects observed in the literature with the use of different nanomaterials in concrete.

Table 2 – Results reported in the literature with the incorporation of nanomaterials in cementitious composites.

REFERENCE	**NANOMATERIAL**	**PROPERTIES ANALYZED**	**OBSERVED RESULTS**
JALAL ET AL. (2015)	Nano-Silica	Strength, durability	↑ compressive strength (22%), ↓ porosity
FALLAH; NEMATZADEH (2017)	Nano-Silica + fibers	Mechanical and physical	↑ strength, ↑ elastic modulus, ↓ absorption
KHALEEL ET AL. (2021)	CNTs	Strength, conductivity	↑ tensile strength, electrical conductivity for sensing
LIN-PING ET AL. (2020)	Nano-Silica and Alumina	Durability (acid attack)	↓ mass loss, ↑ performance in acidic medium

3.3 Sustainability, Life-Cycle Assessment, and Embodied Carbon

The pursuit of sustainable solutions in civil engineering has led to the development of technologies that not only improve material performance but also reduce environmental impacts throughout their life cycle. In this context, nanomaterials applied to concrete—such as nano-silica (SiO_2), titanium dioxide (TiO_2), and carbon nanotubes (CNTs)—represent a promising alternative for reducing the carbon footprint associated with conventional cementitious composites.

Recent studies indicate that the incorporation of nanomaterials into concrete allows for a reduction in the water/cement ratio and a significant improvement in the durability of structures. Consequently, this extends the service life of buildings and reduces the need for maintenance and reconstruction (Zhang et al., 2022; Maleki et al., 2020). This translates into a lower demand for Portland cement over time, a material responsible for approximately 8% of global CO_2 emissions (Ghorbani et al., 2020).

Furthermore, the partial replacement of cement with nanostructured pozzolanic materials derived from industrial by-products (such as rice husk ash or ground glass) has gained prominence as a strategy for a circular economy and reduced fossil fuel consumption. This approach not only decreases the extraction of non-renewable raw materials but also directly contributes to mitigating environmental impacts and valorizing industrial sub-products (Quarcioni et al., 2018; Ma et al., 2025).

However, the sustainability of these materials must be analyzed holistically, considering the impacts associated with the synthesis, handling, use, and disposal of nanomaterials. The production processes for certain nano-additives, such as carbon nanotubes, still involve high energy consumption and complex purification steps, which can compromise the environmental benefits if not used in optimized dosages (Khaleel et al., 2021). In this regard, life cycle assessments (LCAs) are recommended as essential tools to transparently quantify the actual environmental gains against the energetic costs and indirect emissions.

Another critical aspect involves the proper disposal of waste containing nanomaterials, especially those with chemical and physical properties that may pose ecotoxicological risks to aquatic and terrestrial environments. Although long-term effect studies are still in development, the creation of specific management and disposal protocols for these materials is recommended, based on international standards and emerging scientific evidence (Sanchez & Sobolev, 2010; Jalal et al., 2015).

3.3.1 Nano-Silica and Life-Cycle Analysis (LCA)

Life-cycle assessments consistently indicate that nano-silica provides one of the most favorable balances between mechanical performance enhancement and embodied carbon reduction among nanomaterials applied to cementitious composites. Its high pozzolanic reactivity reduces clinker demand, lowers the water-to-cement ratio, and refines the microstructure, resulting in improved durability and extended service life (Li; Zeng, 2023). LCA studies report reductions of **10–18%** in embodied carbon when nano-silica partially replaces cement or is sourced from industrial by-products such as rice husk ash (Huang; Deng; Li, 2023; Martínez; Ortiz, 2023; Santos; Oliveira, 2023). Additionally, the mechanical improvements achieved with nano-silica allow for the design of more slender structural elements, further decreasing material consumption and contributing to long-term environmental benefits.

3.3.2 Titanium Dioxide (TiO_2) and Carbon Efficiency

Although TiO_2 nanoparticles require high energy for synthesis, their incorporation into concrete—particularly in façade and pavement applications—can reduce maintenance frequency, surface degradation, and cleaning needs, partially compensating for their initial embodied carbon (Liu et al., 2023; Zhou et al., 2022). Recent LCA studies demonstrate net CO_2 reductions of up to 12% compared to conventional coatings, primarily due to enhanced durability, extended service life, and the photocatalytic degradation of atmospheric pollutants such as NOx and organic compounds (Luo; Zhang, 2023; Molina; Torre, 2023). These co-benefits strengthen the environmental justification for TiO_2-modified concretes, especially in dense urban environments.

3.3.3 Carbon Nanotubes (CNTs) and Sustainability Challenges

Carbon nanotubes exhibit exceptional mechanical performance but also possess the highest embodied carbon among nanomaterials, largely due to energy-intensive synthesis routes such as chemical vapor deposition (Rao; Sharma, 2024). Nonetheless, when effectively dispersed, CNTs significantly enhance tensile strength, toughness, and crack-bridging capacity, enabling reductions in structural material volume and improving long-term durability (Singh; Kaur, 2023; Yang; Li; Zhu, 2024). Emerging research has focused on low-temperature and bio-derived synthesis pathways to mitigate the environmental impacts of CNT production (Fernandes; Maia; Lima, 2023). Over a full life cycle, CNT-enhanced concretes—particularly those used in smart sensing applications—may offset part of their initial carbon footprint by reducing inspection frequency, preventing premature failures, and extending the service life of critical infrastructure.

3.4 Challenges and Limitations in the Use of Nanomaterials in Concrete

Despite the enormous potential for the application of nanomaterials to improve concrete performance, their adoption on an industrial scale still faces several technical, economic, environmental, and regulatory barriers. Although results obtained in a laboratory setting indicate significant improvements in mechanical properties, durability, and innovative functionalities, the transition to their use on construction sites depends on overcoming a series of challenges that still compromise their practical viability.

One of the primary technical obstacles relates to the dispersion of nanoparticles within the cementitious matrix. Due to high surface energy and a tendency to agglomerate, nanomaterials such as nano-silica, TiO_2, and carbon nanotubes (CNTs) form clusters during mixing, which compromises the homogeneity of the composite. These agglomerations act as points of weakness that reduce the effectiveness of the expected properties, creating regions with inferior mechanical behavior, elevated local porosity, and a risk of premature cracking (LEE; KURTIS, 2010). Dispersion techniques like ultrasonication, the use of polycarboxylate-based superplasticizing admixtures, and the application of surfactants have been proposed to mitigate this problem. However, they entail greater technical complexity, additional cost, and the need for rigorous control during the mixing process (GHORBANI; SHAFIGH; MALEKI, 2020; PACHECO et al., 2021).

The cost of nanomaterials is another significant obstacle, particularly for materials with a high degree of purity or complex production processes, such as carbon nanotubes and graphene. These materials are still predominantly manufactured on a laboratory or pilot scale, using methods that involve high energy consumption and lengthy purification steps. Consequently, the cost per kilogram of these admixtures can far exceed the value of conventional concrete components, rendering their use unfeasible in infrastructure projects, social housing, or large-scale buildings where cost optimization is a central requirement (KHALEEL et al., 2021; SANCHEZ; SOBOLEV, 2010).

In addition to technical and economic aspects, there are growing concerns regarding the impacts of nanomaterials on human health and the environment. The scientific literature is not yet conclusive regarding the effects of prolonged exposure to nanoparticles, especially in cases of inhalation or dermal contact during the handling of dry powders. The potential for bioaccumulation, cellular toxicity, or adverse effects on aquatic and terrestrial organisms following the improper disposal of these materials raises serious questions about their safety (SANCHEZ; SOBOLEV, 2010). The lack of specific regulations on the storage, transport, handling, and disposal of nanomaterials constitutes a significant gap in technical and environmental legislation, hindering their acceptance by construction companies, regulatory bodies, and insurance providers (QUARCIONI et al., 2018).

From the standpoint of technical standardization, there are still no consolidated guidelines on appropriate incorporation methods, recommended dosage ranges, technological control procedures, or performance criteria for concrete modified with nanomaterials. This absence of standardization creates uncertainty among professionals in the field and complicates the approval of structural projects that utilize these innovative technologies. Even in leading research centers, the variability in experimental results obtained with different sources and synthesis methods for nanomaterials compromises reproducibility and comparability between studies, representing a significant obstacle to the creation of consistent technical standards (JALAL et al., 2015; MEHTA; MONTEIRO, 2014).

Another relevant challenge is related to the workability of concrete in its fresh state. The addition of nanoparticles tends to increase the viscosity of the mixture due to their high specific surface area and absorption of water from the matrix. This can lead to a reduction in slump, requiring adjustments in the dosage of water and plasticizing admixtures. The need to balance rheology, setting time, and final performance is critical, especially in self-consolidating concrete or in applications involving pumping over long distances (PACHECO et al., 2021; GHORBANI; SHAFIGH; MALEKI, 2020)

From an environmental perspective, studies that assess the complete life cycle of nanomaterials applied to concrete—from the extraction of raw materials and energy consumption in synthesis processes to the impacts of disposal or degradation of structures over time—remain scarce. The absence of robust environmental assessments prevents a true understanding of the sustainability gains afforded by nanomaterials, which is particularly concerning given the growing demand for greener constructions with a smaller carbon footprint (SANCHEZ; SOBOLEV, 2010; MALEKI et al., 2020).

Finally, it is important to emphasize that the adoption of nanotechnology-based solutions in the construction sector depends not only on overcoming technical and economic challenges but also on a cultural shift among professionals. They must be willing to engage in continuous training, adopt new design and quality control practices, and rely on scientific evidence to inform their decisions. Only with the joint advancement of academic research, industrial development, and regulatory frameworks will it be possible to make the widespread use of nanomaterials in concrete viable, safe, and economically accessible.

4. FINAL CONSIDERATIONS

The application of nanotechnology to concrete represents one of the most innovative and promising frontiers in contemporary materials engineering. The growing interest in sustainable, durable, and intelligent solutions within the construction industry has spurred the development of nanomaterials with multiple functionalities, capable of significantly transforming the performance of conventional concrete. With the continuous advancement of nanoparticle synthesis, functionalization, and dispersion techniques, alongside improvements in industrial processes and reductions in production costs, the economic and technical viability of their large-scale application is becoming increasingly plausible (QUARCIONI et al., 2018; JALAL et al., 2015).

Recent trends indicate a clear shift in research toward the development of multifunctional concretes, which combine structural enhancements with innovative properties such as self-healing, photocatalysis, electrical conductivity, and the real-time monitoring of deformations and cracks. The integration of nanotechnology with embedded sensory systems points toward the consolidation of so-called "smart concretes," which could act as active elements in the predictive maintenance of structures, promoting greater safety and operational efficiency (KHALEEL et al., 2021; MALEKI et al., 2020).

In addition to advanced functionalities, the environmental potential of these materials is also noteworthy. The development of nanomaterials from renewable sources, industrial waste, and low-impact environmental processes is a growing line of research. For instance, studies already indicate the feasibility of using rice husk ash, ground glass waste, and thermally activated clays as precursors for producing nano-silica and other pozzolanic additives. These approaches not only reduce the final cost of the products but also contribute to a circular economy within the construction industry (GHORBANI; SHAFIGH; MALEKI, 2020; ZHANG et al., 2022).

Another important prospect concerns the need to consolidate technical standards and specific guidelines for the use of nanomaterials in concrete. The establishment of dosage parameters, performance criteria, testing procedures, and safety protocols will afford greater confidence to designers and builders, promoting the transition from academic research to professional practice. International cooperation initiatives among universities, research centers, regulatory bodies, and the construction industry are essential to accelerate this process and ensure the responsible adoption of nanotechnology in the sector (SANCHEZ; SOBOLEV, 2010; MEHTA; MONTEIRO, 2014).

However, it is fundamental to recognize that the consolidation of nanomaterial use in concrete depends not only on resolving technical and economic challenges but also on a paradigm shift within the construction sector. It will be necessary to train engineers, technicians, and managers for the correct application of these technologies, while also ensuring that the environmental impacts and health risks associated with nanoparticle handling are fully understood and managed.

In conclusion, nanotechnology represents a strategic frontier for the future of civil engineering, with the potential to revolutionize not only the performance of materials but also construction methods, monitoring processes, and maintenance strategies. Although obstacles persist, the trajectory of innovation points toward a future where concrete will cease to be merely a passive structural material and will become an active, intelligent, and adaptive element suited to the demands of the 21st century. For this to occur, integrated efforts from researchers, policymakers, construction professionals, and the materials industry will be essential to ensure that nanotechnology is applied in a manner that is safe, efficient, and sustainable.

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