DISCIPLINARUM SCIENTIA
Disciplinarum Scientia. Série: Naturais e Tecnológicas
Santa Maria, v. 27, n. 2, p. 61-85, 2026
Recebido em: 20.11.2025. Aprovado em: 09.04.2026.
ISSN 2176-462X | DOI: doi.org/10.37779/nt.v27i2.5615

APPLICATION OF CARBON NANOTUBES IN CONCRETE: A TECHNICAL REVIEW

APLICAÇÃO DE NANOTUBOS DE CARBONO EM CONCRETO: UMA REVISÃO TÉCNICA

Fábio Santos da Rocha Loures[1], Adriano Vasconcellos Sichonany[2], Sergio Roberto Mortari[3], Márcio Felipe Floss[4], William Leonardo da Silva[5] e Cláudia Lange dos Santos[6]

ABSTRACT

The incorporation of carbon nanotubes into concrete has emerged as a promising advancement in civil engineering, offering significant improvements in the mechanical properties and durability of the materials produced. To fully leverage the potential of this revolutionary field, it is essential to understand the role of each of its constituent parts, the production processes, and stay up-to-date on key discoveries, all of which are the objectives of this review. Therefore, an exploratory approach was conducted with bibliographic research on platforms such as Scopus, Web of Science, and Science Direct, covering publications up to 2025. The research included 654 documents, of which 56 were selected after applying exclusion criteria. The results highlight the effectiveness of nanotubes in improving the mechanical properties of concrete and the importance of a good methodology to overcome obstacles such as adequate dispersion of materials. Notably, their use in various fields of civil engineering is rapidly evolving, particularly with the advent of new computational tools, resulting in new production processes and new materials.

Keywords: nanomaterials; cementitious materials; structures; civil engineering.

RESUMO

A incorporação de nanotubos de carbono no concreto tem surgido como um avanço promissor na engenharia civil, oferecendo melhorias significativas nas propriedades mecânicas e na durabilidade dos materiais produzidos. Para aproveitar ao máximo o potencial desse campo revolucionário, é essencial entender o papel de cada uma de suas partes constituintes, os processos de produção, bem como manter-se atualizado sobre as principais inovações do setor, objetivos dessa revisão. Para tanto, foi realizada uma abordagem exploratória, com pesquisa bibliográfica em plataformas como Scopus, Web of Science e Science Direct, abrangendo publicações até 2025. A pesquisa incluiu 654 documentos, dos quais 56 foram selecionados após a aplicação de critérios de exclusão. Os resultados destacam a eficácia dos nanotubos na melhoria das

---

[1] Nanoscience Graduate Program, Franciscan University (UFN), Santa Maria - RS, Brazil. E-mail: fabio.loures@ufn.edu.br. ORCID: https://orcid.org/0000-0002-9800-8216

[2] Nanoscience Graduate Program, Franciscan University (UFN), Santa Maria - RS, Brazil. E-mail: adriano.sichonany@ufn.edu.br. ORCID: https://orcid.org/0009-0009-0129-418X

[3] Nanoscience Graduate Program, Franciscan University (UFN), Santa Maria - RS, Brazil. E-mail: mortari@ufn.edu.br. ORCID: https://orcid.org/0000-0002-1166-3980

[4] Nanoscience Graduate Program, Franciscan University (UFN), Santa Maria - RS, Brazil. E-mail: marcio.floss@ufn.edu.br. ORCID: https://orcid.org/0000-0001-6909-4656

[5] Nanoscience Graduate Program, Franciscan University (UFN), Santa Maria - RS, Brazil. E-mail: w.silva@ufn.edu.br. ORCID: https://orcid.org/0000-0002-7804-9678

[6] Nanoscience Graduate Program, Franciscan University (UFN), Santa Maria - RS, Brazil. E-mail: claudialange@ufn.edu.br. ORCID: https://orcid.org/0000-0003-3492-7157

propriedades mecânicas do concreto e a importância de uma boa metodologia para superar obstáculos tais como a dispersão adequada dos materiais. Notavelmente, seu uso em vários campos da engenharia civil está evoluindo rapidamente, particularmente com o advento de novas ferramentas computacionais, resultando em novos processos de produção e novos materiais.

Palavras-chave: *nanomateriais; materiais cimentícios; estruturas; engenharia civil.*

1 INTRODUCTION

According to a recent publication by the Contractors Society of America (CSA), concrete is considered the most widely used construction material worldwide due to its high mechanical resistance to compression, durability, low cost and energy efficiency. For example, since 2014, concrete consumption has surpassed twice the amount of all other construction materials combined (Gagg, 2014). According to Nilimaa (2023), in 2021, global cement production reached 4.1 billion tons, making it the second most consumed material, just behind the water.

Despite its recognized advantages, concrete has some problems, such as its low tensile strength and its high carbon footprint. According to the Latin American Construction Magazine (CLA, 2023), there is a consensus that, for every ton of standard cement produced, about one ton of carbon dioxide (CO_2) is released into the atmosphere, accounting for approximately 6% of total global carbon emissions. Thus, there is a continuous search for viable solutions to mitigate these characteristics.

To address the issue of low tensile strength, the traditional solution has been the use of steel, whose quality, quantity and positioning vary according to the load and the direction of the forces acting on the structure. However, there are situations where it is desired to produce structures with much higher strength than usual. In these cases, additives and fibers capable of filling voids, altering reaction rates and improving the adhesion between the components of the mixture are used, making it more cohesive and resistant. In this direction, one of the most promising solutions has been the use of Carbon Nanotubes (CNTs), which, if well quantified and adequately distributed, are capable of filling micro and nano-pores, forming micro and nano-bridges and reducing the amount of water and cement used in the mixture, significantly improving the characteristics of the structure (Camacho *et al.*, 2014).

Studies have been proving that the insertion of CNTs in concrete shows very promising results, significantly contributing to the improvement of construction performance (Cea *et al.*, 2025). Despite the meaningful results obtained, it is necessary to emphasize that the manufacturing process of CNTs is still expensive and laborious as it requires the use of detailed physical-chemical processes to overcome the Van der Waals forces acting between the nanotubes and ensure their homogeneous dispersion in the concrete mass (Fenta; Mebratie, 2024).

Interesting initiatives have been taken to find the ideal combinations between the components of the mixture. However, there does not yet seem to be a full consensus on the type and concentration of additives, the sequence of material preparation and their application in the field, which can result in considerable waste of resources or even the compromise of structures intended to support large loads.

In this sense, this work aimed to provide more light on the subject, investigating its main innovations and seeking to find more optimized ways to employ CNTs in concrete structures and, thus, provide an advance in the area of civil construction through the design and execution of more robust and economical buildings.

2 STUDY OF ART

2.1 UNDERSTANDING CONCRETE AND CEMENT HYDRATION PROCESS

Concrete is a widely used building material, consisting primarily of a mixture of cement, aggregates (sand and gravel), water, and occasionally additives. Cement, usually of the Portland type, is the main agglomerating agent that, when mixed with water, forms a paste capable of unite the aggregates into a homogeneous and cohesive mass.

The ratio between the components is crucial to achieving the desired properties of the concrete such as strength, durability, and workability (Mehta; Monteiro, 2014).

The concrete hydration process begins with the chemical reaction between cement and water, forming products such as hydrated calcium silicate (C-S-H) and calcium hydroxide. C-S-H is responsible for most of the mechanical strength of the concrete, while calcium hydroxide contributes to the alkalinity of the medium, protecting steel reinforcements from corrosion. Hydration is an exothermic and progressive process, which extends over years, although most of the strength of concrete develops in the first 28 days of curing the material (Neville, 2016).

It is important to control the amount of water added to the mix, as excess can generate porosity, reducing the strength and durability of the concrete. On the other hand, a lack of water can prevent the cement from fully hydrating, resulting in brittle concrete. The use of additives can improve concrete characteristics such as plasticity, strength, and durability by adjusting the mixing behavior as needed for different applications.

Additives made of nanomaterials are particularly attractive for the replacement of cementitious ones, resulting in environmental, technical and economic advantages (Franco-Luján *et al.*, 2023).

Due to the extraordinary properties of CNTs, such as fine structure, ultra-high specific surface, extremely high modulus of elasticity and strength, elastic and ductile behavior, they have enormous potential to replace part of the main cementitious additives (Jayakumari; Swaminathan; Partheeban, 2023).

2.2 CARBON NANOTUBES IN CONCRETE

CNTs are cylindrical carbon structures with nanometric diameters and micrometric lengths, possessing high tensile strength and excellent electrical and thermal conductivity. Thus, when incorporated into the concrete mass, can act as reinforcements, increasing the mechanical strength, durability and toughness of the material.

During the cement curing process, they contribute to the formation of a denser and more homogeneous matrix by filling microcracks and pores, resulting in a concrete with lower permeability and greater resistance to the penetration of aggressive agents. This characteristic is particularly useful in structures exposed to harsh environments, where the durability of the concrete is a critical factor (Guo *et al*., 2025).

Moreover, CNTs influence the cement hydration process since they can accelerate the hydration reaction, promoting a faster development of hydrated phases, as well as serving as nucleation points for the formation of hydrated products, contributing to a more cohesive and resistant internal structure (Camacho *et al*., 2014). After the curing process, its addition to the concrete results in a material with better mechanical properties and durability. Compression, tensile and flexural strengths can be significantly increased. In addition, the electrical conductivity of CNTs can be exploited to develop the so-called self-sensitive concrete, capable of monitoring deformations and structural damages, providing greater safety and efficiency in the maintenance of infrastructures (Wang; Aslani, 2021).

Despite the various reported advantages of CNTs, due to their exceedingly high morphology and aspect ratio, they have a natural tendency to aggregate, due to the Van der Waals forces acting between them and their low solubility in water, resulting in the loss of their beneficial properties (Dubey, 2021). Because of this, different strategies have been proposed to minimize this problem.

2.3 MAIN DISPERSION METHODS OF CARBON NANOTUBES

The main methods used for the dispersion of CNTs in cementitious matrices can be classified as:

2.3.1 Physical methods

(a) Ultrasonication: a method that uses ultrasonic waves to disperse the CNTs in an aqueous suspension. Ultrasonic energy breaks up clusters of CNTs promoting a more homogeneous distribution. This method is effective, but it must be carefully controlled to prevent degradation of the nanotubes (Rennhofer; Zanghellini, 2021).

(b) Mechanical agitation: This is intense agitation, using high-speed mixers, and can be applied to disperse the CNTs in aqueous suspensions or directly in the cement paste. It is a simple and easy method to implement, but may not be as effective as ultrasonication to completely disperse nanotubes (Rocha; Bacelar; Ludvig, 2023).

2.3.2 Chemical methods

(a) Chemical Functionalization: This is the modification of the surface of the CNTs, with specific functional groups which improve their dispersion in aqueous or cementitious matrices. It can be performed through acid treatments which introduce carboxylic and hydroxyl groups on the surface of the CNTs increasing their affinity with water (Gao *et al.*, 2022).

It is crucial to consider that functionalization must be optimized for each specific application, considering the interactions between the CNTs and the cementitious matrix, as well as the impact of the functional groups on the final properties of the composite. Experimental tests are essential to determine their effectiveness and to optimize the properties of the composite material.

(b) Surfactants: These are compounds that can reduce the surface tension between the CNTs and the aqueous medium, facilitating their dispersion. Surfactants such as SDS (Sodium Dodecyl Sulfate) or Triton X-100 are commonly used to stabilize CNTs suspensions.

The introduction of surfactants has a double advantage as it allows the dispersion of CNTs and other additive particles while minimizing the energy requirements of ultrasound. Their choice is crucial to obtain a stable and homogeneous dispersion as each has advantages and limitations depending on the type of carbon nanotube, on the dispersion medium and on the final application. It is an effective method, but the choice of surfactant is crucial to ensure that there are no adverse effects on the properties of the cementitious matrix due to the potential impact on the cement hydration process and on the final properties of the concrete. Compatibility with other components and the effect on its workability, strength and durability are also principal factors to consider (Reales *et al.*, 2021).

(c) Superplasticizers: These are chemical additives that increase the workability of the concrete mix without the need to add extra water. They are effective in dispersing CNTs as they help keep the nanotubes suspended and well distributed in the cementitious matrix.

The use of superplasticizers can also improve cement hydration, resulting in higher performance concrete (Kim *et al.*, 2017).

2.3.3 Combined methods

Often, combined methods are employed to maximize the dispersion efficiency of CNTs. For example, the combination of ultrasonication with surfactants can provide a more uniform and stable dispersion of the nanotubes in the cementitious matrix. This synergistic approach takes advantage of the benefits of both methods, resulting in cementitious composites with improved mechanical and durability properties (Klemczac *et al.*, 2023).

The optimal amount of surfactant/functionalizer can be estimated using UV-visible spectroscopy and turbidimetry to measure the quality of dispersion of multi-walled carbon nanotubes (MWCNTs) in the aqueous phase; and mechanical strength tests of concrete, such as compressive and flexural strength, can be used as concrete performance criteria to illustrate the effect of the dispersion quality of MWCNTs and the interaction of surfactant/functionalizer on concrete composition and hydration process, compared to plain concrete (Adresi *et al.*, 2016).

2.3.4 Other dispersion methods

Technologies have emerged to overcome the limitations of traditional methods and improve dispersion efficiency. Some innovative methods include:

(a) Microfluidization: A technique that uses a microfluidizer to apply extremely high shear forces to CNT suspensions. This method promotes efficient deagglomeration of the nanotubes, resulting in uniform distribution in various media. It can be combined with surfactants or polymers to further increase suspension stability (Durukan *et al.*, 2016).

(b) Static Mill: This involves the use of ceramic or steel balls to mechanically disperse CNTs into a suspension. This process is performed in a ball mill, where the balls promote the fragmentation and deagglomeration of the nanotubes due to impact and frictional forces, making it efficient for the large-scale production of homogeneous CNT suspensions (Yoshio *et al.*, 2011).

(c) Electric and Magnetic Fields: Electric fields can align nanotubes, promoting uniform dispersion, while magnetic fields can be used to manipulate CNTs functionalized with magnetic nanoparticles, resulting in a homogeneous distribution. This technique is especially useful in systems where the orientation of the CNTs is critical to the final material properties (Klinovaja *et al.*, 2011).

(d) Plasma-Assisted Dispersion: This involves exposing CNTs to a low-temperature plasma that modifies their surfaces, introducing active functional groups. This improves dispersion in aqueous or polymeric media without the need for surfactants (Mcglynn *et al.*,2022).

(e) Ultracentrifugation: uses extreme centrifugal forces to separate CNTs based on their physical properties, such as diameter and chirality. It allows for the production of highly purified and uniformly dispersed suspensions, essential for applications requiring high precision and control over the properties of CNTs (Cohen; Parveen; Williams, 2022).

In summary, the efficient dispersion of CNTs in cementitious matrices is essential to optimize their reinforcing properties. Physical methods (such as ultrasonication and mechanical agitation) are widely used, while chemical methods (such as functionalization, the use of surfactants and superplasticizers) offer complementary approaches. The application of combined methods can maximize the benefits of each technique, resulting in high-performance concrete with carbon nanotubes.

3 METHODOLOGY FOR BIBLIOGRAPHIC RESEARCH

The literature search methodology consisted of exploratory searches of books and scientific articles on the use of carbon nanocomposites in cementitious materials, beginning with systematic and bibliometric searches, using qualitative and quantitative approaches based on the studies by Favretto *et al.* (2023) and three prominent scientific databases: Scopus (Elsevier), Web of Science (Clarivate), and Science Direct. These databases were selected for their broad coverage of scientific publications and their ability to provide reliable data.

No restrictions were imposed on the types of documents, access methods, or areas of knowledge published on the topic, thus covering a wide range of materials, including scientific articles, reviews, book chapters, conference proceedings, contributions to edited volumes, and working papers.

The analysis period considered in the research was up to 2025, when the last database queries were conducted. The initial year of the search was not specified to encompass all possible scientific contributions related to the topic.

The search was conducted using the keywords “carbon nanotubes,” “mechanical properties,” and concrete (“Carbon Nanotubes” AND “Mechanical Properties” AND Concrete), which appear in the “title, abstract, and keywords” of the publications. The use of the AND operator was necessary to ensure that all terms used in the publications appeared; and quotation marks were used to represent a single word in the search, in accordance with Boolean logic.

The selection process consisted of excluding publications that diverged from the topic or were redundant, followed by those not available for full download. Thus, the bibliographic portfolio was reduced to 37 publications, corresponding to specific works on the application of carbon nanotubes in concrete structures.

4 INNOVATIONS AND DISCUSSION

In the next steps, the results and innovations considered most relevant, found in the researched literature, will be presented and discussed.

Adresi *et al.* (2016) sought to determine the ideal type and quantity of surfactant to achieve the greatest possible dispersion of carbon nanotubes in cement mixtures while fully maintaining the properties of concrete. To achieve this objective, they produced samples with diverse types and quantities of surfactants, keeping the amount of MWCNTs constant (0.05% by weight relative to the amount of cement used).

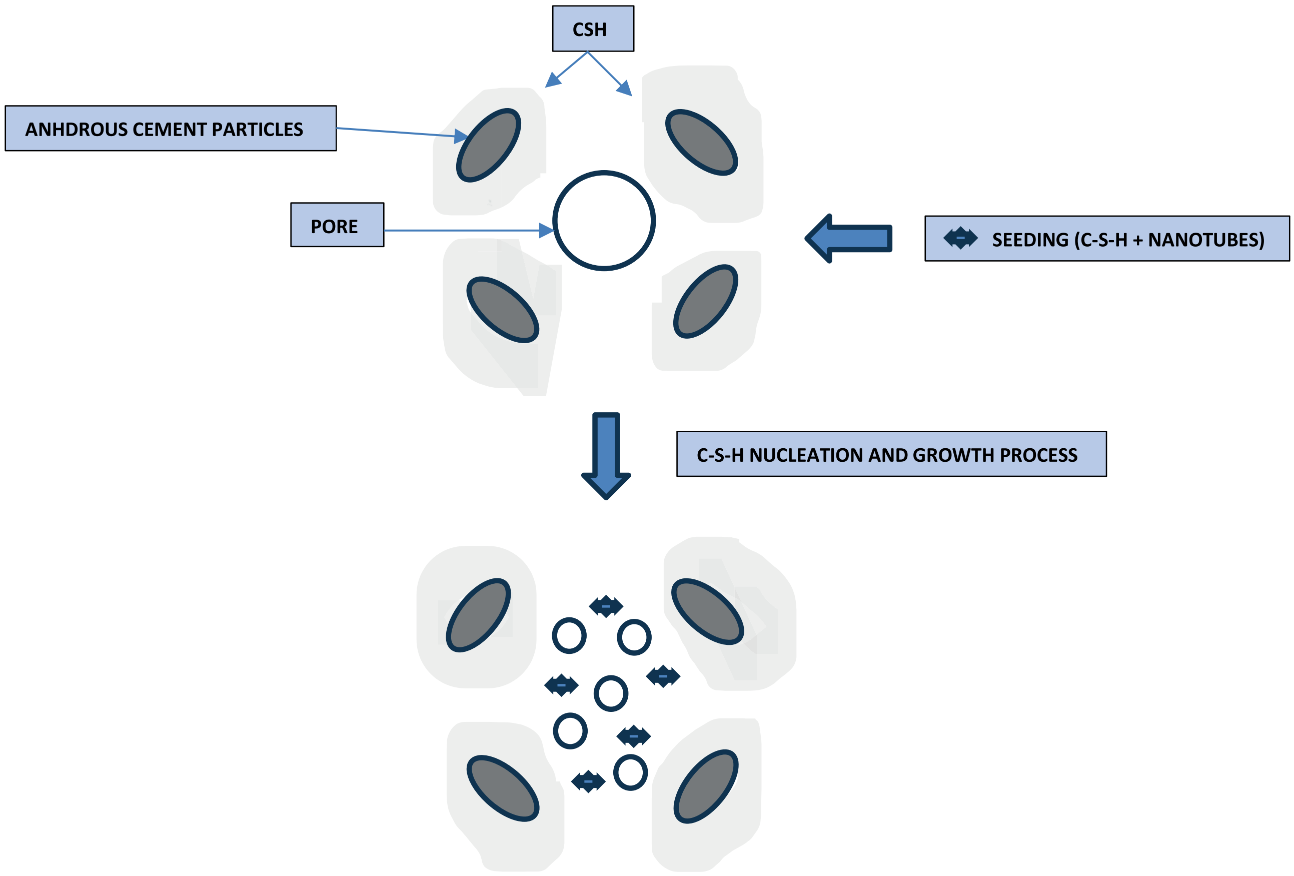
The researchers sought to find a surfactant that was compatible with the concrete composition and capable of eliminating unwanted air bubbles in order to significantly increase the mechanical properties of concrete. The results showed that the surfactant composition consisting of a mixture of Sodium Dodecyl Sulfate (SDS) and Polycarboxylate Superplasticizer (SP-C) dispersed the MWCNTs approximately 24% more efficiently than either alone at the same concentration.

The study provided a guidance on approximate quantities of materials to be used and the synergistic effect of their possible combinations.

Duart (2017) studied the effects of the addition of CNTs and precipitated Hydrated Calcium Silicate (C-S-H) nanoparticles on the properties of cementitious nanocomposites. For Duart and Mortari (2015), the use of CNTs can enable the production of nanocomposites with tensile strength, which is a deficiency of Portland cement-based composites, and also make it possible, in the future, to eliminate materials such as steel bars in reinforced concrete structures.

The addition of C-S-H, in turn, causes a reduction in total porosity, resulting in more resistant nanocomposites. Figure 1 illustrates the effect of the addition of C-S-H in cementitious materials.

Figure 1 - C-S-H nucleation and growth process.



Source: author’s adaptation.

Through several assays that included porosity analysis, permeability and electron microscopy, the work proved that the C-S-H and CNT nanoparticles, especially the compositions prepared with

C-S-H with a Ca/Si=0.8 ratio and oxidized multi-walled nanotubes, favored the hydration kinetics of the cement and contributed to the nucleation and growth of crystals of hydrated products, significantly improving its features. An average increase of 33% in compressive strength, 30% in tensile strength and 38% in dynamic modulus of elasticity was observed. This study was particularly interesting because it uses the main product of cement hydration (C-S-H) in the process increment, avoiding the use of new materials whose effects could be unforeseen, as well as for the use of common raw materials in the market, resulting in a solution that can be produced on a large scale.

Correia *et al.* (2021) found that a surfactant should be added to the cementitious mixture containing MWCNTs to counteract their natural tendency to aggregate. They discovered that the choice of surfactant depended less on the surfactant charge and more on the balance between the concentration and the hydrodynamic diameter/molecular weight of the surfactant due to its impact on geomechanical compression behavior. They observed that smaller surfactant molecules adsorbed more easily onto the surface of the solid particles, ensuring better dispersion and geomechanical behavior; and that, over time, from 7 to 28 days, there was a decrease in the geomechanical benefits associated with the presence of MWCNTs, explained by the development of the cementitious matrix. The authors also found that, for higher surfactant concentrations, non-ionic types exhibited better geomechanical behavior, concluding that nanotubes, applied in appropriate concentrations and enriched with a specific type of surfactant, could be a valid short-term alternative for the partial replacement of traditional additives.

In the military field, several studies have been conducted to strengthen and improve concrete structures using nanocomposites, such as roads and bridges capable of supporting large armored vehicles, high-impact shelters, and landing strips for super-heavy aircraft. In this context, Santos Júnior (2022) developed and validated a new damage evolution law applied to the constitutive modeling of strain-hardening cementitious composites (SHCC). The new law aimed to adequately incorporate plastic energy dissipation into coupled damage and plasticity models, particularly the Concrete Damage Plasticity (CDP) model, focusing on the structural analysis of load transfer devices in jointed concrete pavements (JPCP). The main advantage of this approach is that only monotonic stress-strain experimental envelopes are required.

The application of a widely used load transfer device in rigid pavements and the influence of hardening behavior in the damaged region near the device were studied. Numerical results from finite element models were compared, varying the CDP material parameters and evolution laws to suit both conventional concrete and SHCC, revealing the potential of this alternative composite for reducing pavement damage.

The main results of the new damage evolution laws were shown to be effective in modeling the nonlinear behavior of SHCC, adequately capturing the effect of energy dissipation, both due to damage and plastic deformation. The validated model accurately reproduced the experimental results of the three tests considered.

In practical application to jointed pavements, the simulation showed that the use of SHCC significantly reduced the damaged region around the load transfer bars, when compared to conventional concrete. The use of GFRP bars also contributed to the reduction of stress concentrations and consequent damage, compared to steel bars.

The research proposed a significant advance in the modeling of modern cementitious composites, providing a robust and realistic numerical tool for predicting structural damage in elements subjected to intense loading, such as rigid pavements. The new damage evolution law allows for more accurate analyses based on simple monotonic experimental data, eliminating the need for cyclical testing, thus contributing to durability, safety, and cost-effectiveness in civil engineering projects that employ advanced cementitious materials.

Yang (2023) reviewed the properties, synthesis methods, applications, and prospects of carbon nanotubes in the construction industry. The methodology included a comprehensive analysis of 63 articles focused on the application of CNTs in construction, excluding other unrelated fields such as chemistry and bioengineering.

The main findings highlighted that CNTs possess excellent mechanical, electrical, thermal, and chemical properties that can be used to reinforce structural components, improve energy harvesting and storage, and replace traditional heating and cooling methods in buildings. Furthermore, it was found that CNTs could contribute to carbon dioxide absorption, significantly improve the compressive and tensile strength of concrete, and provide self-sensing properties, enabling structural integrity monitoring without the need for external sensors. The review also addressed challenges and future prospects, such as the need for more research to make their use more common in construction, as well as visionary architectural designs using CNTs such as the Shimizu Megacity Pyramid and the Space Elevator 2050.

Li *et al.* (2023) investigated the hybrid effects of carbon nanotubes and steel fibers (SF) on the dynamic properties of ultra-high-performance concrete (UHPC) under high-speed dynamic loads. The objective was to analyze how the combination of CNTs and SF influences the dynamic behavior of UHPC, specifically in terms of stress-strain ratios, energy absorption capacity and failure patterns.

The results showed that the dynamic compressive properties of UHPC are highly sensitive to strain rates. The individual addition of CNTs significantly improved the dynamic performance of simple UHPC, with an optimal content of around 0.10%.

The combination of CNTs and SF demonstrated the most significant reinforcing effects on the dynamic properties of UHPC, with the sample containing 0.10% CNTs and 2.0% SF exhibiting the highest dynamic compressive strength and toughness.

According to the authors, the work promoted a fundamental understanding of the reinforcing effects of CNTs on UHPC and provided an effective strategy for enhancing UHPC in multiscale perspectives.

Reis *et al.* (2024) evaluated the physical and mechanical properties of concrete with carbon nanotubes, pre-dispersed in cement particles, using isopropanol and water as dispersion media. The study explored the influence of different CNTs contents (0%, 0.05% and 0.10%) on various properties of concrete.

The results showed that the addition of 0.05% of CNTs resulted in significant reductions of up to 12% in porosity and 14% in water absorption, as well as increases of up to 16% in compressive strength, 29% in tensile strength, and 3% in ultrasonic pulse velocity. Significant correlations between some properties were also identified, suggesting the existence of a CNT saturation point. Quadratic regression models were proposed to estimate concrete properties based on CNT content, indicating optimal levels between 0.045% and 0.123%.

The dispersion of CNTs in aqueous suspension has been shown to be a simpler, safer and potentially more efficient solution, especially for industrial production, compared to powder dispersion. The results suggested that optimizing the amount of CNTs requires detailed analysis to avoid undesirable effects. Pre-dispersion methods using isopropanol are effective, but water dispersion may be more practical for large-scale applications.

The work highlighted the potential of CNTs to improve the mechanical performance of concrete and the need for further studies to improve regression models and better understand the interactions between CNTs and the cementitious matrix.

Sldozian *et al.* (2024) investigated the impact of CNTs on the characteristics of Foamed Lightweight Concrete (FLC) with the aim of evaluating how the introduction of CNT-modified sand could improve its mechanical and water absorption properties. The methodology consisted of saturating quartz sand with a solution containing a catalyst for CNT growth, followed by Chemical Vapor Deposition (CVD) for CNT synthesis.

Compression and flexural tests of the FLC samples indicated that the optimal proportion of nanomodified sand was 1% by weight, with a particle size of 0.16 mm, resulting in a 35% increase in compressive strength and approximately 32% in flexural strength. Furthermore, the sample modified with CNT-based sand showed a 27% reduction in water absorption.

The study suggested a potential mechanism to explain the impact of CNT-modified sand on the evolutionary structure of CFL, including the acceleration of the hydration process and the creation of additional crystallization centers in the presence of CNTs, increasing the volume of new compounds such as CSH, tobermorite, and gel phases that fill the intergranular spaces,

improving the mechanical, physical, and operational properties of the samples. An important innovation of the work, according to the authors, was the proposal of a new methodology for producing CNTs that is significantly more efficient and economical than the traditional one.

Teymouri *et al.* (2024) explored the production and application of carbon nanofibers (CNFs) in cementitious mixtures. They reviewed synthesis methods, performance criteria, and challenges in applying CNFs to concrete, highlighting their potential to improve mechanical properties and additional functionalities, such as self-sensing. The methodology included analyzing synthesis, electrospinning, and modeling methods, as well as evaluating the dispersion of CNFs in cementitious mixtures.

The authors reported, as key findings, that adequate dispersion is crucial to harnessing the properties of CNFs in cementitious mixtures and that a combination of physical and chemical methods is most effective for achieving stable dispersion. Furthermore, regarding the effects on the properties of cementitious mixtures, CNTs could delay the hydration of Portland cement, mainly due to the use of dispersants, reduce its workability, and strengthen its microstructure through stress transfer in cracks and densification of the microstructure due to the filling of empty pores. Finally, the study also revealed some crucial differences between geopolymers and cement concrete with CNTs.

Sun (2024) investigated the effectiveness of CNTs on concrete compressive strength using Artificial Intelligence (AI) tools, aiming to develop efficient and sustainable solutions for the construction industry.

Predicting the characteristics of CNT composites proved challenging due to their complex structure and nonlinear behavior. To overcome these challenges, three machine learning (ML) techniques - K-Nearest Neighbor (KNN), Linear Regression (LR), and Artificial Neural Network (ANN) - were applied to predict the compressive strength of concrete with CNTs. A comprehensive database of 282 entities was used to train and test the ML models, whose reliability was assessed using the R^2 test and statistical error analysis.

The ANN model performed best, with an R^2 value of 0.885, followed by the KNN ($R^2 = 0.838$) and LR ($R^2 = 0.744$) models. An RReliefF analysis was used to evaluate the principal components in predicting concrete results, showing that the water/binder ratio was the most influential factor, followed by the proportions of cement and coarse aggregates.

The use of ML has shown promise for predicting the compressive strength of CNT-based composites, saving resources, time, and human effort, and its application across different disciplines has improved the efficiency of testing and prediction, overcoming the limitations of traditional empirical equations and statistical approaches.

Data normalization and standardization were critical steps in preparing for ANN training, and limitations of the study included the need for a large, high-quality database to efficiently train ML models.

According to the author, future studies should focus on compiling more comprehensive databases, considering variables such as CNT percentage and length, aggregate shape and size, and plasticizer and superplasticizer dosages.

Taha, Alnahhal, and Irshidat (2024) evaluated the impact of water-predispersed CNTs, at a concentration of 0.2% by mass of cement on the bond strength between concrete and non-corrosive reinforcement, including stainless steel bars, glass fiber reinforced polymers (GFRP), and basalt fiber reinforced polymers (BFRP). In addition, they examined the influence of CNTs on the compressive and flexural strength of concrete, where 30 specimens were tested to evaluate parameters such as maximum bond strength and bar slip under maximum bond stress.

The addition of CNTs resulted in a reduction in free-end slip, ranging from 5.5% to 24.2%, which indicated an increase in bond stiffness, leading to a smaller crack width and making the bars more suitable for Serviceability Limit State (SLS) design. The study also calibrated two analytical models to account for the specific properties of the reinforcing bars and concrete materials used in order to predict the bonding behavior of the tested members.

Ali *et al.* (2024) investigated the impact of CNT incorporation on the print quality and mechanical properties of 3D-printed cementitious materials. The study compared a control mix with others containing CNTs and superplasticizers, observing significant improvements in print quality and buildability. Rheological properties revealed improved flowability and a notable improvement in mechanical properties. At 28 days, incorporating 0.2% CNTs resulted in significant increases in flexural strength (99%), compressive strength (72%), and Young's modulus (43%), compared to the control mix. The two-layer height error was reduced from 38% to 30%, and buildability increased by 81%.

The materials were prepared with type I Portland cement, fine sand, silica fume, superplasticizer (Master-Glenium ACE 456), and CNTs functionalized with polyethylene glycol (PEG). Three concentrations of CNTs (0.1%, 0.2%, and 0.3 wt.%) dispersed in water, with and without surfactants (SDBS and superplasticizer), were used.

Microstructural investigation revealed that the CNTs formed nanoscale crack bridges, reinforcing the cementitious matrix and improving its mechanical properties. The use of the superplasticizer effectively dispersed the mixture, enabling cementitious matrix reinforcement and minimizing cracks and voids in the printed layers.

Dulaj, Salet and Lucas (2024) investigated the effects of MWCNTs on the properties of 3D-printable concrete, both in its fresh and hardened states. The main objective was to evaluate the concrete's self-sensing capability, which allows for monitoring structural integrity by detecting stress levels and microcracks in critical parts of the structures.The methodology involved preparing four concrete compositions with different concentrations of MWCNTs, which were tested for porosity distribution and mechanical properties.

The results showed that the distribution of MWCNTs in the matrix, strongly influenced by porosity, had a significant impact on the behavior of fresh and hardened concrete, as well as on its self-sensing capacity. The composition with 0.5% MWCNTs showed the best overall performance, including high sensitivity to applied deformation, with a marked increase in resistivity under stress.

It was concluded that MWCNTs, when well dispersed, improve the mechanical properties of concrete, reducing the propagation of microcracks and creating an intelligent material that reacts to stresses and deformations.

Fahimizadeh *et al.* (2024) investigated the efficiency of biological self-sealing concrete using halloysite clay nanotubes (HNTs), loaded with Yeast Extract (YE) encapsulated in calcium alginate microcapsules, along with Bacillus pseudofirmus spores. The objective of the work was to improve the self-sealing function and the resistance of the microcapsules in the cementitious environment.

The methodology included the preparation of B. pseudofirmus spores, grown in YE broth medium, adjusted to pH 10, incubated for 14 days, followed by pasteurization and centrifugation. The concrete samples were prepared according to ASTM C305, incorporating microcapsules in the middle section of the specimens, replacing 5% by mass of the dry concrete mixture. The samples were cured in high humidity for seven days before the introduction of an artificial fissure.

The results showed that the encapsulation of YE-loaded HNTs improved the resistance of the microcapsules in the cementitious environment and maintained the nutrients after contact with the porous cement solution. The self-sealing system reduced crack permeability by more than 95% and improved flexural strength recovery by approximately 75% after 56 days of wet-dry incubation.

The microstructural analysis revealed that the HNTs formed bridges in the cracks, at the nanometric scale, reinforcing the cementitious matrix and improving its mechanical properties. The microcapsules also showed a positive interaction with the concrete samples, promoting the formation of C-(A)-S-H gel at the microcapsule-cement interface.

Zaid *et al.* (2024) examined the incorporation of various nanomaterials (NMs) into geopolymer concrete (GPC) to improve its properties. The objective was to evaluate the effects of inclusion on the workability, strength, durability, and physical-microstructural characteristics of GPC. More than 190 research and review articles were analyzed and presented to develop a database with the critical properties of GPC modified with different doses and types of NMs.

The addition of nanomaterials such as nanosilica, nanoalumina, CNTs, graphene nanoplatelets, and nanoclay has shown promise for the development of high-performance GPC, significantly improving their mechanical, microstructural, and durability properties.

The study highlighted that NMs provided nanofilling effects and promoted the formation of CSH and calcium silicate-aluminate hydrate (CASH) gels in the GPC matrix. It was interesting to highlight the key differences between geopolymers and cement concrete additives containing CNTs. It has been observed that the amount of NMs required to achieve significant improvements is generally lower in geopolymer concrete due to its greater reactivity and efficiency in incorporating NMs, and that this generally presents better results in terms of compressive strength, modulus of elasticity, tensile strength, and durability; however, its preparation process is generally more complex due to the need for rigorous alkaline activation, and they are less widespread in the market due to familiarity and the existing infrastructure for the production of Portland concrete.

Bayat, Kamran and Babaei (2025) presented an extensive review (627 articles) of computational approaches developed to predict the global behavior of structural components enhanced with carbon nanotube and/or graphene nanoplatelet (GPL) fillers. The analysis focused on structures with plate-type configurations, curved cylindrical shells, and beams, emphasizing the computational techniques used to simulate their mechanical behavior.

The authors began by highlighting the widespread use of these materials as reinforcements in cementitious structures due to their exceptional mechanical (Young's modulus of the order of 1 TPa) and electrical (conductivity between 10^5 and 10^7 Sm) properties, which make them very promising for the structural reinforcement of various composites. They warned, however, that their efficient use requires a detailed understanding of their interactions with the matrix and their effects on the overall mechanical response of the structure (Reddy, 2003).

Several computational techniques applied to the modeling of structures reinforced with CNTs and GPLs were reviewed, with emphasis on the methods of 3D Elasticity Theory and Equivalent Single Layer Theory (ESL), including classical (CPT) and shear deformation models (FSDT, TSDT and HSDT), methods generally implemented through the Finite Element Method (FEM), which allow simulating the behavior of different types of structures such as plates, shells, beams and discs subjected to different loading conditions (Reddy, 2003).

The authors also emphasized the role of molecular dynamics (MD) in analyzing atomic interactions between nanomaterials and the matrix, as well as the application of computational fluid dynamics (CFD) in modeling the flow and dispersion of reinforcements during composite processing. They highlighted that the integration of these approaches in multiscale models has proven fundamental to bringing simulated results closer to those observed experimentally, reducing costs and expanding the scope of analyses.

The application of computational techniques was analyzed in different structural contexts. For plates and shells, it was observed that computational models were essential to predict deformations, stresses, buckling modes, and vibrational responses, with particular emphasis on materials with functional distribution of CNTs (FG-CNTs), and that the variation of reinforcement content along the thickness contributed to reducing stress concentrations and increasing structural stability (Bayat *et al.*, 2024).

In the analyses of beams and columns, the ability of the models to capture scaling effects and deformation gradients, as well as predict behavior under axial loads, was highlighted. For porous structures, such as annular plates and functional panels, it was shown that the addition of CNTs could compensate for stiffness losses due to porosity, provided that the nanotubes were properly oriented and distributed. The importance of hybrid composites, which combine CNTs with GPLs, was also highlighted. Simulations indicated that the synergy between these reinforcements resulted in notable gains in mechanical, electrical, and thermal properties.

Models such as Mori-Tanaka and Halpin-Tsai have been successfully applied to estimate the properties of laminated composites, especially under thermal effects, consolidating the role of simulations as guides for the design of advanced cementitious materials (Lin; Xiang; Shen, 2017; Babaei *et al.*, 2022).

The study also presented strategies to prevent nanomaterial agglomeration, one of the main challenges faced in their practical application (Atif; Inam, 2016). Several computational methods capable of predicting and mitigating this phenomenon were presented, including simulations to study the impact of parameters on nanotube dispersion.

Chemical functionalization strategies were also extensively discussed (Vennerberg; Rueger; Kessler, 2014). The authors highlighted that chemical modifications such as acid, amine, or silane treatments could reduce van der Waals forces between nanotubes, facilitating their dispersion and improving their adhesion to the matrix (Ma *et al.*, 2010). These modifications were modeled to predict gains in interfacial energy and charge transfer efficiency.

Finally, the formation of CNT-GPL hybrid networks was analyzed as a way to reduce agglomeration, leveraging the interaction between nanomaterials to increase stability and the contact area with the matrix, and produce a synergistic effect on structural performance (Yang *et al.*, 2011; Wang *et al.*, 2015). Specific theoretical models were also used to quantify the effects of agglomeration on composite properties, allowing for the prediction of performance losses and guidance on adjustments to manufacturing processes.

The article demonstrated the growth and relevance of using new computing and Artificial Intelligence (AI) technologies in work related to the use of nanocomposites in structures by presenting and discussing a wide range of programs and methodologies available in the scientific community, as well as the differences, restrictions, and precautions to be observed when using each of them, constituting an important tool for optimizing work in this area.

Chousidis (2025) evaluated the impact of steel fibers (SF) and carbon nanotubes on the strength and quality of cementitious composites. The study aimed to investigate the individual and combined effects of SF and CNTs on the mechanical, microstructural and durability properties of cementitious composites, focusing especially on compressive and flexural strengths, in addition to evaluating the porosity, thermal behavior and internal integrity of the reinforced matrices.

The methodology involved the production of three experimental groups: a reference mix without additives (REF), one with SF, and a hybrid mix with steel fibers and functionalized CNTs (MIX). Portland cement CEM I 42.5 N, limestone aggregates, a water/cement ratio of 0.65, and the addition of Sika ViscoCrete 4000 superplasticizer were used.

The composites were characterized by mechanical strength tests (compression and flexure), ultrasonic pulse velocity (UPV), porosimetric analysis, capillary sorption, scanning electron microscopy (SEM), and thermogravimetry (TG) and tests were performed at 7, 28, 90, 120, and 240 days of curing.

The results demonstrated that the combination of CNTs and SFs provided significant improvements in the physical and mechanical properties of the composites.

The hybrid blend obtained the highest compressive strength (37.3 MPa at 28 days) and flexural strength (9.9 MPa at 120 days), in addition to better performance in elastic modulus and internal integrity, as indicated by UPV. SEM revealed a denser microstructure, with fewer pores and cracks, while TG indicated modulations in thermal behavior due to the presence of additives. In contrast, capillary sorption was higher in the MIX group, suggesting that the CNT/SF interaction could introduce point heterogeneities.

The study's usefulness lies in demonstrating the synergistic potential of macro- and nanometric reinforcements for producing high-performance concrete with greater strength, lower porosity, and a more cohesive microstructure. The findings support the application of these composites in infrastructure projects with high mechanical demands and durability, such as bridges, tunnels, and pavements, in addition to contributing to the development of lighter, more durable structures with a lower environmental impact.

Afshin and Behnood (2025) conducted a comprehensive analysis of the use of nanomaterials (CNTs, nanoclays, nanosilica, metal oxides, and nanofibers) in improving the performance of asphalt pavements, aiming to investigate their impact on the mechanical, rheological, durability, and environmental sustainability properties of the products. They also sought to outline a comprehensive overview of current trends, knowledge gaps, and future prospects for the application of nanotechnology in road engineering.

The methodology adopted consisted of carrying out a systematic literature review, according to the protocol by Tranfield, Denyer e Smart (2003), in which 867 documents published between 2000 and 2024 were analyzed, with the aid of VOSviewer and SciVal software, to identify trends, co-authorship patterns and scientific impact.

The results showed that the incorporation of nanomaterials significantly increased the tensile strength, stiffness, dynamic modulus, thermal stability, and durability of asphalt mixtures; that nanosilica, nanoclay, and CNTs reduced susceptibility to oxidative aging and increased resistance to thermal cracking and cyclic fatigue; and that the high surface area of the nanomaterials improved the adhesion between binder and aggregate, providing a more homogeneous dispersion.It was also found that the application of nanomaterials made it possible to reduce mixing and compaction temperatures, save energy and reduce CO_2 emissions, as well as enabling greater use of recycled materials and the development of self-repairing and more durable pavements.

The results found were relevant for civil and transportation engineering as they allow for better sizing and a longer service life of pavements, in addition to reducing maintenance costs. The work also contributed to environmental sustainability, mitigating the carbon footprint of road infrastructure and fostering technological innovation by integrating nanotechnology, smart materials, and computational analysis in the development of resilient and eco-efficient infrastructure. The combined use of machine learning and nanotechnology has emerged as a promising tool for optimizing formulations, predicting performance, and designing smart and sustainable pavements.

Finally, Abdulkadir *et al.* (2025) carried out a comprehensive review on the role of nanomaterials in strain-hardening cementitious composites, aiming to analyze their impacts on micromechanical, macromechanical, smart and durability properties. The central goal was to identify how diverse types of NMs (nanosilica, CNTs, graphene oxide, nanofibers, and metal nanoparticles) contributed to microstructure refinement, improved mechanical performance, and extended service life.

The methodology consisted of a systematic literature review based on the analysis of recent experimental studies. The main categories of NMs applied in SHCC were discussed, as well as incorporation methods, including sonication, surfactant dispersion, mechanical agitation, chemical functionalization, and fiber pretreatment.

The review synthesized results from analytical techniques such as SEM, MIP, XRD, and direct mechanical tests (tensile, compression, and flexural), integrating quantitative and qualitative data to understand the mechanisms associated with NMs' performance.

As main results, it was found that the incorporation of nanomaterials in SHCC provided significant advances: nano-silica (NS) reduced porosity by 31.9% and the average pore radius by 40.9%, promoting the formation of a denser and more homogeneous matrix.

The surface modification of fibers with graphene oxide (GO), CNTs or NS strengthened the interfacial transition zone (ITZ), favoring stress transfer and controlling the propagation of microcracks. It was found that CNTs and CNFs functioned as load bridges, increasing tensile strength and modulus of elasticity, in addition to reducing crack spacing.

The conductive network created by CNTs and CNFs gave the material the ability to monitor deformations and identify structural damage in real time, while GO and nanoclay promoted self-repair by retaining water and accelerating the formation of hydration products.

NMs also increased resistance to aggressive agents such as sulfates, acids and chlorides, significantly extending the useful life of the structures.

Finally, it was also found that the combined use of different NMs generated synergistic effects on pore distribution, self-sensitivity and overall mechanical performance.

5 CONCLUSIONS

The interest in the application of carbon nanotubes in concrete has been growing rapidly due to their excellent characteristics and advantages over other additives, being able to reach previously inaccessible points, reducing porosity, increasing mechanical resistance, delaying the expansion of cracks and improving the performance of chemical reactions, among other improvements.

There is an intense search for products and processes that optimize this application, aiming to reduce the undesirable characteristics of nanocomposites, such as the tendency for CNTs to agglomerate, their considerable production costs, and the high carbon footprint of cementitious materials.

In addition, there is a search for simpler, more effective, and more economical ways to prepare the products and their synergistic use.

Although a wide range of tests is still ongoing, some consensus is emerging on the most appropriate amounts of CNTs to use, with optimal levels for a structural reinforcement ranging from 0.05% to 0.2 % wtc, suggesting the existence of a saturation point. The consensus is also on recommended production procedures, where dispersion of CNTs in aqueous suspension and the use of ultrasound are frequently used.

There is also a growing expansion of research with CNTs in several other promising fields, such as their synergistic use with nanofibers in geopolymers, 3D printing, self-healing structures, asphalt pavements, smart highways, and even geocapacitors. The advent of Artificial Intelligence and machine learning have also contributed significantly to the acceleration and reliability of this process, with the publication of several papers in this line of research.

Even though the gains in resistance are not yet high (30% to 50% on average), as well as its production, preparation and application processes are still laborious and expensive, and its standardization is still consolidating, many initiatives are being taken to improve this scenario, which could enable its adoption on an industrial scale soon.

Finally, the importance of this topic in the construction industry is evident, and novel studies aimed at improving the production and application of nanomaterials, as well as regulating and standardizing them, including sanitary aspects, must be encouraged.

As suggestions for future studies, we propose the development of a methodology to identify the optimal concentration of CNTs and their dispersants; toxicology and environmental impact studies; standardization of methods and procedures for the use of nanomaterials; comparison studies between CCP and geopolymers; and structural calculation studies aimed at the optimized application of CNTs to reinforce or reduce the size of concrete works where raw materials are scarce.

REFERENCES

ABDULKADIR, I.; WONG, L. S.; EAN, L. W.; MURALI, G.; MOHAMMED, B. S. A holistic review of nanomaterials in strain-hardening cementitious composites: Insights into micro and macromechanical, deformation, smart, and durability properties. **Results in Engineering**, V. 25, p. 104099, 2015. DOI: 10.1016/j.rineng.2025.104099.

ADRESI, M.; HASSANI, A.; JAVADIAN, S.; TULLIANI, J-M. Determining the surfactant consistent with concrete in order to achieve the maximum possible dispersion of multiwalled carbon nanotubes in keeping the plain concrete properties. **Journal of Nanotechnology**, Article ID 2864028, 2016. DOI: https://doi.org/10.1155/2016/2864028.

AFSHIN, A.; BEHNOOD, A. Nanomaterials in asphalt pavements: A state-of-the-art review. **Cleaner Waste Systems**, V. 10, p. 13278, 2025. DOI: 10.1016/j.clwas.2025.100214.

ALI, M. M.; NASSRULLAH, G.; AL-RUB, R. K. A.; EL-KHASAWNEH, B.; GHAFFAR, S. H.; KIM, T-Y. Influence of carbon nanotubes on printing quality and mechanical properties of 3D printed cementitious materials. **Developments in the Built Environment**, v. 18, p. 100415, 2024. DOI: https://doi.org/10.1016/j.dibe.2024.100415.

ATIF, R.; INAM, F. Reasons and remedies for the agglomeration of multilayered graphene and carbon nanotubes in polymers. **Beilstein Journal of Nanotechnology**, v. 7, p. 1174-1196, 2016. DOI: 10.3762/bjnano.7.109.

BABAEI M.; KIARASI F.; TEHRANI M. S.; HAMZEI A; MOHTARAMI E.; ASEMI K. Three dimensional free vibration analysis of functionally graded graphene reinforced composite laminated cylindrical panel. **Proc Institut Mech Eng, Part L: J Mat: Des Appl.** 2022; 236(8): 1501-14. DOI: 10.1177/14644207211073445.

BAYAT, M. J; KALHORI, A.; BABAEI, M.; KAMRAN, A. Natural Frequency Characteristics of Stiffened FG Multilayer Graphene-Reinforced Composite Plate with Circular Cutout Resting on Elastic Foundation. **International Journal of Structural Stability and Dynamics**, v. 24, n. 18, 2024. DOI: 10.1142/S021945542450202X.

BAYAT, M. J. KAMRAN, A. K. BABAEI, M. Plates, beams and shells reinforced by CNTs or GPLs: a review of their structural behavior and computational methods. **Computer Modeling in Engineering & Sciences**, 2025. DOI: 10.32604/cmes.2025.060222.

CAMACHO, M. C.; GALAO, O.; BAEZA, F. J.; ZORNOZA, E.; GARCÉS, P. Mechanical Properties and Durability of CNT. **Cement Composites. Materials**. 2014,7(3), 1640-1651. DOI: 10.3390/ma7031640. MDPI.

CEA, E. C.; OMISOL, C. J. M.; TUBLE, K. A. Q.; BONGABONG, A. G.; AGUINID, B. J. M.; ASEQUIA, D. M. A.; ERJENO, D. J. D.; AHALAJAL, M. A. N.; MARAVILLAS, F. P.; CAVERO, A. I.; DUMANCAS, G. G.; MALALUAN, R. M.; LUBGUBAN, A. A. Combined Effect of MultiWalled Carbon Nanotubes and Silica Fume on Mechanical, Physicochemical, and Thermal Properties of Concrete Composites. **Buildings**, 2025, v. 15, n.º 7, p. [art. 1087]. DOI: 10.3390/buildings15071087.

CHOUSIDIS, N. Effect of steel fibers and carbon nanotubes on the strength and quality of cementitious composites. **Construction Materials**, 2025, V. 5, I. 2, 103390.X. DOI: 10.3390/constrmater5020023.

COHEN, Z.; PARVEEN, S.; WILLIAMS, R. M. Optimization of ssDNA-SWCNT Ultracentrifugation via Efficacy Measurements. **ECS Journal of Solid State Science and Technology**, 2022, v. 11, e101009. DOI: 10.1149/2162-8777/ac9929.

CORREIA, A. A. S.; CASALEIRO, P. D. F.; FIGUEIREDO, D. T. R.; MOURA, M. S. M. R.; RASTEIRO, M. G. Key-Parameters in Chemical Stabilization of Soils with Multiwall Carbon Nanotubes. **Applied Sciences**, v. 11, p. 8754, 2021.
DOI: https://doi.org/10.3390/app11188754.

DUART, M. A. Efeitos da adição de nanotubos de carbono e C-S-H precipitado nas propriedades de nanocompósitos cimentícios. Tese (Doutorado em Nanociências), Santa Maria - RS, Centro Universitário Franciscano, 2017. Disponível em: http://www.tede.universidadefranciscana.edu.br:8080/handle/UFN-BDTD/576.

DUART, M. A. e MORTARI, S. R. Efeito de nanotubos de Carbono (NTC) na resistência à compressão de nanocompósito cimentício. **Disciplinarum Scientia**. Série Ciências Naturais e Tecnológicas, v. 16, p. 301-309, 2015.

DUBEY, R.; DUTTA, D.; SARKAR, A.; CHATTOPADHYAY, P. Functionalized carbon nanotubes: synthesis, properties and applications in water purification, drug delivery, and material and biomedical sciences. **Nanoscale Advances**. 2021, 3, 5722-5744. DOI: 10.1039/d1na00293g.

DULAJ, A.; SALET, T.; LUCAS, S. S. A study of the effects of MWCNTs on the fresh and hardened state properties of 3D printable concrete. **Case Studies in Construction Materials**, v. 20, p. e02913, 2024. DOI: https://doi.org/10.1016/j.cscm.2024.e02913.

DURUKAN, O.; KAHRAMAN, I.; PARLEVLIET, P.; GEISTBECK, M.; SEYHAN, A. T. Microfluidization, time-effective and solvent free processing of nanoparticle containing thermosetting matrix resin suspensions for producing composites with enhanced thermal properties. **European Polymer Journal**, 2016, (85) 575-587. DOI: 10.1016/j.eurpolymj.2016.11.012.

FAHIMIZADEH, M.; PASBAKHSH, P.; LEE, S. M.; TAN, J. B. L.; SINGH, R.; YUAN, P. Sustainable biologically self-healing concrete by smart natural nanotube-hydrogel system. **Developments in the Built Environment**, v. 18, p. 100384, 2024. DOI: https://doi.org/10.1016/j.dibe.2024.100384.

FAVRETTO, J.; BRAUN, A. B.; FLOSS, M. F.; PRIETTO, P. D. M. The hydraulic conductivity of fuel permeated geosynthetic clay liners: a bibliometric study. **Soils and Rocks**, 2023. DOI: 10.28927/SR.2023.012222.

FENTA, E. W.; MEBRATIE, B. A. Advancements in carbon nanotube-polymer composites: Enhancing properties and applications through advanced manufacturing techniques. **Helyon**, 2024, v. 10 (16). DOI: 10.1016/j.heliyon.2024.e36490.

FRANCO-LUJÁN, V.; MONTEJO-ALVARO, F.; RAMÍREZ-ARELLANES, S.; CRUZ-MARTÍNEZ, H.; MEDINA, D. I. Nanomaterial-Reinforced Portland-Cement-Based Materials: A Review. **Nanomaterials**, v. 13, n. 8, art. 1383, 2023. DOI: 10.3390/nano13081383.

GAGG, C. R. Cement and concrete as an engineering material: An historic appraisal and case study analysis. **Engineering Failure Analysis Revue**. The Open University, United Kingdom, 2014. DOI: https://doi.org/10.1016/j.engfailanal.2014.02.004.

GAO, Y.; LUO, J.; LI, Z.; TENG, F.; ZHANG, J.; GAO, S.; MA, M.; ZHOU, X.; TAO, X. Dispersion of carbon nanotubes in aqueous cementitious materials: A review. **Nanotechnology Reviews**, 2023, v. 12, n. 1, p. 20220560. DOI: 10.1515/ntrev-2022-0560.

GUO, E.; ZHANG, W.; LAI, J.; HU, H.; XUE, F.; SU, X. Enhancement of Cement-Based Materials: Mechanisms, Impacts, and Applications of Carbon Nanotubes in Microstructural Modification. **Buildings** 2025 v. 15, p. 1234. DOI: 10.3390/buildings15081234.

JAYAKUMARI, B. Y.; SWAMINATHAN, E. N.; PARTHEEBAN, P. A review on characteristics studies on carbon nanotubesbased cement concrete. **Construction and Building Materials**, v. 367, art. 130344, p. 111, 2023.
DOI: 10.1016/j.conbuildmat.2023.130344.

KIM, G.; NAM, I. W.; YOON, H. N.; LEE, H. K. Effect of superplasticizer type and siliceous materials on the dispersion of carbon nanotube in cementitious composites. **Composite Structures,** 2018, v. 185, p. 665-674. DOI: 10.1016/j.compstruct.2017.11.011.

KLEMCZAK, B.; GOLDMANN, E.; GOŁASZEWSKA, M.; GÓRSKI, M. Effects of Multi-Walled Carbon Nanotube Dosages and Sonication Time on Hydration Heat Evolution in Cementitious Composites. **Materials,** 2023, v. 16, n. 22, p. 7246. DOI: 10.3390/ma16227246.

KLINOVAJA, J.; SCHMIDT, M. J.; BRAUNECKER, B.; LOSS, D. Carbon nanotubes in electric and magnetic fields. **Physical Review**, 2011, B 84, 085452. DOI: 10.1103/PhysRevB.84.085452.

LI, S.; YAN, J.; MA, H.; LYU, X.; ZHANG, Y.; DU, S. Hybrid effects of carbon nanotubes and steel fiber on dynamic mechanical properties of ultra-high performance concrete. **Materials Research Express**, v. 10, n. 2, 2023. DOI: 10.1088/2053-1591/acbd1b.

LIN F.; XIANG Y.; SHEN H. S. Temperature dependent mechanical properties of graphene reinforced polymer nanocomposites-a molecular dynamics simulation. **Composites Part B: Engineering**, 2017; 111: 261-9. DOI: 10.1016/j.compositesb. 2016.12.004.

MA, P-C.; SIDDIQUI, N. A.; MAROM, G.; KIM, J-K. Dispersion and functionalization of carbon nanotubes for polymer-based nanocomposites: a review. **Composites Part A**, v. 41, n. 10, p. 1345-1367, 2010. DOI: 10.1016/j.compositesa.2010.07.003.

MCGLYNN, R. J.; MOGHAIEB, H. S.; BRUNET, P.; CHAKRABARTI, S.; MAGUIRE, P.; MARIOTTI, D. Hybrid Plasma-Liquid Functionalisation for the Enhanced Stability of CNT Nanofluids for Application in Solar Energy Conversion. **Nanomaterials (Basel)**, 2022, v. 12, n. 15, art. 2705. DOI: 10.3390/nano12152705.

MEHTA, P.K.; MONTEIRO, P.J.M. Concrete: Microstructure, Properties, and Materials. New York: McGraw-Hill, 2017.

NEVILLE, A. M.; BROOKS, J. J. Concrete Technology. Harlow: Prentice Hall, 2019.

NILIMAA, J. Smart Materials and Technologies for susteinable concrete construction. **Developments in the Built Environment Journal**, V. 15, 2023. DOI: 10.1016/j.dibe.2023.100177.

REALES, O. A. M.; JARAMILLO, Y. P. A.; DELGADO, C.; BOTERO, J. C. O.; QUINTERO, J. H.; FILHO, R. D. T. Anionic, Cationic, and Nonionic Surfactants Used as Dispersing Agents for Carbon Nanotubes and Their Effect on Cement Hydration Kinetics. **Journal of Materials in Civil Engineering**, 2021, v. 33, n. 10.DOI: 10.1061/(ASCE)MT.1943-5533.0003955.

REDDY, J. N. Mechanics of laminated composite plates and shells: theory and analysis. 2nd ed. Boca Raton: CRC Press 2003, 858 pages. DOI: 10.1201/b12409.

REIS, E. D.; RESENDE, H. F.; CHRISTOFORO, A. L.; COSTA, R. M.; GATUINGT, F.; POGGIALI, F. S. J.; BEZERRA, A. C. S. Assessment of physical and mechanical properties of concrete with carbon nanotubes pre-dispersed in cement. **Journal of Building Engineering**, 2024. DOI: 10.1016/j.jobe.2024.109255.

RENNHOFER, H.; ZANGHELLINI, B. Dispersion State and Damage of Carbon Nanotubes and Carbon Nanofibers by Ultrasonic Dispersion: A Review. **Nanomaterials,** 2021, v. 11, n. 6, p. 1469. DOI: 10.3390/nano11061469.

ROCHA, V. V.; BACELAR, B. A.; LUDVIG, I. C. P. Nanocomposites Produced with the Addition of Carbon Nanotubes Dispersed on the Surface of Cement Particles Using Different Non-Aqueous Media. **Carbon Letters**, 2023, v. 9, p. 36. DOI: 10.3390/c9010036.

SANTOS JÚNIOR, E. J. A damage evolution lawfor the constitutive modelling of SHCC materials: application to load transfer in pavements. 2022. 78 f. Dissertation (Master of Science in Airport Infraestrutura) - Instituto Tecnológico de Aeronáutica, São José dos Campos, 2022.

SHEN H. S.; XIANG Y.; LIN F. Nonlinear vibration of functionally graded graphene-reinforced composite laminated plates in environments. **Comput Meth Appl Mech Eng.**, 2017; 319: 175-93. DOI: 10.1016/j.cmathermal.2017.02.029.

SLDOZIAN, R. J.; BURAKOVA, I. V.; BURAKOV, A. E.; ALJABOOBI, D. Z. M.; HAMAD, A. J.; TKACHEV, A. G. The effect of multi-walled carbon nanotubes on mechanical properties and water adsorption of lightweight foamed concrete. **Research on Engineering Structures and Materials**, 2024. DOI: 10.17515/resm2024.86ma1119rs.

SUN, H.; AMIN, M. N.; QADIR, M. T.; ARIFEEN, S. U.; IFTKHAR, B.; ALTHOEY, F. Investigating the effectiveness of carbon nanotubes for the compressive strength of concrete using AI-aided tools. **Case Studies in Construction Materials**, 2024. DOI: 10.1016/j.cscm.2024.e03083.

TAHA, A.; ALNAHHAL, W.; IRSHIDAT, M. Effect of carbon nanotubes on the bonding mechanism of non-corrosive reinforcements to concrete. **Structures**, v. 60, p. 105952, 2024. DOI: 10.1016/j.istruc.2024.105952.

TEYMOURI, A.; HAJI HOSSEIN, A.; KHOSHNAZAR, R.; GUZMÁN, H. J. A review on carbon nanofiber production and application in cementitious mixtures. **Journal of Building Engineering**, V.84, 2024, 108519. DOI: 10.1016/j.jobe.2024.108519.

TRANFIELD, D.; DENYER, D.; SMART, P. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. **British Journal of Management**, 2003, V. 14, I. 3, 207-222. DOI: 10.1111/1467-8551.00375.

VENNERBERG, D.; RUEGER, Z.; KESSLER, M. R. Effect of silane structure on silanized multiwalled carbon nanotube-epoxy nanocomposites. **Polymer**, v. 55, n. 7, p. 1854-1865, 2014. DOI: 10.1016/j.polymer.2014.02.018.

WANG, L.; ASLANI, F. Self-sensing performance of cementitious composites with functional fillers at macro, micro and nano scales. **Construction and Building Materials**, 2022, 314, Part B, 125679-X. DOI: 10.1016/j.conbuildmat.2021.125679.

WANG, P-N.; HSIEH, T-H.; CHIANG, C-L.; SHEN, M-Y. Synergetic effects of graphene nanoplatelet and CNT hybrids in epoxy composites. **Journal of Nanomaterials**, v. 2015, p. 1-10, 2015. DOI: 10.1155/2015/838032.

YANG, Shengdan. Properties, applications, and prospects of carbon nanotubes in the construction industry. **Architecture, Structures and Construction**, v. 3, p. 289-298, 2023. DOI: 10.1007/s44150-023-00090-z.

YANG, S. Y.; LIN, W-N.; HUANG, Y-L.; TIEN, H-W.; WANG, J-Y.; MA, C-C. M.; LI, S-M.; WANG, Y-S. Synergetic effects of graphene platelets and carbon nanotubes on epoxy composites. **Carbon**, v. 49, n. 3, p. 793-803, 2011. DOI: 10.1016/j.carbon.2010.10.014.

YOSHIO, S.; TATAMI, J.; YAMAKAWA, T.; WAKIHARA, T.; KOMEYA, K.; MEGURO, T.; ARAMAKI, K.; YASUDA, K. Dispersion of carbon nanotubes in ethanol by a bead milling process. **Carbon**, 2011, V. 49 (13), 4131-4137. DOI: 10.1016/j.carbon.2011.05.033.

ZAID, A. O.; SORB, N. A. H.; MARTÍNEZ-GARCÍAC, R.; PRADO-GILC, J.; ELHADID, K. M.; YOSRI, A. M. Sustainability evaluation, engineering properties and challenges relevant to geopolymer concrete modified with different nanomaterials: A systematic review. **Ain Shams Engineering Journal**, V. 15, I. 2, 2024, 102373. DOI: 10.1016/j.asej.2023.102373.