EJPMR, 2025, 12(12), 292-302 **Research Article** **Impact Factor 7.065**

EUROPEAN JOURNAL OF PHARMACEUTICAL AND MEDICAL RESEARCH

www.ejpmr.com

ISSN (O): 2394-3211
ISSN (P): 3051-2573
Coden USA: EJPMAG

MULTIFUNCTIONAL CARBON NANOMATERIALS IN SELF-HEALING CONCRETE: FROM SYNTHESIS TO REAL-WORLD APPLICATION

Balogun G. Y.[1]*, Fatukasi B. A.[2]

[1]Department of Bioenvironmental Sciences, Morgan State University, USA.
[2]Department of Science Laboratory Technology, University of Ilesha, Nigeria.

***Corresponding Author: Balogun G. Y.**

Department of Bioenvironmental Sciences, Morgan State University, USA.

DOI: https://doi.org/10.5281/zenodo.17735551

How to cite this Article: Balogun G. Y.1*, Fatukasi B. A.2. (2025). Multifunctional Carbon Nanomaterials In Self-Healing Concrete: From Synthesis To Real-World Application. European Journal of Biomedical and Pharmaceutical Sciences, 12(12), 292–302.

Article Received on 03/11/2025 **Article Revised on 24/11/2025** **Article Published on 01/12/2025**

ABSTRACT

The addition of carbon-based nanomaterials into cementitious mixtures represents an important step toward creating a smarter organization that is not only stronger but also capable of repairing itself. In this review, 45 peer-reviewed studies published between 2019 and 2024 were examined, with consideration given to carbon nanotubes (CNTs) and graphene oxide (GO) in self-healing concrete. The findings recommend that including CNTs at levels of 0.1–0.5% of cement weight can increase compressive strength by roughly 15–35%. In evaluation, GO at 0.02–0.08% delivers similar improvements while offering better distribution, which in practice is a critical factor for consistency. The instruments behind self-healing appear to work through processes such as bridging of cracks, stimulation of the material's own natural (autogenous) repair, and responses to external triggers. As a result, repair efficiencies of about 60–85% were observed for crack widths up to 100 µm. Even with these hopeful outcomes, challenges remain. Achieving uniform distribution is difficult, the costs are still high, and no clear standards have yet been established. At present, nanomaterial-improved concrete can be 150–400% more expensive than conventional mixes, which limits its large-scale adoption. These issues may indicate that while the technology is hopeful, practical implementation will require both technical advances and cost reductions. Keywords: carbon nanomaterials, self-healing concrete, carbon nanotubes, graphene oxide, mechanical performance, structural durability.

KEYWORDS: Concrete, graphene, nanotubes, nanomaterial, self-healing.

INTRODUCTION

Concrete remains the most generally used construction material across the world, with annual production now valued at over 4.5 billion tons (Marco, 2021; Ahmadizadeh *et al.*, 2024). Despite this supremacy, conventional concrete has well-documented shortcomings. besides being weak and subjected to cracking, especially when exposed to forms of mechanical load and environmental changes, it has low tensile strength and about 8–12% of its compressive capacity (Pekdogan, 2024). These defects are far from minor, as they result in massive financial costs. For instance, the estimated annual cost of maintaining and repairing aging concrete structures in developed countries is significant. The researchers acted by focusing on the idea of self-healing concrete, which is gradually considered to be a workable solution to long-lasting issues (Adedoyin and Ogunsona, 2025a, 2025b). Inserting materials or devices that enable cracks to repair themselves, this technology also has the potential to extend service life while reducing maintenance costs.

Concrete benefit due to its ubiquity, is particularly vulnerable to cracking once exposed to stresses, making the capacity of independent repair more valuable. Among many methods discovered, carbon-based nanomaterials have drawn some specific attention. Like the unresolved mechanical strength, electrical conductivity, and multifunctional behavior, which make them a strong contender for enhancing both the performance and self-healing capacity (Khandve, 2014; Ahmadizadeh *et al.*, 2024; Adedoyin and Ogunsona, 2025b). The research also reveals the production and processing of carbon nanomaterials, and it also shows how they make things strong and ways in which self-healing is initiated and measured. It also points out cost and practical problems before identifying the research shortcomings and future recommendations. The study analysis concentrates on carbon nanotubes (CNTs) and graphene-based byproducts, which are the focus of the study analysis.

Characteristics and Important Assets of Carbon Nanomaterials

Properties of Carbon Nanotube Structure

Carbon Nanotubes Structure (CNTs) is a one-dimensional carbon allotrope that is formed when graphene sheets are rolled into cylindrical structures. When used in one-dimensional carbon allotropes mixtures, CNTs can significantly improve electrical conductivity, which imparts self-sensing abilities to concrete (Danoglidis *et al*., 2021). There are two main forms of CNTs. Single-walled carbon nanotubes (SWCNTs) are characterized by diameters of about 1–2 nm and lengths extending to several micrometres. Multi-walled carbon nanotubes (MWCNTs) are made up of several concentric graphene cylinders, having outer diameters between 10–50 nm. The strength of the carbon-carbon bonds and the characteristics of the atomic bond structure of CNTs can be used to qualify their appearances. Their theoretical tensile strengths are valued to be greater than 100 GPa, and Young's modulus values that are close to 1 TPa, highlighting their outstanding stiffness and resilience. Their high aspect ratio, often between 100 and 1000, allows efficient load transfer across cement matrices, particularly through mechanisms that bridge cracks. Elsewhere, CNTs also prove excellent electrical conductivity in addition to their mechanical advantages. This property allows concrete filled with CNTs not only to resist damage but also to have a level of durability and functionality (Marco, 2021; Pekdogan, 2024).

Graphene and Graphene Byproducts

Graphene oxide (GO) is a two-dimensional nanoparticle with lateral dimensions typically below 100 nm, operating as a nano-reinforcement in cementitious composites. It serves as a filling material, a crack-bridging agent, and a nucleation site that hastens cement hydration (Sharma and Kothiyal, 2022). Graphene by-product structures offer very high Physical interaction between cement materials, which allows improvement in reinforcing systems for efficient transfer of loads. One of the greatest things about GOs is that they can spread out. GO spreads out in polar solvents such as water, due to the oxygenated functional groups involved in its aromatic framework (Mohammed *et al*., 2019). This property addresses one of the major limitations faced when including nanomaterials into cement, making GO particularly beautiful for real-world applications. The oxygen-containing groups, including hydroxyl, epoxy, and carboxyl functionalities, also enable strong hydrogen bonding with cement hydration products. It improves and promotes the efficiency of load transfer within the cement matrix and contributes to improving both strength and durability. This also allows properties of carbon nanomaterials, such as GO and CNTs, to strongly improve the effectiveness in reinforcement of concrete. To show these differences (Mohammed *et al*., 2019; Sharma and Kothiyal, 2022). Table 1 provides a comparative summary of key structural and mechanical characteristics based on experimental evidence from multiple studies.

Table 1: Fundamental Properties of Carbon Nanomaterials in Concrete Applications.

Property	**SWCNTs**	**MWCNTs**	**Graphene Oxide**	**Reduced GO**	**Units**	**References**
Typical Diameter/Thickness	1-2	10-50	0.7-1.2	0.7-1.0	Nm	Parveen *et al*., 2021; Danoglidis *et al*., 2021; Li *et al*., 2022; Huseien, 2023; Khaleel and Alsharif, 2025
Lateral Dimensions	-	-	0.1-20	0.1-20	Mm	Mohammed *et al*., 2019; Sharmaand Kothiyal, 2022; Li *et al*., 2022; Huseien, 2023; Khaleel and Alsharif, 2025
Aspect Ratio	1000-10,000	100-1000	-	-	-	Zhang *et al*., 2018; Chintalapudi and Pancharathi, 2023
Tensile Strength	50-200	10-60	20-40	30-60	GPa	Li *et al*., 2022; Li *et al*., 2022; Wu *et al*., 2023; Huseien, 2023
Young's Modulus	1000-1500	500-1000	150-300	200-400	GPa	Li *et al*., 2022; Potapov *et al*., 2022; Indukuri *et al*., 2024
Electrical Conductivity	10^4-10^6	10^3-10^5	10^{-6}-10^{-3}	10^2-10^4	S/m	Jeyaseelan *et al*., 2022
Surface Area	400-900	200-400	50-200	100-300	m^2/g	Parveen *et al*., 2021; Huseien, 2023; Jing *et al*., 2023

Self-Healing Mechanisms in Carbon Nanomaterial-Enhanced Concrete

Fundamental Healing Mechanisms

Carbon nanomaterials contribute to self-healing in cementitious composites through several essential mechanisms that operate without the need for external healing agents. Nano and micro scales are basic processes of crack bridges, which help in the transfer of loads and prevent additional crack opening. Nanomaterials that span crack faces and cover load transfer and crack opening prevention, and slow the spread of structural damage, and change over time (Li *et al.*, 20222). Studies show how important concrete is and its features, ensuring long-term service life, and having a high resistance to the formation of cracks. Concrete has been used in construction since ancient times (Chintalapudi and Pancharathi, 2023). The combination of carbon nanomaterials will not only improve the material's traditional autogenous healing but also introduce new performance capabilities. Carbon nanomaterials have an exceptionally big surface area, which creates multiple nucleation sites for hydration reactions. This results in denser microstructures and higher fundamental healing capacity (Wengui *et al.*, 2022; Huseien, 2023). Cement hydration delay is another essential mechanism when moisture is present; carbon nanomaterials can act as nucleation sites for hydration products, enhancing the hydrated cement particles' reaction. In addition to that is their large surface area and chemical reactivity with cement phases, nanomaterials make this process more effective (Li *et al.*, 2022; Huseien, 2023; Khaleel and Alsharif, 2025).

Extrinsic Healing Systems

Extrinsic self-healing systems rely on the deliberate combination of healing agents that are released once cracks form within the concrete matrix. One well-documented method involves the use of bacterial spores, which can aid microbial healing by precipitating calcium carbonate. Protection of endospore bacteria in alkaline concrete environment is a major challenge (Vafaeva and Zegait, 2024) flexible tube-like structure, carbon nanomaterials, or carbon nanotubes (CNTs), which are present and are of good chances for extrinsic healing. Studies also talked about various healing agents that act like nanoscales, such types of healing agents which cyanoacrylate adhesives, epoxy resins, and bacterial spores for bio-mediated repairs. There are also other agents called therapeutic agents. These agents are agents that act as capillary absorption and are assisted by the application of pressure when there is a crack for penetration. Activities like mechanical separation then take place; in these activities, the process of the CNT agent is applied directly in the crack area. This release triggers rapid polymerization or microbial activity, which covers the cracks and restores mechanical integrity. Such a targeted delivery system lowers the possibility of early start during concrete mixing or placement (Huseien, 2023; Khaleel and Alsharif, 2025; Adedoyin and Ogunsona, 2025a).

Mechanisms of Stimulus-Responsive Healing

The brilliant electrical conductivity of carbon nanomaterials enables the development of stimuli-responsive healing systems initiated by external stimuli. Application of control voltage across concrete samples helps in electrical activation, generating heat through heating using the nanomaterial network. Such heating can activate thermoplastic healing agents, such as hasten chemical reactions used for crack repair, and promote polymer chain movement (Li *et al.*, 2022; Khaleel and Alsharif, 2025). The effectiveness of self-healing materials differs based on crack width, environmental conditions, and nanomaterial concentration. Table 2 summarizes the quantitative performance of different healing mechanisms based on verified experimental studies, providing essential data for design applications.

Table 2: Self-Healing Mechanisms and Quantitative Performance Metrics.

Healing Mechanism	Nanomaterial Type	Effective Crack Width	Healing Efficiency (%)	Time to Complete Healing	Environmental Requirements
Crack Bridging	CNTs	0.1-5.0	70-85	Immediate	Minimal moisture
Autogenous Healing	GO, CNTs	0.5-50	60-80	7-28 days	Moisture presence
Chemical Precipitation	Functionalized CNTs	1.0-100	50-75	14-90 days	Alkaline environment
Stimuli-Responsive	Conductive CNTs	0.5-20	65-90	Minutes to hours	Electrical activation
Microbial Healing	CNT-encapsulated	5-200	70-95	7-21 days	Moisture and nutrients

Mechanical Property Enhancement and Performance Analysis

Compressive Strength Improvements

The combination of carbon nanomaterials has constantly been shown to improve the compressive strength of concrete across a wide range of studies and experimental settings. These improvements are generally attributed to several support mechanisms, including crack bend, crack bridging, stronger interfacial bonding between nanomaterials and cement hydration products, and the compaction of the cement matrix through nucleation effects (Li *et al.*, 2022; Vafaeva and Zegait, 2024). Studies show that the best recommended measurement of carbon nanotubes (CNTs) ranges between 0.1-0.5%. To understand the importance of carbon-based nanomaterials in concrete support, critical evaluations are to be carried out (Parveen *et al.*, 2021). Within this range, compressive strength improvements of 15–35% are commonly observed. However, higher CNT measurement often led to reduced effectiveness, largely because of distribution challenges and the tendency of nanomaterials to pile (Reales and Filho, 2017; Li *et al.*, 2022; Vafaeva and Zegait, 2024). Graphene oxide (GO) has proved equal, and in some cases superior, reinforcement efficiency at much lower concentrations, generally between 0.02–0.08% by cement weight. This finding may have important implications for the construction industry, as GO offers a more efficient pathway to achieving mechanical improvements (Mohammed *et al.*, 2019; Janas and Liszka, 2018). The two-dimensional sheet-like structures of GO offer greater interfacial contact area compared to the one-dimensional geometry of CNTs. Research explains that structural advantages are measured efficiently per unit mass (Kumar *et al.*, 2020; Hamidul *et al.*, 2022).

Flexural and Tensile Strength Enhancement

The effect of carbon nanomaterials on the flexural and ductile performance of concrete is a crucial advantage (Silvestro and Gleize, 2020) because of their high aspect ratio, flexibility, and incomparable tensile capacity, which allows the cement substance to deform without causing early fracture. Carbon nanotubes (CNTs) are useful in strengthening tensile problems (Janas and Liszka, 2018). The study also shows that CNT-reinforced concrete can increase tensile strength from 25 – 0% and flexural strength by 20 -60%This strengthening effect is primarily due to the crack-bridging action of CNTs, which operate across different scales from nano-cracks in the cement paste to larger cracks spanning aggregate particles (Sousa *et al.*, 2020). Carbon nanomaterials produce several bonds in the cement structures, ensuring effective cracks and load transfer problems are solved (Sousa *et al.*, 2020; Li *et al.*, 2022; Vafaeva and Zegait, 2024; Adedoyin and Ogunsona, 2025c).

Durability Performance and Long-term Behavior

Studies show different methods of reinforcing mechanisms, such as improving functionality during freeze-thaw cycle, strengthening resistances to chemical weakening, and reducing permeability for carbon nanomaterials, which is very important in improving concrete for last longing performance (Omoike *et al.*, 2025). Combining nanomaterials to compress the cement matrix lowers porosity, which limits the entry of dangerous substances. Simultaneously, these materials are superior to crack resistance, which stops pathways that accelerate weakening from evolving. A significant concern in the durability of concrete is the effect of carbon nanotubes (CNTs) on the microstructural stability, mechanical strength, and development behavior of cement mortar that is visible to the alkali-silica reaction (Sousa *et al.*, 2020; Wu *et al.*, 2022). Table 3 shows a well-detailed experimental result of various carbon nanomaterial categories and levels that provide researchers and engineers with valid data information.

Table 3: Mechanical Property Enhancement - Comprehensive Experimental Data.

Nanomaterial Type	Dosage Range (% by cement weight)	Compressive Strength Increase (%)	Flexural Strength Increase (%)	Tensile Strength Increase (%)	Fracture Toughness Increase (%)	References
MWCNTs	0.05-0.1	15-25	20-40	25-50	40-70	Sousa *et al.*, 2020; Danoglidis *et al.*, 2021; Parveen *et al.*, 2021
MWCNTs	0.1-0.5	20-35	30-60	35-70	50-90	Sousa *et al.*, 2020; Sharma and Kothiyal, 2022; Jeyaseelan *et al.*, 2022
Functionalized CNTs	0.05-0.2	18-32	25-55	30-65	45-85	Sousa *et al.*, 2020; Li *et al.*, 2022; Wu *et al.*, 2022
Graphene Oxide	0.02-0.05	16-28	18-45	22-55	35-65	Janas and Liszka, 2018; Mohammed *et al.*, 2019; Sousa *et al.*, 2020; Indukuri *et al.*, 2024
Graphene Oxide	0.05-0.08	22-38	25-58	30-68	40-80	Sousa *et al.*, 2020; Potapov *et al.*, 2022; Jing *et al.*, 2023
Reduced GO	0.02-0.06	18-33	22-50	28-60	38-75	Chintalapudi and Pancharathi, 2023

Processing Plan and Distribution Technologies

Critical strategies distribution

The research shows problems and challenges with the use of carbon nanomaterials, ensuring that there is uniform distribution within the cementitious system. The van der Waals bond interaction between nanoparticles normally leads to differences in uniform distribution. Findings review that concrete performance is compromised by agglomeration which has low support efficiency that functions as structural faults, producing inferior results in conventional mixtures (Ma *et al*., 2010; Baig *et al*., 2018) such abilities improve concrete strength in aspect such as graphene oxide (GO), mechanical and durability properties (Hamidul *et al*., 2022; Indukuri *et al*., 2024) efficiency strongly depend on the rate of distribution. Poorly distributed systems frequently show negligible improvements or even opposing effects on strength and durability properties. Presently, distribution techniques including ultrasonication, surfactant addition, and functionalization require careful standardization according to application type and mixing conditions. However, the technical methods and energy-intensive nature of these approaches raise questions about their viability and cost-effectiveness on a large scale (Ma *et al*., 2010; Baig *et al*., 2018; Hamidul *et al*., 2022).

Advanced Processes for Techniques

Several processing techniques have been developed to address the ongoing problem of nanomaterial clusters; each has detailed benefits and crucial weaknesses (Baig *et al*., 2018). Ultrasonication continues to be the most popular laboratory-scale method among them. To successfully separate nanoparticles and ultrasonication high frequency of sound energy and achieve uniform distribution is achieved, which depends on the concentration of nanomaterials and volume interruption treatment, which varies from 30-120 minutes. Despite its effectiveness, the technique faces significant barriers to industrial adoption due to its high energy demand, prolonged processing times, and difficulties in scaling beyond controlled laboratory environments (Omoike *et al*., 2025). Another method of reducing interparticle attraction is through the addition of a chemical dispersant. Various agents, which include polycarboxylate-based superplasticizers, sodium dodecyl sulphate, and specially made dispersants for carbon nanomaterials, are frequently used agents. These are techniques that help in increasing stability and a workable method, vital surfactant selection. Findings also show that cement chemistry is unsuitable and can change hydration kinetics, which affect strength development and long-term durability (Baig *et al*., 2018; Omoike *et al*., 2025). Chemical functionalization is another method that helps to increase compatibility in an aqueous cementitious system, which improves nanomaterials covalently or non-covalently. Examples of such functions are the introduction of hydroxyl and carboxyl bonding and improving hydrophilicity by the application of acid treatment. Otherwise, polymer grafting provides steric stabilization, preventing particle clustering even under harsh mixing conditions. While functionalization improves dispersion and reinforcement efficiency, it often requires complex processing steps and can alter the fundamental properties of nanomaterials, raising concerns over cost and performance tradeoffs (Omoike *et al*., 2025).

Quality Control and Characterization Methods

Standardized value control frameworks for carbon nanomaterial improved cementitious mixtures are still developing, creating determined challenges for specification writing, value assurance, and performance verification across various projects and suppliers. Important performance parameters requiring close monitoring include distribution uniformity, nanomaterial structural integrity of interfacial bonding with cement hydration products, and mechanical performance consistency are important performance parameters that need to be closely monitored (Reales *et al*., 2017). Research shows that integration of advanced tactics is very important for optimal optimization and security, where direct visualization of quality distribution, crack-bridges behavior in the cement compound is made possible by scanning electron microscopy (SEM) and nanomaterial distribution. Studies show that Raman spectroscopy, which is a nondestructive method for assessing nanomaterial distribution such as crystallinity, damages incurred during the mixing process (Reales and Filho, 2017; Omoike *et al*., 2025). Table 4 shows the detailed processing methods that are used for evaluation, which include dispersion quality, scalability, and energy consumption compatibility.

Table 4: Processing Methods - Comparative Performance Analysis.

Processing Method	Dispersion Quality	Energy Requirements	Processing Time	Scalability	Cost Factor	Nanomaterial Integrity
Probe Ultrasonication	Excellent	Very High	30-90 min	Poor	High	Medium Risk
Bath Ultrasonication	Good	High	60-180 min	Fair	Medium-High	Low Risk
High-shear Mixing	Good	Medium	15-45 min	Excellent	Low	Low Risk
Surfactant-assisted	Good	Low	45-120 min	Excellent	Low-Medium	Very Low Risk
Chemical Functionalization	Excellent	Medium	2-24 hours	Good	High	Medium Risk
Combined Approaches	Excellent	High	60-150 min	Fair	High	Medium Risk

Smart Detecting Applications and Electrical Properties

Filtration Behavior and Conductivity Improvement

Research also shows that when carbon nanomaterials are combined, they tend to convert insulating concrete into electrically conductive or semi-conductive material (Shchegolkov *et al*., 2024). According to percolation theory, electrical behavior moves in the direction of percolation theory, where conductivity increases above the nanomaterial concentration threshold. Also, there are different types of percolation thresholds, which are based on their nanomaterial type, ratio aspect, and quality of distribution (Shchegolkov *et al*., 2024). The percolation threshold varies significantly based on nanomaterial type, aspect ratio, and distribution quality. Electrical conductivity of carbon nanotubes, which can reach 10^{-2}–10^{-1} S/m, is above the percolation threshold, which is normally between 0.1 and 1.0% by cement weight. Because of its two-dimensional structure, graphene-based materials show a variety of percolation characteristics. According to the percolation threshold, they are likely to show superior conductivity at mass fraction thresholds (De Volder *et al*., 2013; Shchegolkov *et al*., 2024; Omoike *et al*., 2025).

Self-Sensing Capabilities and Structural Health Monitoring

When Structural health monitoring carbon nanotubes (CNTs) and self-sensing capabilities combine, they act as functional fillers which can be used to improve the electrical conductivity of concrete (Danoglidis *et al*., 2021; Li *et al*., 2022). The brilliant piezoresistive behavior of CNTs permits real-time monitoring of structural health through measurable changes in electrical resistance under mechanical loading, thermal cycling, or progressive damage (Nivetha *et al*., 2025). The original self-sensing mechanism operates through several interconnected pathways. Based on findings carried out, there are said to be differences in resistance between adjacent nanomaterials, regular disturbances that affect conductive ways, disturbance of conductive work caused by crack propagation, and a change in electron channeling across nanoscale breaches (Han *et al*., 2009; Li *et al*., 2022). Studies show that gauge factors known as ratio relative resistance change are applied by strain ranging from 50 to 100, depending on the method involved, such as CNT type, distribution quality, and processing (Omoike *et al*., 2025). These values exceed those of conventional metallic strain gauges, allowing exposure of micro-strain fluctuations and early-stage crack development. Such sensitivity positions make CNT improved concrete a versatile construction material capable of supporting simultaneous weight and offering ongoing, integrated structural health monitoring. This lessens the need for external sensors, lowers maintenance expenses over time, and could lead to infrastructure systems that are safer and more resilient (Li *et al*., 2022; Sabet, 2024; Omoike *et al*., 2025).

Integration with Digital Infrastructure Systems

Modern smart concrete systems gradually combine the sensing capabilities of carbon nanomaterials with advanced digital platforms to enable continuous monitoring and predictive maintenance (Li *et al*., 2022). In practice, wireless sensor networks facilitate the transmission of real-time structural data to centralized monitoring hubs, where machine learning algorithms can identify patterns, flag anomalies, and even anticipate performance deterioration (Omoike *et al*., 2025). An important innovation lies in the integration of self-sensing concrete with Building Information Modelling (BIM) is important. This gives engineers and facility managers a unique level of understanding of existing structural conditions by enabling real-time digital models of structures to be updated continuously with sensor-derived data. In addition to BIM, digital twin technology, which combines computational models with physical infrastructure, augments predictive capabilities by modeling future performance under various loading and environmental conditions (Drozdov and Christiansen, 2020; Nivetha *et al*., 2025). Table 5 presents quantitative performance characteristics of these self-sensing systems, synthesizing results from verified experimental studies.

Table 5: Electrical Properties and Self-Sensing Performance Characteristics.

Nanomaterial Type	Percolation Threshold (vol%)	Maximum Conductivity (S/m)	Gauge Factor Range	Strain Sensitivity (με)	Temperature Coefficient (%/°C)	References
SWCNTs	0.05-0.15	10^{0}-10^{2}	300-1000	1-10	-0.2 to -0.6	Drozdov and Christiansen, 2018; Danoglidis *et al*., 2021; Parveen *et al*., 2021; Omoike *et al*., 2025;
MWCNTs	0.1-0.5	10^{-2}-10^{0}	100-500	5-50	-0.1 to -0.4	Drozdov and Christiansen, 2018; Jeyaseelan *et al*., 2022; Nivetha *et al*., 2025
Graphene	0.02-0.1	10^{-3}-10^{-1}	50-200	10-100	-0.05 to -0.2	Mohammed *et al*., 2019; Jing *et al*., 2023; Omoike *et al*., 2025; Nivetha *et al*., 2025
Graphene Oxide	0.5-2.0	10^{-6}-10^{-4}	20-80	50-500	Variable	Potapov *et al*., 2024; Indukuri *et al*., 2024; Omoike *et al*., 2025; Nivetha *et al*., 2025
Reduced GO	0.1-0.4	10^{-4}-10^{-2}	80-300	20-200	-0.1 to -0.3	Wu *et al*., 2022; Chintalapudi *et al*., 2023; Omoike *et al*., 2025; Nivetha *et al*., 2025

Economic Analysis and Practical Implementation

Cost Structure and Economic Viability Analysis

A complete economic valuation shows that the high cost of raw materials remains the major problem for the large-scale use of carbon nanomaterial-based concrete. Presently, the market price of carbon nanotubes (CNTs) ranges between $100 and $500 per kilogram, while graphene oxide is priced around $50 to $200 per kilogram, depending on its grade and production volume. Even at relatively small inclusion levels of 0.1–0.5% by cement weight, these figures translate into an important rise in the overall cost of concrete materials (Omoike *et al*., 2025; Nivetha *et al*., 2025). However, when the total cost of ownership is considered, including longer service life, reduced maintenance needs, and added functionality, the long-term economic value becomes more apparent. Concrete construction to date is still known to be the foundation of current construction, but its limitations in environmental sustainability and durability continue to be a setback challenge (Jing *et al*., 2023). While improving carbon nanomaterials' performance, which can counterweigh cost development by increasing resilience and decreasing frequency of repair beyond material costs, processing expenses further strengthen the economic challenge. Challenges include the need for a longer time for processing, modern tools, and the most importantly, which is quality measures for control. Research has it that processing factors have risen by 50-200% compared to standard concrete construction, which has various methods, such as the distribution method and nanometer (Li *et al*., 2022; Omoike *et al*., 2025; Nivetha *et al*., 2025).

Market Penetration and Commercial Applications

The use of carbon nanomaterial is to improve market and commercial penetration value at large, and specialize in applications to validate the performance of higher cost value. Such values include advanced architectural projects, infrastructure, and specialized construction works in which the safety and financial cost of structural letdown far outweigh the additional materials expenses. Studies show that from recent findings, the role of graphene oxide (GO) in improving static and dynamic behavior in concrete structures (Potapov *et al.*, 2022) discuss their application required under various load conditions. Market implementation shows an advanced course in construction technologies, starting from the application, production cost, and performance benefits. The current market helps in shaping the implementation of such applications, which include durability standards, cost efficiency, and a rise in demand for intelligent and adaptive systems of infrastructure (Omoike *et al*., 2025; Nivatha *et al*., 2025).

Regulatory and Standardization Challenges

The major limitation of nanomaterials is the absence of standardized testing methods and performance evaluations. Conventional concrete standards do not fully capture the unique behaviors introduced by carbon nanomaterials, demanding the creation of new protocols and specification frameworks (Jeevanandam *et al*., 2018). Such measures are reliable criteria, certification, and regulatory approval. Additionally, the variability in nanomaterial quality across suppliers introduces additional difficulty, requiring rigorous quality control procedures and performance verification methods to ensure consistency in structural applications. Effective international organization between standards organizations will be difficult to achieve, with broad compatibility and market acceptance. The economic implications of nanomaterial addition are captured in Table 6, which provides a comparative overview of costs and lifecycle performance across conventional concrete, CNT-improved concrete, and GO-improved concrete. This mixture enables engineers, contractors, and policymakers to assess trade-offs between upfront expenses and long-term savings, offering valuable insights for project evaluation and investment planning.

Table 6: Economic Analysis - Cost Comparison and Lifecycle Assessment.

Economic Parameter	Conventional Concrete	CNT-Enhanced (0.1%)	GO-Enhanced (0.05%)	Units	References
Raw Material Cost	120-180	180-280	140-220	$/m³	Jeyaseelan *et al*., 2022; Indukuri *et al*., 2024; Omoike *et al*., 2025
Processing Cost Premium	0	40-80	20-50	$/m³	Parveen *et al*., 2021; Jing *et al*., 2023; Omoike *et al*., 2025
Total Initial Cost	120-180	220-360	160-270	$/m³	Potapov *et al*., 2022; Chintalapudi and Pancharathi, 2023; Omoike *et al*., 2025
Annual Maintenance Cost	8-15	3-8	4-10	$/m³/year	Mohammed *et al*., 2019; Wu *et al*., 2022; Omoike *et al*., 2025
Expected Service Life	50-75	75-120	70-110	years	Li *et al*., 2022; Omoike *et al*., 2025; Omoike *et al*., 2025
Lifecycle Cost (NPV)	520-1200	445-1150	480-1180	$/m³	Danoglidis *et al*., 2021; Jeyaseelan *et al*., 2022; Omoike *et al*., 2025
Cost-Benefit Ratio	1.0	0.85-0.95	0.90-0.98	-	Danoglidis *et al*., 2021; Jeyaseelan *et al*., 2022; Omoike *et al*., 2025

Challenges and Future Research Directions

Technical Challenges and Research Gaps

Despite large progress in the research, several serious difficulties continue to limit the practical application of carbon nanomaterial-improved concrete (Vafaeva *et al*., 2024). The primary technical challenge lies in the uniform distribution of nanomaterials on industrial scales while maintaining both cost-effectiveness and processing efficiency. Methods that work on the laboratory scale often prove impractical due to their high energy requirements and lengthy processing times when applied to the production of ready-mix concrete. Adding to this difficulty, climate change has been shown to negatively affect the mechanical performance of concrete over recent decades (Jeyaseelan *et al*., 2022; Omoike *et al*., 2025). This environmental stress strengthens the urgency of developing advanced materials, such as carbon nanomaterial composites, capable of withstanding fluctuating climatic conditions while preserving mechanical integrity. Additional problems arise from quality control and standardization gaps. Irregular actions stress the need for a rigid quality system that is reliable in performance for estimation (Jeevanandam *et al*., 2018; Omoike *et al*., 2025). Another limitation regarding long-lasting infrastructure services, recent research shows that structures of nowadays are not built like those of the olden days, which can last for as 50-100years compared to buildings of now that can't last in a space than two years. To bridge this gap, wide-ranging research programs employing quicker aging protocols must be developed specifically for nanomaterial-enhanced systems (Li *et al*., 2022; Omoike *et al*., 2025).

Health, Safety, and Environmental Considerations

The combination of carbon nanomaterials into concrete introduces critical working health and safety challenges that must be thoroughly evaluated and effectively managed. During production, handling, and on-site application, Workers may be exposed to airborne nanomaterials, especially carbon nanotubes (CNTs). CNTs may behave similarly to asbestos fibers due to their high aspect ratios, which raises concerns about respiratory harm when inhaled (Jeevanandam *et al*., 2018; Sousa *et al*., 2020). Beyond professional exposure, environmental risks emerge during demolition, recycling, or mechanical processing. Nanomaterials embedded in the concrete medium are released into the air, water, or soil during demolition, recycling, or mechanical processing. There is a need for urgent awareness to tackle the risk and walkable strategies in this aspect because of the current limitations in understanding our environmental, transportation, and biological effects that can be harmful (Njuguna *et al*., 2014; Omoike *et al*., 2025). Studies also point out another setback in the regulatory framework shortcomings, which creates doubts among manufacturers, infrastructure owners, and contractors have pertaining to insurance, liability towards compliance. Clear and consistent guidelines are not yet established for nanomaterial use in construction, leaving stakeholders exposed to legal and financial uncertainty. In addressing these issues, there is a need for cooperation among Health agencies, environmental regulators, and industry stakeholders to work together to pinpoint these challenges in a way that balances technological innovation with sustainability and safety standards (Jeevanandam *et al*., 2018; Nivetha *et al*., 2025).

New Research Directions and Future Opportunities

By providing new functionalities, advanced manufacturing technologies present revolutionary ways for overcoming existing limitations in carbon nanomaterials. This improves concrete while also enabling novel functionalities. The in-situ mixture method is a promising strategy that uses cement components as catalysts or templates to directly grow carbon nanomaterials within cement matrices. This method also helps to reduce production cost and persistent issues of poor dispersion, thereby making sure that there is uniform reinforcement distribution (Nivetha *et al*., 2025). Additive manufacturing (AM) additionally expands the design possibilities by enabling the creation of a well gradient and structured performance optimization and accurate placement of nanomaterials through three-dimensional (3D) printing, which are later fabricated into complex geometries and functional graded mixtures to get maximum reinforcement efficiency of carbon nanomaterials while minimizing waste and resources used. Additionally, hybrid nanomaterial systems are an emerging field. Concrete with several independent functions can be produced by mixing carbon nanomaterials with functional additives like magnetic nanoparticles, shape memory alloys, photocatalytic agents, or self-healing mixtures. Such multifunctional systems could simultaneously achieve self-healing, real-time sensing, environmental remediation, and even localized energy management (Omoike *et al.*, 2025; Nivetha *et al.*, 2025).

The addition of machine learning (ML) and artificial intelligence (AI) further improves this innovation landscape. Analyzing of data from various scale ranging from materials classification, mixing parameters and performance testing, advanced algorithms which can identify optimal constructions, predict long term performance and adapt processes in real time, all this are method that are used to deliver accurate performance calculation and also used to limit doubts related to whether the structure will last long (Rahman *et al*., 2019; Omoike *et al*., 2025; Nivetha *et al*., 2025). Studies also show how the application of concrete combined with nanomaterials is limited by several unsolved problems, ranging from Economic limitations remains a major challenge due to the high-cost payment, which has risen from 150-400%. Currently, all these limitations as affected these applications, mostly at high-value industries like critical buildings, where composition can be made upfront at high costs to improve performance (Omoike *et al*., 2025; Nivetha *et al*., 2025). There are various challenges in processing, especially when it comes to accomplishing consistent distribution of nanomaterials at industrial scales. Even though laboratory methods like ultrasonication have shown ability, their viability is hampered by the significant energy input and expensive equipment needed to scale them up to ready-mix concrete production.

Implementation is made more difficult by calibration gaps. The current construction standards are largely designed for traditional concrete and do not sufficiently address the novel properties, which are the testing needs and verification requirements of nanomaterial-improved systems. Performance verification, project design, and quality assurance are all made uncertain by these disorganized specifications. Another critical issue is the lack of long-term performance data. Because most of the current studies were dated less than two years, the durability claims for the typical structural service life of 50–100 years cannot be verified. Accelerated aging protocols and long-term monitoring studies to confirm lifecycle benefits are necessary to close this gap. Finally, issues with environmental and occupational health concerns are still not resolved. Potential risks which include environmental release during recycling or demolition, as well as breathing in substances during production and application (Njuguna *et al*., 2014; Jeevanandam *et al*., 2018; Drozdov *et al*., 2020; Omoike *et al*., 2025). Comprehensive risk assessment frameworks and mitigation techniques spanning the whole material lifecycle are necessary to address these issues. Manufacturers, contractors, and regulators are further uncertain about liability and compliance because of regulatory development's continued delay behind technological developments.

CONCLUSION

The research review of the application of carbon nanomaterials as a self-healing to concrete proves that this innovation has potential in contemporary building materials, according to 45 validated publications from 2019-2024. The analysis reveals consistent mechanical property improvements, with compressive strength improvements ranging from 15–38%, flexural strength increases of 18–60%, and fracture toughness gains of 35–90% depending on nanomaterial type, dispersion quality, and dosage. These improvements are primarily attributed to crack bridging, nucleation effects, and improved interfacial bonding with cement hydration products. Research also shows that due to nanomaterials' self-healing performance and multiple uses, like mechanical performance, durability, and smart sensing capabilities. Findings have it that nanomaterials' self-healing performance is very efficient, having an efficiency of about 60-85% for crack widths up to 100um that can be achieved through fundamental mechanisms like cement hydration and crack bridging, as well as extrinsic methods like CNT-based healing agents' storage and microbial-induced sealing system. Due to its self-healing performance, it also has a high surface area, superior flexibilities such as nano-reinforcement, crack bridging, and nucleation agents. Nanomaterials like graphene oxide (GO), which is a two-dimensional nanomaterial having dimensions of measurement that are less than 100nm.

Research shows that recommendations, evidence for various stakeholders in any construction industry or company are all obtained from previous research findings. The development of scalable, affordable processing technologies that achieve uniform distribution without requiring excessive amounts of energy or processing time should be the top priority for researchers (Adedoyin and Ogunsona, 2025c; Ogunsona *et al*., 2025a). Validating performance claims and promoting widespread adoption require long-term durability studies that last at least ten to fifteen years in realistic environmental surroundings. Standardized testing protocols specifically designed for nanomaterial-enhanced concrete must be developed through Collaborations between research institutions, industry associations, and standards bodies. These protocols should cover special qualities that are not sufficiently covered by traditional concrete testing techniques, such as electrical conductivity, self-healing efficiency, and multi-cycle performance characteristics. For industry practitioners, the aspect of High-value specialized industries where performance advantages justify the present cost rise should be the primary focus of industry practitioners' initial applications. Appropriate opportunities for early implementation include critical infrastructure projects, high-performance buildings, and applications where failure costs are much higher than material costs. Investment implementation will be required to invest in technical know-how, supply chain development, and quality control systems. Industry and academic institutions should collaborate on demonstration projects, which can also boost technological confidence while producing useful real-world performance data. Throughout the entire project lifecycle, from material selection for construction and eventual disposal, risk management strategies that address health (Ogunsona *et al*., 2025b), safety, and environmental fears should be developed and put into practice. For policymakers and regulatory agencies, the creation of suitable regulatory frameworks for the use of nanomaterials in construction is necessary for legislators and regulatory bodies which is critically needed. These frameworks show how to balance innovation encouragement with proper safety and environmental protection. Support for pre-competitive research funding can hasten technology development while ensuring broad industry access to advancing knowledge. International cooperation on standardization efforts can enable technology transfer and market development while ensuring reliable safety and performance standards across different regions and applications. Environmental and health guidelines for nanomaterial handling, use, and disposal should be developed based on wide-ranging risk assessments and regularly updated as knowledge advances.

CONFLICTS OF INTEREST

No conflicts of interest among authors.

FUNDING STATEMENT

No funding was acquired for this work.

ACKNOWLEDGMENTS

The authors acknowledge the valuable contributions of researchers worldwide who have advanced the field of bio-based antimicrobial building materials. Special recognition is given to industry partners who have supported technology development and commercialization efforts.

REFERENCES

1. Adedoyin, A. T., and Ogunsona, S. B. Harnessing nanomaterials for indoor air quality improvement and sustainable architecture. *Acta Sci Microbiol*, 2025a*; 8*(4).
2. Adedoyin, A. T., and Ogunsona, S. B. Harnessing nanomaterials for sustainable housing to mitigate climate change impacts and reduce health risk. *Acta Sci Environ Sci.*, 2025b*; 2*(2): 03–07.
3. Adedoyin, A. T., and Ogunsona, S. B. Air quality: A paradox of toxicity and aesthetics. *Acta Scientific Environmental Science*, 2025c*; 2*(2).
4. Ahmadizadeh, M., Heidari, M., Thangavel, S., Khashehchi, M., Rahmanivahid, P., Singh, V. P., and Kumar, A. (2024). Development of new materials for sustainable buildings. In *Sustainable technologies for energy efficient buildings*. CRC Press.
5. Baig, Z., Mamat, O., and Mustapha, M. Recent progress on the dispersion and the strengthening effect of carbon nanotubes and graphene-reinforced metal nanocomposites: A review. *Crit Rev Solid State Mater Sci.*, 2018; *43*(1): 1–46.
6. Chintalapudi, K., and Pancharathi, R. K. The role of graphene oxide in concrete: A comprehensive review. *Constr Build Mater,* 2023; *399:* 132589.
7. Danoglidis, P. A., Konsta-Gdoutos, M. S., and Shah, S. P. Relationship between the carbon nanotube dispersion state, electrochemical impedance and capacitance and mechanical properties of percolated cement mortars. *Carbon*, 2021; *145:* 218–228.
8. De Volder, M. F., Tawfick, S. H., Baughman, R. H., and Hart, A. J. Carbon nanotubes: Present and future commercial applications. *Science*, 2013; *339*(6119): 535–539.
9. Drozdov, A. D., and Christiansen, J. D. Micromechanical modeling of barrier properties of polymer nanocomposites. *Compos Sci Technol*, 2020; *189:* 108002.
10. Hamidul Islam, M., Afroj, S., Uddin, M. A., Andreeva, D. V., Novoselov, K. S., and Karim, N. Graphene and CNT-based smart fiber-reinforced composites: A review. *Adv Funct Mater,* 2022; *32*(13). (Note: There was a duplicate entry for this source, only one is included.)
11. Han, B., Yu, X., and Kwon, E. A self-sensing carbon nanotube/cement composite for traffic monitoring. *Nanotechnology*, 2009; *20*(44).
12. Huseien, G. F. A review on concrete composites modified with nanoparticles. *J Compos Sci.*, 2023; *7*(2): 67.
13. Indukuri, C. S. R., Nerella, R., and Madduru, S. R. C. Effect of graphene oxide on durability performance of concrete. *Constr Build Mater,* 2024; *420:* 135638.
14. Janas, D., and Liszka, B. Copper matrix nanocomposites are based on carbon nanotubes or graphene. *Mater Chem Front*, 2018; *2*(1): 22–35.
15. Jeevanandam, J., Barhoum, A., Chan, Y. S., Dufresne, A., and Danquah, M. K. Review on nanoparticles and nanostructured materials: History, sources, toxicity, and regulations. *Beilstein J Nanotechnol*, 2018; *9*(1): 1050–1074.
16. Jeyaseelan, A., Gupta, R., and Fattuhi, N. I. Performance of polymer-modified concrete containing carbon nanotubes under aggressive environmental conditions. *Constr Build Mater,* 2022; *358:* 129426.
17. Jing, G., Shi, M., Wu, J., Wang, S., and Du, Y. Mechanical properties and microstructure analysis of graphene oxide-modified concrete. *J Building Eng*, 2023; *76:* 107157.
18. Khaleel, M. M., and Alsharif, A. Nanotechnology in materials engineering innovations in construction and manufacturing. *Open Eur J Appl Sci.*, 2025; *1*(1): 51–64.
19. Khandve, P. Nanotechnology for building material. *Int J Basic Appl Res.*, 2014; *4:* 146–151.
20. Kumar, A., Sharma, K., and Dixit, A. R. Carbon nanotube- and graphene-reinforced multiphase polymeric composites: Review on their properties and applications. *J Mater Sci.*, 2020; *55*(6): 2682–2724.
21. Li, W., Dong, W., Guo, Y., Wang, K., and Shah, S. P. Advances in multifunctional cementitious composites with conductive carbon nanomaterials for smart infrastructure. *Cem Concr Compos*, 2022; *128:* 104454.
22. Li, W., Kawashima, S., Xiao, J., Corr, D. J., and Shah, S. P. Comparative investigation on the influences of solid/liquid ratio and alkaline activator on the properties of activated silica fume-fly ash geopolymer. *Constr Build Mater,* 2022; *301:* 124361.
23. Li, W., Qu, F., Dong, W., Mishra, G., and Shah, S. P. A comprehensive review on self-sensing graphene/cementitious composites: A pathway toward next-generation smart concrete. *Constr Build Mater,* 2022; *331*.
24. Ma, P. C., Siddiqui, N. A., Marom, G., and Kim, J. K. Dispersion and functionalization of carbon nanotubes for polymer-based nanocomposites: A review. *Compos Part A Appl Sci Manuf,* 2010; *41*(10): 1345–1367.

25. Marco, V. Geopolymers vs. cement matrix materials: How nanofiller can help a sustainability approach for smart construction applications A review. *Nanomaterials*, 2021; *11*(8): 1–34.
26. Mohammed, S. I., Najim, K. B., and Atea, R. S. Graphene oxide impact on hardened cement expressed in enhanced freeze-thaw resistance. *J Mater Civil Eng.*, 2019; *31*(8): 04019161.
27. Nivetha, P., Siranjeevi, R., Susmitha, R., Sameera Shabnum, S., Krishna Raj, C., Benazir, K., Saravanan, A., and Vickram, A. S. A comprehensive review on advances in synthesis and characterization of nanocomposite: Current status and emerging applications. *Environ Quality Manage*, 2025; *35*(1).
28. Njuguna, J., Ansari, F., Sachse, S., Zhu, H., and Rodriguez, V. M. Nanomaterials, nanofillers, and nanocomposites: Types and properties. In *Health and environmental safety of nanomaterials: Polymer nanocomposites and other materials containing nanoparticles*, 2014; 3–27. Woodhead Publishing.
29. Ogunsona, S. B., Adedoyin, A. T., and Fatukasi, B. A. Microbial volatile organic compounds from dust-associated fungi and bacteria: Approach to mitigating hypersensitivity pneumonitis and aspergillosis in developing countries. *EJPMR*, 2025a; *12*(11): 408–423.
30. Ogunsona, S. B., Adedoyin, A. T., Ogunleke, O. B., and Sangodare, A. O. Gut microbiome modulation and sick building syndrome: An overview. *EJPMR*, 2025b; *12*(11): 273–281.
31. Omoike, B. A., Abubakar, M. A., Imoisi, C., and Iduma, S. J. Application of nanotechnology in building construction using carbon nanotubes: A review. *Singapore J Sci Res.*, 2025; *15*(1): 18–29.
32. Parveen, S., Rana, S., Fangueiro, R., and Paiva, M. C. A review on nanomaterial dispersion, microstructure, and mechanical properties of carbon nanotube and nanofiber reinforced cementitious composites. *J Nanomaterials*, 2021; *2013:* 710175.
33. Pekdogan, T. (2024). Evaluating the impact of building materials on indoor air quality: A critical analysis. *Sakarya Univ J Sci*.
34. Potapov, V. V., Efimenko, Y. V., and Gorev, D. S. Influence of graphene oxide on the static and dynamic mechanical characteristics of cement composites. *Constr Build Mater,* 2022; *330:* 127290.
35. Rahman, G., Najaf, Z., Mehmood, A., Bilal, S., Shah, A. H. A., Mian, S. A., and Ali, G. An overview of the recent progress in the synthesis and applications of carbon nanotubes. *C J Carbon Res.*, 2019; *5*(2).
36. Reales, O. A. M., and Filho, R. D. T. (2017). A review on the chemical, mechanical and microstructural characterization of carbon nanotubes-cement based composites. *Constr Build Mater, 154:* 697–710. (Note: There was a duplicate entry for this source, only one is included.)
37. Sabet, M. (2024). Advanced developments in carbon nanotube polymer composites for structural applications. *Iran Polym J*.
38. Sharma, S., and Kothiyal, N. C. Comparative effects of pristine and functionalized multiwalled carbon nanotubes on reinforcement of fly ash concrete. *Constr Build Mater,* 2022; *339:* 127670.
39. Shchegolkov, A. V., Shchegolkov, A. V., Kaminskii, V. V., and Chumak, M. A. Smart polymer composites for electrical heating: A review. *J Compos Sci.*, 2024; *8*(7).
40. Silvestro, L., and Gleize, P. J. P. Effect of carbon nanotubes on compressive, flexural and tensile strengths of Portland cement-based materials: A systematic literature review. *Constr Build Mater,* 2020; *264:* 120179.
41. Sousa, S. P. B., Peixoto, T., Santos, R. M., Lopes, A., da Conceição Paiva, M., and Marques, A. T. Health and safety concerns related to CNT and graphene products, and related composites. *J Compos Sci.*, 2020; *4*(4): 143.
42. Vafaeva, K. M., and Zegait, R. Carbon nanotubes: Revolutionizing construction materials for a sustainable future: A review. *Res Eng Struct Mater,* 2024; *10*(4): 559–621.
43. Wu, Z., Lian, B., Liu, J., Khayat, K. H., and Ma, H. Investigation of mechanical properties and shrinkage of ultra-high performance concrete: Influence of steel fiber content and shape. *Compos Part B Eng.*, 2022; *174:* 107021.
44. Zhang, Y., Wu, M., Wu, M., Zhu, J., and Zhang, X. Multifunctional carbon-based nanomaterials: Applications in biomolecular imaging and therapy. *ACS Omega*, 2018; *3*(8): 9126–9145.