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Advancements in Smart Concrete: Nanomaterials Enhancing Durability and Self-Sensing Capabilities

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ABSTRACT

Concrete, a widely used construction material, faces challenges such as low tensile strength, brittleness, and long-term durability issues. These limitations have prompted advancements in cementitious materials, including smart concrete enhanced with nanomaterials. Nanomaterials like nano-silica, graphene oxide, and carbon nanotubes improve mechanical properties and durability, enhance resistance to cracking, and enable multifunctional capabilities. Smart concrete also offers self-sensing abilities for structural health monitoring. Despite challenges in nanoparticle dispersion and cost, nanotechnology has revolutionized concrete systems, ensuring sustainable, high-performance materials for modern infrastructure.

Keywords: *Smart Concrete, Nanomaterials, Durability, Self-Sensing.*

I. INTRODUCTION

Concrete has remained the most widely used construction material globally due to its versatility, availability, and cost-effectiveness; however, its inherent limitations such as low tensile strength, brittleness, susceptibility to cracking, and long-term durability issues continue to challenge modern civil engineering practices (Makul, 2020). Infrastructural deterioration caused by micro-crack formation, environmental exposure, and mechanical loading has led to increased maintenance costs and reduced service life of structures. To address these issues, researchers have increasingly focused on the development of advanced cementitious materials with improved mechanical performance and durability characteristics. Among these innovations, smart concrete enhanced with nanomaterials has emerged as a promising solution, offering improved structural behavior along with self-sensing and multifunctional capabilities. The integration of nanotechnology into concrete has introduced a paradigm shift in construction materials, enabling microstructural refinement, improved hydration processes, and enhanced resistance to environmental degradation (Du et al., 2019).

Recent advancements in nanomaterials such as nano-silica (NS), graphene oxide (GO), carbon nanotubes (CNTs), nano-alumina (NA), nano-titanium dioxide (NT), and nano-calcium carbonate (NCC) have significantly contributed to the evolution of high-performance and smart concrete systems. These nanomaterials, due to their extremely small particle size and high surface area, play a crucial role in accelerating cement hydration and promoting the formation of calcium-silicate-hydrate (C-S-H) gel, which is the primary binding phase responsible for concrete strength (Adanu et al., 2026). Studies have shown that incorporating such nanoparticles enhances compressive, tensile, and flexural strength while simultaneously improving durability properties such as permeability resistance and abrasion resistance (Alghrairi et al., 2025). Furthermore, nanomaterials contribute to pore refinement and crack-bridging mechanisms, which help mitigate micro-crack propagation at early stages, thereby improving structural integrity over time. The inclusion of graphene-based materials and carbon nanostructures has also introduced electrical conductivity into concrete, enabling the development of self-sensing smart concrete capable of monitoring strain, stress, and damage in real time (Hanief et al., 2026).

In addition to mechanical enhancement, smart concrete developed using nanotechnology has demonstrated multifunctional capabilities, particularly in the field of structural health monitoring (SHM). Conductive nanomaterials such as graphene, multi-walled carbon nanotubes (MWCNTs), and carbon black nanoparticles have been widely studied for their piezoresistive properties, which allow concrete to act as a self-sensing material (Kanagasundaram & Solaiyan, 2023). These materials exhibit changes in electrical resistance in response to mechanical deformation, enabling real-time monitoring of strain, crack formation, and structural damage. Demircilioğlu and Teomete (2024) reported that the incorporation of graphene and MWCNTs significantly improved strain sensitivity and reduced electrical resistivity, thereby enhancing the sensing performance of concrete. Similarly, Shankar and Mandal (2024) emphasized that nanomaterials not only improve mechanical strength but also impart additional functionalities such as photocatalytic activity, antimicrobial behavior, and improved thermal and electrical conductivity. These multifunctional characteristics make nanomaterial-based smart concrete highly suitable for next-generation sustainable infrastructure systems.

The growing interest in smart concrete is also driven by its potential applications in extreme and challenging environments, including seismic zones, fire-exposed structures, and aging infrastructure systems. Research has demonstrated that nanomaterial-modified cementitious composites can retain their sensing and mechanical properties even under high-temperature exposure, making them suitable for post-fire structural evaluation (Nalon et al., 2021). Moreover, the integration of nanotechnology in cement-based materials has been found to enhance resistance against environmental degradation, corrosion of reinforcement, and moisture ingress, thereby extending the service life of structures (Utsev et al., 2022). Despite these advancements, challenges such as dispersion of nanoparticles, cost-effectiveness, scalability, and long-term performance consistency remain critical areas of concern. However, ongoing research continues to optimize mix designs and improve the compatibility of nanomaterials with conventional cementitious systems. Overall, the development of smart concrete using nanomaterials represents a significant advancement in structural engineering, offering a sustainable, intelligent, and high-performance alternative to traditional concrete systems that can revolutionize future infrastructure development (Li et al., 2022; Shankar & Mandal, 2024).

II. RESEARCH BACKGROUND

Hanief et al., (2026) investigated the importance of maintaining structural integrity over the service life of concrete structures, highlighting extensive research in structural health monitoring (SHM) that employed advanced materials to improve safety and durability. The study reviewed the applications of graphene and its derivatives, specifically graphene oxide (GO) and reduced graphene oxide (rGO), in SHM for self-sensing concrete. It was reported that when GO and rGO were properly dispersed within the cementitious matrix, they significantly enhanced mechanical properties and acted as effective piezoelectric materials, integrating well with the cement microstructure to enable non-destructive self-sensing. The review indicated that these materials outperformed many conventional self-sensing agents, also serving as efficient energy dissipators that increased fracture energy by mitigating crack propagation. The findings suggested that, when proportioned appropriately, the combined mechanical, thermal, and electrical properties of GO and rGO rendered them highly suitable for smart concrete applications, advancing the development of self-sensing structural materials.

Adanu et al. (2026) investigated the limitations of conventional concrete, noting that insufficient tensile strength, low abrasion resistance, and poor fresh-state consistency often led to fractures and reduced durability. They emphasized that tensile stress resistance remained the most critical challenge, as it caused microcracks that propagated to larger scales. The study highlighted nanomaterials, with dimensions ranging from 0.1 to 100 nanometers, as an innovative approach to enhance concrete's mechanical performance through nano-core effects. These materials were reported to contribute significantly to the formation of calcium–silicate–hydrate (C-S-H) gels, seeding effects, and accelerated cement hydration reactions. The review focused on evaluating various nanoparticles, including nano-calcium carbonates (NCCs), iron oxide (NI), nano-aluminum oxide (NA), graphene oxide (GO), nano-silica (NS), and nano-titanium oxide (NT), in terms of their effects on both fresh and hardened concrete properties. The study identified promising nanomaterials for high-performance concrete, outlined existing research gaps, and proposed directions for future investigations to optimize their application in advanced construction materials.

Alghrairi et al., (2025) investigated the incorporation of nanomaterials in concrete to enhance its mechanical and durability properties. The study systematically analyzed the effects of nanosilica, nanoalumina, nanometakaolin, nanoclay, nanocarbon dioxide, and other nanoparticles on compressive, tensile, and flexural strengths of cementitious materials. It was reported that nanomaterial additions significantly improved early-age compressive strength, with enhancements ranging from 12% to 50% compared to conventional mixtures. The authors also highlighted the positive influence of nanosilica, nano–titanium oxide, nano-$CaCO_3$, and nanocarbons on flexural (2%–22%) and tensile (16%–55%) performance. Furthermore, combining nanomaterials with polypropylene fibers was shown to enhance flexural, tensile, and compressive strength, as well as bond strength with reinforcement bars. The study emphasized that composite nanomaterials could further elevate tensile properties, achieving high ultimate tensile strength and reliable predictive accuracy. The research concluded that nanomaterials offer superior alternatives to traditional concrete additives, while ongoing studies were suggested to address challenges and ensure broader applicability in construction.

Demircilioğlu and Teomete (2024) investigated the development of nineteen concrete mixtures incorporating multi-wall carbon nanotubes (MWCNT), graphene, nanoscale industrial waste (iron oxide), and suspensions of nanosized metals including iron, zinc, and a composite of iron, silver, copper, and zinc, with varying volume percentages. They reported that the addition of graphene, MWCNT, nanoscale iron, and the composite suspension significantly reduced the electrical resistivity of the concrete by 229%, 176%, 113%, and 251%, respectively. Furthermore, the compressive strain sensitivity increased markedly by 244%, 211%, and 311% for mixtures containing graphene, MWCNT, and nanoscale zinc suspension, respectively. The study also evaluated tensile strain and crack length sensitivities, particularly in graphene-enhanced mixtures, which exhibited the highest compressive strain sensitivity. Strong linear correlations were observed between compressive strain, tensile strain, and crack length with electrical resistance changes. Detailed phenomenological models were developed to describe the relationships between graphene content, tensile strain, and crack sensitivity, providing a predictive framework for multifunctional, strain-sensing concrete.

Shankar and Mandal (2024) conducted a comprehensive review on the recent advancements in smart cement nanocomposites, emphasizing their significance in sustainable civil infrastructure development. They highlighted that the incorporation of functional nanomaterials, such as titanium oxide (TiO_2), iron oxide (Fe_2O_3), graphene, graphene oxide (GO), carbon nanotubes (CNTs), carbon nanofibres (CNFs), and polymers at low weight percentages, was found to impart smart properties while maintaining mechanical strength. Their review indicated that the addition of TiO_2, SiO_2, Fe_2O_3, CNTs, or GO at concentrations below 5 wt% enhanced mechanical strength by approximately 30–50%, attributed to pore filling, crack bridging, and gap prevention. Moreover, functional nanomaterials were reported to improve photocatalytic dye degradation, microbial inhibition, impermeability, shrinkage reduction, hydrophobicity, and thermal/electrical conductivity, along with piezoelectric properties. The study concluded that while numerous research articles and reviews exist, a systematic understanding of the underlying physical and chemical mechanisms was essential for optimizing smart cement nanocomposites for practical applications.

Kanagasundaram and Solaiyan (2023) investigated the integration of self-sensing capabilities and diverse functional properties of nanomaterials into cementitious composites to develop smart and multifunctional sensor materials. They highlighted that the evolution of Structural Health Monitoring (SHM) had contributed significantly to extending structural lifespan and mitigating damages. Their work emphasized that embedding electrically conductive smart cementitious composites within structural elements proved advantageous for damage evaluation, periodic health monitoring, and life assessment. The review scrutinized various development processes and design methods for smart-sensing cementitious composites, elaborating on the principles of self-sensing, typical functional fillers, trends in percolation threshold, dispersion materials, and technologies. It also discussed the required sensing performance based on conduction theory and examined practical applications of smart cement sensors in SHM. Furthermore, they reported that the incorporation and proper dispersion of nanomaterials enhanced sensitivity, multifunctionality, and economic feasibility, positioning these composites as promising solutions for future structural monitoring.

Utsev et al., (2022) examined the growing role of nanotechnologies and nanomaterials across various civil engineering disciplines, including geotechnical and structural engineering, construction materials, and reinforcement applications. The study provided a comprehensive overview of nanotechnology applications in civil engineering, emphasizing concrete structures and the integration of nanoparticles in construction materials. It highlighted how nanoscale approaches, particularly those employing carbon-based nanoparticles, contributed to enhanced technical properties, such as increased temperature tolerance, moisture resistance, and structural robustness in lightweight concrete. The research further indicated that nanomaterials were instrumental in improving composite concrete strength, durability, and sustainability, while also offering potential solutions for mitigating degradation in concrete structures. The study underscored innovative applications, including intelligent and self-sensing concrete, and emphasized that incorporating specific nanoparticles into key construction materials like cement significantly improved their fundamental properties, performance, and longevity, while also suggesting possible environmental benefits from nanotechnology utilization in construction.

Li et al. (2022) critically reviewed the development of conductive carbon nanomaterials in smart cementitious composites aimed at multifunctional applications such as self-sensing, self-healing, self-heating, and electromagnetic interference shielding. They examined the dispersion and percolation behaviour of 0D, 1D, and 2D carbon materials in cementitious matrices and analysed their effects on electrical and piezoresistive performances. Various dispersion techniques, including mechanical mixing, ultrasonic and high-shear methods, chemical modification, mineral additives, and hybrid approaches, were summarized. The study compared the electrical resistivity and piezo resistivity of composites with single and hybrid carbon materials, highlighting efficiency and self-sensing mechanisms. Additionally, theoretical modelling studies were reviewed, revealing that factors such as water content and nanocomposite agglomeration had often been overlooked. While prior research demonstrated the potential of conductive cementitious composites for self-sensing or heating pavements, Li et al. suggested that further work on sustainable and cost-effective production, as well as on self-sensing stability, data acquisition, and sensor configuration, remained necessary for future smart infrastructure.

Nalon et al. (2021) investigated the potential of smart cement-based composites incorporating multi-walled carbon nanotubes (MWCNT) or carbon-black nanoparticles (CBN) for structural health monitoring of fire-damaged concrete. They produced a total of 112 composites with varying nanofiller concentrations, subjected them to different heat treatments, and performed electro-mechanical tests to evaluate their performance. The study highlighted the effects of temperature on residual capacitance, conductivity, and piezo resistivity, while thermogravimetric analysis and Raman spectroscopy were used to examine nanofiller thermal decomposition. It was reported that the sensing capability of the smart composites improved after exposure to 200 °C. Composites containing 0.8% or 1.2% MWCNT retained sufficient self-sensing ability after heating up to 400 °C, whereas mortars with 6% or 9% CBN maintained residual self-sensing ability up to 600 °C. Additionally, composites with 9% CBN demonstrated a notable capacity for self-detection of fire-induced damage, suggesting their suitability for post-fire structural monitoring.

Makul (2020) reported that concrete ranked as the second most consumed material globally after water and remained the most widely used construction material, although its advantages were countered by significant ecological impacts associated with its production, transportation, and use. It was noted that concrete typically exhibited a brittle nature, low tensile strength, poor resistance to crack formation, and limited strain capacity. Recent research emphasized the enhancement of concrete properties through the integration of innovative solutions, including fibers, chemical admixtures, and supplementary cementitious materials. The increasing demands of modern infrastructure necessitated components with higher durability and mechanical strength, which were suggested to be achievable by incorporating nanomaterials into cement-based products. Examples cited included carbon nanotubes (CNTs), nano-ferric oxide (nano-Fe2O3), and graphene oxide, often used alongside other reinforcements such as glass fibers, steel fibers, fly ash, and rice husk powder. Studies indicated that, with optimum dosages, mechanical performance, workability, water absorption, and the service life of concrete structures could be substantially improved.

Du et al. (2019) reviewed the emerging applications of various nanomaterials in construction, focusing on studies published over the preceding decade. They examined the incorporation of nanomaterials into cement-based materials and highlighted how their dispersion within cement composites influenced resistance to physical and chemical deterioration, as well as rebar corrosion. The review also discussed nanoscale modeling approaches that had been proposed to describe interactions between admixed nanomaterials and cement hydration products. Furthermore, Du et al. summarized recent advancements in characterization techniques used to evaluate the properties of cement-based materials at the nanoscale. Their analysis emphasized the critical role of nanomaterials in enhancing the durability and performance of cementitious composites, while also identifying gaps in understanding the mechanisms governing nanomaterial–cement interactions. Overall, the work was positioned as a comprehensive assessment of the state of nanotechnology applications in cement-based materials, providing insights into both experimental and modeling perspectives.

Taha et al., (2018) reported that polymer concrete (PC) is a type of concrete in which the polymer binder replaced cement and had been employed in field applications since the 1950s. They indicated that PC had found extensive use in precast architectural facades, underground utilities, manholes, machine foundations, bridge deck overlays, and other structural applications. The study highlighted that PC exhibited higher compressive and tensile strengths as well as superior durability compared with conventional Portland cement concrete, although its broader adoption had been constrained by higher costs. Taha et al. suggested that incorporating a very small fraction of nanomaterials—below 2% of carbon nanotubes or alumina nanoparticles by resin weight—could substantially enhance the mechanical performance of PC. Their findings demonstrated that the inclusion of 2.0 wt.% pristine carbon nanotubes notably improved ductility and enabled self-sensing capabilities. They concluded that such integration of nanomaterials could fundamentally advance PC as a smart, resilient material suitable for extreme loading conditions.

Naresh and Dadapeer (2017) highlighted that concrete had been recognized as a highly versatile material, and the persistent demands on its performance had motivated extensive research in concrete technology. They noted that engineers continually sought to enhance concrete properties through innovative chemical admixtures and supplementary cementitious materials such as fly ash, silica fume, granulated blast furnace slag, and steel slag. Variants of concrete composites, including Admixture Concrete, Fiber Reinforced Concrete (FRC), Polymer Impregnated Concrete (PIC), High Performance Concrete (HPC), Self-Compacting Concrete (SCC), and Geopolymer Concrete, had been developed to meet specialized requirements. The study emphasized that the application of nanotechnology in concrete involved nano materials like nano silica and nano fibers, which, due to their high surface-area-to-volume ratio, exhibited enhanced reactivity compared to larger particles. It was observed that nano silica reacted with C3S and C2S in cement to form CSH-2 gel, producing strong bonding. Experimental investigations on M40 and M50 concrete incorporating micro and nano silica demonstrated improved compressive, split tensile, and flexural strength, indicating the potential of smart concrete composites with superior properties.

III. KEY FINDINGS FROM STUDY

Author (Year)	Nanomaterials / Focus	Methodology	Key Findings	Research Gap / Limitation
Hanief et al. (2026)	Graphene oxide (GO), reduced graphene oxide (rGO)	Review of SHM-based self-sensing concrete studies	GO and rGO improved mechanical strength, crack resistance, and enabled self-sensing through electrical conductivity	Lack of long-term field validation of graphene-based SHM systems
Adanu et al. (2026)	Nano-silica, nano-alumina, nano-Fe_2O_3, nano-TiO_2, nano-$CaCO_3$	Review of fresh and hardened concrete properties	Nanomaterials enhanced C-S-H formation, hydration rate, and tensile strength	Limited understanding of optimal dosage and dispersion techniques
Alghrairi et al. (2025)	NS, NA, NT, nanoclay, CNTs	Systematic literature review	Compressive strength increased by 12–50%; tensile strength improved significantly	Durability under long-term environmental exposure needs further study
Demircilioğlu & Teomete (2024)	Graphene, MWCNTs, nano-metals	Experimental mix design and sensing analysis	Electrical resistivity reduced up to 251%; strain sensitivity improved significantly	High cost and scalability issues of nano-enhanced sensing concrete
Shankar &	TiO_2, Fe_2O_3, GO,	Review of cement	Strength increased by	Lack of

Mandal (2024)	CNTs, CNFs	nanocomposites	30–50%; multifunctional properties like photocatalysis and conductivity observed	standardized design guidelines for smart cement nanocomposites
Kanagasundaram & Solaiyan (2023)	Conductive nanomaterials	SHM sensor-based review	Enhanced self-sensing ability and improved structural monitoring efficiency	Need for improved percolation threshold control and field implementation
Utsev et al. (2022)	Carbon-based nanoparticles	Review article	Improved durability, thermal resistance, and sustainability of concrete	Limited lifecycle assessment of nano-modified structures
Li et al. (2022)	CNTs, graphene, hybrid carbon nanomaterials	Review of dispersion and modeling techniques	Improved electrical and piezoresistive behavior for smart sensing	Lack of cost-effective dispersion and stability solutions
Nalon et al. (2021)	MWCNT, carbon black nanoparticles	Experimental study (thermal exposure tests)	Fire-damaged concrete retained sensing ability up to 600°C	Long-term performance after repeated thermal cycles unclear
Makul (2020)	General nanomaterials in concrete	Review of smart concrete progress	Nanomaterials improve strength, durability, and sustainability	Need for eco-friendly and scalable nanomaterial production
Du et al. (2019)	Various nanomaterials	Review + modeling + characterization	Nanotechnology improves durability and corrosion resistance	Limited understanding of nano–cement interaction mechanisms
Taha et al. (2018)	Carbon nanotubes, alumina nanoparticles	Experimental polymer concrete modification	2% CNT improved ductility and self-sensing behavior	High material cost restricts large-scale application
Naresh & Dadapeer (2017)	Nano-silica, nano-fibers	Experimental study on high-strength concrete	Significant improvement in compressive and tensile strength	Limited studies on long-term durability and field applications

IV. CONCLUSION

The reviewed literature clearly indicates that the development of smart concrete using nanomaterials represents a significant advancement in modern construction technology. Conventional concrete, despite its widespread use, suffers from inherent limitations such as low tensile strength, brittleness, crack susceptibility, and durability-related issues under aggressive environmental conditions (Makul, 2020). The integration of nanomaterials such as nano-silica, graphene oxide, carbon nanotubes, nano-alumina, and nano-titanium dioxide has been consistently shown to enhance both mechanical and functional properties of concrete (Adanu et al., 2026; Alghrairi et al., 2025). These materials improve cement hydration, refine pore structure, and promote the formation of calcium-silicate-hydrate (C-S-H) gel, which directly contributes to increased compressive, tensile, and flexural strength. In addition to mechanical enhancement, nanomaterial-based concrete exhibits multifunctional characteristics, including self-sensing, self-monitoring, and improved durability. Conductive nanomaterials such as graphene and multi-walled carbon nanotubes enable piezoresistive behavior, allowing concrete to detect strain, crack formation, and structural deformation in real time (Hanief et al., 2026; Kanagasundaram & Solaiyan, 2023). Studies have also demonstrated that smart concrete can maintain sensing capabilities even under high-temperature exposure, making it suitable for fire-damaged structure assessment and long-term structural health monitoring (Nalon et al., 2021). Furthermore, nanotechnology enhances resistance to corrosion, permeability, and environmental degradation, thereby significantly extending the service life of infrastructure systems (Utsev et al., 2022). Overall, the integration of nanomaterials into cementitious composites has transformed conventional concrete into a multifunctional smart material with applications in sustainable infrastructure, disaster-resistant construction, and real-time structural health monitoring systems. However, despite promising laboratory-scale results, challenges such as uniform dispersion, cost-effectiveness, scalability, and lack of standardized design methodologies still limit widespread industrial adoption.

V. FUTURE SCOPE

- **Optimization of Nanomaterial Dosage and Dispersion Techniques:** Future research should focus on identifying optimal concentrations and advanced dispersion methods (ultrasonication, chemical functionalization) to prevent agglomeration and ensure uniform performance in concrete matrices.
- **Development of Cost-Effective Nanomaterials:** The high cost of materials such as graphene and carbon nanotubes restricts large-scale implementation. Research into industrial waste-derived nanomaterials and hybrid nano-additives can improve economic feasibility.
- **Long-Term Durability and Field Performance Studies:** Most existing studies are laboratory-based; therefore, long-term field exposure studies are required to evaluate performance under real environmental and loading conditions.
- **Standardization of Mix Design and Design Codes:** There is a need to develop standardized guidelines and design codes for nanomaterial-based smart concrete to facilitate its integration into civil engineering practice.
- **Integration with IoT and Smart Infrastructure Systems:** Future smart concrete systems can be integrated with Internet of Things (IoT) technologies for real-time monitoring, data collection, and predictive maintenance of structures.
- **Sustainability and Environmental Impact Assessment:** Further studies should evaluate the environmental impact and carbon footprint of nanomaterial production and explore eco-friendly alternatives to ensure sustainable development.
- **Multifunctional Hybrid Nanocomposites:** Research should focus on hybrid combinations of nanomaterials to achieve simultaneous improvements in mechanical strength, self-healing, thermal resistance, and sensing capabilities.
- **Application in Extreme Conditions and Smart Cities:** Advanced smart concrete systems should be tested for use in seismic zones, fire-prone structures, underwater constructions, and smart city infrastructure development.

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