Policy Research Journal
ISSN (E): 3006-7030 ISSN (P): 3006-7022 Volume 4, Issue 2, 2026

MECHANICAL AND DURABILITY PERFORMANCE OF CONCRETE MODIFIED WITH CARBON NANOTUBES: A REVIEW

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DOI: http://doi.org/10.5281/zenodo.21191599

Keywords
carbon nanotubes, concrete, mechanical properties, durability, reinforcement, microstructure, compressive strength, flexural strength

Article History
Received: 05 December 2025
Accepted: 16 January 2026
Published: 01 February 2026

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Abstract
Carbon nanotubes (CNTs) have emerged as promising nanomaterials for enhancing the mechanical and durability properties of concrete. This comprehensive review synthesizes recent peer-reviewed literature on CNT-modified concrete, focusing on mechanical performance enhancement and long-term durability characteristics. The review examines optimal dosage ranges, dispersion techniques, strengthening mechanisms, and durability against environmental attacks. Results consistently demonstrate that CNT additions of 0.05–0.10 wt% of cement can increase compressive strength by 15–31%, flexural strength by 17–70%, and tensile strength by 20–45%, while simultaneously reducing water absorption, chloride penetration, and sulfate attack vulnerability. The microstructural analysis reveals that CNTs function as crack bridges and pore fillers, creating denser matrices with refined pore structures. Current challenges include achieving uniform dispersion, optimizing cost-effectiveness, and ensuring long-term durability. This review identifies critical research gaps in standardization protocols, large-scale production feasibility, and environmental impact assessment of CNT-modified concrete systems.

1. INTRODUCTION

1.1 Background and Significance

Concrete is one of the most widely used construction materials, though cementitious materials' quasi-brittle behavior leads to cracking and a loss of durability, which is a major concern in structural applications. [1] Traditional concrete exhibits significant limitations in terms of tensile strength, crack resistance, and vulnerability to aggressive environmental conditions. Carbon nanotubes (CNTs) are famous for their extreme tensile strength and flexibility and can be used as a reinforcement to increase the mechanical properties of concrete. [2]

Carbon-based nanomaterials—including carbon nanofibers (CNFs), carbon nanotubes (CNTs), and graphene—have gained significant attention as next-generation reinforcement agents due to their exceptional strength, high aspect ratio, and unique interfacial properties. [3] The integration of CNTs into concrete matrices represents a paradigm shift in construction material engineering, offering the potential to create multifunctional composites with superior performance characteristics across multiple dimensions.

1.2 Types and Properties of Carbon Nanotubes

Multi-walled carbon nanotubes (MWCNTs) are a promising material in the field of civil engineering because they have unique properties of high stiffness and strength, light weight, and good thermal conductivity. [4] CNTs are characterized by their exceptional mechanical properties, with tensile strengths ranging from 50 to 500 GPa and elastic moduli between 1 to 5 TPa, significantly exceeding those of conventional reinforcing fibers. The nanoscale dimensions of CNTs—diameters typically between 1 and 100 nanometers and lengths ranging from micrometers to millimeters—enable them to interact with the cement matrix at fundamental scales and modify microstructural development.

1.3 Motivation for this Review

Despite the promising potential of CNTs in concrete applications, numerous challenges persist regarding optimal dosage selection, dispersion methodology, cost considerations, and long-term performance durability. The improvement of the macro mechanical properties of carbon nanotube-reinforced composite structures has been discussed in the form of functionally graded carbon nanotubes reinforced composites (FG-CNTRC). [1] This review consolidates current knowledge on the mechanical and durability performance of CNT-modified concrete, synthesizing findings from peer-reviewed sources to identify optimal practices and remaining research gaps.

2. Methodology

2.1 Literature Search Strategy

A comprehensive systematic review was conducted using academic research databases including Scopus, Web of Science, and CrossRef. The search strategy employed multiple keyword combinations: "carbon nanotubes concrete," "CNT mechanical properties," "CNT durability concrete," "multi-walled carbon nanotubes reinforcement," and "nano-modified concrete." Publication filters restricted results to peer-reviewed articles, conference proceedings, and review papers published between 2015 and 2025 to ensure contemporary relevance. Exclusion criteria eliminated studies focusing on carbon nanotubes in non-concrete applications, such as asphalt pavements, composites, or polymer matrices, ensuring topical coherence.

2.2 Data Extraction Framework

Information was systematically extracted from selected papers using a standardized protocol capturing: (1) CNT type and characteristics (single-walled, multi-walled, aspect ratio, diameter); (2) dosage ranges tested (in percentage by weight of cement); (3) dispersion methods employed; (4) mechanical properties measured (compressive strength, tensile strength, flexural strength, elastic modulus); (5) durability parameters assessed (chloride penetration, sulfate resistance, water absorption, acid attack resistance); (6) curing ages reported; and (7) microstructural analysis techniques utilized.

2.3 Categorization of Studies

Studies were categorized into five thematic groups: (1) **Basic Mechanical Properties**—compressive, tensile, and flexural strength enhancements; (2) **Durability Performance**—environmental resistance and long-term degradation; (3) **Microstructural Mechanisms**—pore refinement and hydration products analysis; (4) **Dispersion and Processing**—techniques for achieving uniform CNT distribution; and (5) **Hybrid Reinforcement Systems**—combinations of CNTs with other additives or fibers.

2.4 Strength of Evidence Assessment

Individual studies were evaluated according to research design classification: experimental investigations with controlled variables received primary weight, while modeling and simulation studies provided secondary supporting evidence. Methodological quality was assessed based on sample size adequacy, statistical rigor, control group inclusion, replication across multiple concrete grades, and curing period duration. Papers reporting both positive and null findings were included to provide balanced analysis.

2.5 Synthesis Approach

A narrative synthesis approach was adopted, organizing findings chronologically and by research theme to identify temporal trends in optimal dosage recommendations, emerging dispersion techniques, and evolving understanding of mechanisms. Quantitative findings from multiple studies employing identical testing protocols were tabulated to enable cross-study comparison and meta-analytical observation of effect magnitude ranges.

Table 1: Mechanical Property Enhancements from CNT Addition to Concrete

Study Reference
Jalali Mosallam et al. (2021)
Hawreen & Bogas (2019)
Khan et al. (2025)
Li et al. (2023)
Dong et al. (2021)
Hassan et al. (2022)
Zhang et al. (2023)

3. Results: Mechanical Properties Enhancement

3.1 Compressive Strength Performance

The results indicate that the presence of 0.02% of cement weight of CNTs increased compressive strength of the 28-day-old lightweight concrete up to 29%. [2] Multiple studies have documented compressive strength improvements through CNT incorporation, with effects varying based on dosage and concrete grade. The incorporation of CNTs were able to improve the compressive strength up to 21%, but only slightly increased the modulus of elasticity. [5]

The results revealed two effective mix designs with 0.06% and 0.08% MWCNT, achieving compressive strengths of 40 and 45 MPa, respectively, surpassing the traditional concrete strength of 32 MPa and meeting American Concrete Institute and AS3600 standards. [6] The optimal dosage range for maximum compressive strength enhancement appears to fall between 0.05 and 0.10 wt% of cement, above which agglomeration effects diminish returns.

3.2 Flexural and Tensile Strength Enhancement

Adding both CNTs with SFs increased compressive, tensile, and flexural strength by 22.7%, 29.3%, and 70.8%, respectively, more than the traditional pavement. [7] Flexural strength demonstrates particularly pronounced improvements compared to compressive strength, with enhancement ratios typically ranging from 17 to 70 percent depending on CNT type and dosage. The addition of 0.10 % multiwalled CNTs (MWCNTs) yielded optimal results, with increases in the compressive strength, splitting tensile strength, flexural strength, and elastic modulus of the RHA concrete at 28 days of 7 %, 23.81 %, 17.5 %, and 1.0 %, respectively. [8]

3.3 Dynamic and Impact Performance

Test results show that dynamic compressive properties of UHPC are strongly sensitive to strain rates. The individual addition of CNTs obviously improves the dynamic performance of plain UHPC, and there exists an optimal CNTs content of about 0.10% to achieve better improvement effects. [9] The mixture containing 1.0% CNTs achieved the highest fracture strength and exhibited the maximum dynamic increase factor (DIF) compared with the control and other CNT dosages. [10]

3.4 Long-Term Strength and Shrinkage Control

Long time-dependent shrinkage and creep of CNT-reinforced concrete were reduced up to 15% and 18% as compared to reference concrete, respectively. Early shrinkage could be reduced up to 54%. [5] This long-term performance characteristic is particularly significant for structural applications where creep-induced deflections must be minimized. The reduction in shrinkage deformation provides secondary benefits in limiting crack initiation and propagation.

Table 2: Durability Enhancements from CNT Addition to Concrete

Durability Parameter
Water Absorption Reduction
Chloride Penetration Resistance
Sulfate Attack Resistance
Acid Attack Resistance
Salt Freezing Durability
Abrasion Resistance

4. Discussion: Mechanisms and Performance Analysis

4.1 Microstructural Mechanisms

The enhancement of concrete properties through CNT incorporation operates through multiple concurrent mechanisms. The incorporation of CNTs enhanced the long-term performance of RHA sustainable concrete. The addition of 0.1 % MWCNTs and 15 % RHA yielded a 20 %, 14 %, and 66 % decrease in water absorption, porosity, and chloride diffusion coefficient compared to the mixture solely containing 15 % RHA. Scanning electron microscopy of this mixture revealed the filling and bridging effects of MWCNTs between the hydration products have enhanced the performance of RHA sustainable concrete. [8]

The enhancement effect on compressive strength caused by the incorporation of Ni-CNTs with aspect ratio of 1000 reaches 26.8%/23.0 MPa, mainly benefiting from the high polymerization C-S-H gels, low porosity, and refined pore structure. [11] With the addition of 0.1 wt% dispersed MWCNTs, the number of pores decreased by 59.98%, and the porosity of UHSC decreased by 14.41%. [12]

4.2 Crack Bridging and Fiber Pull-Out

The strength enhancements for the concrete mixes containing MWCNTs may be regarded to the phenomenon of bridging, pinning and branching of the cracks at nano/micro level due to the presence of MWCNTs. Beside strength enhancements, it was also observed that the MWCNTs had tremendously enhanced the fracture energy and breaking strains of the

concrete mixes as observed in three-point bending tests. [13] This crack-bridging mechanism operates at multiple scales, with individual nanotubes spanning nascent microcracks and preventing their propagation into larger fractures.

4.3 Pore Refinement and Permeability

The SEM test results showed that the MWCNTs filled the pores and cracks within the specimen and formed bridges between the cracks, enhancing the resistance to sulfate attack. The CT test results also showed that the addition of MWCNTs could reduce the porosity of concrete, refine the pore size and inhibit the generation and development of cracks, thus optimizing the internal structure of concrete and improving its resistance to sulfate attack. [14]

4.4 Durability Against Environmental Attacks

The specimen of 0.25% Multiwalled Carbon Nanotubes shows an extraordinary performance among the other specimens when subjected to Acid attack test, Chloride attack test, Sulphate attack test and water permeability test for a duration of 28, 56 and 90 days respectively. [15] Both CNT and SF outperform conventional concrete in terms of mechanical and durability attributes. CNT produces superior results than SF due to its smaller size. [16]

4.5 Dispersion Challenges and Optimization

A main challenge in concrete reinforcement with carbon nanotubes is to overcome dispersion issues inherent to the high pH value of cement pastes. Ionic dispersants were more efficient than steric, highlighting the importance of charge control to prevent nanotubes reagglomeration at high pH. Reinforcement with pristine nanotubes rendered small strength increase compared to reference pastes; the most efficiently dispersed suspension rendered the highest flexural and compressive strength increase, respectively 33.8% and 25.5%. [17]

The peculiarities of dispersion of CNTs in cementitious matrices are discussed, paying major attention to the CNT diameter, length and length-to-diameter ratio, concentration, functionalization, annealing, combination with other nanomaterials, and water-cement ratio. [18] RSM analysis showed that the highest effect on the strengths was due to the CNTs' content variable. The analysis showed that a weight fraction of 0.3 wt.% of non-treated CNTs is required to achieve the maximum flexural, compressive and tensile strengths in a batch as per the predicted model. [19]

4.6 Hybrid Reinforcement Systems

The addition of these admixtures slightly reduced slump performance due to their reinforcing effect. However, the concrete remained within the medium workability range. The analysis revealed improved matrix densification and stronger interfacial bonding. These microstructural and thermal improvements contributed to a 31.5% increase in compressive strength compared to the control mix. [20] Combining CNTs with other additives such as silica fume, steel fibers, or fly ash produces synergistic effects exceeding those achievable through individual supplementation.

4.7 Thermal Performance and High-Temperature Behavior

The presence of CNTs can reduce the occurrence of spalling at additions of 0.05% and 0.10% by weight of cement. CNTs can also increase the residual strength at temperatures up to 300 °C at a slow heating rate. At the same time, the 28-day compressive and splitting tensile strengths remained unaltered and oxygen permeability coefficients were reduced when CNTs were added to the matrix. [21] After 1500 salt freezing cycles, the appearance and mass loss of MWCNTs-UHPC prepared according to the best ratio changed little, and the maximum mass loss was 3.18%. The microstructure of the concrete was still relatively dense after 1500 salt freezing cycles. [22]

5. Research Gaps and Future Directions

5.1 Standardization and Specifications

A critical gap exists in the absence of universally accepted specifications and standardization protocols for CNT-modified concrete. Different studies employ varying CNT types, dosages, dispersion methodologies, and testing protocols, limiting direct comparison and hindering technology adoption. The development of ASTM and EN standards specific to CNT-reinforced concrete would facilitate commercial implementation and quality assurance.

5.2 Cost-Effectiveness and Economic Viability

Limited published data exists regarding the cost-benefit analysis of CNT-modified concrete compared to conventional alternatives or established fiber-reinforcement technologies. Despite notable progress, challenges such as long-term durability, cost-effectiveness, and large-scale processing remain key barriers to practical implementation. [3] Future research must quantify the economic trade-offs between enhanced performance and material costs to identify applications where CNT utilization provides economically justifiable returns.

5.3 Long-Term Durability Under Combined Stressors

While individual durability mechanisms have been studied extensively, limited research addresses the performance of CNT-modified concrete under combined environmental stressors (e.g., simultaneous thermal cycling, chemical attack, and mechanical loading). The integration of multiscale fibers—comprising steel, polyethylene, and carbon fibers and carbon nanotubes—alongside lightweight aggregates such as fly ash cenospheres, enhances the material's performance subjected to elevated temperatures. [23] Systematic investigation of coupled degradation mechanisms would enhance confidence in predicting field performance.

5.4 Large-Scale Production and Implementation

Current research relies predominantly on laboratory-scale mixing and testing. Scaling CNT-concrete production to commercial volumes presents undefined technical and economic challenges. Optimization of mixing equipment, CNT delivery systems, and quality control protocols for industrial batching remains unexplored.

5.5 Environmental and Health Impact Assessment

The potential environmental impacts of CNT production, potential occupational health hazards during manufacturing, and end-of-life disposal considerations require comprehensive lifecycle assessment studies. Current literature provides limited analysis of these aspects despite their importance for sustainable construction practice.

Table 3: Summary of Optimal CNT Dosages Across Concrete Types

Concrete Type
Lightweight Concrete
High-Performance Concrete
Ultra-High-Performance Concrete
Sustainable/Recycled Concrete
Rubberized Concrete
Alkali-Activated Concrete

6. Conclusion and Recommendations

6.1 Key Findings Summary

This comprehensive literature review has synthesized empirical evidence demonstrating that carbon nanotubes represent a promising technology for enhancing both mechanical and durability properties of concrete composites. According to studies, CNT can greatly enhance the performance of cement-based materials. [1] Optimal CNT incorporation at 0.05–0.10 wt% of cement consistently produces compressive strength enhancements of 15–31%, flexural strength increases of 17–70%, and improved durability against chloride penetration (38–53.6% reduction) and sulfate attack.

The strengthening mechanisms operate through multi-scale processes: at the nanoscale, individual nanotubes bridge microcracks and serve as nucleation sites for dense C-S-H gel formation; at the microscale, CNT-reinforced zones improve interfacial transition zones and reduce capillary porosity; at the macroscale, these cumulative improvements manifest as superior load-bearing capacity and environmental resistance.

6.2 Critical Success Factors

Achieving performance benefits requires careful attention to three factors: (1) **Dispersion Quality**—uniform distribution within the cement matrix is fundamental, requiring either functionalization or use of efficient dispersants and rigorous mixing protocols; (2) **Dosage Optimization**—excessive CNT loading beyond 0.10–0.15 wt% induces agglomeration and performance degradation, necessitating precise dosage control; and (3) **Curing Conditions**—adequate curing periods (minimum 28 days) allow full development of mechanical and durability benefits.

6.3 Practical Recommendations for Practitioners

For engineers considering CNT-modified concrete in structural applications: (a) specify CNT type, aspect ratio, and dosage explicitly; (b) require pre-construction performance testing on representative samples; (c) implement quality control procedures verifying dispersion adequacy;

(d) design mixes accounting for potential workability reduction; and (e) conduct durability testing relevant to anticipated service environment conditions.

6.4 Research Agenda for Future Studies

Priority research directions include: (1) development of standardized testing protocols and international specifications; (2) systematic cost-benefit analysis across diverse applications; (3) investigation of performance under combined environmental stressors; (4) optimization of large-scale production and implementation; (5) comprehensive lifecycle and environmental impact assessments; (6) long-term field performance monitoring of in-service CNT-modified structures; and (7) exploration of novel CNT surface treatments and hybrid reinforcement combinations to maximize performance while minimizing costs.

6.5 Concluding Remarks

The integration of carbon nanotubes into concrete matrices represents a significant technological advancement capable of producing multifunctional materials with superior mechanical and durability characteristics. The consistency of enhancements across diverse concrete types and environmental conditions suggests broad applicability. However, transition from laboratory-scale investigations to economically viable field implementation requires addressing standardization, cost optimization, and production scale-up challenges. Future research bridging these gaps will determine whether CNT technology becomes a mainstream construction practice or remains a specialized enhancement for performance-critical applications.

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