International Journal of
Science, Architecture, Technology and Environment

Mechanical Performance of High-Performance Concrete with Artificial Sand Reinforced by Carbon Nanotubes and Steel Fibers

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DOI: https://doi.org/10.63680/ijsate0726083.84

Abstract

The depletion of natural river sand has increased the use of artificial sand (AS) as a sustainable alternative in high-performance concrete (HPC). However, the limestone powder present in AS may reduce its mechanical performance. This study investigates the combined effect of Carbon Nanotubes (CNTs) and Steel Fibers (SF) on the strength properties of HPC containing 100% artificial sand. CNTs were incorporated at 1%, 2%, and 3% by weight of cement, while steel fibers were maintained at 5%. Ultrasonic dispersion with a surfactant was used to ensure uniform CNT distribution. Experimental results showed that hybrid reinforcement significantly enhanced compressive, splitting tensile, and flexural strengths. The 2% CNT mixture exhibited the best overall performance, whereas 3% CNT reduced workability due to agglomeration. The findings demonstrate that CNT–SF hybrid reinforcement effectively improves the strength and sustainability of artificial sand concrete.

Keywords: HPC, CNT, Strength, Mortar, Concrete.

1. Introduction

The rapid growth of the construction industry has substantially increased the demand for natural resources, particularly river sand, which is extensively used as fine aggregate in cement mortar and concrete. Continuous extraction of river sand has resulted in severe environmental consequences, including riverbank erosion, habitat degradation, groundwater depletion, and ecological imbalance. Concrete is the most widely used construction material because of its excellent compressive strength, durability, and cost-effectiveness. Fine aggregate constitutes nearly 30–40% of the concrete volume and significantly influences its workability, strength, and durability. The continuous extraction of natural river sand has resulted in environmental degradation, depletion of riverbeds, ecological imbalance, and increasing construction costs. Consequently, the construction industry has been compelled to explore sustainable alternatives to natural sand for concrete production [1,2].

Artificial sand (AS), also known as manufactured sand (M-sand), produced by crushing hard rocks under controlled conditions, has emerged as an environmentally friendly substitute for natural river sand. Artificial sand exhibits better particle grading and reduced impurities; however, its angular particle shape and the presence of limestone powder (LP) can adversely affect workability and may influence the mechanical performance of concrete if not properly optimized [1,3]. Several studies have demonstrated that concrete prepared with 100% manufactured sand can achieve mechanical properties comparable to conventional concrete when suitable mix design and supplementary reinforcing materials are adopted [5,9].

High-performance concrete (HPC) is increasingly used in high-rise buildings, bridges, industrial floors, marine structures, and transportation infrastructure because of its superior strength, durability, and long service life. Nevertheless, HPC is inherently brittle and possesses limited tensile strength and crack resistance. The initiation and propagation of microcracks under service loads often reduce its structural performance and durability. Therefore, researchers have focused on incorporating fibers and nanomaterials to improve both the mechanical properties and fracture behavior of HPC [7,10].

Among nanomaterials, Carbon Nanotubes (CNTs) have attracted considerable attention due to their exceptionally high tensile strength, elastic modulus, and large aspect ratio. CNTs act as nano-reinforcing materials by filling nano-sized pores, accelerating cement hydration, refining the microstructure, and strengthening the interfacial transition zone (ITZ) between cement paste and aggregates. Furthermore, CNTs bridge nano-scale cracks and delay crack propagation, thereby improving compressive strength, tensile strength, stiffness, and durability of cementitious composites. However, the effectiveness of CNTs depends largely on their uniform dispersion within the cement matrix, as excessive CNT content may result in agglomeration and reduced performance [8].

Steel fibers are widely recognized for enhancing the ductility, toughness, impact resistance, and post-cracking behavior of concrete. Unlike conventional concrete, steel fiber reinforced concrete effectively bridges macrocracks, redistributes internal stresses, and delays crack propagation under tensile and flexural loading. The incorporation of steel fibers significantly improves splitting tensile strength, flexural strength, energy absorption capacity, and fatigue resistance, making fiber-reinforced concrete suitable for demanding structural applications [4,7].

Recent research indicates that combining nano-scale reinforcement such as CNTs with macro-scale reinforcement such as steel fibers can produce a synergistic improvement in concrete performance. CNTs primarily enhance the cement matrix at the nano level by reducing porosity and strengthening the ITZ, whereas steel fibers control the growth of macrocracks and improve post-cracking ductility. This multiscale reinforcement mechanism offers substantial improvements in strength, toughness, and durability compared with the use of either material individually [5,8].

Despite significant advancements in artificial sand concrete, limited research has investigated the combined effect of Carbon Nanotubes and steel fibers in high-performance concrete incorporating 100% artificial sand. In particular, the optimum CNT dosage and its interaction with steel fibers require further investigation to maximize mechanical performance while maintaining adequate workability. Therefore, the present study evaluates the influence of CNT dosages of 1%, 2%, and 3% by weight of cement together with a constant steel fiber content of 5% on the compressive strength, splitting tensile strength, and flexural strength of high-performance concrete produced entirely with artificial sand. The findings provide valuable insights into developing sustainable, durable, and high-strength concrete for modern infrastructure applications.

2. Literature Review

The use of sustainable materials and advanced reinforcement techniques has become a major research focus in concrete technology. Recent investigations have demonstrated that artificial sand, carbon nanotubes (CNTs), and steel fibers can significantly improve the mechanical and durability properties of cementitious composites when properly incorporated into the concrete matrix.

Jawad Ahmad and Zhou [11] presented a comprehensive review on CNT-modified concrete and reported that carbon nanotubes considerably improve compressive strength, tensile strength, durability, and thermal stability by refining the cement microstructure and strengthening the interfacial transition zone (ITZ). The authors also emphasized that effective dispersion of CNTs is essential, as agglomeration reduces their reinforcing efficiency.

Hassan et al. [12] investigated the combined use of carbon nanotubes and steel fibers in concrete pavement. Their results demonstrated that hybrid reinforcement significantly enhanced compressive, flexural, and splitting tensile strengths compared with conventional concrete. The study concluded that CNTs improve the cement matrix at the nano-scale, while steel fibers effectively bridge macrocracks, producing superior crack resistance and load-carrying capacity.

Yang and co-workers [13] studied the influence of steel fibers on ultra-high-performance fiber-reinforced concrete (UHPFRC). Their investigation revealed that steel fibers substantially increased compressive strength, ductility, energy absorption, and post-cracking behavior. The improvement was mainly attributed to the crack-bridging action of fibers, which delayed crack propagation under loading.

Zhang et al. [14] evaluated the mechanical behavior and microstructural characteristics of steel fiber reinforced concrete. Their experimental observations confirmed that increasing steel fiber content enhanced tensile strength, flexural performance, and fracture toughness while reducing crack width. Microstructural analysis further demonstrated improved bonding between the cement matrix and steel fibers.

Mohammedi and Bagheripour Asil [15] examined self-compacting lightweight concrete reinforced with steel microfibers and carbon nanotubes. The hybrid system produced significant improvements in compressive strength, tensile strength, and durability compared with concrete containing individual reinforcements. The authors attributed these improvements to the complementary action of nano-scale crack control by CNTs and macro-scale crack bridging by steel fibers.

Luo et al. [16] investigated the effects of CNTs on the toughness and microstructure of steel fiber reinforced ultra-high-performance geopolymer concrete. The study reported that CNT incorporation refined pore structure, improved fiber–matrix bonding, and significantly increased fracture toughness and flexural performance. The synergistic interaction between CNTs and steel fibers was found to be more effective than using either reinforcement alone.

Chousidis [17] evaluated the impact of hybrid CNT–steel fiber reinforcement on cementitious composites. The results showed notable improvements in compressive strength, flexural strength, ultrasonic pulse velocity, and microstructural quality. The hybrid composite exhibited enhanced load transfer mechanisms and superior crack resistance due to the multiscale reinforcement provided by CNTs and steel fibers.

Ding et al. [18] investigated manufactured sand steel fiber reinforced self-compacting concrete and reported that manufactured sand can completely replace natural sand when proper mix proportioning is adopted. The study observed improvements in mechanical performance and workability through optimized aggregate packing and steel fiber distribution.

Ramesh et al. [19] reviewed the influence of micro steel fibers on high-performance concrete and concluded that steel fibers effectively improve crack resistance, toughness, fatigue life, and impact resistance. The review highlighted that steel fibers are particularly beneficial for structural elements subjected to repeated loading and dynamic forces.

Recently, Khan and Mahajan [20] investigated high-performance concrete incorporating 100% artificial sand reinforced with Carbon Nanotubes and steel fibers. Their experimental results showed that hybrid reinforcement significantly enhanced compressive, splitting tensile, and flexural strengths. Among the investigated mixtures, 2% CNT with a constant steel fiber dosage produced the optimum mechanical performance, whereas higher CNT dosage resulted in slight strength reduction due to nanoparticle agglomeration.

Overall, the published literature confirms that artificial sand is a sustainable replacement for natural river sand, while Carbon Nanotubes and steel fibers effectively improve the mechanical performance of high-performance concrete through multiscale reinforcement. However, limited studies have focused on optimizing CNT dosage in conjunction with steel fibers in concrete containing 100% artificial sand. Therefore, further experimental investigation is required to establish the optimum hybrid reinforcement system capable of maximizing strength while maintaining acceptable workability and sustainability.

3. Materials and Method

High-performance concrete (HPC) was prepared using Ordinary Portland Cement (OPC) 53 grade conforming to IS 12269:2013 as the primary binding material. Artificial sand (AS), produced by crushing hard granite rock, was used as a complete (100%) replacement for natural river sand in all concrete mixtures. The artificial sand satisfied the grading requirements of IS 383:2016 and exhibited suitable particle size distribution for high-performance concrete. Crushed granite coarse aggregate with a nominal maximum size of 20 mm was used as coarse aggregate, while potable water conforming to IS 456:2000 was utilized for mixing and curing. A polycarboxylate ether (PCE)-based superplasticizer was incorporated to improve the workability of the concrete without increasing the water-to-cement ratio.

Multi-Walled Carbon Nanotubes (MWCNTs) were selected as nano-reinforcement because of their exceptional mechanical properties, including high tensile strength, elastic modulus, and large aspect ratio. Carbon Nanotubes were incorporated at dosages of 1%, 2%, and 3% by weight of cement to evaluate their influence on the mechanical performance of the concrete. Since CNTs have a strong tendency to agglomerate due to van der Waals forces, they were first dispersed in mixing water containing a suitable surfactant and subjected to ultrasonic treatment for approximately 30–45 minutes to obtain a homogeneous suspension. This dispersion technique ensured uniform distribution of CNTs throughout the cement matrix and enhanced their reinforcing efficiency.

Hooked-end steel fibers with an aspect ratio of approximately 60 were incorporated at a constant dosage of 5% in all modified concrete mixtures to improve tensile strength, crack resistance, and post-cracking behavior. The hybrid combination of nano-scale CNTs and macro-scale steel fibers was adopted to investigate their synergistic effect on the mechanical performance of artificial sand-based high-performance concrete. The control mix contained 100% artificial sand without CNTs and steel fibers, while the remaining mixes contained different CNT dosages with a constant steel fiber content.

The concrete mix was designed in accordance with IS 10262:2019 for high-performance concrete. Initially, cement, artificial sand, and coarse aggregates were dry mixed to obtain a uniform blend. The previously prepared CNT suspension was then gradually added along with the remaining mixing water, followed by the superplasticizer to achieve the desired workability. Steel fibers were introduced slowly during the mixing process to ensure their uniform distribution and to prevent fiber balling. Mixing was continued until a homogeneous and workable concrete mixture was obtained.

Fresh concrete was placed into clean, oiled moulds and compacted using a vibrating table to eliminate entrapped air and achieve proper consolidation. After casting, the specimens were covered to prevent moisture loss and demoulded after 24 hours. All specimens were subsequently cured in clean water at room temperature until the specified testing ages of 7 and 28 days. Cube specimens measuring 150 × 150 × 150 mm were prepared for compressive strength testing, cylindrical specimens of 150 mm diameter and 300 mm height were cast for splitting tensile strength, and prism specimens measuring 100 × 100 × 500 mm were prepared for flexural strength evaluation.

The mechanical properties of the hardened concrete were determined using standard testing procedures. Compressive strength was evaluated using a compression testing machine in accordance with IS 516 (Part 1):2021. Splitting tensile strength was determined on cylindrical specimens following IS 5816:1999, while flexural strength was measured using a two-point loading test on prism specimens in accordance with IS 516 (Part 2):2021. The experimental results obtained from all mixes were compared to assess the influence of varying CNT dosages and constant steel fiber reinforcement on the compressive, tensile, and flexural performance of high-performance concrete produced with 100% artificial sand. The study aimed to identify the optimum CNT dosage capable of maximizing the mechanical performance while maintaining the sustainability and structural efficiency of artificial sand concrete.

4. Result

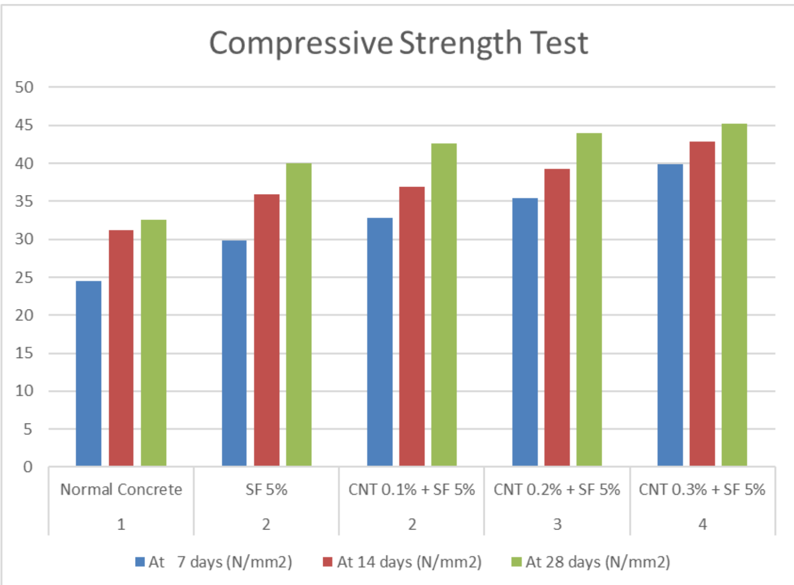

Figure 1 compressive strength- results

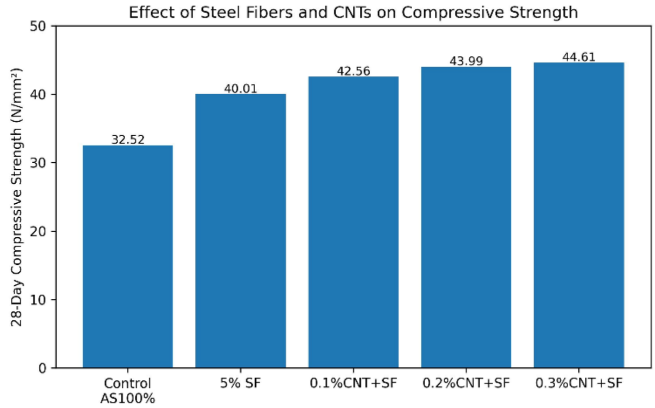

Fig.2 Effect of steel fiber on CS

5. Conclusion

The experimental results demonstrate that the incorporation of steel fibers and Carbon Nanotubes (CNTs) significantly improves the compressive strength of high-strength concrete containing 100% artificial sand. The addition of 5% steel fibers increased the compressive strength by 23% compared to the control mix, while the combined use of CNTs and steel fibers further enhanced the strength by up to 37%. Although the highest compressive strength of **44.61 N/mm²** was achieved with **0.3% CNT + 5% steel fibers**, the **0.2% CNT + 5% steel fiber** mix provided nearly equivalent performance with better cost-effectiveness, making it the optimum mixture for practical applications. Overall, hybrid reinforcement using CNTs and steel fibers offers an effective and sustainable approach for producing high-performance concrete with 100% artificial sand..

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

Funding

The author received no financial support for the research, authorship and publication of this article.

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