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ON THE CARBON NANOTUBES ENHANCED COMPRESSIVE AND FLEXURAL STRENGTH OF CONCRETE

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Abstract

Cement is a key component in infrastructure development. However, cement production is also a major contributor to CO2 emissions, significantly impacting global warming. In response, researchers have explored a variety of alternative materials to partially replace cement and reduce its environmental footprint. One such material gaining considerable attention is carbon nanotubes (CNTs). CNTs have been extensively studied for their potential to enhance the performance of cement-based materials. This paper compiles and analyses the results of previous studies on the use of CNTs in different construction materials, including cement mortars, conventional concrete, and advanced concrete types. Key performance aspects, including compressive and flexural strength, have been analysed to find the optimum dosage of the CNTs that can be added to the concrete to get the improvement in its performance. The findings show that incorporating CNTs in the concrete mixture significantly improves the compressive strength, and the optimum percentage is 0.04% by weight, while the flexural strength is improved when using 0.05% to 0.75% by weight of CNTs, depending on the quantity of the required dosage.

Keywords: Carbon nanotube, Composites, Compressive strength, Flexural strength, Sustainability.

1. Introduction

Building materials such as cement-based products are widely used because of their impressive strength under compressive loads. Nevertheless, they are relatively fragile when it comes to tension. To improve tensile performance, various methods of reinforcement are used, such as incorporating steel bars, rods, fibres, or prestressing them. Recently, there has been significant interest in the application of nanoparticles in cement materials because of their exceptional mechanical properties and numerous potential uses. Among such nanoparticles, carbon nanoparticles seem to be particularly helpful for their considerable enhancement and crack healing in cementitious materials.

According to ASTM 2011c [1], CNFs have diameters between 70 and 200 nm and lengths of 50 to 200 microns. CNTs are smaller still, with diameters ranging between less than one and fifty nanometres and lengths of one micron to one centimetre (ASTM, 2011a) [2]. The initial blending of CNFs and cement-based products was challenging due to the high aspect ratios of both CNFs and CNTs, which hindered even dispersion and uniform distribution. These materials tend to clump together due to Van der Waals forces. Better dispersion can be achieved through ultrasonic agitation and chemical treatments that stabilise the Fibres in solution. When carbon nanomaterials are properly dispersed, they have shown the ability to enhance the performance of cementitious compounds [3].

In the early 1990s, Chen and Chung [4] were the first scientists to integrate short carbon fibres into cement mortar. This was the earliest effort to incorporate carbon Fibres into cementitious materials. The results from this test were positive. There were notable increases in flexural strength by 85%, flexural toughness by 205%, and compressive strength by 22%. All of these enhancements were advantageous. Chung [5] authored a review on cement-based structural composites for intelligent buildings in the year 2000. Subsequently, Li et al. [6] proposed studying the microstructure of cement mortar reinforced with nanoparticles in 2004. Their experiments showed that the strengthened mortar exhibited higher compressive and flexural strength compared to ordinary cement paste. Additional work on the dispersion of fibbers in cement by Chung [7] led to an important development concerning the use of microcarbon Fibres in cement paste. In that study, the dispersion of fibbers was evaluated based on the electrical resistivity of the material. In another study by Li et al. [8], it was found that the effects of adding some nanoparticles on the abrasion resistance of concrete, and some encouraging durability enhancement was observed.

The addition of nanoparticles and Fibres to the cement matrix caused a considerable enhancement in the concrete's resistance to abrasion. Flexural and compressive strength showed a marked improvement when the nanoparticles and fibbers were held at 1% of the weight of the cement, suggesting a synergistic effect between the two additives. Li et al. [9] also analysed the enhancement of flexural fatigue response of concrete owing to nanoparticles and their potential contribution to long-term durability. The highest flexural fatigue strength was observed for 1.0 wt.% of the weight of cement nano-TiO2 concrete.

Gao et al. [10] investigated the mechanical and electrical properties of self-consolidating concrete containing carbon CNFs as reinforcing agents. They observed optimum workability and significantly enhanced compressive strength and electrical resistivity with 1% CNF content.

In 2005, Makar and Beaudoin [11] presented a study on advancements in producing cement composites reinforced with CNTs. He found that adding single-walled CNTs to cement composites helped accelerate the hydration process. The CNT-reinforced materials also demonstrated classic reinforcement mechanisms, such as crack bridging and fibre pull-out, which were confirmed through scanning electron microscopy (SEM) imaging. Later, Cwirzen et al. [12] investigated the wettability of multiwalled CNTs and their impact on the mechanical properties of cement paste. The study found that tip sonication was the most effective method for dispersing CNTs, while bath sonication partially damaged the nanotube lengths. Remarkably, samples containing just 0.045% CNTs treated with polyacrylic acid polymer showed a 50% increase in compressive strength. Li et al. [9] also compared the performance of treated CNTs, using sulfuric and nitric acid, with untreated ones in cement composites. SEM images confirmed uniform dispersion and revealed a clear crack-bridging effect.

Metaxa et al. [13] investigated the fracture behaviour and early strain capacity of CNT-reinforced cement composites, highlighting their potential to enhance toughness and durability. The findings showed that longer CNTs, even in small amounts of 0.025% - 0.048%, and shorter CNTs in higher amounts around 0.08% could both achieve good dispersion within the cement matrix. Nanoindentation tests revealed that CNT-reinforced composites exhibited higher stiffness and reduced porosity. This decrease in porosity significantly improved the early strain capacity of the material. In a 2010 study, Konsta-Gdoutos et al. [14] explored factors affecting CNT dispersion, including ultrasonic energy, surfactant concentration, and their reinforcing effects. The optimal surfactant-to-CNT ratio was found to be 4:1. In a later study, Yazdanbakhsh et al. [15] reported a 150% increase in peak displacement in CNT-reinforced mortar compared to regular cement paste.

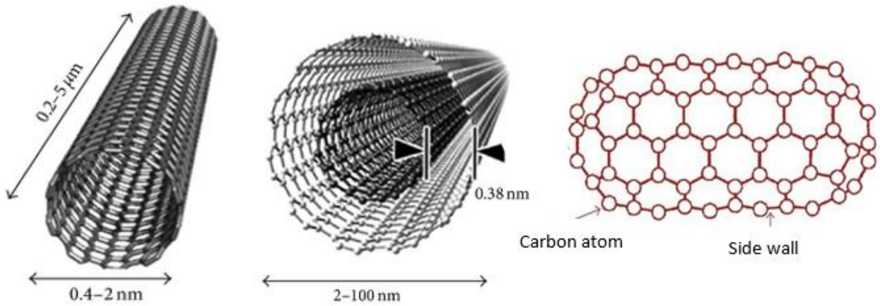
By reviewing the available research on the CNTs, the objective of this paper is to obtain the optimum percentage of CNT added to the concrete mixture that improves its compressive and flexural strength through a comparative analysis.

2. Characteristics of Carbon Nanotubes

CNTs are essentially miniature cylinders that are produced by rolling many sheets of graphite together. According to Tasis et al. [16], these extremely minute structures have a width of only one hundred nanometres, but their length can be many micrometres. A mixture of carbon Fibres and fullerene molecules is what makes up CNTs. For example, according to Polizu et al. [17], they are composed of carbon atoms arranged in a cylindrical fashion that originate from graphene sheets. These nanostructures can be broken down into two primary categories, distinguished by how they are stacked: SWCNTs, which are generated by rolling a single layer of graphene into a cylindrical shape.

In most cases, they are arranged in hexagonally packed bundles, with sizes ranging from 0.4 to 2 nm. In order to create multiwalled carbon nanotubes, also known as MWCNTs, many graphene cylinders are stacked on top of each other. The diameters of these cylinders usually range from 1 to 3 nm, as shown in Fig. 1 [18].

CNTs demonstrate exceptional chemical and physical characteristics, including remarkable tensile strength, ultralow density, unique electronic properties, and outstanding thermal and chemical stability. These superior properties have generated significant scientific interest in CNT nanomaterials. CNTs have become the most extensively utilized for diverse applications within the carbon-based nanomaterials class. Primary implementations include biomolecular interactions, pharmaceutical compounds, targeted drug delivery systems, as well as biosensing platforms for diagnostic and analytical purposes [19].



a. Single-walled carbon nanotubes
b. Multi-walled carbon nanotubes
c. Carbon nanotubes with closed ends

Fig. 1. Common arrangements of CNT. A. single-walled carbon nanotubes (SWCNT), b. multiwalled carbon nanotubes (MWCNT), and c. carbon nanotubes with closed ends [18].

3. Literature Review

3.1. Cement mortar

The mortar specimens incorporating 1.0% CNT as partial cement replacement demonstrated significantly higher compressive strength compared to conventional mortar without CNT addition. Extensive research has been conducted on utilizing CNTs to enhance the mechanical properties of cementitious composites. The investigation of CNT-cement composites dates to the early 1990s, marking nearly three decades of development in this field. Chen and Chung [4] first reported in 1993 that short carbon fibres enhanced cement mortar, increasing flexural strength by 85%, flexural toughness by 205%, and compressive strength by 22%. However, the most substantial advancements in CNT-reinforced cementitious composites emerged in the mid-2000s, when research outcomes demonstrated significantly improved mechanical performance. Li et al. [6] investigated the influence of key parameters on the mechanical properties of CNT-cement composites, proposing an optimised mixing technique and an ideal mix proportion. Building upon these findings, this study explores the functional applications of CNT-reinforced cement mortar, particularly for concrete rehabilitation, including surface restoration and crack repair.

While current repair methods, such as epoxy-based crack fillers and cementitious grouts for spalling, are effective, they present limitations. Spalling damage is not always effectively mitigated with epoxy repairs. Moreover, fast-hardening cementitious grouts are limited by their shallow application, extreme cost, and excessive heat. These factors create a clear need for new, high-quality repair materials that can handle stress, flow, and wear and tear. CNT-cement composites show strong promise for these requirements. They can serve as effective, long-lasting options for concrete rehabilitation [20-22].

3.2. Recycled concrete

Each year, the world generates a substantial amount of construction and demolition (C&D) waste from building, renovation, and demolition activities. In China, C&D waste constitutes about 30-40% of total urban industrial waste [23]. This has led researchers to focus on developing concrete that utilises recycled waste materials as a primary component. There were plans as of 2020 to recycle and reuse up to 70% of concrete derived from C&D waste to reduce CO_2 emissions and alleviate landfill burdens [24].

To enhance the performance of recycled aggregate concrete (RAC), researchers have begun incorporating nanoparticles into RAC mixtures. Although several studies have explored the use of nanomaterials in RAC, e.g., [25-28], the specific impact of CNTs remains relatively limited and not yet fully understood.

Gao et al. [29] examined how CNTs affect the strength of RAC produced using various waste cementitious materials, including 55% clay brick aggregates, 45% recycled concrete aggregates (RCA), and mortar. In their study, 0.1% of MWCNTs were added by weight of cement, and natural aggregates (NA) were replaced with RCA at rates of 50%, 70%, and 100%. The results showed a significant improvement in compressive strength, about 42% higher than untreated RAC and even outperformed RAC modified with nano-$CaCO_3$ and nano-SiO_2. Increased demand for natural aggregates from the building industry has compelled scientists to search for RCA as an eco-friendly alternative for conserving natural aggregates. However, applications of RCA as a substitute for conventional aggregates showed limitations, including lower strength and poorer behaviour under static and dynamic loads.

Song et al. [30] examined MWCNTs as an additive to enhance the behaviour of RAC. They assessed fresh and hardened characteristics of RAC supplemented with different MWCNTs. Different mixes were prepared by replacing natural aggregates with RCA at multiple levels and incorporating MWCNTs at three different dosages based on the weight of cement. Two hundred forty test pieces were tested for workability, compressive strength, and impact resistance after 7 and 28 days. Workability was decreased for mixes because of the MWCNTs additions. However, compressive strength for every concrete mixture with MWCNT was enhanced. Impact resistance also increased significantly with the inclusion of MWCNTs, with the most noticeable improvements observed at a moderate dosage level. Crack patterns and failure behaviour were also analysed, showing enhanced structural performance in the modified concrete [30].

Allujami et al. [31] performed experimental tests on the effect of using CNTs on the compressive strength of concrete composed of RCA. They tested concrete specimens using different replacement ratios of RCA and CNTs. It was noted that the maximum increase in the compressive strength when using 0.05% of CNTs is by replacing 50% of coarse aggregate, while 0.1% of CNTs used is by replacing 75% of the coarse aggregate. If using 0.25% CNTs and replacing 75% of the coarse aggregate, the maximum gain in compressive strength was found. However, it can be concluded that the optimum percentage of the CNTs and RCA to significantly enhance the compressive strength is 0.1% and 75%, respectively, resulting in an increase in the strength by 65%.

3.3. Geopolymer concrete

Cement production accounts for about 8% of global carbon emissions. This has made people want more eco-friendly, cement-free options for building with concrete. Geopolymer concrete (GPC) is one such alternative. Much research has been done on GPC since it was first used to learn more about its physical, mechanical, and microstructural properties [32].

Duxson et al. [33] made GPC from materials high in alumino-silicate, like fly ash or slag. These materials are activated by alkaline solutions like sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). GPC is stronger and lasts longer than regular cement-based concrete. Like concrete, the strength of GPC depends on several mix parameters, such as the concentrations and ratios of activators, the binder-to-activator ratio, and the water-to-binder ratio. GPC gets stronger in normal conditions and does not need to be cured with water because it hardens through a polymerisation reaction instead of the hydration reaction in cement systems. During this reaction, a polycondensation happens, which removes extra water from the geopolymeric gel. Ambient curing is enough but heating the polymerisation process between 60 and 90 °C can improve it, leading to stronger development [34]. Khater and el Gawaad [35] studied the performance of slag-based geopolymer mortar with 1:2 binder/sand containing different ratios of MWCNT from 0.1 to 0.4% by weight of binder. They observed that the 0.1% of MWCNT is the best ratio, which enhances the durability and reduces the shrinkage and water absorption.

Despite the growing interest in GPC, there is limited research on its reinforcement using MWCNTs. Chaipanich et al. [36] produced for the first time mortar and pastes of carbon nanotubes-fly ash composites using 0.5 and 1.0% CNT by weight added to the cement fly ash system. Testing the composites by electron microscope, it was seen that the Portland cement has an angular shape of size ranging from ≈1.0 to 70 μm, the fly ash particles are spherical with around 1–20 μm, with the CNTs having a diameter of less than 100 nm, as shown in Fig. 2. An interesting observation was found regarding the density, which is 2.19 g/cm^3 when adding fly ash to the cement mortar and less than the density of the control mortar of PC, only 2.23 g/cm^3 at day 28, while denser mortar was obtained when adding CNT to the fly ash mortar of 2.29 g/cm^3 at 28 days. The density increase can be attributed to the presence of CNTs, which act as a filler in the composite matrix. Saafi et al. [37] examined the mechanical and electrical properties of fly ash geopolymer containing three percentages of MWCNT: 0.1%, 0.5%, and 1.0%. They found that the electrical and mechanical performance of the specimens greatly enhanced when using MWCNT percentages of 0.1% and 0.5%, but no significant effect for the 1% of CNT by weight.

Kanagaraj et al. [38] studied the structural performance of GPC reinforced beams with different MWCNT dosages. The mix design was kept constant regarding binder content and activator proportions to isolate the effects of MWCNT addition, which ranged from 0.02% to 0.16% by weight of binder. The experimental investigation focused on evaluating the flexural behaviour of reinforced concrete beams, analysing parameters such as load-deflection response, toughness, energy absorption capacity, stiffness, and ductility. The optimum CNTs ratio is 0.12% for the compressive strength, 0.14% for the ductility, and 0.12% for the flexural toughness.

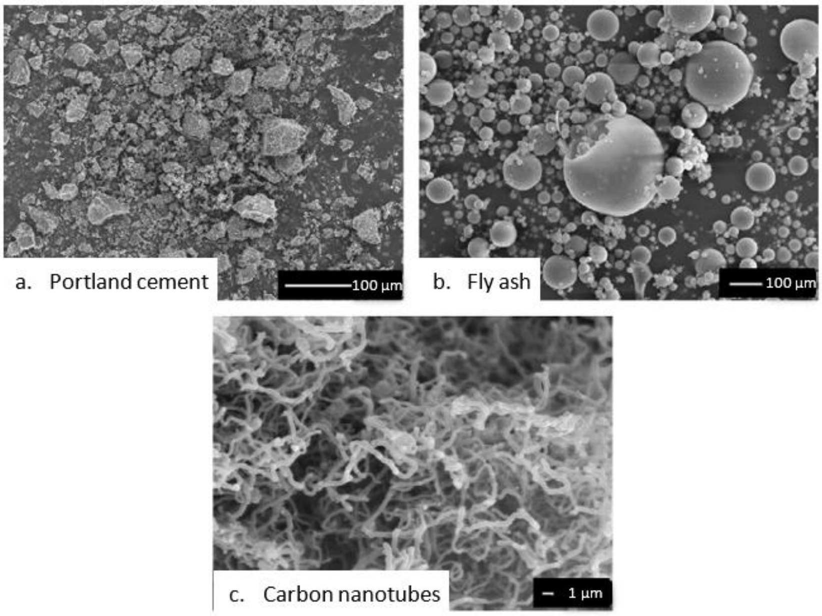


Fig. 2. SEM micrographs of (a) Portland cement, (b) fly ash, and (c) carbon nanotubes [35].

3.4. High-performance concrete

Wang et al. [39] demonstrated that incorporating a suitable amount of functionalized CNTs into ultra-high-performance concrete (UHPC) significantly enhances its dynamic compressive strength, impact toughness, and energy dissipation capacity. This improvement is attributed to the ability of CNTs to fill micro-pores between hydration products and strengthen the interfacial bonding within the cement matrix, thereby increasing the energy required for crack initiation and propagation. The overall strength and ductility of fibre-reinforced UHPC are largely influenced by the quality of the matrix and the strength of the fibre–matrix interface. For efficient load transfer, robust bonding between the fibres and the surrounding matrix is essential.

Huang et al. [40] found that the inclusion of CNTs improves this fibre–matrix interface by enhancing cement hydration and increasing interface density, which in turn boosts both chemical adhesion and frictional resistance between fibres and the matrix. CNTs also enhance UHPC's functional properties. When evenly dispersed, CNTs lower the material's electrical resistivity and establish conductive networks throughout the matrix. As a result, UHPC gains added functionalities such as self-sensing capability for strain and crack detection, as well as improved electromagnetic interference (EMI) shielding performance [41-45].

3.5. Fibre-reinforced concrete

Studies present a novel approach to enhancing the performance of GFRP-reinforced concrete by combining steel fibres (SFs) and CNTs in the mix. Although both additives have been studied individually, their combined effect has not been thoroughly explored. Testing on beam specimens with different reinforcement types showed that adding 0.04% CNTs (by cement weight) and 0.6% SFs (by volume) significantly improved mechanical performance. GFRP-reinforced beams with these additions exhibited reduced crack widths, a 20% increase in load capacity, and a 25% reduction in deflection. SEM and finite element analysis confirmed improved tensile load transfer and stress distribution. The results suggest that this combined reinforcement method can significantly enhance the durability and structural performance of concrete, especially in infrastructure such as bridges and high-rise buildings. Further research is recommended to evaluate practical applications and cost-efficiency [46].

Xing et al. [47] investigated how SFs and CNTs change the mechanical properties of concrete. The main point is how the two types of fibres work together to make the concrete more flexible and able to handle stress. 1.0%, 1.5%, and 2.0% of each type of reinforcement fibre after 28 days to see how they affected the compressive (cubic and axial), splitting tensile, and flexural strengths were added. Hooked end (HSF) and milled fibres were employed as reinforcement in cement. They looked at how CNTs, SFs, and the cement matrix interacted with each other on a smaller scale using SEM. They also utilised DIC (Digital Image Correlation) to see how cracks spread when bent. The results demonstrate that CNTs enhance plain concrete's compressive, tensile, and flexural strength but do not mitigate its inherent brittleness. DIC showed that incorporating SFs enhances the mechanical performance even better and makes the material more ductile by stopping cracks from spreading. Concrete with HSF reinforcement had better compressive and splitting tensile strength. In addition, concrete with MSF reinforcement had better flexural strength. SEM observations indicated that the interface between CNTs, SFs, and the cement matrix was well combined, demonstrating synergistic reinforcement mechanisms. These results indicate that combining CNTs and SFs in a composite concrete may produce a stronger and tougher concrete with a potentially long life [47].

4. Summary of CNT Influence on the Concrete Performance

Table 1 presents the test results from previous research investigating the effect of using CNT as a partial replacement in concrete mixtures on the performance of construction materials, including strength and durability characteristics. The observations of those results have revealed that incorporating various ratios of CNT influences the mechanical properties of the composite materials.

Table 1. Effect of CNT on the performance of the concrete.

Ref.	Replacement material	MWCNT dosage	Enhancement in Compressive Strength	Enhancement in Flexural Strength
[29]	70% Recycled coarse aggregate replacement (RCA)	0.1%	29.5%	
[31]	25% (RCA)	0.05%	21%	
	50% (RCA)		59%	
	75% (RCA)		56.50%	
	100% (RCA)		54.50%	
	25% (RCA)	0.1%	53.50%	
	50% (RCA)		51.80%	

	75% (RCA) 100% (RCA) 25% (RCA) 50% (RCA) 75% (RCA) 100% (RCA)	0.25%	65.20% 63.60% 21.40% 22.20% 39.10% 27.30%	
[35]	20% fly ash	0.5% 1%	8% 9.6%	
[37]	Low calcium fly ash (FA) and ground granulated blast furnace slag (GGBS)	0.02% 0.04% 0.06% 0.08% 0.1% 0.12% 0.14% 0.16%	2.6% 9% 12.5% 17.5% 22% 26.6% 25% 23.2%	
[36]	50% fly ash	0.1% 0.5% 1%		76% 111% -6%
[38]	Replacing micro-reinforcing fibres with carbon nanotubes (CNTs)	0.25%	72.4%	
[39]	Replacing micro-reinforcing fibres with carbon nanotubes (CNTs)	0.5% 0.3%	76.2% 15%	40%
[48]	CNTs, fly ash	0.5%	70 %	
[49]	Long and short CNTs, normal concrete	0.03% 0.04% 0.06% 0.03% 0.04% 0.06%	9.1% 12.7% 10.9% 10.7% 20.3% 10.3%	19.08% 13.37% 12.15% 2.74% 12.35% 13.14%
[50]	CNTs, Metakaolin	0.2%	33%	22%
[51]	CNTs	0.3%	21.2%	23.4%
[52]	CNTS, UHPC	0.1%		25.8%
[53]	CNTs, UHPC	0.05%	66%	
[54]	CNTs, fly ash	0.3%	4.63%	7.56%
[55]	CNTs	0.01%, -0.03%	7, 14, 20%	10,18, 20%
[56]	Normal concrete, CNTs	0.03% 0.08% 0.15% 0.25%		90% 85% 100% 120%
[57]	CNTs	0.03%	38%-	13%
[58]	MWCNTs Nano-Al2O3	0.75%	58%	62%
[59]	CNTs–cement mortar	0.01%	13%	
[60]	(MWCNTs), carbon fibres (CFs).	0.5 %	38%	54%
[61]	CNTs	0.05–0.1%		29%
[62]	CNTs	0.1-0.2	15%	
[63]	CNTs	0%-0.2%	22.7%	70.8%

[64]	Normal concrete, long and short CNTs	0.048% 0.08% 0.048% 0.08%		14.5% 23.6% 25.5% 23.6%
[65]	CNTs	0.5%-0.75%	15%	
[46]	CNTs	0.04%	14%	16%
[66]	CNTs	0.1%	25%	48%

5. Results and Key Findings

5.1. Compressive strength

Figure 3 shows the effect of adding CNTs by weight to concrete on improving the compressive strength. It is observed that the increase in the compressive strength ranged from 8% to 56% of the original concrete strength when adding CNTs by a percentage of 0.01% to 0.05%. Also, when adding CNTs of 0.5% to 1.0%, the increase ranged from 15% to 59%. It can be concluded that the optimum percentage of CNTs to add to concrete is 0.04% if CNTs are to be used at levels below 0.1%. For adding a larger amount of CNTs, it is found that the optimum dose to improve the compressive strength is 0.5%.

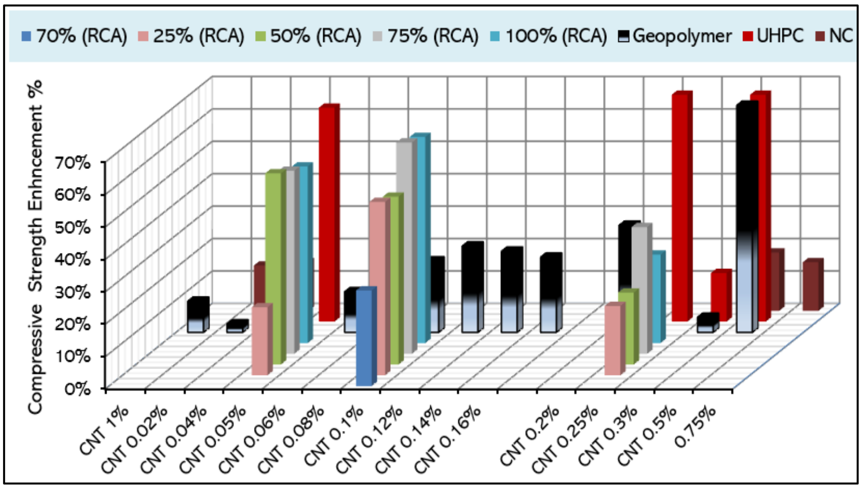


Fig. 3. Effect of CNTs on the concrete compressive strength.

5.2. Flexural strength

Figure 4 shows the effect of adding CNTs by weight to concrete on improving the flexural strength. For the available data on flexural strength, it is observed that adding CNTs by a percentage of 0.01% to 0.05% improves the flexural capacity by 7% to 23% the original concrete strength. Also, when adding CNTs of 0.5% to 1%, the increase ranged from 7% to 62%.

It could be concluded that the optimum percentage of CNTs that can be added to concrete is 0.05% if it is required to use CNTs less than 0.1%. For adding a larger amount of CNTs, it is found that the optimum dose to improve the flexural strength is 62% when using 0.75% of CNTs.

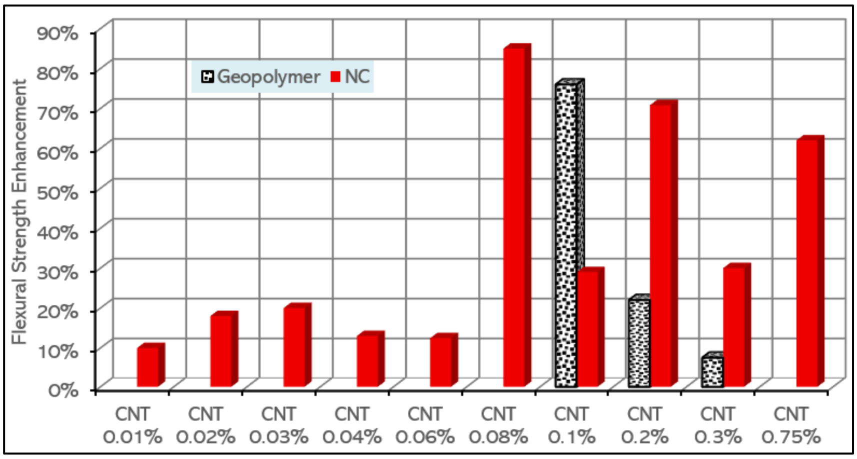


Fig. 4. Effect of CNTs on the concrete flexural strength.

6. Conclusions

Based on the analysis of various studies on the use of multiwalled carbon nanotubes in construction materials, the following conclusions can be drawn:

- Carbon nanotubes have been used in various cement-based materials, including mortars, normal concrete, and specialised concrete such as high-performance, self-compacting, high-strength, and geopolymer concrete, primarily as a partial replacement for cement.
- Carbon nanotubes are incorporated into cement mortar at dosages of 0.01%-0.5% by cement mass. Among these, dosages of ~0.1% were effective in significantly increasing mortar strength.
- When using 0.1% carbon nanotubes to replace a small proportion of fly ash in geopolymer concrete, the microstructure and performance were improved, and the strength of the concrete was enhanced.
- The incorporation of carbon nanotubes into concrete tends to reduce the mix's flowability. This is primarily due to the high surface area and hydrophilic nature of carbon nanotubes, which increases the water demand of the mixture.
- Adding 1% nano-silica by weight of cement to ultra-high-strength concrete improves its bond properties and densifies its microstructure. However, the mix design and its intended use can determine the optimal percentage.
- The incorporation of carbon nanotubes along with steel fibres in fibre-reinforced concrete improved the mechanical properties.

Based on the studies reviewed, it is clear that carbon nanotubes can be effectively used as a partial replacement for cementitious materials, particularly cement, to improve the microstructure, strength, and durability of concrete. Overall, incorporating carbon nanotubes in construction materials offers significant benefits by enhancing their performance and longevity.

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Nnomenclature

Abbreviations

ASTM	American Society for Testing and Materials
CaCO3	Calcium Carbonate
CNFs	Carbon nanofibres
CNT	Carbon nanotube
CO2	Carbon dioxide
DIC	Digital Image Correlation
EMI	Electromagnetic Interference
GFRP	Glass Fibre Reinforced Polymer
GPC	Geopolymer Concrete
HSF	Hooked Steel Fibre
MWCN	Multiwalled Carbon nanotube
NA	Natural Aggregate
Na2SiO3	Sodium Silicate
Na2SiO3	Sodium Silicate
NaOH	Sodium Hydroxide
RCA	Recycled Concrete Aggregate
SEM	Scanning Electron Microscopy
SFs	Steel Fibres
SiO2	Silica
SWCNT	Single-walled Carbon nanotube
UHPC	Ultra High-Performance Concrete

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