Application Of Carbon Nanotubes in Construction: A Review

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Abstract — Incorporating carbon nanotubes (CNTs) in the construction field offers significant potential, particularly for enhancing the mechanical properties of cement-based materials. When partially replacing cement, CNTs can significantly boost both compressive and flexural strengths, making them an effective additive for reinforcing structural elements. CNTs act as micro-reinforcements, effectively bridging cracks in the matrix and distributing the applied loads more evenly. Their inclusion at optimal levels—particularly between 0.15% and 0.25% by weight fraction—yields the most substantial strength improvements, enhancing flexural strength by up to 55% and compressive strength by up to 22%. Beyond 0.25%, however, dispersion issues and increased viscosity reduce the effectiveness of CNTs. This makes proper processing and careful proportioning essential for real-world applications in cement preparation, ensuring that CNTs are fully utilized for improved performance in construction materials.

Keywords: Carbon Nanotubes (CNTs), Cement-Based Materials, Mechanical Properties Enhancement, Micro-Reinforcement, Optimal Dosage

I. Introduction

Nanotechnology is an ever-evolving field centered on the manipulation and use of materials at the nanoscale level, typically ranging between 0 and 100 nm. At the nanoscale, materials display distinct and enhanced properties, including increased strength, reactivity, conductivity, and optical behavior, which differ from the characteristics observed in their larger-scale forms. Among the various nanoparticles, this study focuses primarily on carbon nanotubes (CNTs), a highly studied nanomaterial with broad applications [1, 4, 12].

Concrete is a cornerstone material in the construction industry and plays a vital role in infrastructure development worldwide. It is a mixture of coarse and fine aggregates, water and cement, with global production of approximately 35 billion tons. However, this large-scale production contributes to approximately 7% of the world's CO2 emissions and is largely driven by cement manufacturing [5, 14, 33]. Although concrete is critical for construction, it has inherent weaknesses, such as limited initial strength and susceptibility to nanoscale pores and cracks, which affect its long-term durability [13, 17]. To address these issues, integrating nanomaterials like CNTs into concrete is being explored as a way to improve its strength and crack resistance [3, 6, 9].

Modern concrete types such as lightweight concrete (LWC), high-performance concrete (HPC), high-strength concrete (HSC), and ultra-high-performance concrete (UHPC), outperform traditional concrete in many areas [10, 26, 29]. Researchers have continued to investigated how additives can improve the characteristics of cement-based composites. For instance, geopolymer concrete reinforced with nano clays and CNTs has shown remarkable improvements in both strength and durability [16, 19]. Even small amounts of CNTs, between 0.05% and 0.1%, have been found to reduce spalling and improve residual strength under high temperatures (up to 300°C), while also lowering the O2 permeability coefficient [21, 28].

This study focuses on CNTs, which are cylindrical structures formed by rolling graphite sheets, also called buckytubes [7, 11, 20]. CNTs exhibit exceptional mechanical properties, including a modulus of elasticity and tensile strength far surpassing those of high-strength steel [8, 22]. These attributes make CNTs ideal for enhancing the mechanical, physical, and electrical properties of composite materials. Their use in construction, particularly for reinforcing cement, is gaining attention because of their ability to improve tensile strength and mitigate the formation of microcracks [2, 18, 24].

Due to their high tensile strength, which can range from 100 to 150 GPa, CNTs are highly effective in preventing the formation of microcracks in cement-based composites [15, 23, 27]. Their effectiveness is due to their role as fillers, nucleating agents, and microcrack bridges [32, 36]. With an elastic modulus of around 1 TPa, tensile strength exceeding 50 GPa, and yield strain of up to 10–20%, CNTs possess exceptional mechanical properties that make them suitable for reinforcing cement mixtures and preventing early-stage cracking [25, 35, 40]. However, challenges remain in terms of large-scale production and concerns about their potential toxicity and environmental impact, which are areas of ongoing research [30, 34, 41].

This paper will explore the role of CNTs in the construction industry, emphasizing their ability to significantly boost the effectiveness of cement-based materials, while also addressing the obstacles that must be overcome to fully realize their potential [31, 37, 39].

A. The Structure of Carbon Nanotubes.

Carbon nanotubes (CNTs) are cylinder-like structures at the nanoscale, made up entirely of carbon atoms. These atoms are organized in a hexagonal arrangement, similar to the structure of graphene, which is made up of a single layer of carbon atoms connected in a two-dimensional honeycomb lattice. CNTs can essentially be imagined as graphene sheets that are rolled into seamless, tubular forms.

The configuration of carbon nanotubes imparts exceptional mechanical, thermal, and electrical properties, making them valuable for various applications in fields such as nanotechnology, materials science, and electronics.

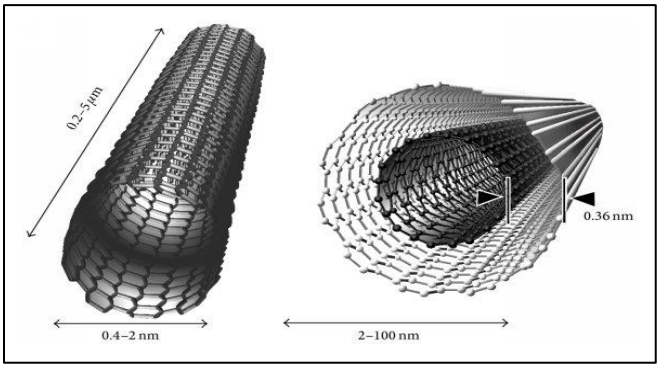

Fig. 1: Image credit: Wikipedia

1) Single Wall Carbon Nanotube (SWCNTs)

Single-Wall Carbon Nanotubes (SWCNTs) shown in fig.(a) do not have a strictly defined diameter limit, but when their diameter exceeds approximately 2.5 nanometers, they tend to collapse into a two-layer ribbon structure [1, 3]. SWCNTs as narrow as 0.4 nanometers have been successfully synthesized, although a diameter of around 1.4 nanometers is the most common, as it represents an optimal balance of properties [2, 5]. While there are no inherent restrictions on the length of SWCNTs, those longer than 2.5 nanometers are relatively uncommon and typically exhibit very high aspect ratios [4, 12]. SWCNTs possess several key characteristics. First, the atoms of carbon in the tube are assembled in hexagonal aromatic rings, with more chemically reactive pentagonal rings typically located at the ends [6, 8]. Second, the curvature of SWCNTs induces a slight sp^3 character in the carbon bonds, which influences both their reactivity and electronic properties [9, 13]. SWCNTs are formed by rolling graphene sheets into various configurations, which are determined by a helicity vector (Ch) and an angle of helicity (θ) [7, 10]. This process gives rise to different structural types, including zigzag, armchair, and helical (chiral) configurations [14, 15]. Unlike zigzag and armchair nanotubes, chiral nanotubes are not superimposable on their mirror images, giving them unique symmetry properties [16, 19]. Additionally, SWCNTs tend to align into hexagonal arrays, or "ropes," particularly when synthesized through methods such as electric arc discharge or laser vaporization [18, 20]. This alignment results in distinct diffraction patterns and imparts SWCNTs with distinct physical and chemical properties [21, 22].

2) Multi-Wall Carbon Nanotube (MWCNTs)

The construction of Multiwall Carbon Nanotubes (MWCNTs) is more sophisticated compared to Single-Wall Carbon Nanotubes (SWCNTs) due to the various possible arrangements of graphene layers. The most basic form of MWCNTs is the concentric type (c-MWCNTs), where multiple SWCNTs are stacked coaxially, resembling a Russian doll structure. These can be produced through techniques such as the electric arc method or catalyst-assisted thermal cracking [1, 2]. The distance between the inner tubes in MWCNTs is approximately 0.34 nanometers, which is somewhat greater than the interlayer spacing in graphite because of the curvature of the tubes [4]. MWCNTs can approximate the three-dimensional structure of graphite under certain conditions [5]. This occurs when the concentric graphene layers have a large radius of curvature or when faceted morphologies develop during synthesis or following high-temperature treatments [6, 7]. Another common MWCNTs texture is the herringbone type (h-MWCNTs), where the graphene layers are angled relative to the nanotube axis, often formed through processes involving catalysts [8]. In some cases, MWNTs exhibit a bamboo-like texture, characterized by sections of the tube being divided by graphene layers, creating a structure similar to nanofibers [9]. When the graphene layers are fully perpendicular to the nanotube axis, the resulting structure is known as a platelet nanofiber [10]. MWCNTs generally have lower aspect ratios compared to SWCNTs, which makes it easier to image their ends using transmission electron microscopy [11]. The properties of MWCNTs are influenced by the orientation and perfection of the graphene layers, both of which are determined by the processing conditions [12]. While the overall texture of MWCNTs is permanent, their nanotexture can be improved through high-temperature treatments or potentially degraded by chemical treatments [13, 14].

II. Properties of Carbon Nanotubes (CNTs)

A. Mechanical Properties

Carbon nanotubes (CNTs) exhibit exceptional mechanical properties due to the robust sp^2 bonding in their curved graphene structures, which surpasses the strength of sp^3 bonds found in diamond [1, 17]. This makes CNTs, including both single-wall (SWCNTs) and multiwall (MWCNTs) varieties, extremely resistant to deformation [4, 22]. SWCNTs exhibit a tensile strength of approximately 45 GPa, making them around 20 times stronger than steel, whereas defect-free MWCNTs can reach tensile strengths of up to 150 GPa [2, 11]. The tensile modulus of MWCNTs ranks among the highest recorded, reaching as much as 1 TPa, with SWCNTs potentially exceeding this measurement [9, 18]. These extraordinary properties highlight the potential of CNTs to transform the creation of high-performance fibrous materials [10, 35].

B. Reactivity

The unique structure of carbon nanotubes (CNTs) has a considerable impact on their chemical reactivity. Unlike other polyaromatic carbon materials, the distinct tubular shape of CNTs significantly affects their reactivity. This reactivity is primarily concentrated at the nanotube caps, where pentagons are present, as well as at structural defects, such as Stone–Wales defects, which enhance chemical reactivity [1, 2]. The method used to synthesize CNTs also plays a crucial role in their reactivity. For instance, CNTs produced through arc-discharge methods tend to be less reactive due to the presence of fewer structural defects compared to those synthesized using chemical vapor deposition (CCVD) [3, 4].

C. Dispersion of Carbon Nanotubes

Before mixing the concrete, carbon nanotubes (CNTs) were first dispersed in water. This process included sonication to break apart CNT bundles, followed by the addition of the surfactant Dolapix PC67 to ensure the stability of the dispersion [1, 2]. Based on earlier research, the dosages of Dolapix PC67 and the sonication time were established. The CNTs (CNTCOOH, CNTPL, and CNTOH) were combined with 40% of the total water, following CNT/Dolapix mass

ratios of 1:0.5, 1:1, and 1:0.25, respectively [5, 6]. The remaining 60% of the water was utilized to saturate the aggregates [7, 8]. These CNT-Dolapix-water mixtures were magnetically stirred for 4 hours and subjected to sonication for 30 minutes [9, 10]. Only magnetic stirring and sonication (for 45 and 30 minutes, respectively) were required for CNTSL and CNTSS, which were supplied in aqueous suspensions pre-stabilized with the TNWDIS surfactant. [11, 12].

Property	FS[a]	CS[b]	FG[c]	CG[d]
Water absorption 24 h (%)	0.189	0.259	0.49	0.349
Oven-dried particle density (kg/m^3)	2606	2625	2645	2684
Apparent particle density(kg/m^3)	2617	2643	2697	2708
Saturated and surface-dried particle density (kg/m^3)	2610	2632	2664	2694
Loose bulk density (kg/m^3)	1568	1509	1309	1346
Voids (%)	39.76	37.74	50.53	49.82
Shape index category			SI_{20}	SI_{20}
Los Angeles category			LA_{35}	LA_{35}
Size (mm)	0/2	0/4	0/8	4/11.2

Table 1: Aggregate Properties

Notation	CNTSS	CNTSL	CNTPL	CNTCOOH	CNTOH
Commercial name	TNIM8	TNIM6	TNIM6	TNIM6	TNIMH4
Form as supplied	Suspension	Suspension	powder	powder	powder
Purity (%)	>90	>90	>90	>90	>90
Outer diameter (nm)	>50	20-40	20-40	20-40	10-30
Inner diameter (nm)	5-15	5-10	5-10	5-10	5-10
Length (µm)	10-30	10-30	10-30	10-30	10-30
Aspect ratio	~300	~667	~667	~667	~1000
True density (g/cm^3)	~2.09	~2.1	~2.1	~2.1	~2.1
Tap density (g/cm^3)	0.179	0.159	0.159	0.159	0.139
COOH (%)	-	-	-	1.35-1.5	-
OH (%)	-	-	-	-	2.48

Table 2: Characteristics of CNT as supplied

D. Compressive Strength

Compressive strength refers to a material's capacity to endure loads that attempt to decrease its size. It quantifies how much compressive stress (force per unit area) a material can bear before it fails or fractures. The compressive strength (fcm) of concrete reinforced with carbon nanotubes (CNTs) was evaluated over various curing periods, demonstrating that CNTs generally enhance strength [1, 3]. The extent of improvement depends on factors such as the type and quantity of CNTs used, as well as the water-to-cement ratio, with more significant effects noted in cylindrical specimens, particularly those with lower water-to-cement (w/c) ratios [2, 8].

Carbon Nanotubes with Shorter Aspect Ratios (CNTSS) dispersed more effectively and provided greater strength enhancements compared to CNTs with longer aspect ratios, which were prone to agglomeration [5, 17]. Although functionalized CNTs contributed to some strength improvements, they were less effective than CNTSS, partly due to structural defects resulting from the functionalization process [4, 12]. Incorporating higher amounts of CNTs (0.5%) often resulted in decreased compressive strength due to inadequate dispersion [11, 21]. The most significant strength improvements were observed at early ages, as CNTs positively impacted cement hydration; however, this effect decreased over time, especially in mixtures with higher CNT dosages [13, 14]. The average compressive strength (fcm) values obtained from cubic (fcm,c) and cylindrical (fcm,cyl) specimens are displayed in Table 4, along with the fcm of CNT-reinforced concretes relative to that of reference concrete (RC) mixes (Δ). Additionally, the "coefficients of variation" (CV) are included in Table [6, 10].

Mixes	$f_{cm,c}$									$f_{cm,cyl}$		
	7 days			28 days			90 days			28 days		
	MPa	CV	Δ	MPa	CV	Δ	MPa	CV	Δ	MPa	CV	Δ
RC(0.55)	36.8	4.6	-	47.5	4.8	-	54.7	3.5	-	45.4	5.6	-
C (0.55) -PL (0.05)	40.4	2.5	9.7	52.1	2.3	9.6	59.2	2.6	8.3	49.3	1.4	8.4
C (0.55) -PL (0.5)	38.6	4.1	4.8	44.5	1.1	-6.3	53.1	0.1	-2.9	-	-	-
C(0.55)-COOH (0.05)	38.4	2.4	4.2	51.6	1.6	8.7	58.4	2.8	6.8	49.1	2.2	8.0
C (0.55)- COOH (0.5)	41.0	2.8	11.4	47.3	2.4	0.4	55.0	2.7	0.6	-	-	-
C (0.55) -SS (0.1)	45.1	2.5	22.5	57.5	4.0	21.0	66.7	4.8	21.8	55.6	0.4	22.3
C (0.55) -SS (0.5)	38.4	5.6	4.1	51.2	1.7	7.8	57.5	3.2	5.1	48.5	2.0	6.8
C (0.55) -SL (0.05)	35.6	7.6	-3.4	46.2	4.0	-2.8	50.7	2.5	-7.3	45.7	1.5	0.7
C (0.55) -OH (0.05)	40.0	1.2	8.5	50.7	2.3	6.7	59.0	1.9	7.9	49.5	1.2	9.0
RC (0.45) -	56.0	1.1	-	64.7	2.4	-	67.8	8.1	-	60.8	0.5	-
C (0.45) -PL (0.05)	55.69	1.0	-0.6	64.0	2.20	-1.1	72.2	2.1	6.4	66.79	0.1	9.8

RC (0.35) -	73.59	4.0	-	78.3	3.20	-	85.3	2.7	-	77.49	7.2	-
C (0.35) -PL (0.05)	78.3	5.1	6.4	84.9	6.1	8.5	91.2	9.2	6.9	88.6	0.3	14.3

Table 3: Compressive Strength of concrete cubes ($f_{cm,c}$) and cylinder ($f_{cm,cyl}$)
Note: RC-reinforced Concrete, C (Concrete), PL (Partial Load), SS (Steel Yield Strength), COOH (Carboxyl Group)

E. Modulus of Elasticity

The Modulus of Elasticity, commonly known as Young's Modulus, is an important mechanical property that indicates how a material behaves under elastic deformation when a force is applied. It measures the stiffness of a material by illustrating the relationship between stress (force applied per unit area) and strain (relative deformation) within the material's elastic range on the stress-strain curve. The inclusion of carbon nanotubes (CNTs) enhances the elastic modulus (Ecm) of concrete by minimizing the propagation of microcracks and nanopores. The most significant improvement was observed with 0.10% CNTSS, resulting in a 15% increase in Ecm compared to the reference concrete [3, 17, 38].

While other types of CNTs also contributed to improved Ecm, larger quantities often resulted in diminishing returns due to agglomeration [9, 10]. The elastic modulus is affected by the age of the concrete, the interfacial transition zone (ITZ), as well as the properties of the aggregates and cement paste [6, 39]. CNTs primarily influence the cement paste, with a notable 15% increase in Ecm recorded for 0.10% CNTSS. This finding aligns with similar results observed in CNT-reinforced mortars and cement pastes [14, 24, 32]. Additionally, a strong correlation ($R^2 > 0.97$) exists between fcm and Ecm at 28 days, although standard equations tend to slightly underestimate Ecm, particularly in high-strength concrete [1, 18, 22].

F. Ultrasonic Pulse Velocity

A non-destructive testing technique called Ultrasonic Pulse Velocity (UPV) is used to assess the consistency, integrity, and quality of materials, notably concrete. This method entails passing ultrasonic pulses through the substance and timing how long it takes the pulses to get from the source to the destination. The velocity of these pulses provides valuable information about the material's properties [2, 5, 12]. UPV in concrete, which depends on stiffness and density, showed minimal variation (less than ±3%) among different CNTs types [3, 13]. The highest UPV was in CNTSS-reinforced concrete [1]. UPV's limited change, compared to more pronounced variations in f_{cm} and E_{cm}, is due to its sensitivity to small differences in elasticity and density and its measurement in uncracked samples [20, 43]. Indicating the mechanical functionality of CNT-reinforced concrete, UPV correlates poorly with fcm but well with toughened density [4, 21].

Mixes	E_{cm}			UPV								
	28 days			7 days			28 days			90 days		
	GPa	CV(%)	Δ(%)	Km/s	CV(%)	Δ(%)	Km/s	CV(%)	Δ(%)	Km/s	CV(%)	Δ(%)
RC(0.55)	36.01	1.50	-	4.50	1.70	-	4.70	0.60	-	4.69	0.7	-
C(0.55) - PL(0.05)	37.61	0.3	4.6	4.6	0.4	2.3	4.8	1.6	2.3	4.8	1.5	2.1
C(0.55)-PL(0.5)	-	-	-	4.60	0.90	1.9	4.8	0.4	1.4	4.8	0.8	0.9
C(0.55)-COOH(0.05)	37.5	0.8	4.5	4.5	2.1	-0.3	4.7	0.8	1.0	4.8	1.2	0.6
C(0.55)-COOH(0.5)	-	-	-	4.7	0.4	2.8	4.8	0.5	1.7	4.8	1.0	2.0
C(0.55)-SS(0.1)	41.2	0.6	14.5	4.6	1.7	2.5	4.8	0.6	2.6	4.9	1.2	2.8
C(0.55)-SS(0.5)	36.6	1.2	1.9	4.6	0.7	1.6	4.7	0.3	1.1	4.7	0.6	0.5
C(0.55)-SL(0.05)	34.9	1.3	-2.9	4.3	0.3	-4.7	4.4	0.8	-7.1	4.4	1.8	-5.9
C(0.55)-OH(0.05)	36.5	1.0	1.5	4.6	2.3	0.6	4.7	0.5	0.2	4.7	1.6	-0.6
RC(0.45)-	41.0	2.0	-	4.80	1.20	-	4.90	0.5	-	4.89	1.4	-
C(0.45) - PL(0.05)	43.39	1.4	6.0	4.8	1.3	0.1	4.9	0.7	1.0	4.9	1.6	0.5
RC(0.35) -	47.09	0.6	-	5.01	0.40	-	5.09	1.10	-	5.01	1.20	-
C(0.35) - PL(0.05)	50.90	1.3	8.1	5.1	0.8	1.7	5.1	0.7	0.8	5.1	1.4	0.8

Table 4: Concrete's Elastic modulus (Ecm) and Ultrasonic Pulse Velocity (UPV)
Note: RC-reinforced Concrete, C (Concrete), PL (Partial Load), SS (Steel Yield Strength), COOH (Carboxyl Group)

G. Splitting Tensile Strength

The introduction of carbon nanotubes (CNTs) is one of the factors that affects the splitting tensile strength of concrete. CNTs can significantly enhance the splitting tensile strength due to their ability to bridge cracks within the concrete matrix [1]. Studies have shown that improvements in tensile strength ranged from 27% at 7 days to a decrease of 14% at 90 days, with specific CNT types and concentrations being more effective [3]. The highest improvement (14%) was noted in concrete with 0.10% CNTSS at 28 days, closely followed by 0.05% CNTPL (13%) [4]. It was observed that concrete having a lower water-to-cement (w/c) ratio exhibited better tensile strength improvements when reinforced with CNTs [5].

However, while CNTs generally enhance concrete's properties, their effectiveness can vary based on type, concentration, and dispersion challenges [6]. Higher concentrations of CNTs may lead to reduced effectiveness due to increased agglomeration (7).

Furthermore, the inherent nature of the splitting tensile test and potential issues with CNT dispersion contribute to the variability in results [8]. Overall, although CNTs can significantly improve the mechanical qualities of

concrete, their practical use is still constrained by issues with cost and dispersion. [9].

Mixes	$f_{ctm,sp}$								
	7 days			28 days			90 days		
	MPa	CV(%)	Δ(%)	MPa	CV(%)	Δ(%)	MPa	CV(%)	Δ(%)
RC(0.55)	2.79	2.0	0.0	3.4	0.0	0.0	3.9	2.0	0.0
C(0.55)-PL(0.05)	3.09	10.0	11.8	3.8	5.0	12.6	4.3	2.0	10.3
C(0.55)-PL(0.5)	3.3	1.0	20.2	3.5	19.0	3.5	4.0	2.0	2.1
C(0.55)-COOH(0.05)	3.1	10.0	10.7	3.6	1.0	4.1	3.8	2.0	-3.1
C(0.55)-COOH(0.5)	2.8	7.0	1.8	3.0	3.0	-12.2	3.4	1.0	-13.8
C(0.55)-SS(0.1)	3.2	3.0	15.8	3.9	2.0	14.1	4.4	1.0	13.5
C(0.55) SS(0.5)	2.9	2.0	6.6	3.5	2.0	1.2	4.2	2.0	7.9
C(0.55)-SL(0.05)	2.6	10.0	-6.9	3.3	0.0	-2.0	4.0	2.0	3.6
C(0.55)-OH(0.05)	2.7	2.0	-3.3	3.5	3.0	1.6	3.6	5.0	-7.8
RC(0.45)-	3.30	16.0	0.0	4.1	1.0	0.0	4.6	2.0	0.0
C(0.45)-PL(0.05)	3.60	22.0	9.2	4.4	9.0	5.5	4.8	2.0	4.2
RC(0.35) -	4.09	12.0	0.0	4.9	5.0	0.0	5.5	1.0	0.0
C(0.35)- PL (0.05)	5.19	7.0	27.1	5.7	12.0	16.5	6.0	1.0	9.1

Table 5: Concrete's Splitting Tensile Strength ($f_{ctm,sp}$).

Note: RC-reinforced Concrete, C (Concrete), PL (Partial Load), SS (Steel Yield Strength), COOH(Carboxyl Group)

H. Durability of CNTC

The durability of Carbon Nanotube Composites (CNTC) refers to the ability of these materials to maintain their mechanical, thermal, and electrical properties over time under various environmental and operational conditions. Carbon nanotube composites possess remarkable strength, stiffness, and conductivity, making them highly appealing for various usage. However, their durability is a crucial factor in determining their long-term performance and reliability in practical uses.

Increasingly, researchers are exploring the addition of specialized materials to extend the lifespan of concrete and improve its durability. Among these, nanomaterials are becoming increasingly popular. Carbon nanotubes (CNTs), in particular, offer exceptional properties compared to other similar materials. As noted earlier, numerous research has demonstrated that CNTs can improve concrete durability. For instance, Carriço et al. investigated the effects of different types of multi-walled carbon nanotubes (MWCNTs) on concrete durability [4, 6, 14]. Various other studies support the beneficial effects of CNTs on concrete strength, impermeability, and crack resistance [1, 12, 23].

I. Flexural Strength

A material's flexural strength indicates its capacity to withstand deformation when subjected to load, particularly when bending or flexing. It is sometimes referred to as the transverse rupture strength, modulus of rupture, or bending strength. Because materials like concrete, ceramics, and composites may experience bending loads in a variety of structural applications, flexural strength is especially crucial in these materials.

Generally, the coefficient of variation (CV) for CNTs-reinforced concretes was below 5%, similar to that of conventional reinforced concrete (RC) mixes, indicating that CNTs agglomeration did not significantly impact test variability. The addition of CNTs generally improved (f_{ctm},f) consistent with previous findings, demonstrating their potential to enhance the tensile strength of concrete.

While the incorporation of CNTs improved the flexural strength (f_{ctm},f) of concrete, though the enhancements were modest and varied with CNTs type and concentration. Improvements ranged from 18% to a decrease of 6% compared to conventional concrete. Higher CNTs concentrations often led to reduced flexural strength, likely due to poor dispersion and interaction with aggregates.

The most significant enhancement in flexural strength—an increase of 9%—was observed with a concentration of 0.1% CNTSS at 28 days. Additionally, the impact of CNTs was influenced by the water-to-cement ratio (w/c); mixtures with lower w/c ratios tended to show more substantial improvements. Despite the potential advantages offered by CNTs, their high cost and challenges associated with large-scale production restrict their widespread use in concrete applications. Although the cost of CNT-reinforced concrete is notably higher than that of standard concrete, prices have been decreasing in recent years.

Flexural strength improvements were consistent with those observed in compressive and splitting tensile strengths, demonstrating a good correlation between these properties. The relationship between flexural and splitting tensile strengths showed that splitting tensile strength ($f_{ctm,\ sp}$) is typically 0.5 to 0.7 times the flexural strength ($f_{ctm,\ f}$).

Mixes	$f_{ctm,sp}$								
	7 days			28 days			90 days		
	MPa	CV(%)	Δ(%)	MPa	CV(%)	Δ(%)	MPa	CV(%)	Δ(%)
RC(0.55)	4.1	2.0	0.0	5.6	1.9	0.0	6.0	2.3	0.0
C(0.55)_PL(0.05)	4.4	1.9	7.3	5.8	1.8	2.7	6.3	1.3	5.1
C(0.55)_PL(0.5)	4.0	2.0	-2.4	5.5	3.9	-2.2	5.9	1.4	-1.9
C(0.55)_COOH(0.05)	4.1	2.0	0.0	5.8	0.9	3.7	6.3	5.7	4.5

C(0.55) COOH(0.5)	4.0	2.0	-2.4	5.6	1.5	0.0	6.0	1.4	0.0
C(0.55) SS(0.1)	4.7	1.7	14.6	6.1	0.8	9.5	6.6	1.2	10.0
C(0.55) SS(0.5)	4.0	2.0	-2.4	5.6	0.4	-0.8	5.7	3.3	-5.7
C(0.55) SL(0.05)	3.9	2.1	-4.9	5.3	3.6	-5.2	6.3	1.2	5.4
C(0.55) OH(0.05)	4.0	2.0	-2.4	6.0	0.4	6.7	6.0	3.5	-0.1
RC(0.45)	5.9	1.7	0.0	6.0	1.0	0.0	6.7	0.8	0.0
C(0.45) PL(0.05)	5.6	1.5	14.3	6.6	2.0	11.2	7.3	2.7	8.9
RC(0.35)	6.1	1.3	0.0	8.5	3.9	0.0	9.2	0.2	0.0
C(0.35) PL(0.05)	7.2	1.1	18.0	9.7	1.0	14.3	10.0	2.6	9.4

Table 6: Concrete's Flexural strength (f_{ctm},f)

Note: RC-reinforced Concrete, C (Concrete), PL (Partial Load), SS (Steel Yield Strength), COOH (Carboxyl Group)

J. Workability

Workability refers to how easily a cement mixture can be mixed, placed, and finished without issues such as segregation or the need for excessive water. The incorporation of carbon nanotubes (CNTs) into cement composites can hinder workability due to their large surface area, which tends to absorb water and increase the viscosity of the mixture. This results in greater difficulty in mixing and placing the cement. As the content of CNTs increases, the likelihood of agglomeration also rises, which further decreases flowability. To mitigate these effects, admixtures such as superplasticizers are commonly utilized to enhance dispersion and help maintain workability.

III. Experimental Result Analysis

Numerous tests have been conducted by partially replacing cement with carbon nanotubes (CNTs). This study presents a comprehensive analysis of the outcomes of these tests. Several research findings suggest that CNTs can serve as an effective partial substitute for cement.

The study investigated the impact of varying CNT concentrations on both the compressive and flexural strength of cement-based materials, as illustrated in Figures 2 and 3.

For flexural strength at 28 days, the addition of 0.03% and 0.08% CNTs resulted in slight increases, reaching 11.13 MPa and 10.7 MPa, respectively, compared to the control batch, which measured 10.48 MPa. A notable improvement was observed at a CNT concentration of 0.15%, yielding a 28% increase (13.5 MPa), and at 0.25% CNTs, where there was a 55% improvement (16.26 MPa). At higher concentrations (0.35% and 0.5%), flexural strength levelled off, with values of 16.43 MPa and 16.86 MPa, respectively. The standard deviation of the results remained within 10%, indicating consistent data across all mixes, contrasting with previous studies.

In terms of compressive strength, the results exhibited a similar pattern, although the enhancements were less pronounced. The inclusion of 0.03% and 0.08% CNTs resulted in increases in compressive strength of 8.5% and 6.5%, respectively, compared to the control sample. At a concentration of 0.15% CNTs, a 15% improvement was noted, while the batch with 0.25% CNTs showed a 22% increase. However, there were significant gains observed beyond this concentration, as the batches with 0.35% and 0.5% CNTs demonstrated increases of 21% and 25%, respectively, which were comparable to the results from the 0.25% batch.

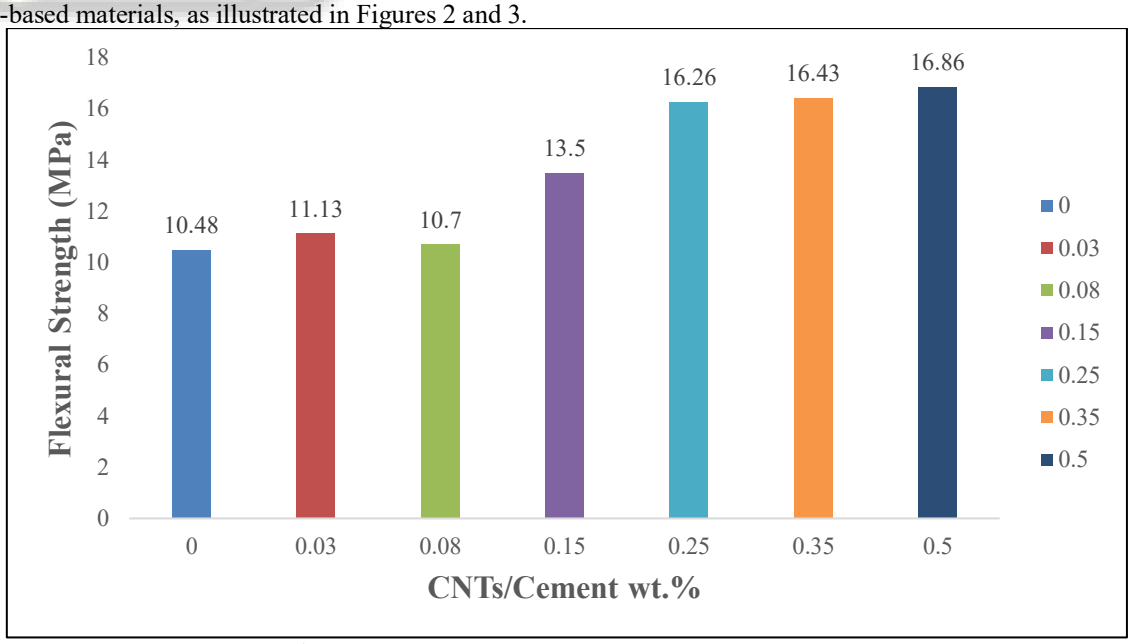

Fig. 2: 28th day flexural strength versus CNTs/cement weight fraction.

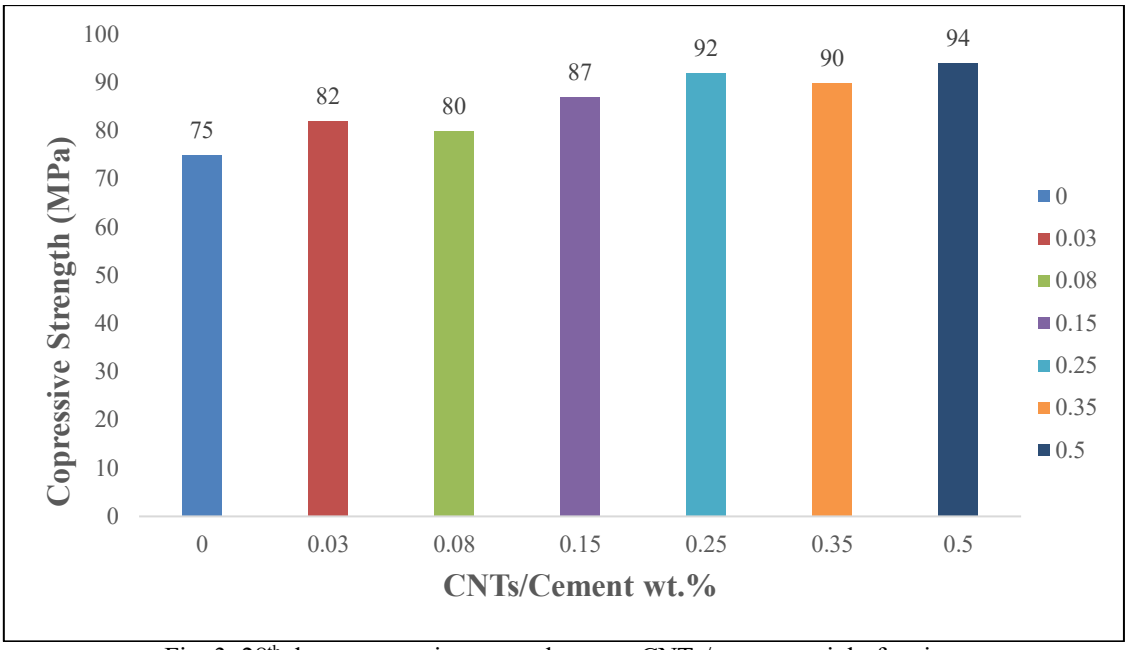

Fig. 3: 28th day compressive strength versus CNTs/cement weight fraction.

IV. Discussion

properties of cementitious materials [1, 3, 5]. The findings of this study provide valuable insights into the effectiveness of carbon nanotubes (CNTs) as a partial cement replacement in improving both flexural and compressive strength. The results clearly demonstrate that CNTs, when introduced at varying concentrations, significantly affect the mechanical

Flexural Strength: Fig.2 illustrates the relationship between the 28-day flexural strength and the CNT-to-cement weight ratio. At lower concentrations (0.03% and 0.08%), the flexural strength increase is relatively small, suggesting that these CNT amounts do not significantly alter the cement matrix's microstructure [7, 8]. However, at 0.15% CNTs, a 28% improvement in flexural strength indicates that this concentration might be the threshold where CNTs begin to reinforce the matrix effectively [2, 4]. A significant 55% increase at 0.25% CNTs further emphasizes the idea that CNTs bridge cracks within the matrix, distributing the applied stress more evenly and enhancing the material's resistance to bending forces [6, 9].

Beyond 0.25%, the strength increases levels off, with 0.35% and 0.5% CNTs yielding only minor gains over the 0.25% batch [10, 12]. This plateau suggests that after a certain concentration, the matrix becomes saturated with CNTs, leading to reduced dispersion and effectiveness [11, 14]. The data consistency, supported by a low standard deviation across mixtures, further strengthens the reliability of these results, particularly for the 0.15% and 0.25% CNT concentrations, which show reliable enhancements in flexural strength [15, 16].

Compressive Strength: Figure 3 presents the compressive strength results of CNT-reinforced cement mixtures compared to the control batch. The compressive strength trend is similar, though the overall improvements are less pronounced than those observed in flexural strength [17, 18]. This may be because compressive forces are more evenly distributed throughout the cementitious matrix, with CNTs contributing more to tensile and crack-bridging properties rather than directly improving compressive strength [19, 20]. Small gains in compressive strength were noted at 0.03% and 0.08% CNTs, while the most significant improvements occurred at 0.15% and 0.25%, with increases of 15% and 22%, respectively [21, 22].

The strength improvements of CNT composites tend to plateau or even decrease beyond a 0.25% weight fraction due to CNT clustering or agglomeration, caused by strong van der Waals forces between individual nanotubes [23, 24]. These agglomerates create stress concentration points and disrupt the uniform distribution of loads within the composite, reducing its overall mechanical performance [25, 26]. Achieving proper dispersion becomes more challenging as CNT concentration increases, leading to weaker regions within the composite, which counteract the expected strength gains from additional nanotubes [27, 28].

For CNTs to effectively strengthen a composite, load transfer from the matrix to the nanotubes must be efficient [31, 32]. However, as the CNT concentration increases, the matrix may struggle to transfer the load effectively, particularly if the CNTs are poorly dispersed [33, 34]. Higher concentrations also increase the composite mixture's viscosity, making processing more difficult and increasing the risk of defects during manufacturing, which further weakens the composite [35, 36].

Incorporating CNTs in construction materials can offer economic advantages by reducing the overall amount of cement needed, thereby cutting material costs and minimizing the environmental impact associated with cement production [37, 38]. Additionally, the improved mechanical properties from CNTs can result in lighter, stronger structures, leading to savings in transportation, labor, and maintenance costs over the lifespan of a building [39, 40].

V. Conclusion

The study demonstrates that CNTs can indeed serve as a viable partial substitute for cement, particularly in enhancing flexural strength. The optimal range for CNT inclusion appears to be between 0.15% and 0.25%, where significant

improvements in both flexural and compressive strength are achieved without reaching a saturation point where additional CNTs offer diminishing strength. The increase in strength of materials reinforced with carbon nanotubes typically plateaus at around 0.25% by weight fraction due to agglomeration and poor dispersion of the CNTs within the matrix. At higher concentrations, CNTs tend to cluster together, reducing their effectiveness in reinforcing the matrix. Furthermore, the mixture's increased viscosity may hinder appropriate processing and weaken the link between the CNTs and the matrix. Thus, beyond 0.25% by weight fraction, the drawbacks of poor dispersion and processing difficulties outweigh the benefits, leading to a stagnation or even a reduction in overall strength. These findings align with existing research while providing a more consistent and detailed analysis, contributing valuable data to the ongoing exploration of CNTs in cementitious materials. Further research could explore the long-term durability and microstructural effects of CNTs in these concentrations to optimize their application in construction materials.

REFERENCES

[1] Qiu, L., Li, L., Ashour, A., Ding, S., & Han, B. (2024). Monitoring damage of concrete beams via self-sensing cement mortar coating with carbon nanotube-nano carbon black composite fillers. *Journal of Intelligent Material Systems and Structures*, *35*(6), 633-648.

[2] Lyashenko, D. A., & Perfilov, V. A. (2024). Modification of fine-grained concrete with carbon nanotubes. *Advanced Materials & Technologies*, *9*(2), 91-99.

[3] Reis, E. D., Resende, H. F., Christoforo, A. L., Costa, R. M., Gatuingt, F., Poggiali, F. S. J., & Bezerra, A. C. S. (2024). Assessment of physical and mechanical properties of concrete with carbon nanotubes pre-dispersed in cement. *Journal of Building Engineering*, *89*, 109255.

[4] Jayakumari, B. Y., Swaminathan, E. N., & Partheeban, P. (2023). A review on characteristics studies on carbon nanotubes-based cement concrete. *Construction and Building Materials*, *367*, 130344.

[5] Ahmad, J., & Zhou, Z. (2023). Properties of concrete with addition carbon nanotubes: A review. *Construction and Building Materials*, *393*, 132066.

[6] Zhang, P., Su, J., Guo, J., & Hu, S. (2023). Influence of carbon nanotube on properties of concrete: A review. *Construction and Building Materials*, *369*, 130388.

[7] Zhang, P., Su, J., Guo, J., & Hu, S. (2023). Influence of carbon nanotube on properties of concrete: A review. *Construction and Building Materials*, *369*, 130388.

[8] Cui, K., Liang, K., Jiang, T., Zhang, J., Lau, D., & Chang, J. (2023). Understanding the role of carbon nanotubes in low-carbon concrete: From experiment to molecular dynamics. *Cement and Concrete*

[9] *Composites*, *142*, 105189 Xing, G., Xu, Y., Huang, J., Lu, Y., Miao, P., Chindasiriphan, P., ... & Ma, K. (2023). Research on the mechanical properties of steel fibers reinforced carbon nanotubes concrete. *Construction and Building Materials*, *392*, 131880.

[10] Mudasir, P., & Naqash, J. A. (2023). Impact of carbon Nano tubes on fresh and hardned properties of conventional concrete. *Materials Today: Proceedings*, *80*, 1920-1925.

[11] Cui, K., Lu, D., Jiang, T., Zhang, J., Jiang, Z., Zhang, G., ... & Lau, D. (2023). Understanding the role of carbon nanotubes in low carbon sulfoaluminate cement-based composite. *Journal of Cleaner Production*, *416*, 137843.

[12] Nazar, S., Yang, J., Amin, M. N., Khan, K., Javed, M. F., & Althoey, F. (2023). Formulation of estimation models for the compressive strength of concrete mixed with nanosilica and carbon nanotubes. *Developments in the Built Environment*, *13*, 100113.

[13] Reis, E. D., Borges, L. A., Camargos, J. S. F., Gatuingt, F., Poggiali, F. S. J., & Bezerra, A. C. S. (2023). A systematic review on the engineering properties of concrete with carbon nanotubes. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *45*(4), 205.

[14] Jiao, H., Wang, Y., Li, L., Arif, K., Farooq, F., & Alaskar, A. (2023). A novel approach in forecasting compressive strength of concrete with carbon nanotubes as nanomaterials. *Materials Today Communications*, *35*, 106335.

[15] Kozlova, I., Zemskova, O., Skopova, A., & Borisenkov, N. (2023). Study of properties of cements and concrete mixtures with carbon nanotubes. In *E3S Web of Conferences* (Vol. 457, p. 01015). EDP Sciences.

[16] Zhang, Y., & Xia, W. (2023). Enhancing effect of carbon nanotubes on the performance of concrete containing surface-treated fly ash cenosphere. *Construction and Building Materials*, *406*, 133322.

[17] Ebrahim, A., & Kandasamy, S. (2023). The effect of using multi-walled carbon nanotubes on the mechanical properties of concrete: a review. *Innovative Infrastructure Solutions*, *8*(9), 251.

[18] Lu, D., Huo, Y., Jiang, Z., & Zhong, J. (2023). Carbon nanotube polymer nanocomposites coated aggregate enabled highly conductive concrete for structural health monitoring. *Carbon*, *206*, 340-350.

[19] Yun, H., Kim, D., Kang, S., & Chung, W. (2023). Effect of Coarse Aggregate and Multi-Wall Carbon Nanotubes on Heat Generation of Concrete. *Buildings*, *13*(12), 3127.

[20] Hwangbo, D., Son, D. H., Suh, H., Sung, J., Bae, B. I., Bae, S., ... & Choi, C. S. (2023). Effect of nanomaterials (carbon nanotubes, nano-silica, graphene oxide) on bond behavior between concrete and reinforcing bars. *Case Studies in Construction Materials*, *18*, e02206.

[21] Liu, Y., Zhong, X., & Mohammadian, H. R. (2023). Role carbon nanomaterials in reinforcement of concrete and cement; a new perspective in civil engineering. *Alexandria Engineering Journal*, *72*, 649-656

[22] Sun, Z., Wan, Z., & Sachs, S. G. (2023). Compatibility of carbon nanotubes in concrete with air entrainer and superplasticizer. *Construction and Building Materials*, *364*, 129944.

[23] Cui, K., Chang, J., Feo, L., Chow, C. L., & Lau, D. (2022). Developments and applications of carbon nanotube reinforced cement-based composites as functional building materials. *Frontiers in Materials*, *9*, 861646.
[24] Mosallam, S. J., Behbahani, H. P., Shahpari, M., & Abaeian, R. (2022, January). The effect of carbon nanotubes on mechanical properties of structural lightweight concrete using LECA aggregates. In *Structures* (Vol. 35, pp. 1204-1218). Elsevier.
[25] Eisa, M. S., Mohamady, A., Basiouny, M. E., Abdulhamid, A., & Kim, J. R. (2022). Mechanical properties of asphalt concrete modified with carbon nanotubes (CNTs). *Case studies in construction materials*, *16*, e00930.
[26] Zhang, Y., & Sun, X. (2022). Influence of multi-walled carbon nanotubes on the multi-scale performance of internally cured concrete containing pre-wetted lightweight aggregate. *Journal of Building Engineering*, *58*, 104986.
[27] Li, Y., Li, H., & Shen, J. (2022). The study of effect of carbon nanotubes on the compressive strength of cement-based materials based on machine learning. *Construction and Building Materials*, *358*, 129435.
[28] Wang, J., Dong, S., Dai Pang, S., Zhou, C., & Han, B. (2022). Pore structure characteristics of concrete composites with surface-modified carbon nanotubes. *Cement and Concrete Composites*, *128*, 104453.
[29] Hassan, A., Galal, S., Hassan, A., & Salman, A. (2022). Utilization of carbon nanotubes and steel fibers to improve the mechanical properties of concrete pavement. *Beni-Suef University Journal of Basic and Applied Sciences*, *11*(1), 121.
[30] Lu, D., Shi, X., & Zhong, J. (2022). Understanding the role of unzipped carbon nanotubes in cement pastes. *Cement and Concrete Composites*, *126*, 104366.
[31] Fu, Q., Zhou, Z., Wang, Z., Huang, J., & Niu, D. (2022). Insight into dynamic compressive response of carbon nanotube/carbon fiber-reinforced concrete. *Cement and Concrete Composites*, *129*, 104471.
[32] Shao, J., Zhu, H., Zhao, B., Haruna, S. I., Xue, G., Jiang, W., ... & Yang, J. (2022). Combined effect of recycled tire rubber and carbon nanotubes on the mechanical properties and microstructure of concrete. *Construction and Building Materials*, *322*, 126493.
[33] Bieliatynskyi, A., Yang, S., Pershakov, V., Shao, M., & Ta, M. (2022). Study of carbon nano-modifier of fly ash in cement concrete mixtures of civil engineering. *Science and Engineering of Composite Materials*, *29*(1), 227-241.
[34] Chukka, N. D. K. R., Reddy, B. S., Vasugi, K., Reddy, Y. B. S., Natrayan, L., & Thanappan, S. (2022). Experimental testing on mechanical, durability, and adsorption dispersion properties of concrete with multiwalled carbon nanotubes and silica fumes. *Adsorption Science & Technology*, *2022*, 4347753.
[35] Song, S., Niu, Y., & Zhong, X. (2022). Study on dynamic mechanical properties of carbon nanotubes reinforced concrete subjected to freeze–thaw cycles. *Structural Concrete*, *23*(5), 3221-3233.
[36] Lan, Y., Zheng, B., Shi, T., Ma, C., Liu, Y., & Zhao, Z. (2022). Crack resistance properties of carbon nanotube-modified concrete. *Magazine of Concrete Research*, *74*(22), 1165-1175.
[37] Allujami, H. M., Abdulkareem, M., Jassam, T. M., Al-Mansob, R. A., Ibrahim, A., Ng, J. L., & Yam, H. C. (2022). Mechanical properties of concrete containing recycle concrete aggregates and multi-walled carbon nanotubes under static and dynamic stresses. *Case Studies in Construction Materials*, *17*, e01651.
[38] Ramezani, M., Kim, Y. H., Sun, Z., & Sherif, M. M. (2022). Influence of carbon nanotubes on properties of cement mortars subjected to alkali-silica reaction. *Cement and Concrete Composites*, *131*, 104596.
[39] Farcas, C., Galao, O., Navarro, R., Zornoza, E., Baeza, F. J., Del Moral, B., ... & Garcés, P. (2021). Heating and de-icing function in conductive concrete and cement paste with the hybrid addition of carbon nanotubes and graphite products. *Smart Materials and Structures*, *30*(4), 045010.
[40] Gao, Y., Jing, H., Zhou, Z., Shi, X., Li, L., & Fu, G. (2021). Roles of carbon nanotubes in reinforcing the interfacial transition zone and impermeability of concrete under different water-to-cement ratios. *Construction and Building Materials*, *272*, 121664.
[41] Karpova, E., Skripkiūnas, G., Barauskas, I., Barauskienė, I., & Hodul, J. (2021). Influence of carbon nanotubes and polycarboxylate superplasticiser on the Portland cement hydration process. *Construction and Building Materials*, *304*, 124648.
[42] Mudasir, P., & Naqash, J. A. (2021). The effect of water cement ratio on the characteristics of multi-walled carbon nanotube reinforced concrete. *Materials Today: Proceedings*, *43*, 3852-3855.
[43] Siahkouhi, M., Razaqpur, G., Hoult, N. A., Baghban, M. H., & Jing, G. (2021). Utilization of carbon nanotubes (CNTs) in concrete for structural health monitoring (SHM) purposes: A review. *Construction and Building Materials*, *309*, 125137.
[44] Liu, Y., Shi, T., Zhao, Y., Gu, Y., Zhao, Z., Chen, J., ... & Shi, S. (2020). Autogenous shrinkage and crack resistance of carbon nanotubes reinforced cement-based materials. *International Journal of Concrete Structures and Materials*, *14*, 1-10.
[45] Silvestro, L., & Gleize, P. J. P. (2020). Effect of carbon nanotubes on compressive, flexural and tensile strengths of Portland cement-based materials: A systematic literature review. *Construction and Building Materials*, *264*, 120237.26.
[46] Irshidat, M. R. (2020). Improved bond behavior between FRP reinforcing bars and concrete with carbon nanotubes. *Construction and Building Materials*, *257*, 119562.
[47] Kang, J., Al-Sabah, S., & Théo, R. (2020). Effect of single-walled carbon nanotubes on strength properties of cement composites. *Materials*, *13*(6), 1305.

[48] Chen, J., & Akono, A. T. (2020). Influence of multi-walled carbon nanotubes on the hydration products of ordinary Portland cement paste. *Cement and Concrete Research*, *137*, 106197.
[49] Xu, S., Liu, J., & Li, Q. (2015). Mechanical properties and microstructure of multi-walled carbon nanotube-reinforced cement paste. *Construction and Building Materials*, *76*, 16-23.
[50] Yazdanbakhsh, A., Grasley, Z. C., Tyson, B., & Al-Rub, R. A. (2009). Carbon nano filaments in cementitious materials: some issues on dispersion and interfacial bond. *ACI Special Publication*, *267*, 21-34.

