THE EFFECT OF DIFFERENT MULTI-WALLED CARBON NANOTUBES ASPECT RATIO ON THE COMPRESSIVE STRENGTH OF THE CEMENT-BASED CONCRETE

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Abstract: *In recent years, there has been extensive research on the mechanical and physical properties of composite cement-based building materials containing nanosized carbon particles, particularly multi-walled carbon nanotubes (MWCNTs), owing to their mechanical and physical advantages. This study investigated the effect of purified multi-walled carbon nanotubes (MWCNTs) with different aspect ratios on the compressive strength of cement-based concrete. This study aimed to enhance the mechanical properties of the composites by optimizing the MWCNT dosage and type. The novelty of this study lies in comparing three MWCNT types (TNM2, TNM3, and TNM7) with aspect ratios ranging from ~250 to ~4347. Concrete samples with 0–0.2 wt.% MWCNTs by the weight of cement were tested after 7 days of curing. The results show that the compressive strength increased by 9.41% (TNM2 at 0.2%), 2.80% (TNM3 at 0.05%), and 12.13% (TNM7 at 0.05%). High-aspect-ratio MWCNTs showed consistent improvement with increasing content, whereas low-aspect-ratio MWCNTs peaked at 0.05%. This effect is attributed to the nanotube dispersion, reinforcement efficiency, and porosity control. A standardized ultrasonic dispersion technique was used to ensure the homogenous distribution of nanotubes in the cement matrix. These findings support the development of nano-engineered concrete with improved early strength for structural and precast construction applications.*

Keywords:. *carbon nanotubes, cement based concrete, compressive strength, aspect ratio, outer diameter*.

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Introduction

Concrete is among the most widely utilized materials in construction, attributed to its notable workability and mechanical properties. Enhancing these attributes, particularly compressive strength, presents a significant challenge. Numerous studies have investigated the incorporation of additives and nanoparticles, such as nanofibers, carbon graphene, single-walled carbon nanotubes (SWCNTs), and multi-walled carbon nanotubes (MWCNTs), to augment the mechanical properties of concrete, thereby achieving superior compressive and tensile strengths [1,2,3,4]. Multi-walled carbon nanotubes (MWCNTs) are among the most extensively employed and robust nanoparticles. Their one-dimensional fibrous nature contributes to a broad range of outer diameters (spanning from 0.4-3 nm to 1.4-100 nm, contingent on the number of layers) and aspect ratios (ranging from 100 to 1000) [5]. MWCNTs exhibit high tensile strength (50-200 GPa) and Young's modulus (1 TPa), which significantly impact the fundamental properties of concrete [5]. This is primarily due to their capacity to function as crack bridges, thereby inhibiting the propagation of microcracks within the matrix [5,6]. Consequently, they enhance various characteristics of concrete, including compressive and tensile strength, as well as crack resistance. Research indicates that the incorporation of carbon nanotubes (CNTs) in concentrations ranging from 0.01% to 0.5% by weight of cement can enhance compressive strength by up to 30% [7,8]. While this finding highlights the potential for improved material properties, a critical area of inquiry is the optimal aspect ratio of multi-walled carbon nanotubes (MWCNTs) in concrete. Variations in the diameters and lengths of MWCNTs can differentially affect the mechanical properties, such as compressive, tensile, and flexural strengths, of cement-based materials, including concretes and mortars. Notably, modifications in the diameter of the nanotubes can significantly influence their compressive characteristics [9,10,11,12]. However, there is a scarcity of studies examining the impact of different aspect ratios (length-to-outer diameter) of MWCNTs on the mechanical properties of concrete. This paper investigates the influence of various aspect ratios of CNTs on the compressive strength of concrete and the optimal concentration of three types of MWCNTs by weight of cement.

Materials and Methods

Materials

Ordinary portland cement with the class 52.5 (M500) made and fabricated by the Factory of Ararat Cement, was used as a binder in the concrete mixture. For the selected cement, sand, and coarse aggregate physical and mechanical properties are detailed in Tables 1, 2, and 3, respectively [5]. Figure 1 illustrates three MWCNTs (TNM2, 3, 7) with different lengths and outer diameters, which were procured from Zhengzhou University, China, and synthesized via the chemical vapor deposition (CVD) method. The requisite technical properties of the MWCNTs are presented in Table 4.

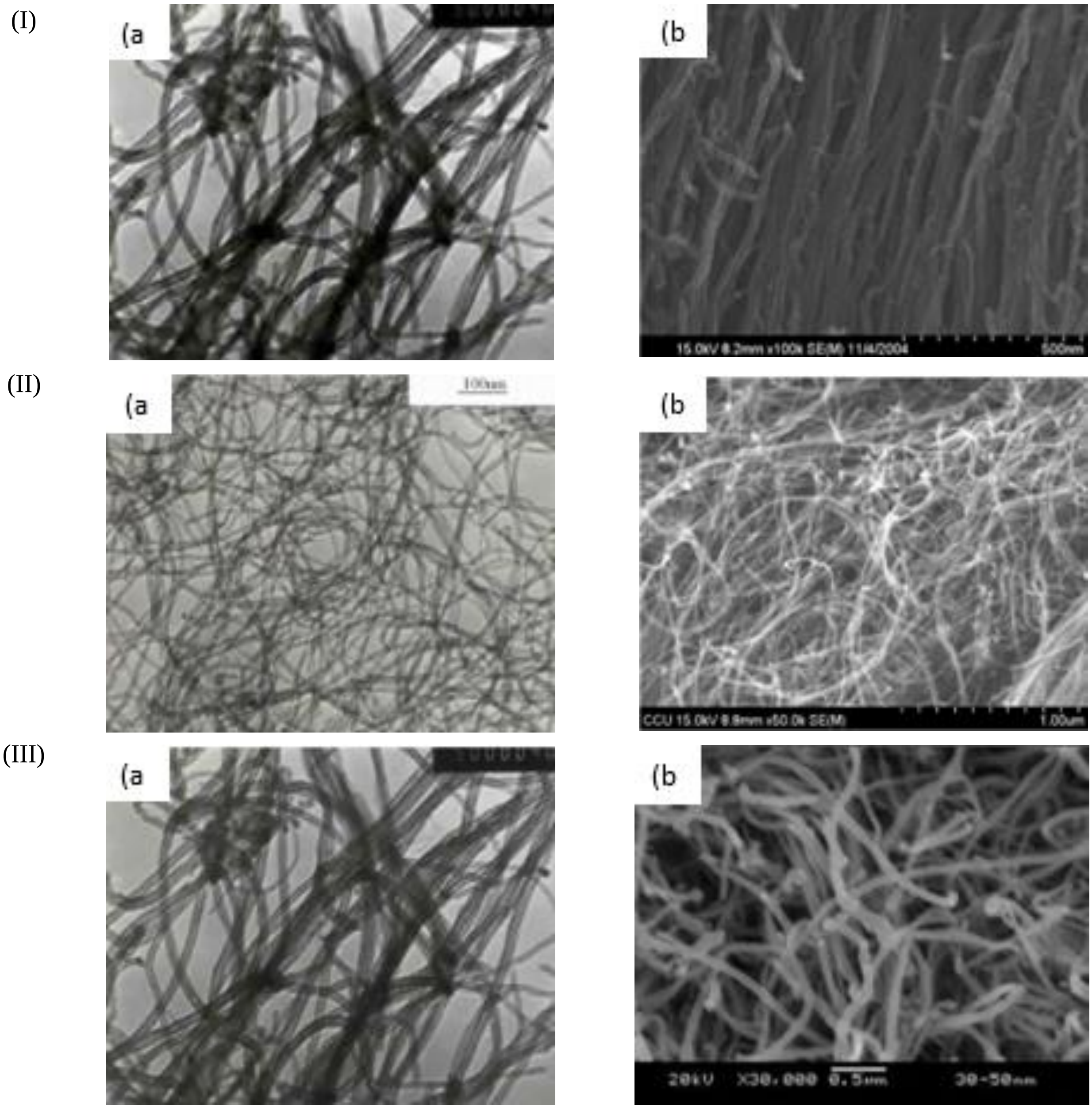

Fig. 1. *(a) Transmission Electron Microscopy (TEM), (b) Scanning Electron Microscopy (SEM) of I) TNM2, II) TNM3, III) TNM7*

Table 1. Physival and mechanical properties and chemical composition of portland cement

(a) [5]			(b) [5]	
Physical and mechanical properties of porland cement (Class 52.5)			Chemical composition of porland cement (Class 52.5) (wt.%)	
Characteristics		Testing results	SiO_2	21.6
Standard consistency (%)		27	Al_2O_3	4.5
Specific gravity (g/cm^3)		3.1	Fe_2O_3	2.2
Blaine fineness (m^2/kg)		328.3	MgO	1.1
Compressive strength of cement specimens (MPa)	3 curing days	20	CaO	61.9
	7 curing days	36	SO_3	2.1
	28 curing days	52	Loss on ignition	3.2
Setting time (min)	Initial	45	Insol. Resid.	1.9
	Final	315	Free CaO	1.5

Table 2. Physical properties of Coarse aggregate

Particle diameter (mm)	Specific gravity (kg/m^3)	Bulk density in Loose state (kg/m^3)
5-10	2650	1830

Table 3. Physical properties of sand (fine aggregate) [5]

Fineness modulus (FM)	Specific gravity (kg/m^3)	Bulk density (Loose state) (kg/m^3)	Bulk density (Compact state) (kg/m^3)
3.4	2450	1700	1925

Table 4. Technical datas of MWCNT

TNM2			TNM3			TNM7		
Outer diameter 8 – 15nm	Length ~50μm	Purity >95wt%	Outer diameter 10– 20nm	Length 10 - 30μm	Purity >98wt%	Outer diameter 30 – 50nm	Length < 10μm	Purity >98wt%

Dispersion of MWCNTs

Various techniques for dispersing MWCNTs have been reported in the literature. In this study, MWCNTs were continuously mixed with water using ultrasonic dispersion. The sonication process was conducted with the ultrasonic device UP400S under ambient temperature conditions for 30 minutes. To enhance the simultaneous plasticizing and dispersing effects of MWCNTs, Mapefluid N200 was employed. The dispersion was performed across all types (TNM 2,3,7) and concentrations (0.05, 0.1, 0.15, 0.2 wt.%) of MWCNTs selected for this research. The mobility and workability of concrete, including those incorporating multi-walled carbon nanotubes, are critical technological attributes that significantly influence the stability and operational characteristics of the material. To enhance these properties, a plasticizing chemical additive can be introduced into the concrete mix to reduce water consumption. In this study, we employed the Italian-manufactured superplasticizer "Mapefluid N200." This product is a 40% active polymer solution that improves concrete strength, decreases water permeability, enhances durability with reduced water usage, and imparts the necessary plasticity to the concrete mix. The solution is brown and constitutes 0.5% to 1.5% of the cement mass in the concrete. According to the provided data, its density is (1.20 ± 0.03) g/cm^3 at 20°C. The solution is free of chlorides and has an alkali content (Na_2O equivalent) of less than 6.0%, ensuring its safety for human use. The superplasticizer is available in containers with capacities of 10 kg, 25 kg, and 200 liters.

Mixing and Sample Preparation

The water-cement, cement-sand, and cement-coarse aggregate ratios applied in this research were 0.45, 0.58, and 0.47, respectively. Ordinary portland cement with a mixture of MWCNTs, superplasticizer, and water was blended using a 1400W handheld electric concrete mixer for 2 minutes. During continuous mixing, the sand and coarse aggregate, already in a mixed state, were added gradually and blended for an additional 5 ± 1 minutes. Specimen cubes with outer dimensions of 100 mm × 100 mm × 100 mm were selected. A vibrating table was employed for approximately 30 seconds to vibrate the molds of the samples. The mixing and preparation process for ordinary concrete (without MWCNTs) was carried out in the same manner as the composite concretes. After 24 hours, the composite samples were demolded and placed into a curing tank at a temperature of (20 ± 2)°C and (95±2)% humidity (Fig. 2).

Fig. 2. *Sample preparation steps, curing and testing processes*

Experiment. Compressive Strength Testing

To assess the average compressive strength of MWCNTs concrete, three specimens were prepared for each batch and evaluated using the automatic Compression Machine (C089) (Matest, Treviolo, Italy) 2000 kN Servo-Plus Progress, in accordance with the standard GOST 10180-2012[1]. The testing of specimens with dimensions of 100 mm × 100 mm × 100 mm was conducted at a loading rate of 0.6 MPa/s at a curing age of 7 days, as per the same standard[2].

Results and Discussion

Figure 3 presents the compressive strength of concrete incorporating three types of purified MWCNTs, categorized as TNM 2, 3, and 7, and varying MWCNTs percentages by weight of cement over 7 days. For the three types of carbon nanotubes, the designations C0, C1, C2, C3, and C4 correspond to 0%, 0.05%, 0.1%, 0.15%, and 0.2% of nanotubes by weight of cement, respectively.

According to the test results shown in Figure 3, the reference sample (C0) exhibited a compressive strength of 60.7 MPa at the 7-day curing age. The following results occurred when concrete mixtures were treated with various quantities of MWCNTs: compressive strength of the concrete increased by 9.41% for TNM2 at 0.2 wt.%, compared to the compressive strength of the reference sample (C0), 2.80% for TNM3 at 0.05 wt.%, and 12.13% for TNM7 at 0.05 wt.%.

As illustrated in Figure 3, the compressive strengths of the selected material composition structure attain their peak values at varying percentages of MWCNTs by weight of cement. Specifically, the data presented in Figure 3a (TNM2) demonstrate that, for a high aspect ratio (approximately 4347), the compressive strength increases with the rising percentage of MWCNTs in the concrete. In contrast, for a small aspect ratio (approximately 250) of nanotubes, as depicted in Figure 3c (TNM7), the compressive strength diminishes beyond 0.05 wt. %. A comparable pattern is evident in Figure 3b (TNM3). However, upon comparing TNM3 and TNM7, in the case of TNM3 the experimental results are approximately analogous, with minimal differences between C0 and C1.

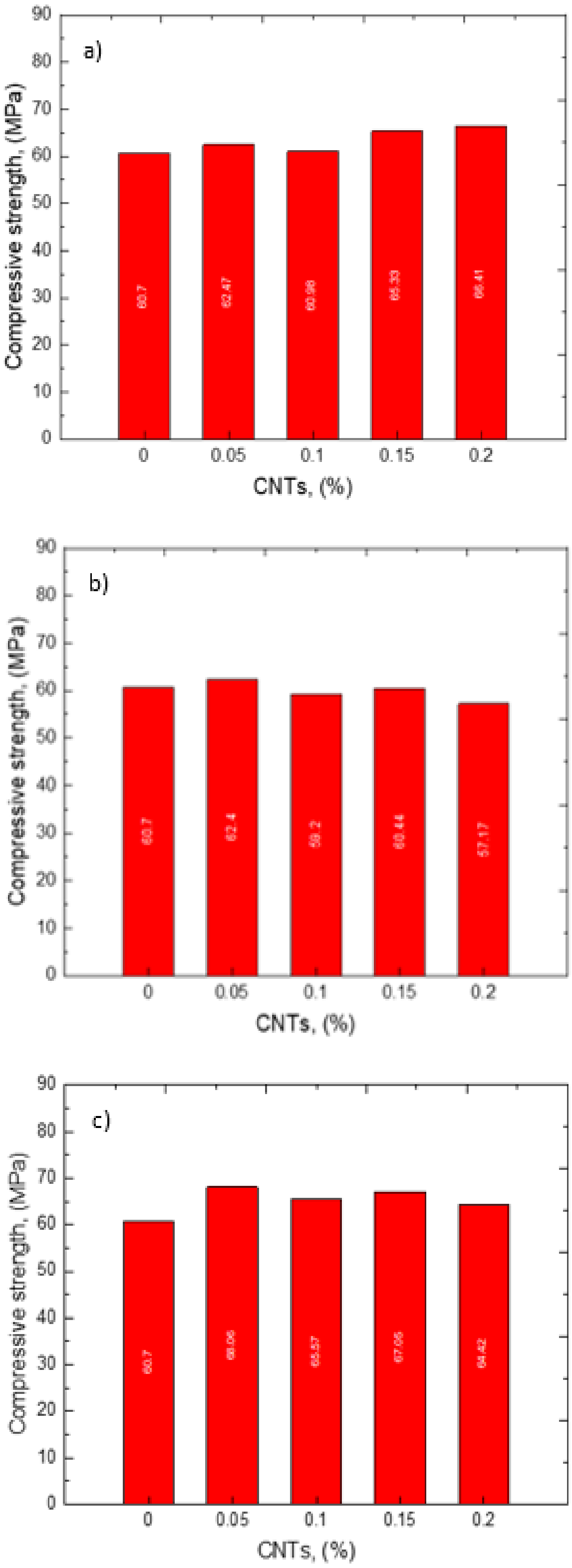

Fig. 3. *Compressive strength of concretes with different amount and types of nanotubes for 7 curing days, (a) TNM2, (b) TNM3, (c) TNM7*

[1] GOST 10180-2012. Betony. Metody opredeleniya prochnosti po kontrol'nym obraztsam. Moscow, Standartinform. 2018.

[2] Ibid.

For all types of multi-walled carbon nanotubes (MWCNTs), the results can be analyzed separately. Based on the references reviewed and the test results, there are significant differences in how various diameters and lengths of MWCNTs affect the compressive strength of concrete [9,10,11,12]. MWCNTs with a smaller diameter and a higher aspect ratio provide better filling and have a more effective reinforcing influence within the matrix, provided that the dispersion process is carried out well [9,10]. As shown in Fig. 3a, there is no evidence of agglomeration. Additionally, it's important to mention that the sonication time and power can damage the particles, possibly reducing their length to less than 50 μm.

In the case of nanotubes with a small aspect ratio, the dispersion effect is more favorable; however, the filling properties and specific surface area are low, which generally decreases the interaction between the nanocarbon and the cement matrix. Some pore structure test results indicate that porosity increases with the diameter of the nanotubes, which can affect the compressive strength of the specimen. In contrast, smaller-diameter multi-walled carbon nanotubes (MWCNTs) effectively increase pore size distribution and reduce porosity in concrete.

Conclusion

This paper investigates the effect of the aspect ratio of different carbon nanotubes on the compressive strength of cement-based concrete. The experimental results show that the average compressive strength of concrete samples cured for 7 days reaches its maximum at varying concentrations of nanotubes, depending on the type of MWCNTs used. Specifically, the compressive strength increased by 9.41% for TNM2 at 0.2 wt.%, 2.80% for TNM3 at 0.05 wt.%, and 12.13% for TNM7 at 0.05 wt.%. For samples with a higher aspect ratio (approximately 4347), an increase in the concentration of nanotubes (0.05%, 0.1%, 0.15%, and 0.2%) results in an enhancement of compressive strength. In contrast, for samples with smaller aspect ratios (approximately 250), the compressive strength decreases after reaching a concentration of 0.05% nanotubes. These results can be explained by considering several factors, including the filling effect of nanotubes, effective reinforcement within the concrete matrix, good dispersion, the agglomeration effect, sonication time, and the distribution of porosity and pore size in the concrete. These findings support the development of nano-engineered concrete with improved early strength for structural and precast construction applications.

Conflict of Interest

The authors declare no conflicts of interest.

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