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RESEARCH ARTICLE

Application of Carbon Nanotube (CNT) to Improve Mechanical Properties of Concrete: A Comparative Analysis with Superplasticizer

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Abstract

Many researchers' interest in carbon nanotube (CNT) materials has grown as a result of their potential use in the construction industry. This is mostly related to the mechanical, electrical, thermal, kinetic, and chemical properties of CNT, which have a big impact on the way concrete functions. Hydrated calcium silicate is a complex network of binding particles that compose the cement composite material known as concrete. Since it has nanoscale features, CNT will interact most strongly with hydrated calcium silicate, improving the concrete's mechanical qualities. The purpose of this study is to ascertain the impact of adding CNT to concrete mixtures. Three distinct mixes were created by varying the types and amounts of admixtures that were added to the concrete mix. Two mixed variations employed CNT at various doses, while one mixed variation used admixture type F (superplasticizer), and the performance of one was compared to the other. Concrete that was both new and hard underwent specimen testing. On fresh concrete, a slump test was conducted using ASTM C163, while for hard concrete, cylindrical specimens measuring 100 mm x 200 mm were tested for unit weight and compressive strength at 7, 14, and 28 days following ASTM C39. According to the test results, utilizing CNT at a lower dose than the typical superplasticizer dose leads to greater workability and compressive strength. The results of the workability and compressive strength tests will be improved by the inclusion of CNT.

Keywords: Carbon nanotube (CNT), Mechanical property, Compressive strength, Unit weight, Superplasticizer

1. Introduction

Concrete is the primary building material utilized in infrastructure development nowadays. Concrete has a high compressive strength in addition to being relatively inexpensive, and there is still plenty of room for performance advancement (Faraj et al., 2022; Faried et al., 2021). The creation of materials on a nanoscale using nanotechnology is one of the new building materials still being developed (Chong, 2004; Lee et al., 2018). In the domains of science and engineering, nanotechnology has made a substantial contribution (Hussain et al., 2022). In the field of nanoscience, the use of carbon nanotubes (CNT) has been regarded as a novel and remarkable material with numerous potential applications in the building sector (Ganesh, 2013; Yang, 2023). Materials that were previously created in bulk are scaled down to the nanoscale scale (100 nm) to change their functionality, attributes, and traits (Morsy et al., 2011; Sinha & Yeow, 2005). Previous studies have demonstrated that reinforcing concrete with nano-scale materials, such as carbon nanotubes (CNTs), has the potential to enhance mechanical strength, crack resistance, and durability (Ahmed et al., 2019; Cui et al., 2022).

CNTs are carbon-based nanostructures characterized by their cylindrical shape formed from rolled graphene sheets. They exhibit diameters on the nanometres scale and lengths ranging up to micrometers (Popov, 2004). CNTs are primarily classified into two main types: single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs), each possessing distinct structural, physical, and chemical properties (Ganesh, 2013b; Jung et al., 2019; Kim et al., 2016). SWCNTs are composed of a single layer of curved graphene, consisting of two key components: the cylindrical sidewalls and the end caps (Jung et al., 2020). In contrast, MWCNTs are formed by concentrically nesting multiple SWCNTs of varying diameters, resulting in significant differences in length, diameter, and physical-chemical properties between the two types (Jung et al., 2019; Kim et al., 2016). The one-dimensional structure of CNTs governs their electrical, chemical, and structural characteristics, which in turn influence the overall performance of the material. (Reza et al., 2004; Wang et al., 2004; Zaheer, 2020)

In cement composites, carbon nanotubes (CNTs) serve as reinforcing materials that enhance compressive and tensile strength, resistance to microcracking, permeability, and durability against environmental degradation (Ahmed et al., 2019; Cui et al., 2022; Hassan et al., 2019)). Additionally, CNTs improve thermal and electrical conductivity within the cement matrix, enabling applications in electrically conductive concrete and smart structural materials (Jung et al., 2020; Kim et al., 2016). They also strengthen the interfacial bonding between cement paste and aggregates while accelerating the cement hydration process, resulting in superior mechanical performance compared to conventional concrete (Liew et al., 2016; Mohsen et al., 2019). By leveraging nanotechnology, CNTs can enhance the structural sustainability, volumetric stability, durability, and mechanical performance of cement-based materials, paving the way for the development of cost-effective, high-performance, and long-lasting cement products that have the potential to revolutionize the construction sector (Adhikary et al., 2021; Micheli et al., 2014; Najaf et al., 2022; Wang et al., 2004).

Calcium silicate hydrate (C-S-H), as a complex network of binding particles, serves as the primary component of concrete, a cement-based composite material. The mechanical properties of concrete can be significantly enhanced through the incorporation of carbon nanotubes (CNTs), which interact strongly with C-S-H due to their nanoscale characteristics (Kekez & Kubica, 2020). CNTs effectively fill the microvoids present in conventional concrete, which are typically susceptible to water infiltration and contribute to material brittleness. By preventing water penetration through microcracks, CNTs improve the water-resistance of concrete (Siahkouhi et al., 2021). The performance enhancement of concrete by CNTs is achieved through both chemical and physical interactions with cement compounds. CNTs act as nucleation sites for C-S-H crystal growth by reacting with calcium hydroxide ($Ca(OH)_2$), thereby increasing the density and cohesion of the concrete's microstructure (Ahmed et al., 2019; Cui et al., 2022). Furthermore, CNTs function as nanoscale bridges that connect the cement matrix and the interfacial transition zone (ITZ), reducing porosity and enhancing the cohesion between cement particles, which in turn improves the mechanical properties of concrete (de Morais et al., 2013). The interaction between oxygen-containing functional groups on the surface of CNTs and ions in the cement paste promotes hydration and results in a more uniform distribution of hydration products (Jung et al., 2020). Proper dispersion of CNTs within the cement matrix not only enhances thermal conductivity and electromechanical properties but also facilitates applications in structural health monitoring and damage detection (Kekez & Kubica, 2020; Kim et al., 2016). Consequently, the integration of CNTs into concrete offers substantial improvements in mechanical performance, durability, and functional versatility, making it a promising advancement in construction materials.

Based on previous studies, the optimal dosage of carbon nanotubes (CNTs) in concrete mixtures typically ranges from 0.02% to 0.5% by weight of cement, depending on the type of concrete and its intended application. Adhikary et al., (2021) recommend a dosage of 0.1%-0.5% to enhance the mechanical and thermal properties of lightweight concrete, while Jung et al. (2020) found that 0.1%-0.3% is optimal for ultra-high-performance concrete (UHPC) to improve strength and electromagnetic interference (EMI) shielding effectiveness. Kim et al. (2016), reported that a dosage of 0.5% accelerates curing and reduces thermal cracking, whereas Morsy et al. (2011) suggested 0.02%-0.08% to enhance the mechanical strength of mortar. In general, lower dosages (0.02%-0.1%) are more suitable for improving mechanical properties, while higher dosages (0.1%-0.5%) are used for specialized applications such as electrical conductivity or EMI shielding (Adhikary et al., 2021; Jung et al., 2020; Kim et al., 2016; Morsy et al., 2011).

This study aims to create the best-performing concrete mix design with the addition of CNT. By varying the types and amounts of admixtures that were added to the concrete mix, three distinct mixes were created. Two mixed variations employed CNT in various quantities, while one mixed variation used type F admixture (superplasticizer).

2. Material and Method

2.1 Portland Cement and Fly Ash Characteristic

Fly ash was obtained from the BSW Power Plant in Jeneponto, South Sulawesi, and portland cement came from a cement plant in Maros, South Sulawesi. Physical and chemical tests are used to determine the characteristics of fly ash and ordinary portland cement (OPC) as a binder. The test results serve as the foundation for a design and are utilized to regulate the outcomes of the concrete mix design. The chemical composition of Portland cement and fly ash was examined using an XRF (X-ray fluorescence) chemical characteristic assay. The purpose of this test is also to ascertain the chemical composition of the key component utilized to create concrete mixtures. The findings of evaluating the physical and chemical properties of fly ash and Portland cement are displayed in Tables 1 and 2. The test results were published by the cement manufacturer. To ascertain whether cement might be utilized as a study's binder material, an analysis of cement's physical and chemical properties was performed. Concrete quality is influenced by cement quality.

Table 1. Physical characteristics of OPC and fly ash

Properties	Unit	OPC	Fly Ash
Autoclave expansion	%	0.12	-
Fineness	m^2/kg	345	-
Compressive strength			
a. 3 days	kg/cm^2	190	-
b. 7 days	kg/cm^2	270	-
c. 28 days	kg/cm^2	362	-
Setting time			
a. Initial Set	Minute	124	-
b. Final Set	Minute	258	-
False set, final	%	83.59	-
Air content	% vol.	4.49	-
Specific gravity	-	3.24	-
Sieve analysis	-	-	92% pass no.200

Table 2. Chemical characteristics of OPC and fly ash

Compound	Unit	OPC	Fly Ash
MgO	%	1.49	-
SO_3	%	2.13	-
SiO_2	%	-	45.56
Al_2SO_3	%	-	14.55
Fe_2O_3	%	-	11.83
$SiO_2 + Al_2SO_3 + Fe_2O_3$	%	-	71.94
CaO		-	12.74
Loss on ignition	%	2.47	0.30
Insoluble residue	%	1.24	-
Alkalis	%	0.38	-

Based on Tables 1 and 2, it is evident that the Portland cement utilized complies with the specifications outlined in ASTM C150. Furthermore, following ASTM C618-12, the fly ash employed is classified under category F. Both the Portland cement and fly ash used in this study have been previously evaluated in prior research on foam concrete. (Sunarno et al., 2022; Sunarno et al., 2024a; Sunarno et al., 2024b)

2.2 Aggregate Characteristic

The crushed stone employed in this study is made at a stone crusher factory in Gowa Regency, South Sulawesi, using raw materials from the Bili-Bili river. It is clear that the coarse aggregate utilized complies with ASTM C33 requirements in terms of its physical qualities. Silica sand from local river in Pinrang, South Sulawesi, is used as the fine aggregate. The physical parameters of the fine aggregate utilized, which complies with ASTM C33 requirements, are shown in Table 3.

Table 3. Physical characteristics of aggregate

Properties	Coarse Aggregate	Fine Aggregate
Colloid content (%)	0.51	3.09
Fineness modulus/FM	6.96	2.71
Water absorption (%)	0.79	2.95
Specific gravity, SSD	2.59	2.57

2.3 Chemical Admixture Characteristic

This study utilized two distinct types of chemical admixtures. The first, Celchem 75 RS superplasticizer (adm-1), was used as the control specimen and functioned as a water reducer. The second admixture, Edencrete Pz (adm-2), is a CNT-enhanced liquid admixture designed to strengthen and improve the durability of the concrete mixture through its pozzolanic properties. Table 4 provides a detailed description of the characteristics of each admixture sourced from the test data of the producers, PT Bosowa Beton Indonesia and Edencrete.

Table 4. Characteristics of admixture

Properties	Adm-1	Adm-2
Base material	Sulfonated naphthalene	Carbon nanotube
Chemical type	Type F	Type S
Appearance	Dark brown	A black, opaque
Physical state	Liquid	Liquid
Specific gravity	1.17 g/ml	1.03±0.02 g/mL
Identified use	Very high workability – high water reducing – low shrinkage and creep	Improves early strength development in mixes using fly ash, higher ultimate strength
Dosage	0.4-1.5 kg/100 kg cementitious	0.2-1.2 L/m3 concrete

Table 5. Mixed design composition (per m^3)

Material	Mixture		
	MD-1	MD-2	MD-3
Cement, kg	405	405	405
Fly ash, kg	173	173	173
Coarse Agg.	1020	1020	1020
Fine Agg., kg	560	560	560
Water, l	185	185	185
Admixture-1, l	2.00	-	-
Admixture-2, l	-	0.30	0.50

2.4 Mix Design

The mix design made in this study was for concrete grade fc40 using the method C94/C94M of Standard Specification for Ready-Mixed Concrete. Three combination variations with different admixtures added to the concrete mix make up the mixed design. A superplasticizer based on sulfonated naphthalene (adm-1) was used in MD-1 at a dose of 2.00 liters per m3 of concrete, CNT admixture was used in MD-2 at a dose of 0.30 liters, and CNT admixture was used in MD-3 at a dose of 0.50 liters.

2.5 Concrete Test

Concrete tests were conducted on the concrete, both in fresh and hardened concrete conditions. As illustrated in Figure 1A, the slump test on fresh concrete was conducted in accordance with ASTM C143 criteria. For the hardened concrete tests, cylindrical specimens with dimensions of 100 mm x 200 mm were prepared and subjected to water immersion curing. The reason for choosing 100 mm x 200 mm specimens is based on the limited capacity of laboratory mixers, ease of handling due to lighter weight, and simpler casting and curing processes. Additionally, using the same batch volume was able to produce more than 150 mm x 300 mm specimens, thus reducing the variability in the test results. These specimens underwent unit weight and compressive strength tests at ages 3, 7, and 28 days. The compressive strength was evaluated using a compression testing machine, following ASTM C39 standard method as shown in Figure 1B.

Fig. 1. (A) Slump Test (B) Compressive test

3. Results and Discussion

3.1 Workability of Fresh Concrete

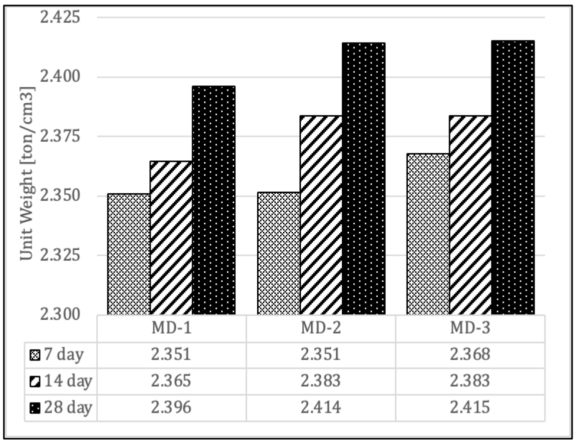
For each of the employed mixtures, Figure 2 displays the value of the fresh concrete slump test results. The slump values for MD-1, MD-2, and MD-3 were 125 mm, 130 mm, and 140 mm, respectively, based on the data from the results of the slump tests for each mixture. This outcome demonstrates the potency of CNT in lowering water consumption. It shows out to generate a larger slump with smaller admixture doses in MD-2 and MD-3 compared to MD-1. The fresh concrete mixture from each mixture is sticky, avoiding segregation or bleeding, according to visual inspection.

CNT are effective in concrete mixtures at the nano scale, providing positive effects on workability even at very low doses. Their dispersion properties facilitate the uniform distribution of aggregates within the mix, thereby reducing friction between cement particles and aggregates. As a nano-lubricant, CNT enhance mobility in the concrete mixture, resulting in improved slump values. This advantage positions CNT as superior in reducing the viscosity of concrete at the molecular level compared to superplasticizers, which operate on a larger scale. Additionally, CNT act as nano-fillers that occupy small voids between cement and aggregate particles, leading to a more cohesive and uniform mixture. This nano-scale filling enhances particle flow, contributing to an overall improvement in the concrete structure. Due to their large surface area, CNT can achieve these results with lower dosage requirements, while superplasticizers often necessitate higher doses to attain similar effects. The efficacy of CNT at low doses makes them an efficient choice for enhancing both the workability and overall quality of concrete mixtures.

Fig. 2. The slump test results for each mixture

3.2 Unit Weight

According to Figure 3, the unit weight of concrete varies from 2.351 to 2.409 ton/m^3. At 7, 14, and 28 days old, MD-1 has the lowest unit weight values (ton/m^3), which are 2.351, 2.365, and 2.396, respectively. In contrast, the unit weight values (ton/m^3) for the MD-2 specimens are 2.351, 2.383, and 2.414. The unit weight (ton/m^3) values for the MD-3 specimen are 2.368, 2.383, and 2.415. Based on the unit weight values of all specimens, between 2.351 tons/m3 and 2.415 tons/m^3, the concrete is categorized as normal specific gravity concrete as per ACI 318-11 standard. With older concrete age, the unit weight will be higher.



	MD-1	MD-2	MD-3
▨ 7 day	2.351	2.351	2.368
▧ 14 day	2.365	2.383	2.383
■ 28 day	2.396	2.414	2.415

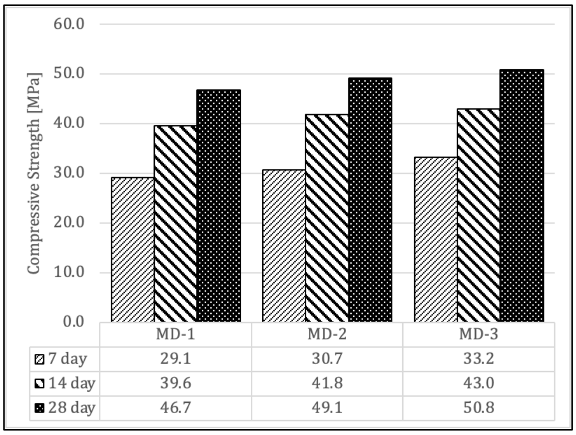
Fig. 3. Unit weight value of the test specimen

Carbon Nanotubes (CNT) can achieve significant increases in concrete unit weight with very low dosage levels, making them a more efficient choice for enhancing concrete unit weight without adding excessive weight. However, based on the results of this study, increasing the dosage of CNT did not increase the unit weight value. In contrast, superplasticizers typically require higher doses to achieve the desired outcomes. CNT enhance unit weight by improving the microstructure of concrete, whereas superplasticizers primarily focus on reducing water content to increase aggregate unit weight. This implies that CNT not only contribute to unit weight but also enhance the strength and durability of the concrete.

Thus, both CNT and superplasticizers significantly affect concrete unit weight, albeit through different mechanisms. CNT provide advantages in dosage efficiency and improvements in microstructural integrity, while superplasticizers are more effective in reducing water requirements and increasing aggregate unit weight.

3.3 Compressive Strength

The results of compressive strength test on hard concrete at 7, 14, and 28 days are shown in Figure 6 for each kind of specimen. The results of the compressive strength test for MD-1 are 29.1, 39.6, and 46.7 MPa. They are 30.7, 41.8, and 49.1 on MD-2 and 33.2, 43.0, and 50.8 on MD-3, respectively. In comparison to other specimens at each curing age, MD-1 has the lowest average compressive strength value, whereas MD-3 has the highest average value. Based on Figure 4, the findings of the MD-2 and MD-3 demonstrate how applying a CNT-based admixture can improve the specimen's compressive strength. With a usage dose of 0.30 and 0.50 liters per m3 of concrete, it can produce a compressive strength of 49.1 and 50.8 MPa at 28 days of age. A dosage of 2 liters per m3 results in a compressive strength of 46.7 MPa when compared to MD-1.



	MD-1	MD-2	MD-3
▨ 7 day	29.1	30.7	33.2
▧ 14 day	39.6	41.8	43.0
■ 28 day	46.7	49.1	50.8

Fig.4. Compressive strength value of the specimen

Carbon Nanotubes (CNT) enhance the compressive strength of concrete through several mechanisms, primarily by acting as nano-fillers that fill the small voids between cement particles and aggregates. The incorporation of CNT at low dosages improves the interactions among particles, thereby reducing porosity and increasing the overall unit weight of the concrete mix. The addition of CNT can increase the compressive strength, this can be attributed to a better bonding mechanism among the particles within the concrete matrix.

In contrast, superplasticizers also contribute to enhancing the compressive strength of concrete, but typically achieve a smaller increase of around 20%, contingent upon the specific type and dosage used. Superplasticizers function by reducing the water content required in the mix and thereby improving the aggregate unit weight. However, their effectiveness in enhancing concrete's microstructure is not as pronounced as that of CNT. Thus, CNT provides significant advantages in terms of efficiency and performance, especially when utilized at low dosages, compared to superplasticizers, which necessitate higher dosages to achieve optimal results.

The results of this study indicate that increasing the dosage of carbon nanotubes (CNTs) in concrete mixtures enhances compressive strength, consistent with previous research findings. Adhikary et al. (2021) reported a 15-20% increase in compressive strength at CNT dosages of 0.1%-0.2%, while observed a 20-25% improvement at similar dosages. Jung et al. (2020) found that CNT dosages up to 0.3% were effective in ultra-high-performance concrete (UHPC), but higher dosages led to agglomeration and reduced performance. In general, dosages exceeding 0.3% are not recommended due to the risk of agglomeration and diminished concrete performance.

Table 6 presents the ratio of unit weight to compressive strength in concrete mixtures incorporating CNTs (MD-1 and MD-2) compared to conventional concrete (MD-0).

Table 6. Ratio of unit weight to compressive strength

Mixture	Ratio (kg/cm^2 per MPa)		
	7 days	14 days	28days
MD-1	80.8	59.7	51.3
MD-2	76.6	57.0	48.8
MD-3	7.1	56.1	47.5

The data presented in Table 6 indicate a decreasing trend in the ratio of unit weight to compressive strength for all concrete mixtures (MD-1, MD-2, MD-3) as the curing age increases from 7 to 14 and 28 days. This trend suggests that the rate of compressive strength development surpasses that of unit weight over time.

The incorporation of carbon nanotubes (CNTs) has a positive effect on concrete performance, as evidenced by the increase in both unit weight and compressive strength. This is reflected in the lower unit weight-to-compressive strength ratio observed in CNT-containing mixtures (MD-3 and MD-2) compared to the control mixture (MD-1) at the same curing age. These findings indicate that CNTs contribute more significantly to the enhancement of compressive strength than to the increase in unit weight.

4. Conclusions

Based on the workability tests conducted on fresh concrete, it can be concluded that the incorporation of CNT at dosages of 0.3 to 0.5 liters per m3 results in slightly higher slump values compared to a naphthalene-based superplasticizer (adm-2) at a dosage of 2 liters per m3. Additionally, an increase in CNT dosage correlates with an enhancement in slump values. In the evaluation of hardened concrete, the unit weight of concrete containing adm-2 was found to be greater than that of concrete using adm-1. A significant increase in compressive strength was observed with the use of adm-2, which demonstrated superior performance compared to adm-1, even at a dosage that was 15-25% lower. Further research is needed to obtain the optimal CNT composition to produce the highest concrete compressive strength.

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