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Performance Enhancement Of Concrete Using Carbon Nanotubes, Steel Fibers, And 100% Artificial Sand.

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Abstract: With the rising depletion of natural river sand and growing environmental concerns, artificial sand (AS) has gained attention as a sustainable replacement in concrete production. This study investigates how Carbon Nanotubes (CNTs) and Steel Fibers (SFs) can work together to enhance the mechanical properties of high-performance concrete made entirely with artificial sand. Concrete samples were prepared using CNTs at 1%, 2%, and 3% by weight of cement, alongside a fixed 5% volume of steel fibers. Standard tests for compressive, flexural, and splitting tensile strength were conducted to evaluate performance. The results revealed a notable improvement in strength and post-cracking behaviour due to the hybrid reinforcement. The mix containing 2% CNTs offered the most consistent improvement across all metrics. However, at 3% CNTs, reduced workability and strength gains were observed, likely due to nanoparticle agglomeration. Steel fibers played a key role in improving crack resistance and enhancing flexural toughness across all concrete batches. Overall, the combination of CNTs and SFs proved to be a promising solution for developing sustainable, high-performance concrete using artificial sand.

Index Terms - Carbon Nanotubes (CNTs), Steel Fibers (SFs), Artificial Sand (AS).

I. INTRODUCTION

Concrete is one of the most extensively used construction materials, accounting for approximately 70% of the volume in most structures. While cement is a critical component of concrete, it poses environmental concerns due to high carbon emissions during production. Recent research efforts aim to reduce cement content and improve concrete performance through innovative technologies—most notably, nanotechnology.Nanotechnology enables the manipulation and control of materials at the nanoscale (1–100 nm), where materials often exhibit unique physical, chemical, and mechanical properties. At this scale, concrete can be treated as a nanostructured, heterogeneous material whose behaviour can be significantly altered by the addition of nanoparticles.

1.1 Carbon Nanotube (CNTs)

A carbon nanotube (CNT) is a tube made of carbon with a diameter in the nanometre range (nanoscale). They are one of the allotropes of carbon. Two broad classes of carbon nanotubes are recognized

- **Single-Walled Carbon Nanotubes (SWCNTs)** have diameters around 0.5–2.0 nanometres, about 100,000 times smaller than the width of a human hair. They can be idealised as cut-outs from a two-dimensional graphene sheet rolled up to form a hollow cylinder.

- **Multi-Walled Carbon Nanotubes (MWCNTs)** consist of nested single-wall carbon nanotubes in a nested, tube-in-tube structure. Double- and triple-walled carbon nanotubes are special cases of MWCNT.

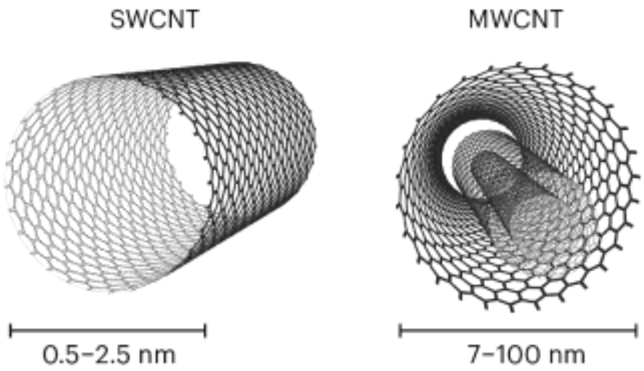

Fig. 1. SWCNTs And MWCNTs.

Carbon nanotubes can exhibit remarkable properties, such as exceptional tensile strength and thermal conductivity because of their nanostructure and strength of the bonds between carbon atoms. Some SWCNT structures exhibit high electrical conductivity while others are semiconductors. In addition, carbon nanotubes can be chemically modified. These properties are expected to be valuable in many areas of technology, such as electronics, optics, composite materials (replacing or complementing carbon fibres), nanotechnology (including nanomedicine), and other applications of materials science. Due to their exceptional tensile strength, electrical conductivity, and Nano-scale structure, are particularly effective in modifying concrete's microstructure. When properly dispersed, CNTs enhance mechanical performance, reduce microcracks, and improve durability. Key properties of Multi-Walled CNTs include high purity (95%), nanoscale diameter (20–30 nm), and high surface area (90–350 m^2/g).

Fig. 2.Carban Nanotubes (CNTs).

1.2 Steel Fiber (SFs)

Steel fibers are short, discrete strands of steel that are added to concrete as a form of micro-reinforcement. They typically range from 0.25–1 mm in diameter and 10–60 mm in length, and are randomly dispersed throughout the concrete mix. Their primary purpose is to enhance the tensile strength, toughness, and crack resistance of the concrete, particularly under dynamic or impact loads. Steel fibers can be made from carbon steel, stainless steel, or recycled materials, and they come in various shapes such as hooked, crimped, straight, or corrugated. When properly distributed in concrete, these fibers bridge microcracks, delay crack propagation, and improve post-cracking ductility.

Fig. 3.Steel Fiber (SF).

1.3 Artificial Sand (AS)

Artificial Sand (AS), also known as manufactured sand (M-sand), is a fine aggregate produced by mechanically crushing hard stones such as granite, basalt, or quartzite. It is used as a replacement for natural river sand in concrete and construction applications due to increasing scarcity, environmental regulations, and the high cost of natural sand.

Fig. 4.Artificial Sand (AS).

1.4 Objective of Carbon Nanotubes and Steel Fiber in Concrete

- Enhance compressive strength using CNTs due to their high surface area and aspect ratio.
- Improve flexural and tensile strength through crack-bridging action of steel fibers.
- Increase ductility and toughness by combining CNTs and SFs for better energy absorption.
- Reduce microcracks and macrocracks, enhancing crack resistance.
- Improve durability by minimizing shrinkage cracks and increasing resistance to corrosion and thermal stresses.

II. LITERATURE REVIEW

There have been various experimental and theoretical investigations performed on the topic of Carbon nanotubes and steel fiber. Some of the experimental studies performed in this field are presented in the following literature review.

Vidivelli B, Ashwini B (2018). This paper discusses with the review of Carbon Nanotube (CNT) from various literature which are integrating Carbon Nanotube as 0.15% to 2.5% on strength characteristics and durability of the concrete. Sonication process is carried out by adding the CNT with surfactants by weight of cement or water. It is obtained from the various literature explains ultrasonic dispersion techniques were adopted to disperse them uniformly. Tensile, compressive strength, durability and bending tests have been conducted on the specimens in the past experimental program. This paper presents the methodologies and results in reference to various research papers on similar experiments. Moreover, this paper is discussed based on to enhance the above given properties.

M.S. Khan, A. Fuzail Hashmi, M. Shariq, S.M. Ibrahim (2023). For a decade, attempts have been made to induce ductility into concrete; fibre-reinforced concrete is one such attempt. Adding fibres to concrete enhances the material's post-cracking strength due to the bridging effect of the fibres. In tunneling, fibres are preferred over reinforcement because they provide all-around reinforcement for the concrete and lessen the risk of concrete spalling. Different types of fibres exist, like steel, glass, polypropylene, and more. However, more research is conducted on steel fibre-reinforced concrete among the mentioned fibres. Steel fibre has various effects on the strength and properties of concrete. The impact of steel fibres on the mechanical characteristics of fibre-reinforced concrete is governed by a number of factors, including fibre geometry, fibre content, fibre orientation, and fibre distribution. Adding fibres reduces the workability of concrete but increases its hardening properties. Fibres enhanced the compressive strength of concrete marginally up to the optimal fibre content. Nevertheless, the flexure and splitting tensile strength increased linearly with increased fibre content. Some researchers noted that fibres oriented perpendicular to the crack arrests the crack more effectively than those oriented parallel to the crack. The literature evaluation indicates that more experimental and analytical research is required to create a technique that controls the orientation and distribution of fibres in concrete. Future research directions are also highlighted in this article for improving concrete's mechanical and structural characteristics via fibre-reinforced concrete.

MohamedSamir Eisa a, Ahmed Mohamady b, MohamedE. Basiouny a Ayman Abdulhamid a, Jong R. Kim (2023). Three different percentages of carbon nanotubes (CNTs) (0.1%, 0.5%, and 1% by mass of asphalt cement) were used to modify conventional asphalt cement (60/70) in this study. Mechanical properties of modified asphalt cement and mixture were evaluated. Penetration grade, kinematic viscosity, softening point and dynamic shear rheometer test were measured to evaluate physical properties of modified asphalt cement. The results exhibited that modifying asphalt cement with CNTs decreased its penetration and increased its kinematic viscosity and softening point. Rutting parameter increased with CNTs at the given temperature for both unaged and RTFOT-aged samples. Marshall stability tests, low temperature cracking tests, indirect tensile tests and wheel tracking tests were conducted to assess the mechanical performance of modified hot asphalt mixture. The Marshall stability increased with CNTs but no significant difference at 0.5 and 1.0 wt%, while Marshall flow decreased with CNTs. The results of wheel tracking test showed that rut depth decreased by 45% upon adding 0.5% CNTs by weight of asphalt cement; also, this percentage of CNTs endowed improvement in low temperature cracking and indirect tensile strength of the asphalt concrete. This study underlines that adding CNTs into asphalt cement enhances the performance of asphalt concrete pavement in both hot and cold weather, which in turn prolongs the pavement’s service life and saves maintenance expenses.

Jawad Ahmad a, Zhiguang Zhou (2023). The addition of carbon nanotubes (CNTs) in concrete has the potential to improve the strength, durability, and thermal characteristics of the concrete, resulting in more durable concrete. However, further study is required to properly understand the benefits and limits of CNT-based concrete. Therefore, this article's goal is to perform a rigorous evaluation of CNT-based concrete and to highlight the need for more research to improve the mechanical or durability features. All the crucial aspects of CNT, including its types, structure, preparation, physical and chemical properties, are reviewed. In addition, the flowability, durability, high-temperature performance, and morphology of CNT-based concrete are also reviewed. Results show that the CNT increased the concrete strength and durability. Additionally, with the inclusion of CNT, concrete performance at high temperatures improved. However, the addition of CNT caused a decline in concrete flowability due to agglomeration, particularly at higher doses. The majority of studies advise 0.10 percent (by weight of binder) as the ideal CNT dosage. The study also identifies the research gaps that need to be filled to further enhance the performance of CNT-based concrete.

Peng Zhang, Jia Su, Jinjun Guo, Shaowei Hu (2023). Carbon nanotube (CNT) has been increasingly used in concrete due to its good mechanical properties and electrical conductivity. Scholars around the world have carried out in-depth researches on carbon nanotube concrete (CNTC). Notably, they have proved that CNTs can play a variety of roles in concrete, such as bridging matrix cracks, filling internal pores and promoting cement hydration reaction. Based on these studies, different dispersion modes of CNTs are compared and the workability of CNTC is analyzed in this paper. At the same time, mechanical properties of CNTC including compressive strength, tensile strength, flexural strength and dynamic performance against impact are systematically reviewed. The durability of CNTC is also reviewed including chloride penetration resistance, carbonation resistance, sulfate resistance, impermeability, high temperature resistance and freezing-thawing resistance. In addition, the application of CNTs as conductive filler in concrete and analysis of the microscopic mechanism of CNTC are also summarized. The results show that the addition of CNTs will generally reduce the workability of concrete, but the pre-dispersed liquid CNTs relatively increase the liquidity. CNTs with OH group and nickeling have an outstanding enhancement on mechanical properties. COOH functionalized and shorter CNTs significantly improve the dynamic impact resistance of ultra-high-performance concrete. CNTs optimize internal pore structure and enhance interface transition zone (ITZ) to improve durability. At the same time, CNTC also shows good quality maintenance at high temperature, and its internal structure changes into a new form at 600 ℃. As self-sensing concrete, CNTC has good strain sensitivity and can be used to detect structures. In general, CNTC is a new building material with good application prospects. The review aims to help scholars systematically understand the action behavior of CNTs in concrete and may further promote the application of CNTC in practical projects.

P. Ramadoss a, L. Li b, S. Fatima c, M. Sofi d (2023). This paper presents the outcome of the investigation of high-performance steel fiber reinforced concrete (HP-SFRC) with water to binder ratio (w:b) of 0.30- 0.40. The binder included cement replacement of 10 and 15% by silica fume. Fiber volume fractions (Vf) of 0, 0.5, 1.0 and 1.5% with aspect ratios of 80 and 53 were used. The study aims to present the effect of the inclusion of micro-silica and steel fibers on the mechanical performance of HP-SFRC. Experimental results show that moderate increase in compressive strength and significant improvement in flexural strength of HP-SFRC at Vf = 1.5% (reinforcing index = 3.88) with 15% micro-silica replacement. Empirical expressions were developed for compressive and flexural strength of HP-SFRC as a function of steel fiber volume fraction. The power relation between flexural tensile and compressive strengths was developed with an integral absolute error of 6.39. Further, the validity of the proposed models was tested against published data. A machine learning framework was established based on an adaptive neuro-fuzzy inference system (ANFIS) to predict the compressive strength of HP-SFRC mixes with higher accuracy. Finally, a multiple linear regression (MLR) model is proposed for the strength of HP-SFRC mixes and tested against published data. The validity of the MLR model is checked with experimental results and it is shown that the model has good prediction cpability.

Jian Yang a b, Baochun Chen b c, Camillo Nuti d (2021). The compressive properties (include compressive strength and modulus of elasticity) of Ultra-high-performance fiber-reinforced concrete (UHPFRC) are the most important performance index in structural design. This paper presents experimental results from tests conducted on 36 UHPFRCs with different volume fractions and aspect ratios of steel fiber to investigate the effect of steel fiber on the compressive properties of UHPFRC. The test results indicated that the compressive strength and modulus of elasticity of the hardened UHPFRC increase as the fiber volume fraction or aspect ratio increases. However, the increase trend of compressive strength and modulus of elasticity slowed down when the volume fraction exceeded 2%. It was observed that the steel fiber can restrain the occurrence and development of cracks when UHPFRC specimens are compressed, provided a positive effect for reinforcing UHPFRC, but it also reduced the flowability of fresh UHPFRC, which is negative for reinforcing effect. X-ray CT scanning revealed that the porosity and pore size of hardened UHPFRC increased with the increase of the fiber volume fraction due to its weakened flowability. A prediction model was established based on the analysis of the positive and negative effects of the steel fiber. Semi-empirical prediction formulas for the compressive strength and modulus of elasticity were proposed by regression analysis of the test data in this paper, which were verified and revised by the experimental database of 155 tests from literature. In addition, a relationship formula between modulus of elasticity and compressive strength of UHPFRC was presented, and was verified and revised by the experimental database of 320 tests conducted around the world.

Jegatheeswaran Dhanapal, Sridhar Jeyaprakash (2019). The paper intends to analyze and study the features of steel fiber reinforced concrete (SFRC) and plain concrete that contains combined fibers of various aspect ratios. Experiments on works are held to examine the features of the new combination of concretes. Simultaneously, the characteristics of the concretes that are hardened are examined by performing tests on compressions, flexural strength tests, and split tensile strength (STS). It further verifies the effects of fibers when they are distributed in the hinged zone of structural components to obtain financial benefits by minimizing the ingredients in steel fiber in the concrete mix. The result shows that the combined reinforced concrete steel fiber can be employed as the better combination to be applied in SFRC for achieving strength in STS, and flexure. Anyhow, enhanced ability for working was achieved as more amounts of microfibers in mixed with concrete. And there is slight variation in the features of concrete between beam of fibers with full length and fibers which are available in hinged zone. Similarly, the categorization of neural network such as Neural Network–Levenberg–Marquardt (NN-LM) and Neural Network-Gradient Descent (NN-GD) is further used to perform the experimentation in an intelligent manner, which comes close to the actual values while calculating the mean absolute error (MAE) and root mean square error (RMSE) values.

Qinyuan Zhang, Wenwen Xu, Yichen Sun, Yongcheng Ji (2021) 9. This paper studied the microscopic and mechanical property degradation of axially compressed concrete with different steel fiber content under chemical erosion and freeze-thaw environment. Concrete cylinders with three types of steel fiber contents (0%, 1%, 2%) were selected to study the durability behavior concerning different environmental effects up to 28 days, which included tap water, 3.5% sodium chloride solution, 10% sodium sulfate solution, 5% sulfuric acid solution, 2 mol/L sodium hydroxide solution, and 100 freeze-thaw cycles. The variation of specimens' microstructure and axial bearing capacity with different fiber content was studied with the chemical erosion cycle increase, and the mass and pH variations of the specimen were measured. According to the law of micro-cracks, the deterioration degree was judged, and a numerical analysis model was established to quantify the reliability of the structure with different fiber content. The results show that the addition of steel fiber can effectively improve the axial bearing capacity of concrete, and a freeze-thaw environment and chemical erosion can accelerate fiber-reinforced concrete's failure. The optimal content of steel fiber was determined, which is 1% for sodium chloride and sodium sulfate environments, and 2% for the freeze-thaw cycle, dilute sulfuric acid, and sodium hydroxide environments. The finite element software Abaqus was used to simulate and analyze the freeze-thaw cycle and mechanical test of concrete, which verified the rationality of the test results. Research results will provide a theoretical basis for predicting the performance deterioration of steel fiber reinforced concrete under different erosion conditions and periods.

Abeer Hassan, Sameh Galal, Ahmed Hassan & Amany Salman (2022). Rigid pavements have become an urgent demand in recent years, as these pavements need less maintenance and renovation than other types. However, traditional rigid pavement faces various challenges and difficulties over its lifetime. It has a much higher initial erection cost than asphalt pavements, a greater sensitivity to dynamic stresses, and a highly susceptible to temperature variations causing cracking. Previous works dealt with these drawbacks by using effective materials as alternatives to cement and/or aggregates in pavements mixtures. In the last few years, much interest has been carried out in nanomaterial applications to improve the mechanical performance of construction materials, which can also be used for rigid pavement constructions. This improvement is due to nanomaterials' role in concrete as Nano reinforcements and nanofillers. On the other hand, various types of fibers have been used to improve the performance of concrete constructions. This study investigates the effect of adding carbon nanotubes (CNTs) and steel fibers (SFs) to concrete mixtures. A series of experiments on concrete mixes with various weight percentages of CNTs (0%, 0.025%, 0.050%, and 0.075%) were added to the mixtures to determine the best cost and amount of CNTs to add to a concrete mix. Compressive, tensile, and flexure strength characteristics are investigated. In the second experimental stage of this work, the effect of adding steel fibers to the mixture was investigated.

Guohua Xing a, Yangchen Xu a, Jiao Huang a, Yongjian Lu a, Pengyong Miao a, Pattharaphon Chindasiriphan b, Pitcha Jongvivatsakul b, Kaize Ma a (2023). Introducing steel fibers (SFs) into carbon nanotubes (CNTs) concrete can fully exert the synergistic effect of SFs and CNTs in both micro and macro, alleviating the high brittleness of CNTs concrete while enhancing its mechanical properties. In this study, the mechanical behavior of CNTs concrete reinforced with hooked-end steel fiber (HSF) and milled steel fiber (MSF) with respective volume fractions of 1.0%, 1.5%, and 2.0% were examined regarding compressive (cubic and axial), splitting tensile and flexural strengths at 28 days. Meanwhile, Digital Image Correlation (DIC) was used to quantify the crack propagation on specimen surface under varied flexural loads. The results confirmed CNTs' ability to improve the compressive, splitting tensile and flexural strength of plain concrete, but the inability to refine brittle failure. Include SFs further enhanced CNTs concrete's strength and reduced its brittleness. In terms of fiber type, HSF-reinforced CNTs concrete outperformed MSF-reinforced in compressive, splitting tensile strength, and reducing the brittleness of CNTs concrete, whereas surrendered the latter in flexural strength. Crack propagation observed by DIC demonstrated the reinforced specimens' good ductility due to the ability of SFs to restrict crack propagation and improve deforms of the whole specimen. Additionally, Scanning Electron Microscope (SEM) observation of CNTs-compacted concrete microstructure revealed the excellent synergistic effect of CNTs and SFs in bonding with cement matrix. Macroscopically, CNTs and SFs together could improve the mechanical properties and ductility of cement materials, and even structure durability.

Luciano Feo a, Annavirginia Lambiase a, Enzo Martinelli a, Rosa Penna a, Marco Pepe b (2023). The addition of carbon nanotubes is an effective method to enhance mechanical properties and durability performance of structural concrete. Recently, experimental studies have investigated the behavior of Ultra-High-Performance fibers reinforced Concrete (UHPFRC) mixtures including steel fibers and the carbon nanotubes duly dispersed within their matrix. The aim of this paper is to present the numerical results of a preliminary analysis on the effect of carbon nanofillers on the stress-strain behavior of the cementitious matrix, as well as on the bond interaction between the matrix and the steel fibers constituting UHPFRC. For this purpose, the meso-mechanical model developed by two of the authors for the study of the post-cracking response of fiber reinforced concrete, is here extended and applied for evaluating the effects of the addition of nanofiller on the cracking and the post-cracking response of UHPFRC specimens. In order to characterize the stress-strain relationships of the cementitious matrix and to back-calculate the bond-slip laws of steel fibers embedded within the latter, a comparison with the experimental results available in the literature has been also developed.

Lightweight Concrete Y. Mohammadi*a, M. Bagheripour Asilb (2022). In this research, the engineering characteristics of self-compacting lightweight concrete (SCLWC) containing carbon nanotubes and steel micro-fiber were evaluated. The variables included the amount of carbon nanotubes (0, 0.02, 0.04, and 0.06% by weight of cement) and steel micro-fiber (0, 0.5, and 1% by volume). Lightweight expanded clay aggregate was used as lightweight aggregates. The experimental tests were self-compacting tests, compressive, splitting tensile, and flexural strengths, ultrasonic pulse velocity, electrical resistivity, water penetration depth, and scanning electron microscope. Adding 0.02 to 0.06 percent of carbon nanotubes to SCLWC reinforced with steel micro-fiber increases the compressive strength by about 33 to 64 percent. The use of 0.06% carbon nanotubes and 1% steel microfiber increased the splitting tensile strength by 36%. The use of carbon nanotubes and steel micro-fiber has the effect of influencing the filling of empty spaces and reducing concrete porosity. This can be attributed to the growing process of cement paste hydration and the filling of pores and capillary pores with the products of cement reactions, resulting in concrete compaction. Adding 0.02% carbon nanotubes to SCLWC samples containing 0.5% and 1% steel micro fibers increased the 28-day compressive strength by 36%, 34% and 33%, respectively.

III. METHODOLOGY

The experimental investigation was carried out to assess the mechanical properties of high-performance concrete reinforced with Carbon Nanotubes (CNTs), Steel Fibers (SFs), and 100% Artificial Sand (AS) as fine aggregate. The methodology involved the following steps:

3.1 Specimen Types

- Cubes: 150 mm × 150 mm × 150 mm (Compressive Strength Test)
- Cylinders: 150 mm × 300 mm (Split Tensile Strength Test)
- Beams: 150 mm × 150 mm × 700 mm (Flexural Strength Test)

3.2 Material Proportions

- Artificial Sand (AS)**:** Used as 100% replacement for natural river sand.
- Carbon Nanotubes (CNTs)**:** Added at 1%, 2%, and 3% by weight of cement.
- Steel Fibers (SFs)**:** Constant dosage of 5% by volume of coarse aggregates.

3.3 Mixing and Dispersion

- CNTs were dispersed using ultrasonic sonication with surfactant to ensure uniform distribution.
- All materials were mixed using a mechanical mixer to ensure homogeneity.

3.4 Curing and Testing

- All specimens were cured for 7,14 & 28 days.
- Mechanical tests included Compressive Strength Split Tensile Strength and Flexural Strength

IV. RESULTS AND DISCUSSION

4.1 Compressive Strength

Compressive strength is a critical parameter for evaluating the performance and structural integrity of concrete under various loading and environmental conditions. In this investigation, M30 grade concrete incorporating 100% artificial sand (AS) and 53-grade cement was used. cube specimens (150 mm × 150 mm × 150 mm) were tested to assess compressive strength at 7, 14, and 28 days for different combinations with Carbon Nanotubes (CNTs), Steel Fibers (SFs), and 100% Artificial Sand (AS). Compressive strength tests were conducted using a universal testing machine under standard loading conditions. The results demonstrate a clear enhancement in strength due to the inclusion of steel fibers and carbon nanotubes.

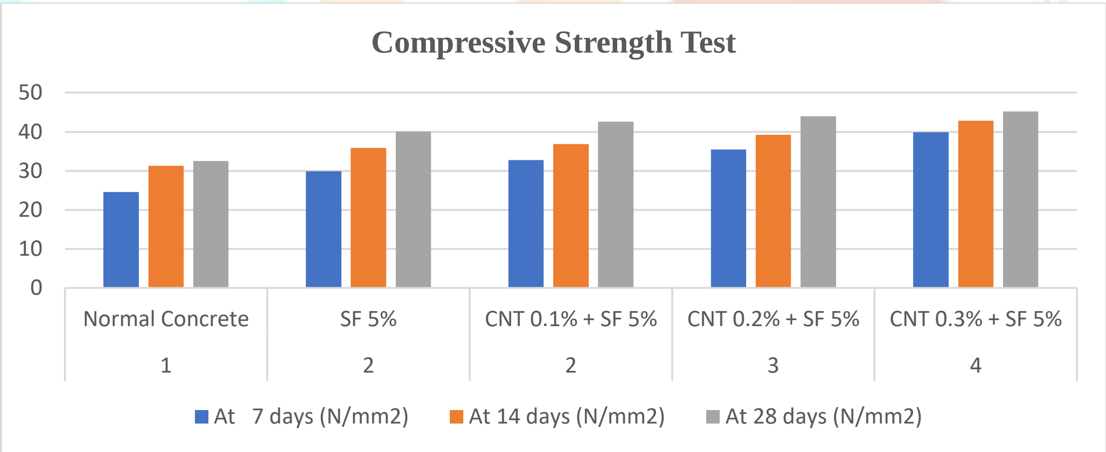

Fig. 5.Graph Showing Compressive Strength of The Specimens

4.2 Flexural Strength

Flexural strength is the ability of the material to withstand bending forces applied perpendicular to its longitudinal axis. It is also known as modulus of rupture, or bend strength, or transverse rupture strength. Itis a material property, defined as the stress in a material just before it yields in a flexure test. In this experiment we taken M30 grade of concrete with the cement of 53 grade. For the test of flexural strength, we taken beams with different amount with Carbon Nanotubes (CNTs), Steel Fibers (SFs), and 100% Artificial Sand (AS).

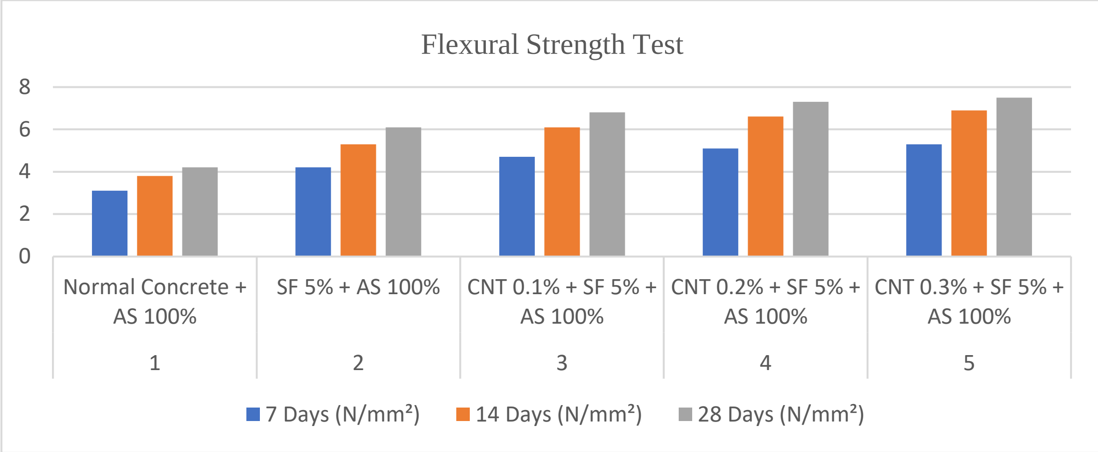

Fig. 6.Graph Showing Flexural Strength of The Specimens

4.3 Splitting Tensile Strength

The splitting tensile strength test was conducted by applying a diametrical compressive load along the length of cylindrical specimens until failure. This loading induces tensile stresses across the vertical plane and compressive stresses in the surrounding regions. In this study, M30 grade concrete with 53-grade cement was used. A total of 24 cylindrical specimens (150 mm × 300 mm) incorporating varying dosages of with Carbon Nanotubes (CNTs), Steel Fibers (SFs), and 100% Artificial Sand (AS) were tested.

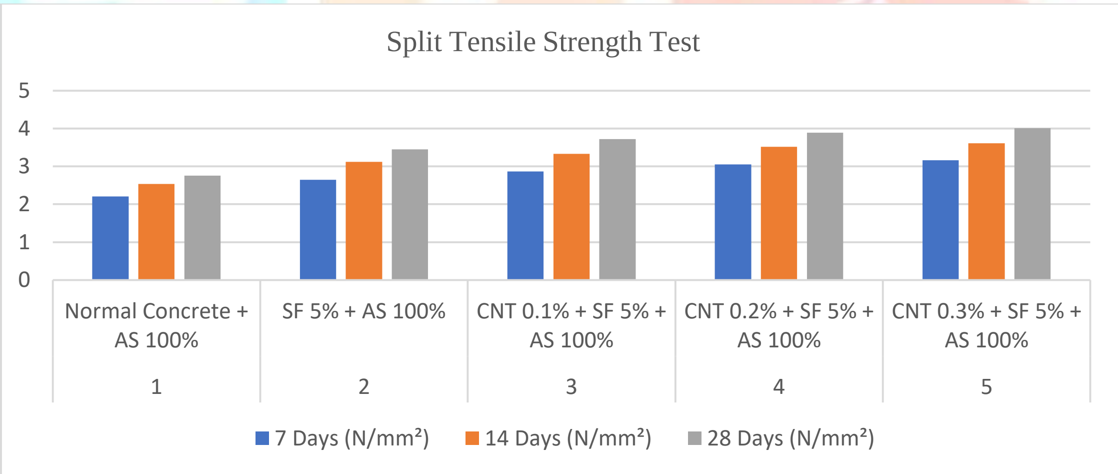

Fig. 7.Graph Showing Splitting Tensile Strength of The Specimens

V. CONCLUSION

A This study evaluated the mechanical performance of high-strength concrete made with 100% artificial sand (AS), reinforced with 5% steel fibers (SF) and varying dosages of carbon nanotubes (CNTs) ranging from 0.1% to 0.3%. The concrete mixes were tested for compressive strength, flexural strength, and split tensile strength at 7, 14, and 28 days.

The experimental results confirmed that the inclusion of steel fibers significantly enhanced all three mechanical properties compared to the control mix made with artificial sand alone. The addition of CNTs further improved performance, demonstrating a strong synergistic effect with SF.

- Compressive Strength: Increased from 32.52 N/mm² (control) to 44.61 N/mm² with 0.3% CNT and 5% SF, a total improvement of 37%.
- Flexural Strength: Improved from 4.2 N/mm² to 7.5 N/mm², indicating a 78% increase due to the combined reinforcement.
- Split Tensile Strength: Increased from 2.76 N/mm² to 4.01 N/mm², marking a 45% enhancement in

tensile resistance.

The results also revealed that while strength gains continued with increasing CNT content, the rate of improvement diminished beyond 0.2% CNT. This suggests that 0.2% CNT + 5% SF may be the most efficient combination in terms of cost and performance.

Overall, the study concludes that the hybrid reinforcement of steel fibers and carbon nanotubes effectively enhances the mechanical performance of concrete made with 100% artificial sand. The multi-scale reinforcement mechanism—combining macro-scale crack bridging by steel fibers and nano-scale densification by CNTs—offers a promising approach for the development of high-performance concrete with sustainable alternatives to natural sand.

VI. ACKNOWLEDGMENT

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