Hassan *et al. Beni-Suef Univ J Basic Appl Sci (2022) 11:121*
https://doi.org/10.1186/s43088-022-00300-5

Beni-Suef University Journal of Basic and Applied Sciences

RESEARCH **Open Access**

Utilization of carbon nanotubes and steel fibers to improve the mechanical properties of concrete pavement

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Abstract

Background 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 nanoreinforcements 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.

Results According to the results, the optimal carbon nanotube content in concrete is 0.05%. Compared to other concrete combinations with varying proportions of CNTs, this quantity offers the maximum compressive, tensile, and flexural strength. Additionally, SFs can improve the mechanical properties of the mix as well as enhance its post-cracking and fatigue behavior. Adding both CNTs with SFs increased compressive, tensile, and flexural strength by 22.7%, 29.3%, and 70.8%, respectively, more than the traditional pavement.

Conclusion This work found that combining SFs with CNTs improves the mechanical properties of the concrete mortar, resulting in a stronger mortar that can withstand more loads than the traditional one.

Keywords Rigid pavement, Concrete pavement, Carbon nanotubes (CNTs), Steel fibers (SFs)

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1 Background

Roads are the most commonly used way to transport people and goods for certain purposes [1]. Pavements are generally classified into three main categories based on the materials from which they are constructed: rigid or concrete pavement, flexible or asphalt pavement, and composite pavement. Rigid pavements are usually constructed of Portland cement concrete (PCC), asphalt pavements are usually constructed of hot mix asphalt (HMA), and composite pavements are a combination of both PCC and HMA [2].

Rigid pavements (RP) are increasingly in demand because they require less maintenance and reconstruction compared with other types of pavements. RP have many advantages, such as longer service life, improved weather resistance, fewer support system requirements, faster construction, quicker repair times, and lower surface temperature (as they reflect more radiation energy than other pavements) [3, 4]. They also improve night vision and can be built directly over poor soils [5]. RP is, therefore, commonly used in the design of major highways and airports; it is also used as heavy-duty slabs on industrial floors, in ports, and in parking pavement for heavy vehicles [6]. Concrete pavements, on the other hand, have a number of disadvantages, including high construction costs and limited tensile strength, and their construction represents a major contribution to global carbon dioxide emissions [5].

The main causes of highway deterioration are rutting and fatigue cracking in the pavements. The characteristics of the aggregates and binders used in asphalt mixtures are thought to play an essential role in pavement performance. Binders are regularly adjusted to satisfy the demands of loads and temperatures. In recent decades, rapid population growth and urbanization have resulted in a significant increase in traffic volume and vehicle loads. As a result, normal pavements cannot reach the end of their lifespan due to significant fatigue cracking rutting. Consequently, the criteria for constructing new roadways and transportation infrastructure greatly need updating [7].

Fatigue failure is a prevalent problem on large motorways due to the loading that occurs due to the millions of vehicles that use it during its service life [8]. In RP design, the minimization of fatigue failure due to repeated traffic stresses is a critical factor. Considerable research has been devoted to the addition of fibers to concrete as a way to improve the fatigue resistance of the concrete [9].

Over time, the materials utilized in road construction have evolved. This advance in materials has been accompanied by novel methodologies used to apply these materials to pavement structural design [8]. Cement has been replaced by various materials, including fly ash and silica fume. It was found that replacing 20% of the cement with fly ash enhances compressive strength by up to 4% after 91 days [10]. Ref. [11] reported that replacing cement with fly ash reduces flexural strength by 12%–13% after 28 days. Silica fume has been commonly used in RP for many centuries despite its expensive cost; it is used due to the significant enhancements in mechanical properties and fine particle concentration. However, there have been a few cases in which the flexural strength of RC pavements was observed to decrease in the case of the addition of silica fume [5]. It has been reported that the compressive strength, flexural strength, and elastic modulus can be increased by 29%, 22%, and 14%, respectively, when adding 10% silica fume to a concrete mix [12].

It should be noted that these strategies cannot improve the microstructure of the cement matrix at the nanoscale. Consequently, the inner defects of cement-based composites like pores and cracks continue to be an issue.

Nanotechnology has progressed quickly in recent years. It is a multidisciplinary subject combining science and engineering that focuses on controlling matter at length scales in the range of 1–100 nm; on this length scale, the unique features of nanoscale materials permit to allow for the creation of materials with novel potential applications [13]. Construction industry processes based on nanotechnology could yield many benefits with applications that increase the quality of concrete, steel, and isolating materials [14–16].

Nanocalcium carbonate (NCC), nano-silica (nano-SiO_2), and alumina nanoparticles (nano-Al_2O_3) have been used as advanced nanomaterials with the aim of enhancing the properties of RP mixtures. Ref. [17] found that adding a small quantity of nano-SiO_2 (up to 2%) to RP enhanced its strength significantly. However, Ref. [18] observed that when cement was partially replaced with 10% nano-SiO_2 (produced from rice hush ash), the compressive strength of porous concrete pavement was comparable to that of conventional concrete samples. In Ref. [19], cement was replaced with NCC, also known as nanolimestone, with a percentage replacement of 0%, 0.5%, 1%, 2%, and 3%; it was found that the compressive strength (tested at 7 and 28 days) was increased by 10% in the mixture with 1% NCC compared with the traditional pavement. In Ref. [20], the effect of nano-Al_2O_3 on the compressive strength of RP was investigated; it was found that the strength of concrete mixes containing 1% nano-Al_2O_3 was enhanced and reached a maximum rate of 36% when compared to conventional mixes.

Carbon nanotubes (CNTs) are one of the most used reinforcement materials for the next generation of high-performance nanoparticles due to their remarkable mechanical properties [21]. CNTs offer various distinct advantages in applications as a reinforcing material compared with other fibers used due to their high strength in cemented composites and their remarkable physical properties [21–23]. CNTs have much greater strength and rigidity than traditional fibers; they thus have the potential to improve overall mechanical properties compared with composites, including traditional fibers. CNTs have a high aspect ratio that effectively inhibits nano-cracks from spreading [24, 25]. CNTs are extremely flexible, and their microstructure as tubes allows them to bend in circles and build bridges across micro-cracks and nano-cracks in cement composites; in this manner, they increase the strength of the cement composites [26]. Concrete is a cement-based substance with complicated calcium–silicate–hydrate binding article network (C–S–H). CNTs interact strongly with C–S–H due to the nanoscale features of the CNTs, where the interface of CNTs is produced by a vast number of atoms present on the surface of the nanotube [27].

In recent years, many studies have shown that adding fibers to concrete structures improves their performance because concrete is brittle and has low tensile strength [28]. Fiber-reinforced concrete (FRC) was first utilized in the nineteenth century, and it has been commonly used to improve concrete characteristics since then. Fibers used for FRCs are produced from various materials, like steel, glass, carbon, polyethylene, and nylon and are used for different purposes [29]. The shape and size of fibers and their volume content and orientation significantly impact their performance in concrete and their effect on mechanical characteristics [30]. The key advantage of the fibers is their ability to transfer stresses across cracks, which thus improves the toughness and ductility of the concrete as well as its impact absorption capacity [31].

Several studies have found that adding SFs into concrete mixes improves the performance of the mix. SFs are commonly used to improve the toughness, tensile, and flexural strength of concrete, as well as to restrict crack transmission in the post-peak zone [32]. Due to these improved characteristics, steel fiber reinforced concrete is (SFRC) commonly used in pavements, bridges, and decks. The main goal of adding fibers into any product is to improve performance by increasing strain resistance. Steel fiber properties like modulus of elasticity, stiffness modulus, and tensile strength allow for better inner mechanical connection. Consequently, SFRC performs better when exposed to fatigue, impact, and impulsive load [33].

Ref. [33, 34] observed that SFs could significantly enhance the cracking load and ductility of RC constructions. Ref. [35] discovered that strengthening corroded RC beams with SFRC can significantly minimize the development of cracks while still having good ductility. Ref. [36, 37] investigated the failure mechanism of steel–concrete beams and observed that SFs could modify the mode of failure from shear to bending. Ref. [38] proved that by adding 2% SFs to SFRC beams, the lap-spliced length could be reduced by approximately 20% while keeping ductility and bearing capacity.

Compressive strength tests are often used to evaluate the quality of paving materials. This is because, in pavement design, the tensile and flexural strengths are the most important properties to consider, and their values are directly related to the compressive strength, and the performance of the concrete pavement is related directly to the concrete tensile strength [5]. In other words, RP of high compressive strength indicates a low porosity, microcracks that do not hinder the mechanical properties of the concrete before failure, and good interfacial transition zones [39].

In addition, the flexural properties of concrete pavement are affected by cracking failure on the concrete pavement surface.

Therefore, this research continues the investigation into CNTs and SFs in reinforced concrete pavements to evaluate their effect under traffic loads and reach a better mix than standard pavements. The compressive, tensile, and flexural strengths of the tested samples with and without the additive materials were investigated. The microstructure of the produced samples was studied using a Scanning Electron Microscope (SEM).

2 Research objective

The aim of this research is to improve the performance of concrete mixtures by including the following ingredients:

- Adding various ratios of CNTs to concrete mixtures and determining the optimum percent that improves overall concrete mix behavior.
- Mixing steel fibers into the concrete and observing the results
- The ability to add both CNTs and SF to the concrete mixture to optimize concrete behavior compared to the preceding specimens.

3 Methods

3.1 Experimental program

To achieve the objectives of this research, an experimental program was developed to evaluate the optimum percentage of CNTs and SFs in terms of improvement in the mechanical properties of concrete pavement. Figure 1 presents the experimental program of the presented study.

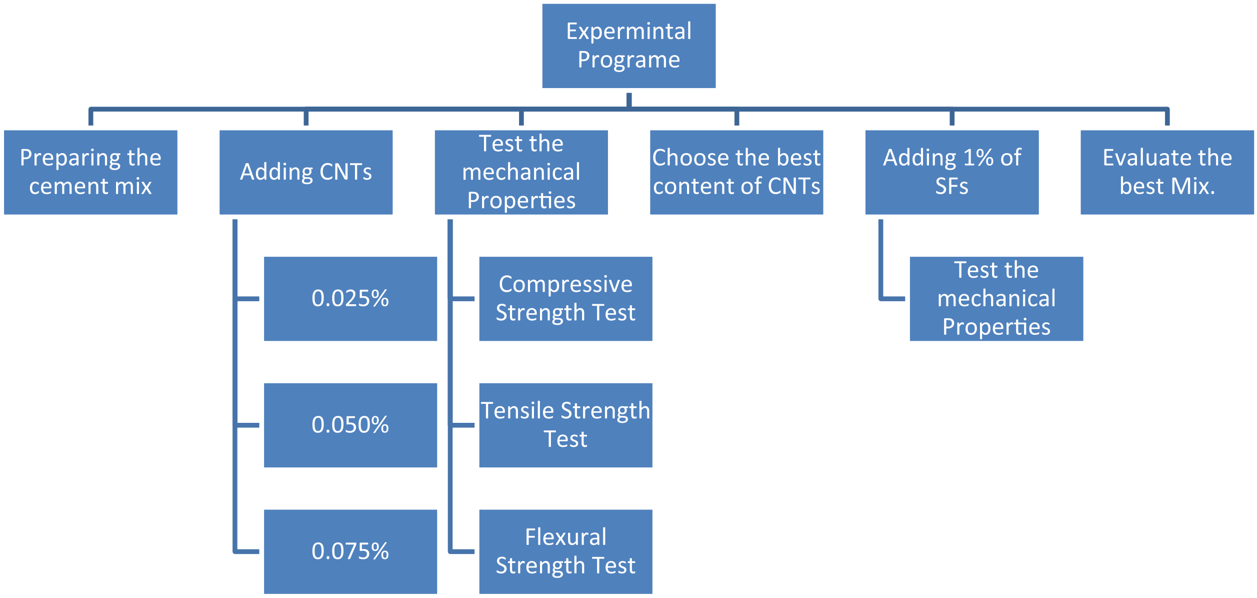


Fig. 1 Flowchart of the experimental program

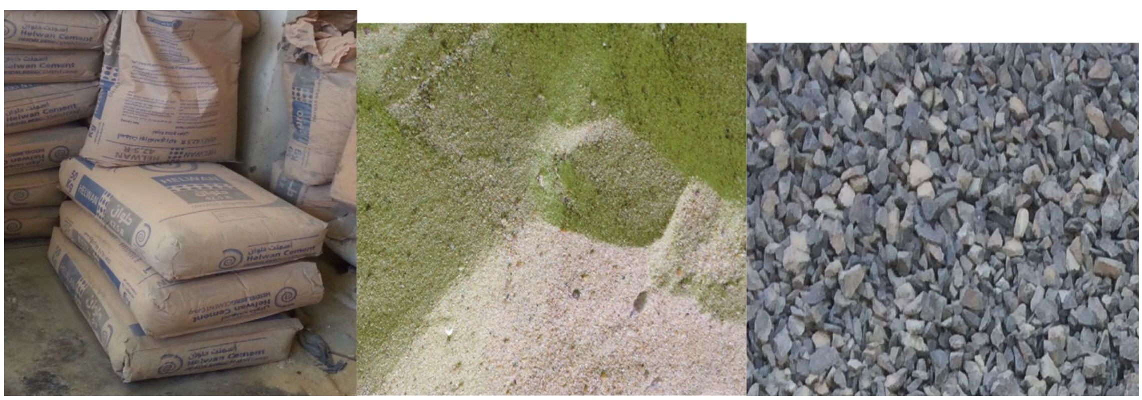


Fig. 2 Cement, sand, and gravel used in the experimental work

Table 1 Ordinary Portland cements properties

Element	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	L.O.I
Cement	21.2%	4.53%	3.61%	61.63%	2.38%	2.80%	0.36%	0.22%	1.96%
Property					Result				
Initial setting time (min)					97 min				
Final setting time (min)					198 min				
Compressive strength (3 days)					247 kg/cm^2				
Compressive strength (7 days)					350 kg/cm^2				

3.2 Material properties, mix proportions, and mix procedure

The concrete mix used in this study consists of cement, sand, and gravel, as depicted in Fig. 2. According to the ASTM C150 standard [40], type II ordinary Portland cement was utilized in all of the mixtures considered

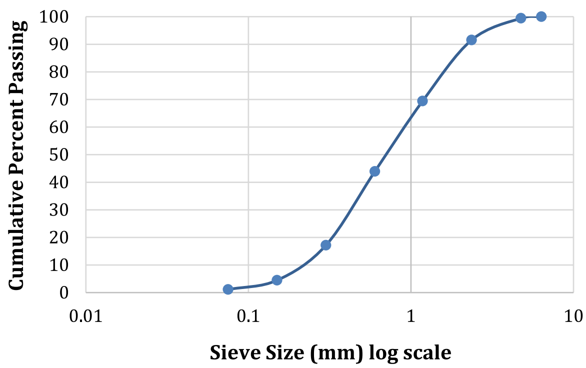


Fig. 3 Fine aggregates sieve analysis according to [41]

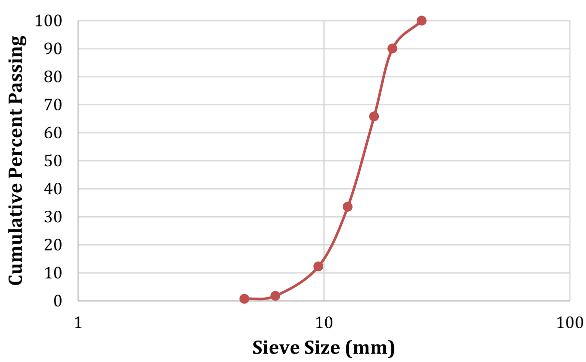


Fig. 4 Basalt sieve analysis according to [41]

Table 2 Concrete mix proportions for the control mix

Fc (MPa)	Water (kg/m^3)	Cement (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Super-plasticizer (G) (kg/m^3)
25	175	350	1200	600	0.9

in this work. Table 1 shows the physical and chemical properties of the cement utilized. Figure 3 shows a sieve analysis of the fine aggregates considered in this investigation. As a coarse aggregate, basalt with particle sizes of 5, 10, and 20 mm and a specific gravity of 2.77 g/cm^3 was used; Fig. 4 shows the sieve analysis of the coarse aggregates used in this work. In the mixing process, potable water was used. The intended strength of the concrete was 25 MPa. Table 2 shows the proportions of the control mix, and Fig. 5 shows the shape of CNT powder and dissolved in water. A representative transmission electron microscope micrograph and X-ray diffractograms (XRD) of the CNTs are shown in Figs. 6 and 7, respectively. Three different percentages of CNTs, 0.025%, 0.050%, and 0.075% by cement weight, were added to concrete mixes. SFs were added with a percentage of 1% by cement weight. Figure 8 and Table 3 show the shape and physical characteristics of the SFs, respectively. In a laboratory mixer with a capacity of 0.125 m^3, the dry aggregate and cement were mixed for 2 min. The water containing the CNTs was then added, and the mixing continued for another 2 min.

3.3 Test specimens preparation

There were two stages to this experimental study: First, the optimal CNT content for the mix was established. Then, the performance of test specimens containing SFs and specimens containing both SFs and CNTs was evaluated. The experimental program criteria were as follows:

1. Compressive strength test.
2. Tensile strength test.
3. Flexure strength test.
4. Concrete Cylinder Compression Testing
5. Scanning Electronic Microscope (SEM) test

3.4 Testing specimens with different percentages of CNTs

Twelve concrete cubes with a side length of 100 mm, twelve cylinders with a diameter of 100 mm and height of 200 mm specimens, and twelve beams of 100 × 100 × 500 mm^3 were cast to determine the compressive strength, tensile strength, and flexure strength of the concrete after 28 days, respectively, according to BS EN 12,390–3 and ASTM C 496 [42, 43]. Three specimens made of the control concrete mix (virgin mix without any additives) and three specimens for each concrete mix incorporating different amounts of CNTs were used. Figures 9 and 10 depict the preparation and water curing of the specimens.

3.5 Testing specimens with CNTs and SFs

Six concrete cubes with a side length of 100 mm, six cylindrical specimens with a diameter of 100 mm and length of 200 mm, and six beams measuring 100 mm × 100 mm × 500 mm were cast to determine the compressive strength, tensile strength, and flexure strength of the concrete after 28 days, respectively, according to BS EN 12390–3 and ASTM C 496 [42, 43]. Three specimens with 1% by cement weight SFs and three mixes of 0.05% by cement weight CNTs combined with 1% by cement weight SFs were made. Each batch was made up of three cubes for compressive strength testing, three cylinders for calculating the tensile strength, and

Fig. 5 CNTs powder and after mixing with water

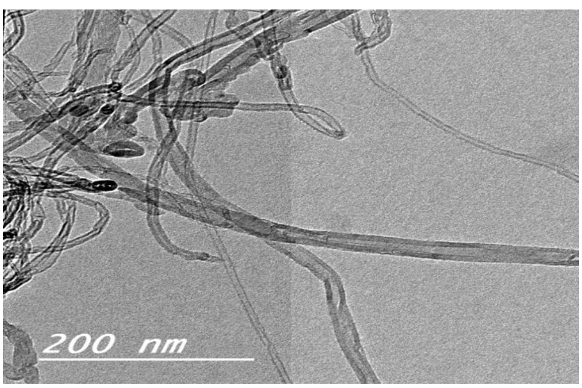


Fig. 6 CNTs transmission electron microscope micrograph

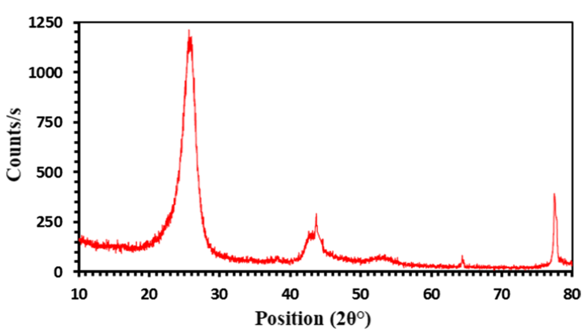


Fig. 7 X-ray diffraction pattern of the CNTs

Fig. 8 Steel fibers used in this work

Table 3 Mechanical properties of the SFs

Length (mm)	Width (mm)	Thickness (mm)	Tensile strength (MPa)	Young's modulus (GPa)
50	3	0.5	532	210

three beams for flexure strength testing. The specimens were cured in normal pure water at 27 °C (as shown in Fig. 9) prior to testing and after being shaped at one day old. Figure 11 shows some of the specimens after they have been cast and cured.

Fig. 9 Specimens with different percentages of CNTs

Fig. 10 Curing of the specimens in water

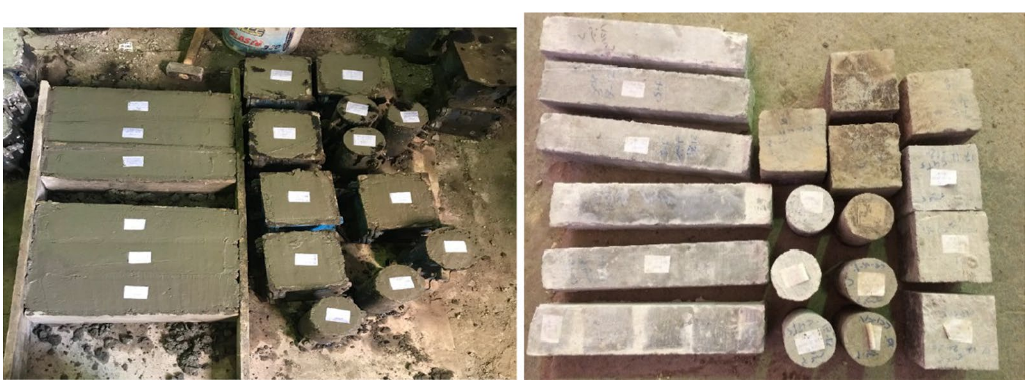


Fig. 11 Cubes, cylinders, and beams after casting and curing

4 Results

4.1 Results of specimens with different percentages of CNTs

The specimens were tested for compressive, tensile, and flexure strength using a 1000-kN universal testing machine to test cubes, cylinders, and beams specimens and subsequently analyzed via scanning electron microscopy (SEM) using an Oxford Instruments JEOL JSM6300.

Table 4 Compressive, tensile, and flexure strength of concrete specimens

Concrete type	Compressive strength (MPa)	Tensile strength (MPa)	Flexure strength (MPa)
Control	25.06	2.32	9.18
0.025% CNTs	26.74	2.651	10.94
0.050% CNTs	29.54	2.794	11.77
0.075% CNTs	29.47	2.807	11.32

Table 4 and Fig. 12 show the compressive strength, tensile strength, and flexure strength data obtained after 28 days.

4.2 Results of adding SFs and CNTs on the strength of concrete

4.2.1 Specimens with SFs Mix

The compressive, tensile, and flexural strength of the specimens containing 1% SFs was also evaluated. The findings of the strength tests that were undertaken after 28 days of curing are summarized in Table 5.

4.2.2 Specimens with both CNTs and SFs Mix

At the end of the 28-day curing period, the compressive, tensile, and flexural strength of the control specimen, the specimen with 1% SFs, the specimen with 0.05% CNTs, and the specimen with both 1% SF and 0.05% CNTs were investigated. Table 5 shows the results, and Fig. 13 shows how adding both SF and CNTs to concrete mixtures improves the behavior of the resulting mixture. Figures 14, 15 and 16 show the failure of the cubes, cylinders, and beams made from the control mixture and mixtures with SFs and/or CNTs.

4.3 Stress–strain curves of the mixes

Twelve cylinders with a radius of 150 mm and a length of 300 mm made from four different concrete mixtures were tested to obtain compressive stress–strain curves. The first group consisted of three plain concrete specimens, the second group consisted of three specimens with concrete mix with 0.05% CNTs, the third group consisted of three cylinders with 1% SFs, and the fourth group consisted of three cylinders with 0.05% CNTs and 1% SFs added to the concrete mix. After 24 h, the specimens were de-molded and cured in water until they were tested after 28 days of curing. All the specimens were tested using a Concrete Cylinder Compression Testing machine with a rate of loading controller in accordance

Table 5 Strengths of the control samples and the samples containing CNTs and/or SFs

Concrete type	Compressive strength (MPa)	Tensile strength (MPa)	Flexure strength (MPa)
Control	25.06	2.32	9.18
0.050% CNTs	29.54	2.794	11.77
1% SF	29.59	2.92	14.62
0.050% CNTs + 1% SF	30.75	3.00	15.68

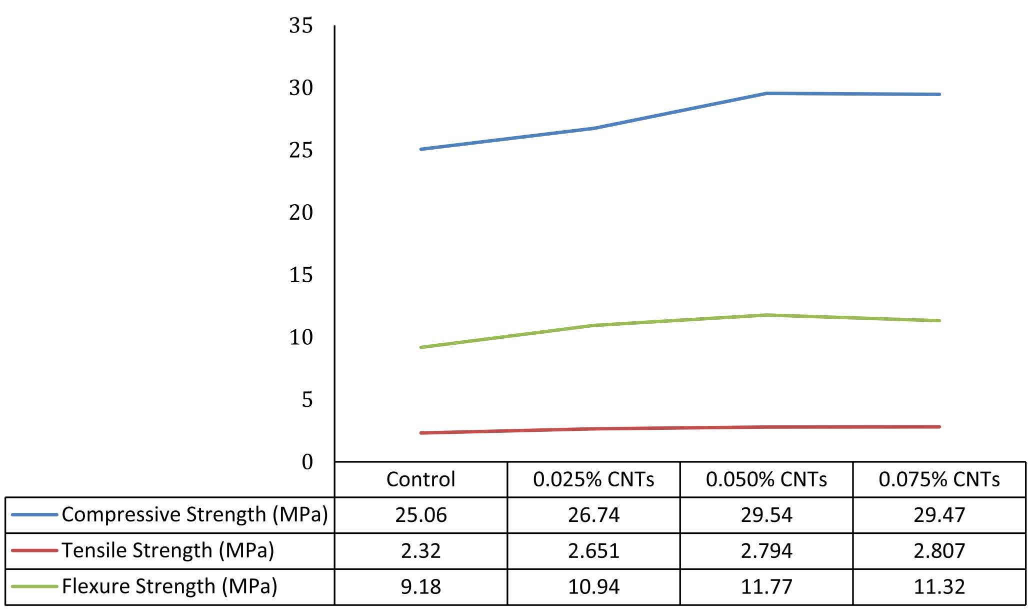
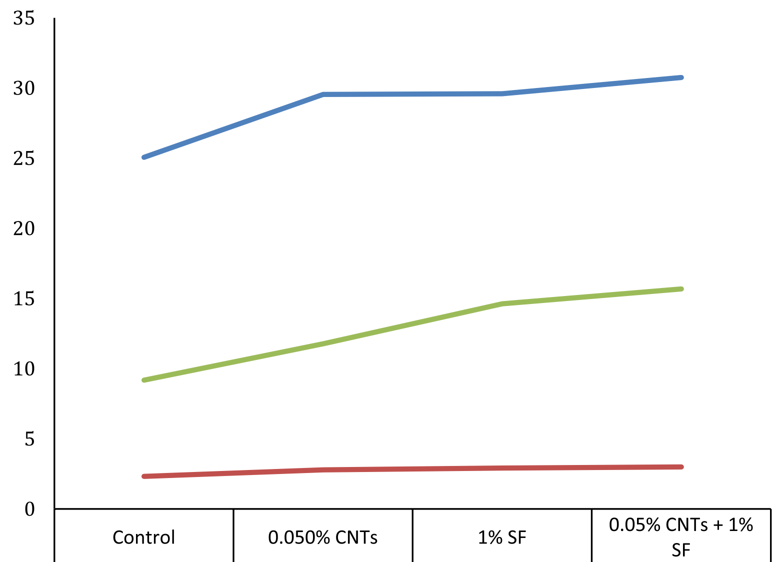


Fig. 12 Compressive strength, tensile strength, and flexure strength of the control and concrete containing CNTs



	Control	0.050% CNTs	1% SF	0.05% CNTs + 1% SF
Compressive Strength (MPa)	25.06	29.54	29.59	30.75
Tensile Strength (MPa)	2.32	2.794	2.92	3
Flexure Strength (MPa)	9.18	11.77	14.62	15.68

Fig. 13 Effect of mixing both steel fibers and CNTs on the strength compared to previous specimens

Fig. 14 Failure modes of the cubes made from various mixtures

with the ASTM C-39 standard. The testing head was gradually lowered until it was in contact with the specimen. At this moment, the dial gauge was set to zero. The load was then gradually increased. Deformations were recorded at a rate of 50 measurements per second. The average measurements were determined after deformations, and the accompanying loads were recorded. The resulting stress–strain curves are shown in Fig. 17. It can be noted that peak stress increased by 19.7%, 26.8%, and 30.6% for the samples with CNTs, SF, and the blend of CNTs and SFs included in the mixtures, respectively, relative to control specimens. It is also noted that adding SFs and CNTs to a normal concrete mix improves the ductility and increases the modulus of elasticity of the resultant sample. Figure 18 shows a sample before and after failure.

4.4 Microstructure of CNTs concrete samples

The observed structure of a prepared surface of material examined by a microscope at a magnification of more than 25 × is known as the microstructure [44]. The control specimen and specimens, including CNTs, were analyzed via SEM. The results are shown in Fig. 18. In comparison with the control specimen, which had at least one substantial break in its structure (Fig. 19a), the images demonstrate that the CNTs specimen was

Control Cylinder CNTs Cylinder SF Cylinder SF + CNTs Cylinder

Fig. 15 Failure modes of the cylinders made from various mixtures

Fig. 16 Flexural test of the beam made from a concrete mixture including SFs and CNTs before and after failure during testing

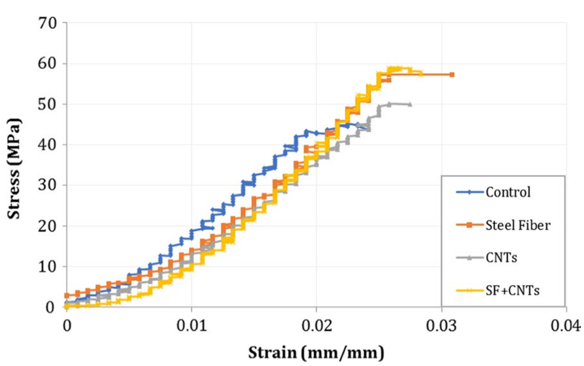


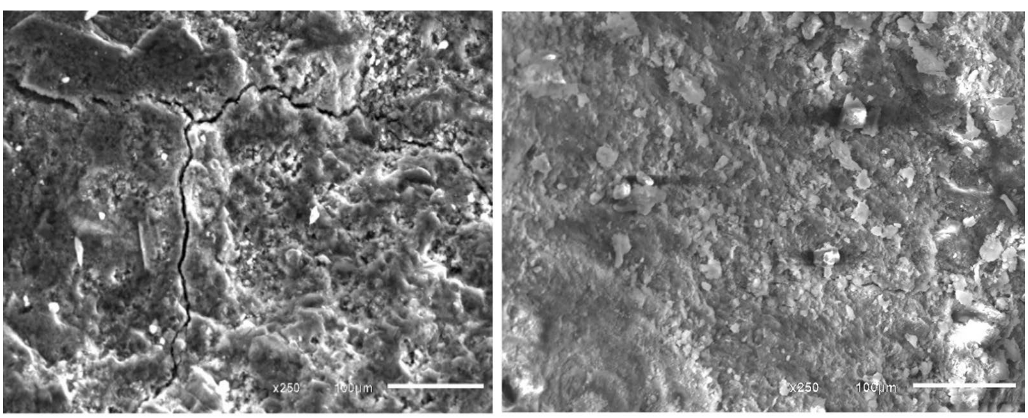
Fig. 17 Stress–strain curves of different mixtures

well-formed (Fig. 19b). The influence of 0.5% and 1% CNTs in a fly ash cement matrix on the mechanical characteristics of the CNT–fly ash cement composite has been examined by Chaipanich et al. [45]; micrographs were analyzed, and a SEM analysis was conducted. In that study, including CNTs in the mixture was found to help fill the pores between the hydration products, such as calcium silicate hydrates and ettringite. Furthermore, compared with a CNT-free reference fly ash mix, the micrographs show that CNTs interact well with the fly ash cement matrix; this is because CNTs act as filler, and thus, a denser and stronger microstructure is formed.

5 Discussion

Overall, adding CNTs to the concrete mix can be seen to increase the compressive strength of the specimens compared with the control specimens. We found that the increase in compressive strength was 6.7% for the sample with 0.025% CNTs, 17.9% with 0.05% CNTs, and 17.6% with 0.075% CNTs. Camacho and Konsta [46, 47] also found that adding 0.06% CNTs to concrete mixes increased the strength by up to 20%. According to Hawreen and Bogas [48], the improvement in compressive strength of concrete with CNTs compared with conventional concrete is due to the filler, nucleation, and bridging effects of the CNTs. Another study by Petrunin et al. [49] indicated that adding 0.13% CNTs to mortar boosted compressive strength by 37% and 20% after one day and 28 days of curing, respectively.

Fig. 18 A cylinder before and after failure during testing



(a) (b)

Fig. 19 SEM images for **a** a control sample and **b** a sample containing CNTs

We note that CNTs appear to be more advantageous in the early stages of curing when the mortar is weak.

When CNTs were added to the concrete mix, the splitting tensile strength of the studied specimens improved relative to the control specimens. The increase in tensile strength was found to be 14.3% with 0.025% CNTs, 20.4% with 0.05% CNTs, and 21% with 0.075% CNTs.

According to Qissab and Abbas [50], adding up to 0.06% CNTs to a sample increased the splitting tensile strength by between 3.1% and 37.5%; they used both short and long CNTs in their research and also found that the CNTs split along the damaged surfaces of the samples, as observed in SEM images. Furthermore, when compared to normal mortar samples, Hunashyal et al. [51] state that mortar samples containing 0.5% CNTs had a 19% increase in direct tensile strength, and they observed a lower strain on the CNT samples that failed.

It was found that introducing CNTs increases flexural strength by 19.2% for additions of 0.025% CNTs by cement weight, 28.2% for 0.05% CNTs, and 23.3% for 0.075% CNTs. These findings are in agreement with those of Konsta et al. and Li et al. [47, 52]. These previous words concluded that adding 0.08% and 0.05% of short, multi-walled CNTs to a cement mix increased flexural strength and Young's modulus by 35% and 25%, respectively.

After comparing the effects of different CNT ratios in concrete mixtures, it can be stated that the ideal CNT percentage is 0.05%.

Therefore, adding CNTs into the concrete mix could strengthen the bonding between cement and aggregates, leading to concrete with high mechanical performance.

The tested SFs samples increased compressive strength by 19.5%, tensile strength by 25.9%, and flexural strength by 59.3%; these results are comparable with findings in the literature. It controls the development of flexural cracks in beams and performs better under the applied loads. SFs also add rigidity to the beams, which may ensure better performance of the pavement slab.

According to Sahin and Köksal [53], due to the presence of the SFs, the splitting tensile strength increased by 36.3%, and the samples had a greater ductility. Vikrant et al. [54] found that adding 0.5% of 50 mm coated copper-covered crimped around the SF with an aspect ratio of 53.85 to concrete with a compressive strength of 25 MPa improved split tensile strength by 61.1%.

When the CNTs were combined with SFs in the concrete mix, the strength is increased due to the aforementioned properties of both the SFs and CNTs. The combination of SFs and CNTs in the mixture resulted in increases of 22.7%, 29.3%, and 70.8% in compressive, tensile, and flexural strength, respectively, compared to the control samples.

6 Conclusion

This study is limited to evaluate how different ratios of CNTs, steel fibers, and both CNTs and steel fibers affect the performance of concrete mixtures, as well as to specify their compressive strength, tensile strength, and flexural strength to maximize their behavior.

The experimental work performed in this study evaluated the effect of adding CNTs and SFs to concrete for use in the RP mixture. The principal results are as follows:

1. Adding CNTs to the concrete mixture increased the compressive, tensile, and flexural strengths slightly compared to the control specimen.
2. The best content of CNTs to add concrete mixture is 0.05%; this is because the compressive and flexure strengths were higher than those of the other samples; the tensile strength was slightly higher for 0.075% CNTs than that obtained for the sample with 0.05% CNTs. This was explained by the fact that CNTs agglomerate readily at high dosages.
3. SEM analysis revealed that the CNTs specimens show a higher degree of structure and dispersion than the control specimen. This demonstrates that the CNTs operate as bridges over micro-cracks that boost bond strength.
4. The addition of SFs significantly enhances the compressive strength, splitting tensile strength, and flexural strength, and it increases the toughness and ductility of the concrete.
5. Adding both CNTs with SFs to the concrete mix has a higher effect on the strength than the other tested mixtures. It led to an increase in compressive, tensile, and flexure strength of 22.7%, 29.3%, and 70.8%, respectively.
6. The stress–strain curves reveal that the mixture, including both CNTs and SFs, had higher ultimate stress at the same strain value than the other tested mixtures. This blend gives the concrete a higher modulus of elasticity.

7 Recommendations

To continue the study in this research, a practical study on a real model of rigid pavement slabs should be applied and evaluate its performance under traffic loads.

Also, the impact of other parameters should be considered, such as the type of concrete, a different type of fiber with a different ratio, a different type of Nano material, and so on.

Abbreviations

RP	Rigid pavement
CNTs	Carbon nanotubes
SFs	Steel fibers

Acknowledgements
Not applicable.

Author contributions
AH did the experimental work and wrote the research. SG reviewed the research. AH reviewed the research. AS co-wrote the research. All authors read and approved the final manuscript.

Funding
The author received no specific funding for this work.

Availability of data and materials
All data used are mentioned in the paper.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Received: 26 April 2022 Accepted: 10 September 2022
Published online: 29 September 2022

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