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SELF-SENSING OF ECC SUBJECTED TO FLEXURAL AND DIRECT TENSILE LOADS INJECTED WITH CARBON NANOTUBES AND REINFORCED WITH MECHANICAL FIBERS

Shatha Riyadh AHMED[1,*], Ali Majeed AL-DAHAWI[1], Shatha Sadeq HASSAN[1]

[1]Civil Engineering Dept., University of Technology Baghdad -Iraq.
[*] Corresponding author: 11064@uotechnology.edu.iq

Abstract

Research today aims to transform the cementitious system, in whole its forms, from a non-functional structural system into a smart system that can serve various civil facilities and infrastructure. One of the important applications in this field is the early detection of damage to the concrete structure before it develops by injecting the simple cementitious system with functional fillers capable of forming an electrical network inside it that can capture different scenarios of applied loads. This may include direct tensile loads and the flexural strength of mortar samples made from a cementitious matrix infused with multi-walled carbon nanotubes (MWCNT) and reinforced with polyvinyl alcohol fibers (PVA) in one instance and nylon fibers (NF) in another. The study examines different curing durations: 28, 56, 90, and 180 days at room temperature with water. To advance prior research and address a portion of the existing gap, the conventional matrix was infused with carbon nanotubes at a concentration of 0.5 by weight of cementitious components, alongside one of the reinforcement fibers (PVA) or (NF) at a consistent rate of 2% of the total volume of the mixture, maintaining this dosage throughout the investigation. A plain matrix devoid of additives was also established for comparative purposes. The results indicate the high mechanical behavior of the innovative alloys under the proposed loading scenarios; the CNT0.5PVA2 matrix proved its mechanical superiority over both the reference and innovative alloys, with improvement ratios under flexural strength for ages 28, 56, 90, and 180 days being 162%, 142%, 128%, and 103%, respectively. At the curing ages of 28, 56, 90, and 180 days, respectively, the improvement ratios under direct tensile strength were 10%, 5%, 5%, and 15%. The CNT0.5NF2 matrix excelled in its damage sensing ability with self-sensing values reaching 170 and 200% under direct bending and tensile loads, respectively.

Keywords:

Functional fillers;
Multi-walled carbon nanotubes;
Self-sensing;
Polyvinyl alcohol fibers;
Nylon fibers.

1 Introduction

The limited multifunctional uses of standard concrete construction materials are a result of their lack of electrical conductivity and functional qualities. New technology has been developed to overcome this restriction by incorporating an electrical network into conventional concrete. An early damage detection system based on the electrical conductivity and resistance of a network generated by "Engineered Cementitious Composites" (ECC)—a specifically manufactured functional material—is one of many potential uses made possible by this breakthrough [1-4]. To achieve low costs and address challenges related with integrating electronic sensors, such as sensing capabilities, durability, and compatibility with cementitious structures, a technology has been developed for self-monitoring the structural health of concrete. This involves incorporating specific proportions of electrically conducive fillers to enhance functional performance by detecting damage or its early onset, The shift from conventional concrete to advanced smart concrete necessitates components that integrate with the structural composition of standard concrete and enhance it. The primary components are various kinds of fillers, including macro, micro, and nanoforms. Nanomaterials have garnered significant attention, particularly regarding their influence on the properties of cement compounds. These materials can be used in many important areas, such as self-sensing damage before it gets worse. They are a cost-effective solution that avoids some of the problems that come with using electronic sensors, like how well they work, how long they last, and how well they work with cement structures [4-8]. The general approach in this field focuses on enhancing the ability of cement matrices to respond to the damage applied to them according to the proposed loading type without compromising the matrix durability. So, there are two main ways to go about it: the first is to improve the electrical conductivity of the matrix by adding electrically conductive fillers that make the network stronger; the second is to see how these matrices behave mechanically and how much the conductive fillers affect their durability by putting samples of the new matrices through different types of loading. To figure out the link between electrical resistivity and damage, we look at how much the electrical resistivity of the new matrix changes in a fractional way under the suggested loading type every second, this is known as the fractional change in electrical resistance (FCER). In other words, electrical resistance data are recorded every second in which the values of the applied stress on the matrix increase. The self-sensing capability of damage prior to its progression relies on the conductivity of the material, which aids in damage resistance and the formation of the conductive network within the matrix. Carbon is frequently utilized to meet these objectives in various forms, including nanomaterials like multi-layer carbon nanotubes. With the help of these fillers, a continuous electrical network may be formed, with resistivity values that change continually in response to loads. This is a huge step forward for materials used in cementitious' self-sensing systems; how effectively they disperse and distribute themselves inside the smart system, in addition to their physical and chemical qualities, and determines how much current they can enhance [9-12]. Wang, et al. [4] concluded that adding 4% by weight of carbon nanotubes improves the performance of the cement system in terms of durability and self-sensing behavior. Jawed Roshan, Abedi [11] confirmed that carbon nanotubes improve the mechanical capacity of cement-stabilized sand in addition to making the system monitor its structural health automatically under different types of loads, including cyclic loading. A previous study found that the best mechanical performance of carbon nanotubes with Portland cement was at a water-to-cement ratio of 0.3 [13]. Comprehensive investigations have been carried out on the sensing capability of cementitious composites incorporating various functional additives. The application of carbon nanotube (CNT) to enhance the self-sensing properties of cementitious composites was investigated by Yu and Kwon [14] and Han, et al. [15]. Suchorzewski, et al. [16] found that by using low concentrations of carbon nanotubes, the strength of cementitious composites can be improved to high-performance composites (HPC) under split tensile loads and cyclic loading in compression. The incorporation of (CNTs) led to a notable decrease in the electrical resistivity of UHPC, enhancing its strength and displacement hardening response when subjected to flexural loads. This resultant system exhibited notable crack sensing capabilities, broadening the use of UHPC for on-site casting and structural crack detectors [17]. A prior investigation examined the influence of CNTs on the flexural strength, stress-bearing capacity, permeability, and microstructure of concrete. The findings indicated that a higher content of CNTs led to an increase in flexural strength exceeding 100%, a rise in stress-bearing capacity of 150%, and an enhancement in permeability of at least 45%. Every sample exhibited a uniform dispersion of CNTs threads within the concrete hydration products [18]. Yao, et al. [19] found that adding polyvinyl alcohol (PVA) fibers to unreinforced cementitious soil made it stronger in compression, tensile, and flexural tests. It also changed the way it breaks when it gets brittle, which made it last longer and be more flexible. A study conducted by Dehghani and Aslani [20] confirmed that the addition of PVA fibers in a hybrid form enhances the ability of matrices under flexural stress due to their bridging phenomenon to fill cracks. The addition of nylon fibers to cement mortar improves the durability and strength properties at low cost [21]. Research by Yap, et al. [22] shown that the use of polypropylene and nylon fibers into oil palm shell concrete resulted in a 19–86% enhancement in splitting tensile strength of the concrete. Fernando, et al. [23] found that adding 0.5 vol.% nylon fibers to the cement matrix increases the flexural and compressive strength due to the behavior of the fibers in the cohesion of the matrix components. This percentage also increases the resistance of the matrix to corrosion because the nylon fibers have excellent elasticity that makes them capable of lasting in the mortar for a long time. This study aims to understand how some fillers embedded in a cementitious matrix behave over time and how they can self-detect damage. For this purpose, special cementitious mixtures were developed that were infused with carbon nanotubes that could self-sensing damage. While maintaining the strength of the cementitious mortar, the smart composites were reinforced with PVA fibers and then with NF fibers at fixed ratios of 2% by volume. The current goal is to improve the sensing capability by looking at the change in the fractional electrical resistance (FCER) under different stresses, such as bending and direct tension, at four different curing ages. These results were then compared to a control mixture to see how it helped improve the mechanical and electrical performance.

2 Materials and Standards

This section addresses the raw materials and functional fillers used, their characteristics, the quantities of their combinations, and the optimal mixing process for this research. The flowchart in Figure 1 illustrates the two main categories of laboratory testing in the last part of this section: mechanical tests and the electrical reaction of the created mixtures under different stress conditions.

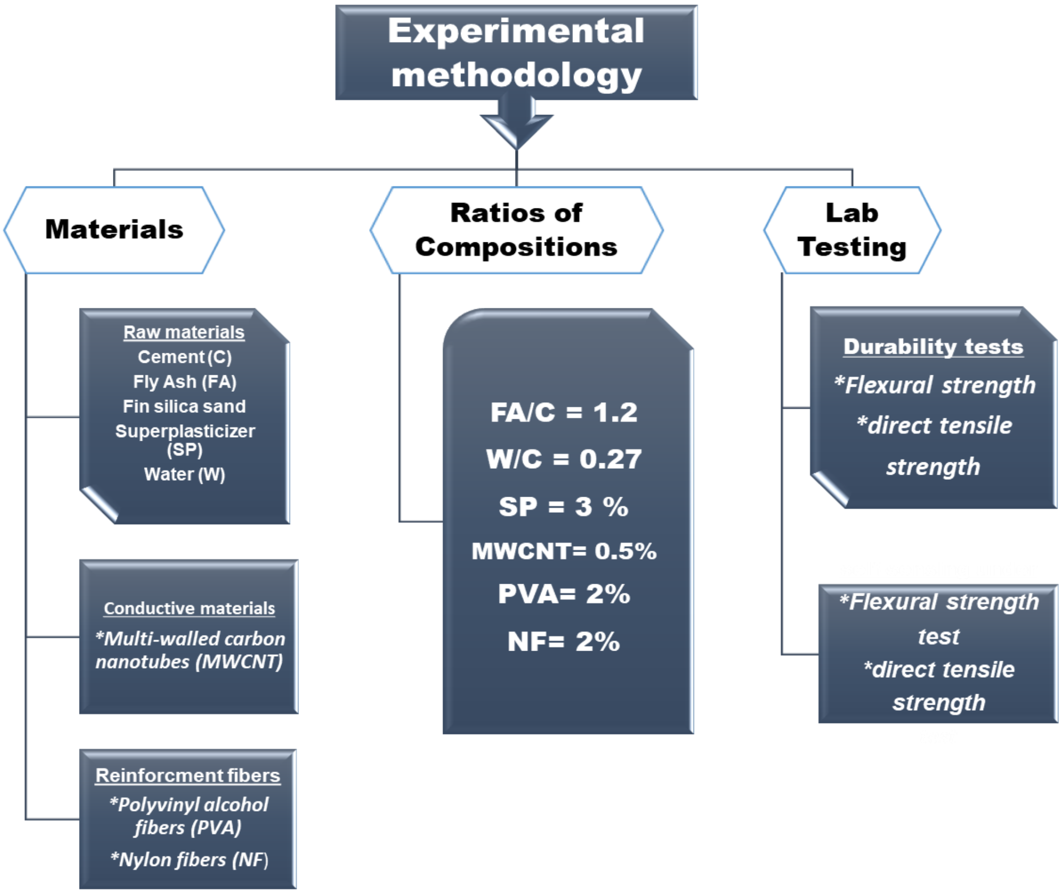
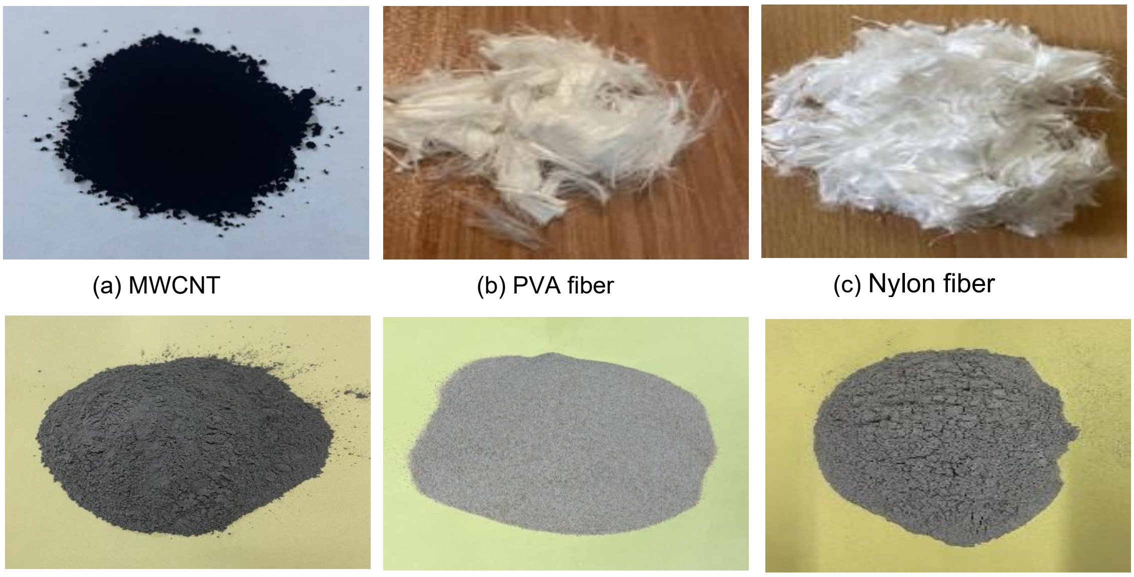


Fig. 1: Procedures of the experimental approach.

2.1 Materials

To manufacture smart arrays, it is necessary to go through the stage of detailing the basic materials and functional fillers, which together can form the self-damage-sensing ECC. The materials used in manufacturing the samples can be detailed into raw materials, functional fillers, and reinforcing fibers. Multi-walled carbon nanotubes with a diameter of 5–20 nm, a length of 10–30 μm, a surface area of 150–250 m2/g, and a maximum density of 0.04-0.08 g/cm3 were used as functional fillers in this study for self-sensing (Figure 2-a). The optimum dosage of MWCNT was 0.5% by weight of the cementitious materials throughout the study [24]. To give it more durability, two types of strengthened fibers were used. Polyvinyl alcohol (PVA) fibers measuring 8 mm in length and 39 μm in diameter were the first ones. Figure 2-b shows that these fibers had a specific gravity of 1.3, a modulus of elasticity of 42.8 GPa, and a tensile strength of 1620 MPa. The second type of reinforcing fiber was nylon fiber (NF) with a length of 19 mm and a diameter 0.55 mm and a tensile strength of 966 MPa; the elongation was 35.2% and the moisture content was 14.46%, (Figure 2-c). As for the raw materials, ordinary Portland cement type I was used according to Iraqi Standard Specification No. 5/1984 and European Specification No. EN 197-1:2011, (Figure 2-d). Silica sand from was used as fine aggregates in mortar mixes with a maximum particle size of 0.40 mm, a specific gravity of 2.6, and it can absorb 0.3 percent of water of its own weight (Figure 2-e). In accordance with ASTM C 618 (Figure 2-f), FA class F was used. The water-to-cementitious ratio in all of the mixtures was 0.27, and the water utilized was potable. The superplasticizer was used for workability. It satisfies ASTM-C494/C494M Type (F) standards and has a specific gravity of 1.095 kg/L. Table 1 displays the physical and chemical characteristics of silica sand, PC, and FA.



(a) MWCNT (b) PVA fiber (c) Nylon fiber

(d) Portland cement (e) Silica Sand (f) Fly Ash (FA)

Fig. 2: Examples of the raw components used.

Table 1: Chemical properties and physical characteristics of OPC, FA, and silica sand.

Chemical composition [%]	**OPC [wt.%]**	**FA [wt.%]**	**Silica sand**
CaO	63.35	8.08	--
SiO2	21.65	51.98	>= 50 - <= 100 %
Al2O3	3.52	17.04	--
Fe2O3	4.87	6.55	--
MgO	3.79	2.14	--
SO3	2.03	0.025	--
Loss on ignition [LOI]	2.05	10.33	--
Insoluble residue	0.71	-	-
Lime saturated Factor	0.89	-	-
Physical properties	**OPC [wt.%]**	**FA [wt.%]**	**Silica sand**
Specific gravity	3.16	2.09	2.65
Blaine fineness [cm2 g−1]	3941	2689	----

Table 2: Characteristics of the Reinforcement Fibers.

Characteristics	**PVA**	**NF**
Diameter [μm]	0.039	0.055
Length [mm]	12	19
Elongation [%]	6	8
Tensile strength [MPa]	280-400	699
Modulus of elasticity (GPa]	16.20	4
Shape	Straight	Straight
Color	white	White

Table 3: Physical Properties of Multi-Wall Carbon Nanotubes.

Physical properties	
Diameter [nm]	5-20
Length [μm]	10-30
Surface area [m2 /g]	150–250
Bulk Density [g/cm3]	0.04–0.08
Purity	>95

2.2 Ingredients and Proportion Formulation

In this section, the study dosage ratios and the process of making smart composites are explained, where a ratio of 1.2 for FA/OPC and a ratio of 0.27 for W/CM were used. These ratios were adopted according to previous studies in the same field and specialty [3, 25-29]. In order to obtain good workability and due to the absorption properties of PVA fibers, two ratios of superplasticizer were used:

the first ratio was 3 wt.% of cementitious materials for PVA fiber-reinforced matrices, and the second ratio was 1 wt.% for nylon fiber-reinforced mixtures. As for the additive fillers, 0.5 wt.% for CNT, 2 vol.% for PVA, and 2 vol.% for NF were used [24]. To produce the smart samples, the entire amount of mixing water containing the superplasticizer (SP) and nanomaterials was mixed using a kitchen mixer set at 3000 rpm for five minutes. A 20-liter Hobart mortar mixer was used to mix the components for 10 min at 100 rpm Then, the superplasticizer and CNT/SP/water solution were gradually added to the dry mixture with the speed kept at 100 rpm for ten seconds. Then another ten minutes were spent combining the dry and wet components at 300 rpm. To incorporate the reinforcement fibers, the mixer was slowed down to 100 rpm for ten minutes Then, the speed was increased to 300 rpm for another ten minutes to fully incorporate all the materials [24, 30, 31].

2.3 Laboratory Tests

2.3.1 Evaluations of Mechanical properties

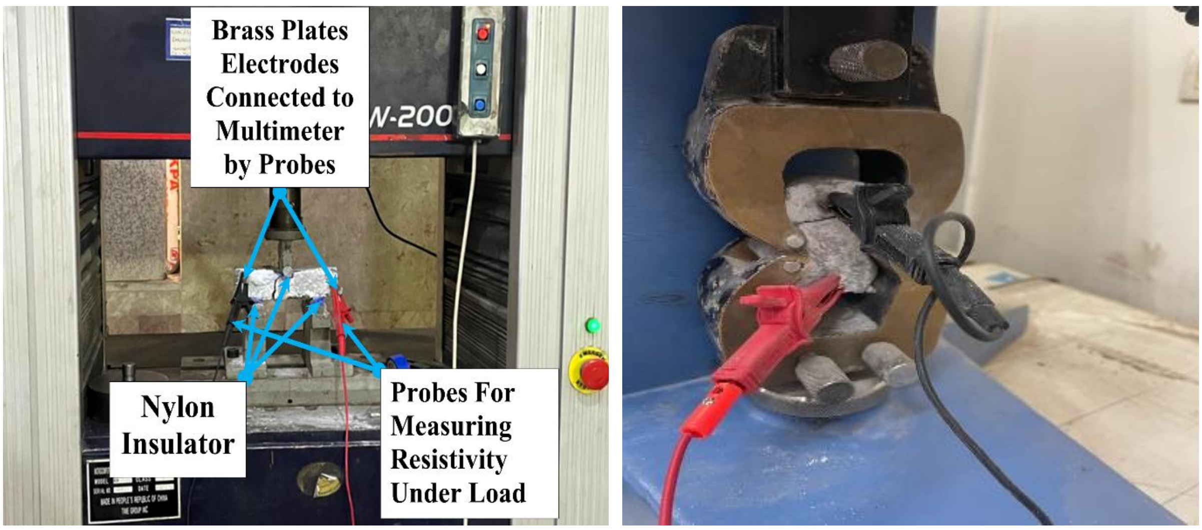
The specimens in this section were measured after undergoing direct tensile and three-point flexural tests, as well as four different treatments for 28, 56, 90, and 180 days in water at room temperature. This method is designed to provide more accurate and realistic results that represent the self-sensing response under different loading conditions.

2.3.2 Test for bending strength

The bending test was conducted on prismatic specimens with dimensions of 40mm×40mm×160mm, according to [32]. The smart prisms were mechanically evaluated by supporting them at two points separated by 120 mm, which corresponds to the exact distance between the two probes placed inside the prism. Then, the load was applied using a 200 kN digital testing machine (WDW-200E) connected to a computer data logger. The applied load rate was 0.5 mm/s. The software in the testing machine documented the correlation between the bending force, deflection, and time. Figure 3-a shows a prismatic specimen under the flexural test.

2.3.3 Test of Direct Tensile strength

The direct tension method was used to perform the direct tensile strength test, as mentioned in [33]. A 10 kN ELE mechanical testing equipment was used at a load rate of 0.02 kN/s on dog bone specimens, measuring 40*75*25 mm, and three specimens of each combination design at intervals of 28, 56, 90, and 180 days were tested. Figure 3-b shows the dog bone specimen under direct tension testing.



(a) Flexural test, according to [32] (b) Direct tension test , according to [33]

Fig. 3: The settings for mechanical assessment.

2.3.4 Investigation of the self-sensing property

The self-sensing response to the applied load was tested using functionalized nanocomposite ECC composites. These were made up of nano-based conductive materials. The sensing behavior of the smart samples reinforced with PVA and nylon fibers was monitored under two types of loading: four-point flexural stresses and direct tensile stresses. It was also checked how well each functional matrix could find the small changes in electrical resistivity when stress was put on them. The proposed configuration for this study involves the use of dog bone specimens for direct tensile evaluation and prismatic specimens for flexural evaluation, including the control composites. Before testing at all suggested study ages (28, 56, 90, and 180 days), the samples were oven-dried at 60 °C for a 24 hr. to reduce the polarization process that resulted from the treatment of the samples in water. To evaluate the damage sensing ability of the fabricated specimens, electrodes were embedded within them using strips cut from a copper sheet of two different lengths to suit the dimensions of the specimen being measured. For example, the length of the prismatic specimen electrodes was 6 cm, while the length of the dog bone specimen electrode was 4 cm, both with a constant width of 1 cm and a thickness of 0.1 mm. The resistance of the strips was measured as 0.3 ohms, and they were symmetrically placed around the center of the specimen, as shown in Figures 5 and 6. The remaining exposed part of the electrode was connected to an electrical resistance tester. This arrangement is consistent with previous researches [2, 3, 25-27, 34, 35]. The electrical resistivity was measured by using a Pro'sKit MT-1820 DC multimeter [36]. The interaction between the specimen and the load testing machine was avoided by placing thin nylon insulators above and below the specimen. This arrangement aims to prevent the electrical signal moved to the electrical resistivity tester from interfering with the mechanical testing machine. Fig. 6 illustrates self-sensing settings under suggested stresses in this paper. Electrical resistivity and mechanical stress measurements were performed simultaneously for each second under loading conditions. This indicated that the average mechanical resistance values and the fractional change in electrical resistivity (Equation 1) could be plotted over time.

$$FCER(\%) = \frac{RL-RO}{RO} \times 100 \quad (1)$$

where RO stands for initial electrical resistance, FCER for fractional changes in electrical resistance, and RL for electrical resistance under loading at a specific time during the test.

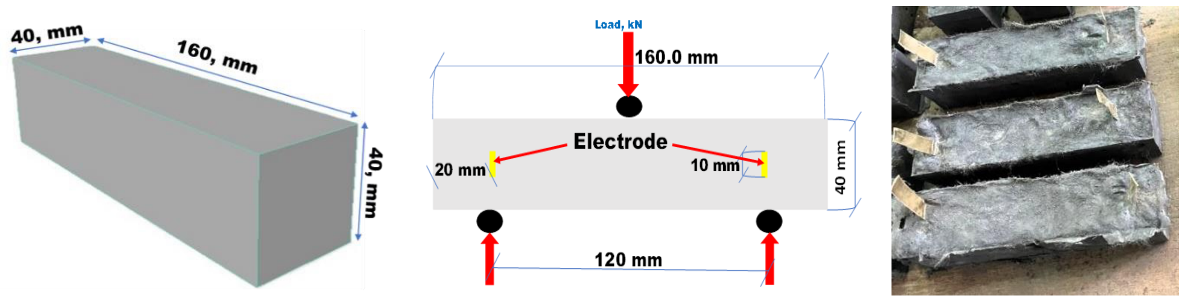


Fig. 4: The geometric dimensions of the prismatic specimens.

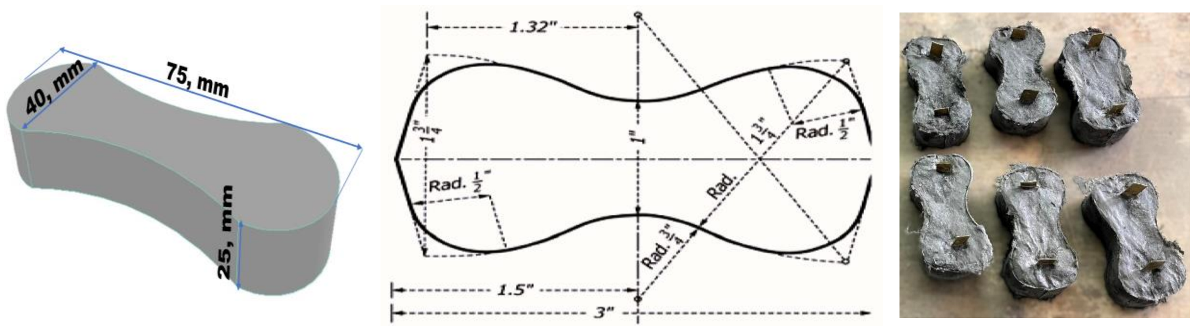
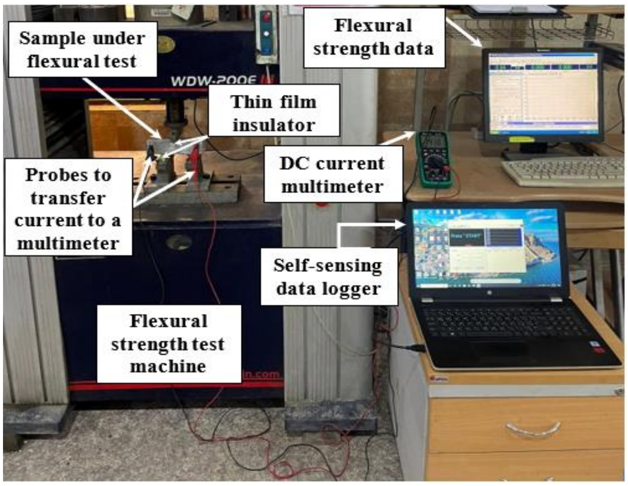


Fig. 5: The geometric dimensions of the dog-bone specimens [33].



(a) Self-sensing under flexural strength


(b) Self-sensing under direct tensile strength

Fig. 6: self-sensing setup under loading.

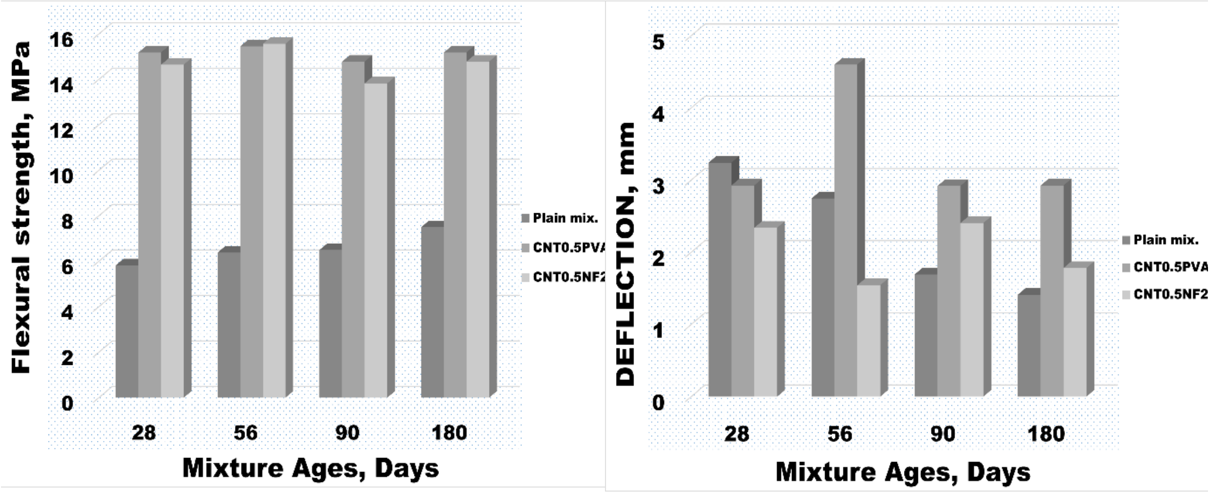
3 Results and discussion

3.1 Mechanical features

This section discusses and evaluates the test results for mortar specimens, both with and without conductive elements, at treatment ages of 28, 56, 90, and 180 days. This study looked at how self-monitoring works in new mixes of mortar that have nano-scale conductive additives and different kinds of reinforcing fibers added to them. The study concentrated on mechanical properties, specifically flexural strength and direct tensile strength.

3.1.1 Evaluation of flexural strength

Before starting to discuss and evaluate the results of self-damage sensing of the arrays manufactured by electrically conductive nanomaterials and reinforced with fibers in this investigation, it is very necessary to analyze the effect of these additives on the durability properties after comparing them with the reference mixtures for the study ages of 28, 56, 90, and 180. Figure 7-a shows the average flexural strength values of three prism samples measuring 4×4×16cm, while Figure 7-b shows the average mid-span deflection values. The results can be analyzed in comparison with the reference arrays to become clearer. Looking at Figure 7, the development in the flexural strength of the innovative mixtures can be observed, indicating excellent performance under the applied load for both smart mixtures (CNT0.5PVA2 and CNT0.5NF2), as well as for all the proposed ages for the study. The results proved the superiority of the mixtures reinforced with PVA fibers over those reinforced with NF fibers due to the higher tensile strength of PVA fibers than that of nylon fibers. The functional mixture CNT0.5PVA2 can be evaluated compared with the normal mixtures. The improvement percentages in terms of flexural strength for ages 28, 56, 90, and 180 were 162%, 142%, 128%, and 103%, respectively. While the gradual improvement of the mixture CNT0.5NF2 for ages 28, 56, 90, and 180 was 152%, 144%, 112%, and 97%, respectively. In general, the results presented in Figure 7-A clearly show the improvement in the average flexural strength of the innovative matrices with age and are superior to the reference mixtures for the same proposed curing age. These results are in complete agreement with what was reached by Yıldırım, et al. [24], who attributed this improvement to the increase in the amounts of superplasticizer used in mixtures containing PVA fibers, Resulting in delayed development of flexural strength properties of later ages due to development of fiber bond and cement matrix interface [37, 38]. The percentage of carbon nanotubes may also have a direct relationship with the increase in flexural strength [18]. The improvement of the properties of functional mortar with CNTs can be attributed to the physical role of CNTs in filling the gaps between C-S-H and ettringite, which in turn leads to a reduction in the permeability of the cement matrix [39]. In addition, the nanofiller bridges the microcrack and prevents it from developing, which leads to enhancing the durability properties of cement matrices [40]. The present results are in good agreement with the findings of [41] on the significant effects of multi-walled carbon nanotubes on the flexural behavior. The results of the study conducted by Sadiq, et al. [41] indicate that the incorporation of multi-walled carbon nanotubes into cementitious mortar effectively increased the flexural strength, energy absorption, and degradation in the ultra-high performance of cementitious mortar by 30%, > 100%, and > 200%, respectively. These improvements are attributed to the enhanced load transfer efficiency at the interface. Because they have strong interactions with other materials, carbon nanotubes make the interface for stress transfer better and stronger. This stops microcracks from spreading [42]. The results of the study conducted by [43] show that the addition of nano-reinforcements and microfibers produces a composite that can support much more weight in the elastic phase. This is evident from the fact that the first crack strength increases by about 100%. The results obtained by [44] indicate that adding a dosage of (0.5–1%) nylon fibers significantly improve the flexural properties, and the higher the percentage of fibers, the higher the flexural strength, while it reduces the compressive strength of cementitious matrices. This is consistent with the results of the flexural strength values obtained in this study at a dosage of 2% per volume of the total mixture. The great results in flexural strength are mostly due to the useful effects that nanofillers have on the mortar's microstructure and the way they work together with the mechanical reinforcement fibers. As for the contribution of the reinforcement fibers, it is largely related to the phenomenon of crack bridging and increased plasticity of the matrix. Regarding the average deformation values under flexural loading, the results were different depending on the age of curing, and this was evident in all mixtures, both normal and smart. The deformation values of the reference mixtures were continuously decreasing due to the hydration process and matrix hardening, which accelerated the development of the initial crack. The behavior of the innovative nano-based matrices differed in the early ages compared to the late ages, during which there was a noticeable increase in the deformation values. It's possible that this is because the fiber-matrix interface and the fiber-CNT interface work together to connect and bridge the cracks, which slows down the matrix's failure. This is completely consistent with what was reached by [18, 24].



(a) (b)

Fig. 7: The mechanical characteristics for various ages of composite substances include: a) flexural strength; b) flexural deflection.

3.1.2 Evaluation of Direct Tensile Strength

Figure 8 shows the average direct tensile strength values of three dog bone specimens measuring 75×40×25mm from each type of mixture over the study ages. The innovative smart mixtures of nanofillers that are reinforced with fibers are compared with reference mixtures of the same ages in this study in order to know the effectiveness of the fillers incorporated into the plain matrix under this type of loading. Figure 8 presents a noticeable gradual development in the direct tensile strength values for all ages. The superiority of the reinforced mixtures with PVA fibers was recorded over those reinforced with nylon fibers, indicating that the nanofillers and the reinforcement fibers of the plain matrix had a clear positive effect in improving the tensile strength. Since the two matrices contain the same dosage of carbon nanotubes, the superiority of the CNT0.5PVA2 matrix was due to the PVA fibers that excel in their physical properties related to tensile strength. This is completely consistent with what were reached by the researchers [45, 46]. The improvement percentages of the smart mixtures compared to the control mixtures can be summarized as follows. For example, the gradual improvement with curing age of the CNT0.5PVA2 matrix at ages 28, 56, 90 and 180 days was 10%, 5%, 5%, and 15%, respectively. At ages 28, 56, 90 and 180 days, the CNT0.5NF2 matrix improved its strength values by 8%, 4%, 3% and 2%, respectively. The strength development of smart blends from 28 to 180 days can, also, be summarized. For example, the strength development of the CNT0.5PVA2 blend from 28 to 180 days of initial cure was 21%—from 5.6 to 6.8 MPa—while the strength development of the CNT0.5NF2 blend from 28 to 180 days was 9%—from 5.48 to 5.95 MPa. It is believed that fibers, especially PVA, help the cement matrix stick together by crossing over cracks and stopping them from getting worse and spreading through the matrix. This makes the cement system more resistant to tensile loads at later stages of displacement [19].

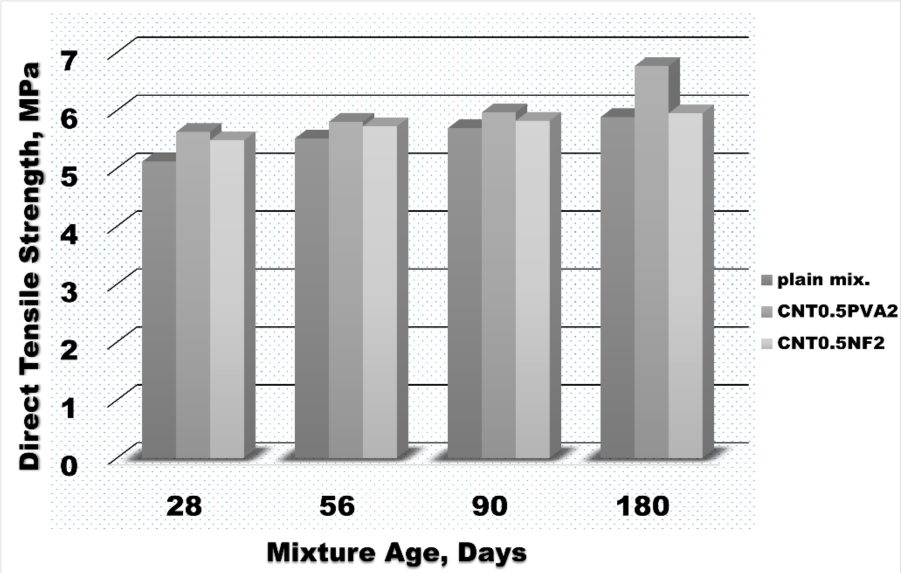
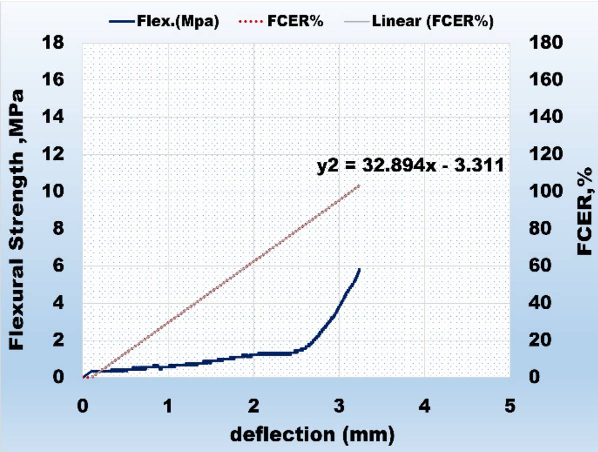


Fig. 8: Intelligent mixes' direct tensile strength Vs age.

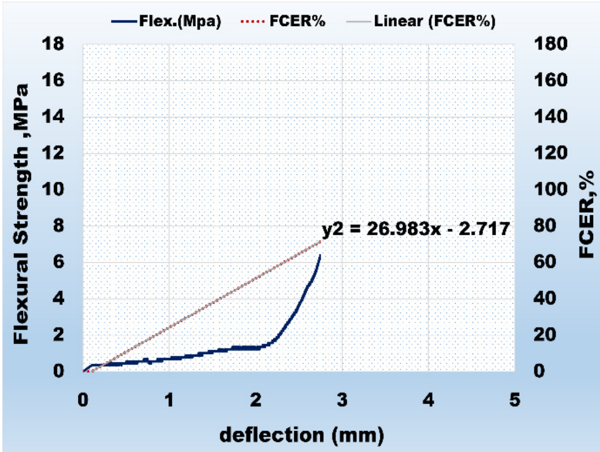
3.2 Piezoresistivity Capability Results of the Intelligent ECC

3.2.1 Evaluation of ECC's Self-Damage Sensing Response Under Three-Point Bending Stress

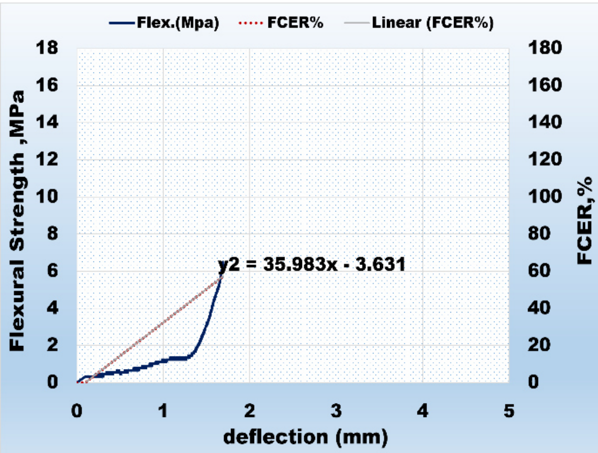
This section discusses and evaluates the self-sensing results obtained from subjecting the innovative, clever samples fabricated of carbon nanotubes reinforced with PVA and NF fibers to three-point bending stresses for early and late curing ages. Figs. 9–11 display the self-sensing behavior of both smart and regular mixtures. They show the connection between the fractional change in electrical resistance (FCER) (sensing behavior under load) and the bending stress (vertical axis) with the deformation (horizontal axis). Generally, it can record the behavior of the electrical resistance change in all mixtures, both with and without conductive materials, from the outset. This behavior grows irreversibly in a linear direction, with the FCER percentage varying depending on the type of matrix and the curing age for a specific graph. Figure 9 shows the behavior of the control mixtures for the self-sensing response under compressive loading for ages 28, 56, 90, and 180. Although the modest FCER values and the absence of conductive fillers, the control mixtures perform well, showing a continuous increase in the sensing values under load, starting from zero. In the elastic phase (initiation of loading), where no tiny cracks are apparent , the slight differences in the FCER results can be linked to the imposition of certain carbon-based materials and electrically conductive phases of the samples subjected to flexural loading, The sensing values of the reference and smart mixtures for early ages may also be related to polarization due to the abundance of hydration water that has not yet participated in the hydration processes, in addition to the possibility of the presence of micro-cracks in the microstructure of the matrix-aggregate interface [24, 35, 47]. With increasing flexural loading and deflection hardening experience, FCER results consistently increased for all mixtures regardless of curing age due to separation and/or collapse of conductive paths due to microcracks. The continuous increases in FCER during deflection hardening were followed by more dramatic increases at stress near ultimate failure, likely due to the localization of a specific microcrack. The moderate gradual trend in FCER results with progressive flexural loading was found to be similar to that observed under uniaxial compression, likely due to the distance between the electrode location (Fig. 4) and the expected microcrack zone (directly below the upper loading heads) for prismatic specimens. As mentioned in the introduction to this section, FCER values increased linearly for matrices regardless of matrix type or age. This behavior, which is common to prismatic specimens under flexural stress, is likely due to damage to the electrical network, which leads to the interruption of the conductive paths after the crack develops as a result of the flexural load progressing over time. Figures 10 and 11 show the behavior of the smart blends CNT0.5PVA2 and CNT0.5NF2 respectively. Although they barely outperform the reference blends, they have recorded a noticeable improvement in FCER values. This is undoubtedly due to the development of the electrical network within the cementitious system due to the injection of carbon dosage at the nano- scale, in addition to another effect that can positively affect the increase in sensing values, related to the bridging of the fibers to the crack before failure, which keeps the network in contact with the remaining valid conductive paths [48].



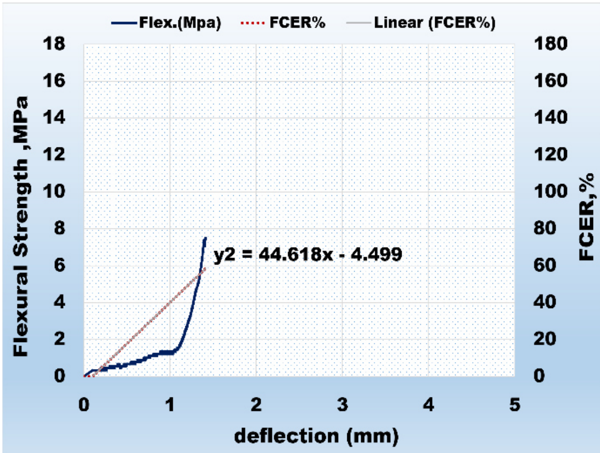
a) Self-sensing behavior of plain mixture prism samples under bending test, age 28



b) Self-sensing behavior of plain mixture prism samples under bending test, age 56

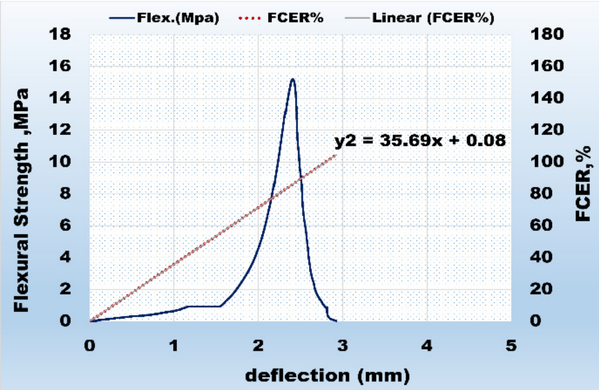


c) Self-sensing behavior of plain mixture prism samples under bending test, age 90

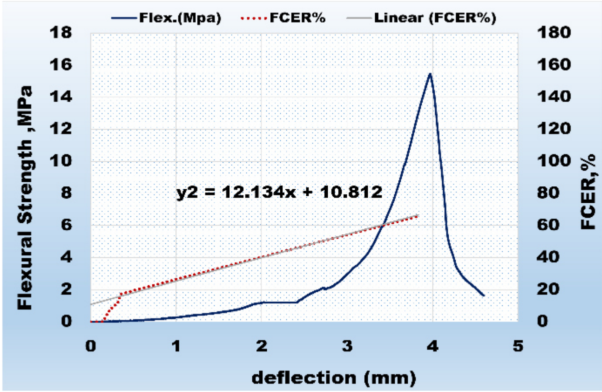


d) Self-sensing behavior of plain mixture prism samples under bending test, age 180

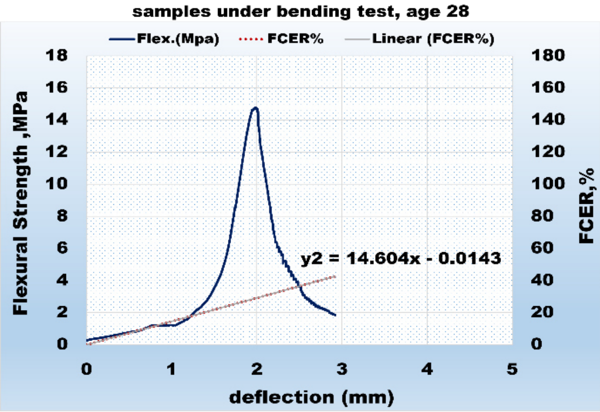
Fig. 9: Self-sensing of plain mixtures under flexural strength for different curing age.



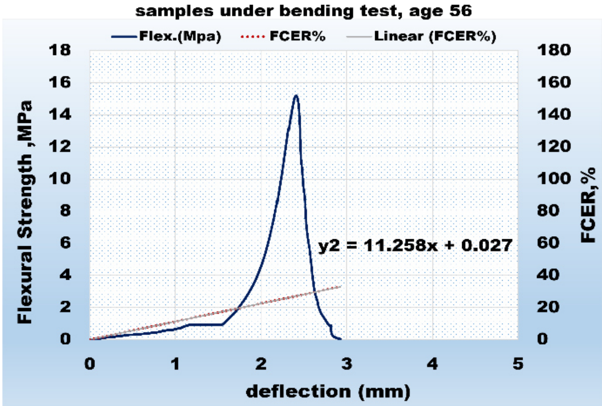
a) Self-sensing behavior of CNT0.5PVA2 mixture prism samples under bending test, age 28



b) Self-sensing behavior of CNT0.5PVA2 mixture prism samples under bending test, age 56

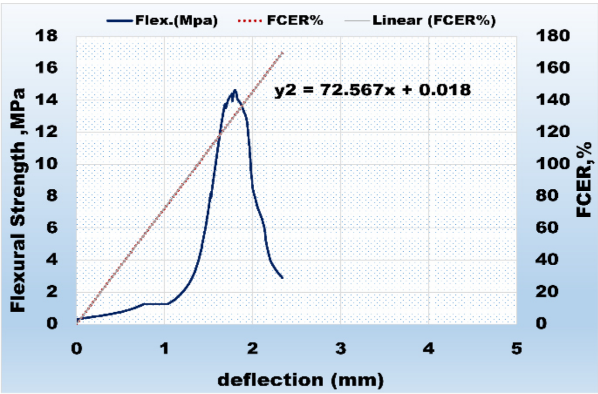


c) Self-sensing behavior of CNT0.5PVA2 mixture prism samples under bending test, age 90

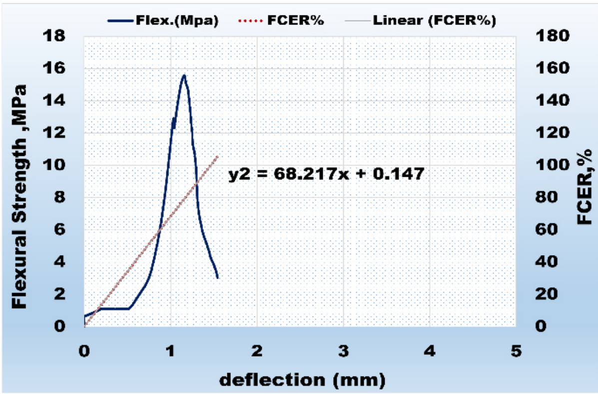


d) Self-sensing behavior of CNT0.5PVA2 mixture prism samples under bending test, age 180

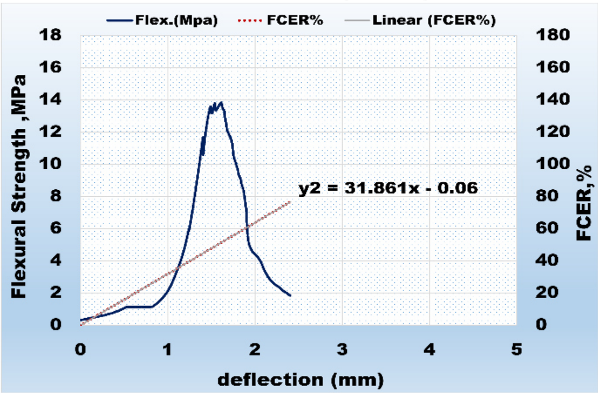
Fig. 10: Self-sensing of CNT0.5PVA2 mixtures under flexural strength for different curing age.



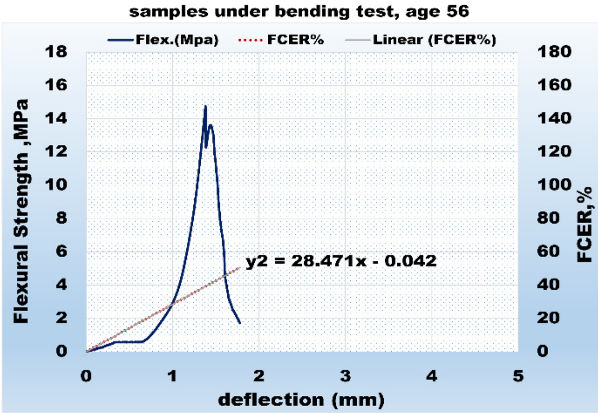
a) Self-sensing behavior of CNT0.5NF2 mixture prism samples under bending test, age 28



b) Self-sensing behavior of CNT0.5NF2 mixture prism samples under bending test, age 56



c) Self-sensing behavior of CNT0.5NF2 mixture prism samples under bending test, age 90

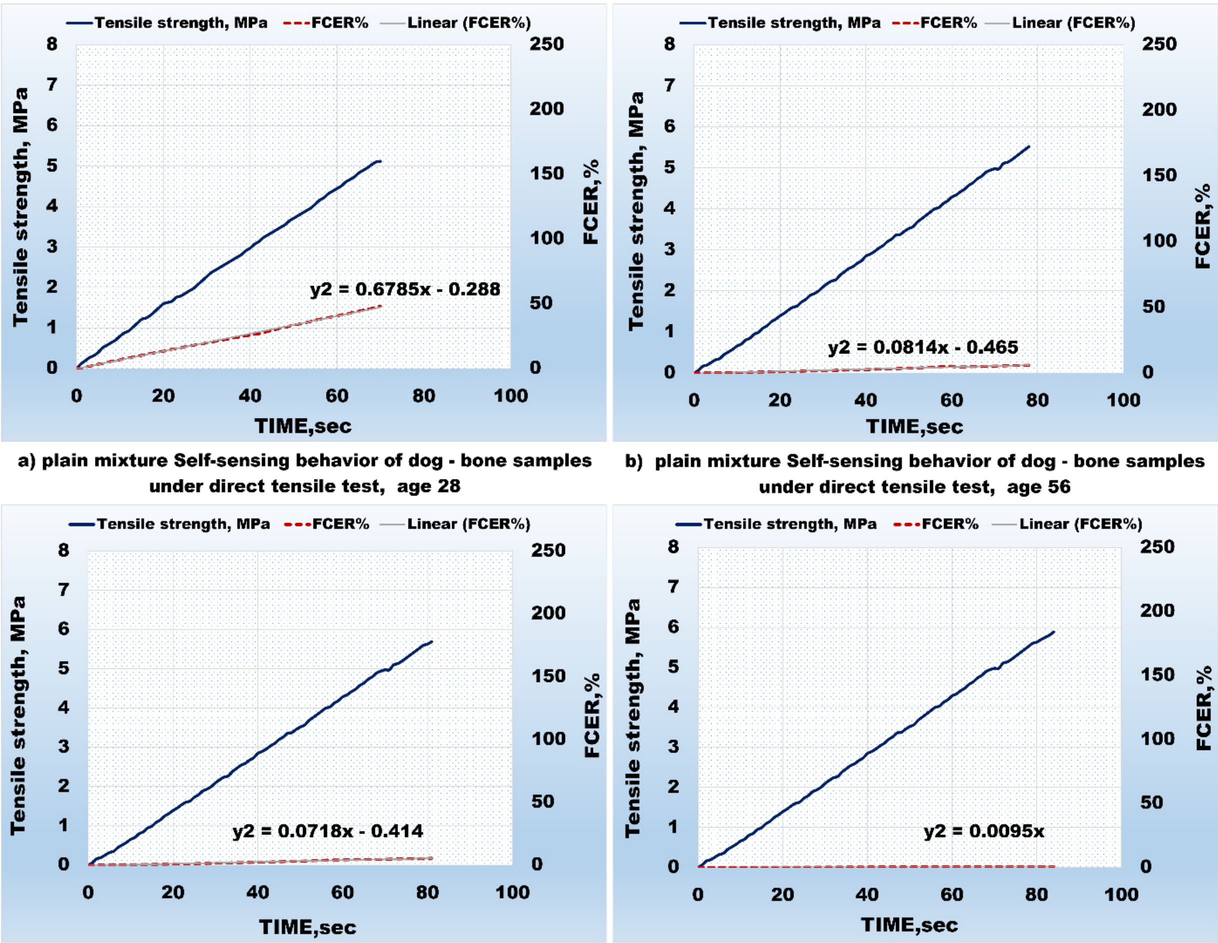


d) Self-sensing behavior of CNT0.5NF2 mixture prism samples under bending test, age 180

Fig. 11: Self-sensing of CNT0.5NF2 mixtures under flexural strength for different curing age.

3.2.2 Evaluation of ECC's Self-Damage Sensing Response Under Direct Tension Stress

Figures 12-14 present a visualization of the behavior of ECC arrays for average damage sensing values under direct tensile loads for the reference and novel smart alloys over time. The remarkable improvement in the self-sensing properties of the matrices developed with conductive nanofillers is due to the activation of electron transfer through tunneling between carbon nanotubes or fibers-to-fibers [45, 46], especially for PVA fibers due to their coating with carbon nanotube particles that improve the polarization process, and this is evident at early ages (Figs. 13 and 14) at ages of 28 and 56 days. The development of self-sensing associated with carbon nanotube arrays is due to the contact of carbon nanotube particles with the surfaces of polyvinyl alcohol or nylon fibers due to the hydration processes and pozzolanic interactions of cementitious compounds, which enhances the polarization level of electron movement as we mentioned earlier, and this conclusion is consistent with the conclusion of a study conducted by [49, 50]. In a study conducted by Al-Bahrani [51], the improvement in the levels of self-sensing of carbon nanotube arrays was attributed to the quality of load capture resulting from several positive influential factors, including the tunnel effect that contributes to improving the electrical network interconnection, the orientation of CNTs, and the contact area between neighboring CNTs. A previous study [52] has proven the validity of the results shown in Figures 13 and 14 (regardless of the treatment age) by increasing the FCER values under monotonic direct tensile force, which is related to the behavior of the fibers to break or separate when applying this monotonic stress, including nylon fibers and PVA fibers carbon coated, and the difference is only in the behavior pattern of the graph. In addition to the effect of the applied direct tension stress on the behavior of the fractional change in electrical resistivity, the crack pattern also directly affects the self-sensing values of functional arrays [53-59].



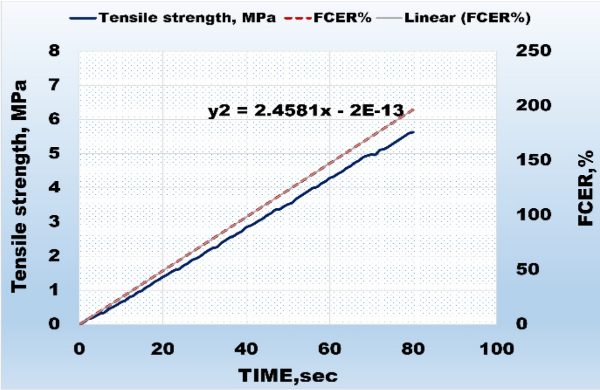
a) plain mixture Self-sensing behavior of dog - bone samples under direct tensile test, age 28

b) plain mixture Self-sensing behavior of dog - bone samples under direct tensile test, age 56

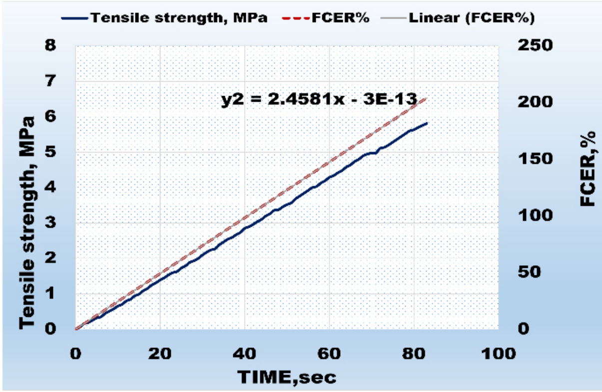
c) plain mixture Self-sensing behavior of dog - bone samples under direct tensile test, age 90

d) plain mixture Self-sensing behavior of dog - bone samples under direct tensile test, age 180

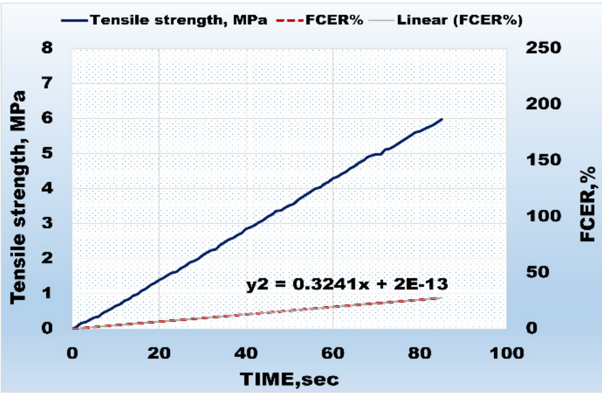
Fig. 12: Self-sensing of plain mixtures under direct tensile strength for different curing age.



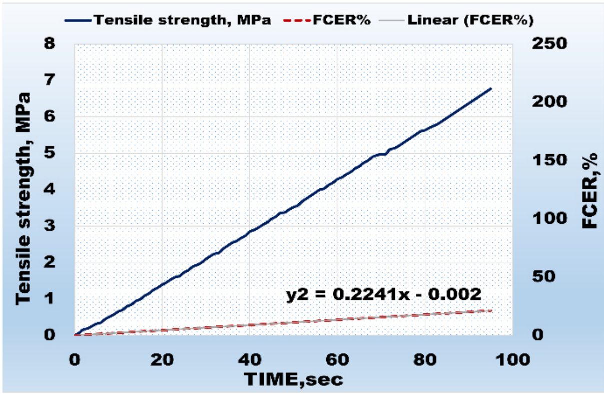
a) CNT0.5PVA2 mixture Self-sensing behavior of dog - bone samples under direct tensile test, age 28



b) CNT0.5PVA2 mixture Self-sensing behavior of dog - bone samples under direct tensile test, age 56

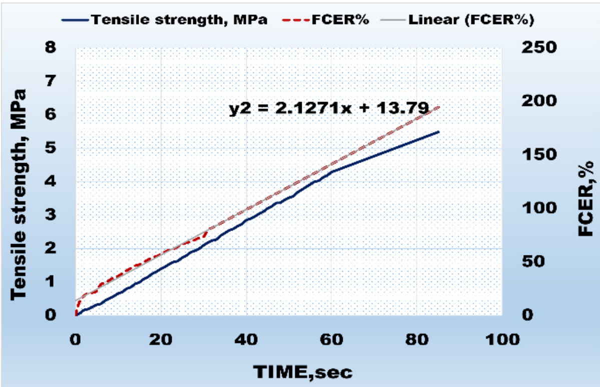


c) CNT0.5PVA2 mixture Self-sensing behavior of dog - bone samples under direct tensile test, age 90

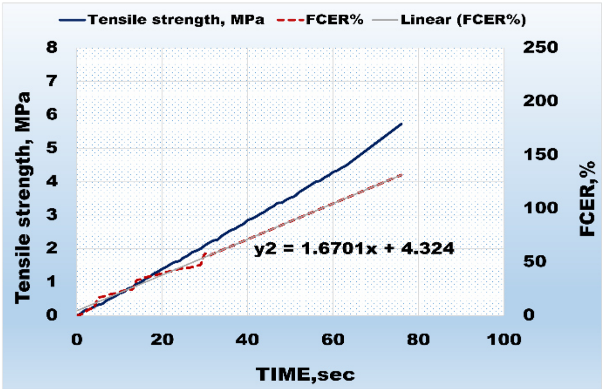


d) CNT0.5PVA2 mixture Self-sensing behavior of dog - bone samples under direct tensile test, age 180

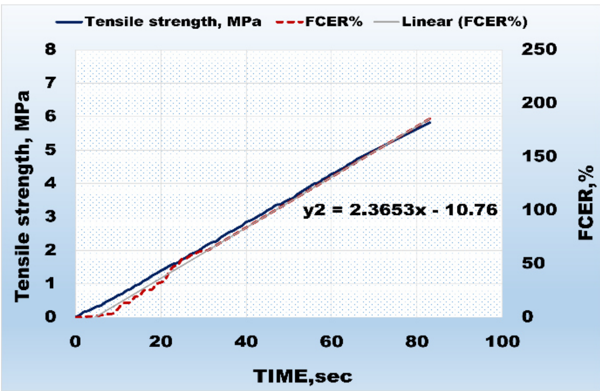
Fig. 13: Self-sensing of CNT0.5PVA2 mixtures under direct tensile strength for different curing age.



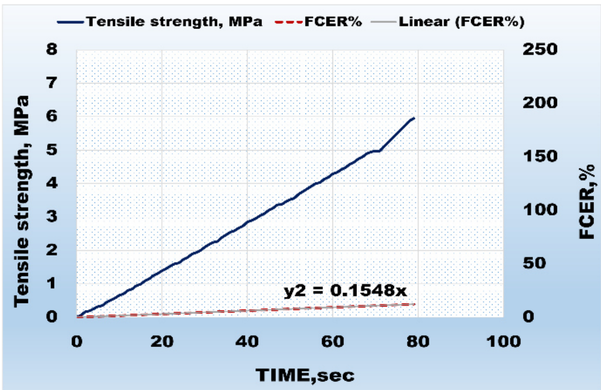
a) CNT0.5NF2 mixture Self-sensing behavior of dog - bone samples under direct tensile test, age 28



b) CNT0.5NF2 mixture Self-sensing behavior of dog - bone samples under direct tensile test, age 56



c) CNT0.5NF2 mixture Self-sensing behavior of dog - bone samples under direct tensile test, age 90



d) CNT0.5NF2 mixture Self-sensing behavior of dog - bone samples under direct tensile test, age 180

Fig. 14: Self-Sensing of CNT0.5NF2 mixtures under direct tensile strength for different curing age.

The relationship between electrical resistance and tensile strength, as well as the role of electrical resistance in damage propagation under tensile loading, can be understood through their interconnected effects on self-sensing cementitious composites.

Electrical resistance is sensitive to the structural integrity of cementitious composites. When these materials are subjected to tensile stress, the electrical network established by conductive fillers such as multi-walled carbon nanotubes (MWCNTs) respond to microcracks and deformations by increasing fractional changes in electrical resistance (FCER). This change corresponds to the disruption of the conductive pathways. Wang et al., 2023 [4] indicate that composites reinforced with carbon nanotubes and fibers (e.g., PVA or nylon) demonstrate both enhanced tensile strength and damage detection capabilities. For instance, the CNT0.5PVA2 matrix showed superior mechanical performance, with increased tensile strength up to 15% at 180 days of curing, compared to a reference mix. Simultaneously, these materials exhibited robust self-sensing capabilities, with electrical resistance increasing proportionally with crack propagation and stress levels, allowing early detection of damage before catastrophic failure.

Thus, tensile strength improvements provided by reinforcements complement the piezoresistive behavior, where electrical resistance serves as a real-time indicator of structural integrity. The synergy of mechanical reinforcement and electrical responsiveness makes these materials effective for both load-bearing and monitoring purposes.

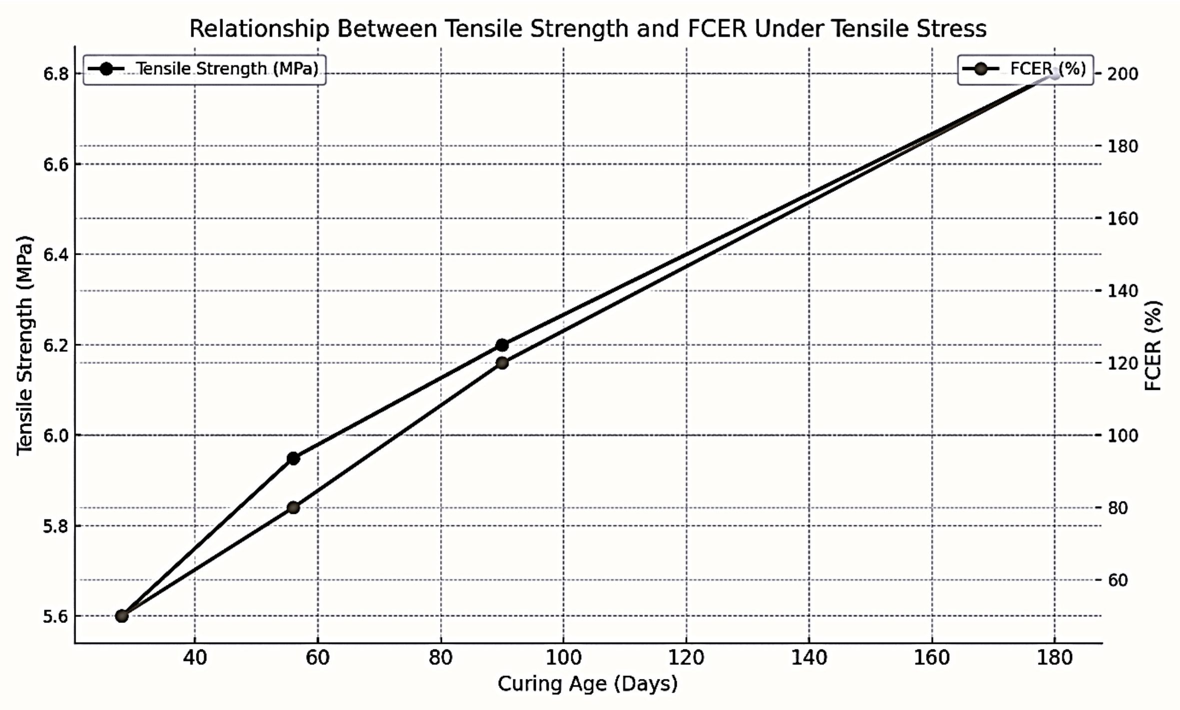


Fig.15: the tensile strength with fractional change in electrical resistivity under tensile stress.

Figure (15) illustrates the relationship between tensile strength and the fractional change in electrical resistance (FCER) under tensile stress over different curing ages. The tensile strength (blue line) Increases gradually with curing age, showing improved mechanical properties due to the matrix's enhanced bonding and reinforcement by PVA fibers and CNTs. Also, the FCER (red line) Rises significantly with curing age, reflecting the material's enhanced ability to detect damage as the conductive network develops and becomes more responsive to applied stress.

4 Conclusions

An extensive study was conducted on the evaluation of the innovative matrices of carbon nanotube incorporation and reinforced with nylon and polyvinyl alcohol fibers through their response to the applied load as well as the reflection of the effect of these additives on the durability of the system in this paper. This assessment was carried out after curing periods of 28, 56, 90, and 180 days beneath direct flexural and tensile load conditions. The following was concluded:

1) Flexural tests showed that the new mortar made with carbon nanotubes and polyvinyl alcohol fibers (CNT0.5PVA2) is stronger than both the regular mixtures and those made with nylon fibers (CNT0.5NF2). Overall, these smart mixtures are beneficial for building infrastructure and concrete structures because they handle bending loads better than the regular mixtures studied at all ages. The percentage of improvement in the CNT0.5PVA2 matrix for ages 28, 56, 90, and 180 was 162%, 142%, 128%, and 103%, respectively. The percentage of improvement in the CNT0.5NF2 matrix for ages 28, 56, 90, and 180 was 152%, 144%, 112%, and 97%, respectively. Compared to control mixtures.

2) Under direct tensile tests, the CNT0.5PVA2 matrix showed a clear advantage in its response to the applied load compared to the smart and simple CNT0.5NF2 matrix. The tensile strength development ratios of the innovative matrices compared to the control blends were as follows. The CNT0.5PVA matrix outperformed by 10%, 5%, 5%, and 15% at curing ages of 28, 56, 90, and 180 days, respectively. The CNT0.5NF2 matrix showed an improvement of 8%, 4%, 3%, and 2% for the same treatment ages.

3) The new smart mortar matrices can detect damage when they are under bending and direct tension loads. They demonstrated their effectiveness in detecting damage by gradually increasing the fractional change in electrical resistivity as the loading scenarios and curing ages in the study changed. They also have superior FCER values compared to the reference matrices and are recordable from the beginning and continuously increasing in a linear direction under the applied load. The superiority in this field was for the CNT0.5NF2 matrix, where the self-sensing values reached 170 and 200% under flexural and direct tensile loads, respectively.

5 Recommendations For Future Research

1) A hybrid matrix can be made by integrating nylon fibers and polyvinyl alcohol with carbon nanotubes in a single matrix and studying the effect of this hybrid integration on the strength and self-sensing behaviors.

2) Conducting more laboratory tests including ultrasonic testing and studying the effect of additives on the accuracy of wave transmission and recorded data.

3) Based on the results of this study, these arrays could be used in paving and civil infrastructure works, as well as other concrete structures. The self-sensing properties could also be used if further studies are conducted, including field testing on an actual cement mortar sample on site.

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