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Self-sensing engineered cementitious composites with carbon nanotubes and reinforcing fibers for damage detection

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HIGHLIGHTS

- The mechanical and self-sensing properties of ECC with nano-additives were assessed.
- In split tensile loading, the CNT0.5NF2 matrix had a higher electrical resistance by 20% than the CNT0.5PVA2 matrix.
- PVA and nylon fibers at 2 vol.% were applied to enhance mechanical properties.
- A synergistic effect between CNTs and fibers improved the overall mechanical behavior.
- PVA fibers enhanced electrical conductivity by absorbing nanofillers.

Keywords:

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

ABSTRACT

Engineered Cementitious Composites (ECC) represent innovative construction materials that exhibit established mechanical properties and strength features. The exceptional characteristics of this substance render it a compelling option for various kinds of facilities. However, the increased implementation of ECCs necessitates monitoring the structural integrity of the systems that utilize them. This paper focuses on developing this concept by employing the traditional matrix after incorporating it with conductive fillers. These fillers transform the matrix into a functional state to sense the damage caused by various loads. Such loads include indirect tensile loads and compressive strength of mortar samples composed of cementitious matrix injected with multi-walled carbon nanotubes (MWCNT) and reinforced once with polyvinyl alcohol fibers (PVA) and with nylon fibers (NF) at another time, with different study ages of 28, 56, 90, and 180 days of curing with water at room temperature. In order to develop previous works and fill part of the gap, the traditional matrix was injected with carbon nanotubes at a dose of 0.5 by weight of cementitious materials with one of the reinforcement fibers of (PVA) or (NF) at a rate of 2% by the total volume of the mixture, which is a constant ratio throughout the study. In addition, a control mix free of additives was created for comparison. The results indicate that clever matrices have excellent mechanical properties. The PVA fiber-reinforced matrix performed better than the other matrices under applied loads. The electrical properties of the matrices were recorded from the start of load application and increased with increasing load. The CNT0.5PVA2 matrix had more gains under compressive loading, with a self-sensing ratio reaching about 200%. In split tensile loading, the CNT0.5NF2 matrix had a higher electrical resistance by about 20% than the CNT0.5PVA2 matrix, which had a resistance of less than 10%.

1. Introduction

It is well known that the concrete structure does not contain any functional structure or electrical conductivity that enables it to perform multi-functionally to serve many directions in various applications. Therefore, a new technology based on the concept of creating an electrical network within conventional concrete has been used to enable its employment in these many applications, including early detection of damage before it develops through the concept of electrical conductivity and the network resistance formed within the matrix by the functional fillers prepared for this purpose, which are called "Engineered Cementitious Composites" (ECC) [1-3]. Thus, to achieve low cost and eliminate the disadvantages of integrating electronic sensors in terms of sensing, durability, or incompatibility with cementitious structures, a technology for self-monitoring the structural health of concrete structures has been invented. This technology integrates specific proportions of electrically conductive fillers to ensure their functional performance by detecting damage or its early development [3-6]. The self-sensing feature of damage before its development depends on the material's conductivity, which helps it resist damage and form the matrix's conductive network. In this regard, carbon has been commonly used to achieve these goals in its various forms, including nanomaterials, such as multi-layer carbon nanotubes, which can contribute to the creation of a continuous electrical network. This network resistance value changes under the applied load continuously, announcing a new chapter in the development of

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materials that form the self-sensing system in the cement compounds, which makes the flow of current smoother depending on their physical and chemical properties and the quality of their dispersion and their highly regular distribution within the cementitious system [7-10].

Wang et al. [3], concluded that adding 4% by weight of carbon nanotubes improves the performance of the cement system in terms of durability and self-sensing behavior. Roshan et al. [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 [12]. Comprehensive investigations have been carried out on the sensing capability of cementitious composites incorporating various functional additives. Yu and Kwon [13], investigated the application of carbon nanotube (CNT) to enhance the self-sensing properties of cementitious composites and Han et al., [14]. Suchorzewski et al. [15], 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 [16]. 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 CNT threads within the concrete hydration products [17].

Regarding using (PVA) fibers as, Yao et al. [18], 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 [19], 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 [20]. Research by Alengaram et al. [21], showed that the use of polypropylene and nylon fibers in oil palm shell concrete resulted in a 19–86% enhancement in the splitting tensile strength of the concrete. Fernando et al. [22], 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. The selection of polyvinyl alcohol and nylon fibers is for comparison and to know the synergistic effect of each with carbon nanotubes on the durability and self-sensing behavior together. In addition, this difference can be more obvious if the current study is based on other studies with the same approach. To fill in some of the gaps in the research, this study looked at the electrical behavior of carbon nanotube arrays made from the percolation threshold, as well as the mechanical behavior of the array after being mixed with PVA fibers and then with NF fibers. The results were compared considering different study ages. In particular, the current focus is on determining how to enhance the sensing behavior by comparing the fractional change in the electrical resistance (FCER) under different loading conditions for four curing ages and comparing it with that of the control mixtures to investigate how to improve the results.

2. Empirical methodology

This part covers the raw substances and functional filler used, their properties, the combination proportions, and the ideal mixture procedure for this study. The concluding segment of this section delineates lab testing, categorized into two primary components: mechanical tests and the electrical response of the produced mixes beneath various stress situations

2.1 Materials

The materials used in manufacturing the samples can be detailed into raw materials, conductive fillers, and reinforcing fibers. More precisely, multi-walled carbon nanotubes with a diameter of 5–20 nm, a length of 10–30 µm, a surface area of 150–250 m^2/g, and a maximum density of 0.04-0.08 g/cm^3 were used as functional fillers in this study for self-sensing, as illustrated in Figure 1 (a). In addition, the dosage of MWCNT was 0.5% by weight of the cementitious materials throughout the study, according to [23]. Xiamen TOB New Energy Technology Co., Ltd., China, provided these materials. Two types of reinforcing fibers were used. The first type includes polyvinyl alcohol (PVA) fibers with a length of 8mm and a diameter of 39µm. These fibers have a modulus of elasticity of 42.8 GPa, a tensile strength of 1620 MPa, and a specific gravity of 1.3 Figure 1 (b). This type of fiber was imported from Luoyang Tongrun Info Technology Co., Ltd., China. The second type of reinforcing fiber was nylon fiber (NF) with a length of 19 mm and a tensile strength of 966 MPa; the elongation was 35.2%, and the moisture content was 14.46%, and its source was LTP Group Limited, Hong Kong, Fiber Technology Department Figure 1 (c). As for the raw materials, ordinary Portland cement type (Tasluja) type 1 was used according to Iraqi Standard Specification No. 5/1984 and European Specification No. EN 197-1:2011, and its source was Lafarge Holcim Group Figure 1 (d). Silica sand from Sika, Iraq, was used as a fine aggregate in mortar mixes. The largest particles were 0.4 mm. They could absorb 0.3% of their weight, and their specific gravity was 2.6, as shown in Figure 1 (e). Moreover, fly ash (FA) class F was used, which complies with ASTM C 618 Figure 1 (f). Potable water was used in all mixes with a water-to-cement ratio of 0.27 [2, 24-26]. For workability, Visco Crete® 5930 superplasticizer imported from Sika Iraq was used, which meets ASTM-C494/C494M Type F specific gravity of 1.095 kg/L. The chemical and physical properties of PC, FA, and silica sand are presented in Table 1.

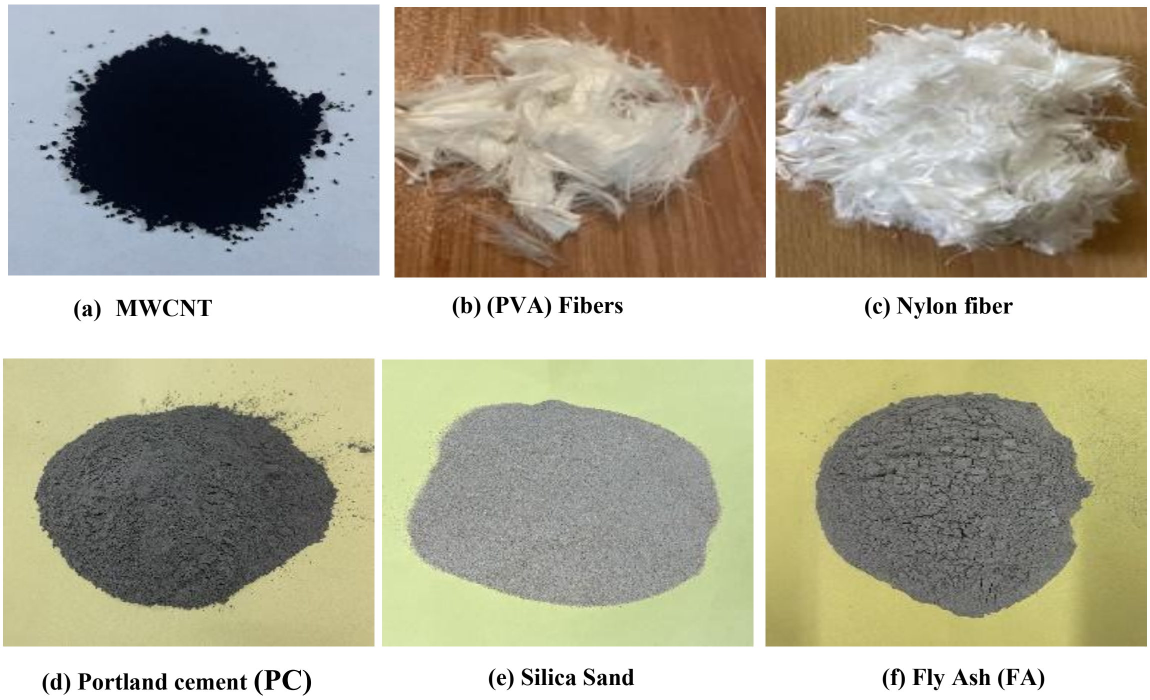


Figure 1: Types of raw materials, functional filler, and reinforcing fibers utilized

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	--
SiO_2	21.65	51.98	>= 50 - <= 100 %
$A_{l2}O_3$	3.52	17.04	--
Fe_2O_3	4.87	6.55	--
MgO	3.79	2.14	--
SO_3	2.03	0.025	--
Loss on ignition (LOI)	2.05	10.33	--
Insoluble residue	0.71	-	-
Lime saturated Factor	0.89	-	-
Physical properties			
Specific gravity	3.16	2.09	2.65
Blaine fineness (cm^2/g)	3941	2689	----

2.2 Preparation of composites

The dosage ratios (FA/OPC) used in the study and the method of manufacturing the smart mixtures, according to previous studies [2, 24-28], (FA/OPC) was 1.2, while the ratio (W/CM) was 0.27. To obtain good workability, two different ratios of the superplasticizer were used according to the type of reinforcing fibers used each time. For mixtures reinforced with PVA, 3% by weight of the cementitious materials was used, while 1% was used for mixtures reinforced with nylon fibers. The dosages used for the additives (MWCNT), PVA, and NF were 0.5% by weight, 2% by volume, and 2% by volume, respectively [23]. To manufacture the smart samples, a kitchen mixer was used at a speed of 3000 rpm to mix the superplasticizer with the nanomaterials for the entire amount of mixing water. This process took 5 minutes. Specifically, the raw materials were mixed in a 20-liter Hobart mortar mixer at 100 rpm for 10 minutes. Then, the pre-formed solution of the superplasticizer and MWCNT nanofiller was slowly added to the dry mixture while the speed stayed at 100 rpm for 10 seconds. Next, the wet and dry mixtures were mixed for another 10 minutes. After that, the mixing speed was increased to 300 rpm for 10 minutes before slowing down the mixer to 100 rpm to add the reinforcing fibers and then increasing the speed again to 300 rpm for another 10 minutes to mix all the ingredients [23,29,30].

2.3 Mechanical tests

2.3.1 Compression test

The compression test was conducted under stress control utilizing a digital electrical testing machine (ELE) ADR Touch SOLO 2000 BS ENGLAND Compression Machine equipped with a digital readout and self-centering platens that operates at a loading rate of 0.9 kN/sec [2, 24, 26]. The test was conducted under constant load until failure on three samples from each examined set, as shown in Figure 2 (a). In particular, a cubic mold with dimensions of 2 inches (50 mm) was utilized for pouring the blend, and the compression evaluation was conducted following the procedures outlined in [31].

2.3.2 Indirect tensile test

The indirect tensile test was conducted following the guidelines outlined in [32], employing an (ELE) ADR Touch SOLO 2000 BS ENGLAND Compression Machine equipped with a digital readout and self-centering platens that operates at a loading rate of 0.9 kN/sec [2,24,26], utilizing 50×50×50 mm^3 specimens positioned among two square bars measuring (width of 10×height of 10). All specimens of the mixture underwent testing for the splitting tensile strength until failure, with consideration given to their average values.

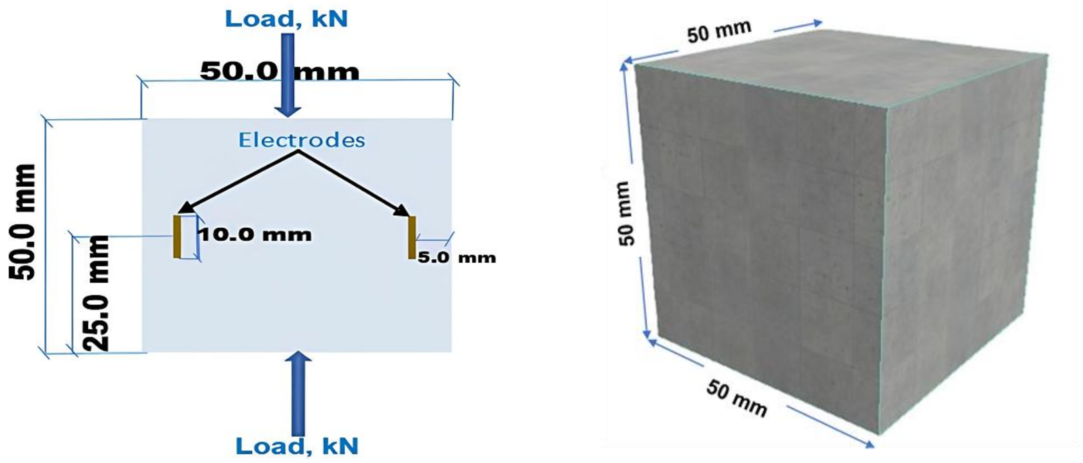
2.3.3 Measurement of the electrical resistivity

To evaluate the self-sensing capability, ECC blends containing carbon-based conductive materials were developed at the nanoscale. As previously presented for the two types of loading (monotonic compressive load and indirect stress load), the sensing behavior of the smart samples made of carbon nanotubes reinforced with PVA and nylon fibers was monitored. Moreover, the behavior of each matrix in capturing the fractional change in the electrical resistance under the applied load type was monitored. The proposed setup for this work involves using 50 mm^3 cubic samples for all matrices, including the control blends. To prevent the polarization process resulting from curing the samples in water, the samples were oven-dried at 60 °C for all the proposed study ages (28, 56, 90, 180) for a full day before being subjected to the tests. Additionally, to test how well the manufactured samples could sense damage, electrodes were put inside them from a brass plate that had been cut into strips that were 75 mm long, 10 mm wide, and 0.1 mm thick. The resistance of these strips was 0.3 ohms, and they were placed symmetrically around the middle of the sample, as shown in Figure 2. The two probes were embedded 50 mm inside the samples, and the remaining portion was used to connect it to the electrical resistance device, 5 mm away from the electrode's embedded faces. This arrangement was consistent with that of previous studies [1,2], [24-26], [33,34].

The electrical resistance was measured using the Pro'sKit MT-1820 DC Multimeter [35]. Moreover, the contact between the sample and the loading test machine was taken into consideration. Hence, pieces of plywood were placed below and above the sample to prevent interference of the electrical signal sent to the electrical resistance tester with the mechanical testing machine. In particular, the electrical resistance and the applied load readings were taken simultaneously for each second. This means that the average mechanical resistance values and the fractional change in the electrical resistance Equation 1 can be plotted as a function of time.

$$\mathrm{FCER}(\%)=\left(\frac{R_L-R_o}{R_o}\right)\times 100 \quad (1)$$

R_o stands for the initial electrical resistance, FCER represents the fractional change in the electrical resistance, and R_L is the electrical resistance under loading at a specific period during the test.



(a) (b)

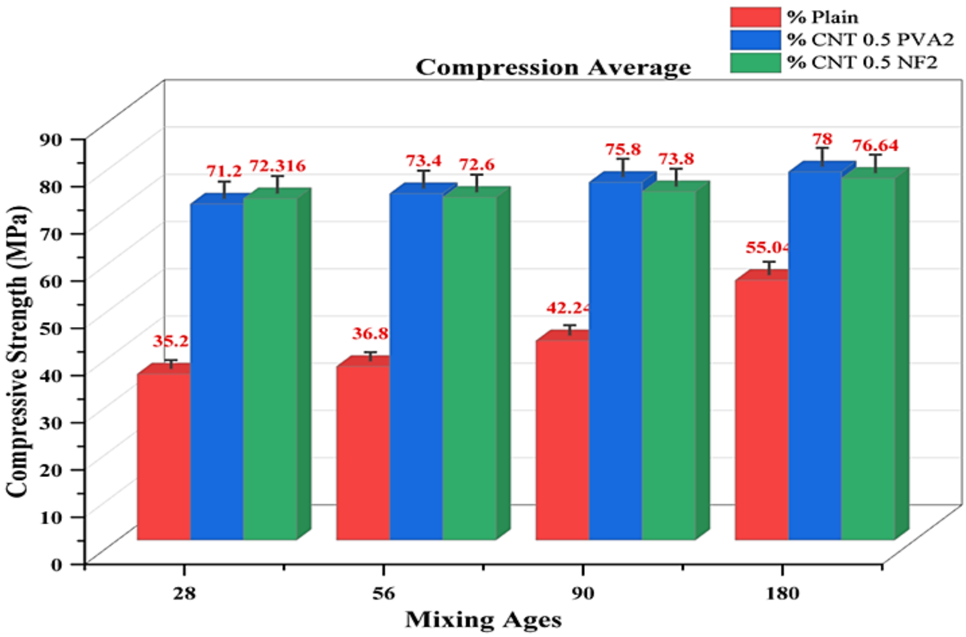
Figure 2: a) Top view of electrode setup dimensions, and b) The geometric dimensions of the cubic specimens

3. Results and discussion

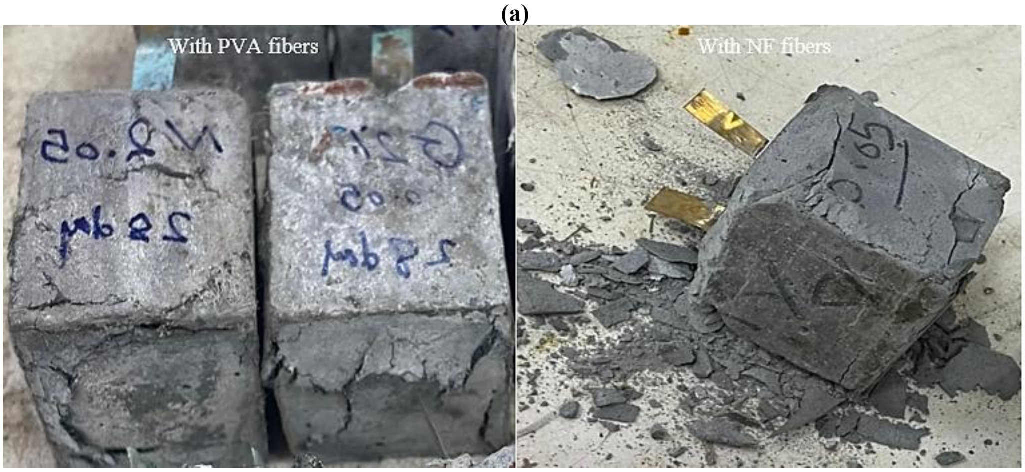
3.1 Compressive strength assessment

Before proceeding to analyze and evaluate the results of self-damage sensing for the mixtures manufactured by smart electrically conductive nano-fillers reinforced with mechanical reinforcement fibers in this study, it is necessary to assess the effect of these fillers on the strength and durability properties, especially after comparing them with the control mixtures (without functional fillers and reinforcement fibers). Such effect will be more evident for the study ages of 28, 56, 90, and 180. Figure 3 (a) displays the average compressive strength values for two 2-inch cube specimens, demonstrating excellent performance under uniaxial compression force for both smart mixtures (CNT0.5PVA2, CNT0.5NF2) as well as for all the ages included in the proposed study. The gradual improvement in the monotonous compressive strength according to the age of the specimens was distinct as if the two mixtures were in a race to see which one would win the highest endurance value. This outcome ultimately proved that the mixtures reinforced with PVA fibers barely won at the expense of those mixtures reinforced with NF fibers.

When the functional mixture CNT0.5PVA2 was evaluated in comparison with the normal mixtures, the improvement percentages for ages 28, 56, 90, and 180 were 102, 99.5, 79.5, and 42%, respectively.



(a)



(b)

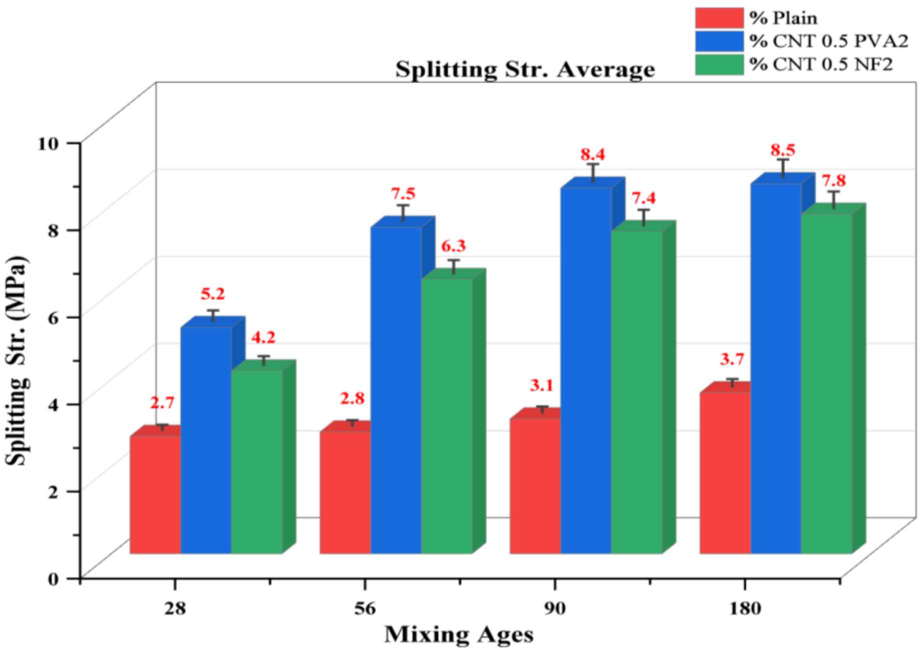
Figure 3: a) compressive strength for various innovative blends during curing age, and b) Samples after testing

On the other hand, the gradual improvement percentages of the mixture CNT0.5NF2 for ages 28, 56, 90, and 180 were 105, 97, 75, and 39%, respectively. Regarding the effect of carbon nanotube powder on the strength properties, the strength results mentioned earlier are in complete agreement with the results reached by the researchers in [36, 37], who proved that adding carbon nanotube to the matrix increases the compressive strength and increases the resistance to conditions unsuitable for cementitious compounds, such as carbonation and chloride ions. Sarwary [33], attributed the novel CNT arrays' increased compressive strength to their concentrated and large packing within the mixture. Because the CNT composites have a lot of surface area, they reduce the area of the hydration components in the short term. This makes room for the arrays to get stronger over time. The chosen nano dosage and the consistent behavior and strength values under monotonic compressive loading align perfectly with this study. This is completely consistent with what Myungjun et al. [16], found. Particularly, the incorporation of PVA fibers into the cementitious composites enhances the durability of the cementitious compound, particularly in relation to cracking, which is influenced by the connection qualities at the interface of the fiber matrix [26,38,39].

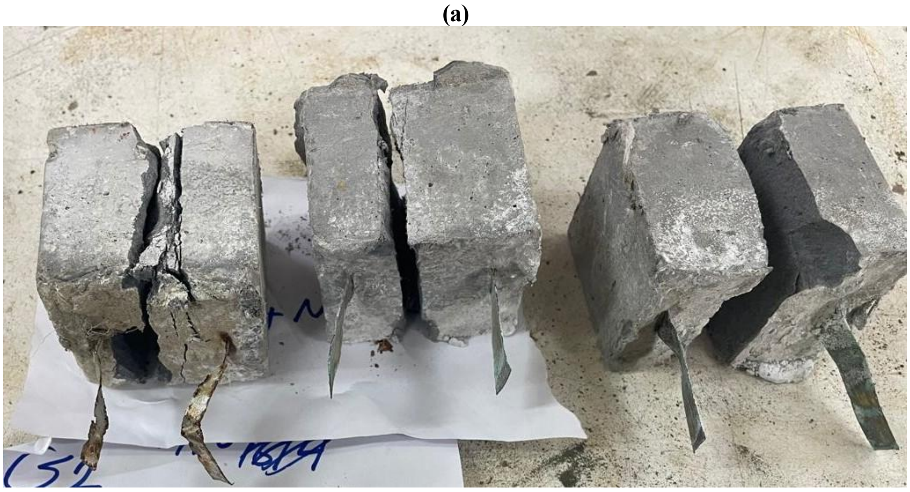
Regarding the CNT matrix reinforced with nylon fibers, in addition to the positive effect of the conductive nanofiller in improving the strength of the mortar under compressive load, nylon fibers have a major role in the improvement either by the mechanism of distributing the applied load at the fiber-matrix interface or by increasing the flexibility of the innovative matrix according to the flexibility of the reinforcing fibers embedded in it. These fibers flow under the applied load without breaking, especially when the length and concentration of fibers in the matrix are high [20,40]. Figure 3 (b) shows the samples tested to failure, which proves the perspective explained in the previous few lines and the opinions of researchers on the role played by nano-fillers and mechanical reinforcement fibers in developing the capacity of mortar under compressive stress.

3.2 Splitting tensile strength assessment

Figure 4 displays the average indirect tensile strength values of three 2-inch specimens of each type of mixture for both early and late curing ages. In particular, this figure compares the innovative smart mixtures of nanofillers reinforced with mechanical reinforcement fibers to the control mixtures for the same ages in the previously mentioned study. Upon evaluating the behavior of the mixtures under this type of loading, Figure 4 reveals a remarkable improvement in the indirect tensile strength values for all ages, which is almost identical to the behavior of the samples under the compressive load. The superiority of the mixtures reinforced with PVA fibers was recorded over those reinforced with nylon fibers, which indicates that the nanofillers and reinforcement fibers of the normal matrix had a clear positive effect in improving the split tensile strength. More specifically, the improvement percentages of the smart mixtures compared to the control mixtures can be summarized as follows: the gradual improvement percentages with the treatment age of the CNT0.5PVA2 matrix at ages 28, 56, 90, and 180 were 93, 168, 171, and 130%, respectively. At ages 28, 56, 90, and 180, the CNT0.5NF2 matrix developed resistance values of 55, 125, 139, and 111%, respectively.



(a)



(b)

Figure 4: a) Indirect tensile strength during curing age, and b) Samples after testing

One can summarize the strength development of the smart mixtures from 28 to 180 days. For example, the strength development of the CNT0.5PVA2 mixture from 28 to 180 days of initial treatment was 63%, from 5.2 to 8.5 MPa, while the development rate of the CNT0.5NF2 mixture from 28 to 180 days was 86%, from 4.2 to 7.8 MPa. Other complex material properties that influence indirect tensile characteristics could explain this observation, which did not apply to the compressive strength. This is especially true for strain-hardening cementitious materials like engineered cementitious composites, which include ultimate tensile strength, tensile strain capacity, and tensile first cracking strength [30]. The presence of carbon-based nano-sized fillers, like the one in this work, CNT, interacts with PVA fibers through their absorption by the fibers. This interaction, in turn, results in high frictional bond strength and improves the plasticity properties during the formation of initial cracks under splitting tensile stress, which explains the improvement in the splitting tensile strength values of smart blends, particularly with CNT0.5PVA2 blends [41]. Furthermore, adding electrodes to the specimen may significantly help with mechanical support near the area where the split tensile stress distribution is changing [23]. Based on the above discussion, the strength gains of the CNT0.5PVA2 mixture over the CNT0.5NF2 mixture can be explained by the latter's inability to absorb the nano-carbon filler, which in turn loses the properties of the smart matrix reinforced with PVA. In addition, the properties of the two types of fibers used in this paper differ.

3.3 Self-sensing experiments with a single-axis compressive stress

This section presents the results of laboratory tests on samples manufactured with carbon-based conductive fillers reinforced with PVA and NF fibers. In addition, this section discusses the impact of these fillers on the self-sensing capability under uniaxial compressive loading conditions for different processing ages. In this context, the self-sensing behavior of the control mixture and the smart mixtures CNT0.5PVA2 is shown in Figures (5–7). These figures show the FCER relationship under the applied load over time. The solid lines represent the progression of the applied load values, while the dashed lines represent the fractional change in the electrical resistance. Figure 5 (a-d) demonstrates the behavior of the control mixtures for the self-sensing response under the compressive load for ages 28, 56, 90, and 180. Despite the modest FCER values and the absence of conductive fillers, the control mixtures perform excellently, demonstrating a continuous increase in sensing values under load, starting from zero. When an electric field is applied, the conductive phases can separate in regular ECC-plain samples. This can cause the presence of an infinite amount of water and dissolved ions in the micropores, which could cause a piezoresistive response [26, 42].

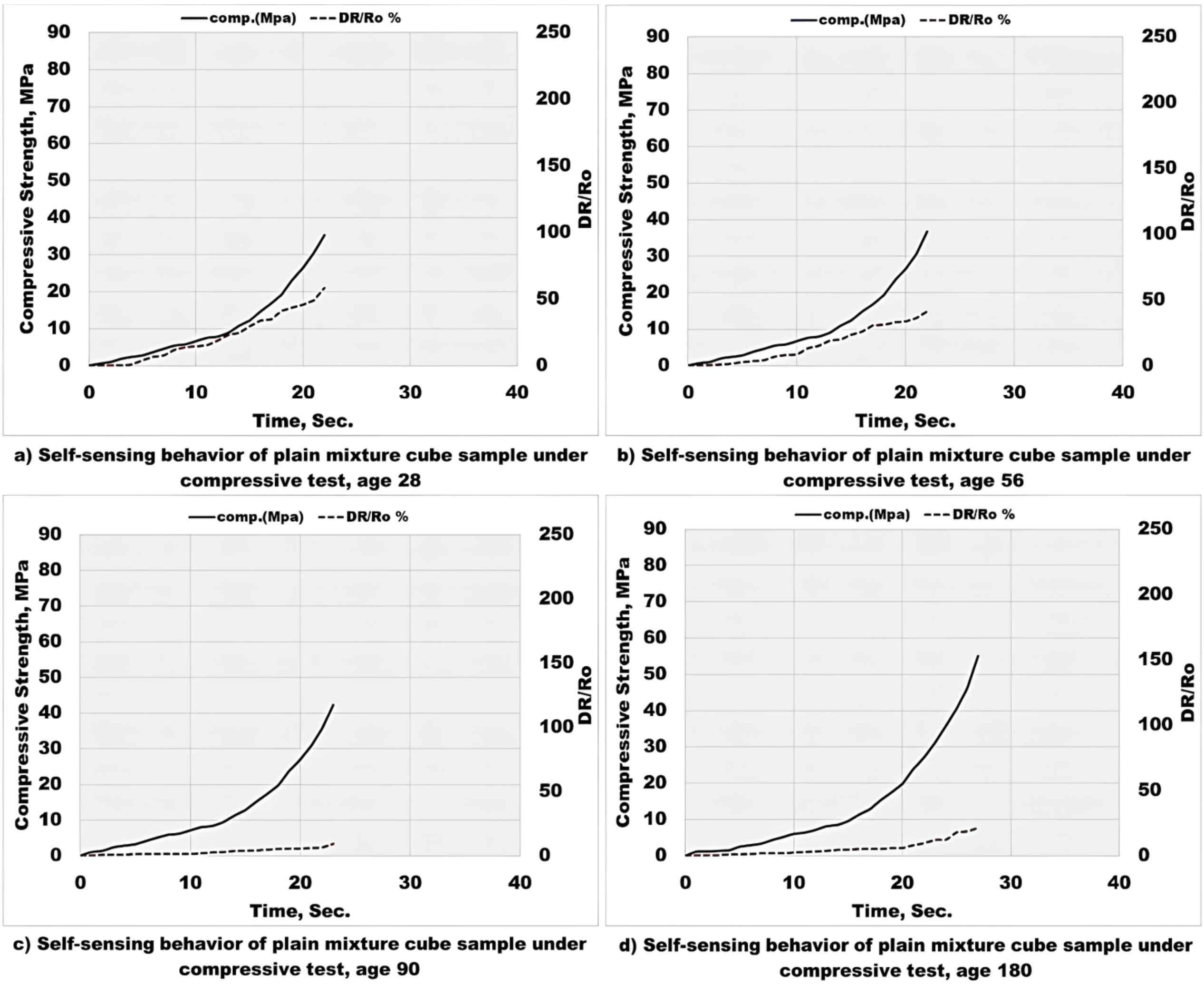
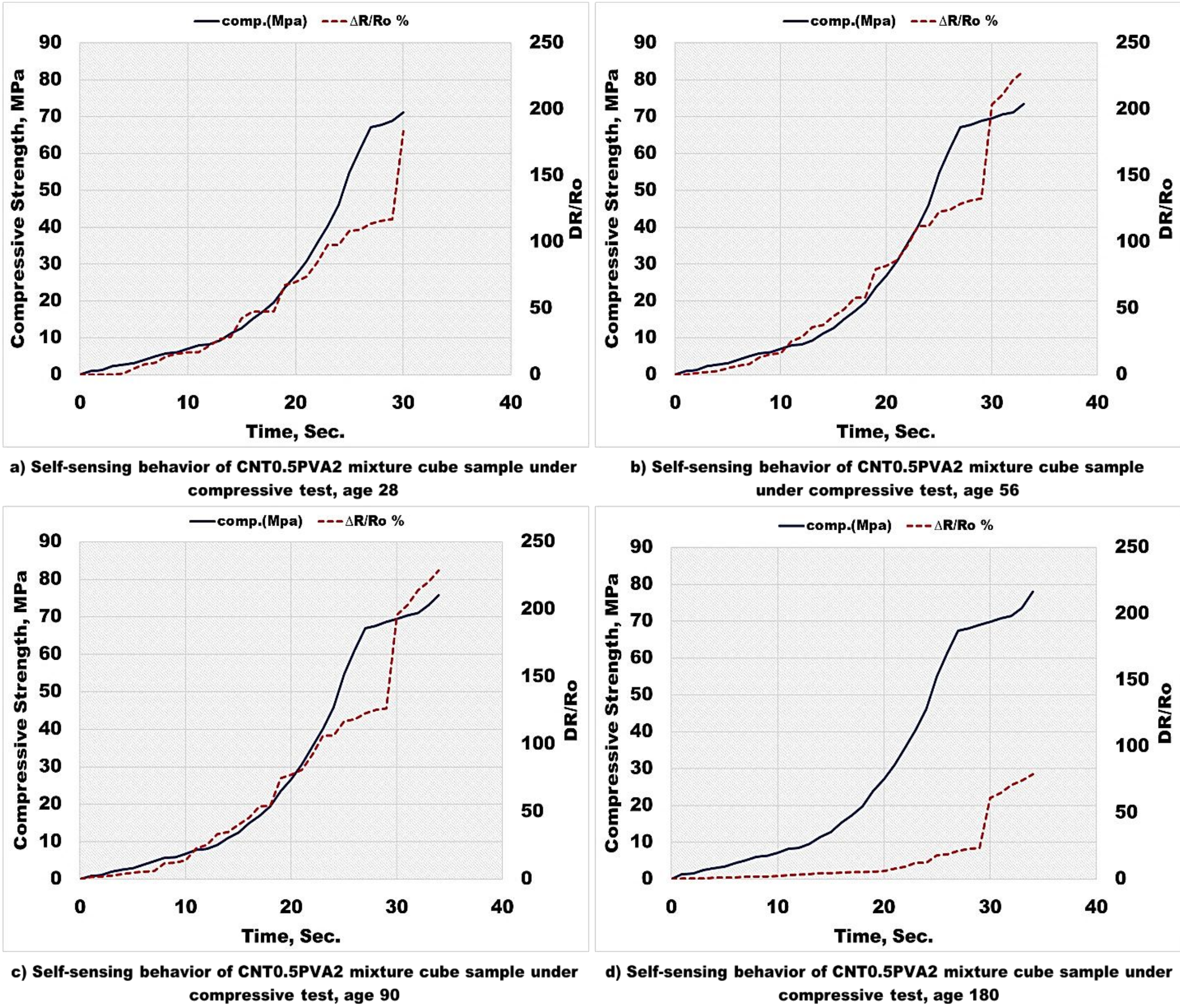


Figure 5: Self-sensing of plain mixtures under uniaxial compressive strength for different curing ages

In particular, there is a definite possibility that this behavior is available with the availability of fly ash class F, which can be considered the basis of smart mixtures that can not be dispensed with on the mechanical or electrical level, along with other functional fillers [43]. It can be clearly observed that the FCER values are high for early ages, followed by successive decreases for late ages. This is due to the process's dependence on the abundance of hydration water in the initial reactions, and then, it begins to recede as a result of the formation of the gel that fills the pores [23, 28, 44, 45]. Figures 6 and 7 illustrate a distinct behavior in the self-sensing of damage by compressive loading compared to the values of the control matrices. This result indicates that the conductive nanofiller played a positive role in improving the ability of the smart blends manufactured in this study to respond to the self-sensing of damage due to the applied load. This can be observed between the blends reinforced with PVA fibers at the expense of those reinforced with nylon fibers (NF). This behavior may be due to the increase in chemical bonding and fracture toughness between PVA and ECC, which leads to an increase in the width of the microcrack as a result of tearing or damage to the PVA fibers. This increase, in turn, leads to noticeable increases in the values of the electrical resistance under the applied compressive load until failure at the expense of other reinforced blends [30].



a) Self-sensing behavior of CNT0.5PVA2 mixture cube sample under compressive test, age 28

b) Self-sensing behavior of CNT0.5PVA2 mixture cube sample under compressive test, age 56

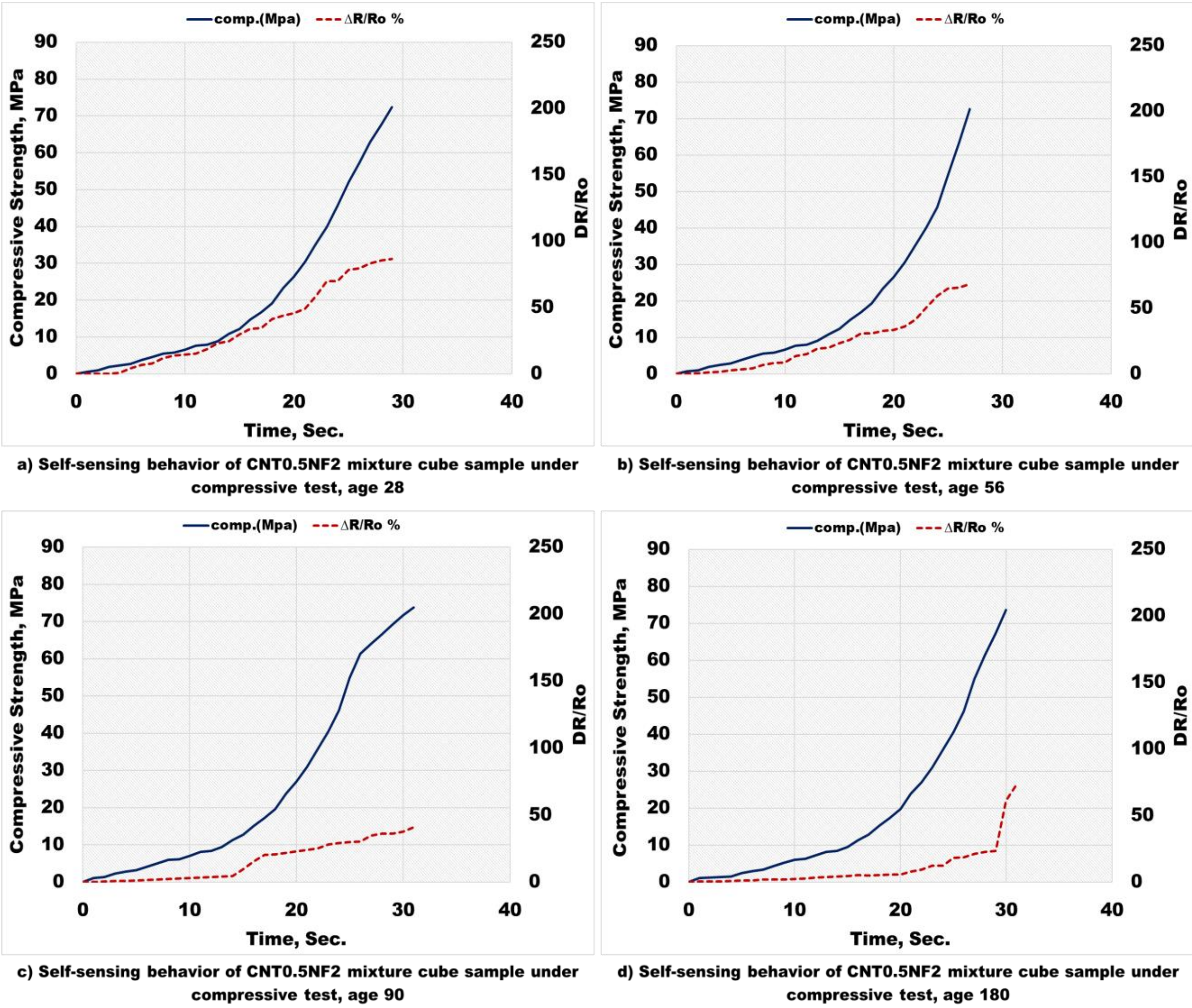
c) Self-sensing behavior of CNT0.5PVA2 mixture cube sample under compressive test, age 90

d) Self-sensing behavior of CNT0.5PVA2 mixture cube sample under compressive test, age 180

Figure 6: Self-sensing of CNT0.5PVA2 mixtures under uniaxial compressive strength for different curing ages

The improved sensing ability of mixtures containing carbon nanotubes may be attributed to their high-order uniform dispersion behavior in addition to their excellent electrical conductivity behavior [33, 34]. Particularly, the sensing behavior of smart mixtures made of functional fillers at the nanoscale was valid for all ages of the study, even the plain ones. As the treatment age went up, the partial change in the electrical resistance went down.

This outcome is thought to be a natural event that happened because the hydration processes grew, which formed the gel. The hydration water that was not involved in the hydration processes decreased, as shown in Figures 6 (a, b) and 7 (a, b). In addition, at an early age, and as a result of the above, the formation of pores is still small, which provides continuity for the network and greater freedom of movement for ions. Then, in the late aging stage, the matrix is exposed to two important factors that cause a decrease in its stress sensitivity values, namely the continuous decrease in wetting water, which negatively affects polarization, and the formation of a gel, which weakens the continuity of the electrical network inside the cementitious matrix, as shown in Figures 6 (c, d) and 7 (c, d) [23, 46, 47]. The behavior of ECC typically progresses through three different stages, including a decrease phase, a balance phase, and an abrupt increase phase. These phases correspond to pressure compaction, the initiation of new cracks, and the propagation of existing cracks under monotonic uniaxial compression, respectively. The application of pressure compaction facilitates the proximity of functional fillers, thereby enhancing the conductive network within the ECC. Moreover, the emergence of new cracks results in the disruption and subsequent reformation of the conductive network. Consequently, the propagation of cracks leads to the disruption of the conductive network [40].



a) Self-sensing behavior of CNT0.5NF2 mixture cube sample under compressive test, age 28

b) Self-sensing behavior of CNT0.5NF2 mixture cube sample under compressive test, age 56

c) Self-sensing behavior of CNT0.5NF2 mixture cube sample under compressive test, age 90

d) Self-sensing behavior of CNT0.5NF2 mixture cube sample under compressive test, age 180

Figure 7: Self-sensing of CNT0.5NF2 mixtures under uniaxial compressive strength for different curing ages

3.4 Self-sensing performance under indirect tensile stress

It is crucial to evaluate the sensing ability of cementitious composites under this type of loading, which has been reported to be a single microcrack initially and then grows and enlarges with continuous loading over time into multiple cracks. However, in the end, a single crack develops through which self-sensing data can be recorded. The self-sensing ability of the average of three 2-inch specimens is shown in Figures (8–10). These specimens were subjected to indirect tensile stresses for four ages of curing, as mentioned before. The direct addition of electrodes on the top surface of the specimen and at a distance of 0.5 cm from the edges of the cube specimens created a restricted self-sensing region [23]. The way the specimen cracks when the test setup applies indirect tensile stress has a direct effect on how well the new smart blends sense their properties. The graphs can be analyzed through the FCER values and the evolution of the fractional change in electrical resistance data of the functional blends in this study. For instance, the behavior of the plain blends (without functional and mechanical additives), as shown in Figure 8 (a-d), was very modest, especially at late ages after 28 curing age. This result was justified in Section 3.2.1 regarding the growth of the sensing at early ages.

The FCER percentage of the blends made from functional CNT fillers in Figures 9 (a-d) and 10 (a-d) showed self-sensing values that were clear and easy to record from the start of the load application. These values were stronger in the blends reinforced with nylon fibers compared to the control blends. It can be said that there is a similar behavior in the self-sensing performance of mixtures under splitting tension with those subjected to compressive loading, especially for late ages, and this result is completely consistent with the result reached by the authors in [23]. Microcracks that were formed under the split tension stress opened more rapidly and more extensively than those that were formed under compression, and this variation, in effect, was thought to explain the disparities in the self-monitoring characteristic for various mixtures. The role of CNTs in the matrix has significantly improved the sensitivity development of matrices under applied indirect tensile loads that result in the movement of carbon nanotube molecules apart, causing their separation due to the development of microcracks during loading, which increases the electrical resistance values [15,48].

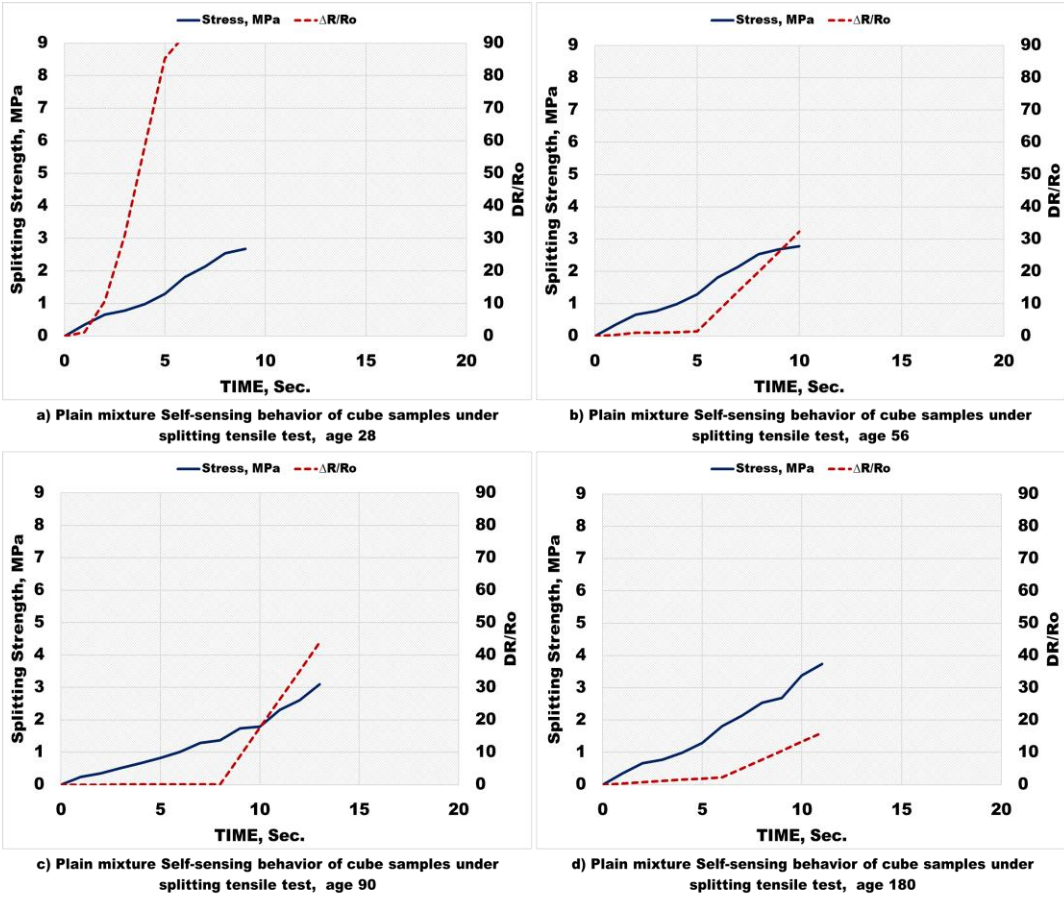


Figure 8: Self-sensing of plain mixtures under the indirect tensile strength for different curing ages

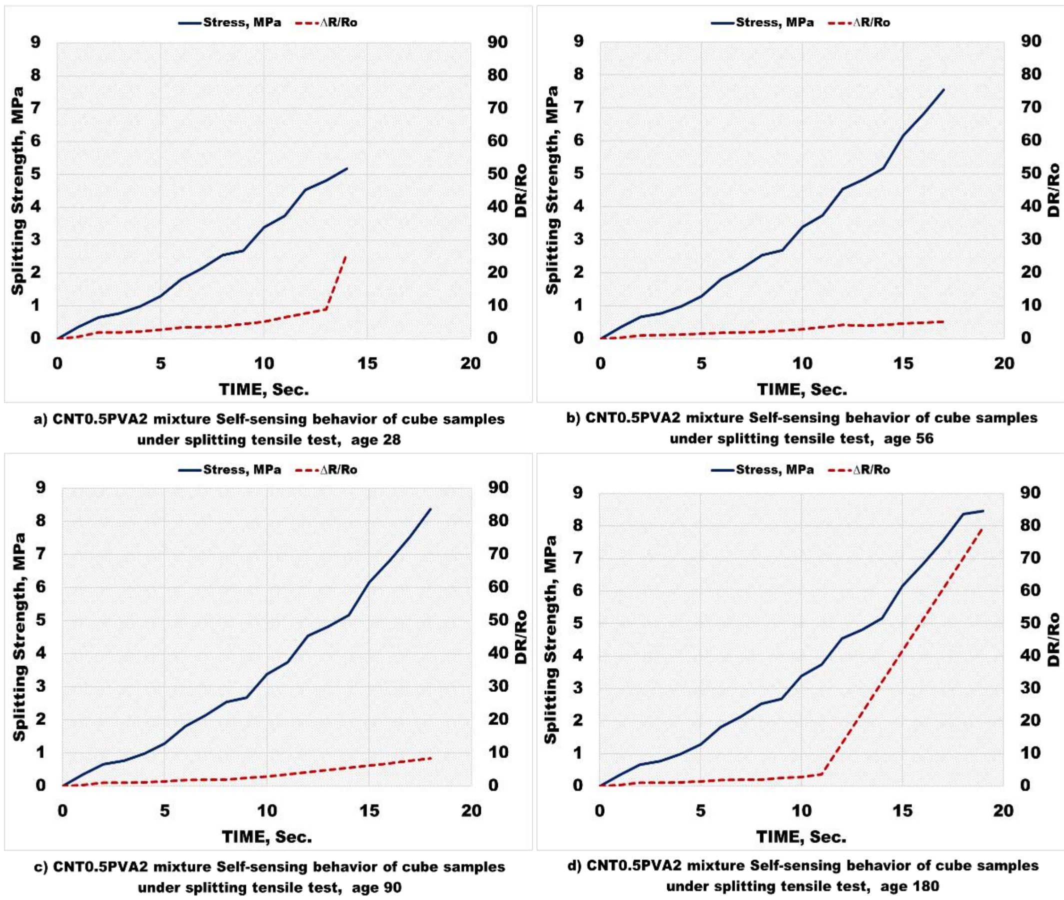


Figure 9: Self-sensing of CNT0.5PVA2 mixtures under the indirect tensile strength for different curing ages

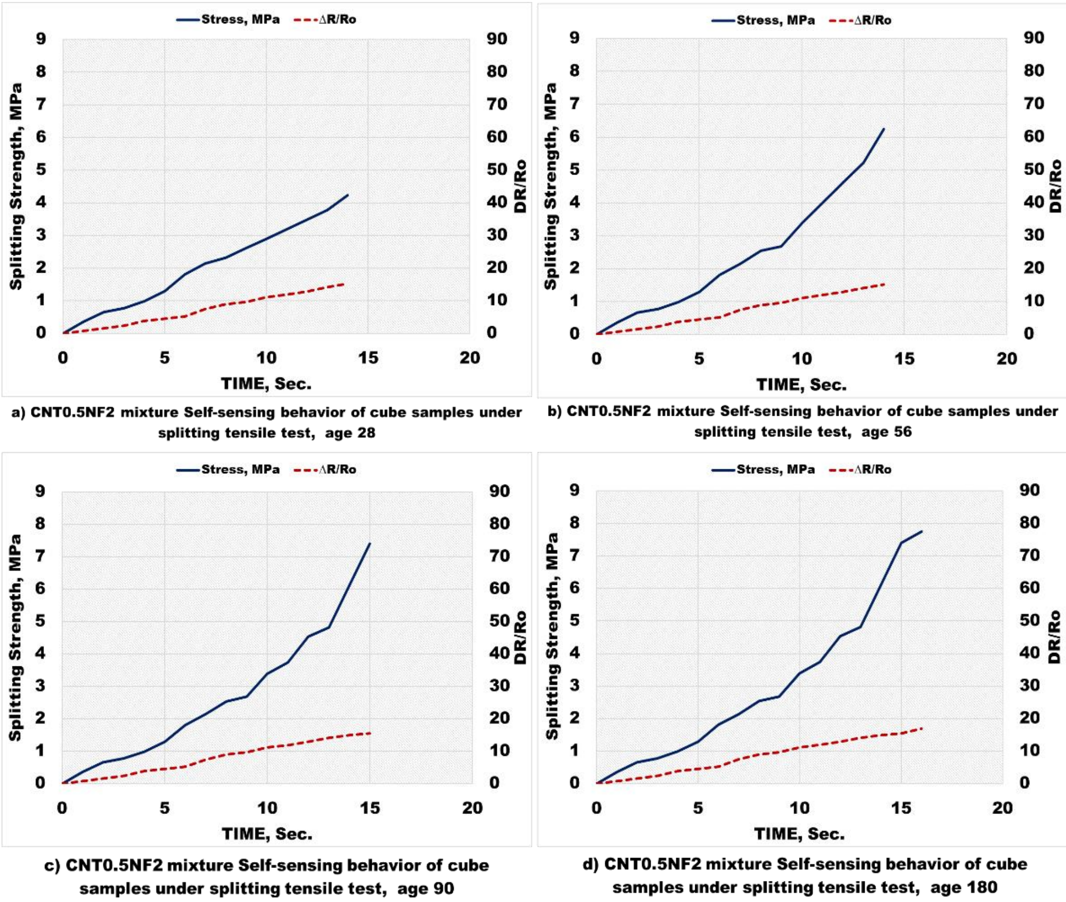


Figure 10: Self-sensing of CNT0.5NF2 mixtures under the indirect tensile strength for different curing ages

4. Conclusion

In this work, a thorough investigation was conducted to assess the self-sensing ability and the mechanical characteristics of ECC incorporating carbon-based materials with nanoscale. This evaluation took place after initial curing durations of 28, 56, 90, and 180 days and involved testing under conditions of uniaxial compression and indirect tension. The following conclusions have been derived:

1) The inclusion of CNT in the cementitious matrix according to the dosage proposed in this paper has clear results on the durability behavior on the one hand and the ability of self-sensing damage on the other hand, which proves the suitability of the new innovative matrices for many applications related to conductivity or electrical resistance.
2) Mechanical Properties: The novel matrices showed excellent strength behavior for the loading scenarios applied in this paper on the one hand and regular strength development with curing age on the other hand. Although there were no significant differences in strength between the CNT0.5PVA2 and CNT0.5NF2 matrices, the performance of the PVA fiber-reinforced matrix was superior compared to the other matrix. All matrices of all ages showed clear excellence in their mechanical performance evaluation by recording high strength values under different loading scenarios, making them widely qualified for various uses of concrete structures and civil engineering works.
3) Electrical properties: the sensing behavior of the CNT0.5PVA2 and CNT0.5NF2 matrices was recordable from the beginning of the load application and increased with increasing the applied load. In addition, the FCER values gradually decreased with the age of the treatment, which is a natural behavior resulting from the development of the gel. The difference between the two matrices lies in the type of applied stress. It was easy to see that the CNT0.5PVA2 matrix had more gains under compressive loading because its self-sensing ratio reached about 200%. On the other hand, the CNT0.5NF2 matrix didn't go above 100%, even though these values went down over time. Under split tensile loading, the CNT0.5NF2 matrix modestly outperformed in terms of fractional change values in electrical resistance by approximately 20% with regular behavior in the sensing response under the applied load, while the CNT0.5PVA2 matrix recorded only less than 10% with irregular behavior in the load sensing in the elastic range.

Author contributions

Conceptualization, **S. Ahmed, A. Al-Dahawi,** and **S. Hassan**; data curation, **S. Ahmed**; formal analysis, **S. Ahmed**; investigation, **S. Ahmed**; methodology, **A. Al-Dahawi**; project administration, **S. Hassan**; resources, **A. Al-Dahawi**; software, **S. Ahmed**; supervision, **A. Al-Dahawi** , **S. Hassan**, and **S. Ahmed**; visualization, **A. Al-Dahawi**; writing—original draft preparation, **S. Ahmed**; writing—review and editing, **S. Ahmed**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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