Research Article

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An investigation of self-sensing and mechanical properties of smart engineered cementitious composites reinforced with functional materials

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Abstract: In this study, hybrid functional fillers were used to create an electrical network that is used to develop self-damage sensing ability within conventional cementitious mixtures. This electrical network was used to examine the self-sensing properties of cementitious composites under different loading scenarios such as compression, splitting tensile, and cyclic loading for three ages, those are 7, 14, and 28. With the help of a single type of functional filler or fiber, the self-sensing capabilities of the majority of previous works are demonstrated. This study incorporates two types of functional fillers for sustainability and low cost: micro-scale carbon fibers (CF) and waste iron (Ir) powder in the form of microparticles. The purpose of the current work is to fill up the subject's gap using two different types of functional fillers as a hybrid form. Three hybrid proportions of a micro-scale CF (vol% of mixture) and waste iron powder (Ir) (wt% of cementitious materials) are utilized. These are (0.33, 15), (0.67, 10), and (1.00, 5), respectively. Unlike carbon-based materials, polyvinyl alcohol is used as a mechanical reinforcing fiber 2% by volume of the cementitious mixture. Additionally, a control combination without any fillers has been created. The electrical resistivity of the fabricated samples was monitored during various loading applications for every second to confirm their self-sensing capabilities. Regarding the fractional change in electrical resistivity, the self-sensing behavior was superior for mixes containing high dosages either of waste iron powder or CF in the same hybrid matrix. Quite the contrary to that, the piezoresistivity was modest in the middle hybrid ratio.

Keywords: FCER, functional fillers, waste iron powder, carbon fiber, electrical resistivity, self-sensing, piezoresistivity

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1 Introduction

Although it is commonly known that traditional concrete lacks any electrical characteristics, new electrically conductive concrete has been produced recently for use in a variety of applications, including monitoring stress changes on structures by detecting changes in electrical resistance under an applied load. So-called "Smart Engineered Cementitious Composites" are newly created mortar mixtures that have both structural and non-structural features [1–3]. Because of their functional properties, such as stress sensing, cost savings, and increased durability, these multifunctional cementitious composites are useful as structural and structural health monitoring materials that have a wide range of applications, especially in the pavement structures [4–7]. The introduction of electrically conductive compounds into the nominal matrix results in lower electrical resistance allowing these uses [1,8–12]. The use of conductive fillers such as iron powder, carbon fibers (CF), fly ash, and carbon black is used to create conductive cementitious composites. Considerations such as cost reduction are taken into account when creating composites with hybrid fillers, such as partially replacing an electrically conducting ingredient [13,14]. Most studies on the self-monitoring of cementitious compounds rely on a single class of additives, which may be pricey and are in charge of creating the cementitious compounds' electrical networks. It also adopted the method of partial replacement of those conductive materials with raw materials. For sustainability and low costs, this work includes two kinds of functional fillers in hybrid form – waste iron (Ir) powder in the form of microparticles and micro-scale CF – to close a portion of the gap. The methodology of adding electrically conductive materials to the entire base mix was adopted instead of substitution, and three pairs of these materials were compared to determine the ideal proportion. Additionally, polyvinyl alcohol (PVA) fibers were employed to improve these smart combinations' mechanical qualities. This research examines the mechanical and self-monitoring characteristics of smart ECC when filled with waste hybrid fillers while also maximizing the fractional change in electrical resistivity (FCER) over the course of three ages. The self-sensing and some mechanical characteristics were examined and contrasted with those of ordinary mixtures.

2 Experimental approach

In this section, the details of the materials and additives used and their characteristics in this paper will be reviewed, in addition to the mixture ratios and the optimal mixing method for these works. The last part of this section represents the laboratory tests that were divided into two main parts: mechanical tests and the self-sensing behavior of the manufactured mixtures under these different load scenarios, as shown in the flow chart in Figure 1.

2.1 Materials

To produce the mixtures, ASTM Type I ordinary Portland cement (OPC) was used. It is a production of Mas-Iraq Cement Factory, Sulaymaniyah, Iraq (Figure 2a). Class F fly ash (FA) was from EUROBUILD Company, Dubai, UAE (Figure 2b), which complies with ASTM C 618 requirements. The silica sand with 0.3% water absorption capacity was used as aggregates (Figure 2c) with a maximum aggregate size of 0.25 mm and a specific gravity of 2.6. This material was from SIKA Company, Istanbul, Turkey. A high-range water-reducing admixture (HRWRA), ViscoCrete® 5930, was used. This product of type F complies with ASTM-C494/C494M (1999). Its density is 1.095 kg/l. This additive is manufactured by Sika Company, Istanbul, Turkey. Moreover, potable water was used. Table 1 displays the chemical and physical properties of PC, FA, and silica sand. For the self-sensing purposes, hybrid-conducting fibers and particles were used to create the electrically conductive arrays. Iron powder was utilized as conductive particles. The bulk density of the waste iron (Ir) powder was 4.3 (g/cm^3), and the particle size ranged from 0 to 50 μm (Table 1). The (Ir) is a local industrial waste (Figure 2d) [15,16]. Chopped CF (12 mm length) with an aspect ratio of

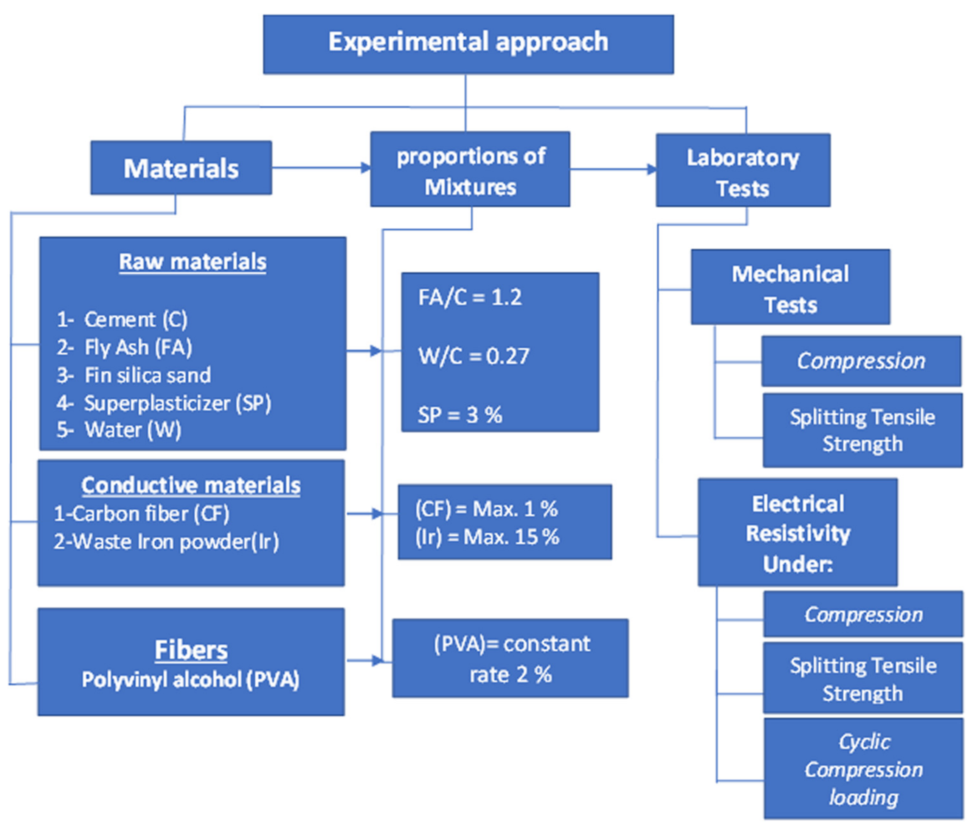


Figure 1: Flow chart of the experimental approach.

(a) (b) (c) (d) (e) (f)

Figure 2: Samples of the utilized materials. (a) Portland cement (PC), (b) fly ash (FA), (c) fine silica sand, (d) waste iron (Ir), (e) CF, (f) PVA fibers.

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

Chemical composition (%)	OPC (wt%)	FA (wt%)	Silica sand	Ir (wt%)
CaO	62.35	7.98	—	1.08
SiO_2	21.33	52.22	≥50 to ≤100%	8.43
Al_2O_3	3.74	16.58	—	0.85
Fe_2O_3	4.76	6.60	—	87.41
MgO	3.73	2.10	—	0.30
SO_3	2.01	0.02	—	0.89
Loss on ignition (LOI)	2.07	10.36	—	—
Insoluble residue	0.68	—	—	—
Lime saturated factor	0.9	—	—	—
Physical properties				
Specific gravity	3.15	2.10	2.65	4.30
Blaine fineness ($cm^2\,g^{-1}$)	3,940	2,690	—	3.15

1,600 was used as a miniature electrical conductor. The tensile strength of CF was 4,150 MPa, its elastic modulus was 252 GPa, its elongation was 1.8%, its density ranged from 1.7 to 2.0 g/cm^3, and its diameter was 7 µm. The CF was from the ELG Carbon Fibre Ltd., UK (Figure 2e) [1,2,10]. PVA fibers from Luoyang Tongrun Info Technology Co., Ltd., China (Figure 2f), with a 39-µm diameter, 8-mm length, nominal tensile strength of 1,620 MPa, an elastic modulus of 42.8 GPa, and a specific gravity of 1.3 were used to strengthen matrices containing various conductive materials. PVA fibers were utilized at a rate of 2% of the total volume of the ECC matrix.

2.2 Preparation of mixtures and proportions

The ratio of FA to OPC (FA/OPC) and water to cementitious materials was 1.2 and 0.27, respectively, to fabricate cementitious composites (with and without reinforcing fibers). According to [1–3,10,17,18], these ratios were employed while the HRWRA dosage used in this work was 3% by the total weight of cementitious materials to obtain good workability mixture. The proportions of the electrically conductive hybrid composites utilized are displayed in Table 2. The amount of waste iron powder (Ir) was determined by the total weight of cementitious materials (OPC + FA), whereas the quantity of micro-scale materials (CF) was utilized by the total volume of the specimen. The electrically conductive filler ratios used in this work were adopted from earlier research [1,16,17,19]. A hand blender at 3,000 rpm for 5 min was used to combine the HRWRA with the entire amount of the mixing water. To evenly distribute the CF throughout the cementitious system, the dry raw materials (OPC, FA, and silica sand) were combined with CF and waste iron powder (Ir) (see Figure 3a) for 10 min at 100 rpm in a mortar mixer (20-l capacity). The pre-mixed raw ingredients were then progressively combined with the pre-prepared HRWRA solution over 10 s at 100 rpm (Figure 3b). After fully incorporating the HRWRA-water solution for a further 10 min, the speed is raised to 300 rpm. To add the reinforcing fibers (PVA), the mixer was slowed down to 100 rpm once more (Figure 3c). The entire mixture was then mixed for an additional 10 min at 300 rpm [1,3]. Figure 4 shows the technical drawing of the smart sample manufacturing process for hybrid cementitious mortar, as detailed in this section.

Table 2: Percentages of electrically conductive particles and fibers utilized

Type of material	Dosage of materials utilization (%)[a]		
	1st ratio	2nd ratio	3rd ratio
Carbon fibers (CF)	0.33	0.67	1.00
Waste iron powder (Ir)	5	10	15
Proportions of pairs of fillers (CF + Ir)	0.33, 15	0.67, 10	1.00, 5
Polyvinyl alcohol (PVA) fibers	2.00	2.00	2.00

[a]By total volume of mixtures for CF and by total weight of cementitious materials (PC + FA) for waste iron powder.

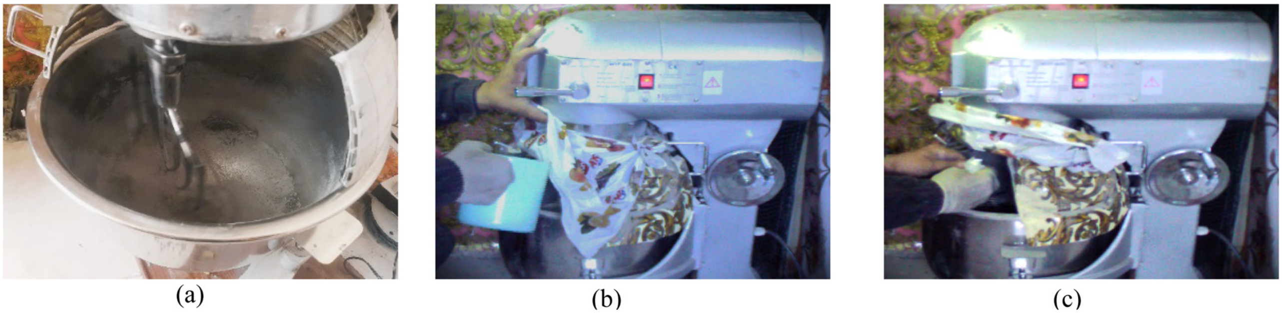


Figure 3: Stages of smart cementitious composites' mixing process. (a) Dry mixing. (b) Wet mixing. (c) Addition of reinforcing fibers.

2.3 Laboratory tests

2.3.1 Mechanical tests

This section includes the dimensions of the different samples according to the type of testing conducted, such as compression, and indirect tensile, in addition to three ages of curing by water at room temperature (7, 14, and 28 days), to obtain more accurate and realistic results that simulate the self-sensing behavior under different loading scenarios.

2.3.1.1 Compression test

A 2-in. (50 mm) cubic mold was used to pour the mixture, and compression testing was carried out in accordance with [20]. The compression test was carried out under stress control using a digital electrical testing machine (ELE) with a capacity of 3,000 kN and a loading rate of 0.36 MPa/s. The test was run under continuous loading until failure to three specimens from each kind of combination being investigated, as presented in (Figure 5a).

2.3.1.2 Splitting tensile test

Due to the fact that rigid pavement structures are exposed to it, this kind of stress test is seen as important. This test was performed in accordance with [21], utilizing an ELE ADR Touch SOLO 3000 BS EN Compression Machine with Digital Readout and Self Centering Platens, Industry in the United Kingdom, with a capacity of 3,000 kN and a loading rate of 0.9 kN/s on 2-in. (50 mm) cubic samples placed between two square bars of dimensions (10 × 10 mm^2). Each mixture's sample was tested under splitting tensile until failure while accounting for their average. Figure 5b exhibits the splitting tensile test setup.

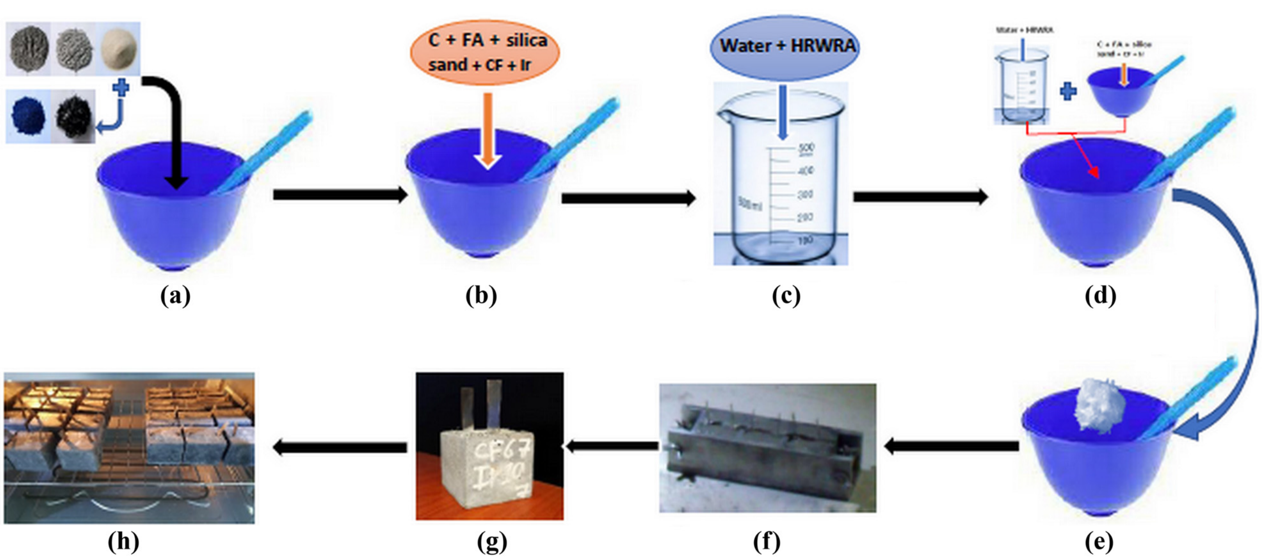
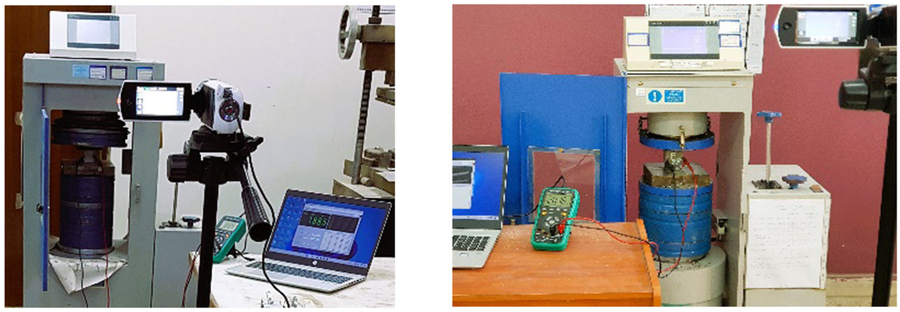


Figure 4: Technical drawing and details of the sample manufacturing process. (a) Raw and conductive materials in the pan. (b) Dry mixing for 10 min. (c) Preparation of water and HRWRA solution for 5 min with the aid of a hand blender. (d) Wet mixing of all materials for 10 min except PVA. (e) Adding of PVA gradually to the mixture and mixing all for 10 min. (f) Pouring of the mixture into oiled molds and placing of electrodes. (g) Demolding of the specimens. (h) Placing the samples in the oven at 60°C for 24 h before conducting the tests.



(a) (b)

Figure 5: Mechanical test configurations. (a) Compression test, (b) split tensile test.

2.3.1.3 Cyclic compressive test

The laboratory cyclic loading simulates the load applications of moving of vehicles on the pavement. So, this test is very important to do on laboratory specimens that are being prepared to use as a rigid pavement mixture. The test was done on three samples of each mixing type within the elastic range of compressive strength. This value was determined to be 25 kN, which is equivalent to or less than 30% of the compressive strength of each mixture type. This test was performed at the age of 28 days, depending on the compression test settings previously mentioned, through loading and unloading for four successive cycles. The load application was carried out according to two settings: once in the direction parallel to the electrodes and the other in the direction perpendicular to the electrodes.

2.3.2 Electrical resistivity measurement

In this work and under all mechanical testing, two strips of tin tapes as electrodes were used, with a 0.1 mm thickness, 0.1–0.3 Ω resistance, 10.0 mm width, and a length for cubic specimens of 7 mm, symmetrically placed around the samples' middle, This approach was based on what Azhari [22], Al-Dahawi et al. [17], Abdullah et al. [3], and Abdullah et al. [1] achieved, as exhibited in Figure 6. The Pro'sKit MT-1820 DC Multimeter was used to measure the electrical resistance [23]. To prevent the electrical connection between the loading machine and the samples, which may affect the accuracy of the results, a thin wooden cover was put below and above the specimen. As a result of the previous, the electrical resistivity data are determined, which is then translated into the fractional change in electrical resistance (FCER, percent) using equation (1)

$$\mathrm{FCER}\left(\frac{\Delta R}{\mathrm{RO}}\right)\% = \left(\frac{\mathrm{RL} - \mathrm{RO}}{\mathrm{RO}}\right) \times 100. \quad (1)$$

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

3 Results and discussion

3.1 Mechanical features

This section describes and discusses the test results of mortar specimens with and without hybrid conductive components of various 7, 14, and 28-day curing ages. For innovative mortar compositions reinforced by hybrid

(a) (b)

Figure 6: The geometric dimensions of the cubic specimens (a) and the manufactured specimens (b).

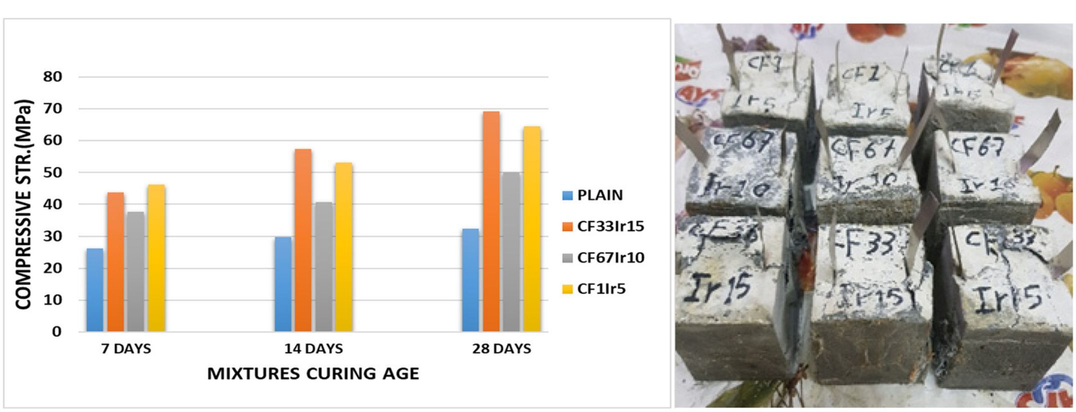
conductive fillers and different reinforcing fibers, self-monitoring behavior for the cementitious mortar test and mechanical parameters (compressive strength, and splitting tensile strength) were assessed.

3.1.1 Compressive strength

The average compressive strength values of three 50-mm cubic specimens after 7, 14, and 28 days of initial curing are presented in Figure 7. These results are based on specimens of different hybrid materials. According to the findings in Figure 7, compressive strength assessments for all types of smart mixes and the three curing ages showed a progressive rise depending on the hybrid (fiber/particle) materials. For instance, the results of the average 7-, 14-, and 28-day compressive strength tests of the CF0.33Ir15 (see Table 2) mortar specimens were 43.68, 57.31, and 69.08 MPa, respectively. The compressive strength progression was more pronounced with hybrid mixtures than they were with plain specimens. For instance, the increase in compressive strength results between 7 and 28 days for plain specimens was 23% (from 26.28 to 32.44 MPa), whereas the corresponding values for specimens CF0.33Ir15, CF0.67Ir10, and CF1Ir5 were 58% (from 43.68 to 69.08 MPa), 33% (from 37.64 to 50.12 MPa), and 40% (from 46.08 to 64.4 MPa), respectively. The continuous hydration reactions that work to intensify the concrete matrices have a direct impact on this and cause the gradual increase seen for all mixtures, according to the properties of the hybrid fillers and the reinforcing fibers and their direct effect on the compressive strength [24]. This improvement may be explained by the fact that each iron powder particle in concrete has a cubic pattern and that the spacing between the nanoparticles is controllable. Due to the particles' microscopic size, they fill the pores, which causes the microstructure to further compact. By minimizing the number of pores, strengthening the link between the aggregate and cement matrix, and raising the density of the cementitious composite, these primary processes enhance the microstructure [25]. The quick consumption of $Ca(OH)_2$, which was generated during the hydration of Portland cement, especially at early ages due to the strong reactivity of nano-Fe_2O_3 particles, is what causes the significant enhancement of compressive strength in blended concrete [19,26]. Increases in the compressive strength of specimens at various ages after adding CF12 are due to the ability of this type of fibers to stop crack propagation. When used as internal pore and/or microcrack bridging reinforcements, CF12 fibers are anticipated to improve the compressive strength of the hybrid mixtures over the control mixture while also changing pre- and post-peak microcracking behavior [17]. Adding fibers such as PVA to the cementitious mortar would increase the strength of the cementitious compound for cracking influenced by the bond characteristics at the fiber–matrix interface [27,28].

3.1.2 Splitting tensile strength

The average splitting tensile strength values of three 50-mm cubic samples after 7, 14, and 28 days of primary treatment with smart mortar samples that correspond to those made using hybrid particles/fibers are given in Figure 8. Based on the information in Figure 8, the splitting tensile strength test measurements revealed a progressive rise in strength. For instance, the CF1.00Ir5 mortar samples' 7, 14, and 28-day split tensile strength findings were 4.8, 5.7, and 6.4 MPa, respectively. The gains were more noticeable with control samples as compared to samples created from hybrid powders/fibers, as opposed to samples made from hybrid materials. For instance, the split tensile strength of plain samples increased by 44 percent, or from 1.8 to 2.6 MPa,



(a) (b)

Figure 7: (a) Compressive strength results for different ages of smart mixtures and (b) samples after testing until failure.

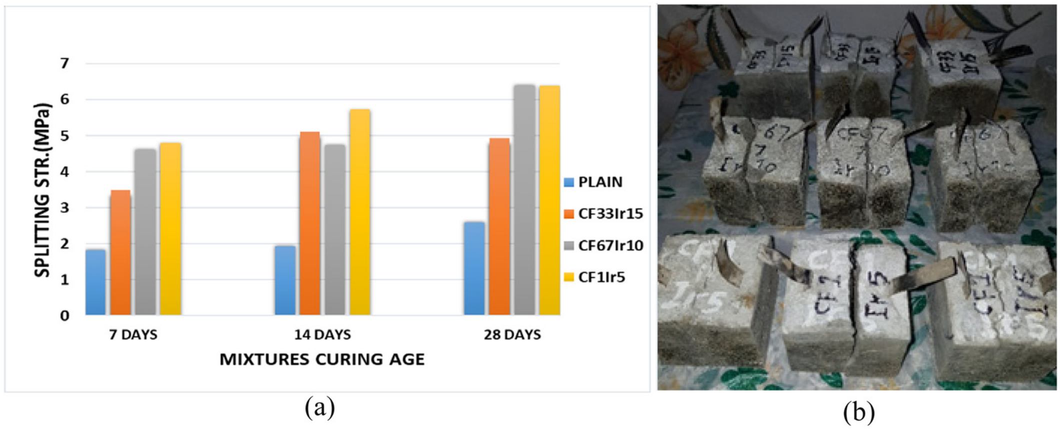


Figure 8: (a) Indirect tensile strength results for different ages of smart mixtures and (b) samples after testing until failure.

between 7 and 28 days, whereas the corresponding values for samples CF0.331Ir15, CF0.67Ir10, and CF1.00Ir5 were 40% – from 3.47 to 4.93 MPa, 39% – from 4.6 to 6.4 MPa, and 33% – from 4.8 to 6.4 MPa, respectively. This is completely consistent with what Ma et al. [29] found, which proved that by combining PVA fibers with CF the tensile strength of cracking increased by 43%. It

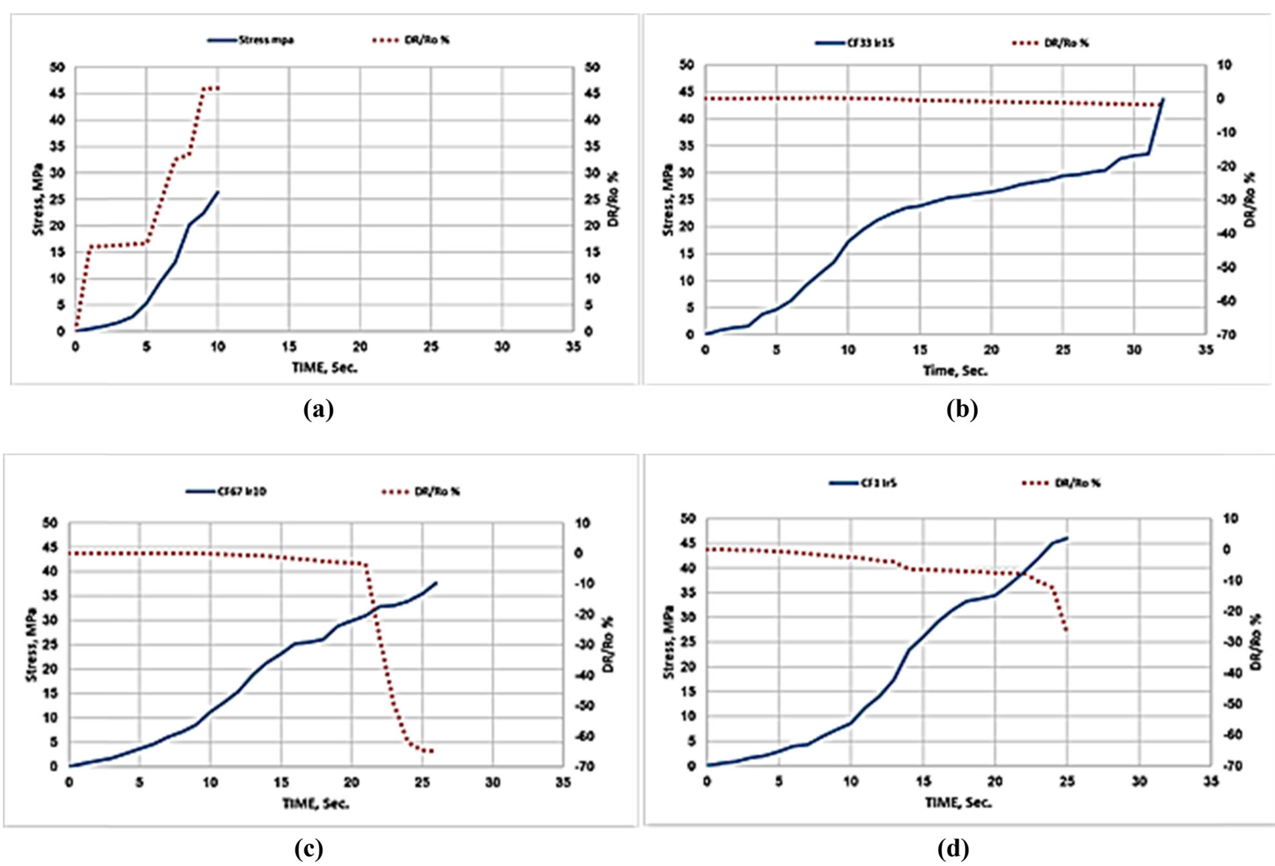


Figure 9: Self-sensing of various mixtures under uniaxial compressive strength for 7 days curing age. (a) Plain mixture self-sensing behavior of cube samples (M45) under uniaxial compression test, age 7. (b) CF33 Ir 15 mixture self-sensing behavior of cube samples (M45 + 0.33 vol% CF + 15.0 wt% Ir + 2.0 vol% PVA) under uniaxial compression test, age 7. (c) CF67 Ir 10 mixture self-sensing behavior of cube samples (M45 + 0.67 vol% CF + 10.0 wt% Ir + 2.0 vol% PVA) under uniaxial compression test, age 7. (d) CF1 Ir 5 mixture self-sensing behavior of cube samples (M45 + 1.0 vol% CF + 5.0 wt% Ir + 2.0 vol% PVA) under uniaxial compression test, age 7.

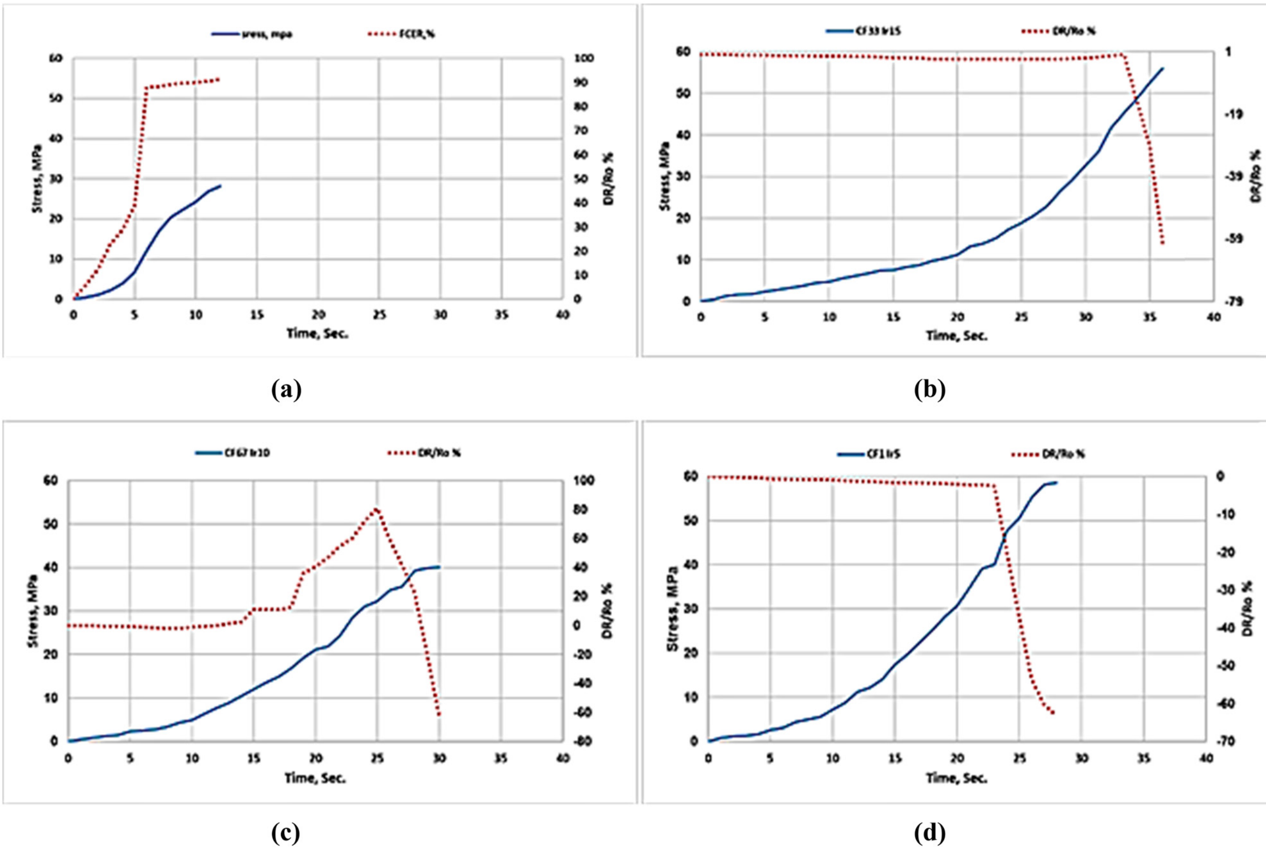


Figure 10: Self-sensing of various mixtures under uniaxial compressive strength for 14 days curing age. (a) Plain mixture self-sensing behavior of cube samples (M45) under uniaxial compression test, age 14. (b) CF33 Ir 15 mixture self-sensing behavior of cube samples (M45 + 0.33 vol% CF + 15.0 wt% Ir +2.0 vol% PVA) under uniaxial compression test, age 14. (c) CF67 Ir 10 mixture self-sensing behavior of cube samples (M45 + 0.67 vol% CF + 10.0 wt% Ir +2.0 vol% PVA) under uniaxial compression test, age 14. (d) CF1 Ir 5 mixture self-sensing behavior of cube samples (M45 + 1.0 vol% CF + 5.0 wt% Ir +2.0 vol% PVA) under uniaxial compression test, age 14.

should be mentioned that the splitting tensile strength of CF with a length of 12 mm rises with time. Because it improves the tension area and significantly lowers deviations, it increases the split tensile strength [30]. On the contrary, when the amount of iron powder is reduced, the split tensile strength increases. This could be because there were more particles in the mixture than were necessary for them to react with the freed lime during the hydration phase, causing excess silica to leak out and create a shortfall due to replacing some of the supporting material. It had no impact on the increment in strength of the structure [26]. Because the effect of adding fibers to concrete is more in the nature of energy absorption and crack control than it is in increasing load-bearing capacity, PVA fibers also increase the splitting tensile strength. By bridging fractures, the fibers assist in raising the volumetric stress capacity of post-cracking concrete and enhancing post-peak behavior [31]. According to Ekaputri et al. [32], the addition of PVA fibers to the powders enhances the tensile strength of the split in the tested samples.

3.2 The smart ECC's self-sensing behavior results

3.2.1 Self-sensing behavior under uniaxial compressive loading

The self-sensing behavior of cubic specimens of different combinations subjected to uniaxial compressive strength at various curing ages is presented in Figures 9–11. For all self-sensing graphs in this work, straight and dashed lines, respectively, represent changes in stress and the FCER values over time. Figure 9a illustrates how ECC-Reference specimens after each testing age behaved in terms of self-sensing responsiveness under uniaxial compression with varied FCER values. Due to the spatial separation of conductive phases in traditional ECC-Reference specimens, the motivation of unbounded water and dissolved ions in micropores with the introduction of an electric field may result in a piezoresistive reaction [33]. In contrast to the

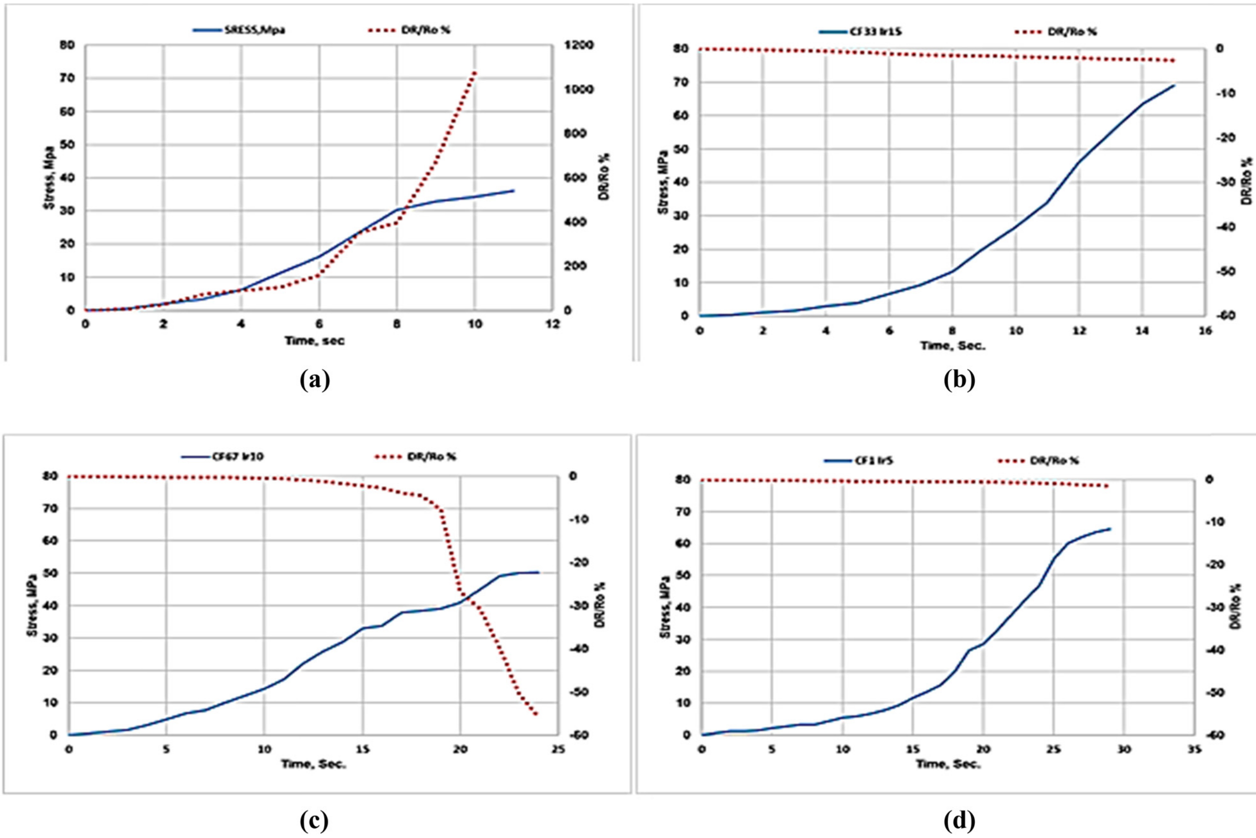


Figure 11: Self-sensing of various mixtures under uniaxial compressive strength for 28 days curing age. (a) Plain mixture self-sensing behavior of cube samples (M45) under uniaxial compression test, age 28. (b) CF33 Ir 15 mixture self-sensing behavior of cube samples (M45 + 0.33 vol% CF + 15.0 wt% Ir + 2.0 vol% PVA) under uniaxial compression test, age 28. (c) CF67 Ir 10 mixture self-sensing behavior of cube samples (M45 + 0.67 vol% CF + 10.0 wt% Ir + 2.0 vol% PVA) under uniaxial compression test, age 28. (d) CF1 Ir 5 mixture self-sensing behavior of cube samples (M45 + 1.0 vol% CF + 5.0 wt% Ir + 2.0 vol% PVA) under uniaxial compression test, age 28.

control samples, the smart hybrid mixtures for all treatment ages showed a different behavior by increasing the conductivity under loading until failure with modest (FCER, %) values, but rather the conductivity increased after increasing the compressive load, due to the effective delivery of iron metal, and this fills part of the research gap from the point of view of adding it to the entire ratio of the smart mixture instead of partially replacing any of the basic components of the mixture, and this totally agrees with what previously found in the literature [34]. The synergistic effect of iron powder with CF led to this increase in conductivity under loading, which fills the gap in this research by creating smart mixtures and injecting them with hybrid conductive fillers, which improves the conductivity of the electrical network within the smart cementitious mortar. The increased bulk resistivity of smart-ECC compared to the control mixture may be due to higher air porosity [33]. A previous study confirmed that iron (Ir) powder shows an improvement in electrical resistivity when mixed with CF, which indicates the synergistic interaction of the additives. Due to its larger surface area compared to carbonyl iron powder (CIP), according to experimental data, the best composite with suitable mechanical qualities, high electrical conductivity, and electromagnetic interference shielding is synthesized by mixing 20% CIP with 0.7% of 12 mm CF [35], which is the closest for this research.

3.2.2 Self-sensing behavior under splitting tensile loading

The self-sensing behavior of different age samples of hybrid smart mixes under splitting tensile loads is exhibited in Figures 12–14. The majority of self-sensing results reported under indirect tensile strength showed a behavior in FCER that was clear from the onset and recordable and increased with increasing load at early ages, but it was noted that this increase began to decline at later ages, especially at 28 days of age. Self-sensing data were typically reported as a single

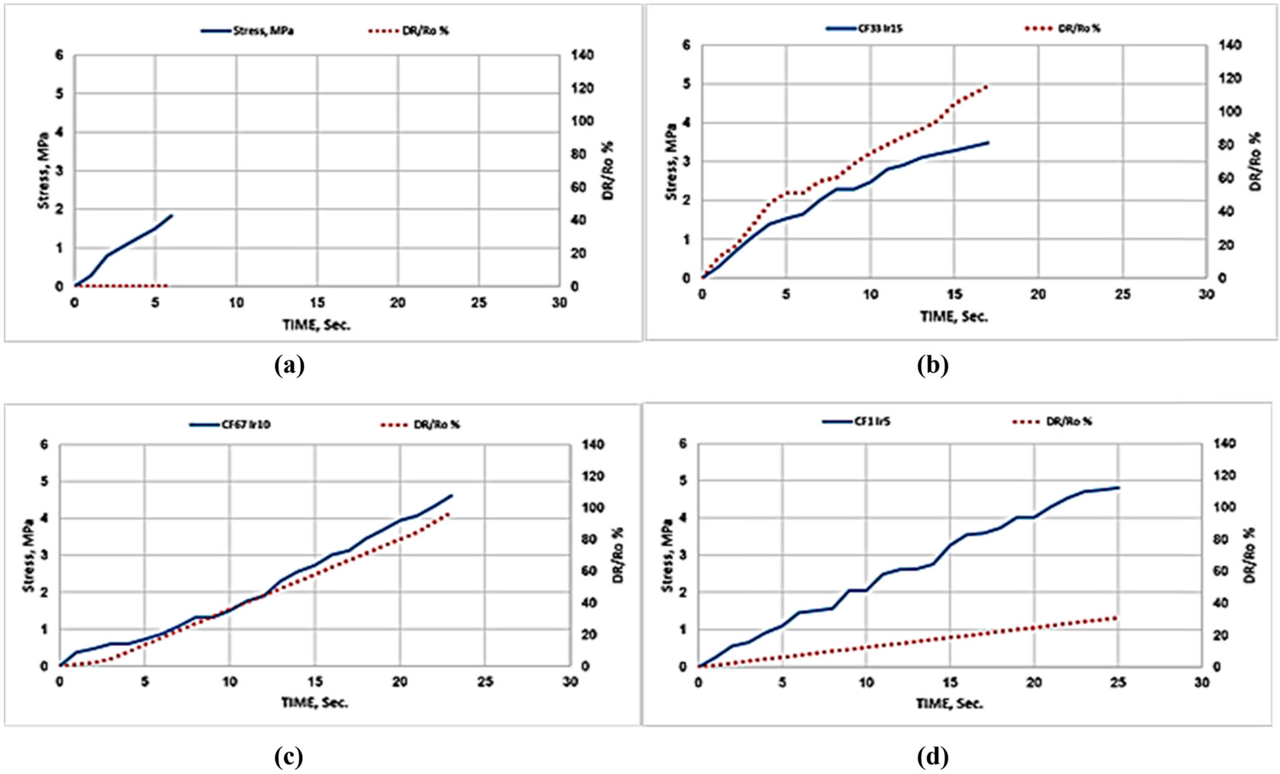


Figure 12: Self-sensing of various mixtures under indirect tensile strength for 7 days curing age. (a) Plain mixture self-sensing behavior of cube samples (M45) under splitting tensile test, age 7. (b) CF33 Ir 15 mixture self-sensing behavior of cube samples (M45 + 0.33 vol% CF + 15.0 wt% Ir + 2.0 vol% PVA) under splitting tensile test, age 7. (c) CF67 Ir 10 mixture self-sensing behavior of cube samples (M45 + 0.67 vol% CF + 10.0 wt% Ir + 2.0 vol% PVA) under splitting tensile test, age 7. (d) CF1 Ir 5 mixture self-sensing behavior of cube samples (M45 + 1.0 vol% CF + 5.0 wt% Ir + 2.0 vol% PVA) under splitting tensile test, age 7.

crack developing and expanding across a selected sample, and only a limited area for self-sensing was observed due to direct insertion of copper electrodes at the top and 5 mm from the edges of the cube samples [24]. From the figures and in all samples, the gains were clear for the hybrid mixtures that contain a higher dosage of metal and less CF at the expense of the rest of the mixtures, due to the higher conductive metal ratio and the optimal ratio of CF within the matrix, and this is completely consistent with what was reached by [34]. The essential cause why the resistance grew with age is that the continuous hydration by cement and water decreased the quantity of water in the holes of the hardened cement paste with time, causing the free pores filled with hydration items [36].

3.2.3 Self-sensing behavior under cyclic compression loading

As previously mentioned, periodic loading of the smart mortar samples under compression loading at the age of 28 days was carried out in both directions: the direction parallel to the loading axis with the electrodes of the electrical sample and the direction perpendicular to the loading axis on the electrodes of the electrical sample. The fractional change in the electrical resistance under loading was measured in the elastic range, which represents 25% of the compressive strength. The formation of cracks during the compression phase and the resulting crack opening during the unloading phase led to a slight increase in the electrical resistance of the reference mortar at unloading, and this justifies the increase in the electrical resistance values under cyclic loading (Figure 15a) [37]. With regard to the hybrid mixtures in parallel, the mixture containing CF 0.33% by volume of the total mixture and Ir15% by the total weight of the mixture showed the best sensing behavior under cyclic loading, as shown in Figure 15b. This is very compatible with a previous study conducted by Donnini et al. [38], who proved that the optimal dosage of CF, which guarantees an optimal match between mechanical properties and self-sensing ability, is about 3% of the volume of cementitious composites and that the electrical resistance

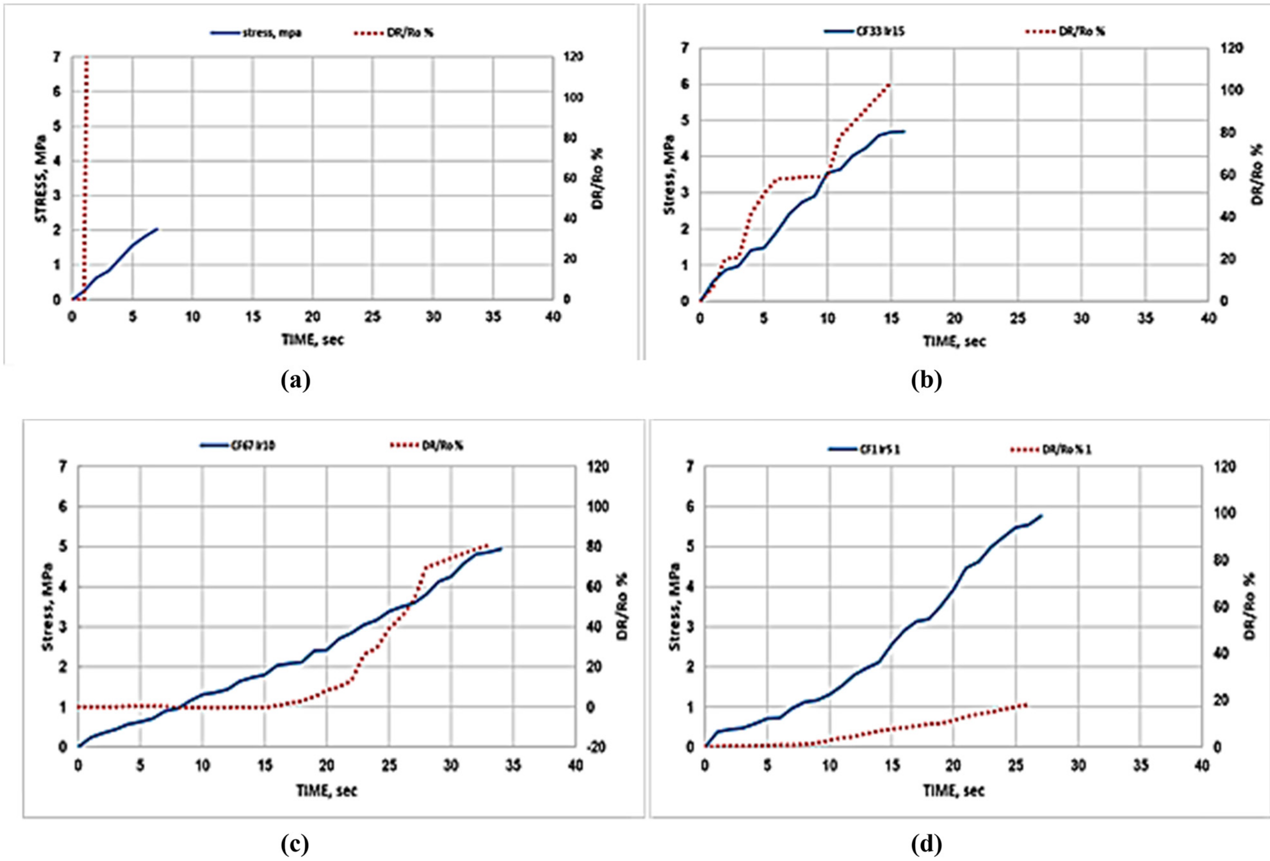


Figure 13: Self-sensing of various mixtures under indirect tensile strength for 14 days curing age. (a) Plain mixture self-sensing behavior of cube samples (M45) under splitting tensile test, age 14. (b) CF33 Ir 15 mixture self-sensing behavior of cube samples (M45 + 0.33 vol% CF + 15.0 wt% Ir + 2.0 vol% PVA) under splitting tensile test, age 14. (c) CF67 Ir 10 mixture self-sensing behavior of cube samples (M45 + 0.67 vol% CF + 10.0 wt% Ir + 2.0 vol% PVA) under splitting tensile test, age 14. (d) CF1 Ir 5 mixture self-sensing behavior of cube samples (M45 + 1.0 vol% CF + 5.0 wt% Ir + 2.0 vol% PVA) under splitting tensile test, age 14.

decreases at compression loading in both cycles due to the pushing of the fibers and increases upon unloading due to the opening of the cracks and the pulling of the fibers. Traces of small damage can be seen on the matrix after the first loading cycle during unloading as the resistance increases to higher values than the initial values. Perhaps this is due to the gradual damage to the matrix during compression loading and the formation of small cracks inside the cement matrix, which leads to an irreversible increase in resistance. On the contrary, the self-sensing of the samples manufactured by hybrid connectors in the vertical direction showed a different behavior from those that were subjected to cyclic loading in the parallel direction, as the mixtures CF67Ir10 and CF1.00Ir5 showed acceptable and regular behavior of the self-sensing under cyclic loading, which is similar to the behavior of the optimal mixture in the direction parallel, which was explained a short while ago, and the direction of the electrodes can play the main role in this behavior, which results in a large convergence instead of divergence of the electrodes during loading, which increases the conductivity under loading as a result of bridging the imbalance and shortening the conduction distance, which results in a regular movement of ions within the matrix to and from the electrodes as shown in Figure 15(f) and (g).

4 Conclusions

1. By causing a discernible fractional change in the electrical resistance under the applied load over time, the formation of cementitious composite mixtures from conductive hybrid materials (CF and iron powder) has clear effects on their piezoresistive properties, making it very useful in a variety of applications, particularly in monitoring the structural health of concrete structures.

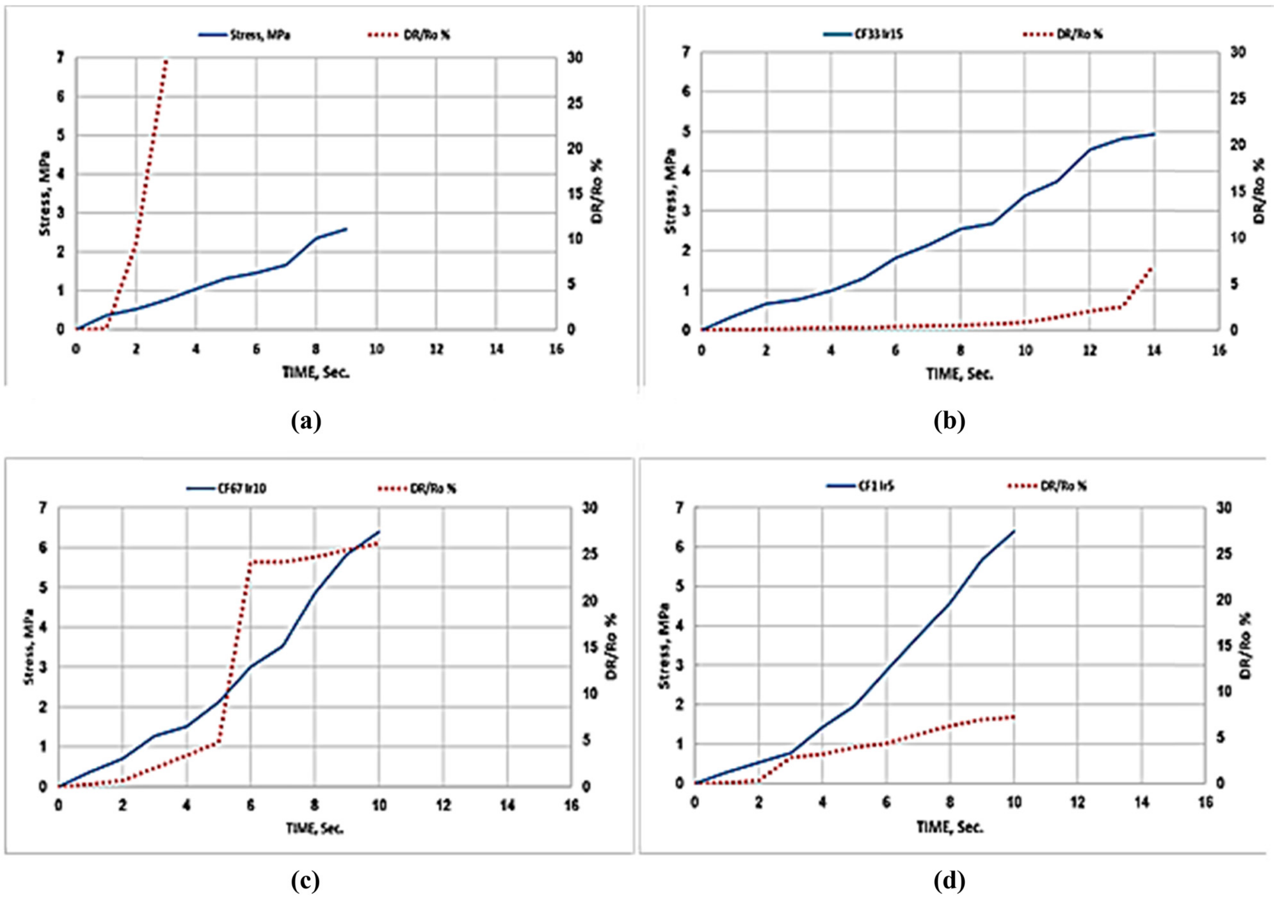


Figure 14: Self-sensing of various mixtures under indirect tensile strength for 28 days curing age. (a) Plain mixture self-sensing behavior of cube samples (M45) under splitting tensile test, age 28. (b) CF33 Ir 15 mixture self-sensing behavior of cube samples (M45 + 0.33 vol% CF + 15.0 wt% Ir + 2.0 vol% PVA) under splitting tensile test, age 28. (c) CF67 Ir 10 mixture self-sensing behavior of cube samples (M45 + 0.67 vol% CF + 10.0 wt% Ir + 2.0 vol% PVA) under splitting tensile test, age 28. (d) CF1 Ir 5 mixture self-sensing behavior of cube samples (M45 + 1.0 vol% CF + 5.0 wt% Ir + 2.0 vol% PVA) under splitting tensile test, age 28.

2. The design of the mixtures in this hybrid form gave high results for the mechanical properties thanks to the synergistic effect for the additive materials among them, and this effect reflected positively on improving the self-sensing of these mixtures.
3. All manufactured mixtures with hybrid functional materials in this article are suitable for mechanical applications under different loading scenarios and according to their practical needs in the field. As for self-sensing, the optimal smart mixture for all ages was CF at a dosage of 0.33% in the total volume of the mixture and iron powder (Ir) at a dosage of 15% by total weight of cementitious materials, and reinforced with PVA fibers at a constant rate of 2% by total mixture volume.
4. The smart hybrid mixtures for all curing ages showed different behaviors by increasing the conductivity under loading until failure by modest values (FCER, %). Conductivity even increased after increasing the compressive load, due to the effective conductivity of the iron metal in addition to the synergistic interaction between the hybrid materials added in the same matrix. On the other hand, under cyclic compressive loading, the electrical resistance decreased during the two cycles of compressive loading due to the pushing of the fibers and increased when unloading due to the opening of cracks and the pulling of the fibers. Traces of minor damage to the matrix can be seen after the first loading cycle during unloading as the resistance increases to values higher than the initial values. This is probably due to the gradual damage of the matrix during compressive loading and the formation of micro-cracks within the cement matrix, leading to an irreversible increase in resistance.

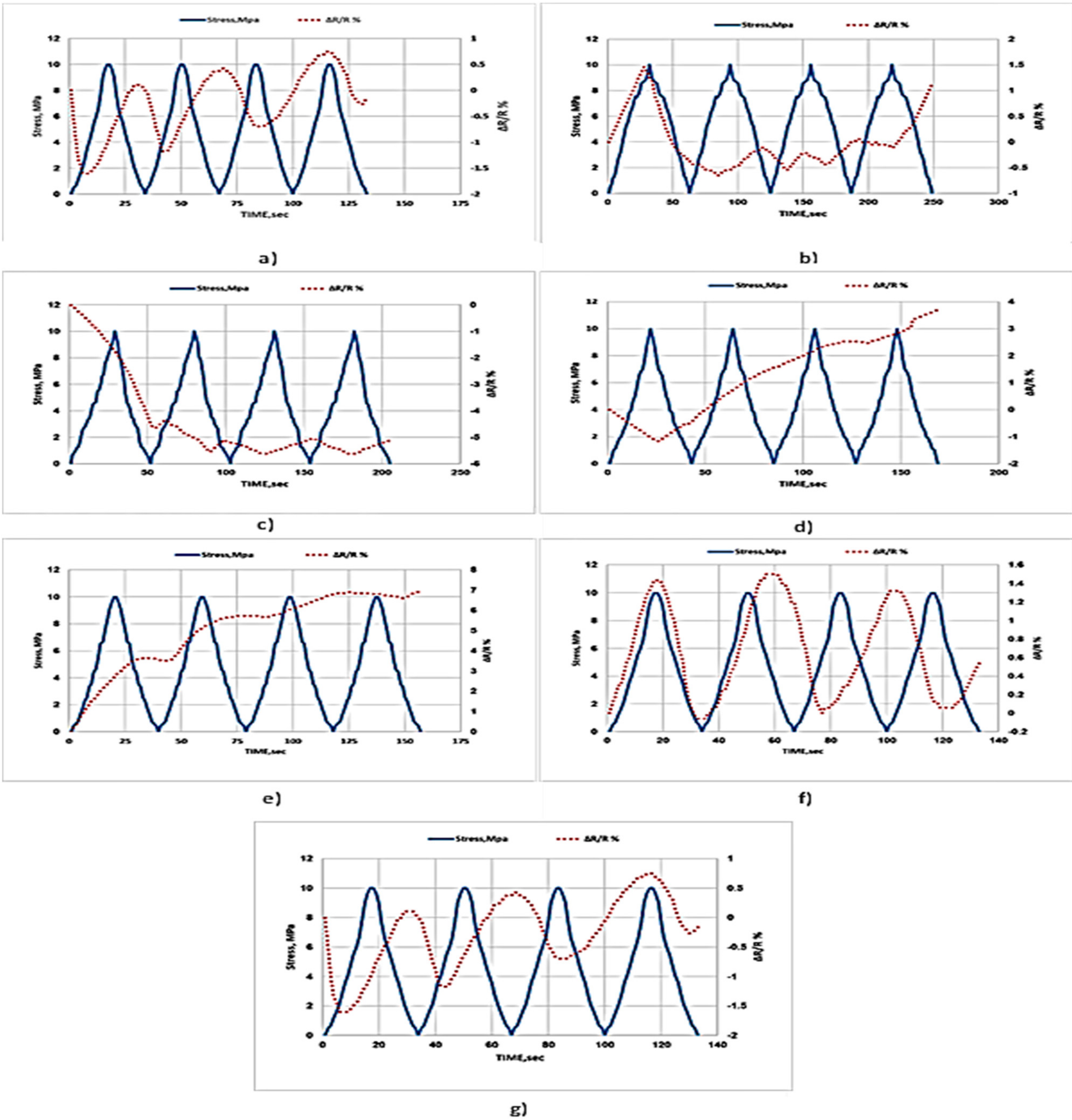


Figure 15: Self-sensing of various mixtures under cyclic compressive loading for 28 days curing age. (a) ECC-plain mixture. (b) ECC-CF33 lr 15 mixture, parallel. (c) ECC-CF67 lr 10 mixture, parallel. (d) ECC-CF1 lr 5 mixture, parallel. (e) ECC-CF33 lr 15 mixture, perpendicular. (F) ECC-CF67 lr 10 mixture, perpendicular. (g) ECC-CF1 lr 5 mixture, perpendicular.

5 Recommendations for future works

1. The ECC mixes chosen from this work (using the best combination of the hybrid mixture) are used in the field to monitor both the mechanical and self-sensing performance of the rigid pavement under different site load conditions.
2. looking into the application of these hybrid ECC mixes for overlay rehabilitation and other pavement maintenance tasks because of their superior mechanical properties to resist loads.

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Data availability statement: Most datasets generated and analyzed in this study are comprised in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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