Carbon-Based Nanomaterial Embedded Self-Sensing Cement Composite for Structural Health Monitoring of Concrete Beams - A Extensive Review

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Abstract. Structural health monitoring has proven to be a dependable source for ensuring the integrity of the structure. It also aids in detecting and estimating the progression of cracks and the loss of structural performance. The most compelling components in the structural health monitoring system are sensing material and sensor technology. In health monitoring systems, fiber optic sensors, strain gauges, temperature sensors, shape memory alloys, and other types of sensors are commonly used. Even though the sensors bring monetary value to the system, they have some apparent drawbacks. As a result, self-sensing cement composite was established as a sensor alternative with better endurance and compatibility than sensors. Carbon nanotubes, nanofibers, graphene nanoplates, and graphene oxide are carbon-based nanomaterials with unique mechanical and electrical properties. As a result, this review comprises a complete assessment of the fresh, mechanical, and electrical properties of self-sensing cement composite developed using carbon-based nanoparticles. The research also focuses on the self-monitoring performance of cement composite in concrete beams, both bulk and embedded, by graphing the deviation of fractional change in resistivity with strain. The network channel development of carbon-based nanomaterials in cement composites and their characterization acquired using scanning electron microscopy (SEM), and X-Ray diffraction spectroscopy (XRD) research are also comprehensively discussed. According to the study, increasing carbon-based embedment decreased the relative slump and flowability while increasing the composite's compressive, split tensile, flexural, and post-peak performance. Also, the amount of carbon in the carbon-based nanomaterial directly relates to the composite's conductivity. As a result, the development of piezoresistive and sensing capabilities in carbon-based self-sensing cement composites not only improves mechanical and conductive properties but also serves as a sensor in structural health monitoring of flexural members.

Introduction

Concrete is the most widely utilized material for numerous infrastructures, including residential, government, and commercial buildings, all of which contribute to the nation's economic development. However, the concrete structures were damaged due to weather conditions, a lack of improved design and condition assessment methods, and non-periodic maintenance [1]. As a result, enormous efforts are required to restore the failing infrastructure to a safe and serviceable

state. Although numerous concrete repair procedures, such as epoxy injection and grouting, are available, they are not continuous and are only used once structural deterioration is evident. As a result, a continuous monitoring system is required to check the concrete structure's performance [2,3] which is called as Structural health monitoring. Metallic sensors are commonly employed in the structural health monitoring procedure [4]. Sensors such as accelerometers [5], corrosion sensors [6], ultrasonic sensors [7], fiber optic sensors [8], electrochemical sensors [9], strain gauges [10], and wireless strain sensors [11] are used in structural health monitoring. However, due to incompatibility and low durability, the use of specific sensors is limited. As a result, an alternative solution for sensors is necessary, leading to the invention of self-sensing cement composite.

The application of self-sensing cement composite in developing intelligent infrastructure with conductive and sensing capabilities is excellent [12,13]. The creation of these composites increases the infrastructure's serviceability, safety, and durability [14]. Similar to structural steel [15,16], concrete construction has experienced significant advancements, both structurally [17] and in terms of material [18–20], yet concrete degradation is unavoidable. In the areas of bricks [21,22], soil [23–25], and concrete [26–28], material modification for property improvement is also on the growth. Nanomaterials have the power to change the mechanical and electrical properties of any composite due to their unique features. As a result, the nanomaterial's advantages are utilized to develop the self-sensing cement composite. To improve the conductivity properties of the cement composite, nano conductive materials such as carbon fiber [27], carbon nanofiber [13], carbon nanotube [12], steel fiber [29], graphite powder [30], and nickel powder [31] are utilized. Such a composite can sense stress, strain, cracks, and damage [32,33]. Those composites can also improve the mechanical properties of the composite, such as compressive strength, tensile strength, and flexural strength [12,13,34]. The integrated conductive components in the composite form a conductive network, which boosts the composite's conductivity. Although nanoparticles build the conductive network, aggregates and hydration products act as a barrier to the conductive network's creation in the composite.

As a result, this review paper focuses on the conductive substance that aids in the construction of self-sensing cement composites used in beams. The barriers that become a hurdle for creating self-sensing cement composite are also discussed in the article. Workability, compressive strength, flexural strength, conductivity, and piezoresistivity of the self-sensing cement composite are also reviewed, along with their morphological characterization.

Materials and Methods

Cement, fine aggregate, and water are the conventional components used to make cement composites [35,36]. The water-to-cement ratio is kept at 0.4. To increase the composite's workability, polycarboxylate ether polymers (=1% mass of cement) were added as a superplasticizer. Since dispersion of carbon nanomaterials in aqueous solutions is difficult, a specific fabrication technology, as illustrated in Fig. 1, is used to produce good dispersion [12,13]. The nanoparticles are dispersed with preliminary mechanical mixing (sonication for 30 mins) in deionized water with a superplasticizer as the dispersion. The cement powder was then mixed with water and plasticizer before being poured into oiled moulds. The cement composite is allowed to cure for a total of 28 days. The cement composite with electrodes was utilized for mechanical and electrical tests once solidified.

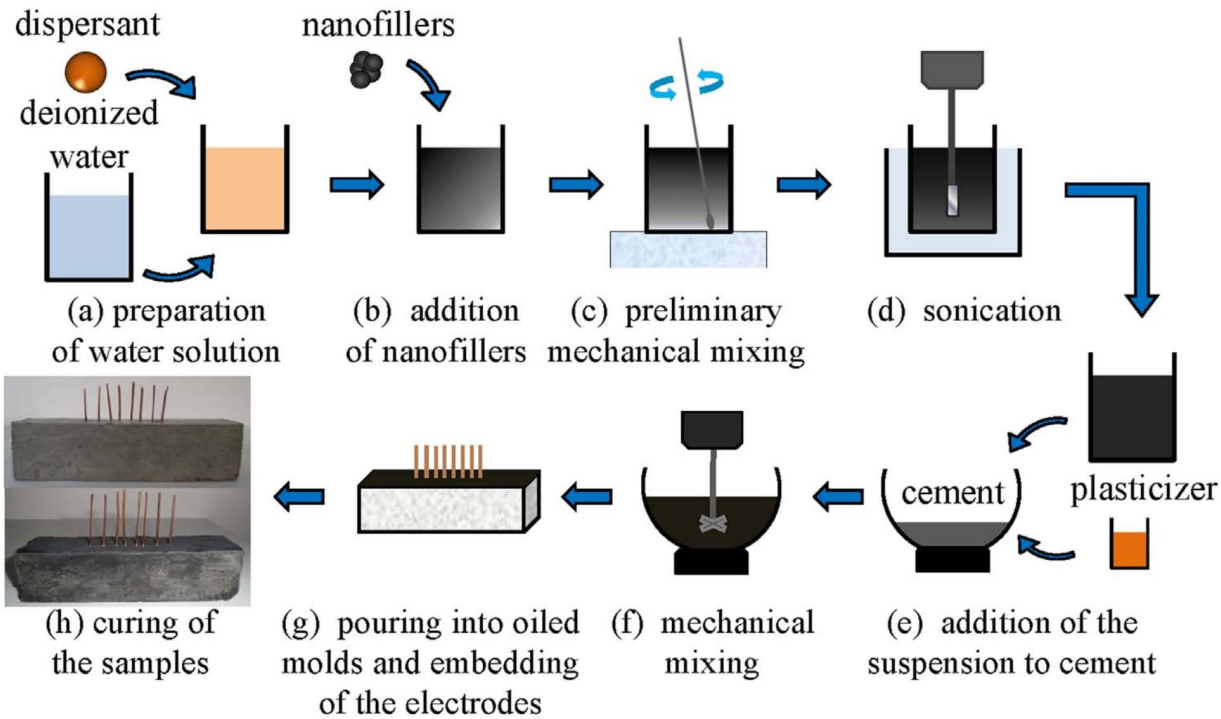

Fig. 1. Fabrication Methodology for developing self-sensing cement composite [37]

The conductivity of the cement composite is typically determined using a two or four-probe approach. The most frequent method is the four-probe method, which uses four electrodes, as illustrated in fig. 2 (a) and (b) [27]. Current is supplied by the outer two electrodes, while the inner two electrodes measure voltage. To test the electrical resistance, electrodes are inserted in the fresh mix [38,39].

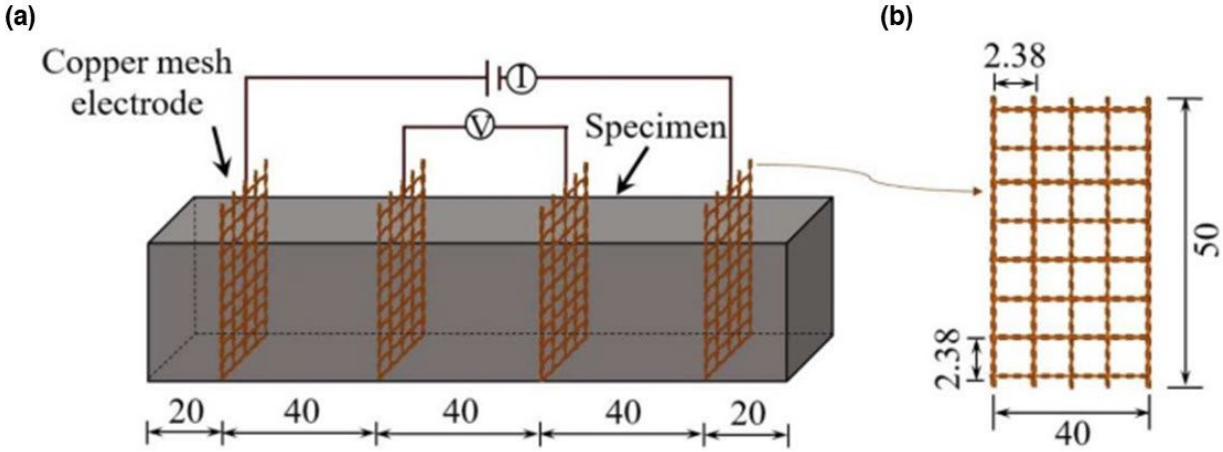

Fig. 2. (a) Schematic representation of electrical resistivity specimens using the four-probe method and (b) Configuration of electrode embedded in the composite [27]

Portland cement, fine aggregate (fineness modulus = 2.94), and coarse aggregate (maximum radius = 20mm) are used to make reinforced concrete beams of grade C40. A water reducing agent

and silica fume (radius = 100nm) are commonly employed to prepare concrete. The beam's clear span, width, and depth are 2400mm, 150mm, and 300mm, respectively. The upper bar and hooping bar are made of 235 MPa yield strength steel. During the experiment, a concentrated load is given to the beam and dissipated through two points, dividing the span of the beam into three equal spans, as illustrated in Fig. 3. As a result, the internal span will experience flexure, whereas the outer span will experience both flexure and shear [40]. The self-sensing cement composite is used in the uniaxial compression zone (center top), uniaxial tension zone (center bottom), and combined compression and shear zone (side top) of the beam.

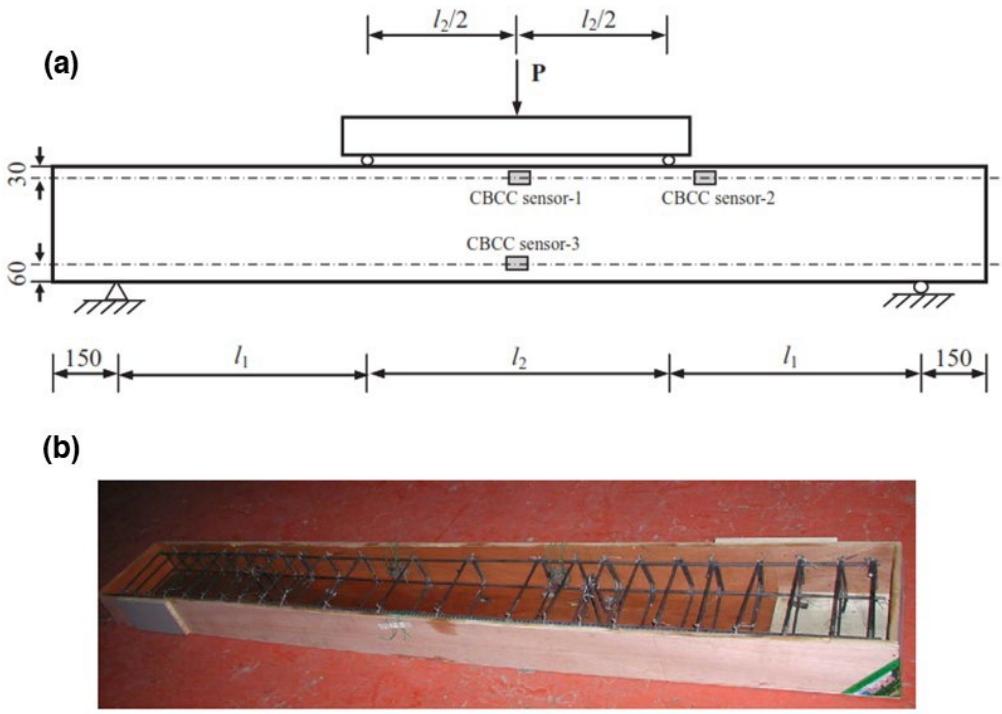

Fig. 3. (a) Schematic of the loading arrangement and location of CBCC sensors location in the beam and (b) CBCC sensor location in the concrete beam model [40]

Results and Discussions

Workability

The presence of conductive materials substantially impacts the composite's workability. As illustrated in Fig. 4, including CF in the composite diminishes the composite's workability. The superplasticizer dosage must be modified to get the same amount of workability for all percent inclusions of CF [41]. The workability of the composite is influenced by the water-cement ratio and the high concentration of fine particles [35,42]. The slump values for different aspect ratios of CF are shown in the graph with regard to CF concentration. It has been identified that when the length of CF and the concentration of conductive materials increases, the composite's workability decreases. When the length of CF is extended for the same concentration of CF, the workability is lowered. Similarly, if the CF dosage is doubled for the same period of time, the workability is lowered.

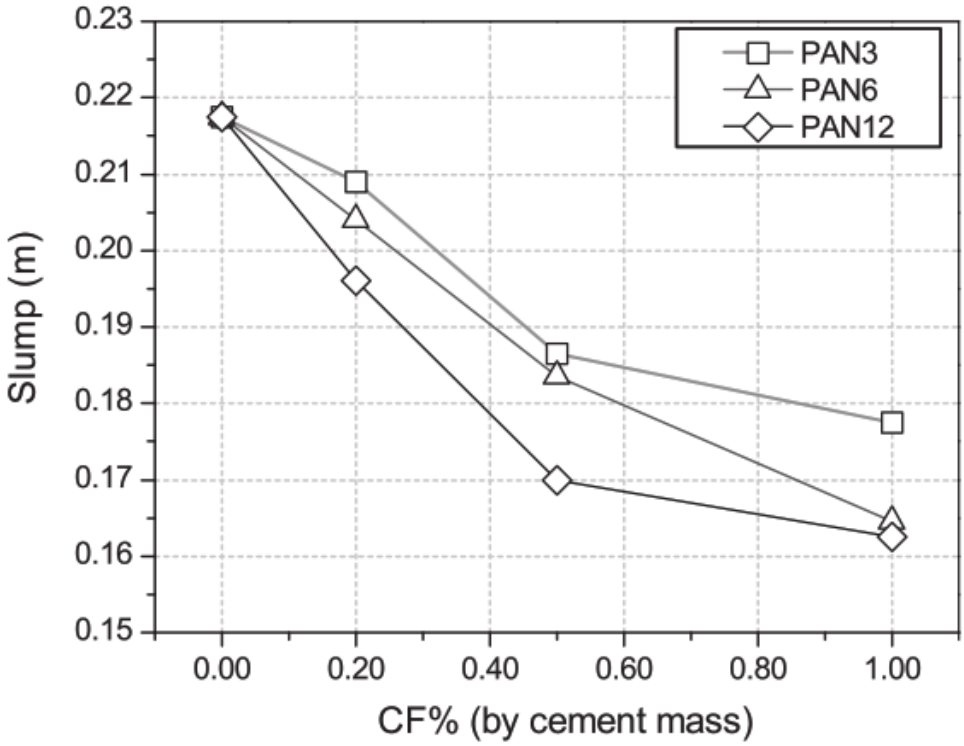

Fig. 4. Variation of the slump concerning increase in the concentration of CF (%) [41]

Strength

The flexural strength of the composite, as shown in Fig. 5., varies according to the addition of CF (PAN3 = 3mm, PAN6 = 6mm, PAN12 = 12mm). The flexural strength of the composite increases as the concentration of CF in the composite increases, as shown in the diagram. The higher the failure load levels, the shorter the CF [41]. Because shorter fibers have more fibers to support the crack area. As a result, the short fibers have a more significant impact on the composite's flexural strength.

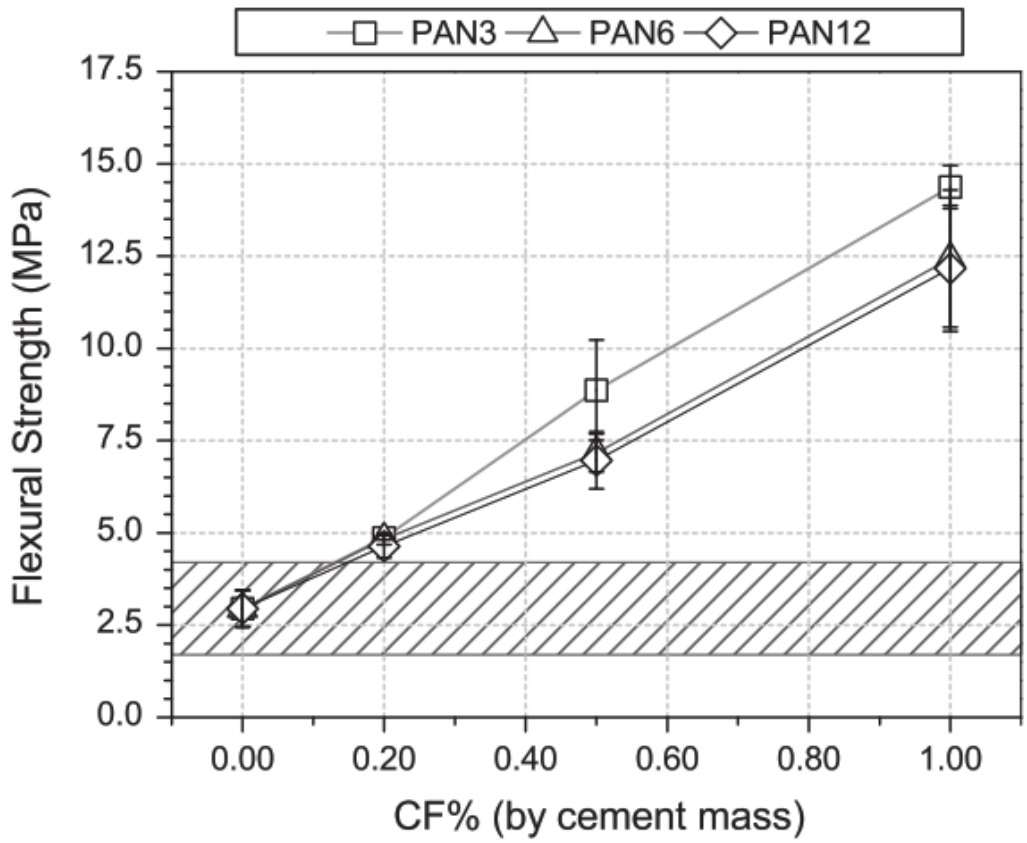

Fig. 5. Variation of flexural strength concerning increase in the concentration of CF (%) [41]

Because of the inclusion of CF of various lengths, the compressive strength of the CF embedded cement composite varies (3mm, 6mm, 12mm), as shown in Fig. 6. According to the data, the strength increments range from 2.6% to 25%. At 1% PAN3 cement paste, the maximum compressive strength values are observed. The higher concentration of PAN3 CF in the composite improves the strength of the cement composite in PAN3 embedded cement paste. Surprisingly, when the concentration of CF in the composite increases for PAN6, the strength of the cement composite decreases. The compressive strength of the PAN12 embedded cement composite is raised first, followed by drop in compressive strength at 1%. The highest strength of the cement composite is attained at 0.63% PAN12 CF, assuming a parabolic curve. Beyond that, the compressive strength of the composite was lowered because the CF embedded composite tended to form clusters due to the longer embedded CF.

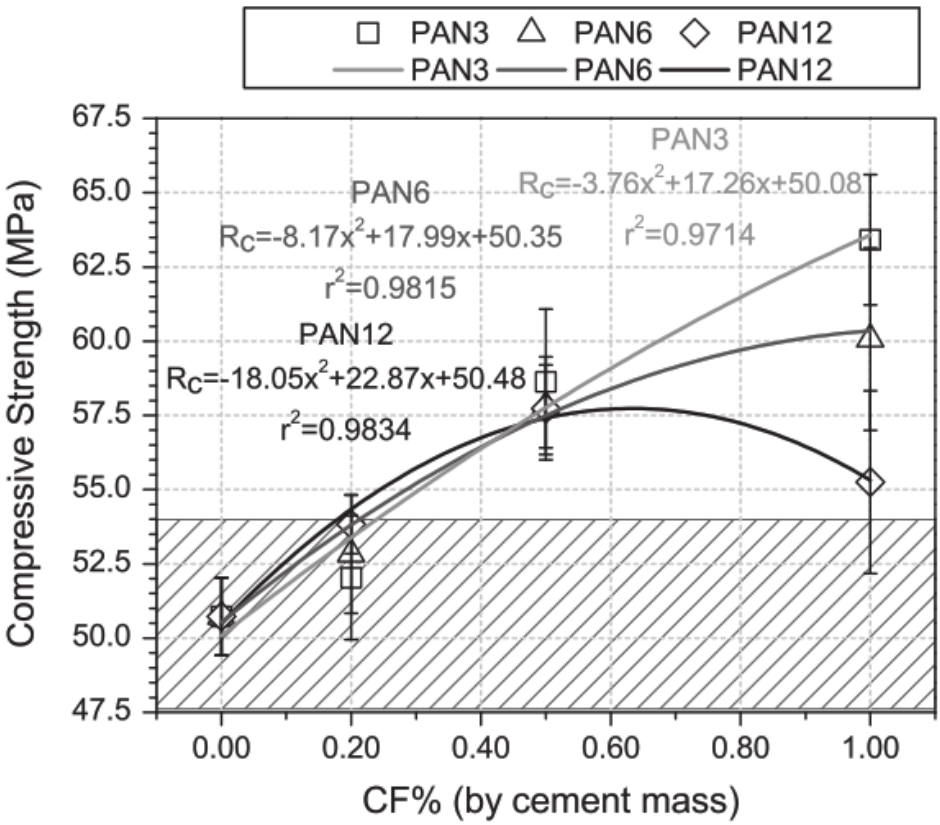

Fig. 6. Variation of compressive strength concerning increase in the concentration of CF (%) [41]

Conductivity

The conductivity of traditional cement composites is extremely high, necessitating some lowering to convert them to self-sensing cement composites. The researchers shown that adding up to 1.5% SMA and SF in the composite did not improve its self-sensing characteristics considerably. The conductivity of the composite may be enhanced to 5.79 X 10^{-6} S/cm by including 1.5% SMA, which is comparable to the conventional composite. This is because the lower concentrations of SMA and SF could not improve the composite's conductivity. The addition of 0.1% CF, on the other hand, considerably increases the composite's conductivity by forming conductive channels. The percolation transition zone of the CF embedded cement composites is S-shaped, as shown in Fig. 7. Fig. 7 shows the conductivity of the SMA and SF embedded cement composites. The random orientation in the number and quality of interconnections of the CF utilized in the composite causes the S-Shape curve. According to the research, the fibers are consistently disseminated in the composite at lower concentrations of conductive elements. However, at more significant concentrations, the fibers agglomerate and form clusters, which improves the composite's conductivity. The clusters are generated individually until a certain concentration of CF is reached, after which they are cross-connected and form a conductive channel in the composite, as illustrated schematically in fig. 7.

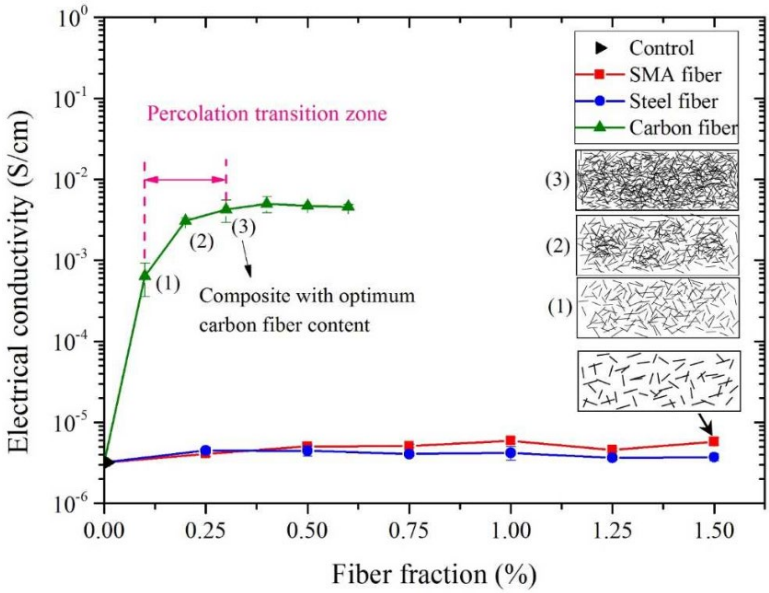

Fig. 7. Variation of electrical conductivity of the cement composite without and with SMA, SF, and CF [27]

Piezoresistivity

Under external load with frequency ranging from 0.1 Hz to 10 Hz, the piezoresistive behavior of cement composites with embedded MWCNT, CNF, CB, and GNP is shown in Fig. 8. The strain is measured with two strain gauges, and the electrical resistance is monitored with electrodes. The resistance varies with strain for all the cement composites embedded with MWCNT, CNF, CB, and GNP, as shown in fig. 8. This indicates that the conductive materials utilized are more strain-sensitive. MWCNT embedded composites have a higher sensitivity to strain than composites implanted with CNF, CB, or GNP.

In comparison to other samples, the MWCNT embedded composite has a more excellent gauge factor (=4139) and strain sensitivity (=3.763e10), according to the research. MWCNT embedded composite has excellent mechanical properties in addition to electrical ones. The elastic modulus of the MWCNT cement composite (=23410 MPa) is about four times that of the ordinary cement composite (=8821 MPa) [37]. The study also found that the elastic modulus of CNF, CB, and GNP embedded composites is comparable to that of the conventional cement composites. This demonstrates that the form and aspect ratio of conductive materials significantly impact the composite's strength increase.

The use of CF and CB yields similar results. They showed that combining CF and CB in the composite leads to good piezoresistivity repeatability. The sensitivity of such cement composites with CF and CB is 0.0138%, and the repeatability is 4.36% [43]. In the case of beams, it has been discovered that when the strain value exceeds 0.2%, the elastic modulus decreases, resulting in a significant increase in resistance owing to CF fracture [44]. This demonstrates that CF embedded composites are inappropriate for sensing composite strain and stress. The piezoresistive behavior of the hybrid conductive materials implanted in cement composites is also good. Because of their high dispersion in the composite, the cement composite with CNT/NCB has a good piezoresistive behavior (=55.28). [36].

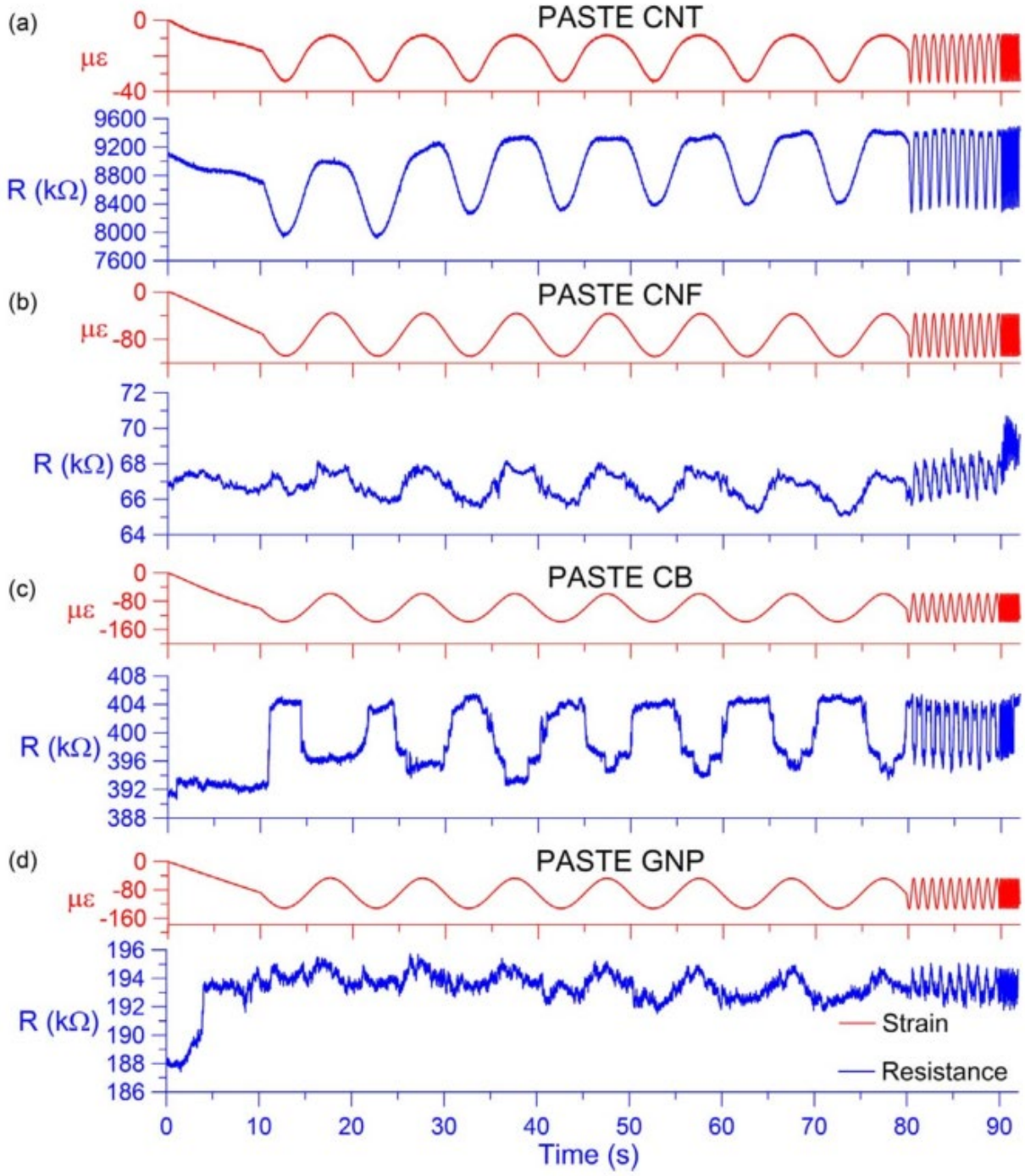

Fig. 8. Sample with time records of measured strain and electrical resistance were recorded. with (a) MWCNT, (b) CNF, (c) CB, and (d) GNP from strain sensing tests [37]

Morphology Characterization

The cement composite's effective dispersion of conductive components is depicted in the SEM image [37]. As seen in the picture, the conductive particles (MWCNT, CNF, CB, and GNP) used

in the composite are not fractured throughout the mixing process. Due to their geometric characteristics, CB particles, on the other hand, are less well-known than other materials. Furthermore, the fig. 9. shows that the particles are adequately dispersed in the matrix and that no particle agglomeration in the form of bundles has occurred in the composite. A SEM picture of the cement paste, for example, might reveal a non-uniform distribution of CNF [45]. According to SEM, the microcracks in the designed cement composite have also been amended, according to SEM [46]. They may also identify the presence of CFs bridged across healed microcracks. The development of hydration products can also be seen in the SEM images.

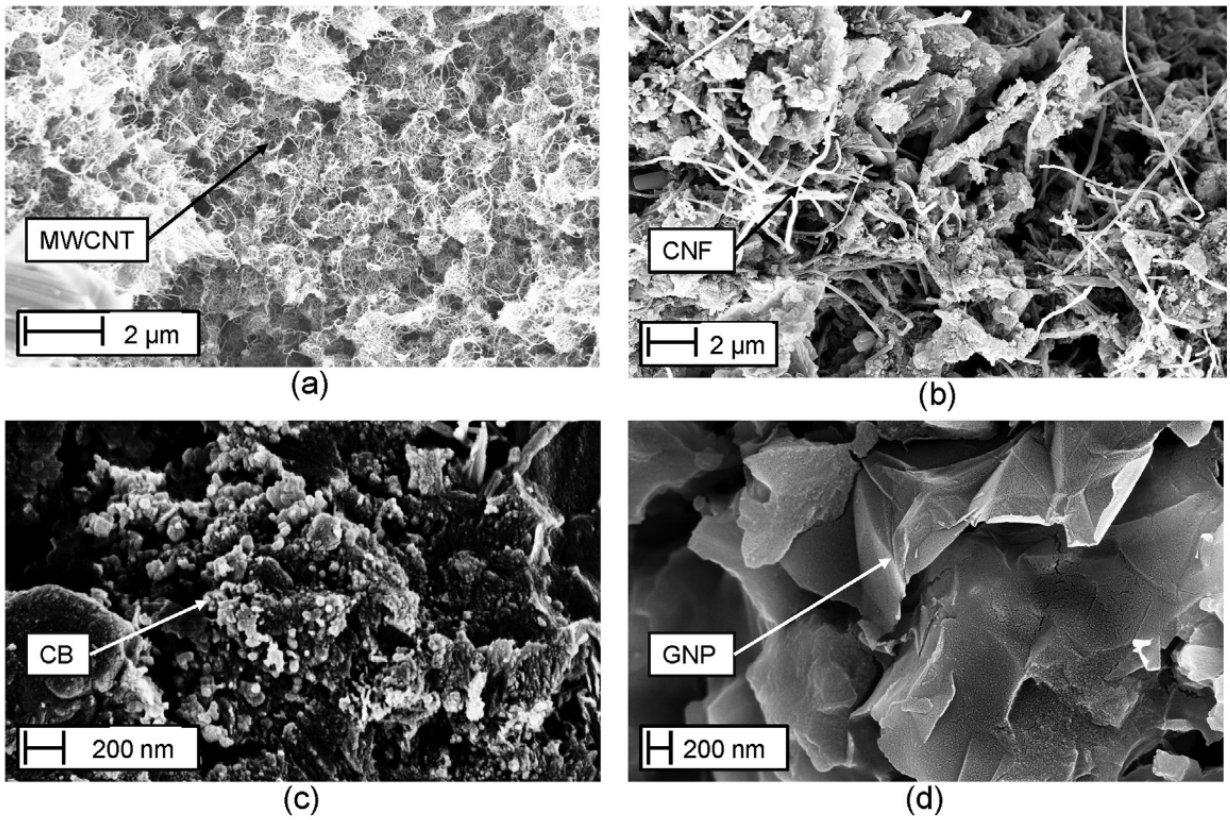

Fig. 9. SEM images of nano modified cement composite with (a) MWCNT, (b) CNFs, (c) CB and (d) GNPs [37]

Conclusions

The fresh, mechanical, and electrical properties of a self-sensing cement composite produced with carbon-based nanoparticles are investigated in detail. By graphing the deviation of fractional change in resistivity with strain, the study also focuses on the self-monitoring performance of cement composite in concrete beams, both bulk and embedded. SEM and XRD are used to characterize network channels in carbon-based nanomaterials embedded cement composites. As a consequence of the investigation, the following conclusions were made.

Mechanical Characteristics: Self-sensing cementitious composites can be made using both individual and hybrid fillers. The embedment of self-sensing cement composite does not affect the load-bearing capacity of structural components. The composite's self-sensing qualities alter before and after embedding due to the shift in poisson ratio and youngs modulus. The implanted self-sensing cement composite can reflect the stress/strain state of beams/columns, implying that it could be used as a sensor in SHM. The ultrasonic velocity through concrete might depict the

damage development. When cracks in the ultrasonic transmission channel are blocked, the velocity might soon drop to zero. This shows that ultrasonic velocity can detect cracks formation in the composite.

Electrical Characteristics: The damage evolution process can be depicted using resistivity, including an elastic phase with little damage propagation, a moderate damage development stage, an expeditisve following the force peak, and a relaxed stage with macro fractures. The self-sensing cementitious composite displays a robust and repeatable self-sensing feature under cyclic and monotonic compression. The innovative concrete with steel fibres and tiny steel slag particles demonstrated a clear reverse electrical resistivity response when compressed. The use of FSSAs instead of silica sand enhanced the piezoelectric sensitivity due to the quantum tunneling effect, while the addition of short steel fibers considerably increased the conductive network.

Morphology: According to SEM data, most CNFs can be evenly disseminated in the epoxy matrix to form conductive networks. However, when the CNF concentration was high, there were more agglomerations of CNFs, which had a negative impact on the mechanical and piezoresistive properties of the nanocomposites.

Thus, the review concludes that by creating a high-sensitivity, well-compatible, and long-serve life self-sensing cement composite, infrastructure monitoring can be done on a wide scale and at a cheap cost.

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