Smart Cementitious Composites for Road Traffic Monitoring and Weighing in Motion

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Abstract. The addition of electrically conductive materials at micro scale, such as carbon fibres (CF) or steel fibres (SF), to conventional cementitious materials makes piezo-resistive behaviours possible in terms of changes in electrical resistivity due to applied stresses. Smart cementitious composites (SCCs) may thus be able to detect traffic density and sense weight in motion thanks to such piezo-resistive property. Three types of cement-based sensors, with CF, SF, or a hybrid of CF and SF, were experimentally evaluated by applying quasi-static and dynamic load cycles after seven days of curing in different load directions reflecting the electrodes and different circuit type connections of the specimens. The performance of each type of sensor was assessed based on measuring the changes in electrical resistivity (ER) under compressive and flexure stresses, with test results revealing that the use of CF in these composites was the best choice because this generated more sensitivity to applied loads in terms of the change in ER compared with other types. These results were achieved when the applied load was parallel to the electrode direction. The findings also indicated arrangement of specimens as an electric series circuit type was the best setup configuration for traffic monitoring and weight in motion measurement.

Keywords: Smart Cementitious Composites, Cement-Based Sensors, Traffic monitoring, Weight in motion, Piezo-resistive property.

1. Introduction

Accurate traffic monitoring is a critical element in traffic management, design, and maintenance. Currently, various instrumentation systems are used to gather and process traffic data such as traffic flow, vehicular speed, traffic density, travel time, and weight in motion, with sensors either embedded within the pavement or installed along the highway. Various types of vehicle detection sensors, such as electrical, magnetic, optical, acoustic and video detectors are used, yet many such options have some negative effects on pavement surface, or are too expensive to be used extensively, as well as having high maintenance costs [1].

Advances in materials science and the development of information technology now allow the use of new generations of multifunctional and intelligent cementitious materials, thus offering durable and
inexpensive sensors for engineering applications without additional components being embedded or attached [2-10]. The use of such cementitious composites eliminates many of the problems with conventional sensors, making it interesting solution to the need for traffic detection systems [11]. Smart cementitious composites are fabricated by adding conductive fillers, such as carbon fibre (CF), to create material-wide sensors based on the principle of piezo-resistivity, which causes changes in electrical resistivity with external loading. The use of these composites thus allows the material to act as a self-sensor based on changes in electrical properties when it is subjected to external load, creating opportunities for uses such as vehicle-speed monitoring systems [12].

Cementitious materials with conductive fillers have been studied since the 1990s [13, 14]. Carbon fibres were the first inclusions used as conductive materials to turn cement pastes into piezo-resistive materials [15-17]. Some authors then carried out research studies to develop chemical and mechanical mixing methods to create multifunctional cementitious composites with optimal electrical and mechanical properties based on conductive carbon-based materials, with nanocarbon nanotubes (CNT) and graphene nanolamellae (GNP) used alongside and micro-scale CF, in addition to the experiments with several other conductive materials, for uses such as structural health monitoring and traffic detection. A large number of studies have also been carried out to investigate the sensing ability of CF cement-based materials under various loading conditions [12, 18-23]. CF have been found to be the best option for tailoring matrix properties among all carbon-based materials, as they provide very effective continuity and improve the conductivity of cement-based composites as well as being of low cost and facilitating easier dispersal in cementitious systems [22, 24]. However, other researchers [25, 26] have examined the electrical and self-sensing capacities of cement-based composite including micro steel fibres and have reported that these composites also have the potential to be used as strain sensors and damage sensors.

This research focuses on the utilisation of a multifunctional cementitious composite intended for traffic monitoring purposes, created by the addition of carbon fibres and steel fibres to the cementitious mix. The piezo-resistive response of sensors was then experimentally evaluated by applying quasi-static and dynamic load cycles with different setups and circuit type connections to verify whether the composites were sensitive enough to monitor traffic loads in the field in terms of traffic counts, traffic composition and traffic weight in motion.

2. Experimental program

2.1 Materials and mixture proportions

Two types of conductive materials were used in this work: chopped carbon fibre (CF) with 12 mm length and density of 1.7 g/cm³, and steel fibre (SF) with length ranges between 12 to 14mm and a density of 7.8 g/cm³. Figure 1 shows the sample for both CF and SF. The tensile strength and elastic modulus of the CF were 4,200 MPa and 240 GPa, respectively, while those of SF were 2,850 MPa and 200 GPa, respectively. Polyolefin fibre (PE) with a length of 48 mm, a diameter of 0.9 mm and a specific gravity of 0.9, was further added to enrich the mechanical properties of the composites produced with regard to loads; this was done in spite of their negative impact in terms of reducing the conductivity of the composite due to having dielectric content. The mixtures produced in this study consisted otherwise of common ingredients used in the composition of mortar matrices. These were Portland cement (PC) (ASTM Type I), manufactured in Iraq in compliance with the I.Q.S (5), 1984 [27]; Class-F fly ash (FA), compatible with the requirements of ASTM-C 618 (2005) [28]; and silica sand with a maximum particle size 0.3 mm and specific gravity of 2.6. The sand particle size distribution complied with Iraqi specification IQS 45/1984 [29]. Potable water was used for mixing and a high performance superplasticizer concrete admixture (HPSCA) with a density of 1.08 Kg/litre was also used in order to develop acceptable workability. This also acted as a dispersant agent to compensate for the lack of water needed for correct cement hydration that occurred as a result of the
addition of conductive materials [30]. The chemical and physical properties of PC and FA are provided in table 1, while figure 2 provides the particle size distribution of silica sand.

![Image of chopped carbon fibres and steel fibre](image)

**Figure 1.** Samples of (a) chopped carbon fibres and (b) steel fibre

**Table 1.** Chemical compositions and physical properties of cementitious materials.

| Chemical Composition % | Cement | Fly Ash |
|------------------------|--------|--------|
| SiO2                   | 21.33  | 52.22  |
| Al2O3                  | 3.74   | 16.58  |
| Fe2O3                  | 4.76   | 6.6    |
| CaO                    | 62.35  | 7.98   |
| SO3                    | 2.01   | 0.02   |
| MgO                    | 3.37   | 2.1    |
| Loss on ignition       | 2.07   | 10.36  |

| Physical Properties    |        |        |
|------------------------|--------|--------|
| Specific Gravity       | 3.15   | 2.1    |
| Specific surface area  | 394    | 295    |
The proportions of water to cementitious materials (PC+FA) ratio (W/CM), fly ash/Portland cement ratio (FA/PC), and aggregate to cementitious materials ratio (aggregate/CM) were 0.27, 1.2, and 0.36, respectively. The dosage of CF was 1% by volume of mixture. These rates were decided based on the work by Al-Dahawi et al. [31], and similar dosages were used for SF by You et al. [26]. In addition, based on Al-Dahawi et al. [31], the proportion of HPSCA was 0.85% by volume of mixture in order to obtain the same workability in mixtures as in the previously mentioned studies. PE fibre was used at a percentage of 0.5% by volume of mixture.

2.2 Mixing methods

According to previous studies in this field, the uniform distribution of conductive materials within cementitious systems is crucial for the formation of a continuous electrical network capable of capturing or sensing changes in strain in real-life structures [32-34]. In order to gain the highest electrical conductivity in specimens without negatively affecting the mechanical properties, the mixing method suggested by Al-Dahawi et al. [24] was thus adopted in the present work. This method involves the CF being mixed with the other raw materials (Portland cement, Fly ash and fine silica sand) in dry conditions in a mortar mixer of 5-litre-capacity at 100 rpm for 10 minutes. After that, the mixing water is added over 10 seconds, and the speed of mixer is increased to 300 rpm while the HPSCA is added over 30 seconds. The mixing process then continues for an additional 10 minutes, at which point PE are added. Mixtures containing both carbon fibre and steel fibre were produced according to the steps suggested by Nguyen et al. [35], in which Portland cement, silica sand, fly ash and carbon fibre are dry-mixed using a Hobart type mixer for 10 minutes, at which point water is added and mixed in for 5 minutes. HPSCA is then added to the mixture, followed by PE. Finally, steel fibres are carefully distributed into the mixture during ongoing mixing until the mixture shows appropriate workability for casting. A similar method was used with the mixture with only steel fibre added, with the dry materials are mixed without the addition of CF. Figure 3 shows the main steps of these mixing methods.

Figure 2. Gradation for fine silica sand

![Gradation for fine silica sand](image-url)
Figure 3. Production steps for smart cementitious composites mixtures: (a) Dry raw materials (PC+FA+ Silica sand), (b) Adding CF (where appropriate) and mixing, (c) Adding water to the materials, (d) Adding HPSCA to the mixture then adding SF (where appropriate)

2.3 Selection of the proper electrical measuring setup

According to the results of preliminary studies made by the authors to examine the workability and conductivity of metals that can be used as embedded electrodes inside cementitious composites, the best type, dimensions, and positions for electrodes were determined to allow measurement of electrical resistivity [36]. Brass plate of 0.1mm thickness and 0.3Ω resistance was used in strips of 1 cm width and 6 cm length (5 cm within the fabricated cube and 1 cm externally); as the height of the prepared prismatic specimens was 10 cm, a 2 cm width, 12.5 cm length (10 cm inside the cementitious composites and 2.5 cm as an external part) was used. Figure 4 shows these brass plate electrodes. After determining the electrodes’ dimensions and positions, the best ways to measure the electrical resistivity of the specimens were investigated. A digital multi-meter, which employs direct current (DC) with two probe settings, was thus used. This device can be interfaced to a computer to record the electrical resistance during the applied load at a pre-specified interval of one second. Load values are thus taken from the loading machine each second, allowing the electrical resistivity to be determined and the fractional change in electrical resistivity values (FCER, ΔR/Ro %) to be plotted against the applied compression stresses in MPa. Moreover, for third point loading, the FCER was also presented figuratively against the flexural strength in MPa and mid-span deflections in mm. All loading measurements, time (sec.), force (kN), and mid-span deflection (mm), were taken from the loading machine every second.

Figure 4. Brass plate electrodes

2.4 Specimen preparation

After sufficient mixing to disperse the electrically conductive materials (CFs and SFs) within the cementitious composites, the preparation of the specimens began with oiling the internal surfaces of the moulds; the fresh mixtures were then poured to create 50 × 50 × 50 mm³ cubic specimens and 100 × 100 × 400 mm³ prismatic specimens. The specimens were vibrated to minimise internal air bubbles, and the pre-prepared brass plate electrodes were embedded, at a distance of around 0.5cm from the
edges of the cubic moulds. Similarly, for prismatic specimens, to avoid failure from the positioning of electrodes placed below the loading areas, two electrodes were placed at a distance of around 2 cm from the edge of the moulds at the tension/compression surface of each prism. After casting, the specimens were kept in their moulds at 50±5% RH, 23±2 °C for 24 hours. After 24 hours, the specimens were removed from their moulds and moved into water tanks and kept there until one day before testing age, which was at seven days. Twenty-four hours before the testing date, the specimens were removed from the water tanks and put in the oven at 60 °C to remove all unwanted water, as this might otherwise affect the ER measurements by inducing polarization [30, 31]. Figure 5 illustrates the casting and curing process.

Figure 5. Preparation of SCC specimens.

3. Testing configuration for compression and flexural tests
The piezo-resistive response of specimens was experimentally evaluated by applying compressive loads according to the requirements of ASTM C1609/C1609M–12 (2005) [37] using a 2,000 kN capacity, ELE Digital Electrical testing machine with a loading rate of 0.36 MPa/sec. The flexural tests were carried out according to ASTM C1609/C1609M – 12 (2005) [38] using a loading rate of 0.1 mm/sec, as recommended after seven days of curing, and applying different load directions based on the electrodes and different circuit type connections of the specimens in order to verify whether the composites were sensitive enough to sense field traffic loads.

All tests were carried out in such a manner as to obtain precise data, especially with regard to electrical resistivity, due to the likelihood of electrical connectivity between the specimens and the loading machine that might affect the resistivity values. To mitigate this, a nylon sheet was inserted between the loading machine and the specimens and the two-probe sensor was arranged to measure the electrical resistance in ohms, allowing the resistance values to be converted to resistivity values using equation (1):

\[ \rho = R \times \frac{A}{L} \]  

where, \( \rho \), \( R \), \( A \) and \( L \) are the resistivity (\( \Omega \cdot m \)), electrical resistance, cross-sectional area of the contact area between the brass electrode and the cementitious composite (\( m^2 \)), and distance (m) between the internal electrodes, respectively.

After gathering the required data, the fractional change in electrical resistivity (FCER, %) was, calculated according to equation (2), representing the piezo-resistivity behaviour of the SCCs:
where \( R_L \) is the electrical resistivity during flexural loading and unloading and \( R_o \) is the initial electrical resistivity.

### 3.1 Monotonic Compression Test setup

Four electrical setups were proposed to examine electrical resistance changes under compression testing.

**3.1.1 First configuration.** The electrodes of the specimen of each group were perpendicular to the load direction.

**3.1.2 Second configuration.** The electrodes of the specimen of each group were parallel to the load direction.

The geometric details of these setups are illustrated in figure 6, while figure 7 shows the specimens during testing for both setups.

![Figure 6. Geometric details of cubic specimens](image)

**Figure 6.** Geometric details of cubic specimens

a) first setup, b) second setup.

![Figure 7. Compression test setup](image)

**Figure 7.** Compression test setup. a) Cubic specimen, b) Computer interface, c) Digital multi-meter.

**3.1.3 Third configuration.** Three specimens were arranged as an electrical parallel circuit (Figure 8a).

**3.1.4 Fourth configuration.** Three specimens were arranged as an electrical series circuit (Figure 8b).

Figure 9 presents the testing configurations of the third and fourth setups.
3.2 Cyclic compression testing setup

A similar arrangement of electrodes as in the first setup was employed to identify electrical resistivity changes due to cyclic compression loads (Figure 6b).
3.3 Flexural testing setup

Two electrodes were inserted at the lower top and side surfaces, which is the tensile region and two other electrodes were placed in the upper top/side surface, the compression region of the specimen. Figure 10 exhibits the geometric details of this test and figure 11 shows a specimen during testing.

![Figure 10. Geometric details of prismatic specimens](image)

![Figure 11. Flexural testing setup a) Prismatic specimen, b) Data acquisition system, c) Computer interface.](image)

4. Results and discussion

4.1 Self-sensing behaviours under monotonic compression testing

Figure 12 (a) shows the relationship between compressive stress and fractional changes in electrical resistivity for all cubic specimens within the first setup.

The trend of FCER in CF-bearing specimens mirrored the trend of compressive load due to the conduction lengths between the electrodes decreasing, which tends to generate more contact among the conductive fibres with more electrical pathways allowing electrical current to pass through being generated. The FCER reached to around 61.61%, and comparable behaviours were obtained by Han et al [39]. In terms of the piezo-resistive properties of specimens with steel fibres, the measured FCER
did not noticeably change in response to compressive loads up to 13.25 MPa. One possible reason for this, mentioned by You et al. [26], is because the size of the SF with diameters of 200 µm as used are too high to effectively form continuous conductive pathways under applied load. With increasing applied compressive loading, the applied fibres moved closer together, however improving their connectivity up to failure. The FCER specimens with hybrid CF and SF remained unchanged until micro cracks were formed, which caused an increase in fractional change in electrical resistivity by disabling and disconnecting the conductive pathways among fibres. This is again consistent with You et al. [26].

Figure 12(b) shows the self-sensing response under the second setup: the compressive loading caused an increase in electrical resistivity for CF-bearing specimens due to the separation of the electrodes from each other potentially leading to weak contact among them. Additionally, according to equation 1, the electrical resistivity should be increased with the slight increase in ℓ and decreases in A. The value of FCER determined in this case was around 140%, and similar behaviours were reported by Sobolkina et al. [33]. The behaviours of other specimens incorporating SF and both CF and SF were comparable to those seen with the first setup. The change in FCER in specimens containing SF began to increase similarly as in the first test after the formation of multiple microcracks followed by failure of some portions of specimens; this was also reported by Banthia et al. [22].

Figure 12. Change in FCER and stress variations for a) first setup and b) second setup.

Among all the cement-based conductive materials, carbon fibres were more effective than steel fibres due to their capacity to sense even relatively small loads levels. Similar findings were reported by Chung [40]. The piezo-resistive response in the second setup was better than in the first in term of self-sensing, however, as it offered high values of FCER of up to around 140% as compared to the 61.6% seen in the first setup.

Figure 13 (a) plots the piezo-resistive response of one of the specimens under compression testing of the third setup. Irregular behaviours of the FCER can be clearly identified, which are not fully compatible with the expected behaviours, due to the multiple electrical conductive pathways through specimens created within this arrangement as a result of disconnection or weakness in the network under applied loading.

Figure 13 (b) shows a considerable increased in FCER for one specimen, offering similar behaviours to the first setup. This increase occurred as a result of the change in the microstructure of the test specimen.

Based on the findings, the last setup was determined to be the best configuration to use in sensor arrangements for traffic monitoring and weighing in motion in the field due to it offering higher performance in terms of sensitivity to applied stress.
4.2 Self-sensing behaviours under cyclic compression tests
Figure 14 shows good repeatability and sensitivity in specimens upon cyclic loading within an elastic regime. The electric resistivity values’ increase with the increase in compressive load is clearly seen and these decrease to the initial value on unloading. These results support the work of Azhari et al.[41].

![Figure 13](image1)

**Figure 13.** Changes in FCER and stress variations for both: a) third setup and b) fourth setup.

![Figure 14](image2)

**Figure 14.** Self-sensing behaviours of specimens under flexure testing.

4.3 Self-sensing behaviours under flexure test
Figure 15 illustrates the curves of flexure stress and fractional change in electrical resistivity (FCER) versus mid-span beam deflection for the prismatic specimens in both the first and second setups. Figure 15 (a) shows that the change in FCER is more indicative in term of self-sensing, as the electrical resistivity increased from the start of loading until the failure point, due to the generation of multiple cracks in the lower half of the specimen, leading to fibres being spaced further from each other. Figure 15 (b) illustrates an inverse relationship between the applied stress and mid-span deflection on the one hand and electrical resistivity on the other due to the convergence of conductive fibres in the compression surface of the prisms under low levels of loading and within crack free
regions. However, this relationship becomes positive with the increase in flexure stress that promotes the creation of many cracks.

![Graph showing stress/Mid-span deflection curve and Electric Resistivity changes/Mid-span deflection curve](image)

**Figure 15.** The change in FCER and stress variations for a) third setup; b) fourth setup.

5. **Conclusions**

Cementitious composites loaded with micro-scale electrically conductive materials (CF, SF or both CF and SF) were investigated, with an eye to developing composites able to detect traffic and sense weight in motion using piezoresistive properties. The piezoresistive behaviours of these composites were thus studied using quasi-static, dynamic cyclic, and flexure loads. The test results revealed that the use of CF in cementitious composites offered the most effective way to tailor matrix properties in terms of electrical resistivity and compressive strength as this material displayed more sensitivity to the applied load in terms of the change in ER as compared with other types. The best results were achieved when the applied load was parallel to the electrode direction (perpendicular to the direction of the measured resistivity). The findings also indicated that the specimens' arrangement as an electric series circuit offered the best configuration for traffic monitoring in the field in terms of traffic flow, vehicle speed detection, and weight in motion measurement.

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