Sensitive Smart Concrete Loaded with Carbon Black Nanoparticles for Traffic Monitoring

Monteiro, A.O.[a,b,c], Cachim, P.B.[a,b], Costa, P.M. F. J.[d,e], Oeser, M.[c]

[1] Department of Civil Engineering, University of Aveiro, Aveiro, Portugal
[2] RISCO, University of Aveiro, Aveiro, Portugal
[3] RWTH Aachen University, ISAC – Institute for Highway Engineering, Aachen, Germany
[4] Physical Sciences and Engineering Division, King Abdullah University of Science and Technology, KAUST, Thuwal, Kingdom of Saudi Arabia
[5] Department of Materials and Ceramic Engineering, University of Aveiro, Aveiro, Portugal

ABSTRACT: A new generation of multifunctional construction materials has been lately developed, based on recent advances in nanotechnology. Now, new composites may be able to sense stress stimuli, thanks to their piezoresistive property, given by the addition of conductive nanofillers. Here, a cement-based composite loaded with carbon black (CB) is investigated and its pressure-sensitive response is evaluated. The purpose is to study whether such composite can be used in pavements as a traffic monitoring solution or not. The mixture was established in a previous optimization analysis and contains 1.91 vol% of CB. Specimens were experimented under quasi-static and dynamic uniaxial compressive loading. The variations in electrical resistance, deformations and stresses were continuously monitored over time and the pressure-sensitivity was quantified. The composites showed a linear and reversible piezoresistive behavior and average gauge factors between 48 and 52. The findings suggest the possibility to use multifunctional CB-cement composites for traffic monitoring in roadways.

1 INTRODUCTION

Monitoring has been a growing concern in civil engineering infrastructures. Instrumentation systems are increasingly present and allow to control and understand their behavior, benefiting the health monitoring, logistics and management disciplines. Advances in materials science allow the manipulation of materials at their micro and nanoscale and opened recently the doors to the development of a new generation of multifunctional construction materials. Besides traditional sensors, an innovative technology is being developed based on the piezoresistivity principle, i.e., the property of some materials in variating their electrical resistivity with external strain stimuli. It proposes the use of conductive cement-based mixtures which act as self-sensors relying on their electrical properties changes when subjected to external strain (commonly named PCSS – Piezoresistive Cement-based Self-Sensor) (Han et al., 2014). Those may be an interesting monitoring alternative given their main advantages as, high sensing ability, better compatibility with the structure, reduced cost and life spans similar the concrete structure itself. The first report on piezoresistive concrete dates from 1993 (Pu-Woei et al., 1993). Carbon fibers (CF) were initially used to turn conventional cement pastes into a piezoresistive material

(Chung, 1998; Chung, 2000; Han et al., 2007). Subsequently, carbon nanotubes (CNT) (Han et al., 2009; Li et al., 2009; Yu et al., 2009), steel fibers (SF) (Teomete et al., 2013; Sun et al., 2014) and carbon black (Li et al., 2006; Monteiro et al., 2016; Monteiro et al., 2017) were also experimented. Among all these, the addition of CB demonstrated a particular advantage, in terms of cost-effectiveness.

Traffic monitoring systems became common in roads and benefit their management and design (Sun et al., 2006). However, most embedded sensors have problems related with poor durability, high costs, and low compatibility. The integration of stress-sensitive materials in pavement sections may be an interesting low-cost solution, since they might monitor flow rates, vehicular speeds and even weighing, without need of external sensors (Han et al., 2015). That said, this research focuses on the development of a multifunctional concrete composite, intended for traffic monitoring purposes, by the addition of low-cost carbon black nanoparticles. The piezoresistive response is experimentally evaluated by applying quasi-static and dynamic loads cycles with low amplitudes, to verify whether the composite is sensitive enough to sense traffic-like loads.

2 METHODS

2.1 Materials

The materials used to build the PCSS were Portland cement CEM II 32.5R (Cemex AG), carbon black type N330 (Orion Engineered Carbons), high performance polycarboxylate polymer-based water-reducing agent (Sika AG), commonly called as superplasticizer (SP) and fine sand. Galvanized #6 meshes were used as electrodes, for resistivity measurement.

2.2 Specimens preparation

The composition derives from a prior research (Monteiro et al., 2017), wherein the optimal CB addition was investigated, in order to get the most effective piezoresistive response. Slightly lower cement to aggregate ratio was however considered to improve the piezoresistive mechanism. Here, the mixture contains 6.5% of CB by mass of binder (equivalent to 1.91 vol% or 1.48 wt%). The water to cement ratio is 0.6 in weight and the cement to aggregate ratio is 0.5 in bulk volume. The CB filler used is composed of primary particles with diameters of approximately 20 nm, adsorbing great amounts of water due to their high specific surface area. Superplasticizer was thus added in proportion of 4% by mass of cement, to compensate the lack of water and ensure a correct cement hydration and workability (Han et al., 2015). Additionally, it acted as a dispersant agent without prejudice in the hydration process.

The correct dispersion of carbon nanoparticles into the cementitious matrix is a critical issue, once it highly influences the conduction mechanisms (Li et al., 2006) and thus the sensitivity of the PCSS. The ultra-sonication technique has been the most widely adopted, due to its ease of execution (D'Alessandro et al., 2016). The CB particles were first sonicated in the water for 15 minutes, together with half of the plasticizer with a probe-type sonicator. The cement was then joined to the solution and mixed for 5 minutes until a homogeneous cement paste is obtained. The sand is joined lastly and mixed for additional 5 minutes. The fresh mixture is finally poured into molds (100x100x60 mm) in which two mesh electrodes are previously placed, spaced 40 mm apart. Three samples were considered. After 4 days, the samples are demolded and cured into water for additional 24 days. Last of all, the samples are dried in oven for 10 days at 50 ºC. A thin layer of epoxy resin is applied in the samples' surface to avoid variations in water content, since the scope of the study did not encompass moisture influence. Acrylic plates were installed in the contact faces of the specimens to prevent possible current passage from the samples to the press plates. Fig. 1 illustrates the fabrication process.

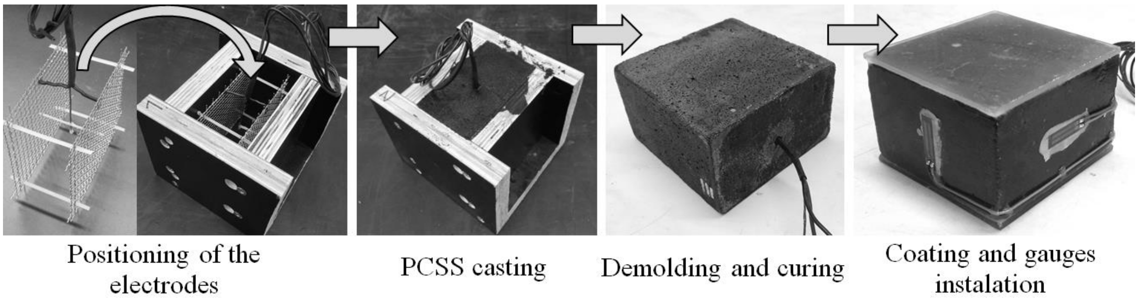

Figure 1. Fabrication process of the PCSS specimens.

2.3 Measurement

The piezoresistivity of the composite was experimented by applying cyclic compressive loads and computing simultaneously the deformation and the electrical resistance by a universal data acquisition device (HMB Quantum X), through a computer. The loads were applied by a universal press, equipped with thermal chamber (Josef Freundl), at a controlled temperature of 25 °C. The specimens were powered with an analog power supply capable of 45V DC (Hameg). The deformation was measured via strain gauges (HBM) with a temperature compensated Wheatstone quarter bridge configuration. The setup is shown in Fig. 2.

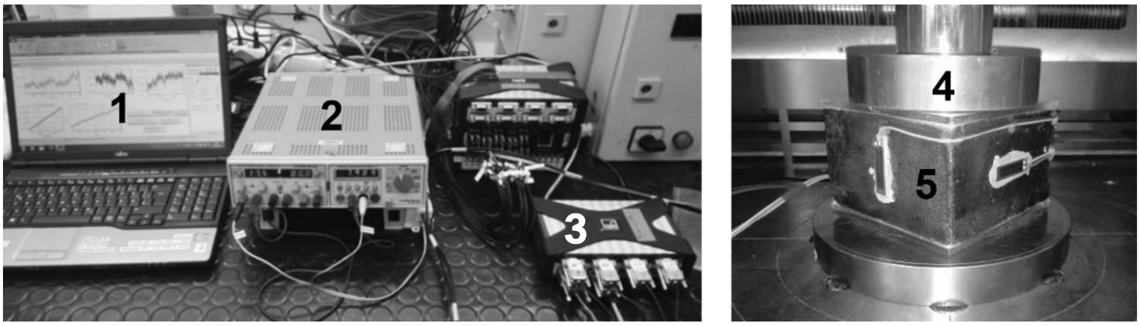

Figure 2. Experimental set-up. The devices are numbered as 1-computer interface, 2-power supply, 3-data acquisition device, 4-press actuator and 5-PCSS sample.

Quasi-static and dynamic load cycles were used with low amplitudes, ranging from 1kN (0.1MPa) to 20kN (2MPa), close to traffic-like contact pressures. The first consisted of six load/unload cycles with crescent amplitudes (1, 2, 5, 10, 15 and 20 kN), applied at a rate of 1 $kN.s^{-1}$ (0.1 $MPa.s^{-1}$), repeated five times. The second uses the same stress range but in a random order (5, 1, 15, 10, 2 and 20 kN), at a fast rate of 200$kN.s^{-1}$ (20 $MPa.s^{-1}$), to simulate the effect of the eventual passage of cars. A conditioning load of 0.2 kN (0.02 MPa) was used during experiments.

For convenience, the piezoresistive behavior is quantified by computing the variation in electrical resistance, since variations in resistivity and resistance are equivalent. The explanation is as follows. Eq. 1 defines the resistivity ρ_s of the sensors, in function of time, by using the first and second statement of Ohm's law, which define the resistance R_s of an element (Shedd et al., 1913), if a potential difference U_s and a current I are provided across the electrodes (with area A and spaced l). As the deformation of the sensors under compression is very small, l is considered constant over time. Given constant A and l, it can thus be concluded that the fractional change of electrical resistivity (FCR) is equivalent to the fractional change in electrical resistance (Eq. 2). This is more convenient because the area A to consider in Eq. 1 is an ambiguous value between the PCSS cross sectional area and the contact area of the electrodes. Actually, the definition stands for the use of external plates, occupying all the cross-section. By adopting this method, this uncertainty is eliminated.

$$\because\ R_s = \frac{U_s}{I} \wedge R_s = \rho_s \frac{l}{A} \Rightarrow \rho_s(t) = \frac{U_s(t)}{I(t)}\frac{A}{l} \tag{1}$$

$$FCR = \frac{\Delta\rho_s}{\rho_s} = \frac{\Delta R_s}{R_s} = \frac{R_s(t) - R_{s,0}}{R_{s,0}} \tag{2}$$

For more effective measurements and ease of data acquisition, the resistance computation was based only on voltage signals (Han et al., 2007). A voltage divider was thus implemented, using a known precision reference resistance R_r of 3319 Ω. The resistance of the specimen R_s and the current are computed by measuring the potential differences from the power supply output (U_p) and between electrodes (U_s). Eq. 3 shows how to calculate I and R_s based on fundamentals of electric circuits. Fig. 3 depicts the measurement principle, along with the configuration of the PCSS and the application of the load.

$$I_s = I_r \Rightarrow \frac{U_s(t)}{R_s(t)} = \frac{U_r(t)}{R_r} = \frac{U_p(t) - U_s(t)}{R_r} \Leftrightarrow R_s(t) = R_r \frac{U_s(t)}{U_p(t) - U_s(t)} \tag{3}$$

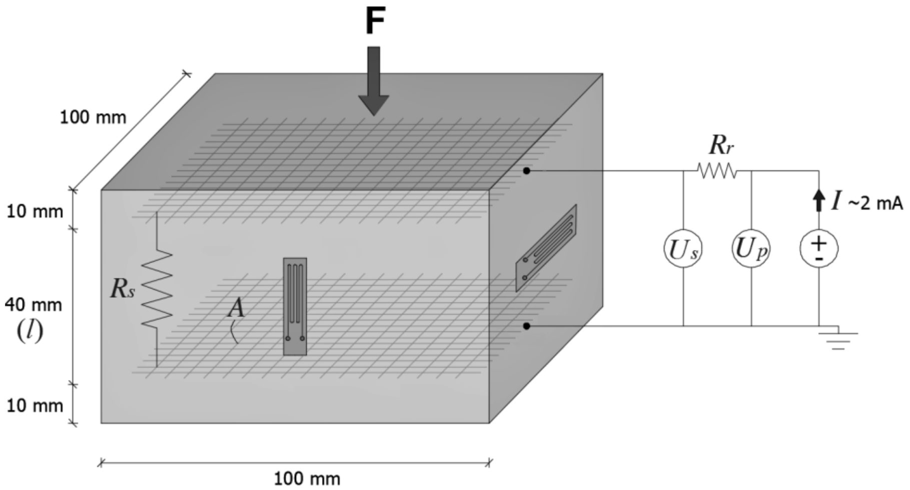

Figure 3. Electrical measurement principle and geometrical configuration of the PCSS.

Because of their electrical capacitance and polarization effect (Han et al., 2012; Ubertini et al., 2016), PCSS are able to store electric charges, which originates a delay from the power-up until they reach a stable resistance. Thus, the samples must be powered during a certain amount of time, in order to reach a stable resistance value before the experiments. Previous specific experiments claimed to a loading time of 180 s and a working current intensity of 2 mA.

For the following analysis, it is important to define two parameters associated with the PCSS performance: the stress sensitivity and the gauge factor (GF). The stress sensitivity relates the variation in resistivity and axial stress by the Eq. 4. The gauge factor is defined by the Eq. 5 and relates the variation in resistivity and deformation.

$$stress\ sensitivity = \frac{FCR}{\Delta\sigma} \quad (4)$$

$$GF = \frac{FCR}{\varepsilon} \quad (5)$$

3 RESULTS AND DISCUSSION

Fig. 4 plots the piezoresistive response of one of the specimens for both described load cycles. Fig. 4a and 4c depicts part of the FCR and stress variations over time, for quasi-static and dynamic loadings, respectively. The change in resistivity showed a reversible behavior upon loading and a linear relation between stress and resistivity, as demonstrated by Figs. 4b and 4d.

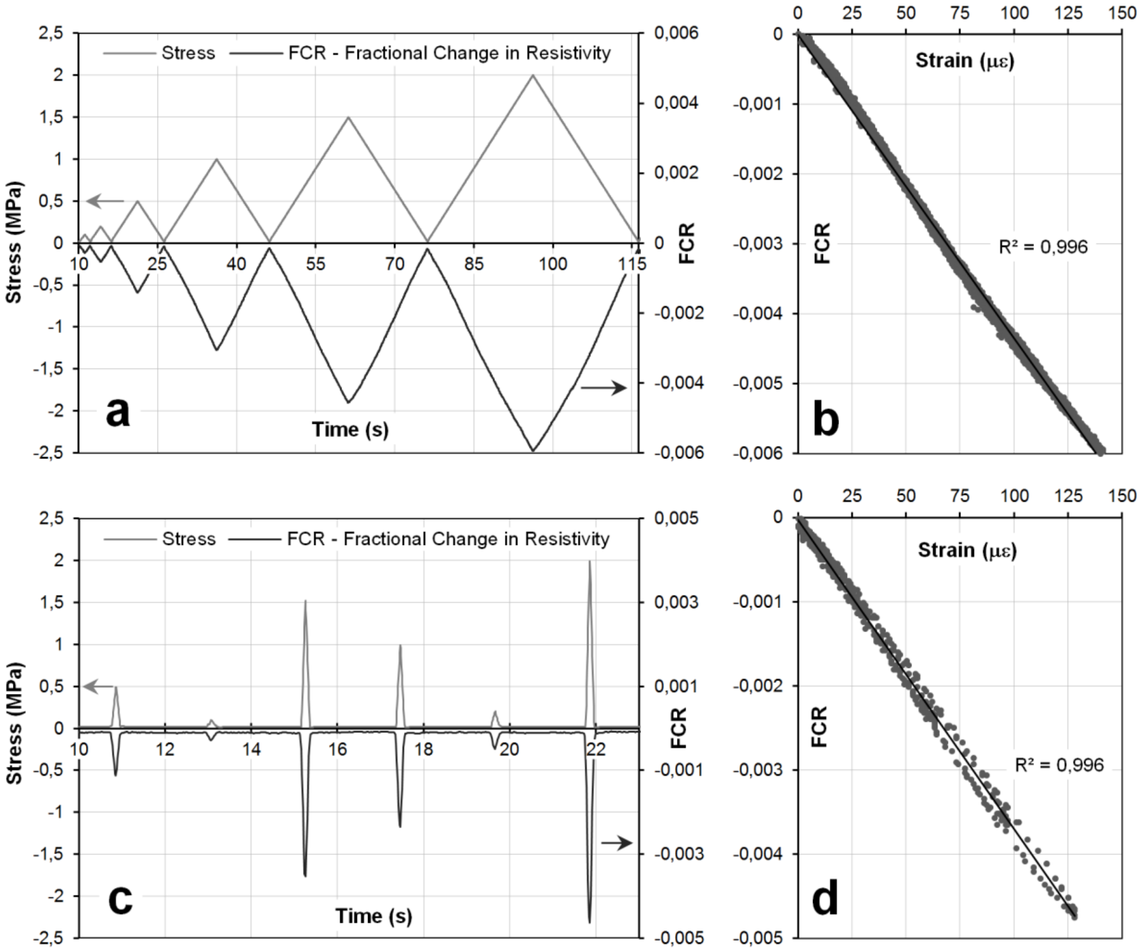

Figure 4. Results of the piezoresistive experiments: a) FCR and stress vs. time from part of the quasi-static loading; b) FCR vs. strain of the quasi-static loading; c) FCR and stress vs. time from part of the dynamic loading; d) FCR vs. strain of the dynamic loading.

Table 1 summarizes the average electrical and piezoresistive properties from both experiments. Interestingly, the piezoresistive parameters calculated by the dynamic loading demonstrated lower average values. The results go towards similar experiments found in literature (Li et al., 2006), wherein a GF of 55 and a stress sensitivity of 0.63 $\%/Mpa^{-1}$ were found. Remarkably, our composite uses more than 4 times less CB filler (in vol%) and showed good repeatability and better linearity.

Table 1. Average electrical and piezoresistive properties of the PCSS of both experiments.

Loading	$R_{S,0}$ (kΩ)	Max. variation of R_s (Ω)	Max. *FCR* (%)	Stress sensitivity (%/MPa)	*GF*
Quasi-static	11.1 ± 1.3	78.4 ± 13.5	0.70 ± 0.12	0.35 ± 0.06	52.4 ± 10.9
Dynamic		61.5 ± 9.5	0.56 ± 0.09	0.28 ± 0.04	48.3 ± 8.3

Despite one order of magnitude away, in terms of piezoresistive response, from certain PCSS built with CNT, CF or hybrid additions (Li et al., 2006; Azhari et al., 2012; Materazzi et al., 2013; Han et al., 2015), the composite showed good signal definition, linearity, repeatability and sensitivity, even at very low stresses and high load rates. Such factors, combined with the cost-effectiveness advantage of the CB, suggest that CB-cement composites are suitable to monitor traffic-like loads.

4 CONCLUSIONS

A cement-based composite loaded with carbon black nanoparticles was investigated, with the aim to develop a multifunctional pressure-sensitive concrete, suitable for traffic monitoring in pavements, thanks to their piezoresistive property. The piezoresistive parameters of the composite were studied using quasi-static and dynamic cyclic loads. Low stress amplitudes, up to 2MPa, were used, to evaluate whether the sensors were appropriate to monitor accurately traffic-like stresses or not. To sum up, results demonstrated that the PCSS have favorable pressure-sensitive performance, with average GF values between 48 and 52. Additionally they suggest that it is possible to use common low-cost CB fillers instead of more expensive lab-scaled nanomaterials. The findings pave the way for the embedment of such PCSS in pavements and validate concept under real conditions. The effect of moisture must also be further analyzed.

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