Accepted Manuscript

Self-sensing piezoresistive cement composite loaded with carbon black particles

André O. Monteiro, Paulo B. Cachim, Pedro M.F.J. Costa

PII: S0958-9465(16)30166-4

DOI: [10.1016/j.cemconcomp.2017.04.009](https://doi.org/10.1016/j.cemconcomp.2017.04.009)

Reference: CECO 2820

To appear in: *Cement and Concrete Composites*

Received Date: 18 May 2016

Revised Date: 5 March 2017

Accepted Date: 10 April 2017

Please cite this article as: André.O. Monteiro, P.B. Cachim, P.M.F.J. Costa, Self-sensing piezoresistive cement composite loaded with carbon black particles, *Cement and Concrete Composites* (2017), doi: 10.1016/j.cemconcomp.2017.04.009.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Self-sensing piezoresistive cement composite loaded with carbon black particles

André O. Monteiro^{a,b,*}, Paulo B. Cachim^{a,b}, Pedro M. F. J. Costa^{c,d}

^a Department of Civil Engineering, University of Aveiro, 3810-193 Aveiro, Portugal

^b RISCO, University of Aveiro, 3810-193 Aveiro, Portugal

^c King Abdullah University of Science and Technology (KAUST), Physical Sciences and Engineering Division, KAUST, 23955-6900 Thuwal, Kingdom of Saudi Arabia

^d Department of Materials and Ceramic Engineering, University of Aveiro, 3810-193 Aveiro, Portugal

* Corresponding author.

Keywords: Concrete, Cement-based sensors, Piezoresistivity, Carbon black, Conductive concrete, Smart concrete

Abstract

Strain sensors can be embedded in civil engineering infrastructures to perform real-time service life monitoring. Here, the sensing capability of piezoresistive cement-based composites loaded with carbon black (CB) particles is investigated. Several composite mixtures, with a CB filler loading up to 10% of binder mass, were mechanically tested under cyclic **uniaxial compression**, registering variations in electrical resistance as a function of deformation. The results show a reversible piezoresistive behaviour and a quasi-linear relation between the fractional change in resistivity and the compressive strain, in particular for those compositions with higher amount of CB. Gage factors of 30 and 24 were found for compositions containing 7 and 10% of binder mass, respectively. These findings suggest that the CB-cement composites may be a promising active material to monitor compressive strain in civil infrastructures such as concrete bridges and roadways.

1. Introduction

Monitoring of civil engineering infrastructures has been a growing concern of the last few decades. As a result, a new discipline originated, structural health monitoring (SHM).

The development of SHM has enabled a more effective evaluation of the stresses/deformations that take place in buildings, bridges and dams, for instance [1, 2]. Roadways management and logistics have also benefited from SHM [3]. Overall, the aim is to use computer software to control the functional reliability of a civil infrastructure by autonomously gather information of critical parameters such as service loads, cracks, corrosion rate, moisture, pH, etc. Abrupt changes in the readings of one or more of these parameters prompt an automated warning message to be sent to the technical team managing the infrastructure. Underlining this new technology is the conjunction of traditional sensors (potentiometers, optic fibre, strain gauges...) with, for instance, cement-based mixtures loaded with electrically conductive additives [4]. Commonly named cement-based self-sensors such an ensemble enables the autonomous and real-time probing of electrical resistance of the composite material and relies on a stimulus-triggered property called piezoresistivity).

The resistivity of a composite material can be decreased by adding conductive fillers, thereby undergoing an insulator-to-conductor transition. This is explained by the percolation theory [5]. Piezoresistivity is a physical property of materials defined as the change of the electrical resistivity when subjected to mechanical strain [6-8]. For cement mixtures such as those used in SHM, when an uniaxial compression is applied, the inter-particle distance of the conductive filler changes and new conduction paths are created. Hence, the closer the conductive particles are, the easier an electrical current can flow, decreasing the resistivity. Upon unloading, the composite material returns to its relaxed state and the initial resistivity is recovered, provided there is no plastic deformation. Overall, this phenomenon may be seen as piezoresistivity (that is induced on the cement composite) though it only takes place past a critical level of conductive particles addition (thus resembling the percolation threshold of classical composites).

Based on the above concepts, piezoresistive cement-based strain sensors (PCSS) have been built. Here, either small sections of the cement composite are included in a larger structure or the mixture entirely replaces the classical concrete [9]. The first report on piezoresistive concrete dates back to 1993 [10]. Then, carbon fibres (CF) were used to increase the conductivity of cement pastes, a phenomenon that was strain-dependent as confirmed by compressive loading essays. Besides this, improved flexural and axial strengths were noticed, along with more freeze-thaw durability and drying shrinkage reduction. Subsequent studies report not just the use of CF additives [10-31] but also of carbon

nanotubes [12, 32-34], steel fibres [16, 30, 35] and CB [15, 17, 36-39]. In particular, CB particles have demonstrated some advantages for SHM applications when compared with other conductive additives [37, 40]. Top amongst these is their lower cost. This is a critical point as, while a SHM system results in significant safety enhancements and reduction of management/inspection costs, its implementation in large-scale infrastructures will be unfeasible if the production and integration costs of the cement filler are too high.

The aim of this work is to study whether CB-based PCSS could be a viable material for long-term service monitoring of civil infrastructures. To our best knowledge, there is merely one relevant report in the literature [36]. While Lit et al. used CB as the only conductive additive, their PCSS specimens showed good piezoresistive behaviour. However, the piezoresistivity was verified for very high CB concentrations which is detrimental for the mechanical response of the cement [37]. In an attempt to improve the previous results by Li et al., we investigate the piezoresistive response of cement-based composites containing lower CB loadings that can furthermore retain the mechanical strength of the cement matrix.

2. Methods

2.1. PCSS Preparation

The materials used to build the PCSS were Portland cement CEM II 32.5N (Cimpor), carbon black type N330 (Orion Engineered Carbons), high performance polycarboxylate polymer-based water reducing agent (Sika AG) – known as superplasticizer (SP), fine sand (<1 mm) and copper plates with a thickness of 0.4mm (which worked as electrodes). The cement and aggregates were first added to the water and mixed for 5 min using a conventional mortar rotary mixer with a flat beater (Controls). The SP was then added, mixed for 3 min, followed by the CB addition and mixing (5 min). The mixtures were poured into oiled moulds and finally vibrated to ensure good compaction. Note that it is agreed that the homogeneous dispersion of the CB filler particles optimizes the electrical conduction of composites, particularly as the tunnelling effect is often the predominant mechanism for the transport of charge carriers [36]. Several dispersion techniques have been studied and are described in the literature [33, 34, 41-45]. Despite this, in this study, no attempts were made to optimise the dispersion of the CB particles and they were used as-received. The reasoning behind this was

to preserve, as much as possible, the original characteristics of the CB filler. Table 1 summarizes the main physical characteristics of the CB material used.

Table 1. Characterization of the CB used in the experiments (from manufacturer).

Density (g/cm³)	1.7-1.9
Bulk Density (g/cm³)	0.370
Average particles diameter (nm)	120
Specific Surface Area (m²/g)	76

Five different compositions were investigated (table 2), wherein the CB filler loading was varied in percentage of the binder mass: without CB (CB0, this acted as the control sample), with 1, 4, 7 and 10% binder mass (CB1, CB4, CB7 and CB10, respectively). For all compositions, the water/cement and cement/aggregate ratios were constant, at 1:2 in weight and 1:3 in volume, respectively. The water reducing agent was used in amounts from 0% to 3% of cement mass. This compensated the lack of water for correct cement hydration, consequence of the addition of CB particles, and maintained the material's workability.

Table 2. Mix proportions of the five experimented compositions (kg/m³).

	Cement	Water	Aggregates	Carbon Black	SP
CB0	447.8	223.9	1582.1	0	0
CB1	445.8	222.9	1574.9	4.5	2.2
CB4	440.7	220.3	1557.0	17.6	6.6
CB7	436.6	218.3	1542.5	30.6	8.7
CB10	431.7	215.8	1525.2	43.2	13.0

Seven prismatic samples were considered (40x40x160 mm) for each composition and cured for 14, 28 and 120 days, at room temperature (20 °C) while exposed to a humidity level of >95%. Among the seven specimens, six of them were plain specimens, used for tensile and compressive strength experiments. The remaining one had four embedded copper electrodes, in order to measure the electrical resistivity, as well as a strain gauge to measure the axial deformation.

2.2. Piezoresistivity testing

After 120 days of curing, the specimens with the embedded electrodes were dried in an oven at 60°C for 2 days. This was to reduce the effect of moisture on the electrical conduction. After this drying step, the resistivity measurements were carried out. These followed the four electrodes method [14, 46]. The piezoresistivity of the PCSS was studied using cyclic loads, computing simultaneously the resistivity and the axial deformation of each specimen. The resistivity $\rho(t)$ is calculated as a function of time by combining the first (eq. 1) and second (eq. 2) Ohm's laws, as expressed in eq. 3.

$$R = \frac{U}{I} \quad (1)$$

$$R = \rho \frac{l}{A} \quad (2)$$

$$\rho(t) = \frac{U(t) A}{I(t) l} \quad (3)$$

In equation (3), $U(t)$ is the potential difference across the inner electrodes, $I(t)$ is the current measured between the outer electrodes, A is the contact area between the electrodes and the material and l is the spacing between the inner electrodes. The scheme in Fig. 1 further illustrates the resistivity measurement principle, along with the geometrical parameters, electrodes disposition and application of the unidirectional load employed.

Figure 1. Representation of the resistivity measurement principle and the geometrical parameters of the PCSS.

A Shimadzu press AG-IC, capable of applying loads up to 100 kN, was coupled to a data acquisition device (Data Taker DT80) and a power supply (Protek) through a computer. First, a potential difference of 12 V was applied via the outer electrodes using a DC power supply. The **uniaxial compression** was then applied in two steps: first, a 2 kN force was exerted along the major axis of the PCSS sample and maintained **for 2 min** until the resistivity stabilised; then, a cyclic load was applied at a rate of 250 N.s⁻¹ with amplitudes of 15 kN, which led to stresses of 9.4 MPa. The resistivity variation was continuously monitored using the data acquisition device and the axial deformation was measured with a 25 mm, 120 Ω strain gauge. The experiments were performed at room temperature, ~20 °C.

For the following analysis, it is important to define fractional change in resistivity (FCR) and sensitivity. FCR is a measure of how much the resistivity departs from its initial value (ρ_0) with time and is given by equation (4):

$$FCR = \frac{\rho(t) - \rho_0}{\rho_0} \quad (4)$$

The sensitivity, which relates the FCR with axial stress (Q), can also be extracted as given in equation (5):

$$sensitivity = \frac{FCR}{\Delta\sigma} \quad (5)$$

2.3. Capillarity experiments

In order to understand the permeability of the composites, a water absorption experiment was done for all the compositions, using prism halves and following the specifications of the EN1015-8 standard [47]. The specimens were dried in a ventilated oven at 60°C until a constant mass was reached. The rupture face of each sample (obtained from mechanically breaking the prisms in two) was rectified and then immersed in a tray with 5 mm of water. The water absorption coefficient, due to the capillarity action, was determined based on the weight gain of each specimen during 80 minutes of immersion.

3. Results and Discussion

3.1. Mechanical properties

Conventional compressive and 3-point bending tests were carried out (as per the EN1015-11 standard [48]), in order to quantify the compressive and tensile strength, respectively, of the composite samples. Figs. 2a and 2b show the evolution of compressive and tensile strengths with increased curing time. Each point is defined by the resulting mean of the experiment performed in 3 specimens. Fig. 2c shows the Young's modulus, as calculated from strain vs. stress experiments, using the specimens cured for 120 days and equipped with strain gauges.

Figure 2. Results of the ultimate strength tests carried for: a) compression; b) traction; each point corresponds to the mean value of 3 essays. c) Elastic modulus of the different composites taken after 120 days of curing.

Consistently, the compressive strength increases with curing time. This is expected as it results from the classical hydration process of Portland cement. Of interest, the maximum

compressive strength was obtained for the CB4 sample with minimums obtained at both compositional extremes of the composite mixtures. This implies there is an optimal binder/filler ratio for best compressive strength of the PCSS. The increase of compressive strength from CB0 to CB4, at 28 and 120 days, confirms the mechanical reinforcement effect of the additive used. Interestingly, CB4 showed a lower compressive strength than CB1 and CB7 at 14 days, contrary to what was seen at 28 and 120 days. Past the 4% threshold, these mechanical benefits start to wane as the material increasingly becomes more brittle (likely due to the overload of filler particles that prevents proper textural binding in the cement matrix). In fact, tests done with >10% of CB loading, in binder mass, revealed the presence of segregation and extremely low strength values (not shown). These observations are supported by the elastic modulus analysis. An increase in modulus was registered from CB0 to CB4 but, contrary to the results of the compressive and tensile strengths essays, the CB7 and CB10 specimens showed lower values than the control sample. CB4 was again the specimen showing the greatest value overall. Here, it should be noted that a non-optimal dispersion method of the filler may eventually contribute to the results. A better CB scattering could allow higher CB contents and, possibly, increase the strength achieved. One other important factor that should be considered is the water-binder ratio. Despite the use of a superplasticizer, the correct hydration of the cement may not have been attained, a point for further investigation in the future.

3.2. Piezoresistive properties

Only two samples showed piezoresistive behaviour, CB7 and CB10. Fig. 3 depicts the FCR variations, under cyclic compressive loading, for CB7 and CB10, respectively. The plots in Figs. 3a and 3c show that the FCR is reversible as it decreases upon loading and increases upon unloading. This establishes a straightforward correlation between deformation and resistivity, as shown in Figs. 3b and 3d. Both samples showed good repeatability and global linearity. Interestingly, CB10 showed better precision, as demonstrated by the narrower scatter distribution and linearity, this despite the lower gage factor and sensitivity value. Looking at the CB7 results, it is possible to identify a slight hysteresis in the FCR values. Such can be the result of insufficient stabilization of the sensor before the load-unload cycles as, for non-cycled essays, we observed that after applying a potential difference through the PCSS, the electrical resistance tends to fluctuate until an equilibrium value is reached.

Figure 3. Results of the cyclic loading on CB7 and CB10 samples. a) FCR and strain vs. time (CB7); b) FCR vs. strain for the 10 cycles (CB7); c) FCR and strain vs. time (CB10); d) FCR vs. strain for the 10 cycles (CB10).

Table 3 summarizes the electrical and piezoresistive properties of the entire set of samples. Additionally, the gauge factor (GF), which relates the variation between the resistivity and the deformation, is also included. Looking at the values obtained, CB0, CB1 and CB4 have relatively large resistivity, which could explain the absence of piezoresistivity readings. The increased resistivity is possibly a result of the addition of superplasticizer, as previously claimed [49] (another likely contributing factor is the lower CB concentration combined with the mentioned non-optimal filler dispersion). By contrast, CB7 and CB10 showed lower resistivity thereby enabling the measurement of piezoresistivity. We believe this observation points to a threshold of maximum resistivity beyond which it is not possible to consider these composites for PCSS.

Table 3. Initial electrical resistance (R_0) and calculated resistivity (ρ_0), maximum FCR, GF and sensitivity for the five composites tested.

	CB0	CB1	CB4	CB7	CB10
R_0 (Ω)	1.02×10^5	1.08×10^5	1.24×10^5	1.43×10^4	3.02×10^2
ρ_0 ($\Omega \cdot m$)	1.53×10^3	1.62×10^3	1.85×10^3	2.14×10^2	4.54×10^0
max. FCR (%)	-	-	-	2.68	1.79
GF	-	-	-	30.28	24.13
Sensitivity (MPa^{-1})	-	-	-	2.86×10^{-3}	1.72×10^{-3}

As referred above, there is only one reference where CB was used as the unique conductive additive for PCSS [36]. In this study, the authors observed piezoresistive behaviour from CB loadings in amounts of 15% of cement mass. The behaviour of the specimens with lower CB concentrations was considered too noisy to be meaningful. The present work demonstrates that CB can be used as a conductive additive for cement in much lower amounts. One reason for this discrepancy could be the type of CB used. In fact, there is a large range of CB materials available in the market and their properties depend highly on the purpose for which they were produced. The main characteristics that differentiate them are the size of the particles, the specific area and the so-called “structure”. For instance, CB particles with smaller size, higher surface area and higher structure provide higher conductivity. Therefore, piezoresistivity can be reached using lower CB fractions. Unfortunately, no information was provided regarding the type of CB used by the authors in [35]. The sensitivity values obtained for our CB7 specimen (see Table 3) are *ca.* 50% lower when compared with the figures provided for the 15% of Li et al. [35]. Remarkably, our CB7 uses 53% less CB filler but it still showed good linearity and repeatability levels.

3.3. Porosity properties

Figure 4 depicts the capillarity coefficients values of the five compositions. The capillarity clearly decreases with the addition of CB making the filler effect well visible, eventually contributing to reduce the permeability in the PCSS. The registered capillarity for all the compositions with carbon black was similar, with a reduction of more than 50%, if compared with the capillarity of the control sample, CB0. Interestingly, the CB7 had the lowest average capillarity coefficient but the error bar is larger meaning that globally the

results are similar from CB1 to CB10. The reduction of capillarity seems to indicate that the composite pores were closed by the addition of CB, reinforcing the continuity of the microstructure and, thus, contributing to its increased electrical conductivity.

Figure 4. Capillarity coefficients. Results for the 5 compositions studied.

Taken together, the above results imply that a balance of properties is necessary to obtain the best PCSS. There was not one composition that showed optimal properties across the mechanical, electrical and permeability tests. For the samples that showed piezoresistivity (CB7 and CB10), and with the exception of the Young's modulus, CB7 showed better mechanical parameters and higher sensitivity. However, CB10 demonstrated slightly better linearity and repeatability, noticeable by the higher coefficient of determination (R^2) and narrower scatter distribution, respectively (Fig. 3). Taken together, CB7 could be taken as the best compromise as it retains satisfactory mechanical strength while providing reliable piezoresistive responses, low value of permeability (traditionally related with the material durability) and lower concentration of CB.

4. Conclusions

With the purpose of developing a piezoresistive self-sensing concrete for civil engineering infrastructures, the addition of CB particles in cement-based materials was investigated. The present experiments established a piezoresistive response from the cement

composites and shed light on how the CB inclusion influences their mechanical and electrical properties. It was observed that CB additions of up to 4% of cement mass are favourable to enhance mechanical performance, whilst amounts between 7 and 10% are more promising for sensing purposes. Accordingly, the 7% composition provided an optimised balance of mechanical and electrical responses suggesting that it is possible to use common, low-cost CB fillers for conductive concrete and PCSS. Future work should concentrate in lowering this CB mass fraction through filler dispersion procedures.

Acknowledgements

AOM acknowledges support from the Portuguese Foundation of Science and Technology (PhD scholarship SFRH/BD/84644/2012). PMFJC is grateful to KAUST for financial support and dedicates this work to Arlindo Costa, on occasion of his 70th birthday.

References

1. C.R. Farrar and K. Worden, *An introduction to structural health monitoring*. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 2007. **365**(1851): p. 303-315.
2. P.C. Ken, J.C. Nicholas, and W. Glenn, *Health monitoring of civil infrastructures*. Smart Materials and Structures, 2003. **12**(3): p. 483.
3. Z. Sun, G. Bebis, and R. Miller, *On-road vehicle detection: A review*. IEEE Transactions on Pattern Analysis and Machine Intelligence, 2006. **28**(5): p. 694-711.
4. B. Han, X. Yu, and J. Ou, *Self-Sensing Concrete in Smart Structures* 2014: Elsevier Science.
5. D. Stauffer and A. Aharony, *Introduction To Percolation Theory* 1994: Taylor & Francis.
6. S. Zhu and D.D.L. Chung, *Analytical model of piezoresistivity for strain sensing in carbon fiber polymer–matrix structural composite under flexure*. Carbon, 2007. **45**(8): p. 1606-1613.
7. Y. Cao, X. Yang, R. Zhao, Y. Chen, N. Li, and L. An, *Giant piezoresistivity in polymer-derived amorphous SiAlCO ceramics*. Journal of Materials Science, 2016. **51**(12): p. 5646-5650.
8. F. Carmona, R. Canet, and P. Delhaes, *Piezoresistivity of heterogeneous solids*. Journal of Applied Physics, 1987. **61**(7): p. 2550.
9. B. Han, S. Ding, and X. Yu, *Intrinsic self-sensing concrete and structures: A review*. Measurement, 2015. **59**: p. 110-128.
10. C. Pu-Woei and D.D.L. Chung, *Carbon fiber reinforced concrete for smart structures capable of non-destructive flaw detection*. Smart Materials and Structures, 1993. **2**(1): p. 22.

11. R.M. Chacko, N. Banthia, and A.A. Mufti, *Carbon-fiber-reinforced cement-based sensors*. Canadian Journal of Civil Engineering, 2007. **34**(3): p. 284-290.
12. F. Azhari and N. Banthia, *Cement-based sensors with carbon fibers and carbon nanotubes for piezoresistive sensing*. Cement and Concrete Composites, 2012. **34**(7): p. 866-873.
13. S. Wen and D.D.L. Chung, *Effects of Strain and Damage on Strain-Sensing Ability of Carbon Fiber Cement*. Journal of Materials in Civil Engineering, 2006. **18**(3): p. 355-360.
14. B. Han, X. Guan, and J. Ou, *Electrode design, measuring method and data acquisition system of carbon fiber cement paste piezoresistive sensors*. Sensors and Actuators A: Physical, 2007. **135**(2): p. 360-369.
15. S. Wen and D.D.L. Chung, *Partial replacement of carbon fiber by carbon black in multifunctional cement–matrix composites*. Carbon, 2007. **45**(3): p. 505-513.
16. N. Banthia, S. Djeridane, and M. Pigeon, *Electrical resistivity of carbon and steel micro-fiber reinforced cements*. Cement and Concrete Research, 1992. **22**(5): p. 804-814.
17. Y. Ding, Z. Chen, Z. Han, Y. Zhang, and F. Pacheco-Torgal, *Nano-carbon black and carbon fiber as conductive materials for the diagnosing of the damage of concrete beam*. Construction and Building Materials, 2013. **43**: p. 233-241.
18. X. Fu and D.D.L. Chung, *Self-monitoring of fatigue damage in carbon fiber reinforced cement*. Cement and Concrete Research, 1996. **26**(1): p. 15-20.
19. R.N. Howser, H.B. Dhonde, and Y.L. Mo, *Self-sensing of carbon nanofiber concrete columns subjected to reversed cyclic loading*. Smart Materials and Structures, 2011. **20**(8): p. 085031.
20. C. Pu-Woei and D.D.L. Chung, *Carbon fiber reinforced concrete as an intrinsically smart concrete for damage assessment during static and dynamic loading*. Materials Journal, 1996. **93**(4).
21. S. Wen and D.D.L. Chung, *Electrical-resistance-based damage self-sensing in carbon fiber reinforced cement*. Carbon, 2007. **45**(4): p. 710-716.
22. D.G. Meehan, W. Shoukai, and D.D.L. Chung, *Electrical-resistance-based Sensing of Impact Damage in Carbon Fiber Reinforced Cement-based Materials*. Journal of Intelligent Material Systems and Structures, 2009. **21**(1): p. 83-105.
23. S. Wen and D.D.L. Chung, *Model of piezoresistivity in carbon fiber cement*. Cement and Concrete Research, 2006. **36**(10): p. 1879-1885.
24. Z. Sirong and D.D.L. Chung, *Numerical assessment of the methods of measurement of the electrical resistance in carbon fiber reinforced cement*. Smart Materials and Structures, 2007. **16**(4): p. 1164.
25. W. Sihai and D.D.L. Chung, *Piezoresistivity-Based Strain Sensing in Carbon Fiber-Reinforced Cement*. Materials Journal, 2007. **104**(2).
26. S. Wen and D.D.L. Chung, *The role of electronic and ionic conduction in the electrical conductivity of carbon fiber reinforced cement*. Carbon, 2006. **44**(11): p. 2130-2138.

27. S. Wen and D.D.L. Chung, *Self-sensing of flexural damage and strain in carbon fiber reinforced cement and effect of embedded steel reinforcing bars*. Carbon, 2006. **44**(8): p. 1496-1502.
28. S. Zhu and D.D.L. Chung, *Theory of piezoresistivity for strain sensing in carbon fiber reinforced cement under flexure*. Journal of Materials Science, 2007. **42**(15): p. 6222-6233.
29. S. Wen and D.D.L. Chung, *Uniaxial tension in carbon fiber reinforced cement, sensed by electrical resistivity measurement in longitudinal and transverse directions*. Cement and Concrete Research, 2000. **30**(8): p. 1289-1294.
30. E. Teomete and O.I. Kocyigit, *Tensile strain sensitivity of steel fiber reinforced cement matrix composites tested by split tensile test*. Construction and Building Materials, 2013. **47**: p. 962-968.
31. G. Di, S. Mariel, and Y.L. Mo, *Electrical resistance of carbon-nanofiber concrete*. Smart Materials and Structures, 2009. **18**(9): p. 095039.
32. G.Y. Li, P.M. Wang, and X. Zhao, *Pressure-sensitive properties and microstructure of carbon nanotube reinforced cement composites*. Cement and Concrete Composites, 2007. **29**(5): p. 377-382.
33. X. Yu and E. Kwon, *A carbon nanotube/cement composite with piezoresistive properties*. Smart Materials and Structures, 2009. **18**(5): p. 055010.
34. A. D'Alessandro, M. Rallini, F. Ubertini, A.L. Materazzi, and J.M. Kenny, *Investigations on scalable fabrication procedures for self-sensing carbon nanotube cement-matrix composites for SHM applications*. Cement and Concrete Composites, 2016. **65**: p. 200-213.
35. M.-q. Sun, R.J.Y. Liew, M.-H. Zhang, and W. Li, *Development of cement-based strain sensor for health monitoring of ultra high strength concrete*. Construction and Building Materials, 2014. **65**: p. 630-637.
36. H. Li, H.-g. Xiao, and J.-p. Ou, *Effect of compressive strain on electrical resistivity of carbon black-filled cement-based composites*. Cement and Concrete Composites, 2006. **28**(9): p. 824-828.
37. A.O. Monteiro, P.B. Cachim, and P.M.F.J. Costa, *Electrical Properties of Cement-based Composites Containing Carbon Black Particles*. Materials Today: Proceedings, 2015. **2**(1): p. 193-199.
38. H. Li, H. Xiao, and J. Ou, *Electrical property of cement-based composites filled with carbon black under long-term wet and loading condition*. Composites Science and Technology, 2008. **68**(9): p. 2114-2119.
39. V.W.J. Lin, M. Li, J.P. Lynch, and V.C. Li. *Mechanical and electrical characterization of self-sensing carbon black ECC*. 2011.
40. A.O. Monteiro, P.B. Cachim, and P.M.F.J. Costa, *Carbon nanoparticles cement-based materials for service life monitoring in International RILEM Conference on Materials, Systems and Structures in Civil Engineering 2016*: Lyngby, Denmark.
41. M.L. Miglietta, G. Rametta, and G. Di Francia, *Characterization of Carbon Based Nanoparticles Dispersion in Aqueous Solution Using Dynamic Light Scattering Technique*. Macromolecular Symposia, 2009. **286**(1): p. 95-100.

42. S.M. Aldoshin, E.R. Badamshina, A.A. Grishchuk, A.E. Tarasov, Y.I. Estrin, R.F. Ganiev, et al., *Study of the influence of single-wall carbon nanotube dispersion techniques upon the properties of epoxy resin-based nanocomposites*. Journal of Machinery Manufacture and Reliability, 2015. **44**(3): p. 271-275.
43. Y. Liu, Y. Kong, C. Cheung, L. Li, and J.H. Xin, *Dispersion and Modification of Carbon Nanotubes Using a Surface Gel-Sol Technique*. Chemistry Letters, 2006. **35**(11): p. 1258-1259.
44. S. Parveen, S. Rana, R. Fangueiro, and M.C. Paiva, *Microstructure and mechanical properties of carbon nanotube reinforced cementitious composites developed using a novel dispersion technique*. Cement and Concrete Research, 2015. **73**: p. 215-227.
45. X. Zeng, G. Zhou, Q. Xu, Y. Xiong, C. Luo, and J. Wu, *A new technique for dispersion of carbon nanotube in a metal melt*. Materials Science and Engineering: A, 2010. **527**(20): p. 5335-5340.
46. C.-Y. Lee and S.-R. Wang, *Application of Four-electrode Method to Analysis Resistance Characteristics of Conductive Concrete*. World Academy of Science, Engineering and Technology, 2010. **4**: p. 77-80.
47. BSI, *BS EN 1015-8. Methods of test for mortar for masonry - Part 8: Determination of water retentivity of fresh mortar*, 1999, British Standards Institution: London.
48. BSI, *BS EN 1015-8. Methods of test for mortar for masonry - Part 11: Determination of flexural and compressive strength of hardened mortar*, 1999, British Standards Institution: London.
49. G. Xu, J.J. Beaudoin, C. Jolicoeur, and M. Pagé, *The effect of a polynaphthalene sulfonate superplasticizer on the contribution of the interfacial transition zone to the electrical resistivity of mortars containing silica and limestone fine aggregate*. Cement and Concrete Research, 2000. **30**(5): p. 683-691.