REVIEW ARTICLE

Towards smart concrete for smart cities: Recent results and future application of strain-sensing nanocomposites

Antonella D'Alessandro[1], Filippo Ubertini[1*], Simon Laflamme[2] and Annibale Luigi Materazzi[1]

[1] Department of Civil and Environmental Engineering, University of Perugia, Via G. Duranti, 93, 06125 Perugia, Italy

[2] Department of Civil, Construction and Environmental Engineering, Iowa State University, 416A Town Engineering, Ames, IA 50011, USA

Abstract: The use of smart technologies combined with city planning have given rise to smart cities, which empower modern urban systems with the efficient tools to cope with growing needs from increasing population sizes. For example, smart sensors are commonly used to improve city operations and management by tracking traffic, monitoring crowds at events, and performance of utility systems and public transportation. Recent advances in nanotechnologies have enabled a new family of sensors, termed self-sensing materials, which would provide smart cities with means to also monitor structural health of civil infrastructures. This includes smart concrete, which has the potential to provide any concrete structure with self-sensing capabilities. Such functional property is obtained by correlating the variation of internal strain with the variation of appropriate material properties, such as electrical resistance. Unlike conventional off-the-shelf structural health monitoring sensors, these innovative transducers combine enhanced durability and distributed measurements, thus providing greater scalability in terms of sensing size and cost. This paper presents recent advances on sensors fabricated using a cementitious matrix with nanoinclusions of Carbon Nanotubes (CNTs). The fabrication procedures providing homogeneous piezoresistive properties are presented, and the electromechanical behavior of the sensors is investigated under static and dynamic loads. Results show that the proposed sensors compare well against existing technologies of stress/strain monitoring, like strain gauges and accelerometers. Example of possible field applications for the developed nanocomposite cement-based sensors include traffic monitoring, parking management and condition assessment of masonry and concrete structures.

Keywords: smart cities, smart sensors, cement-based sensors, carbon nanotubes, structural health monitoring, nanotechnology

*Correspondence to: Filippo Ubertini, Department of Civil and Environmental Engineering, University of Perugia, Via G. Duranti, 93, 06125 Perugia, Italy; Email: filippo.ubertini@unipg.it

Received: April 13, 2015; **Accepted:** July 15, 2015; **Published Online:** September 17, 2015

Citation: D'Alessandro A, Ubertini F, Laflamme S, *et al.* 2015, Towards smart concrete for smart cities: Recent results and future application of strain-sensing nanocomposites. *Journal of Smart Cities*, vol.1(1): 3–14. http://dx.doi.org/10.18063/JSC.2015.01.002.

1. Introduction

The vast majority of the world's population lives in cities, which results in important urban growths. Such growth exerts an important pressure on existing resources and climate-related challenges. This provides important challenges on operations and management of urban systems. Recent advances in smart technologies have provided opportunities to modernize cities with sensors and other feedback systems to empower urban system operators and managers with efficient tools to cope with growing needs from increasing population size. These are known as smart cities. Sensors and other feedback systems have become critical components in infrastructure control. For example, smart sensors are commonly used to improve city operations and management by tracking traffic, monitoring crowds at events, and performance of utility systems and public transportation.

For these approaches to be effective, sensors have to be installed in large numbers and interconnected, and sensing data transmitted to a central information system, where information-based decisions can be conducted. Traditional off-the-shelf sensors and transducers are affected by known drawbacks that severely limit their scalability. These include challenges associated with cost, durability against environmental effects, data transmission and signal processing.

Recent advances in nanotechnology have led to the development of a new family of sensors, termed self-sensing materials, which would provide smart cities with means to also monitor structural health of civil infrastructures. This includes smart concrete, which has the potential to provide any concrete structure with self-sensing capabilities. Such functional property is obtained by correlating the variation of internal strain with the variation of appropriate material properties, such as electrical resistance. Unlike conventional off-the-shelf structural health monitoring sensors, these innovative transducers combine enhanced durability and distributed measurements, thus providing greater scalability in terms of sensing size and cost.

This paper presents recent advances on sensors fabricated using a cementitious matrix with nanoinclusions of Carbon Nanotubes (CNTs). After a brief description of the background of multifunctional cementitious materials, the fabrication procedures providing homogeneous piezoresistive properties are presented, and the electromechanical behavior of the sensor is investigated under static and dynamic loads. Tests are conducted on a full-scale reinforced concrete beam for output-only identification of natural frequencies. Lastly, possible applications of these new sensors enabling smart cities are discussed.

2. Overview

The recent developments in nanotechnology have provided tools for the fabrication and design of new materials to improve on functionalities of traditional materials. In particular, cement-based materials lend themselves to nano-modifications, because of their microscopic characteristics. Micro- and nano-inclusions, such as CNTs, into cementitious matrices have the potential to modify mechanical and electrical properties[1,2]. This is due to the remarkable mechanical and electrical properties of CNTs themselves, which make these nanoparticles ideal for the fabrication of smart cementitious composites with self-sensitive ability.

Self-sensing materials are able to detect their own state of strain or stress reflected as a change in their electrical properties. The variation of an applied strain or stress is associated with the variation in material's electrical characteristics such as resistance or impedance. This way, it is possible to detect and localize the spread of cracks and damages in a monitored structure. Such information can lead to a rapid structural condition assessment, thus enabling a more effective management of maintenance programmes. Applications are possible in the form of coatings over large surface areas or over large volumes[3–6].

Cementitious materials have very low conductivity. This conductivity can be improved by including conductive microparticles and nanoparticles until a phase transition occurs and the nanocomposite becomes a conductor. A high-sensitivity transducer can be obtained at the phase transition, termed percolation threshold[7]. However, it is critical to obtain a homogenous dispersion of the nanoparticles to ensure linearity of the sensor[8,9]. CNTs possess two main geometrical characteristics: a nanometric size and a high specific surface. These two factors are responsible for their poor solubility within aqueous matrices, because Van der Waals attraction forces between the particle additives increase with increasing specific surface[10]. There exists three widely used dispersion methods to obtain a homogeneous suspension of carbon nanoparticles in water[11]: chemical, physical and mechanical methods. These methods are based on the use of covalent surface modification, non-covalent surface modification and mechanical mixing, respectively. In aqueous solutions, ultrasonic treatment is the most standard mixing method, but suitable physical dispersants represent an alternative to avoid the presence of large agglomerates and filaments[9,12].

Another possible challenge in the fabrication of self-sensing cementitious materials is the significant dielectric properties of cement-based materials, which results in polarization effects. These effects can cause apparent variations of electrical resistance during measurements, even without any applied load. This phenomenon needs to be corrected and compensated. Polarization is typical of any dielectric material subjected to an electric field. A higher material conductivity determines a lower tendency to polarization[13].

The scientific literature shows a growing interest in the use of microparticles, nanoparticles and composites, in particular for the development of smart materials with innovative functionalities. Fu and Chung[14] investigated the strain sensitivity of carbon fiber reinforced cement compared to that of normal cement. Methyl cellulose, latex and silica fume were used to help the dispersion of fibers. Surface treatment of particles was also studied[15]. The electrical resistance of cementitious matrices (without fibers) was found to vary only after cracking because of the lower conductivity of air with respect to the matrix. The fiber-reinforced matrix instead experienced variations of resistivity with applied load even before cracking as a consequence of the piezoelectric effect[16]. Damage-induced variations in electrical resistance of cement composites were studied[17], where increases in resistance were observed as a consequence of irreversible permanent damage. In the elastic range, the strain sensitivity of cement-based nanocomposite materials doped with multi-walled (MWCNTs) is caused by a change in the distance between the nanoparticles caused by strain, which also alters the tunneling effects between nanotubes that are responsible for electrical conductivity[18–21]. The most commonly used fillers for self-sensing cementitious materials are carbon nanofibers (CNFs)[14–17,22,23,24], carbon black (CB)[25,26], and CNTs, both single-walled (SWCNTs) and MWCNTs[21,27,28–30]. Some studies investigated hybrid particles, such as carbon nanotubes and nickel powders[31] or carbon fibers and carbon nanotubes[32]. The majority of literature conducted strain-sensing investigations under static or quasi-static loads. The response of nanomodified composite materials to dynamic loads is often overlooked[33,34]. The first theoretical attempt to model the self-sensing ability of composites was published in 2006[35]. The study was based on the piezoresistive effect of pull-out of fibers that passed through micro-cracks. The ability of the material to self-detect cracks and strain was due to the modification of the characteristics of electrical paths developing within the material[36–39].

2.1 Cementitious Smart Sensor Based on CNTs

This section provides results and discussions on cementitious smart sensors developed by the authors using CNTs. In particular, challenges associated with CNTs dispersion are discussed, the fabrication procedure is presented, the sensing principle is derived, the electromechanical behavior is studied and modeled, and the possible applications to smart cities are discussed.

2.2 Dispersion

The conductive nanoparticles used in the fabrication of the smart sensor were MWCNTs type Graphistrength® C100 from Arkema. They appear as a black powder with low apparent density. Due to their structure consisting of cylindrical nets of graphite layers, they provide a larger strain sensitivity in comparison to single-walled CNTs[40,41]. The principal geometrical and mechanical properties of the selected MWCNTs are summarized in Table 1.

As mentioned previously, the dispersion of MWCNTs in a cementitious matrix is rather delicate, because the nanoparticles tend to agglomerate due to their nanometric dimensions and hydrophobia. In order to achieve an optimal bundle-free homogeneous three-dimensional net, the effect of different physical dispersants in water has been investigated. In a systematic experimental campaign, nine types of dispersants with different chemical characteristics were considered, namely: "BYK 154" (ammonium polyacrylate-based), "G. SKY 624" (polycarboxylate ether-based), "DISPERBYK 190" (high molecular weight block copolymer with pigment affinic groups), "BYK 9076" (alkylammonium salt of a high molecular-weight copolymer), "NaDDBS" (sodium dodecylbenzenesulfonate), "SLS" (lignosulfonic acid sodium salt), "PSS" (polystyrene sulfonates), "PVA" (polyvinyl alcohol) and "NaDDBS-TX100" (a combination of sodium dodecylbenzenesulfonate and copolymers of polyethylene oxide and aromatic hydrocarbon group). MWCNT-modified aqueous solutions were prepared by varying type and amount of dispersant and mixing procedure. First the dispersant was dissolved in 40 g of deionized water (Figure 1(A)). Then, 0.1 g MWCNTs were added and manually mixed (Figure 1(B) and (C)). Assuming a water/cement ratio equal to 0.4 in the composite material, the choice of 0.1 g of MWCNTs in 40 g of water corresponds to a nanotube-cement mass ratio of 0.1%. Dispersants were tested in different amounts:

Table 1. Properties of adopted MWCNTs[41]

Property	Value
Length	0.1–10 μm
Outer mean diameter	10–15 nm
Aspect ratio	7–1000
Bulk apparent density	50–150 kg/m^3
Surface area	100–250 m^2/g
Young's modulus	>1 TPa
Tensile strength	150 GPa

0.1:1, 1:1 and 10:1 with respect to the mass of the MWCNTs. After preliminary mixing, two alternative procedures were tested and compared: (i) sonication during 30 minutes (Figure 1(D)); or (ii) mechanical mixing for 60 minutes (Figure 1(E)). Both sonication and mechanical mixing are physical dispersion methods used in the production of nanomodified suspensions[11,42,43]. Sonication is a well accepted and adopted dispersion method, while mechanical mixing is simple and practical.

During sonication, the dispersion was conducted in cool water to reduce evaporation. The ultrasound device was equipped with a probe series VibraCell model 75043, Bioblock Scientific, (Figure 2(A)), with a maximum input power of 750 W. The mechanical mixes were performed with a high speed dissolver, Dispermat LC2, with a speed of rotation of 4000 rev/min (Figure 2(B)). The integrity of the nanotubes was verified via the inspection of scanning electron microscope (SEM) images of the nanomixtures after the mechanical mixing (Figure 2(C)).

For all the achieved suspensions, a tube was filled with 1 mL of the nanomodified suspension diluted in 10 mL of deionized water (0.24 mg/mL of MWCNTs concentration), and a silicon wafer with a drop of the admixture was produced. The quality of MWCNTs dispersion was investigated by measuring the time of settling and by SEM analyses on wafers. Settling of nanoparticles was investigated after one day and after 28 days, in order to assess the separation of the MWCNTs over short term and at the end of typical concrete curing time[44]. The settling value is low (corresponding to 0) if MWCNTs appear separated and sank to the bottom of the test tube. The value is high (corresponding to 2) when the admixture is dark and opaque to light, while it is intermediate (corresponding to 1) when the suspension appears semi-transparent (Figure 3(A)–(C)). The SEM pictures were analyzed at different magnifications to detect the

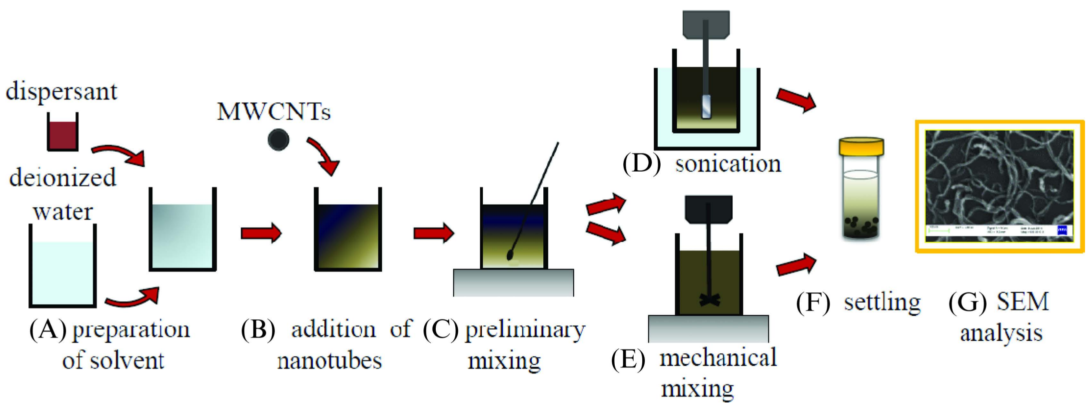

Figure 1. Procedure for investigating the dispersion of MWCNTs in aqueous solution.

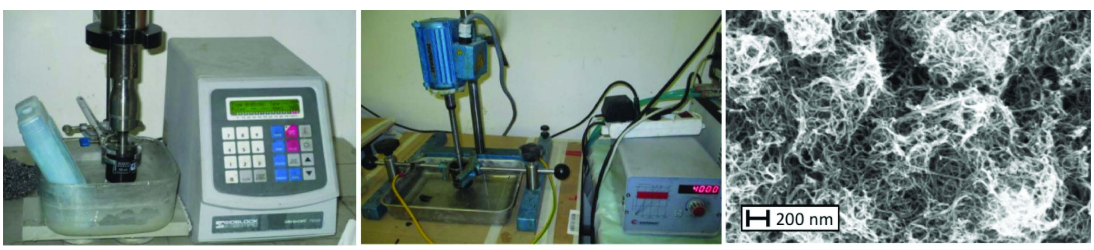

Figure 2. Preparation of nanomodified aqueous suspensions. Set up for sonication (A) and mechanical mixing (B); SEM picture of the suspension after mechanical mixing (C).

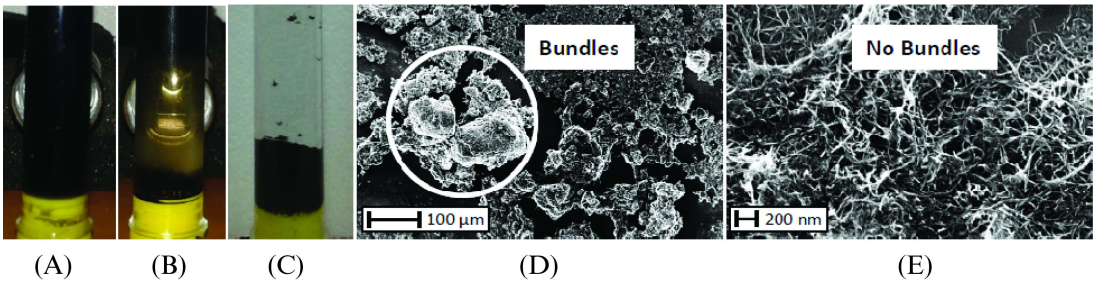

Figure 3. Illustrative samples corresponding to settling factors of 2, 1 and 0 (A, B, C); illustrative SEM pictures showing bad dispersion (D) and good dispersion (E).

presence of bundles (Figure 3(D)). The most successful samples did not exhibit thick clusters of nanotubes even at a magnification of 100,000x (Figure 3(E)). From the results of the dispersion tests, SLS (lignosulfonic acid sodium salt) dispersant was selected for the preparation of cementitious mixes, because both sonicated and mechanically mixed suspensions of 1:1 and 10:1 dispersant-to-nanotube ratios demonstrated good dispersion scores.

2.3 Fabrication Procedure

After identifying the best dispersing additive, cement-based samples were fabricated in order to investigate electrical conductivity, percolation threshold and electromechanical properties of the nanomodified materials. Cement paste, mortar and concrete nanocomposite specimens of various prismatic shapes were prepared, using different contents of MWCNTs and different fabrication procedures as better detailed in the following. A plasticizer based on polycarboxylate ether polymers was added to the mix in the amount up to 1% by mass of cement when necessary to increase work ability. Cubes of 51 mm sides were fabricated with paste, mortar and concrete with different percentages of MWCNTs varying from 0 to 1% with respect to the mass of cement, with step increments of 0.25%, and from 1% to 1.5% with a step increment of 0.5%. The electrodes consisted of stainless steel nets embedded along 85% of their thickness and placed symmetrically along their central axis. Square-base prism specimens were 40×40×160 mm^3, with embedded 1 mm diameter copper wires electrodes, disposed symmetrically with respect to the center of the specimens, at a mutual distance of 10 mm. The amount of MWCNTs in such specimens is 2% by mass content of the cement. The addition of MWCNTs in all the cement matrices was conducted by adding the nanomodified suspension to cement powder, plasticizer, when necessary, and aggregates, to produce mortar and concrete[45]. Then, the admixtures were manually mixed (Figure 4(A)). The control of the effective dispersion of carbon nanotubes in the aqueous solution and in the cement paste was performed using a SEM. The resulting mix was poured into oiled molds (Figure 4(B)) and the electrodes were embedded (Figure 4(C)). After proper settling, the samples were unmolded for curing (Figure 4(D)).

2.4 Sensing Principle

The enhanced electrical characteristics of CNT-reinforced cement-based matrices are a result of the formation of a three dimensional meshwork of conductive paths. The more concentrated and homogeneous dispersion of nanotubes produce higher conductivity

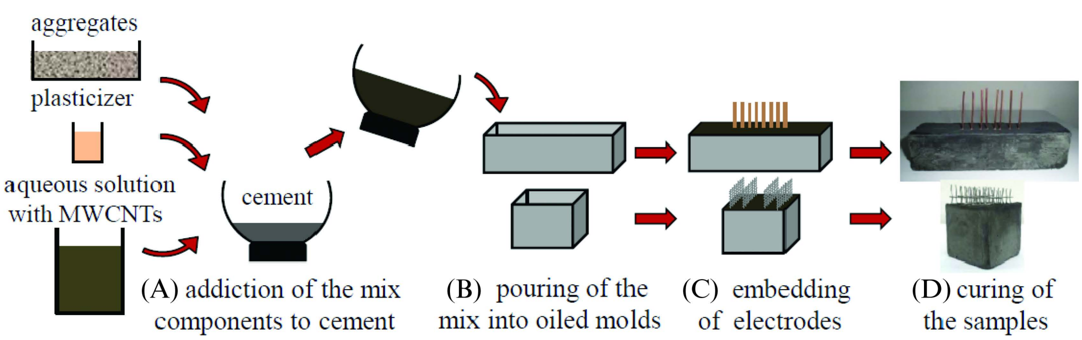

Figure 4. Fabrication process of MWCNT cement-based sensors.

of the nanomodified cementitious material. The conductivity increases the approaching of the percolation threshold, when the nanotubes form a continuous electrical conductive network. The behavior of nano-reinforced cementitious materials is both capacitive and piezoresistive. The capacitive behavior is due to materials' dielectric characteristics and to the presence of double layer phenomenon at the electrodes. Due to their dielectric characteristics, cementitious materials exhibit an important polarization effect concurrently with an electric field. A particle content below the percolation threshold enhances the piezoresistive sensitivity under compressive loads, while this relationship is inverted passing the threshold. The electrical resistance of such materials comes from the intrinsic piezoresistance of nanotubes, the intrinsic resistance of the cementitious matrix, the contacting conduction from the contact points of the mesh and the tunneling and field emission conductions due to nanosize effects[11]. The self-sensing functionality is achieved by correlating the variation of the applied stresses with the variation of appropriate parameters and properties of the material, in particular the electrical resistance. Through resistance or electrical resistivity changes, deformation or tension state can be estimated. Literature suggests that the electrical behavior of cement-based sensors with carbon nanotubes can be modeled through a system of resistors and capacitors[36–38] (Figure 5). The relationship between electrical resistance (ΔR) and axial strain (ε) is assumed to be linear for small ε, as commonly modeled in electrical strain gauges[38]:

$$\frac{\Delta R}{R_0} = -\lambda\varepsilon \quad (1)$$

In Equation 1, λ is the gauge factor and R_0 the unstrained internal electrical resistance of the material. Gauge factors of CNTs cement-based materials reported in literature can reach up to about 400[32], which constitutes two orders of magnitude greater than the gauge factor of typical strain gauges. The sensitivity S can be determined from Equation 2:

$$S = \frac{\Delta R}{\varepsilon} = -\lambda R_0 \quad (2)$$

Figure 5 shows the electrical circuit proposed by the authors[38], where C_0 is the internal capacitance and R_c represents contact resistance. With an applied compressive axial load, a mechanical deformation occurs, the distance between the electrodes d_0 changes, and the change in the electrical properties of the material can be measured.

3. Response To General Loading Conditions and Scalable Applications

The electromechanical characterization of the nanocomposite sensor has been conducted under static and dynamic loads. Figure 6 shows the experimental setup for both tests. A source measure unit, model NI PXI-4130, provided a stabilized current to the two electrodes through coaxial cables. The electrical current was measured using a high speed digital multimeter, model (NI) PXI-4071, at a sampling rate of 1 kHz for all tested specimens.

The first test investigated the electrical response of the smart sensor to loading-unloading cycles at a constant rate of 0.5 kN/s and increasing amplitudes of 1.0, 1.5 and 2.0 kN. Paste, mortar and concrete sensors with 1% mass content of MWCNTs with respect to cement were used. The load was applied through a servo-controlled pneumatic universal testing machine (IPC Global UTM-14P) with an environmental chamber for maintaining a constant temperature (Figure 6(A)).

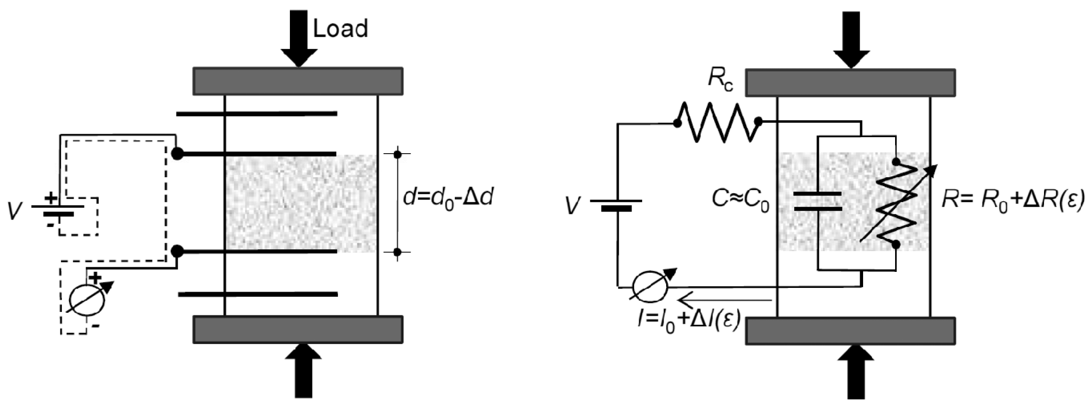

Figure 5. Sketch of the proposed electromechanical behavior of a MWCNT cement-based under compressive load.

The results of the tests show that concrete, mortar and paste nanomodified sensors clearly manifest a strain-sensing ability with increasing performance from concrete to mortar and paste (Figure 7). This is explained by the absence of aggregates in cement paste that enhances interactions between nanotubes and increases the piezoresistive effect. Moreover, cement-based nanomodified sensors fabricated with mechanical addiction of nanotubes show a higher sensitivity than samples fabricated through sonication. Table 2 reports a comparison between unstrained electrical resistance, gauge factors and sensitivity of two concrete specimens fabricated with the same mix design, but with different type of nanotube mixing. Quantities reported in the table are defined according to equations 1 and 2. These results show that the higher sensitivity of mechanically mixed specimens is mostly attributed to their larger unstrained electrical resistance. This electrical resistance is highly affected by the nanotube dispersion procedure.

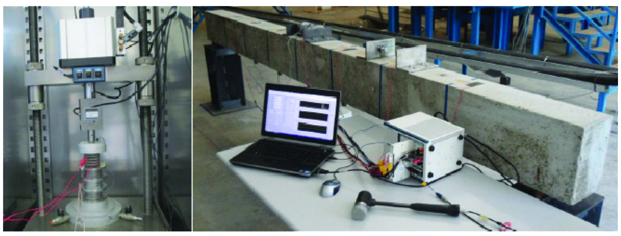
(A) (B)

Figure 6. Setup of electromechanical tests: with low speed loads (A) and dynamic loads (B).

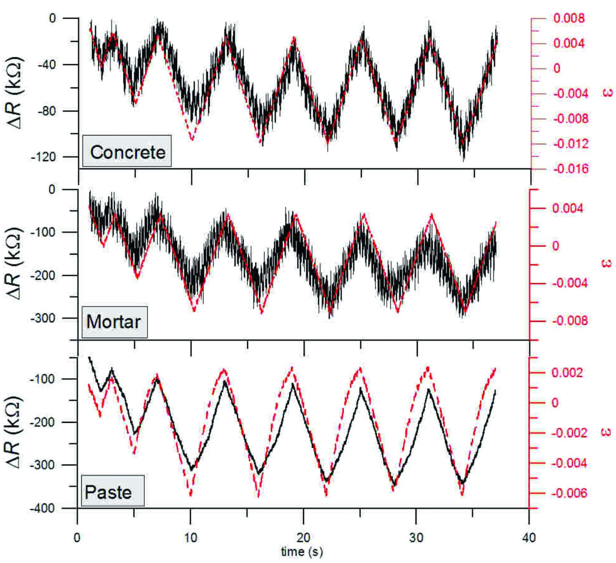

Figure 7. Results of strain sensing tests for paste, mortar and concrete added with MWCNTs.

Table 2. Unstrained electrical resistance, gauge factor and strain sensitivity of concrete samples obtained from axial compression test

Nanomaterial	Type of CNT mixing	$R_0(\Omega)$	l	$S(\Omega)$
Concrete	Sonication	37	12	444
Concrete	Mechanical mixing	521	30	15630

The second test evaluated the dynamic sensing capability and provided a full-scale validation of CNT cement-based sensors against off-the-shelf sensors. Vibration tests were conducted on a simply supported reinforced concrete beam of rectangular cross-section of dimensions 20 × 30 cm^2 with a distance between supports of 400 cm. The beam was instrumented on the bottom surface with seven accelerometers, model PCB 393C, and on the top surface with seven resistive strain gauges, 6 cm long, with nominal resistance of 120 Ω and gauge factor of 2.1, all equally spaced.

Vibration tests were conducted by randomly hitting the beam using an impact hammer, model PCB 086D20C41. The cementitious sensor, made of a nanomodified cement paste of 2% mass content of MWCNTs with respect to cement, was installed onto the top surface of the beam by means of an L-shaped steel connection device that simulates the embedding of the sensor. The sensor was preloaded by 1.5 kN. Data from hammer, strain gauges, accelerometers and CNTCS were simultaneously acquired through a NI PXIe-1073, containing appropriate modules. Figure 6(B) shows the experimental setup, while Figure 8 represents a sketch of the main elements of the test. The output of the sensor was sampled at 1000 Hz. Before the start of each experiment, a constant tension of 15 V was applied to the sensor for 30 minutes to reduce the effect of polarization. Figure 9 shows the time history of the acquired data: the raw data (Figure 9(A)), and the signal after a high pass filtering above 10 Hz (Figure 9(B)), which eliminated the residual polarization effect[34].

The results obtained using acceleration or strain gauge data allowed to clearly identify 12 modes of vibration in the interval between 0 and 500 Hz: five vertical modes (V1, V2A, V2B, V3 and V4), five lateral modes and two additional lateral modes due to lateral rolling. Table 3 presents the comparison between the frequencies of the vertical modes identified from acceleration data and from the nanomodified sensor's output. These quantities have been estimated by spectral analysis using 900 s time

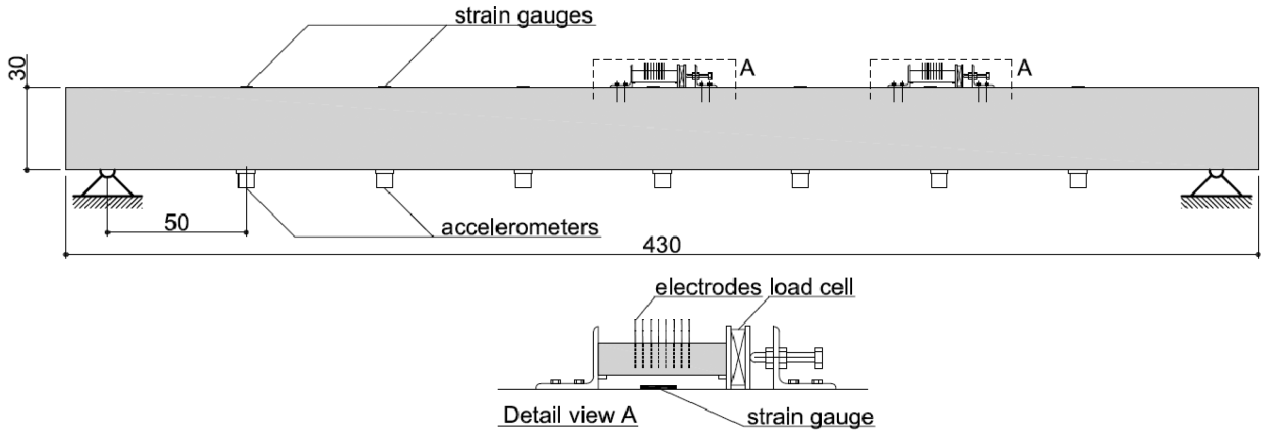

Figure 8. Layout of the experimental setup and plans of the investigated RC beam (dimensions in cm).

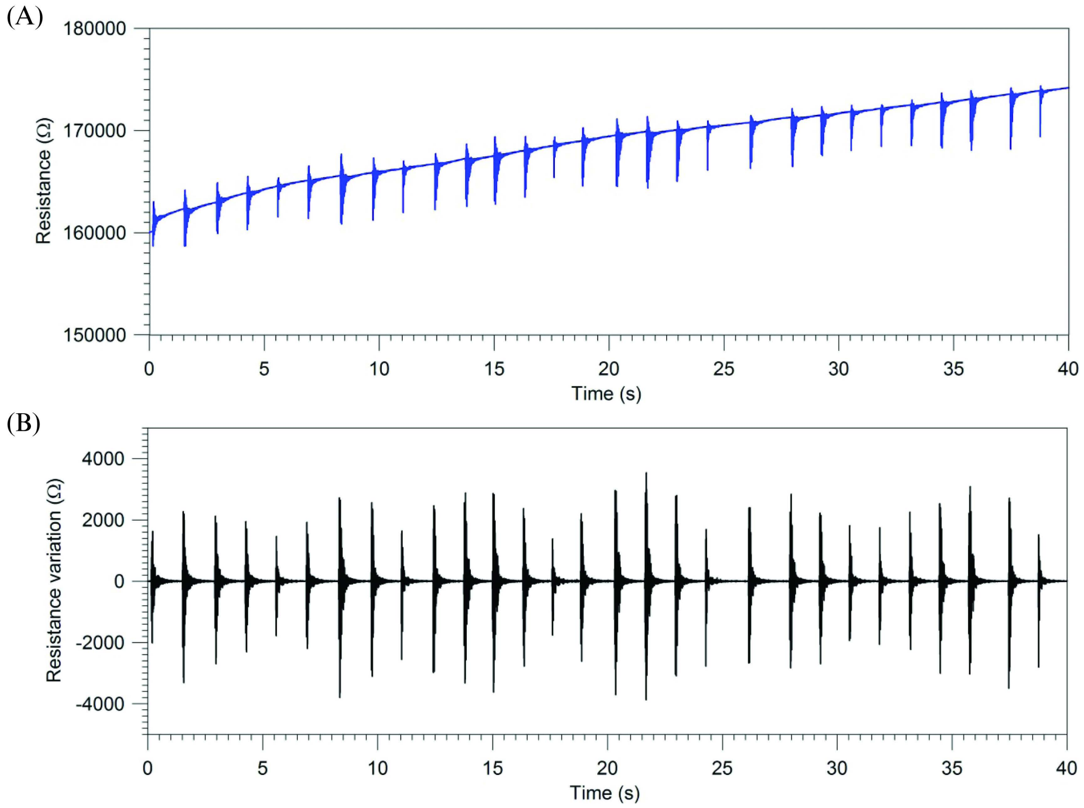

Figure 9. Vibration monitoring of the RC beam using CNTs cement-based sensor placed at mid-span: sensor output before high-pass filtering (A); sensor output after high-pass filtering (B).

Table 3. Identified (ID) natural frequencies (Hz) using acceleration data and CNTs cement-based sensor's output and their percentage difference Δ

Mode	V1	V2A	V2B	V3	V4
ID (accel)	27.10	82.52	113.5	171.1	431.4
CNTCS	27.10	81.05	113.3	172.9	423.6
Δ (%)	0.0	1.8	0.2	1.0	1.8

histories sampled at 1000 Hz and by computing spectra via the classic Welch's method. This method averages spectra among overlapping windows of the base signal using, in this case, 2048 points for each time window. The results of the identified frequencies are in good agreement. CNT cement-based sensors provided a good dynamic sensing ability in terms of modal identification. This can be explained by the excellent frequency response of these sensors, which was investigated by the authors in previous studies[5,33,34]. These sensors tend to reach a linear behavior at high loading frequencies.

4. Electromechanical Modelling

The electrical response of the CNT cement-based sensors under a step change in the input voltage was evaluated to validate the equivalent circuit model sketched in Figure 5[38]. Step response tests were conducted in response to a constant voltage difference of 1.5 V for different electrode distances d_0. For each value of d_0, the current output was measured at a 1 kHz sampling rate for 1 hour. Output data were optimally fitted to identify salient parameters (of R_0, R and C). Figure 10 shows the comparison between experimental results and model predictions in case of a distance between electrodes of 1 cm.

After the identification of the model parameters, electromechanical behavior of the CNT cement-based sensors was examined under dynamic tests. Figure 11 represents the time history of the ratio between the output current and the step input voltage (A) and its power spectral density (PSD) (B) under harmonic axial loads of 5 Hz[39]. The dynamic response was not monochromatic and showed super harmonics at multiples of 5 Hz. This evidence can be explained by introducing a time-varying internal resistance associated with the time-varying axial strain in equation 1. The solution of the resulting system with time-varying coefficients would support the existence of super harmonics[38].

5. Prospective Applications in Smart Cities

CNT-based cementitious sensors represent a novelty in the field of structural engineering and SHM. To the best of the knowledge of the authors, they are yet to be implemented in the field. Possible applications are various and multidisciplinary. These nanocomposites are suitable for fabricating smart self-sensing sensors, which can be used to improve city operations and management by deploying large arrays of distributed

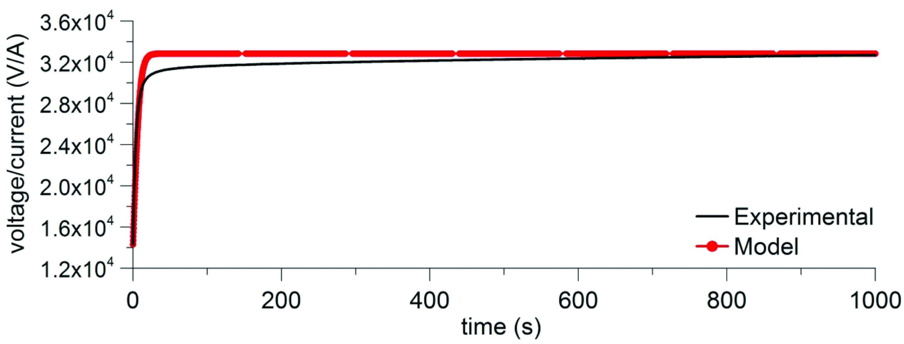

Figure 10. Comparison between experimental results and analytical predictions for the step response of CNTs cement-based sensor with distance between the active electrodes of 1 cm.

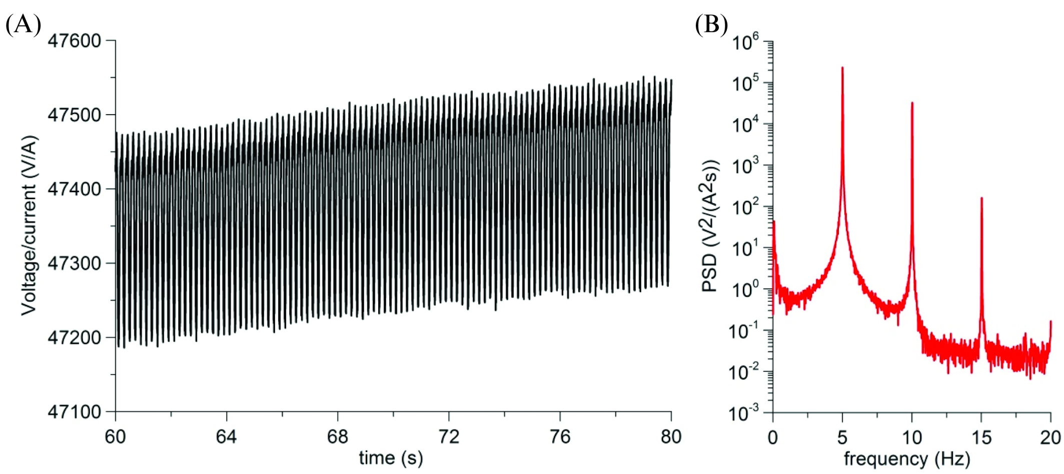

Figure 11. Resistance variation (A) and PSD (B) of the output of CNTs cement-based sensor under 5 Hz sinusoidal axial loading.

sensors, at low cost. With proper algorithms, it is possible to create an automatic link between the sensor's signal and the state of interest, which would enable direct decision making on a system operation and management perspective.

An application example is weigh-in-motion sensing via self-sensing cementitious slab, which could assist traffic and crowd management by detecting a weight and its location, indirectly derived from strain. Nevertheless, given the static and dynamic monitoring characteristics described above, a promising application would be structural health monitoring of civil infrastructures, including energy systems (e.g., dams, wind turbine bases), transportation infrastructures (e.g., roads, bridges), and building structures. For example, a smart mortar could be produced and applied during retrofit of masonry structures (e.g., historic structures), which would enable very fast post-earthquake condition assessment. This would be done by detecting a change in the vibration signature that would correspond to damage.

Other prospective applications of cement composites doped with electrically conductive nanoparticles within smart cities are: conductive slabs with anti-static ability for data and computer centers in smart grids, thermally conductive concrete road pavements for de-icing applications using electrical power, thermally conductive concrete for geothermal applications, embedded thermal and hygroscopic sensors for environmental control including applications within critical environments such as museums, thermally and energetically efficient concrete materials including combination of conductive nanoparticles and phase change materials, and more.

6. Conclusion

This paper presented an overview of the current research on novel piezoresistive nanocomposite cement-based sensors. After a brief state-of-art, the technology was described and demonstrated, and future challenges were examined. In particular, this new generation of smart cementitious sensors has both resistive and capacitive characteristics, and has self-sensing capability for static and dynamic loads, which includes vibration signatures. Experimental tests demonstrated performance comparable to conventional monitoring sensors such as accelerometers and strain gauges. Moreover, the sensor exhibits a very high electrical sensitivity compared with off-the-shelf resistive sensors.

The results reflected that the multifunctional cementitious materials have promising applications to enable smart cities. Examples of applications include smart slabs for weigh-in-motion sensing, smart materials for rapid condition assessment of civil infrastructure and other applications described within the paper.

Conflict of Interest and Funding

No conflict of interest was reported by the authors. This research was partially supported by Regione Umbria, within ESF-funded research-grant Scheme.

Acknowledgements

The authors gratefully acknowledge for their support to Prof. J. M. Kenny and the other members of the Group of Materials Science of University of Perugia, in particular, Prof. L. Torre, Dr. M. Natali and Dr. M. Rallini.

References

1. Mondal P, Shah S P and Marks L D, 2008, Nanoscale characterization of cementitious materials. *ACI Materials Journal*, vol.105(2): 174–179. http://dx.doi.org/10.14359/19758.
2. Li G Y, Wang P M and Zhao X H, 2007, Pressure-sensitive and microstructure of carbon nanotube reinforced cement composites. *Cement and Concrete Composites*, vol.29(5): 377–382. http://dx.doi.org/doi:10.1016/j.cemconcomp.2006.12.011.
3. Laflamme S, Ubertini F, Saleem H, *et al*. 2015, Dynamic characterization of a soft elastomeric capacitor for structural health monitoring, *Journal of Structural Engineering*, vol.144(8): 04014186. http://dx.doi.org/10.1061/(ASCE)ST.1943-541X.0001151.
4. Monti M, Natali M, Petrucci R, *et al*. 2011, Carbon nanofibers for strain and impact damage sensing in glass fiber reinforced composites based on an unsaturated polyester resin, *Polymer Composites*, vol.32(5): 766–775. http://dx.doi.org/10.1002/pc.21098.
5. Ubertini F, Laflamme S, Ceylan H, *et al*. 2014, Novel nanocomposite technologies for dynamic monitoring of structures: A comparison between cement-based embeddable and soft elastomeric surface sensors. *Smart Materials and Structure*, vol.23(4): 045023. http://dx.doi.org/10.1088/0964-1726/23/4/045023.
6. Cohen D J, Mitra D, Peterson K, *et al*. 2012, A highly elastic, capacitive strain gauge based on percolating nanotube networks. *Nano Letters*, vol.12(4): 1821–1825.

http://dx.doi.org/10.1021/nl204052z.

7. Cochrane C, Koncar V, Lewandowski M, *et al.* 2007, Design and development of a flexible strain sensor for textile structures based on a conductive polymer composite. *Sensors*, vol.7(4): 473–492. http://dx.doi.org/10.3390/s7040473.
8. Fu X, Lu W and Chung D D L, 1997, Improving the strain-sensing ability of carbon fiber-reinforced cement by ozone treatment of the fibers. *Cement and Concrete Research*, vol.28(6): 183–187. http://dx.doi.org/10.1016/S0008-8846(97)00265-2.
9. Konsta-Gdoutos M S, Metexa Z S and Shah S P, 2010, Highly dispersed carbon nanotube reinforced cement-based materials. *Cement Concrete Research*, vol.40(7): 1052–1059. http://dx.doi.org/10.1016/j.cemconres.2010.02.015.
10. Lourie O, Cox D M and Wagner H D, 1998, Buckling and collapse of embedded carbon nanotube. *Physical Review Letters*, vol.81(8): 1638. http://dx.doi.org/10.1103/PhysRevLett.81.1638.
11. Han B G, Yu X and Ou J P, 2011, Multifunctional and smart nanotube reinforced cement-based materials, in *Nanotechnology in Civil Infrastructure*, Springer Berlin Heidelberg, Germany, 1–47. http://dx.doi.org/10.1007/978-3-642-16657-0_1.
12. Cicco S R, Farinola G M, Martinelli C, *et al.* 2010, Pd-promoted homocoupling reactions of unsaturated silanes in aqueous micelles. *European Journal of Organic Chemistry*, vol.1(12): 2275–2279. http://dx.doi.org/10.1002/ejoc.201000021.
13. Cao J Y and Chung D D L, Electric polarization and depolarization in cement-based materials, studied by apparent electrical resistance measurement. *Cement and Concrete Research*, vol.34(3): 481–485. http://dx.doi.org/10.1016/j.cemconres.2003.09.003.
14. Meehan D G, Wang S and Chung D D L, 2010, Electrical-resistance-based sensing of impact damage in carbon fiber reinforced cement-based materials. *Journal of Intelligent Material Systems and Structure*. vol.21(1): 83–105. http://dx.doi.org/10.1177/1045389X09354786.
15. Wen S H and Chung D D L, 2005, Strain-sensing characteristic of carbon fiber-reinforced cement. *American Concrete Institute*, vol.102(4): 244–248. http://dx.doi.org/10.14359/14617.
16. Chen P W and Chung D D L, 1993, Carbon fiber reinforced concrete for smart structures capable of non-destructive flaw detection. *Smart Materials and Structures*, vol.2(1): 22–30. http://dx.doi.org/10.1088/0964-1726/2/1/004.
17. Bontea D M, Chung D D L and Lee G C, 2000, Damage in carbon fiber-reinforced concrete, monitored by electrical resistance measurement. *Cement and Concrete Research*, vol.30(4): 651–659. http://dx.doi.org/10.1016/S0008-8846(00)00204-0.
18. Han B G, Ding S Q and Yu X, 2015, Intrinsic self-sensing concrete and structures. *Measurements*, vol.59: 110–128. http://dx.doi.org/10.1016/j.measurement.2014.09.048.
19. Kuronuma Y, Takeda T, Shindo Y, *et al.* 2012, Electrical resistance-based strain sensing in carbon nanotube/polymer composites under tension: Analytical modeling and experiments. *Composites Science and Technology*, vol.72(14): 1678–1682. http://dx.doi.org/10.1016/j.compscitech.2012.07.001.
20. Gong S, Zhu Z H and Meguid S A, 2014, Carbon nanotube agglomeration effect on piezoresistivity of polymer nanocomposites. *Polymer*, vol.55(21): 5488–5499. http://dx.doi.org/10.1016/j.polymer.2014.08.054.
21. Feng C and Jiang L Y, 2013, Micromechanics modeling of the electrical conductivity of carbon nanotube (CNT)-polymer nanocomposites. *Composites Part A: Applied Science and Manufacturing*, vol.47: 143–149. http://dx.doi.org/10.1016/j.compositesa.2012.12.008.
22. Xu Z H and Liu Z T, 2007, Fatigue damage in smart carbon fiber concrete by electrical resistance measurement. *Key Engineering Materials*, vol.348–349: 435–438. http://dx.doi.org/10.4028/www.scientific.net/KEM.348-349.345.
23. Galao O, Baeza F J, Zornoza E, *et al*. 2014, Strain and damage sensing properties on multifunctional cement composites with CNF admixture. *Cement and Concrete Composites*, vol.46: 90–98. http://dx.doi.org/10.1016/j.cemconcomp.2013.11.009.
24. Gao D, Sturm M S and Mo Y L, 2009, Development of carbon nanofiber self-consolidating concrete, In *2nd International Symposium on Design, Performance and Use of Self-Consolidating Concrete*, RILEM Publications sarl, Bagneux, 126–134.
25. Li H, Xiao H G and Ou J P, 2006, Effect of compressive strain on electrical resistivity of carbon black-filled cement-based composites. *Cement and Concrete Composites*, vol.28(9): 824–828. http://dx.doi.org/10.1016/j.cemconcomp.2006.05.004.
26. Laflamme S, Pinto I, Saleem H S, *et al*. 2015, Conductive paint-filled cement paste sensor for accelerated percolation: SPIE Proceedings, Structural Health Monitoring and Inspection of Advanced Materials, Aerospace, and Civil Infrastructure 2015, vol.9437: 943722. http://dx.doi.org/10.1117/12.2084408.
27. Konsta-Gdoutos M S and Aza C A, 2014, Self sensing carbon nanotube (CNT) and nanofiber (CNF) cementitious composites for real time damage assessment in smart structures. Cement and Concrete Composite, vol.53: 162–169.

http://dx.doi.org/10.1016/j.cemconcomp.2014.07.003.
28. Coppola L, Buoso A and Corazza F, 2011, Electrical properties of carbon nanotube cement composites for monitoring stress conditions in concrete structures. *Applied Mechanics and Materials*, vol.82: 118–123. http://dx.doi.org/10.4028/www.scientific.net/AMM.82.118.
29. Wansom S, Kidner N J, Woo L Y, *et al*. 2006, AC-impedance response of multi-walled carbon nanotube/cement composites. *Cement and Concrete Composites*, vol.28(6): 509–519. http://dx.doi.org/10.1016/j.cemconcomp.2006.01.014.
30. Yu X and Kwon E, 2009, A carbon nanotube/cement composite with piezoresistive properties. *Smart Materials and Structures*, vol.18(50): 055010. http://dx.doi.org/10.1088/0964-1726/18/5/055010.
31. Han B G, Qiao G F and Jiang H F, 2012, Piezoresistive response extraction for smart cement-based composites/sensors. *Journal Wuhan University of Technology*, vol.27(4): 754–757. http://dx.doi.org/10.1007/s11595-012-0542-z.
32. Azhari F and Banthia N, 2012, Cement-based sensors with carbon fibers and carbon nanotubes for piezoresistive sensing. *Cement and Concrete Composites*, vol.34(7): 866–873. http://dx.doi.org/10.1016/j.cemconcomp.2012.04.007.
33. Materazzi A L, Ubertini F and D'Alessandro A, 2013, Carbon nanotube cement-based transducers for dynamic sensing of strain. *Cement and Concrete Composites*, vol.37: 2–11. http://dx.doi.org/10.1016/j.cemconcomp.2012.12.013.
34. Ubertini F, Materazzi A L, D'Alessandro A, *et al.* 2014, Natural frequencies identification of a reinforced concrete beam using carbon nanotube cement-based sensors. *Engineering structures*, vol.60: 265–275. http://dx.doi.org/10.1016/j.engstruct.2013.12.036.
35. Wen S H and Chung D D L, 2006, Model of piezoresistivity in carbon fiber cement. *Cement and Concrete Research*, vol.36(10): 1879–1885. http://dx.doi.org/10.1016/j.cemconres.2006.03.029.
36. Han B G, Guan X C and Ou J P, 2007, Electrode design, measuring method and data acquisition system of carbon fiber cement paste piezoresistive sensors. *Sensors and Actuators A: Physical*, vol.135(2): 360–369. http://dx.doi.org/10.1016/j.sna.2006.08.003.
37. Han B G, Zhang K, Yu X, *et al.* 2012, Electrical characteristics and pressure-sensitive response measurements of carboxyl MWNT/cement composites. *Cement and Concrete Composites,* vol.34(6): 794–800. http://dx.doi.org/10.1016/j.cemconcomp.2012.02.012.
38. D'Alessandro A, Ubertini F, Materazzi A L, *et al*. 2014, Electromechanical modelling of a new class of nanocomposite cement-based sensors for structural health monitoring, *Structural Health Monitoring,* vol.14(2): 137–147. http://dx.doi.org/10.1177/1475921714560071.
39. D'Alessandro A, Ubertini F, Materazzi A L, *et al*. 2014, Electrical modelling of carbon nanotube cement-based sensors for structural dynamic monitoring: *American Institute of Physics Conference Proceedings*, vol.1603: 23. http://dx.doi.org/10.1063/1.4883038.
40. Abu Al-Rub R K, Ashour A I and Tyson B M, 2012, On the aspect ratio effect of multi-walled carbon nanotube reinforcements on the mechanical properties of cementitious nanocomposites. *Construction and Building Materials*, vol.35: 647–655. http://dx.doi.org/10.1016/j.conbuildmat.2012.04.086.
41. McAndrew T P, Laurent P, Havel M, *et al.* 2008, Arkema Graphistrength® multi-walled carbon nanotubes, *Nanotechnology 2008: Materials, Fabrication, Particles, and Characterization – Technical Proceedings of the 2008 NSTI Nanotechnology Conference and Trade Show*, vol.1: 47–50.
42. Huang Y Y and Terentjev E M, 2012, Dispersion of carbon nanotubes: Mixing, sonication, stabilization, and composite properties. *Polymers,* vol.4(1): 275–295. http://dx.doi.org/10.3390/polym4010275.
43. Parveen S, Rana S and Fangueiro R, 2013, A review on nanomaterial dispersion, microstructure, and mechanical properties of carbon nanotube and nanofiber reinforced cementitious composites. *Journal of Nanomaterials*, vol.2013: 1–19. http://dx.doi.org/10.1155/2013/710175.
44. Eurocode 2: Design of concrete structures – Part 1-1, 2004, *General rules and rules for buildings*: EN 1992-1-1.
45. Collepardi M, 2010, The advantages of fly use in concrete structures. *Journal of the Polish Engineering Mineral Engineering Society*: 436.