State of the Art on Sensing Capability of Poorly or Nonconductive Matrixes with a Special Focus on Portland Cement–Based Materials

Thanyarat Buasiri[1]; Karin Habermehl-Cwirzen[2]; and Andrzej Cwirzen[3]

Abstract: Concrete, a well-established and well-characterized building material, is also the most used building material in the world. However, many old and new-build structures suffer from premature failures due to extensive deterioration and decreased load-bearing capacity. Consequently, structural monitoring systems are essential to ensure safe usage of concrete structures within and beyond their designed life. Traditional monitoring systems are based on metallic sensors installed in crucial locations throughout the structure. Unfortunately, most of them have relatively low reliability and a very short life span when exposed to often very harsh environments. The ideal solution is therefore to develop a smart concrete having self-sensing capability. A number of studies have shown that conductive cementitious matrixes will undergo changes in their electrical resistivity with variations of stresses and strains or development of microcracking. This behavior can be used as a reliable tool to measure changes. This review provides a comprehensive overview of several nonconductive matrixes, with a special focus on portland cement–based materials, showing self-sensing capabilities by description of detection mechanisms, sensing capabilities, limitations, and potential applications. **DOI:** 10.1061/(ASCE)MT.1943-5533.0002901. *© 2019 American Society of Civil Engineers.*

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Introduction

Deterioration of concrete can originate from the corrosion of reinforcement (Cabrera 1996), carbonation (Chi et al. 2002), frost and frost deicing salt attack, seawater attack, and alkali silica reaction, among others (Boyd and Skalny 2007; Darwin et al. 2008). The presence of a monitoring system enables evaluation and assessment of the extent of damage, and estimation (Yazdani and Mohanam 2014) of the remaining load-bearing capacity (Housner et al. 1997). Early detection of developing damages and successive application of a proper repair mechanism enhances the durability and prevents reduction of or even elongates the life span of affected concrete structures (Rana et al. 2016). Structural health monitoring (SHM) is a method aiming to detect the damage of civil structures (Aggelis et al. 2014; Chang et al. 2003; Han et al. 2015a; Sun et al. 2010; Ye et al. 2014) especially bridges, dams, roads, and high-rise buildings. SHM uses embedded sensors designed to discover and measure various crucial parameters like stress, strain, crack formation, humidity, and chloride content. Unfortunately, most have serious constraints related to poor durability, high cost, and short lifespan (Monteiro et al. 2017).

A new generation of monitoring systems being widely studied at present is based on a self-sensing portland cement–based matrix. The binder matrix itself acts as a sensor using changes in electrical properties when subjected to stress or strain. Theoretically, the self-sensing capability should be able to produce systems that are significantly more reliable, accurate, and sensitive but at lower cost and ensuring a longer service life. This paper reviews sensing mechanisms and effects of various types of conductive materials on the monitoring capabilities of modified nonconductive matrixes, with a special focus on portland cement–based matrixes.

Sensing Mechanism in Nonconductive Matrixes

Nonconductive or poorly conductive composites (i.e., cementitious polymers and ceramics) are widely used in electronics, packaging, as adhesive, interconnections, and electromagnetic shields as well as in automotive, aerospace, and space industries (Awaja et al. 2016; Chen and Chung 1995). Cement-based materials are classified as quasi-brittle materials (Bajare et al. 2012). A hardened cement matrix shows limited electrical conductivity only in the wet state. The addition of electrically conducting material, including, for example, carbon fiber, carbon black, or steel fiber, can induce some conductivity, which could be in some cases utilized in limited structural health monitoring (Wang and Chung 2000). The sensitivity of such a system depends on the type, quantity, and distribution of the incorporated conductive material. A uniform distribution combined with a sufficient amount of conductive material can create a conductive path throughout the binder matrix. The conductivity of such a system will change with the applied load or development of internal damage such as microcracks. The relation

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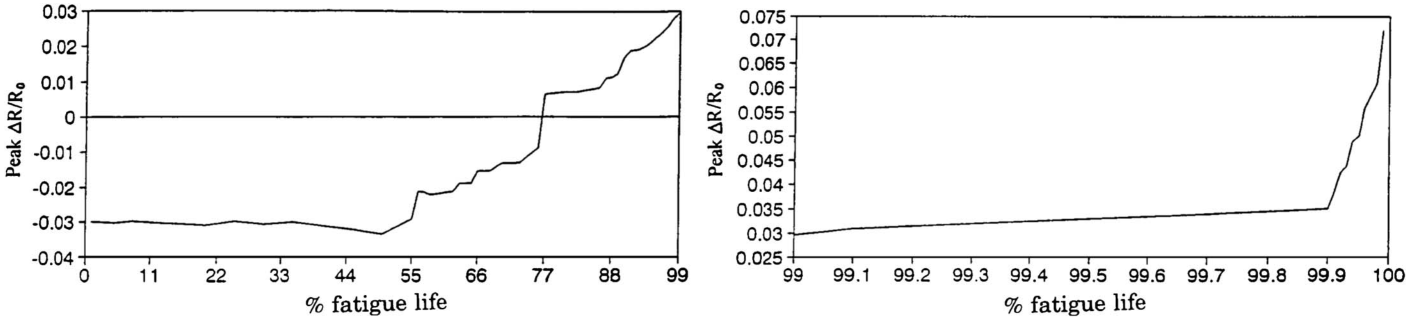


Fig. 1. Variation of the peak $\Delta R/R_0$ with the percentage of fatigue life. (Adapted with permission from Springer Nature: Springer, *Journal of Material Science*, "Sensing damage in carbon fiber and its polymer-matrix and carbon-matrix composites by electrical resistance measurement," X. Wang, S. Wang, and D. D. L. Chung, © 1999.)

between the electrical conductivity and amount of the conductive phase shows a maximum threshold value, which marks the maximum sensitivity of the matrix. Below and above the threshold value, the sensitivity decreases (Baeza et al. 2010). The value is commonly named as the electrical percolation threshold (EPT) (Zeng et al. 2011).

Strain Sensing

Strain sensing refers to the ability of certain materials to sense strain or stress through a change of the electrical resistance when exposed to various forces, i.e., so-called piezoresistive behavior. For a polymer matrix composite, the strain sensitivity is defined as the ratio between the reversible change of the fractional resistance ($\Delta R/R_0$) and the strain amplitude (Chung 2002a). Damage sensitivity is related to the irresistible increase in resistance. The measurement of the electrical response during loading is recorded and used to estimate the strain value (Kuronuma et al. 2012). Resistivity increases due to progressive breakage of the conduction paths under tensile loading, whereas resistivity will decrease in compression due to the fiber push-in, thus increasing the chance of fibers in the adjacent laminae touching one another along the direction of fiber orientation (Chung 1998, 2002a). As a result, electrical resistance rises along the perpendicular direction and declines along the longitudinal direction (Chung 2002a). The measurement of irreversible strain allows structural health monitoring, and the sensing of reversible strain permits dynamic-load monitoring.

The strain sensitivity of composites is measured by calculating the so-called gauge factor (GF). The GF is defined as the ratio of fractional change of the electrical resistance to the fractional change of the strain ($\Delta R/R_0/\varepsilon$). A higher GF indicates better strain sensitivity. Continuous carbon fiber in a polymer matrix creates a sensitive strain sensor having a GF of up to 38. A cement-based matrix with embedded short carbon fibers can reach a very high strain-sensing capability with GF up to 700 (Chung 1998). Higher contents of nanoconducting materials are required if materials are exposed to larger strain/stress levels to prevent premature breakage of the fibers. Nanocomposites have shown sufficiently high strain sensitivity when the filler content is close to the percolation threshold (Georgousis et al. 2015).

Fatigue Sensing

Fatigue is a common cause of damage of structures subjected to repeatable dynamic loading. The measurement of the electrical resistivity proved to be an efficient method to determine fatigue in cyclic loading. Wang et al. (1999) showed that with carbon-fiber polymer-matrix composites, fatigue sensing can be achieved. It can be clearly seen that the peak of $\Delta R/R_0$ has increased significantly from approximately 50% fatigue life onward, as shown in Fig. 1. At 218,277 cycles in Fig. 2 (55% of fatigue life), $\Delta R/R_0$ showed a continuous increase from cycle to cycle and reached 396,854 cycles when fatigue failure took place. This behavior shows that fiber breakage increased resistivity in the composites. The degree of the damage depended on how the resistivity of cycles changes. Minor fatigue damage was reported when the resistivity increased discontinuously in spurts. A gradual increase in resistivity was attributed to severe fatigue damage with more extensive fiber breakage.

Wang et al. (2008) studied the sensitivity of a reinforced concrete beam incorporating a layer of short carbon fiber–reinforced concrete (CFRC) with diameter and length of carbon fibers of 6 μm and 5 mm, respectively. The aim was to determine its sensing capability under applied repeated fatigue flexural loading at a stress amplitude equal to 0.8 of the ultimate stress. The results showed that $\Delta R/R_0$ increased with applied loading and decreased during unloading in each cycle. Within the first five cycles, the fractional resistance increased slightly from 2.8% to 3.6% due to occurrence of small damage. The failure of the beam occurred after 38 loading cycles, with irreversible fractional resistance increasing up to 179% of its initial value. Limited damage caused only a small reversible change in electrical resistivity due to rearrangement of the fiber distribution. An irreversible increase of the electrical resistance was caused by major damage to and breakdown of the conductive network and fibers. Similar effects were also reported by Wang et al. (2006).

Temperature Sensing

High-temperature sensing is essential in modern power plants, especially in turbine engines, coal gasification systems, materials processing systems, and energy systems (Chung 2002a; Leal-Junior et al. 2018; Moraleda et al. 2013; Zhao et al. 2014). Several different methods are well-studied and used for monitoring in those harsh environments (Zhao et al. 2014). Thermistors, thermocouples resistance, and temperature detectors are traditional sensors using changes in electrical resistivity with temperature variations (Leal-Junior et al. 2018; Tapetado et al. 2015). In conductive polymer composites, the electrons overcome the potential barrier, leading to the so-called tunneling effect. If the distance between adjacent conductive materials is small enough, an effective conductive path is formed. When the path is long enough, it contributes to the conductivity of the composite. A composite with a cellular structure is sensed in a negative temperature coefficient unit

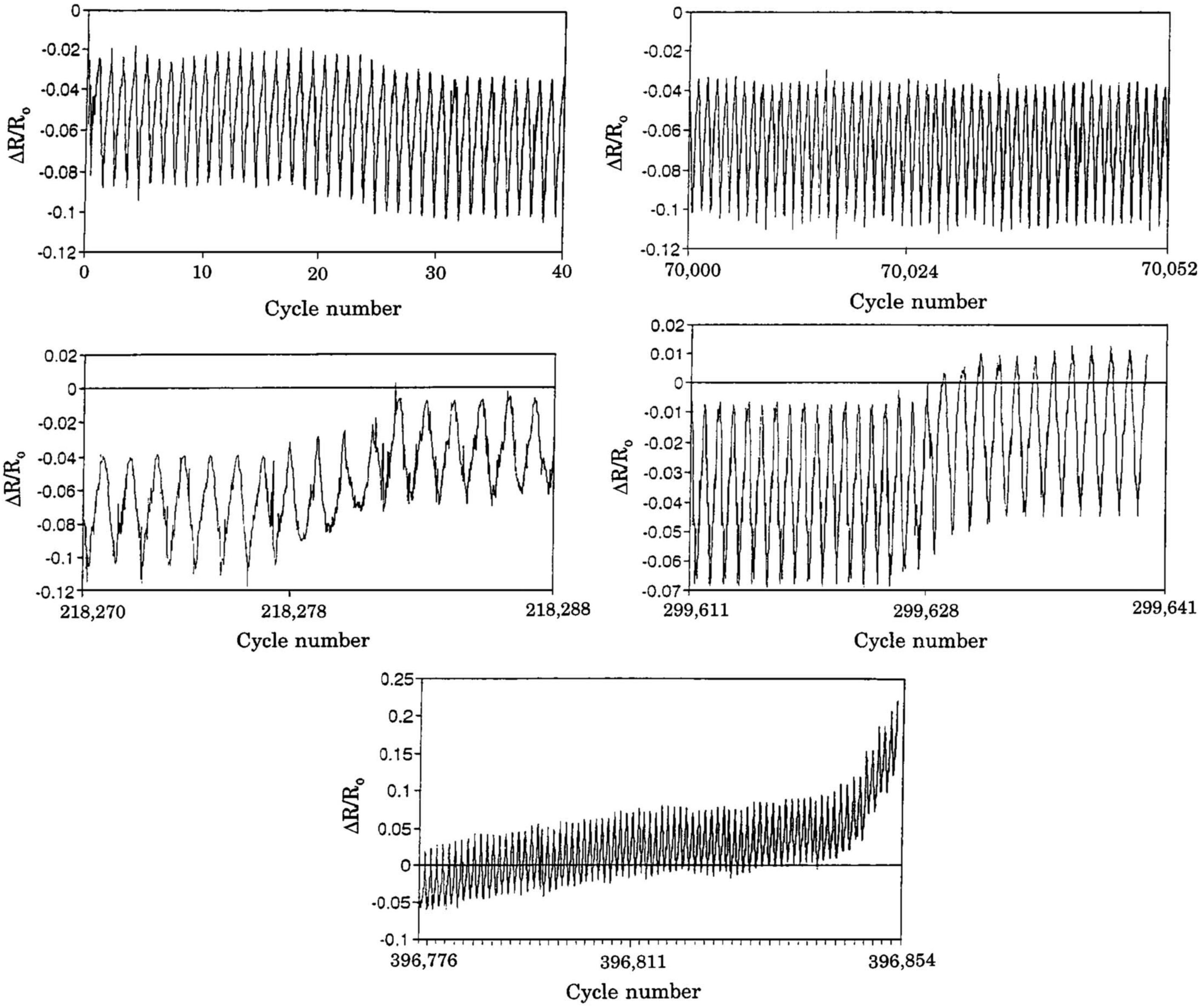


Fig. 2. Variation of $\Delta R/R_0$ with number of cycles in fatigue test in polymer matrix composite with carbon fiber. (Adapted with permission from Springer Nature: Springer, *Journal of Material Science*, "Sensing damage in carbon fiber and its polymer-matrix and carbon-matrix composites by electrical resistance measurement," X. Wang, S. Wang, and D. D. L. Chung, © 1999.)

(NTCU) [Fig. 3(a)]. The resistivity of the composite decreases with increasing temperature.

In contrast, a composite without a cellular structure is used as a sensitive material in the positive temperature coefficient unit (PTCU) [Fig. 3(b)]. In this case, the resistivity of the composite increases with increasing temperature (Wang 2015). An increase in temperature leads to an expansion of the matrix, which increases the distances between the conductive materials. As a result, the resistivity of the composite in the PTCU increases. On the other hand, in the NTCU, the resistivity of the composite decreases when the temperature increases due to expansion of the gas-filled voids. Due to this expansion, the distances between the conductive fillers are reduced, and more conductive networks are formed.

Fig. 4(a) shows the effects of the temperature on the resistivity of polymeric matrixes with conductive filler in NTCU and Fig. 4(b) shows the effects in PTCU systems. PTCU based on a carbon black–filled silicone rubber composite and NTCU based on a carbon-nanotube–filled polyurethane foam composite are good examples where the effective temperature range for the measurement is between 25°C and 75°C, respectively (Wang 2015). Due to changes in electrical resistivity with increasing temperature, epoxy-based matrixes with continuous carbon fibers used for temperature sensing

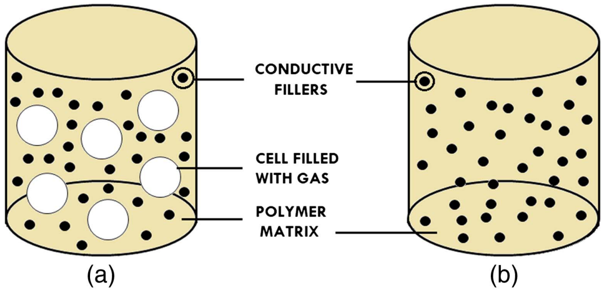


Fig. 3. Conductive polymer composite: (a) with cellular structure; and (b) without cellular structure.

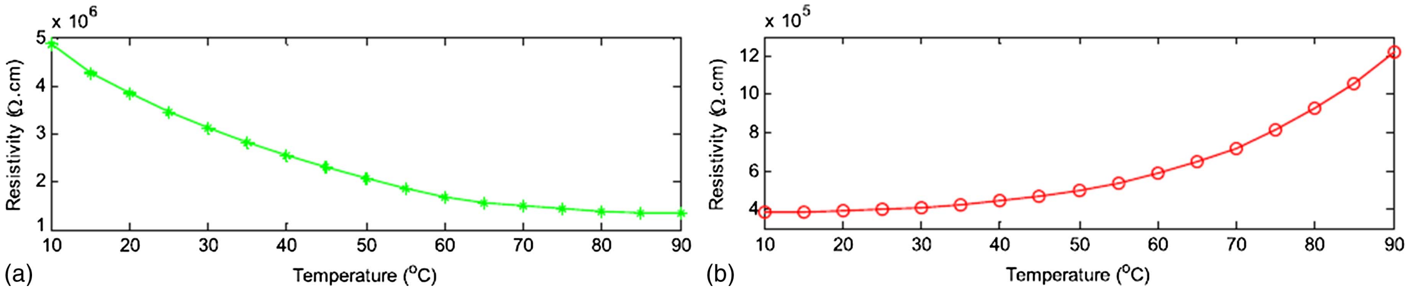


Fig. 4. Variation of resistivity with temperature in (a) carbon nanotube–filled polyurethane foam composite; and (b) carbon black–filled silicone rubber composite. [© 2015 IEEE. Reprinted, with permission, from L. Wang, "Differential structure for temperature sensing based on conductive polymer composites," *IEEE Transactions on Electron Devices* 62 (9): 3025-3028.]

acted as a thermistor (Chung 2002a; Wang and Chung 1998b, 1999) and thermocouple (Chung 2002a; Wang and Chung 1998a).

Crack and Microcrack Sensing

Microcracking, which is one of the major causes of premature failure of composite materials (Awaja et al. 2016; Nairn 2000; Pang and Bond 2005), is difficult to detect due to the limited resolution of visual methods. An alternative method is to use conductive fillers embedded in the matrix to detect the propagation of cracks and microcracks through determination of fibers acting as bridges across cracks (bridging effect) (Awaja et al. 2016). Shindo et al. (2012) investigated the relation between crack formation and the electrical resistance of polymer composites incorporating multiwalled carbon nanotubes (MWCNTs) in tensile loading. The specimen was notched with an initial crack length a_0 equal to 9.3 mm (Fig. 5). During fracture testing, the load was applied at an angle between 0° and 30°. The formed crack propagated straight at the load angle of 0° and inclined at the load angle of 30°. The electrical resistivity increased according to the projected crack length increase, as shown in Fig. 6 (Takeda et al. 2013). MWCNT-based polymer composites were used successfully as a damage sensor by Li et al. (2008a).

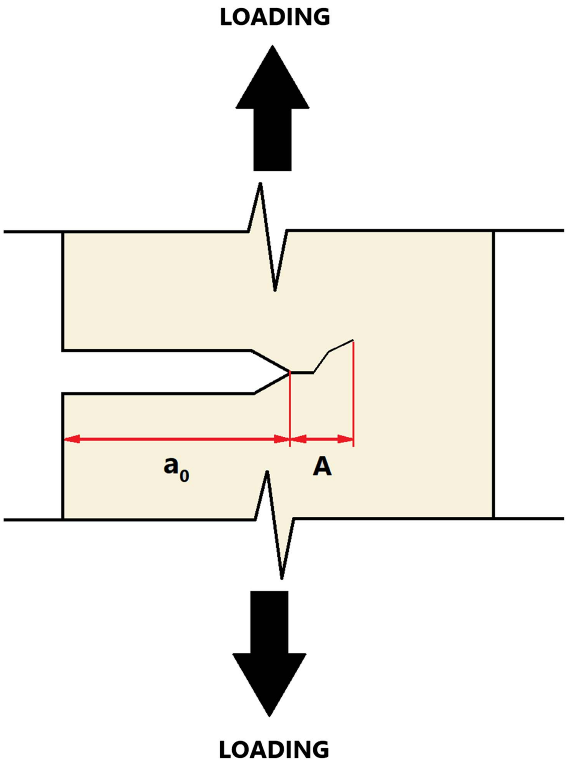


Fig. 5. Fracture mode I test.

Currently Used Systems for Monitoring of Concrete Structures

Nondestructive testing (NDT) is commonly applied to assess the quality of concrete structures. Examples are ultrasonic inspection and Foucault current technique (eddy current technique) used for crack detection. A so-called half-cell potential test is used to assess corrosion of the reinforcement. NDT techniques are often limited to a single-point measurement (Helal et al. 2015). At present, the SHM system has become a well-known method aiming to diagnose the condition of a structure and formulate a prognosis related to various possible environmental conditions. The SHM system consists of various measurement techniques, and each technique has its own application area, advantages and limitations.

A concrete structure can be monitored at any point of its service life. The collected data are crucial for forecasting and risk management with respect to the SHM. The SHM integrates NDT techniques using remote sensing and smart materials to create smart self-monitoring structures. The SHM system consists of sensors and data collection and evaluation systems (Aggelis et al. 2014; Sun et al. 2010). Sensors are chosen based on planned measurements and monitoring strategy. Each type of sensor has different

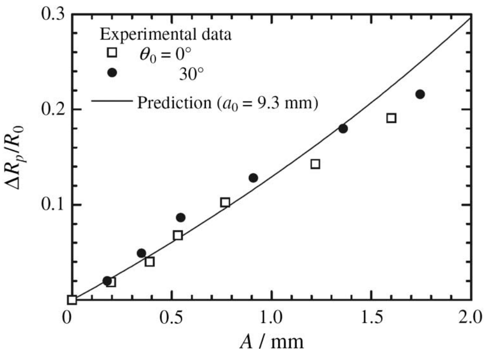


Fig. 6. Variation of resistance change due to crack propagation with projected crack length. (Reprinted from Takeda et al. 2013, with permission from The Japan Institute of Metals and Materials.)

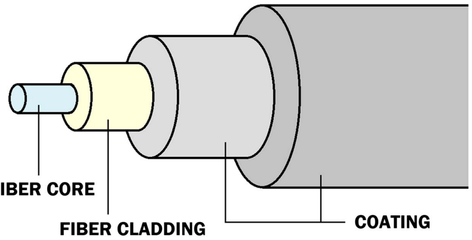


Fig. 7. Schematic diagram of an optical fiber.

sensing capabilities in different applications. Thus the quality of the result obtained from SHM depends on proper design of the system (Lim et al. 2006; Ou and Zhou 2008; Sun et al. 2008; Wan and Leung 2007). The following sections will describe the most commonly used sensors.

Fiber-Optic Sensors

A fiber-optic sensor (FOS) is a fiber-based device that uses fiber optics to transmit light from a superluminescent source. The reflected light shows changes of amplitude, phase, frequency, and polarization state, which are then used to determine changes in temperature and strain (López-Higuera et al. 2011). The fiber optic consists of three parts as shown in Fig. 7. The core and cladding layer are made of a dielectric material. The index of refraction of the cladding material is less than that of the core to reduce the loss of light transmitted in the core. The coating layer protects the fiber optic against physical damage. FOS can be classified based on the light transmitted in the sensing segment, operating principle, and the application (Fidanboylu and Efendioglu 2009). Some examples include Frabry-Perot FOS, Fiber Braff grating (FBG), and Brillouin-scattering-based FOS. FOS can be used in concrete to monitor strain, displacement, vibration, cracking, corrosion, and chloride concentration. In old structures, FOS are mounted on the surface, whereas in new structures, sensors are usually embedded inside the material. Examples of applications are shown in Fig. 8 (Leung et al. 2008). Fig. 9 gives a schematic overview of available types of FOS (Fidanboylu and Efendioglu 2009).

Piezoelectric Sensors

The conversion of mechanical energy into electrical energy and vice versa is the principle utilized in the piezoelectric effect (Fig. 10). When mechanical stress is applied to a piezoelectric material, an electrical current or voltage is produced. Conversely, when an electric current is applied to a piezoelectric material, it will be polarized, causing it to shrink or expand. This phenomenon enables the detection of impacts and deformations (Tzou et al. 2004). Piezoelectric materials include, for example, ceramics, polymers, and composites. Lead zirconate titanate (PZT) is a commonly used piezoelectric material due to its low cost, light weight, high energy

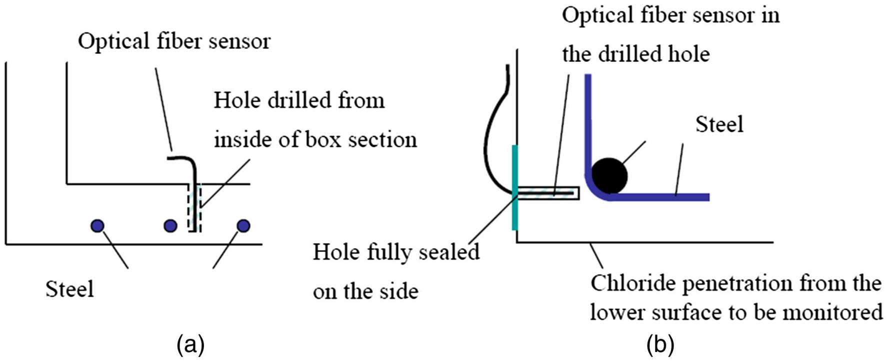


Fig. 8. Possible ways for retrofitting the sensor on an existing structure. [Reprinted from Leung et al. 2008, © MDPI under CC-BY 4.0 (https://creativecommons.org/licenses/by/4.0/).]

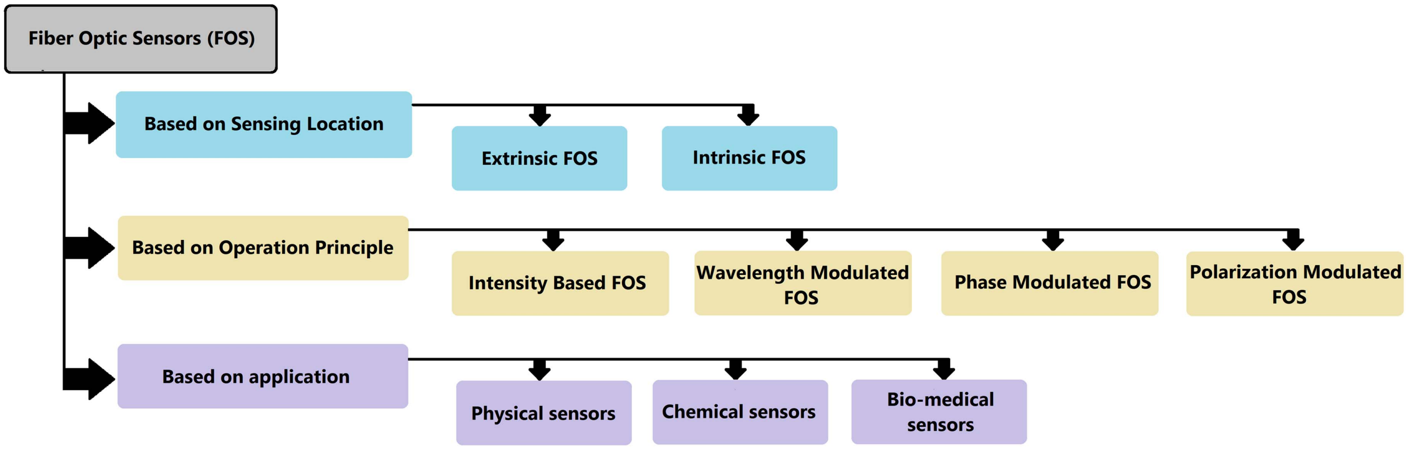


Fig. 9. Fiber optic sensor types.

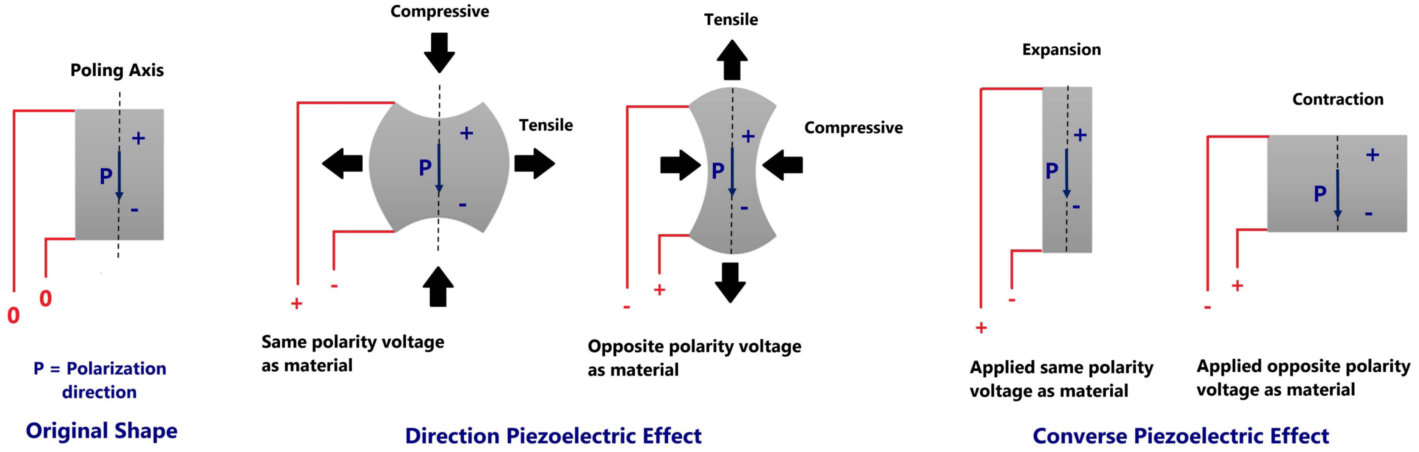


Fig. 10. Piezoelectric effect.

density, and easy implementation. Application of piezoelectric sensors (PS) as actuators and transducers in the SHM is gradually increasing (Chalioris et al. 2016). Embedded PS can also be used as aggregates or fillers (Zhang et al. 2017) to harvest energy from vehicles' movement and for dynamic monitoring of traffic. Such a system is, for example, able to detect and classify passing vehicles (Rana et al. 2016).

Magnetostrictive Sensors

The phenomenon of magnetostriction occurs when ferromagnetic materials, particularly nickel, iron, and cobalt, are able to change their shape or dimensions when placed in a magnetic field. Magnetostrictive materials convert magnetic energy to mechanical energy and vice versa. They are mainly used as transducers for emitting and receiving elastic waves to detect defects, estimate the concrete thickness, and determine the position and distribution of cracks, as well as to monitor acoustic emissions (Ausanio et al. 2005; Calkins et al. 2007; Dong et al. 2011; Hison et al. 2005; Hristoforou and Ktena 2007).

An example usage of magnetostriction is the so-called electromagnetic hammer (EMH). The EMH uses a small magnetostrictive oscillator and receiver consisting of polycrystallized magnetostrictive material (Hattori et al. 2001). The oscillator generates an elastic wave with wide bandwidth at low frequency, which is enhanced by applied additional compressive stress. The oscillator is placed adjacent to the receiver and uses impulse and frequency sweep drive control modes to characterize and evaluate the propagation of cracks in concrete. The system records acoustic reflections at a distance L. Together with the acoustic velocity, v, the delay in propagation, $\Delta t = 2L/v$, and peak frequency, $f = 1/\Delta t$ can be obtained. The presence of defects can be calculated by using $L = v/2 \cdot \Delta t$. The experimental results showed high effectiveness of the system.

Portland Cement–Based Materials Sensing Incorporating Conductive Fibers

Steel Fiber

Steel fibers (SF) are commonly used to reinforce concrete structures. They improve the mechanical properties, particularly flexural and tensile strengths, and limit drying shrinkage cracking. The primary function of SF in the cementitious matrix is to bridge forming cracks.

In addition, electrical conductivity can be enhanced by addition of SF (Shi et al. 2017). A cement paste incorporating 0.36% by volume of steel fibers and showing sensing capabilities was produced by Wen and Chung (2003). SFs having a diameter of 8 μm and length of 6 mm were used and tested in a cement matrix in repeated tensile and compressive stresses. Teomete and Kocyigit (2013) used between 0.20% and 1.50% by volume of 6-mm-long fibers. The results showed an increased electrical resistivity while under tension, which was related to the formation and propagation of microcracks. The change of electrical resistance was possible above the percolation threshold, which was around 1% by volume of steel fibers. The highest recorded GF of the cement-based matrix incorporating the steel fibers was 5,195, which is much higher than the factors achieved with a metal strain gauge (Wen and Chung 2003).

Carbon Black

Yet another alternative to produce matrixes with sensing capabilities is to add conductive powders, such as, for example, carbon black (CB). CB has a high electrical conductivity, nanosize particles with a high specific surface area to volume ratio, and low cost (Wen and Chung 2007). The amorphous CB is highly compressible, which supports the creation of conductive paths throughout the matrix during loading (Leong et al. 2006; Leong and Chung 2004; Wen and Chung 2007). Li et al. (2006, 2008b) fabricated a strain-sensing cement paste incorporating CB and determined that that percolation threshold oscillated at around 12%–20% by weight of the cement. The resistivity decreased linearly with increasing compressive strain until failure occurred (Fig. 11) (Li et al. 2006). Crack formation was visualized by a bump on the otherwise nearly linear correlation. The strain sensitivity of the GF was 55.28 with 15% by weight of carbon black content.

Results obtained by Lin et al. (2011) showed also that cement matrixes incorporating CB are sensitive to strain. The increase of the tensile strain caused an increase of the matrix's electrical resistivity. Interestingly, in the elastic part of the strain-stress curve, the resistivity remained constant. The formation of microcracks, which appeared on the resistivity-strain curve as significant positive or negative variations of the recorded values, were also detectable, as shown in Fig. 12.

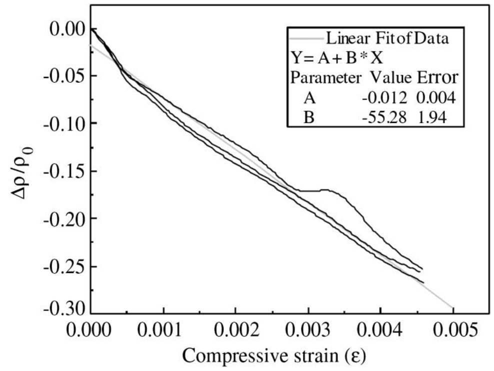


Fig. 11. Variation of fractional resistivity with 15% CB with compressive strain. (Reprinted from *Cement and Concrete Composites*, Vol. 28, H. Li, H.-G. Xiao, and J.-P. Ou, "Effect of compressive strain on electrical resistivity of carbon black-filled cement-based composites," pp. 824–828, © 2006, with permission from Elsevier.)

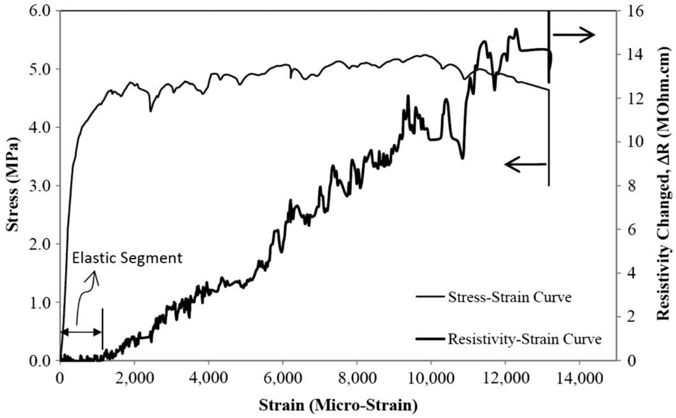


Fig. 12. Variation of resistivity with strain response of elastic and inelastic regime. (Reprinted with permission from V. W. J. Lin, M. Li, J. P. Lyncha, and V. C. Li, "Mechanical and electrical characterization of self-sensing carbon black ECC," *Proc. of SPIE*, Vol. 7983, 2011, © SPIE.)

Carbon Fibers

Carbon fibers (CFs) are formed mostly of carbon atoms and have a diameter in the micrometer range. Studies showed that the addition of CF to portland cement–based mortar enhanced the flexural strength by 85%, flexural toughness by 205%, and compressive strength by 22%. It was also possible to monitor the fatigue damage in cement mortar incorporating 0.5% by weight of CFs (Chen and Chung 1993; Chung and Fu 1996).

The percolation threshold of the CF used in concrete subjected to 2- and 10-MPa loads was about 1% by weight (Shifeng et al. 2007). The electrical resistivity of CFRC was also found to be temperature sensitive with increasing temperature. First, the resistivity decreased due to the increase of the tunneling effect. The electrons move quickly and have more energy to absorb heat energy. After a certain temperature is reached, the unreacted water is fully evaporated, leading to disconnection of some of the conduction paths, which results in an increase of electrical resistivity. The results showed that the CFRC has both negative and positive temperature coefficients (NTC and PTC) (Fig. 13). Materials with a more defined (narrower) peak marking the minimum resistivity, as in the case of composites, can be better used as temperature-sensitive materials.

CFRC showed piezoresistive properties under cyclic loading (Chung 2002b; Wen and Chung 1999, 2003). In the elastic regime, the fractional change in resistance decreased at loading and increased when unloaded. It was found that the irreversible piezoresistivity occurred when the strain was larger than 0.2%. Consequently, the CFRC was not suited for stress-strain sensing under heavy load.

Carbon Nanotubes

Carbon nanotubes (CNTs) have a cylindrical structure consisting of hexagonal graphite sheets rolled in tubes. It is one of the strongest materials in the world (Wong et al. 1997; Yu et al. 2000a, b). One of the first to observe the CNTs was Iijima (1991). CNTs can be classified depending on the applied synthesis conditions, which are single-walled carbon nanotubes (SWCNTs) [Fig. 14(a)] and multiwalled carbon nanotubes (MWCNTs) [Fig. 14(b)]. CNTs are characterized by remarkable physical, mechanical, and electrical properties. They are nanosized, have high strength and Young's modulus, large deformation response, high ductility, high aspect

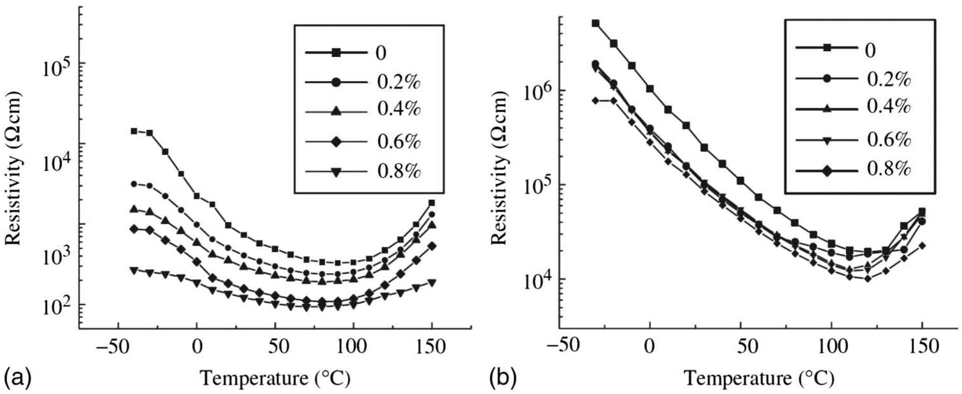
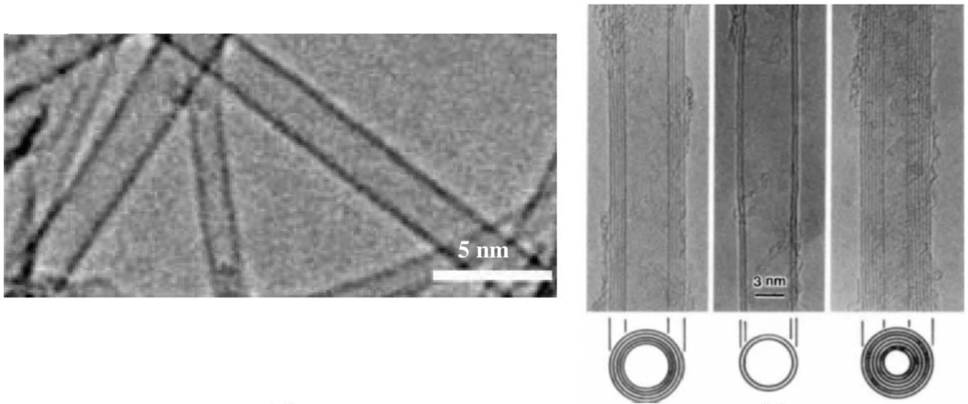


Fig. 13. Variation of resistivity with temperature of CFRC under a load of (a) 2 MPa; and (b) 10 MPa. [H. Shifeng, X. Dongyu, C. Jun, X. Ronghua, L. Lingchao, and C. Xin, "Smart properties of carbon fiber reinforced cement-based composites," *Journal of Composite Materials* 41 (1): 125–131, copyright © 2007 by SAGE, reprinted by permission of SAGE Publications, Ltd.]



(a) (b)

Fig. 14. Transmission electron microscope (TEM) images of (a) SWCNTs [from K. Hata, D. N. Futaba, K. Mizuno, T. Namai, M. Yumura, S. Iijima, “Water-assisted highly efficient synthesis of impurity-free single-walled carbon nanotubes,” *Science* 605 (5700): 1362–1364, © 2004, adapted with permission from AAAS]; and (b) MWCNTs with 5, 2, and 7 layers, respectively (adapted with permission from Springer Nature: Springer, *Nature*, “Helical microtubes of graphitic carbon,” S. Iijima, © 1991).

ratio, and excellent electrical (Bhatia et al. 2010; Guadagno et al. 2011; Thostenson et al. 2009) and thermal (Guthy et al. 2007; Thostenson et al. 2009; Yang et al. 2008) conductivity (Thostenson et al. 2001). Cementitious binders with incorporated CNTs showed enhanced mechanical properties, including compressive and flexural strength, in a number of studies, e.g., those by Cwirzen et al. (2008) and Konsta-Gdoutos et al. (2010). CNTs were also used to prepare advanced cement-based sensors for SHM (Materazzi et al. 2013).

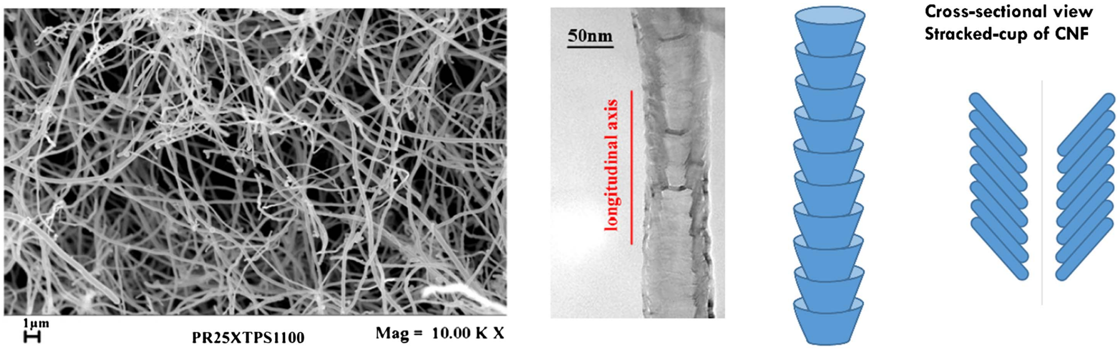
Due to CNTs’ hydrophobic nature and tendency to agglomerate as bundles or ropes, the biggest challenge (Hata et al. 2004) is to ensure their uniform dispersion in the cement matrix. A typical procedure to disperse CNTs in cementitious matrixes is to use a surfactant and intensive sonication to produce a homogeneous water dispersion. The dispersion is then added as a mixing water to the mix.

The sensing properties of the CNT/cement composites are based on changes in electrical resistance. During the last few decades, the possibility of using CNT/cement composites as sensors was studied by a number of researchers. For example, a self-sensing MWCNT/cement composite used to monitor traffic showed a remarkable responsiveness to loads originating from passing vehicles (Han et al. 2009). Nam et al. (2016) showed that the percolation threshold of the MWCNT cement–based matrix was 0.25% by weight. With this amount, the highest electrical resistance change was measured. A vehicle-loading test verified that a sensor based on 0.2% by weight of MWCNT was clearly able to detect the change of load.

Carbon Nanofibers

Carbon nanofibers (CNFs) are built of cylindrical graphene layers arranged in stacks of cones, plates, or cups (Guadagno et al. 2013; Mo and Roberts 2013; Rana et al. 2016) to create a cylindrical nanostructure (Fig. 15). Because of their stacked structure, the CNFs have a larger surface area, and the edges of the fiber can be used to help anchor the fiber in the matrix, meaning better bond characteristics (Mo and Roberts 2013). CNFs have diameters up to 200 nm, and a length between 50 and 200 μm (Yazdani and Mohanam 2014). The addition of CNF to a cement-based matrix not only enhanced the electrical properties, but also the advantages gained in the concrete’s performance, included increased tensile and flexural strengths, tensile ductility, and flexural toughness, and decreased drying shrinkage (Han et al. 2015b).

CNF-reinforced concrete having a sensing capability was reported by Geo et al. (2009). The electrical resistance decreased when the concentration of CNFs increased due to the tunnel



(a) (b) (c)

Fig. 15. (a) Scanning electron microscope (SEM) image of CNFs; (b) TEM image of CNFs; and (c) structure of CNFs. [Adapted (a) and (b) from Guadagno et al. 2013, © IOP Publishing Ltd. under CC BY 3.0 (https://creativecommons.org/licenses/by/3.0/).]

Table 1. Summarized advantages and limitations of cement-based matrix incorporating various types of conductive materials

Conductive material	Size	Percolation threshold	Advantages	Limitations
Steel fiber	Diameter = 8 μm • Length = 6 mm	• 0.27%–0.36% by volume (Wen and Chung 2003)	• SF cement–based matrix is more effective with tensile strain sensing because it has high fiber-fiber contact between each steel fiber under tensile loading (high fractional change in electrical resistivity to fractional strain when applied tensile loading).	• Threshold value will change depending on size, degree of dispersion, and orientation direction of SF. • Less strain and damage sensitivity due to poor fiber-fiber contact when compared with the same amount of other conductive materials.
Carbon black	Average particle = 20–100 nm	• 7.22%–11.39% by volume (Li et al. 2006) • 2.00% by weight of binder (Al-Dahawi et al. 2016)	• Higher specific surface area and aspect ratio of CB enhanced piezoresistive behavior of cement-based matrix at low strain level. • Good dispersion of CB in cementitious matrixes have bridging cracks and pores in nanostructures and microstructures, which leads to high sensing ability.	• Excess CB influence to reduce the rheology of the matrix and cause the mechanical and electrical properties to be decreased. • Performance of sensing capability due to size of CB. • Quality of CB has an effect on level sensing ability of damages (conductive value of fiber itself).
Carbon fibers	Diameter = 8 μm • Length = 3 mm	• 0.20% by volume (Chiarello and Zinno 2005)	• Small size of CFs attributed to interfiber continuity and give better damage sensing.	• Longer fibers reduce the threshold value.
	• Length = 6 mm	• 0.15% by volume (Chiarello and Zinno 2005)	• CFs have strain-sensing ability at low strain level and sensed temperature effects at both positive and negative temperatures.	• Less stress-strain sensing under heavy load. • An amount of CFs below the percolation threshold provides better sensitivity of the piezoresistive response.
	Diameter = 7.5 μm • Length: =6 mm	• 2.00% by volume (Al-Dahawi et al. 2016)		
	• Length =12 mm	• 1.00% by volume (Al-Dahawi et al. 2016)		
Carbon nanofibers	Average diameter = 150 nm	• 1.00% by volume of binder (Gao et al. 2009)	• Nanosized carbon materials enhanced the mechanical properties by the filler effect and have sensing ability for nanoscale and microscale damages. • Good dispersion of CNTs in cementitious matrixes can bridge cracks and pores in nanostuctures and microstructures, which leads to high sensing ability.	• More effective stress-strain sensing for CNF below percolation threshold than above. • High agglomeration and requires uniform distribution of CNFs in matrix for more sensing capability. • Excess amount of CNFs lead to poor dispersion and has a negative effect for damage sensing.
Carbon nanotubes	Diameter = 5–15 nm • Length =< 10 μm	• 0.25% by weight of binder (Nam et al. 2016) • 0.15% by weight of binder (Naeem et al. 2017)	• Higher specific surface area than other carbon nanomaterials. • Higher level of damage sensing. • Good dispersion of CNTs in cementitious matrixes can bridge cracks and pores in nanostructures and microstructures, which leads to high sensing ability.	• Threshold value depends on size, dispersion level, and tunneling level. • High agglomeration and requires uniform distribution of CNTs in matrix for more sensing capability.
	Diameter = 20–30 nm • Length = 10–30 μm	• 0.55% by weight of binder (Al-Dahawi et al. 2016)	• CNT particles with a diameter close to the diameter of C-S-H gel are wrapped by C-S-H gel and improve dramatically the sensing capability by measuring electrical resistivity.	

Note: C-S-H = calcium-silicate-hydrate.

conductivity effect. Otherwise, excess CNFs did not affect the change in resistivity with increased strain. The stress-strain sensing of a CNF cement–based matrix has been shown for CNFs concentrations below the percolation threshold. Piezoresistive behavior of a cementitious matrix with CNF was studied under cyclic compression load in the elastic regime (Konsta-Gdoutos and Aza 2014). The resistivity tended to decrease during loading, when cracks were closing, and to increase during unloading, when cracks were opening. The average change of resistivity for the sample containing 0.1% by weight of CNF was 5.0% and therefore higher than for the sample containing 0.3% by weight of CNF, showing a change in resistivity of 1.5%. The produced mixes showed a strong piezoresistive behavior sufficient for application in strain sensors.

The main problem with matrixes incorporating CNF is to achieve uniform dispersion of the nanofibers. So far, the best dispersion was obtained when using an intensive ultrasonication and surfactants (Yazdanbakhsh et al. 2010). During measurement of the electrical conductivity in moist conditions, polarization takes place due to the electrolytic effect. Chemical reactions occurring at electrodes liberate hydrogen and oxygen, which deposit around the electrodes in the form of a thin film, which eventually results in a polarization effect. To eliminate the polarization effect, specimens should be dry, and a high-frequency alternating current should be used (Banthia et al. 1992).

Hybrid Fibers

Hybrid fiber systems consisting of two or more types of fibers showed promising results. The approach aims to combine the best performances of each fiber type. In the case of a cement-based matrix, the main effort was to use a mix of microscale and nanoscale fibers, leading to enhanced mechanical properties and better electrical conductivity. Numerous studies focused on hybrid fillers to improve the self-sensing capacity and sensing reliability and sensitivity. For example, Ou and Han (2009) showed reproducible piezoresistive cement–based strain sensors in samples exposed to compressive strain by adding a combination of 0.18% by volume of CFs and 15% by volume of CB. It was possible to detect the compressive strain in concrete beams and columns under field conditions.

Several years later, Luo et al. (2010) investigated the sensitivity of a hybrid consisting of 0.5% by weight of short CFs and 0.1% by weight of MWCNTs. Results showed nearly no improvement of stress-strain sensitivity when compared with the piezoresistive effect obtained from a mix containing 0.1% by weight of MWCNTs. The fractional resistivity change was linear and more effective to improve the self-sensing repeatability and variation stability. Hybrids of dissimilar nanomaterials containing 0.1% by weight of both nano-CB and MWCNTs showed more strain sensitivity under cyclic loading in comparison with material containing only MWCNTs.

Another study showed that a mix of 15% by weight of CFs and 1% by weight of MWCNTs significantly increased the electrical conductivity of the cement matrix, enabling it to be used as a sensor (Azhari and Banthia 2012). Under both monotonically and cyclically applied strain, the material provided better signal quality, improved reliability, and increased sensitivity in comparison with composites incorporating only CF. Composites had the greatest strain-sensing property with incorporation of 0.1% by volume of CFs and 0.5% by volume of MWCNTs. The GF reached 160.3; however, the sensing performance was almost the same with cement composites having 1% by volume of MWCNTs (Lee et al. 2017).

Conclusion

The present paper has reviewed the sensing capability of nonconductive matrixes incorporating various types of conductive materials with a focus on portland cement–based matrixes. In most cases, addition of conductive materials decreased the resistivity and enhanced the mechanical properties of the produced composites. One of the major issues related to nanomaterials is their uniform dispersion in a cementitious binder matrix. A summary of observed advantages and limitations for matrixes incorporating various types of conductive materials together with percolation threshold amounts of fibers in some studies, is given in Table 1.

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References

Aggelis, D. G., N. Alver, and H. K. Chai. 2014. “Health monitoring of civil infrastructure and materials.” *Sci. World J.* 2014: 1–2. https://doi.org/10.1155/2014/435238.

Al-Dahawi, A., M. H. Sarwary, O. Öztürk, G. Yildirim, A. Akin, M. Şahmaran, and M. Lachemi. 2016. “Electrical percolation threshold of cementitious composites possessing self-sensing functionality incorporating different carbon-based materials.” *Smart Mater. Struct.* 25 (10): 105005. https://doi.org/10.1088/0964-1726/25/10/105005.

Ausanio, G., A. C. Barone, C. Hison, V. Iannotti, G. Mannara, and L. Lanotte. 2005. “Magnetoelastic sensor application in civil buildings monitoring.” *Sens. Actuators, A* 123–124 (Sep): 290–295. https://doi.org/10.1016/j.sna.2005.03.027.

Awaja, F., S. Zhang, M. Tripathi, A. Nikiforov, and N. Pugno. 2016. “Cracks, microcracks and fracture in polymer structures: Formation, detection, autonomic repair.” *Prog. Mater. Sci.* 83 (Oct): 536–573. https://doi.org/10.1016/j.pmatsci.2016.07.007.

Azhari, F., and N. Banthia. 2012. “Cement-based sensors with carbon fibers and carbon nanotubes for piezoresistive sensing.” *Cem. Concr. Compos.* 34 (7): 866–873. https://doi.org/10.1016/j.cemconcomp.2012.04.007.

Baeza, F. J., D. D. L. Chung, E. Zornoza, L. G. Andión, and P. Garcés. 2010. “Triple percolation in concrete reinforced with carbon fiber.” *ACI Mater. J.* 107 (4): 396–402. https://www.doi.org/10.14359/51663866.

Bajare, D., G. Bumanis, G. Sahmenko, and J. Justs. 2012. “High performance and conventional concrete properties affected by ashes obtained from different type of grasses.” In *Proc., 12th Int. Conf. on Recent Advances in Concrete Technology and Sustainability Issues*. New York: Curran Associates.

Banthia, N., S. Djeridane, and M. Pigeon. 1992. “Electrical resistivity of carbon and steel micro-fiber reinforced cements.” *Cem. Concr. Res.* 22 (5): 804–814. https://doi.org/10.1016/0008-8846(92)90104-4.

Bhatia, R., V. Prasad, and R. Menon. 2010. “Characterization, electrical percolation and magnetization studies of polystyrene/multiwall carbon nanotube composite films.” *Mater. Sci. Eng. B: Solid-State Mater. Adv. Technol.* 175 (3): 189–194. https://doi.org/10.1016/j.mseb.2010.07.025.

Boyd, A. J., and J. Skalny. 2007. “Environmental deterioration of concrete.” In *Environmental deterioration of materials*, 143–184. Southampton, UK: WIT Press.

Cabrera, J. G. 1996. “Deterioration of concrete due to reinforcement steel corrosion.” *Cem. Concr. Compos.* 18 (1): 47–59. https://doi.org/10.1016/0958-9465(95)00043-7.

Calkins, F. T., A. B. Flatau, and M. J. Dapino. 2007. “Overview of magnetostrictive sensor technology.” *J. Intell. Mater. Syst. Struct.* 18 (10): 1057–1066. https://doi.org/10.1177/1045389X06072358.

Chalioris, C. E., C. G. Karayannis, G. M. Angeli, N. A. Papadopoulos, M. J. Favvata, and C. P. Providakis. 2016. "Applications of smart piezoelectric materials in a wireless admittance monitoring system (WiAMS) to structures-tests in RC elements." *Case Stud. Constr. Mater.* 5 (Dec): 1–18. https://doi.org/10.1016/j.cscm.2016.03.003.

Chang, P. C., A. Flatau, and S. C. Liu. 2003. "Review paper: Health monitoring of civil infrastructure." *Struct. Health Monit.: Int. J.* 2 (3): 257–267. https://doi.org/10.1177/1475921703036169.

Chen, P. W., and D. D. L. Chung. 1993. "Concrete reinforced with up to 0.2 vol% of short carbon fibres." *Composites* 24 (1): 33–52. https://doi.org/10.1016/0010-4361(93)90261-6.

Chen, P. W., and D. D. L. Chung. 1995. "Improving the electrical conductivity of composites comprised of short conducting fibers in a nonconducting matrix: The addition of a nonconducting particulate filler." *J. Electron. Mater.* 24 (1): 47–51. https://doi.org/10.1007/BF02659726.

Chi, J. M., R. Huang, and C. C. Yang. 2002. "Effects of carbonation on mechanical properties and durability of concrete using accelerated testing method." *J. Mar. Sci. Technol.* 10 (1): 14–20.

Chiarello, M., and R. Zinno. 2005. "Electrical conductivity of self-monitoring CFRC." *Cem. Concr. Compos.* 27 (4): 463–469. https://doi.org/10.1016/j.cemconcomp.2004.09.001.

Chung, D. D. L. 1998. "Self-monitoring structural materials." *Mater. Sci. Eng. R: Rep.* 22 (2): 57–78. https://doi.org/10.1016/S0927-796X(97)00021-1.

Chung, D. D. L. 2002a. "Composites get smart." *Mater. Today* 5 (1): 30–35. https://doi.org/10.1016/S1369-7021(02)05140-4.

Chung, D. D. L. 2002b. "Piezoresistive cement-based materials for strain sensing." *J. Intell. Mater. Syst. Struct.* 13 (9): 599–609. https://doi.org/10.1106/104538902031861.

Chung, D. D. L., and X. Fu. 1996. "Self monitoring of fatigue damage in carbon fiber reinforced cement." *Cem. Concr. Res.* 26 (1): 15–20. https://doi.org/10.1016/0008-8846(95)00184-0.

Cwirzen, A., K. Habermehl-Cwirzen, and V. Penttala. 2008. "Surface decoration of carbon nanotubes and mechanical properties of cement/carbon nanotube composites." *Adv. Cem. Res.* 20 (2): 65–73. https://doi.org/10.1680/adcr.2008.20.2.65.

Darwin, D., J. A. Browning, L. Gong, and S. R. Hughes. 2008. "Effects of deicers on concrete deterioration." *ACI Mater. J.* 105 (6): 622–627.

Dong, X., J. Ou, and X. Guan. 2011. "Applications of magnetostrictive materials in civil structures: A review." In *Proc., 6th Int. Workshop on Advanced Smart Materials and Smart Structures Technology.* Champaign, IL: Univ. of Illinois at Urbana–Champaign.

Fidanboylu, K., and H. S. Efendioglu. 2009. "Fiber optic sensors and their applications." In *Proc., 5th Int. Advanced Technologies Symp.*, 1–6. Karabük, Turkey: Karabük Univ.

Gao, D., M. Sturm, and Y. L. Mo. 2009. "Electrical resistance of carbon-nanofiber concrete." *Smart Mater. Struct.* 18 (9): 095039. https://doi.org/10.1088/0964-1726/18/9/095039.

Georgousis, G., et al. 2015. "Strain sensing in polymer/carbon nanotube composites by electrical resistance measurement." *Composites Part B* 68 (Jan): 162–169. https://doi.org/10.1016/j.compositesb.2014.08.027.

Guadagno, L., B. De Vivo, A. Di Bartolomeo, P. Lamberti, A. Sorrentino, V. Tucci, L. Vertuccio, and V. Vittoria. 2011. "Effect of functionalization on the thermo-mechanical and electrical behavior of multi-wall carbon nanotube/epoxy composites." *Carbon* 49 (6): 1919–1930. https://doi.org/10.1016/j.carbon.2011.01.017.

Guadagno, L., M. Raimondo, V. Vittoria, L. Vertuccio, K. Lafdi, B. De Vivo, P. Lamberti, G. Spinelli, and V. Tucci. 2013. "The role of carbon nanofiber defects on the electrical and mechanical properties of CNF-based resins." *Nanotechnology* 24 (30): 305704. https://doi.org/10.1088/0957-4484/24/30/305704.

Guthy, C., F. Du, S. Brand, K. I. Winey, and J. E. Fischer. 2007. "Thermal conductivity of single-walled carbon nanotube/PMMA nanocomposites." *J. Heat Transfer* 129 (8): 1096–1099. https://doi.org/10.1115/1.2737484.

Han, B., S. Ding, and X. Yu. 2015a. "Intrinsic self-sensing concrete and structures: A review." *Measurement* 59 (Jan): 110–128. https://doi.org/10.1016/j.measurement.2014.09.048.

Han, B., S. Sun, S. Ding, L. Zhang, X. Yu, and J. Ou. 2015b. "Review of nanocarbon-engineered multifunctional cementitious composites." *Composites Part A* 70 (Mar): 69–81. https://doi.org/10.1016/j.compositesa.2014.12.002.

Han, B., X. Yu, and E. Kwon. 2009. "A self-sensing carbon nanotube/cement composite for traffic monitoring." *Nanotechnology* 20 (44): 445501. https://doi.org/10.1088/0957-4484/20/44/445501.

Hata, K., D. N. Futaba, K. Mizuno, T. Namai, M. Yumura, and S. Iijima. 2004. "Water-assisted highly efficient synthesis of impurity-free single-walled carbon nanotubes." *Science* 306 (5700): 1362–1364. https://doi.org/10.1126/science.1104962.

Hattori, S., T. Shimada, and K. Matsuhashib. 2001. "Highly accurate low frequency elastic wave measurement using magnetostrictive devices." *NDT E Int.* 34 (6): 373–379. https://doi.org/10.1016/S0963-8695(01)00003-2.

Helal, J., M. Sofi, and P. Mendis. 2015. "Non-destructive testing of concrete: A review of methods." *Electron. J. Struct. Eng.* 14 (1): 97–105.

Hison, C., G. Ausanio, A. C. Barone, V. Iannotti, E. Pepe, and L. Lanotte. 2005. "Magnetoelastic sensor for real-time monitoring of elastic deformation and fracture alarm." *Sens. Actuators, A* 125 (1): 10–14. https://doi.org/10.1016/j.sna.2005.05.019.

Housner, G. W., L. A. Bergman, T. K. Caughey, A. G. Chassiakos, R. O. Claus, S. F. Masri, R. E. Skelton, T. T. Soong, B. F. Spencer, and J. T. P. Yao. 1997. "Structural control: Past, present, and future." *J. Eng. Mech.* 123 (9): 897–971. https://doi.org/10.1061/(ASCE)0733-9399(1997)123:9(897).

Hristoforou, E., and A. Ktena. 2007. "Magnetostriction and magnetostrictive materials for sensing applications." *J. Magn. Magn. Mater.* 316 (2): 372–378. https://doi.org/10.1016/j.jmmm.2007.03.025.

Iijima, S. 1991. "Helical microtubes of graphitic carbon." *Nature* 354 (6348): 56–58. https://doi.org/10.1038/354056a0.

Konsta-Gdoutos, M. S., and C. A. Aza. 2014. "Self sensing carbon nanotube (CNT) and nanofiber (CNF) cementitious composites for real time damage assessment in smart structures." *Cem. Concr. Compos.* 53 (Oct): 162–169. https://doi.org/10.1016/j.cemconcomp.2014.07.003.

Konsta-Gdoutos, M. S., Z. S. Metaxa, and S. P. Shah. 2010. "Highly dispersed carbon nanotube reinforced cement based materials." *Cem. Concr. Res.* 40 (7): 1052–1059. https://doi.org/10.1016/j.cemconres.2010.02.015.

Kuronuma, Y., T. Takeda, Y. Shindo, F. Narita, and Z. Wei. 2012. "Electrical resistance-based strain sensing in carbon nanotube/polymer composites under tension: Analytical modeling and experiments." *Compos. Sci. Technol.* 72 (14): 1678–1682. https://doi.org/10.1016/j.compscitech.2012.07.001.

Leal-Junior, A., A. Frizera-Neto, C. Marques, and M. Pontes. 2018. "A polymer optical fiber temperature sensor based on material features." *Sensors* 18 (2): 301. https://doi.org/10.3390/s18010301.

Lee, S. J., I. You, G. Zi, and D. Y. Yoo. 2017. "Experimental investigation of the piezoresistive properties of cement composites with hybrid carbon fibers and nanotubes." *Sensors* 17 (11): 2516. https://doi.org/10.3390/s17112516.

Leong, C. K., Y. Aoyagi, and D. D. L. Chung. 2006. "Carbon black pastes as coatings for improving thermal gap-filling materials." *Carbon* 44 (3): 435–440. https://doi.org/10.1016/j.carbon.2005.09.002.

Leong, C. K., and D. D. L. Chung. 2004. "Carbon black dispersions and carbon-silver combinations as thermal pastes that surpass commercial silver and ceramic pastes in providing high thermal contact conductance." *Carbon* 42 (11): 2323–2327. https://doi.org/10.1016/j.carbon.2004.05.013.

Leung, C. K. Y., K. T. Wan, and L. Chen. 2008. "A novel optical fiber sensor for steel corrosion in concrete structures." *Sensors* 8 (3): 1960–1976. https://doi.org/10.3390/s8031960.

Li, C., E. T. Thostenson, and T. W. Chou. 2008a. "Sensors and actuators based on carbon nanotubes and their composites: A review." *Compos. Sci. Technol.* 68 (6): 1227–1249. https://doi.org/10.1016/j.compscitech.2008.01.006.

Li, H., H. Xiao, and J. Ou. 2006. "Effect of compressive strain on electrical resistivity of carbon black-filled cement-based composites." *Cem. Concr. Compos.* 28 (9): 824–828. https://doi.org/10.1016/j.cemconcomp.2006.05.004.

Li, H., H. Xiao, and J. Ou. 2008b. "Electrical property of cement-based composites filled with carbon black under long-term wet and loading condition." *Compos. Sci. Technol.* 68 (9): 2114–2119. https://doi.org/10.1016/j.compscitech.2008.03.007.

Lim, Y. Y., S. Bhalla, and C. K. Soh. 2006. "Structural identification and damage diagnosis using self-sensing piezo-impedance transducers." *Smart Mater. Struct.* 15 (4): 987–995. https://doi.org/10.1088/0964-1726/15/4/012.

Lin, V. W. J., M. Li, J. P. Lynch, and V. C. Li. 2011. "Mechanical and electrical characterization of self-sensing carbon black ECC." In *Proc., Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security*, 798316. Washington, DC: SPIE.

López-Higuera, J. M., L. R. Cobo, A. Q. Incera, and A. Cobo. 2011. "Fiber optic sensors in structural health monitoring." *J. Lightwave Technol.* 29 (4): 587–608. https://doi.org/10.1109/JLT.2011.2106479.

Luo, J. L., Z. D. Duan, T. J. Zhao, and Q. Y. Li. 2010. "Hybrid effect of carbon fiber on piezoresistivity of carbon nanotube cement-based composite." *Adv. Mater. Res.* 143–144: 639–643. https://doi.org/10.4028/www.scientific.net/AMR.143-144.639.

Materazzi, A. L., F. Ubertini, and A. D'Alessandro. 2013. "Carbon nanotube cement-based sensors for dynamic monitoring of concrete structures." In *Proc., FIB Symp.*, 22–24. Lausanne, Switzerland: Fédération Internationale du Béton International Federation for Structural Concrete.

Mo, Y. L., and R. H. Roberts. 2013. "Carbon nanofiber concrete for damage detection of infrastructure." In *Advances in nanofibers*, 125–143. Rijeka, Croatia: INTECH.

Monteiro, A. O., P. B. Cachim, P. M. F. J. Costa, and M. Oeser. 2017. "Sensitive smart concrete loaded with carbon black nanoparticles for traffic monitoring sensitive smart concrete loaded with carbon black." In *Proc., 4th Int. Conf. on Smart Monitoring, Assessment and Rehabilitation of Civil Structures*. Zurich, Switzerland: RWTH Publications.

Moraleda, A., C. García, J. Zaballa, and J. Arrue. 2013. "A temperature sensor based on a polymer optical fiber macro-bend." *Sensors* 13 (10): 13076–13089. https://doi.org/10.3390/s131013076.

Naeem, F., H. K. Lee, H. K. Kim, and I. W. Nam. 2017. "Flexural stress and crack sensing capabilities of MWNT/cement composites." *Compos. Struct.* 175 (Sep): 86–100. https://doi.org/10.1016/j.compstruct.2017.04.078.

Nairn, J. A. 2000. "Matrix microcracking in composites." *Polym. Matrix Compos.* 2: 403–432. https://doi.org/10.1016/B0-08-042993-9/00069-3.

Nam, I. W., H. Souri, and H. K. Lee. 2016. "Percolation threshold and piezoresistive response of multi-wall carbon nanotube/cement composites." *Smart Struct. Syst.* 18 (2): 217–231. https://doi.org/10.12989/sss.2016.18.2.217.

Ou, J., and B. Han. 2008. "Piezoresistive cement-based strain sensors and self-sensing concrete components." *J. Intell. Mater. Syst. Struct.* 20 (3): 329–336. https://doi.org/10.1177/1045389X08094190.

Ou, J., and Z. Zhou. 2008. "Applications of optical fiber sensors of SHM in infrastructures." In *Proc., Smart Sensor Phenomena, Technology, Networks, and Systems*, 693311. Washington, DC: SPIE.

Pang, J. W. C., and I. P. Bond. 2005. "A hollow fibre reinforced polymer composite encompassing self-healing and enhanced damage visibility." *Compos. Sci. Technol.* 65 (11–12): 1791–1799. https://doi.org/10.1016/j.compscitech.2005.03.008.

Rana, S., P. Subramani, R. Fangueiro, and A. G. Correia. 2016. "A review on smart self-sensing composite materials for civil engineering applications." *AIMS Mater. Sci.* 3 (2): 357–379. https://doi.org/10.3934/matersci.2016.2.357.

Shi, L., Y. Lu, and Y. Bai. 2017. "Mechanical and electrical characterisation of steel fiber and carbon black engineered cementitious composites." *Procedia Eng.* 188: 325–332. https://doi.org/10.1016/j.proeng.2017.04.491.

Shifeng, H., X. Dongyu, C. Jun, X. Ronghua, L. Lingchao, and C. Xin. 2007. "Smart properties of carbon fiber reinforced cement-based composites." *J. Compos. Mater.* 41 (1): 125–131. https://doi.org/10.1177/0021998306063378.

Shindo, Y., Y. Kuronuma, T. Takeda, F. Narita, and S. Y. Fu. 2012. "Electrical resistance change and crack behavior in carbon nanotube/polymer composites under tensile loading." *Composites Part B* 43 (1): 39–43. https://doi.org/10.1016/j.compositesb.2011.04.028.

Sun, M., W. J. Staszewski, and R. N. Swamy. 2010. "Smart sensing technologies for structural health monitoring of civil engineering structures." *Adv. Civ. Eng.* 2010: 13. https://doi.org/10.1155/2010/724962.

Sun, M., W. J. Staszewski, R. N. Swamy, and Z. Li. 2008. "Application of low-profile piezoceramic transducers for health monitoring of concrete structures." *NDT E Int.* 41 (8): 589–595. https://doi.org/10.1016/j.ndteint.2008.06.007.

Takeda, T., Y. Shindo, F. Naraoka, Y. Kuronuma, and F. Narita. 2013. "Crack and electrical resistance behaviors of carbon nanotube-based polymer composites under mixed-mode I/II loading." *Mater. Trans.* 54 (7): 1105–1109. https://doi.org/10.2320/matertrans.M2013080.

Tapetado, A., P. J. Pinzón, J. Zubia, and C. Vázquez. 2015. "Polymer optical fiber temperature sensor with dual-wavelength compensation of power fluctuations." *J. Lightwave Technol.* 33 (13): 2716–2723. https://doi.org/10.1109/JLT.2015.2408368.

Teomete, E., and O. I. Kocyigit. 2013. "Tensile strain sensitivity of steel fiber reinforced cement matrix composites tested by split tensile test." *Constr. Build. Mater.* 47 (Oct): 962–968. https://doi.org/10.1016/j.conbuildmat.2013.05.095.

Thostenson, E. T., Z. Ren, and T.-W. Chou. 2001. "Advances in the science and technology of carbon nanotubes and their composites: A review." *Compos. Sci. Technol.* 61 (13): 1899–1912. https://doi.org/10.1016/S0266-3538(01)00094-X.

Thostenson, E. T., S. Ziaee, and T. W. Chou. 2009. "Processing and electrical properties of carbon nanotube/vinyl ester nanocomposites." *Compos. Sci. Technol.* 69 (6): 801–804. https://doi.org/10.1016/j.compscitech.2008.06.023.

Tzou, H. S., H. J. Lee, and S. M. Arnold. 2004. "Smart materials, precision sensors/actuators, smart structures, and structronic systems." *Mech. Adv. Mater. Struct.* 11 (4–5): 367–393. https://doi.org/10.1080/15376490490451552.

Wan, K. T., and C. K. Y. Leung. 2007. "Applications of a distributed fiber optic crack sensor for concrete structures." *Sens. Actuators, A* 135 (2): 458–464. https://doi.org/10.1016/j.sna.2006.09.004.

Wang, L. 2015. "Differential structure for temperature sensing based on conductive polymer composites." *IEEE Trans. Electron Dev.* 62 (9): 3025–3028. https://doi.org/10.1109/TED.2015.2438075.

Wang, S., and D. D. L. Chung. 1998a. "Carbon fiber polymer-matrix composite interfaces as thermocouple junctions." *Compos. Interfaces* 6 (6): 519–529. https://doi.org/10.1163/156855499X00198.

Wang, S., and D. D. L. Chung. 1998b. "Interlaminar interface in carbon fiber polymer-matrix composites, studied by contact electrical resistivity measurement." *Compos. Interfaces* 6 (6): 497–505. https://doi.org/10.1163/156855499X00170.

Wang, S., and D. D. L. Chung. 1999. "Temperature/light sensing using carbon fiber polymer-matrix composite." *Composites Part B* 30 (6): 591–601. https://doi.org/10.1016/S1359-8368(99)00020-7.

Wang, S., and D. D. L. Chung. 2000. "Electrical behavior of carbon fiber polymer-matrix composites in the through-thickness direction." *J. Mater. Sci.* 35 (1): 91–100. https://doi.org/10.1023/A:1004744600284.

Wang, W., H. Dai, and S. Wu. 2008. "Mechanical behavior and electrical property of CFRC-strengthened RC beams under fatigue and monotonic loading." *Mater. Sci. Eng. A* 479 (1–2): 191–196. https://doi.org/10.1016/j.msea.2007.06.046.

Wang, W., S. Wu, and H. Dai. 2006. "Fatigue behavior and life prediction of carbon fiber reinforced concrete under cyclic flexural loading." *Mater. Sci. Eng. A* 434 (1–2): 347–351. https://doi.org/10.1016/j.msea.2006.07.080.

Wang, X., S. Wang, and D. D. L. Chung. 1999. "Sensing damage in carbon fiber and its polymer-matrix and carbon-matrix composites by electrical resistance measurement." *J. Mater. Sci.* 34 (11): 2703–2713. https://doi.org/10.1023/A:1004629505992.

Wen, S., and D. D. L. Chung. 1999. "Piezoresistivity in continuous carbon fiber cement-matrix composite." *Cem. Concr. Res.* 29 (3): 445–449. https://doi.org/10.1016/S0008-8846(98)00211-7.

Wen, S., and D. D. L. Chung. 2003. "A comparative study of steel- and carbon-fibre cement as piezoresistive strain sensors." *Adv. Cem. Res.* 15 (3): 119–128. https://doi.org/10.1680/adcr.2003.15.3.119.

Wen, S., and D. D. L. Chung. 2007. "Partial replacement of carbon fiber by carbon black in multifunctional cement-matrix composites." *Carbon* 45 (3): 505–513. https://doi.org/10.1016/j.carbon.2006.10.024.

Wong, E. W., P. E. Sheehan, and C. M. Lieber. 1997. "Nanobeam mechanics: Elasticity, strength, and toughness of nanorods and nanotubes." *Science* 277 (5334): 1971–1975. https://doi.org/10.1126/science.277.5334.1971.

Yang, Y., M. C. Gupta, J. N. Zalameda, and W. P. Winfree. 2008. "Dispersion behaviour, thermal and electrical conductivities of carbon nanotube-polystyrene nanocomposites." *Micro Nano Lett.* 3 (2): 35–40. https://doi.org/10.1049/mnl:20070073.

Yazdanbakhsh, A., Z. Grasley, B. Tyson, and R. K. A. Al-Rub. 2010. "Distribution of carbon nanofibers and nanotubes in cementitious composites." *Transp. Res. Rec.* 2142 (1): 89–95. https://doi.org/10.3141/2142-13.

Yazdani, N., and V. Mohanam. 2014. "Carbon nano-tube and nano-fiber in cement mortar: Effect of dosage rate and water-cement ratio." *Int. J. Mater. Sci.* 4 (2): 45. https://doi.org/10.14355/ijmsci.2014.0402.01.

Ye, X. W., Y. H. Su, and J. P. Han. 2014. "Structural health monitoring of civil infrastructure using optical fiber sensing technology: A comprehensive review." *Sci. World J.* 2014: 11. https://doi.org/10.1155/2014/652329.

Yu, M. F., B. S. Files, S. Arepalli, and R. S. Ruoff. 2000a. "Tensile loading of ropes of single wall carbon nanotubes and their mechanical properties." *Phys. Rev. Lett.* 84 (24): 5552–5555. https://doi.org/10.1103/PhysRevLett.84.5552.

Yu, M.-F., O. Lourie, M. J. Dyer, K. Moloni, T. F. Kelly, and R. S. Rouff. 2000b. "Strength and breaking mechanism of multiwalled carbon nanotubes under tensile load." *Science* 287 (5453): 637–640. https://doi.org/10.1126/science.287.5453.637.

Zeng, X., X. Xu, P. M. Shenai, E. Kovalev, C. Baudot, N. Mathews, and Y. Zhao. 2011. "Characteristics of the electrical percolation in carbon nanotubes/polymer nanocomposites." *J. Phys. Chem. C* 115 (44): 21685–21690. https://doi.org/10.1021/jp207388n.

Zhang, X., S. Song, and M. J. Yao. 2017. "Fabrication of embedded piezoelectric sensors and its application in traffic engineering." In *Proc., 2nd IEEE Int. Conf. on Intelligent Transportation Engineering*, 259–265. New York: IEEE.

Zhao, R., G. Shao, Y. Cao, L. An, and C. Xu. 2014. "Temperature sensor made of polymer-derived ceramics for high-temperature applications." *Sens. Actuators, A* 219 (Nov): 58–64. https://doi.org/10.1016/j.sna.2014.08.012.