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Self-sensing cement-based sensors for structural health monitoring toward smart infrastructure

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Abstract

Since its first appearance more than 100 years ago, concrete has had a significant impact on urban development — buildings, roads, bridges, ports, tunnels, railways and other structures. While traditional concrete is a structural material without any function, a new branch of concrete technology has produced smart (or intelligent) concrete, with superior self-sensing capabilities that can detect stress, strain, cracks and damage, and monitor temperature and humidity. With the incorporation of functional conductive fillers, traditional concrete can exhibit electrical conductivity with intrinsic piezoresistivity. This piezoresistivity means that the electrical resistivity of concrete is synchronously altered under applied load or environmental factors. The self-sensing electrical resistivity thus obtained can be an index or parameter to detect stress or strain changes in concrete, or cracks and damage to concrete. On the other hand, because of the relationship between electrical resistivity, temperature and humidity, self-sensing concrete can also monitor environmental factors. This smart self-sensing concrete can therefore be a promising alternative to conventional sensors for monitoring structural health and detecting traffic information from concrete roads, all of which are critical to achieving smart automation in concrete infrastructures.

Introduction

In addition to their mechanical strength and durability, the question is asked as to why a concrete structure needs intrinsic functionalities, such as damage and crack sensing capacity as well as temperature and humidity monitoring ability. When we think of the heartbreaking news reports of terrorist attacks, accidental explosions, bushfires and earthquake disasters happening in the world, we remember the images of people injured or killed by the unexpected collapse of the structures around them, because they were not warned in advance to escape from these dangerous buildings (Kaewunruen, 2008; Nurse, 1956). However, in smart self-sensing concrete buildings with damage/crack detection and temperature and humidity monitoring properties, people inside those structures can be alerted in a timely manner when the structures become unstable and unsafe (Chung, 2012; Dong, 2019a). In addition, and based on the structural health monitoring (SHM) messages given out by self-sensing concrete structures, construction agencies can make their own decisions on whether to demolish or repair the damaged infrastructure.

Traditional concrete contains water, cement, and fine and coarse aggregate. Self-sensing concrete has one addition of functionally conductive filler (Warren, 1901; Ou, 2009). The purpose of functional conductive fillers, bearing in mind that they do not significantly weaken the strength and durability of concrete, is to improve the volumetric conductivity of concrete, which is normally considered as an electrically isolated material. Basically, some carbon and metal materials as conductive fillers provide concrete not only with enhanced electrical conductivity but also with improved strength and durability. Carbon nanotube (CNT) and nanocarbon black (CB) are two particularly popular conductive fillers for self-sensing abilities to detect damages/cracks and monitor humidity and temperature in concrete (Dong, 2020b). Compared to traditional concretes, the mechanical and durability performance of smart self-sensing concrete is also improved due to the fibrous bridging effect of CNT and CB (Materazzi, 2013; Howser, 2011).

How can an increase in electrical conductivity in concrete introduce the function of detecting and monitoring damage or cracks? In the case of a commercially available foil strain gauge, for example, the deformation of the strain gauge can transfer to the electrical resistivity changes in the sensitive alloys fixed to the plate. Similarly, deformations or strain can be displayed by the electrical resistivity changes of self-sensing concrete, which incorporates conductive fillers. Once the relationship of the electrical resistivity to damage, stress, strain, temperature and humidity is determined in the calibration process, the self-sensing concrete becomes a cement-based sensor that can be embedded in infrastructures for structural health monitoring or traffic flow information detection.

The data acquisition system of self-sensing concrete is similar to that of a conventional strain gauge. To obtain electrical resistivity changes, a multimeter and power supply should be provided. In addition, two or four electrodes are attached to the concrete, based on either the two-point or four-point method. Two alternatives of electrode configuration, namely either embedded or surface electrodes, can then be selected (Li, 2020). Electrical signals can be collected automatically to analyse their changes and determine the type and magnitude of the forces to which the concrete is under. An amplifier might be used to magnify the electrical resistivity changes. Thus, structural health monitoring using self-sensing concrete with cement-based sensors can detect load capacity and the specific degree and type of external force on a structure.

Production of cement-based sensors

Raw material

For the mix design of self-sensing concrete, carbon or metal materials, such as CNTs or nano CB, are usually used as conductive fillers. In addition, the application of conductive rubber products with cementitious materials shows satisfactory conductivity and piezoresistivity (Dong, 2020). When carbon materials are selected (due to their nanoscale sizes and high surface energy), special treatments should be carried out to ensure good uniform dispersions.

Treatment of conductive filler

Is the manufacture of smart self-sensing concrete as simple as manufacturing traditional concrete? As is well known, after preparing raw materials, traditional concrete production consists of the main procedures of mixing, casting and curing. The manufacture of self-sensing concrete requires only one extra procedure, namely the dispersion of conductive fillers for the mixture. Given the very small size of the conductive fillers used, they may agglomerate and further influence the mechanical property of self-sensing concrete. Conductive fillers are therefore treated before mixing to reduce the number and size of agglomerations. As a result, the dispersion process is adopted to separate the conductive fillers to ensure they can connect to each other and form conductive networks in the cement matrix (Konsta-Gdoutos, 2010; Ma, 2010).

Ultrasonic treatment of solutions with conductive fillers is critical to separate agglomerated carbon nanomaterial. However, it should be noted that both sonication time and intensity also affect the dispersion efficiency of carbon nanomaterials. Prolonged sonication may increase the temperature of the solution which then causes the re-agglomeration of carbon nanomaterials. Moreover, especially for fibrous carbon materials such as CNTs and carbon nanofibers, long-term sonication at high intensity might damage the fibrous structures of conductive fillers. Another treatment to disperse carbon nanomaterials is chemical dispersant and surfactant. This method coats the surface of carbon materials to reduce the mutual attraction among nanoparticles.

Manufacturing procedure

Once a uniformly dispersed solution with conductive fillers had been prepared, the mixing procedures and specimen casting of self-sensing concrete were similar to those of traditional concrete (Milner, 1964), following standard of ASTM C305-14 (Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency). Specifically, the self-sensing concrete was compacted using a vibration table. Copper meshes were inserted into the fresh specimen materials during this vibration process to enhance the cohesion among electrodes and concrete in order to reduce the interferences from contact resistivity. Finally, the self-sensing concrete with embedded electrodes was cured in a standard chamber in a temperature of 23 ±2 °C and relative humidity of 90%. The basic manufacturing process of self-sensing concrete as cement-based sensors with CNTs is shown in Figure 1.

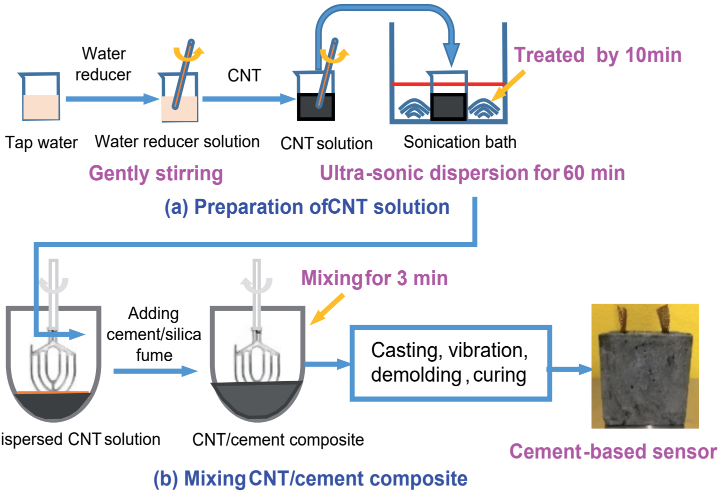

Figure 1: Manufacturing process of self-sensing concrete as cement-based sensors

Activation and calibration

The activation of self-sensing concrete as a cement-based sensor includes calibration, preservation, and electrical current design. The calibration was the initial electrical resistivity of cement-based sensors preset as the initial state, so that altered resistivity could be related to applied external forces or deformations. The reliability and repeatability of self-sensing concrete as a cement-based sensor means that the initial electrical resistivity should remain constant during its service life. For example, electrical resistivity changes in self-sensing concrete should be due only to the forces applied to the structures; other environmental factors such as temperature and humidity should be eliminated. A temperature compensation circuit or specific hydrophobic coating can be used to eliminate the effect of temperature and humidity. Similarly, for cement-based temperature sensors, the influences of external forces or humidity should in a practical application be eliminated. The current design of self-sensing concrete as a cement-based sensor is critical to obtaining reliable piezoresistivity signals. The variables consist of direct (DC) or alternate (AC) current, the intensity of electrical current supply and its frequency (for DC), and whether a two-point method or four-point method is used. These factors affect the measured electrical resistivity and directly influence the accuracy and reliability of cement-based sensors.

Self-sensing performance

Piezoresistivity is a physical property of self-sensing concrete defined as the change of the electrical resistivity when subjected to mechanical loadings (Rovnaník, 2019). For self-sensing concrete as a cement-based sensor used in SHM, when a uniaxial compression is applied, the inter-particle distance of the conductive fillers changes and new conduction paths are created. Hence, the closer the conductive particles are, the more easily an electrical current can flow, decreasing the electrical resistivity. During unloading, the concrete material returns to its relaxed state and the initial resistivity is recovered, provided there is no plastic deformation. Overall, this phenomenon may be seen as piezoresistivity. Based on the above concepts, piezoresistive cement-based strain sensors were established. The piezoresistivity performance of smart self-sensing concrete was then tested, including the compressive machine, digital multimeter, control panel and data collection system, as shown in Figure 2.

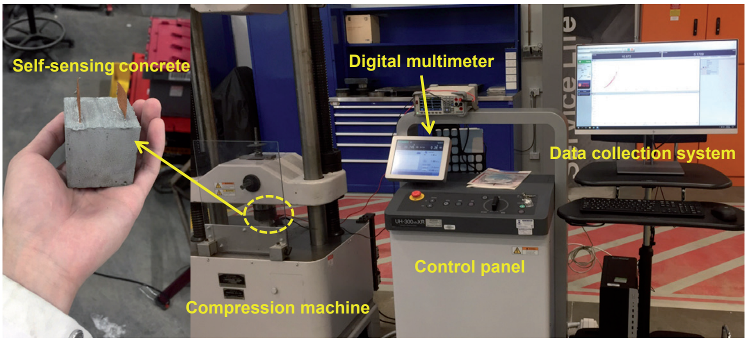

Figure 2: Piezoresistive performance of self-sensing concrete under compression

Stress and strain self-sensing

The electrical resistivity of self-sensing concrete as a cement-based sensor with damage and crack sensing capacity altered when it was subjected to external loadings. For instance, the sensing performance of self-sensing concrete with conductive CNTs can be seen in Figure 3. The applied compressive stress was arranged in three cycles of cyclic loading with an increasing stress magnitude of 4 MPa, 6 MPa, 8 MPa and 10 MPa. The compressive strain was obtained by the foil strain gauge attached to the surface of the specimens, and their electrical resistivity changes were collected by the digital multimeter. It can be seen that the fractional changes in the resistivity of self-sensing concrete with CNTs were highly consistent with the compressive stress/strain. Generally, the ratio of strain to electrical resistivity was named the gauge factor, which is proposed for the sensing efficiency evaluation. For commercially available foil strain gauges, the value of the gauge factor is normally 2. However, the gauge factor of self-sensing concrete with conductive functional fillers can reach several hundred, which means great potential to assess the stress/strain and damage/crack conditions of concrete infrastructure.

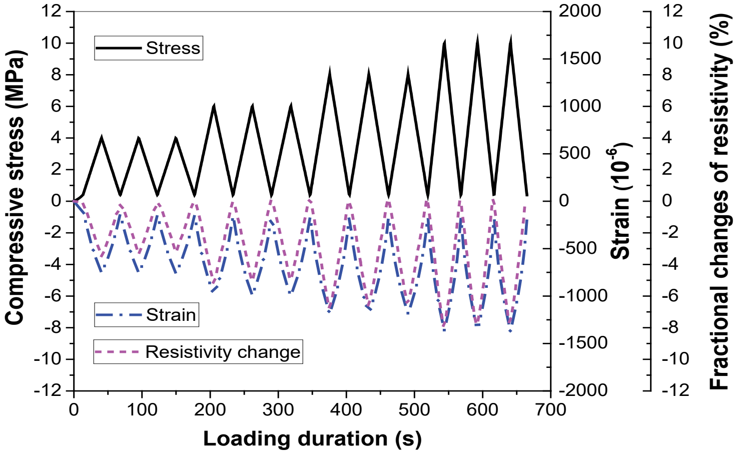

Figure 3: Stress/strain performance of self-sensing concrete with CNTs

Damage and crack detection

The above results were based on stress applied directly onto the self-sensing concrete. The next test was the performance of self-sensing concrete for SHM, such as embedded cement-based sensors in a concrete beam. In the case of beam failure detection, it was found that the electrical resistivity of embedded self-sensing concrete gradually increased with the increase in bending stress, as shown in Figure 4. Because the cement-based sensors were embedded in the compression zone of concrete beams, the cement-based sensors were subjected to compressive load, which was why the electrical resistivity decreased. The fractional changes in resistivity achieved the highest value when the concrete beam reached the ultimate state of flexural strength. Afterwards, once the concrete beam was damaged, the loading stress suddenly decreased and the electrical resistivity simultaneously changed. Consequently, sudden changes in the electrical resistivity of self-sensing concrete can be used as a cement-based sensor to detect whether or not the state of full destruction is reached.

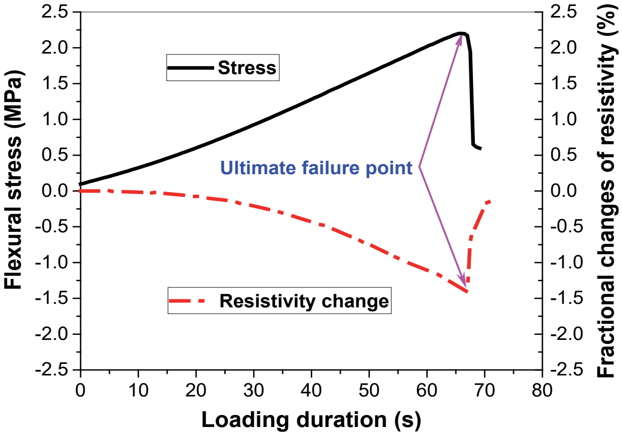

Figure 4: Piezoresistive behaviours of cement-based sensor embedded in concrete beam

Temperature monitoring

Self-sensing concrete can monitor temperature variation based on changes in electrical resistivity. However, given that it takes time to reach the equilibrium between the ambient temperature and the internal temperature of the concrete, there might be continual changes in the electrical resistivity of smart concrete at the beginning when the external temperature changes. An increase in temperature lowers the electrical resistivity of self-sensing concrete, and this altered electrical resistivity is possibly due to the changed viscosity and ionic activity of pore solutions (Dong, 2019b; Dong, 2020b). When the temperature falls from 100 °C to −20 °C, the electrical resistivity gradually increases and returns almost to its initial values. The slightly altered electrical resistivity of self-sensing concrete subjected to subzero temperature is mainly due to the freezing of pore solutions which themselves cause minor damage in the concrete. For temperature cycles above 0 °C, the electrical resistivity exhibits excellent consistency with the temperature. Hence, the electrical resistivity can be a perfect index to monitor the temperature of both concrete and the ambient environment. However, as mentioned previously, the freezing of pore solutions and damage to the microstructures of smart concrete might lead to an extra increase in the electrical resistivity, which can disturb the repeatability of electrical resistivity during temperature detection. Therefore, a self-sensing cement-based sensor is recommended for monitoring temperature of pore solutions only above freezing point.

Humidity monitoring

The water content of self-sensing concrete relates closely to the electrical and piezoresistive properties, due to the moveable ions inside pore solutions. Normally, with any decrease in water content, the electrical resistivity increases and vice versa. Based on the investigation on the self-sensing concrete with a high dosage of nanocarbon black (CB) (Dong, 2019a). The low electrical resistivity of self-sensing concrete with 3% CB indicates conductive passages inside of composite are effectively established. Previous studies have shown that with the increase of water content from dry state to saturation state there is a gradual increase in electrical resistivity. Therefore, higher water content induces more moveable ions and decreases electrical resistivity, while an increase in resistivity is mainly due to strengthened ionic conduction and weakened electric conduction. Given a high concentration of CB, the direct contact between CB nanoparticles leads to strong electric conduction and significantly improves the electrical conductivity of cementitious composites. In addition, the efficiency of electric conduction in reducing electrical resistivity is better than that of ionic conduction. With an increase of water content, some nano CB particles are enclosed by a water film, which results in a strengthened ionic conduction and an increase in contact resistivity among conductive fillers. These two factors are responsible for the increase in the electrical resistivity of concrete with 3% CB. This implies the correlation between electrical resistivity and water content inside self-sensing concrete as cement-based sensor and their great potential for monitoring the humidity or water content of concrete infrastructures.

Future application

Figure 5 schematically demonstrates the application of self-sensing concrete as cement-based sensors to achieve smart/intelligent concrete infrastructures. For instance, concrete building integrated with cement-based sensors can automatically detect damage and cracks and monitor temperature and humidity to provide structural health condition information and alert people to escape from structures that have become dangerous. Cement-based sensors can also be used in bridges and tunnels to identify deformations, monitor cracks and provide alarms for differential settlement and leakage. In particular, intelligent motorways with self-sensing cement-based sensors could detect traffic volume, vehicle speed and even vehicle weight very accurately.

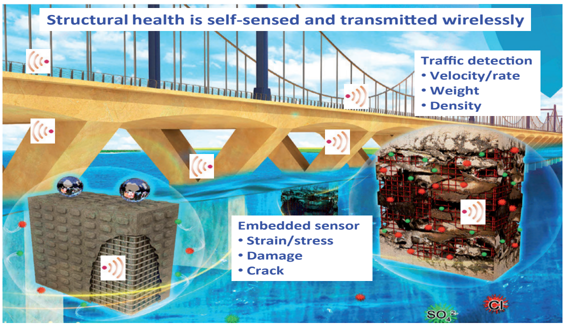

Figure 5: Potential application of self-sensing cement-based sensor for structural health monitoring and traffic detection

Advantages

In view of the many other structural damage detection techniques available, such as piezo ceramic, optical fibres and strain gauge, there is the question why the application of self-sensing concrete as a cement-based sensor to self-monitor damage, stress or strain conditions is promising. First, the cost of self-sensing concrete is much lower than that of other sensor systems. Second, the sensitivity of self-sensing concrete is much higher than that of conventional sensors. For instance, the gauge factor (a coefficient for sensitivity evaluation) for a foil strain gauge is usually 2, while the value of intelligent concrete can reach several hundred and show much higher sensing efficiency. Third, the durability of self-sensing concrete is many times greater than that of conventional sensors. Conventional sensors might have a service life of several month or years, but the durability of self-sensing concrete is as high as traditional concrete, which can be used for decades. Last but not least, the cohesion of self-sensing concrete to concrete structures is much stronger than that of non-intrinsic sensors. Typically, the mechanical properties and durability of concrete structure are not significantly affected by cement-based sensors as an introduction of foreign material, rather than the piezo ceramic and optical fibres.

Challenges

Self-sensing concrete is influenced by factors such as temperature and humidity variations, which hinder its practical application for SHM and traffic detection. Cement-based sensors with conductive fillers are similar to semiconductors, whose electrical resistivity can be greatly affected by ambient temperature, because of the altered movements of ions, electrons and pores. This means that, except for the specific loadings applied, the fractional changes in the resistivity of self-sensing concrete might be induced from temperature and humidity variations which affect its stress/strain and temperature/humidity sensing accuracy and reliability. To solve these problems, this study has proposed the application of a supplementary temperature circuit to completely eliminate the effect of temperature on the electrical resistivity. Moreover, ambient humidity affects the water content of self-sensing concrete in that it directly alters its electrical resistivity, because several types of ions such as Ca^{2+}, OH^{-}, and Al^{3+} are movable in solutions. Actually, in addition to the conductive fillers, these ions in the pore solutions of self-sensing concrete might make a considerable contribution to its self-sensing capacity. It might improve the stress/strain and temperature/humidity sensing efficiency when the self-sensing concrete has appropriate water content. To reduce the impact of external humidity, self-sensing concrete shows excellent water impermeability, which means it can be used in various working conditions, such as harsh and coastal environments. In addition, the layout of cement-based sensors inside of concrete structures and data collection system should be investigated.

Conclusion

Self-sensing concrete in the form of cement-based sensors can be applied in multiple concrete structures for structural health monitoring and traffic detection, for the detection of stress/strain and cracks or other damage, and to monitor temperature and humidity. It possesses the advantages of lower cost, higher sensing efficiency, better durability and serviceability than that of conventional sensors. Most importantly, it provides the conventional concrete structures with a multifunctionality that can automatically monitor their structural health status.

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