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Intelligent Pavement for Traffic Flow Detection – Phase I

Final Report

Prepared by:

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This project explored a new approach in detecting vehicles on a roadway by making a roadway section itself a traffic flow detector. Sections of a given roadway are paved with carbon-nanotube (CNT)/cement composites; the piezoresitive property of carbon nanotubes enables the composite to detect the traffic flow. Meanwhile, CNTs can also work as the reinforcement elements to improve the strength and toughness of the concrete pavement. In contrast to current traffic flow detection technologies that require separate devices to be installed either in the pavement or over the road, the proposed sensing approach enables the pavement itself to detect traffic flow parameters. Therefore, the proposed sensor is expected to have a long service life with little maintenance and wide-area detection capability.

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We thank Dr. Eil Kwon, director of NATSRL, for many productive discussions.

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Executive Summary

This project explored a new approach in detecting vehicles on a roadway by making a roadway section a traffic flow detector. Carbon-nanotube (CNT)/cement composites were investigated for this purpose. The piezoresitive property of carbon nanotubes enables the composite to detect traffic flow. Meanwhile, CNTs can also work as reinforcement elements to improve the strength and toughness of concrete pavement.

Piezoresistive CNT/cement composites were developed and tested in this study. Experimental results show that the electrical resistance of the composite changed proportionally to the compressive stress levels. The piezoresistive responses of the composite with different fabrication methods were also studied. The CNT acid-treated method showed stronger piezoresistive response and higher signal-to-noise ratio than the surfactant-assistant dispersion method in which the surfactant could block the contacts among nanotubes thus impairing the piezoresistive response of the composite. However, the acid-treatment of CNTs is difficult to scale up for larger samples. The involvement of strong acids also makes it hard to be implemented in the field. The surfactant wrapping of CNTs is also effective to disperse CNTs into the cement matrix and give promising piezoresistive properties. The experimental results, including the lab tests and preliminary road tests, demonstrated the potential of using the CNT/cement composite as a traffic flow detector.

In contrast to current traffic flow detection technologies that require separate devices to be installed either in the pavement or over the road, the proposed sensing approach enables the pavement itself to detect traffic flow parameters. Therefore, the proposed sensor is expected to have a long service life with little maintenance and wide-area detection capability.

Chapter 1. Introduction

1.1 Review of Traffic Flow Sensors

Traffic flow sensors are an integral part of modern intelligent transportation systems (ITS). Sensors provide real-time input data in support of a variety of ITS services and strategies, such as freeway ramp metering, traffic signal control, driver information and guidance. Therefore, the success of ITS depends to a large extent on the accuracy and reliability of traffic flow sensors.

A large number of researchers have investigated different kinds of traffic sensing technologies. These sensors can be categorized into two major classes [1-3]:

- **In-roadway (intrusive) sensor**: it is embedded in the pavement such as inductive loop detectors and magnetometers.
- **Over-roadway (non-intrusive) sensor**: this kind of sensor is mounted over the roadway such as microwave radar sensors, ultrasonic sensors, laser radar sensors, infrared sensors, and video image processors.

Among these various sensors, inductive loop detectors are the predominant traffic flow sensors, due to their mature technology, insensitive to weather conditions, and relative low costs. The configuration of an inductive loop detector is shown in Figure 1 [3], which typically consists of a coil that is embedded in the road, a pull box, a lead-in cable, and a controller. As the vehicle passes over the coil, the inductance of the coil will reduce, which will change the oscillation frequency of an oscillator.

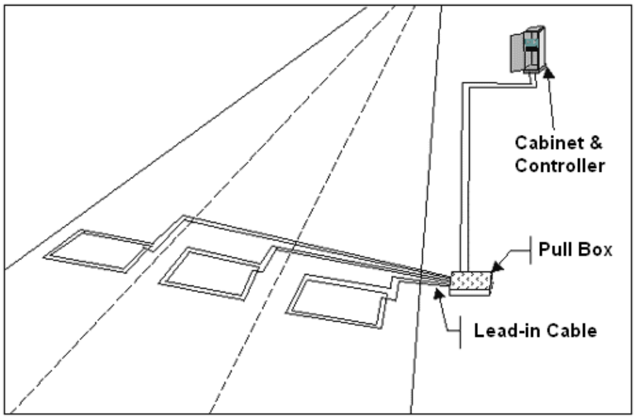


Figure 1. Configuration of an inductive loop detector [3]

Inductive loop detector can accurately measure occupancy, vehicle speed, and gaps. However, there are several limitations with inductive loop detectors:

1. Installation of inductive loops requires pavement cut (the typical size of a loop is 6 ft x 6 ft).
2. Installation and maintenance require lane closure, which could bring severe traffic congestion and high maintenance cost.
3. Wire coil suffers from the stresses of traffic and temperature.

4. If not properly installed, the inductive loop will decrease the pavement life.

The above issues with inductive loops and recent advances in computing and communication technologies have led to the development of non-intrusive detection technologies, such as microwave radars, infrared sensors, and video image processors. However, these non-intrusive sensors face limitations of high sensor costs, high maintenance cost, and poor performance in inclement weather conditions (rain, snow, and fog). Many of them also need additional mounting structures and time-consuming calibration. These limitations make the intrusive sensors (mainly inductive loops) still primary traffic detection systems in the field. The lack of low cost, low maintenance, long service, and reliable traffic detectors motivates this proposed research.

1.2 Review of CNT and CNT-Based Composites

In this project, we propose the investigation of carbon nanotube (CNT)/cement composites for traffic flow measurement by detecting the change of electrical resistance of the composite when subject to the stress of a vehicle. Being an integral part of the pavement with strong mechanical strength, the proposed traffic sensor will provide several advantages over the inductive loop detectors, such as easy installation and maintenance, long service life and little maintenance, wide detection area, and potential applications for structural health monitoring.

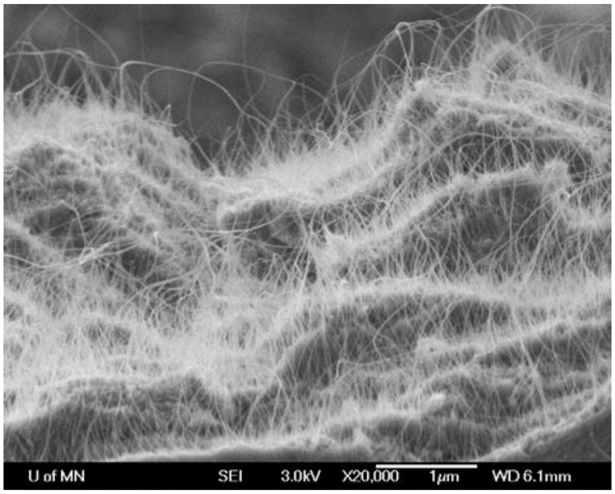


Figure 2. A SEM (scanning electron microscope) picture of CNTs

Carbon nanotubes (CNTs) are seamless tubular structures rolled up forming a one-atom sheet of graphite, with diameter in the order of a nanometer (10^{-9}m). The nanotubes may consist of one shell of carbons (single-walled carbon nanotubes (SWNTs)), or up to tens of concentric shells of carbons (multi-walled carbon nanotubes (MWNTs)). The diameters of CNTs are in the range of 1~20 nm, and the lengths are in the range of 0.2~5 μm.

Since the discovery of CNTs by S. Iijima in 1991 [4], carbon nanotubes have been widely used for a variety of applications due to their excellent physical properties: high strength (the Young's modulus of individual CNTs is about 1.8 TPa) [5], metallic or semi-conductive electrical properties depending on their roll up charity [5]; and high aspect ratio (>500). The extremely high aspect ratio of CNTs makes them easy to form a conductive and reinforcement network with doping level as low as 0.1% wt of CNTs [6-8]. Carbon nanotubes also have interesting electromechanical properties. When subject to stress/strain, the electrical properties of CNTs will change with the level of stress/strain, expressing a linear and reversible piezoresistive response [9-12, 25]. Most of those prior works were performed with individual nanotubes or nanotube membranes. Recently, CNT/polymer composites have also been investigated for strain/stress sensing [13, 26-27]; their results also show linear electrical resistance changes with respect to the strain/stress and the sensitivity is 3.5 times of regular stain gage. These previous works show that CNT based composite could be a promising stress/strain sensor. However, no previous study has been performed on the piezoresistive responses of the CNT/cement composites. Since the properties of cement are much different from polymers, it would be very interesting to investigate the electromechanical property of the CNT/cement composite, and how the interface between CNTs and cement will influence the electromechanical property of the composite.

On the other hand, with the advances of CNT synthesis techniques, the price of CNTs has decreased dramatically in recent years. For example, MWNT can be purchased at $0.2/g (TimesNano, China). The decreasing price and the ultra low needed doping level of CNTs enable them possible to be used in large structures, e.g., concrete pavements, which had not been investigated by previous studies.

A literature survey reveals very few previous research efforts on the CNT/cement composites. Li *et. al.* studied the mechanical properties of CNT/cement composites [14]. They found that the compressive strength and flexural strength of the 0.5% CNT cement composites were increased by 19% and 25% respectively, compared to the un-reinforced cement. However, they did not study the piezoresistive properties of CNT/cement composites. Another research group in Canada conducted a similar mechanical reinforcement study but not the piezoresistive behavior of the composites [20].

It should be noted that another class of carbon material – carbon fibers (CFs), have been extensively studied as reinforce elements in cement concrete. CFs are different from CNTs with much larger diameters (1~15 μm), smaller Young's modulus (~560 MPa) and aspect ratio [15]. The piezoresistivity and piezoelectric properties of CF/cement have also been investigated by Chung *et. al.* [16-18] and Sun *et. al.*[19]. However, it was found that the piezoresistivity and piezoelectric of the CFs would be *irreversible* due to the fiber breakage when the strain was larger than 0.2% [16]. Therefore, CF/cement composite is not appropriate as a strain/stress sensor to detect heavy stresses of traffic flows. On the contrary, Tombler *et. al.* found that the piezoresistive characteristics of CNTs were highly reversible even for a huge strain of 3.4% [9]. This indicates CNT/cement could be a promising distributed stain/stress sensor for traffic flow detection.

Chapter 2. Fabrication of CNT/Cement Composites

In order to form a conductive network and explore their physical properties, CNTs need to be fully dispersed in cement matrix. However, CNTs tend to aggregate together in most solvents, due to van der Waal's forces, and form nanotube clusters and bundles. To be dispersed in aqueous solvent, CNTs' surfaces have to be modified such as by using surfactants (e.g. sodium dodecyl sulfate (SDS) and Triton X-100) or by surface acid-treatment. In this research, we used two CNT surface modification methods to functionalize and disperse CNTs for the fabrication of CNT/cement composites, the composite properties were compared for both methods.

In this study, the cement used is Portland cement (ASTM Type I) provided by Holcim Inc., USA. The MWNTs used are carboxyl MWNTs provided by Timesnano, Chengdu Organic Chemicals Co. Ltd. of Chinese Academy of Sciences, China. Their properties are given in Table 1. Figure 3 shows a scanning electron microscope (SEM) picture of the received MWNTs.

Table 1. Properties of carboxyl multi-wall carbon nanotubes

Parameters	Values
Outside diameter	<8nm
Inside diameter	2~5nm
-COOH content	3.86 wt.%
Length	10~30µm
Purity	>95%
Ash	<1.5 wt.%
Special surface area	>500 m2/g
Electrical conductivity	>102 s/cm
Density	~2.1 g/cm3

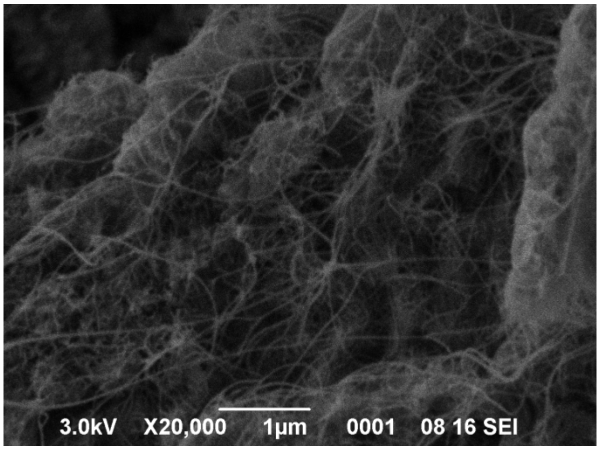


Figure 3. SEM picture of as-received MWNTs

Method #1: In our previous studies on the fabricating transparent conductive CNT thin films [21, 22], CNTs have been successfully dispersed in water by treating CNTs with a mixture of sulfuric acid and nitric acid for an adequate length of time. It is well known that, during acid treatment, oxygen atoms from acids react with carbon atoms on the nanotubes, especially on the ends, curvatures, and defects of the nanotubes where carbon atoms are more reactive [23]. Negatively charged carboxylic groups will be introduced on the SWNT surfaces as a result of the oxidation (covalent surface modification). The electrostatic repulsion force between these negative charges can be utilized to disperse SWNTs in water without any surfactant. Figure 4 shows a diagram of this proposed fabrication process for CNT/cement composites. Acid-treated MWNTs were dispersed in water and then mixed with Portland cement (Type I) without adding sand or aggregate, the water/cement ratio was 0.6 and MWNT is 0.1% weight of cement. The CNT/cement pastes were molded into 50.8 x 50.8 x 50.8 mm^3 shapes. The sample was de-molded in one day, cured in water for 20 days, and then dried in air at room temperature for 10 days.

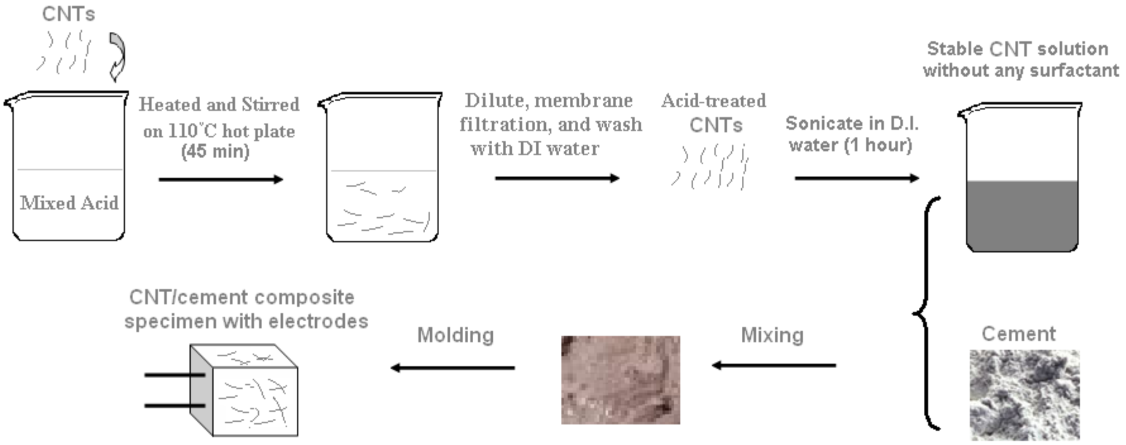


Figure 4. Illustration of the CNT/cement fabrication process based on the acid treatment of CNTs

Method #2: An alternative method of dispersing CNTs in cement matrices is to use non-covalent surface modification for CNT surfaces, as opposed to the above covalent surface modification. With non-covalent interactions, surfactants can be wrapped around the nanotubes, which in turn can render CNTs to be dispersed in aqueous solution and mixable with cement. In this project, surfactant sodium dodecylbenzene sulfonate (NaDDBS) was used. The critical micelle concentration of 1.4×10-2mol/L of NaDDBS was used as the input surfactant concentration. The surfactant was firstly mixed with water (the water/cement ratio is 0.6:1) using a magnetism stirrer (PC-210, Corning Inc., USA) for 3 min. Next, MWNTs (0.1% by weight of cement) were added into this aqueous solution and sonicated with an ultrasonicator (2510, Branson Ultrasonic Co., USA) for 2hr to make a uniformly dispersed suspension. Then, a mortar mixer was used to mix this suspension and cement for about 3 min. Finally, a defoamer in the amount of 0.25 vol. % of cement was added into the mixture and mixed for another 3 min. After pouring the mixes into molds and embedding two electrodes with 1cm apart, an electric vibrator was used to ensure good compaction. The specimens were then surface-smoothed, and covered with plastic films. All specimens were demolded 24h after casting. Thereafter, they were cured under the standard condition at a temperature of 20°C and a relative humidity of 100% for 28 days. All specimens were dried at a temperature of 50°C for five days before testing.

Figure 5 shows the picture of the fabricated CNT/cement composite samples and the illustration of the electrodes. Figure 6 shows a SEM picture of the microstructure of the CNT/cement sample.

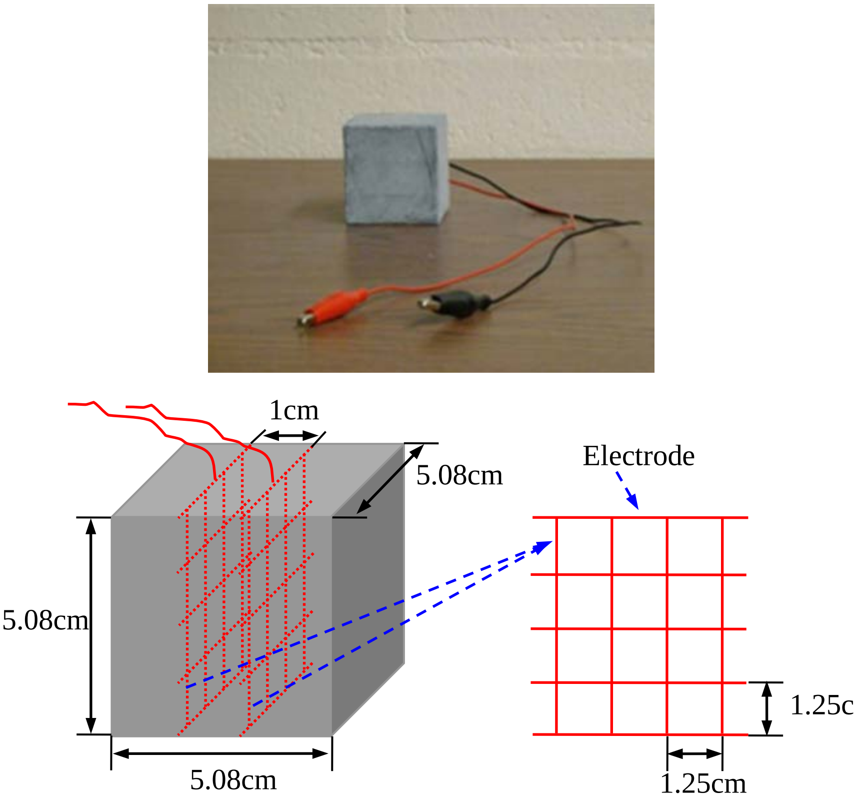


Figure 5. Picture of CNT/cement composite sample and the illustration of electrodes

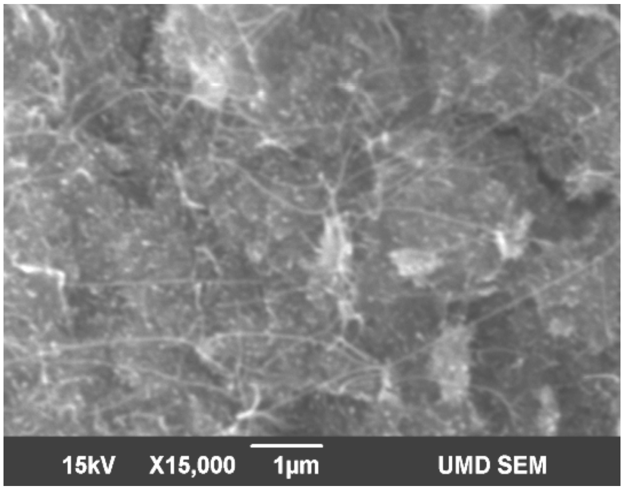


Figure 6. SEM Picture of the microstructure of the CNT/cement composite sample

Chapter 3. Piezoresistive Properties of CNT/Cement Composites

The piezoresistive responses of the CNT/cement composite were studied in lab tests first before being tested for traffic flow detection. The lab test setup is illustrated in Figure 7. Compressive loads were applied using a material testing machine (ATS 900, Applied Test Systems, Inc., USA). Electrical resistance is measured in the compressive stress direction perpendicular to electrodes under repeated compressive loading and impulsive loading. Electrical resistance measurements were made by a two-electrode method using a digital multimeter (Keithley 2100, Keithley Instruments Inc., USA). All of the measurements interfaced with a PC are automatically recorded.

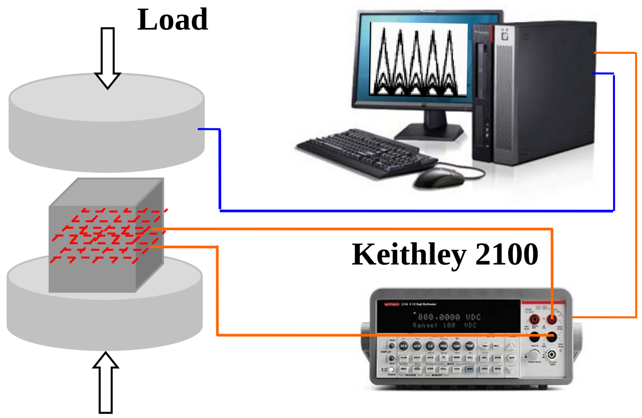


Figure 7. Sketch of experimental equipments for repeated compressive loading and impulsive loading

3.1 Piezoresitvity of CNT/Cement Composite made by Method #1 (Acid-Treatment of CNTs)

Figure 8 shows the piezoresistive responses of the composite fabricated with method #1(acid-treatment method) with 0.1 wt% MWNTs. As can be seen, the electrical resistance changes linearly with the compressive stress and the changes are proportional to the stress levels.

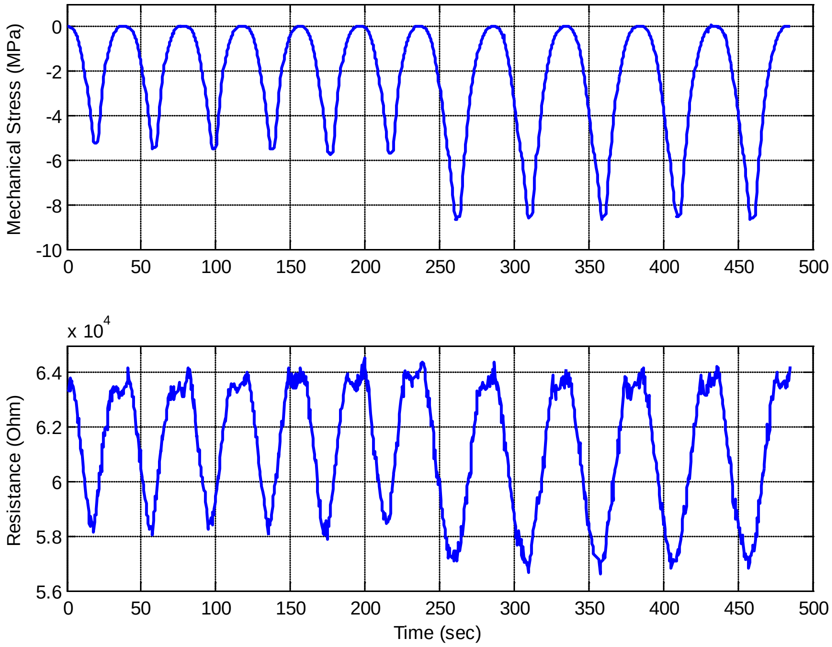
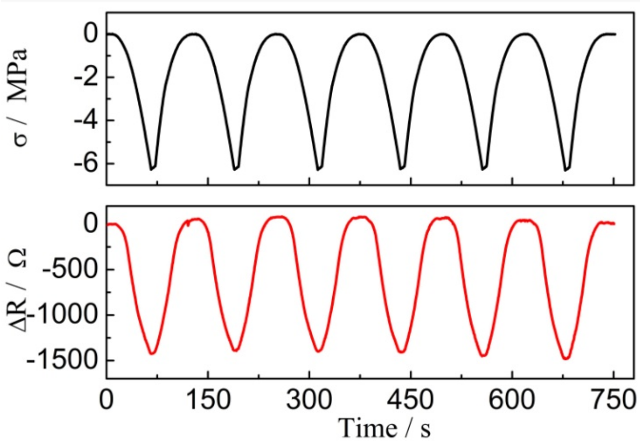


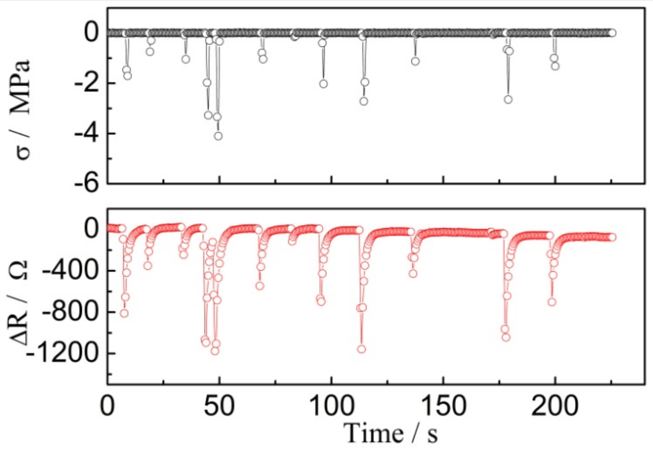
Figure 8. Piezoresistive response of CNT/cement composite fabricated by method #1 (acid-treatment).

3.2 Piezoresitvity of CNT/Cement Composite made by Method #2 (Surfactant Wrapping of CNTs)

Figure 9 depicts the variation of the electrical resistance R of the self-sensing CNT/cement composite under repeated compressive loading and impulsive loading. Figure9 a) shows that the electrical resistance of the composite decreases upon loading and increases upon unloading in every cycle under repeated compressive loading with amplitude up to 6MPa. It indicates that the response of electrical resistance of this composite to compressive stress σ is regular under repeated compressive loading. The change in electrical resistance ΔR (i.e. $R - R_0$, where R_0 is the initial electrical resistance of specimens without compressive loading) reaches about 1500Ω maximum as compressive stress is 6MPa. As shown in Figure9 b), the impulsive loadings also cause regular changes in the electrical resistance of self-sensing CNT/cement composite. According to these results, it can be seen that the response of electrical resistance of self-sensing CNT/cement composite to compressive stress is reversible and sensitive, which means that the self-sensing CNT/cement composite has excellent sensing capability.



a) Under repeated compressive loading with amplitude of 6MPa



b) Under impulsive loading

Figure 9. Relationships between compressive stress and electrical resistance of the self-sensing CNT/cement composite

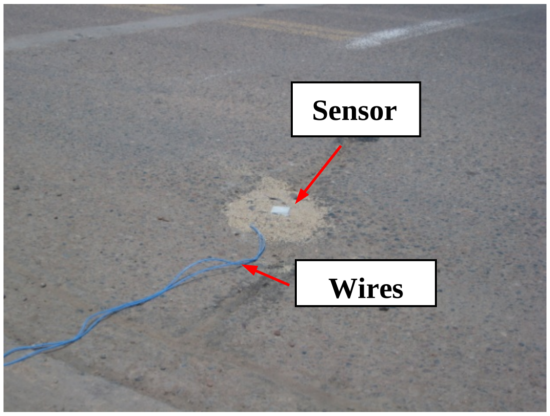
3.3 Discussion on Piezoresistive Mechanism of the CNT/Cement Composite

The piezoresistivity for composites with CNTs is caused by the following four reasons. (1) the electrical conductivity of CNTs varies under external stress (according to Tombler et. al.[24], the electrical resistance of CNTs will increase 100 times when strain changes from 0.0% to 3.2% under tensile loading. CNT's resistance thus will decrease under compressive loads); (2) the number of contact points of CNTs increases with the increase of compressive loading, which can cause an enhancement of conductivity; (3) the separation distance between CNTs decreases under compressive loading, which can cause an enhancement in tunneling effect conduction; (4) the field induced tunneling effect enhances due to compressive loading [25-29]. According to the Fowler-Nordheim theory, CNTs have a strong field emission effect under electric field [27]. The smaller the diameter of CNTs, the higher the field emission effect (CNTs used in this study is the MWNTs with the smallest diameter, which is smaller than 8nm). The local high electrical field in composites increases the potential energy of electrons through tunneling barrier between CNTs, which causes the enhancement in tunneling effect conduction. Furthermore, when the composites are deformed under compressive loading the separation between CNTs will be reduced, i.e. the tunneling barrier to be transited by electrons will decrease and the field induced tunneling can more easily occur in the composites [30, 31]. As a result, the piezoresistivity of MWNTs filled cement-based composites are strongly influenced by the conductive network in composites.

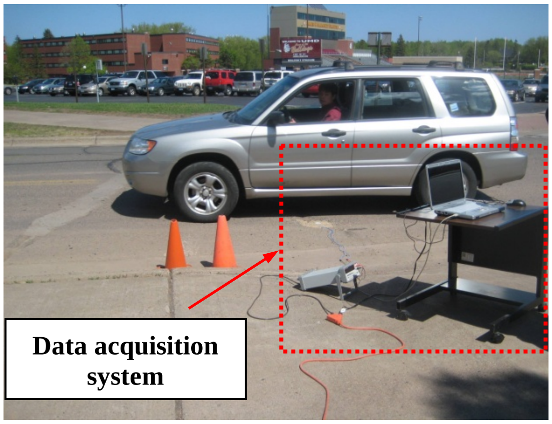
Comparing the experimental results in Figure 8 and Figure 9, it can be seen that the composite made by Method #1 has higher piezoresistive response. This difference of piezoresistive response between two composites made with different methods could be attributed to the different nanotube to nanotube interfaces. In the Method #1, CNTs are dispersed in cement matrix without any surfactant. Therefore the nanotubes could contact directly with each other in the CNT network. However, for the Method #2, the nanotube surfaces are wrapped with surfactants (SDS). Nanotube contacts could be blocked by the surfactant between nanotubes, which impedes the piezoresistive response levels.

Chapter 4. Preliminary Road Test of the CNT/Cement Composite for Traffic Flow Detection

Figure 10 shows the road test setting. Self-sensing CNT/cement composite sensors are embedded in concrete pavement as shown in Figure10 a) (the composite sample used in the test is the one made by Method #2, i.e., surfactant wrapping of CNTs). Vehicles were driven passing over the sensor to investigate the feasibility of traffic monitoring, as shown in Figure10 b).



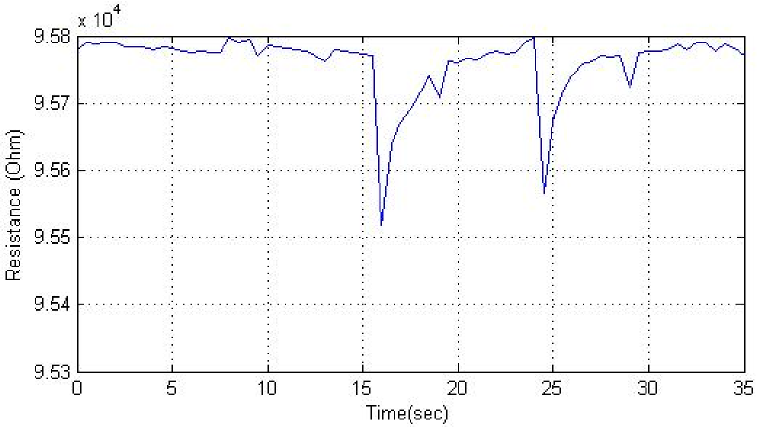
a) Self-sensing CNT/cement composite sensor embedded in concrete pavement



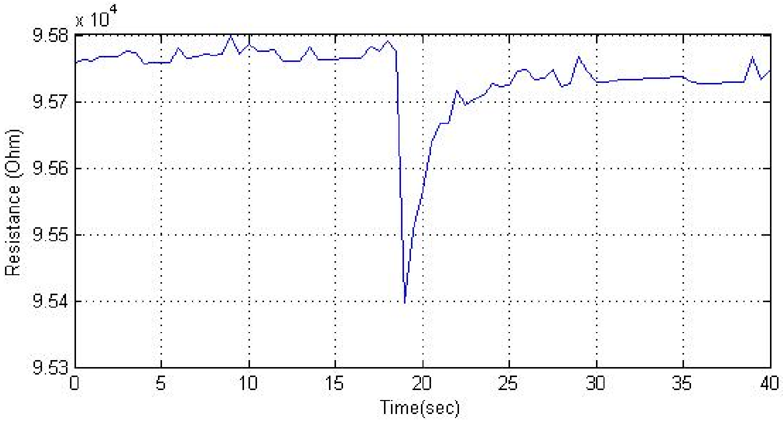
b) Vehicular loading experiment

Figure 10. Vehicular loading experiment of self-sensing CNT/cement composite sensors embedded in concrete pavement

The variation in electrical resistance of self-sensing CNT/cement composite under vehicular loading is illustrated in Figure 11, where Figure 11 a) shows the changes of resistance when two mid-size passenger vehicles pass over the sensor and Figure 11 b) shows the results when a mini-van vehicle passes over the sensor (note: the size of current sensor is a little too small, we could not drive the cars that both axis passed over the sensor. So there is only one peak of resistance change for each vehicle. Large size sensors are being fabricated for further tests). As can be seen in Figure 11, vehicular loads can lead to remarkable change in electrical resistance of the sensors.



a) Two middle size passenger vehicles pass over the sensor



b) A mini-van passes over the sensor

Figure 11. Variation in electrical resistance of the self-sensing CNT/cement composite under different vehicular loadings

Comparing Figure11 b) with Figure11 a) carefully, we can also find that the change amplitude in electrical resistance of a mini-van passing over is larger than that of passenger vehicles, which is due to the heavier axis weight of the mini-van (i.e. larger mechanical stress). These findings indicate that self-sensing CNT/cement composite can detect traffic flow and even possible to identify different vehicular loadings (weight-in-motion detection). The vehicle weight measurement is needed to prevent damages to highways due to overweight vehicles, such as heavy trucks. It is currently conducted in weighing stations off the highway while the vehicle is stationary. The monitoring of vehicle weights can be more convenient and effective if the weighing is performed on the highway while the vehicle is moving normally. In this way, traffic is not affected and time is saved.

In addition, as shown in Figure 12, if a pair of self-sensing CNT/cement composite sensor arrays is used, the vehicle-speed V can be calculated as

$$V = \frac{L}{t_2 - t_1} \qquad (1)$$

where L is the distance between the first row of sensors and the second row of sensors, t_1 and t_2 are the time of vehicles running over the first row of sensors and the second row of sensors respectively. According to the results and analyses above, the self-sensing CNT/concrete pavement embedded with piezoresistive MWNTs filled cement-based sensors as shown in Figure 12 presents great potential for traffic monitoring such as vehicle detection, weigh-in-motion measurement and vehicle-speed detection.

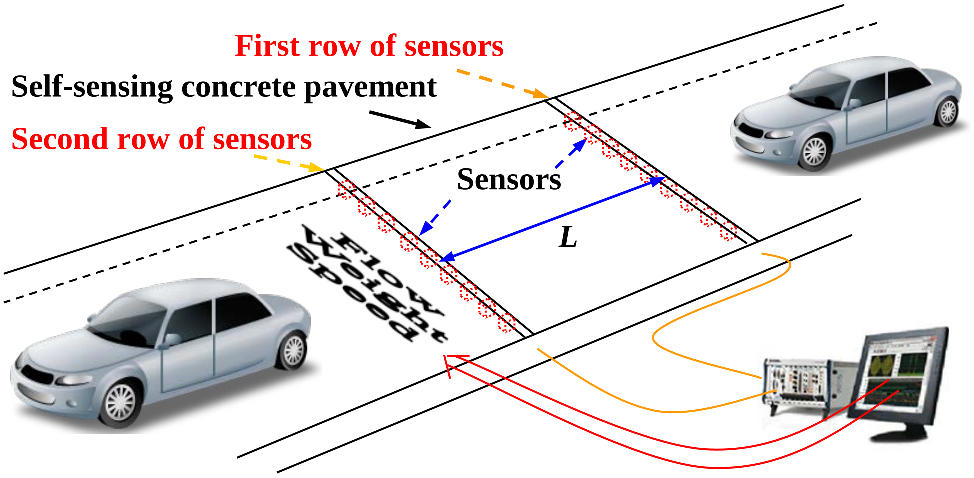


Figure 12. Illustration of self-sensing concrete pavement for traffic flow detection

Chapter 5. Conclusion and Discussion

Piezoresistive CNT/cement composites were developed and tested in this study. Experimental results showed that the electrical resistance of the composite changed proportionally to the compressive stress levels. The piezoresistive responses of the composite with different fabrication methods have also been studied. The CNT acid-treated method showed stronger piezoresistive response and higher signal-to-noise ratio than the surfactant-assistant dispersion method, in which the surfactant could block the contacts among nanotubes thus impairing the piezoresistive response of the composite. However, the acid-treatment of CNTs is difficult to scale up for larger samples. The involvement of strong acids also makes it hard to be implemented in the field. The surfactant wrapping of CNTs is also effective to disperse CNTs into the cement matrix and give promising piezoresistive properties. The experimental results, including the lab tests and preliminary road tests, have demonstrated the potential of using the CNT/cement composite as a traffic flow detector.

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