

Self-Sensing Carbon Nanotube Reinforced Composites for Smart Cities

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ABSTRACT: Self-sensing composite materials are becoming attractive for civil engineering application to improve the safety and performance of structures. Current structural health monitoring still requires many sensing devices and technicians for their visual inspection, which are expensive and time consuming. Proposed self-sensing composite materials consisting of carbon nanotubes and polymer provide innovative way for structural health monitoring. The smart composites show significant change in their electrical resistance with applied loadings such as static and impact loadings. In this study, we will fabricate highly conductive carbon nanotube reinforced composite materials for sensor integrated construction materials. The author reports materials design and optimisation of carbon nanotube reinforced composite materials in terms of electrical conductivity and mechanical property. Moreover, we investigate the electro-mechanical response of carbon nanotube reinforced composite materials under static and impact loadings. Finally, we will present new Internet of Things (IoT)-based sensing system that capture various data from smart composite material itself without any additional sensing elements.

1 INTRODUCTION

Smart cities are the safe, secure, environmental and efficient urban centre of the future with advanced infrastructures such as sensors, electronic devices and networks to simulate sustainable economic growth and a high quality of life (Bakici et al. 2013). Therefore, advanced and functional infrastructure materials are essentially required to promote the smart cities with other technologies.

In recent years, carbon nanotubes (CNTs) have attracted significant interest for many engineering applications because of superior mechanical, electrical, and thermal properties of CNTs. Therefore, CNT reinforced composites have proposed for many applications such as self-sensing and self-heating materials (Jang and Yin 2015a, Jang et al. 2017, Jang and Park 2018). In particular, self-sensing materials have a promising infrastructure material that can monitor itself without the need of additional external sensor devices considering that current structural health monitoring system requires enormous maintenance costs including expensive equipment and highly skilled technicians. Azhari and Banthia (2012) developed the electrically conductive cementitious composite with carbon fibers and CNTs and showed their ability to sense an applied compressive load through the change in resistivity. Meoni et al. (2018) investigated the self-sensing cement-based strain sensors by using CNTs and found that the samples are capable of maintaining the strain-sensing capabilities. Those self-sensing cementitious-based composites



relatively requires high concentration of CNTs due to difficulty in dispersing CNTs in cementitious-based materials and still shows low electrical conductivity compared to that of CNT reinforced polymer-based composite materials.

In this study, we fabricated CNT reinforced composite materials for self-sensing application in civil engineering. CNTs were dispersed into an epoxy-based matrix to achieve high electrical conductivity. Electro-mechanical response of CNT/epoxy composites was investigated under both a static compressive loading and an impact loading.

2 EXPERIMENTAL

2.1 Materials and fabrication

Multi-walled carbon nanotubes (CNTs) was purchased from US Research Nanomaterials Inc. (Houston, USA). Their average diameter and length of CNTs were 4 – 10nm and 50µm, respectively. Epoxy resin (IN2 Epoxy Infusion Resin) and hardener (AT30 slow) were obtained from Easy Composite (Staffordshire, UK). The viscosity of the epoxy resin is 200 – 450mPas and a pot life is 80 – 100min at a room temperature. High purity acetone (>95 %) was purchased from Acros Organics Ltd (Loughborough, UK).

CNT reinforced epoxy composites were fabricated by dispersing CNTs in the epoxy matrix based on previous studies (Jang and Yin, 2015b). Various concentrations of CNTs were mixed with 50 ml of mixture consisting of acetone and monomer. A horn-type ultrasonicator was used to disperse CNTs in the mixture. The ultrasonicator operated in a pulse mode (15s on and 15s off) for 1 h in an ice bath to reduce an overheating effect. Then, the mixture was placed in an oven at 70 °C to remove solvent. After fully evaporation of the solvent, crosslinker was added with a mix ratio of 10:3, followed that the mixture was stirred for 5 min. The mixtures were cast in a cylinder mold for further characterization.

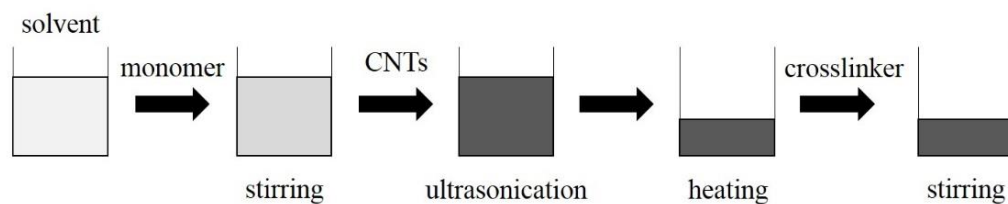


Figure 1. Fabrication of CNT reinforced composite materials.

2.2 Characterisation

A two-point probes resistivity measurement system (Keithley 2700) was adopted to measure the resistance of the CNT reinforced composite materials. Each data point was obtained by an average value taken from a total 10 different measurement on each sample. The samples are painted at both sides with a silver paint in order to minimize a contact resistance between a probe and an electrode. The electrical conductivity of samples was calculated by

$$\sigma = \frac{L}{AR} \quad (1)$$

where R is the electrical resistance and A and L are an area of electrode and a length between the electrodes, respectively. Electro-mechanical response was investigated under a static compressive loading as well as an impact loading. During the mechanical testing, we measured the electrical resistance of samples with a DAQ system. For static compressive testing, a universal testing machine was used at a displacement control of 0.5 mm/min. For impact testing, izod testing method was performed where a pendulum falls from a certain height and hits the sample and the sample absorbs part of pendulums kinetic energy.

3 RESULTS AND DISCUSSIONS

3.1 Electrical conductivity

CNTs were used as filler to enhance the electrical conductivity of CNT reinforced composite materials. Figure 2 showed the electrical conductivity of CNT reinforced epoxy composite materials as a function of CNT concentration. Pure epoxy is non-conductive material. The electrical conductivity of CNT/epoxy composite significantly enhanced as increasing CNT concentrations because of percolation threshold where CNT network formed at first. According to the percolation theory, an electrical percolation threshold occurs at which a through conductive pathway forms throughout a polymer matrix, resulting in the transformation of the composite from an insulator into a semi-conductor or conductor (Wang, FX et al. 2018). In this study, we obtained the percolation threshold at 0.25 wt.% of CNT, which highly depends on quality of CNTs, solvents, and dispersion techniques. After the percolation threshold, the electrical conductivity generally increased as increasing CNT concentrations.

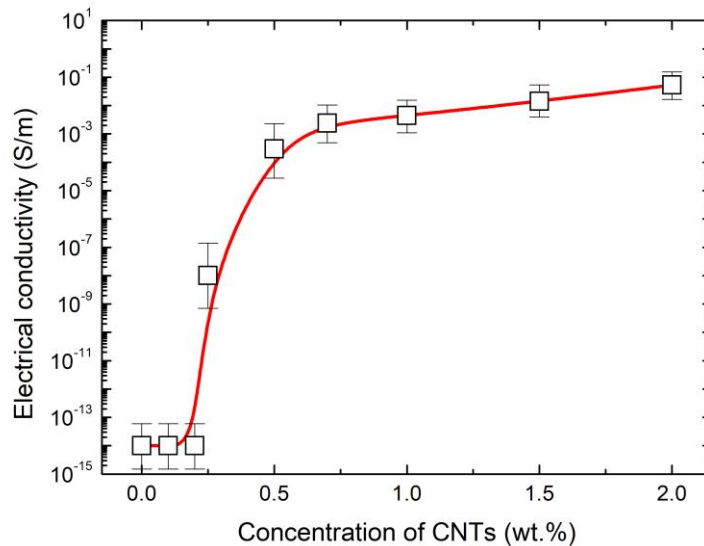


Figure 2. Electrical conductivity of CNT reinforced composite materials.

3.2 *Electro-mechanical response*

The resistance of CNT/epoxy composites generally decrease when the compressive loading is applied due to denser CNT networks (Dinh, NT and Kanoun, Olfa. 2015). Figure 3 showed the electro-mechanical response of CNT/epoxy composites as a function of CNT concentrations. Both curves show a non-linear behavior between compressive strain and change in resistance. CNT/epoxy composite with lower CNT concentration provides higher resistance change, leading to higher sensitivity to compressive strain. This is because the total resistance change is induced by the change of the number of the contact resistance and the tunneling resistance. We observed that CNT/epoxy composite with 2.0 wt.% CNTs presented stable performance than that with 0.5 wt.% CNTs. Figure 4 showed the electro-mechanical response of 2.0 wt.% CNT/epoxy composites under the compressive cyclic loading for ten cycles. We applied the compressive strain of 0.5 % to the sample. The electrical resistance of sample decreased as increasing the compressive strain due to denser CNT network. The cyclic response between the loading and unloading was robust and maintained $\Delta R / R_0$ after 10 continuous cycles, leading to the excellent cycling stability of the sample.

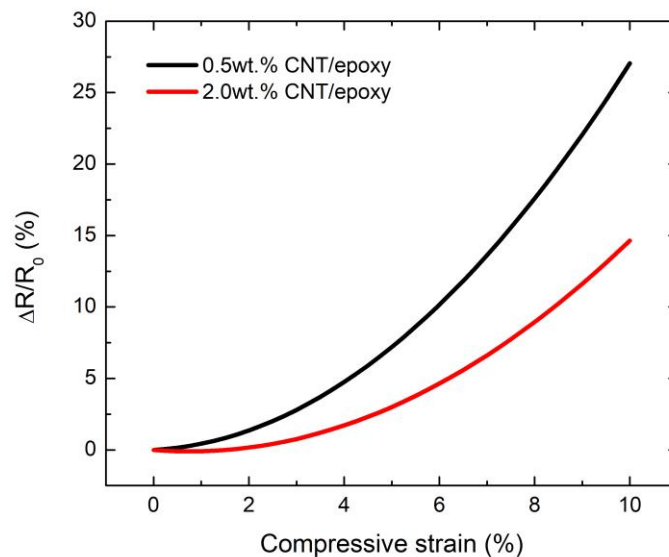


Figure 3. Electro-mechanical response of CNT/epoxy composites under compressive loading.

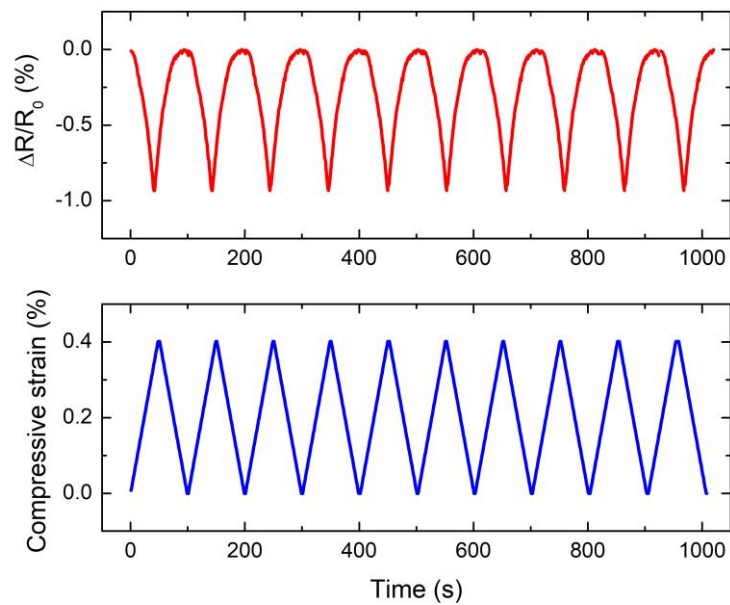


Figure 4. Cyclic behavior of CNT reinforced composite materials.

Figure 5 showed the electro-mechanical behavior of 2.0 wt.% CNT/epoxy composite under various impact loadings. As the impact energy was increased, the electrical resistance of the samples also increased. Also, the electrical resistance of the samples generally recovered after the impact loading. Table 1 showed the maximum normalized resistance of CNT/epoxy composites under the impact loadings. The maximum normalized resistance of 20 was observed at the impact energy of 20 J.

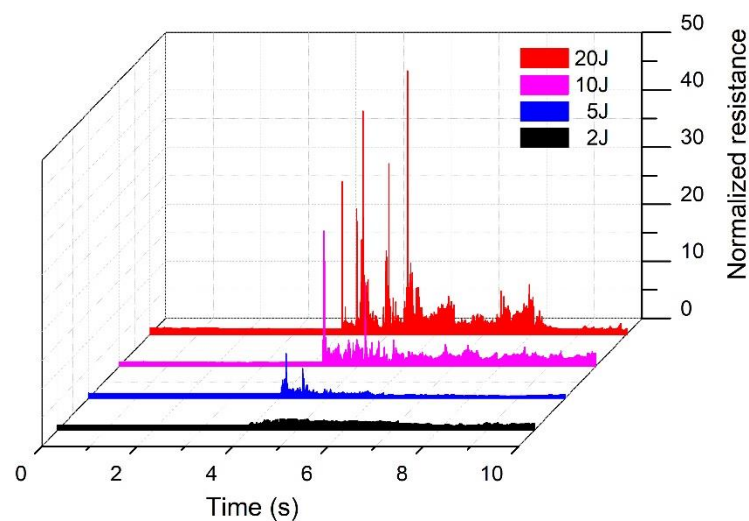


Figure 5. Electro-mechanical response of CNT/epoxy composites under impact loadings.

Table 1. Maximum normalized resistance of CNT/epoxy composite under impact loadings.

	Impact energy (J)			
	2	5	10	20
Max. R/R_0	2	8	20	45

4 CONCLUSIONS

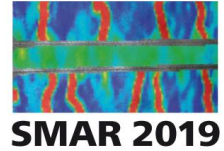
In this paper, we proposed the self-sensing infrastructure materials consisting of carbon nanotubes and epoxy matrix for smart cities. CNT/Epoxy composites showed high electrical conductivity as increasing CNT concentration. Electro-mechanical characterization of CNT/Epoxy composites under the static and dynamic compressive loading was investigated. It was found that CNT/Epoxy composites exhibited good sensing capability against the compressive loadings. Therefore, proposed CNT/Epoxy composites can employ as the self-sensing infrastructure materials for smart cities. They are suitable for monitoring civil infrastructures without any additional sensors, leading to significant saving for maintenance cost. Although the study was only includes a single component, in the future, the author will extend multiple components for real application to detect a crack and fracture. Future applications covers all traditional infrastructures such as bridges, buildings, and defence-related facilities that requires the structural health monitoring.

5 ACKNOWLEDGEMENT

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