Development of Carbon Nanofiber Aggregate for Concrete Compressive Strain Monitoring

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Abstract

Fiber research in concrete construction is an ongoing field and the use of carbon nanofibers (CNFs) is critically examined in this study. Short-fiber composites are a class of strain sensor based on the concept of short electrically conducting fiber pull-out that accompanies slight and reversible crack opening. The electrical conductivity of the fibers enables the direct current (DC) electrical resistivity of the composites to change in response to strain damage, allowing sensing. Because of the high cost associated with CNF, a CNF aggregate (CNFA) is developed. The CNFA is a 16.39 cm^3 (1.00 $in.^3$) cubic specimen of CNF mortar. It can be embedded in reinforced or prestressed concrete structures and used to monitor localized damage.

1. Introduction

Because of the past success at the University of Houston demonstrating that self-consolidating carbon nanofiber concrete (SCCNFC) can be used as a strain sensor (Gao et al. 2009; Howser et al. 2011), a CNFA was developed to determine localized strain in concrete structures. The development of a CNFA is significant because it is possible to use the strain sensing capabilities of SCCNFC with a greatly reduced cost since only the CNFAs placed in the structure would contain CNFs. For the purpose of compressive strain monitoring, the CNFAs were embedded in concrete cylinders and tested in compression to determine a relationship between compressive strain and electrical resistance.

2. Development of the Carbon Nanofiber Aggregate

A CNFA is developed with self-sensing capabilities. The CNFA is a 2.54 cm by 2.54 cm by 2.54 cm (1.00 in. by 1.00 in. by 1.00 in) cube of mortar contain 0.70% CNFs by weight of cement. This size allowed for both reasonable construction limitations and manageable space in which to place the four wire meshes needed for the four probe method. The electrical resistance is measured in the CNFAs through the embedment of four steel meshes and the use of the four-probe method (shown in Fig. 1). Based on results from the tests completed to determine the optimal CNF dosage, a mix design was developed to optimize the material and electrical properties. See Table 1 for the CNFA mix design proportioned by the total weight of the mortar.

The mixing procedure used for the CNFAs is a hybrid of the mixing procedure proposed by the University of Michigan for a high performance self-consolidating steel fiber reinforced concrete mix (Liao et al. 2006) and the mixing procedure proposed by the University of Houston for a self-consolidating CNF concrete (Gao et al. 2009). In this newly proposed hybrid mixing procedure, the water, high-range water reducer (HRWR), and CNFs were premixed and added to the cement, silica fume and fine aggregates in several steps to create a homogenous paste. The mixing procedure is appropriate for small mortar mixes.

3. Carbon Nanofiber Aggregate Compressive Strain Study

The goal of the experiment was to measure how the electrical resistance of an embedded CNFA varies with strain. The CNFAs were embedded in 7.62 cm (3 in.) by 15.24 cm (6 in.) cylinders. To measure the electrical resistance, the outer wires of the CNFA were connected in series with a 5.6 kΩ resistor and a 10 V power supply. The voltage drops across the inner wires of the CNFA and resistor were measured using the data acquisition system dSpace. As there was an impedance problem within the data acquisition system, differential amplifiers were placed between each component of the circuit and the data acquisition system. Here we discuss two groups of cylinders. Group 1 contains 12 cylinders using monotonic loading, Group 2 contain 3 cylinders using cyclic loading.

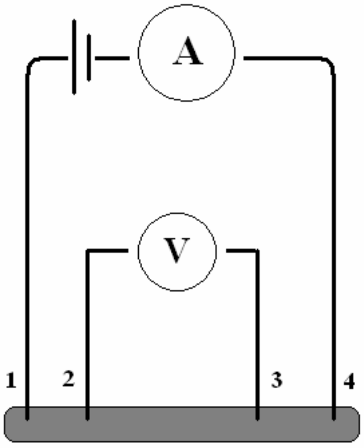

Fig. 1 Four Probe Method

Table 1 CNFA Mix Design

Material	Percentage of Total Mortar Weight
Fine Aggregate	52.9%
Cement	28.6%
Water	12.14%
Silica Fume	4.29%
HRWR	1.957%
CNFs	0.200%

The experimental results for Group 1 showed that when each cylinder began loading as the electrical resistance variation (ERV) increases from 0 simultaneously with the stress and strain. The maximum ERV occurs near a strain of 0.001 for each case. From the voltage variation (VV) curves, failure is clearly shown by a sudden drastic change in the negative direction. After introducing a calibration factor to reduce the variation in the tested results, Equation 1 was developed to describe the relationship between calibrated ERV and strain (shown in Fig. 2).

$$ERV_c = \frac{C}{393}\left(7.59\sqrt{\varepsilon} - 112\varepsilon\right)$$

Equation 1

where:

ERV_c: Calibrated ERV.

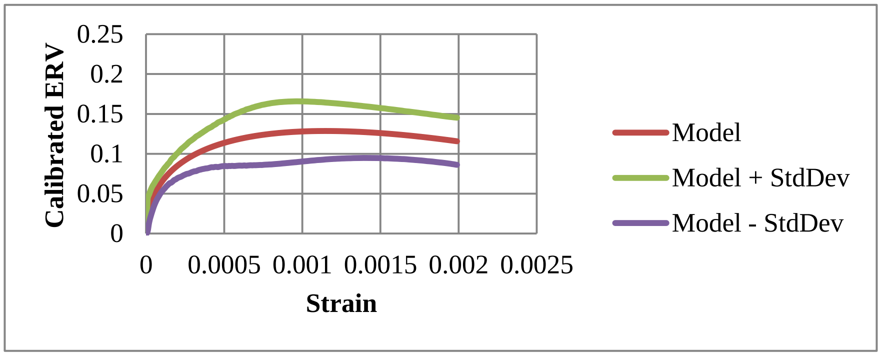

Fig. 2 Strain versus Calibrated ERV for Group 1

Group 2 contained 3 cylinders using displacement-control cyclic loading. A base displacement of 0.0381 mm (0.0015 in.) was chosen. Two cycles were applied at n times the base displacement where n=1, 2, 3, etc. until failure. The experimental results for Cylinder A are shown in Fig. 3, the other two cylinders exhibited similar behavior. Some simple modifications were made to the model found for Group 1 in an attempt to predict the cyclic behavior of embedded CNFAs. The model is shown graphically in Fig. 4 and Equations 2-5. Cylinder A was modeled using the proposed equations; the validation shows the calibrated and modeled EVR versus time and strain roughly agree.

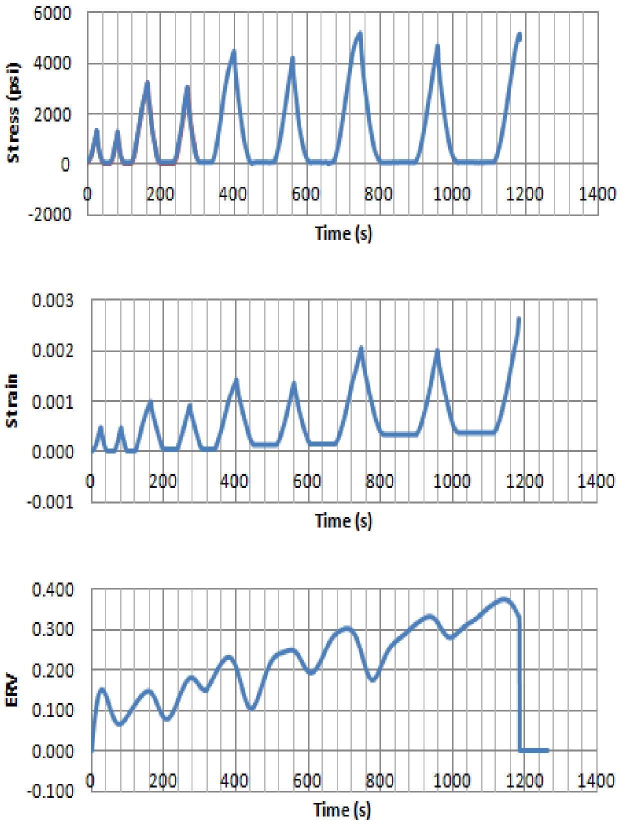

Fig. 3 Cylinder A Stress, Strain, and ERV versus Time

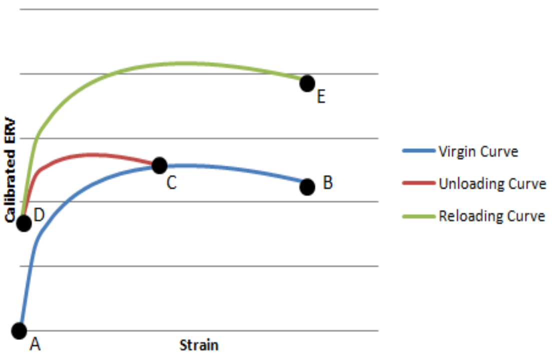

Fig. 4 Cyclic Strain versus Calibrated ERV Model

For curve A-C-B, it follows Equation 1

For curve C-D, it follows:

$$R_u = ERV_t - \frac{2}{3}\frac{C}{393}\left(7.59\sqrt{\varepsilon_t} - 112\varepsilon_t\right) \quad \textbf{Eq.2}$$

$$ERV_u = \frac{2}{3}\frac{C}{393}\left(7.59\sqrt{\varepsilon} - 112\varepsilon\right) + R_u \quad \textbf{Eq.3}$$

For curve D-E, it follows:

$$R_r = ERV_t - \frac{C}{393}\left(7.59\sqrt{\varepsilon_t} - 112\varepsilon_t\right) \quad \textbf{Eq.4}$$

$$ERV_r = \frac{C}{393}\left(7.59\sqrt{\varepsilon} - 112\varepsilon\right) + R_r \quad \textbf{Eq.5}$$

4. Summary

A carbon nanofiber aggregate (CNFA) was developed with self-sensing capabilities. Two groups of cylinders with CNFAs embedded were tested in compression monotonically and cyclically. A qualitative assessment of the electrical data from a CNFA embedded in a cylinder can show when loading began on the cylinder, a strain of approximately 0.001, and failure. A calibration factor was applied to the ERV value to obtain a reasonable coefficient of variation and two models were developed to estimate the monotonic and cyclic ERV versus strain relationship.

5. Acknowledgement

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6. References

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