Structural Health Monitoring Using Carbon Fibre Reinforced Concrete

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Abstract: Self-sensing concrete (SSC) refers to a structural material that can monitor itself without the need of any embedded, attached or remote sensors. By measuring electrical resistance of the self-sensing concrete, the stress, strain, crack and damage can be in situ monitored. Compared with conventional structural materials which require additional sensors for monitoring or detection, the SSC is advantageous in terms of high sensitivity, good mechanical property, natural compatibility, identical lifespan with concrete and easy installation and maintenance. It has been found that carbon fibre reinforced concrete can function as a smart structure material that allows non-destructive electrical probing for the monitoring of flaws. In this study the effect of addition of short carbon fibers (0.5-2.5% by weight of cement) on the electrical behavior of concrete was investigated. Both strain and damage sensing properties of carbon fiber reinforced concrete were investigated in the present study. Strain sensing tests were first made on the material's elastic range, by gradually loading specimen up to 54KN. At the same time both strain and resistivity were measured. The former was controlled using strain gages, and the latter using a Key sight digit multimeter on a two probe setup. The electrical resistance of carbon fiber reinforced concrete was found to decrease reversibly upon increasing compressive loading and reversibly increased upon unloading.

Keywords: self-sensing concrete (scc), carbon fibres, strain gauges, resistivity.

Introduction

Concrete is the second most used resource in the world after water. Regardless of long service life of civil engineering infrastructures, they cannot be considered as maintenance-free. These engineering structures are the most expensive investments and assets of any nation. Worldwide incidents of tragic failures of civil infrastructures remind that suitable measures are required to avoid sudden collapse of civil structures and associated loss of money and lives.

The weakening and failure of concrete structures occur mainly due to ageing of materials, aggressive environmental conditions, prolonged usage, overloading, difficulties involved in proper inspection methods, and lack of maintenance. Within the microstructure of concrete, it contains numerous cracks in nano-scale. These cracks are formed during manufacturing or use. With time, nano-cracks join to form micro-cracks, which in turn, leads to formation of macro-cracks and failure of structures. Increasing concern about the status of existing structures, particularly after earthquakes, has motivated numerous studies on damage detection using various non-destructive evaluation methods. Through early detection of these inherent damages, sudden collapse and accidents can be avoided. Timely detection of damages and proper maintenance can greatly enhance the service life of concrete structures.

Review of Literature

The structure of self-sensing concrete depends to a high degree on the composition of the composites. As a composite, self-sensing concrete consists mostly of matrix materials (i.e., conventional concrete materials) and functional filler. In addition some auxiliary materials may be necessary to disperse functional fillers into the matrix materials. Therefore, selection of suitable materials and determination of their proportions are important for fabricating self-sensing concrete. The influence of the carbon fiber as a smart material was developed and application of carbon fiber as a smart material for damage assessment and for static and dynamic loading. The carbon fiber reinforced cement as a strain sensing coating was then after investigated.

Objective

Self-sensing carbon fibre based concrete has high sensing ability that can be easily applied for health monitoring purpose. But the addition of these fibres changes the basic properties of concrete and hence the earlier method for conventional concrete cannot be applied directly to this concrete. The primary objective of this research is to study health monitoring of concrete by casting sufficient specimens like cubes, cylinders and beams reinforced with carbon fibres and without fibres and to form the co-relation between the conventional concrete and specimens reinforced with carbon fibres. The main objectives of the work are:

- To study the electrical resistivity behavior of concrete by adding various percentages of carbon fibers (0-2.5% by weight of cement).
- To study the strain sensing and damage sensing ability of the fibre reinforced concrete.
- To find the threshold percentage of carbon fibres for making effective self-sensing concrete.

Structural Health Monitoring (SHM)

Structural Health Monitoring (SHM) is a fairly new engineering field oriented to the development of damage detection systems able to facilitate the transition from scheduled maintenance to condition based maintenance, Semperlotti (2009). Engineers define health monitoring as the measurement of the operating and loading environment and the critical responses of a structure in order to track and evaluate the symptoms of operational anomalies and/or deterioration or damage that may impact service or safety reliability. Indeed, SHM resembles to a great extent the nervous system of humans. The nervous system of humans consists of a complex collection of nerves and specialized cells and the main processing unit (brain). The nerve cells transmit signals between different parts of the body and the brain. The brain is the main control unit for receiving and processing information as well as issuing instructions. In the same manner, SHM consists of a sensory network to gather information and a control unit for data processing and decision making.

It is important to mention that besides damage detection, the objectives of structural monitoring systems may be extended to include: quality control during the construction, serving as a warning system under successive loading, as well as condition assessment about its serviceability and ultimate limit state. So, one of the important works to be done by civil engineers is to maximize the degree of mobility of the system. This requires not just routine or critical event (such as an earthquake) based inspections, but rather a means of continuous monitoring of a structure to provide an assessment of changes as a function of time and an early warning of an unsafe condition using real-time data. Based on the monitored state, appropriate repair and/or strengthening of structures are properly programmed to keep these structures operational and further to lengthen their lives. Therefore, health monitoring of civil structures has been attracting much attention from research community and practicing engineers, as more and more structures are suspected to deteriorate by aging, especially, in many development countries, Abe (1998).

In general, a typical SHM system consists of three major components: a sensor system, a data processing system (containing data procuring, storage and transmission systems), and an evaluation system (comprising information management and diagnostic algorithms). The primary step to set-up an SHM system is to use stable and reliable sensing tools or sensors). Different sensors such as fibre optic sensors, piezoelectrics, magnetostrictive sensors, self-sensing composite materials, etc. possess capabilities of sensing various physical and chemical parameters related to the health of civil structures.

Carbon fibers

Carbon fibers (alternatively CF, graphite fiber) are fibers about 5–10 micrometers in diameter and composed mostly of carbon atoms. Carbon fibers have several advantages including high stiffness, high tensile strength, low weight, high chemical resistance, high temperature tolerance and low thermal expansion. These properties have made carbon fiber very popular in aerospace, civil engineering, military, and motorsports, along with other competition sports. 6mm long carbon fibers were used in this research. Carbon fibers are electrically conductive and also have a small diameter, making them the best choice for use in smart materials. The addition of carbon fibers has proved to be one of the most effective ways of improving the electrical conductivity of cement concrete.

Fig.carbon fibres (6mm long)

Dodecylbenzenesulfonic acid sodium salt (surfactant)

Surfactants can improve aqueous dispersion of nanomaterial's by reducing surface tension of water and, moreover, lead to stable dispersion as a result of electrostatic and/or steric repulsions between the surfactant molecules adsorbed on the nanomaterial's surface. However, the dispersion capability of surfactants strongly depends on their concentration, and an optimum surfactant to nanomaterial's ratio should be used for preparing cementitious composites. As per literature review a ratio between 3 to 5 gives a good dispersion of the fibres.

Dodecyl benzene sulfonic acid sodium salt was used as a surfactant in the present work. The surfactant to fibre ratio used in the present work is 4.5.

Fig.Dodecylbenzenesulfonic acid sodium salt (surfactant)

Methodology

1. Collection of Material.

This step involved procurement of the materials required for construction of cube samples viz.

- Cement
- Fine aggregates
- Coarse aggregates
- Carbon fibers
- Dodecylbenzenesulfonic acid sodium salt (surfactant)
- Master Glenium Sky 8866 (super plasticizer)

2. Testing of Materials.

The materials were tested in order to authenticate the quality of material to be used for casting. The tests involve physical tests for cement, fine aggregates and coarse aggregates.

3. Casting of Cubes.

A total of 21 cubes of size 100mm *100mm were casted for the present work. The specifications of the cubes and the percentage of carbon fibres (by weight of cement) in each sample are as under:

- Sample 1: Three cubes containing 0% of carbon fibres.
- Sample 2: Three cubes containing 0.5% of carbon fibres.
- Sample 3: Three cubes containing 1% of carbon fibres.
- Sample 4: Three cubes containing 1.5% of carbon fibres.
- Sample 5: Three cubes containing 2% of carbon fibres.
- Sample 6: Three cubes containing 2.5% of carbon fibres.
- Sample 7: Three cubes containing 3% of carbon fibres.

4. Testing of Cubes.

Cubes were tested in loading frame and UTM to determine stress, strain and resistivity behavior of concrete. Two types of tests were conducted:

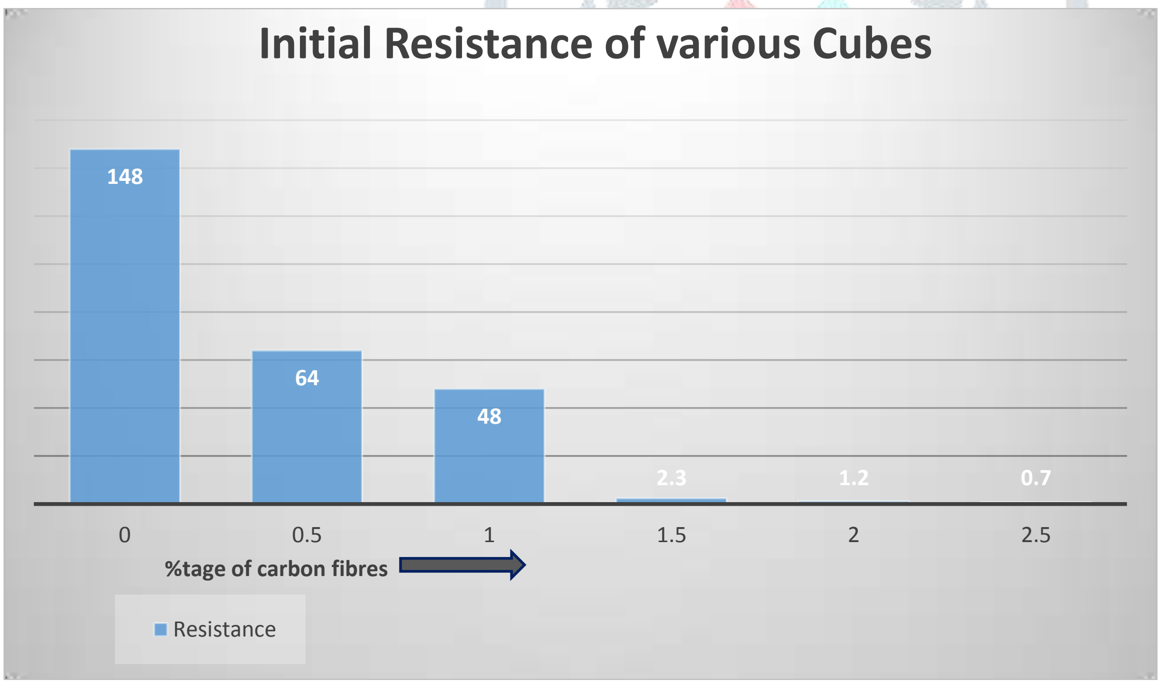
- Strain sensing test

- Damage sensing test

Results and Discussion
Initial Resistance of Cube Specimens
Table shows the average initial resistance of the various cube specimens.

Table: Initial resistances of various cube samples

Serial no.	Percentage of carbon fibres (by weight of cement)	Resistance (10^3 ohms)
1	0	**148**
2	0.5	**64**
3	1.0	**48**
4	1.5	**2.3**
5	2.0	**1.2**
6	2.5	**0.7**

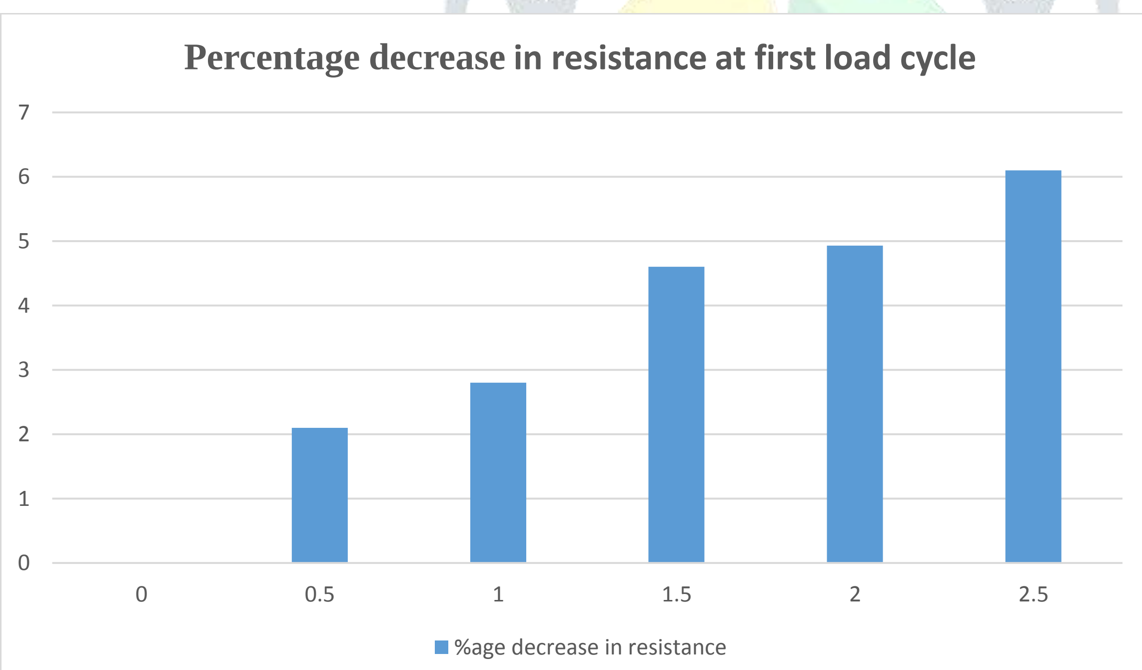


The resistivity dropped upon addition of the fibers. The most abrupt decrease occurred at a carbon fiber content of 1.5%.

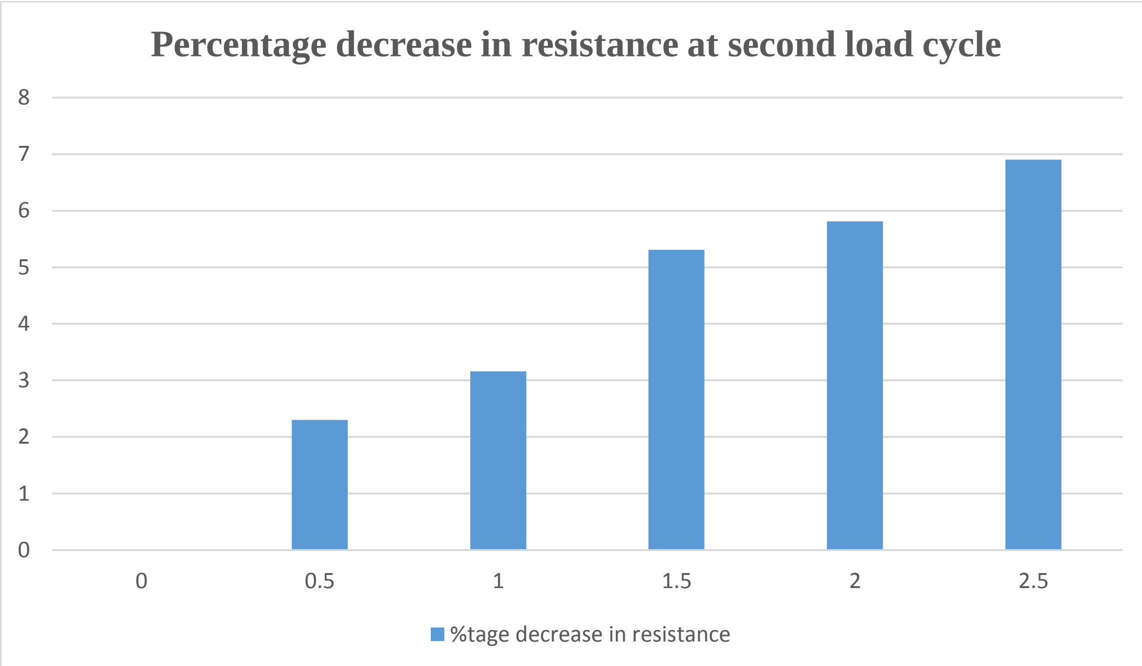
Strain Sensing Test
After resistivity characterization, CNF self-sensing tests were run. All cube specimens were loaded to a maximum stresses of 5.4 MPa to guarantee elastic behavior in concrete specimens. Each test consisted of two consecutive loading–unloading cycles (compressive). Testing was done on cubes after 28 days of curing. Cube samples without fibers showed no change in the resistance during the stress cycling. All mortars with fibers showed:

- Reversibly decreasing resistance during the loading,
- Reversibly increasing resistance during unloading in any cycle

Setup for strain sensing test



Comparison of percentage decrease in resistance at different percentages of carbon fibre during first load cycle.



Comparison of percentage decrease in resistance at different percentages of carbon fibre during second load cycle.

Discussion

The onset of the resistivity decrease during loading in the First and second cycle occurred at a compressive stress of 0 and 0 MPa for the all concrete cube samples except cubes with 0% fiber content. The maximum load applied was 54 KN corresponding to a stress value of 5.4 MPa. The cubes with 0% fibre content showed negligible change in resistance upon loading. The fractional decrease in the resistivity upon loading in the first cycle was **2.1** %, **2.8** %, **4.6**%, **4.93**% and **6.1** % for the cubes with 0.5%, 1.0%, 1.5%, 2.0% and 2.5% fiber content respectively.
The fractional decrease in the resistivity upon loading in the second cycle was **2.3** %, **3.16** %, **5.31**%, **5.81**% and **6.9**% for the cubes with 0.5%, 1.0%, 1.5%, 2.0% and 2.5% fiber content respectively. These results point to a proper performance of the sensors, as their general behavior matches previously detected trends in CNF paste specimens axially loaded.
The roughly linear behavior of the resistivity decrease (versus stress) for the cubes with fibers indicates that these composites can be used as smart structure materials that are capable of non-destructive monitoring of concrete structures.

Conclusion

Drop in electrical resistance was observed by the addition of carbon fibres and the most abrupt decrease occurred at a carbon fiber content of 1.5%.The electrical resistance of carbon fiber reinforced concrete was found to decrease reversibly upon increasing compressive loading up to 54 KN load in the first loading cycle, and reversibly increased upon unloading. This effect is attributed to reversible crack opening in subsequent unloading and reversible crack closure in subsequent loading. In contrast, the resistance was constant during loading and unloading in any cycle for the case of concrete without fibers. Thus, carbon fiber reinforced concrete can serve as a smart structure material, the resistance of which can be non-destructively monitored to detect flaws. Roughly linear relationships were observed among the percentage resistance change, the compressive stress and the compressive strain in any cycle for cubes containing carbon fibres. Thus, among the concrete mixes containing variable percentages of carbon fibres, the ones having fibre percentage greater than 1.5 were most attractive, as they exhibited a combination of linearity (between resistivity and stress) and large fractional resistivity increase.

Keeping economy in mind, it can be concluded that the concrete containing 1.5% carbon fibers is the most attractive for use as a smart structure material.

Acknowledgement

The first author wishes to express sincere thanks to “NIT Srinagar and Al-Falah University” for providing all the facilities to carry out this work.

References

[1] Chen, P.-W., Chung, D. D. “Concrete as a new strain/stress sensor”. Composites Part B.

[2] S.Wen andD.D. L.Chung, “Self-sensing of flexural damage and strain in carbon fiber reinforced cement and effect of embedded steel reinforcing bars,” Carbon, vol. 44, no. 8, pp. 1496–1502, 2006.

[3] B. Han and J. Ou, “Embedded piezoresistive cement-based stress/strain sensor,” Sensors and Actuators A: Physical, vol. 138, no. 2, pp. 294–298, 2007.

[4] P.-W. Chen and D. D. L. Chung, “Carbon fiber reinforced concrete for smart structures capable of non-destructive flaw detection,” Smart Materials and Structures, vol. 2, no. 1, pp. 22– 30, 1993.

[5] M. Sun, Z. Li, Q. Mao, and D. Shen, “Study on the hole conduction phenomenon in carbon fiber-reinforced concrete,” Cement and Concrete Research, vol. 28, no. 4, pp. 549–554, 1998.

[6] S. Wen and D. D. L. Chung, “Uniaxial tension in carbon fiber reinforced cement, sensed by electrical resistivitymeasurement in longitudinal and transverse directions,” Cement and Concrete Research, vol. 30, no. 8, pp. 1289–1294, 2000.

[7] S. Wen and D. D. L. Chung, “Uniaxial compression in carbon fiber-reinforced cement, sensed by electrical resistivity measurement in longitudinal and transverse directions,” Cement and Concrete Research, vol. 31, no. 2, pp. 297–301, 2001.

[8] B. Chen, J. Liu, and K.Wu, “Electrical responses of carbon fiber reinforced cementitious composites to monotonic and cyclic loading,” Cement and Concrete Research, vol. 35,no. 11,pp. 2183– 2191, 2005.

[9] M. Chiarello and R. Zinno, “Electrical conductivity of self-monitoring CFRC,” Cement and Concrete Composites, vol. 27, no. 4, pp. 463–469, 2005.

[10] Wen S, Chung DDL (2007), “Electrical-resistance based damage self-sensing in carbon-fiber reinforced cement”. Carbon 45: 710–716.

[11] Wang W, Dai H, Wu S (2008), “Mechanical behaviour and electrical property of CFRC strengthened RC beams under fatigue and monotonic loading”. Mater Sci Eng A 479:191–196.

[12] IS: 383-1970.

[13] IS: 456-2000.

[14] IS: 10262 -2010.