Experimental behaviour of smart concrete embedded with micro carbon fibres as a sensing material

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Abstract. While there are distinct structural health monitoring methods available, health monitoring using smart concrete is a newly emerging technique. In this technique, cement mortar/concrete is made as self-sensing by introducing carbon fibres in the conventional concrete that can sense strains/stresses/loads. Therefore to study in detail about this technique, in the present research, concrete cubes made from self-compacting concrete of 15 cm size reinforced with carbon fibres in various dosages were cast. Different tests have been performed on sufficient specimens that include stress/strain sensing and crack/damage sensing that resulted in finding co-relation between properties of concrete cube and change fractional resistance (FCR). The obtained results promised that when carbon fibres in the specimen are dosed with 1.5% can give the best co-relation between FCR and concrete cube properties and also the same dosage found to be best suited for stress sensing and crack/damage sensing.

Keywords: Electrical properties, Carbon Fibres, Gauge factor, Self-compacting concrete.

1. Introduction

Structural health monitoring (SHM) refers to the mechanism by which damage/crack identification and characterization techniques are applied for structures such as bridges and houses. In an internal building element, it is a common procedure to mount tension/compression recording devices such as extensometers/strain gauges, load cells, dial gauges, etc. at a given localization on the surface / internal areas of the structural element for structural health monitoring[1], [2]. SHM by this process may not give actual internal stresses in the reinforced concrete element and also restricted SHM for the complete structure.

To overcome this demerit, research by different investigators has found that unlike other fibres, carbon fibres, multiwall carbon nanotubes, nanotubes, carbon black, etc., have the very good self-sensory ability. When such fibres are haphazardly distributed in cement/mortar composites, they activate the sensory properties of these composites [3]. Such fibres can be immediately seen to modify the cement composites electrical resistance subjected to loads, and thus cause the corridor to be continuous health monitoring [3], [4]. Hence, the system of SHM can be applied by deputizing internal attaching sensors to concrete if the same technique is extended into the concrete.

The current literature review by different researchers noted that, under externally applied load (compressive), the electrical resistance changes (increases/decreases) for carbon fibre (CF) based cement specimen/smart concrete/self sensing concrete [5], [6]. Likewise, the compression surfaces
electrical resistance reduces during flexural loading as fibre moves towards each other due to stretching of surface, and then the same electrical resistance increases during unloading at the tensile surface as the fibres are pulled away from each other. [5], [7]. Several scientists investigated the behavior of cementitious composites when CF was introduced into it [5], [9], [10]. In different studies, CF and CNT’s each of individual percentages, and combined, on cement composites were investigated for damage and strain sensing properties [11]-[15]. Few more investigators have investigated the real use of carbon fibre for traffic control when used in cement composites [16] and SHM [17].

Recent work has been performed on the use of CNT and CF as cement sensors to track structural vibration [18] and are found to be useful in vibration monitoring of structure as these sensors can detect natural frequency. These have been shown to be of use for structure vibration monitoring as these nano-modified cement sensors can detect natural frequencies. Recent work on columns found that fabrication of column using carbon nano fibres can help in structural health monitoring [19] that level of damage in RC columns. However, in the above experiments, on the column author could not establish accurately the relation between compressive stress and electrical resistance. [5]. A few experiments have also been performed [20]–[22] on conventional concrete specimen’s reinforced with CF’s/Multi Walled Carbon Nano Tubes (MWCNT’s)/ Carbon nano Tubes (CNT’s) where, mechanical properties have been concentrated in tests. Similar experiments by Baoguo Han et al. [23] witnessed that, if CF of 3 mm in length is added with ultrasonic methods, compressive strength was found to increase but the strength was not increased by adding CF’s of 6 mm length.

In order to evaluate strain/stress sensing property of carbon fibre based concrete, one has to understand the term gauge factor (GF). Gauge factor is a terminology used for the measurement capability of fibre based concrete to stress/strain sensing and can be explained as the ratio of change in FCR upon strain(unit) in the specimen [8] and can be calculated using equation 1.

\[
GF = \frac{(\Delta R/R_0)}{(\Delta L/L)} = \frac{(\Delta R|0)}{Strain}
\]

\[
FCR = \frac{\Delta R}{R_0}
\]

Existing literature review reflects that major amount of work done in this field is restricted to cement/mortar specimen only. Therefore it becomes imperative to study in detail about the strain/stress/damage sensing behaviour of structural concrete rather than cement mortar. In order to evaluate the same, and also to obtain percolation threshold of carbon fibres, concrete cubes made from self compacting concrete has been fabricated with varying dosages of carbon fibres from 0% to 2%. The fabricated cubes (self sensing/smart concrete cubes) have been tested to check different properties like electrical, mechanical, stress and damage sensing properties when embedded with carbon fibres. The percolation threshold is defined as the state in which continuous electrical charging flow occur due to the haphazard dispersion of conductive fibres within the concrete body.

2. Experimental Procedure

2.1. Material properties

The cement blend was made from 43-degree OPC cement. Tap water in the specified water-cement ratio (w/c) of 0.4 has been used for all sample preparations. Also a surfactant named Dedocyclic benzene sulfonic sodium salt [16] is blended in water to assure an effective dispersion of CF’s. Carbon fibres SYC-TR-PU (supplied by Sanyung company, China) with various percentages starting from 0 to 2% and 0.5% step increments each is used in self-compacting concrete (SCC). Though there are different types of fibres like steel fibres, glass fibres, asbestos fibres etc., among all carbon based fibres are found to be very advantageous for self sensing purpose. In present study chopped carbon fibres have been selected over CNF’s, MWCNT’s, Single walled Carbon Nano Tubes (SWNT’s),
carbon black etc., as these fibres can be dispersed in concrete with little efforts and are easily available in market in a economical way. Different doses of CF’s have been used with aspect to study stress sensing, damage sensing behavior and the percolation limit for further analysis. The percolation limit can be defined as a condition in which carbon fibre contacts each other at random distribution and forms tend to have a low electrical resistance. The least amount of fibres necessary for this leading path is known as the threshold for percolation [6]. Table 1 presents the physical properties of CF’s implemented in this analysis. SCC is developed in this experimental study to achieve improved fibre dispersion and concrete workability. To generate SCC, a super plasticizer based on polycarboxylic ether (PCE) was added one percent by weight of cement.

| Table 1. Carbon fibres (CF) Properties |
|---------------------------------------|
| Length | Mm | 6 |
| Carbon Content | % | 95 |
| Filament Diameter | µm | 6.97 |
| Density | g/cm³ | 1.78 |
| Tensile Strength | MPa | 4,810 |
| Density | g/cm³ | 1.78 |
| Tensile Modulus | GPa | 225 |
| Elongation | % | 2.3 |
| Electrical Resistivity | w.cm | 1.54x10⁻³ |

2.2. Fabrication of Specimen
Concrete cubes of 15 cm were fabricated with varying dosage of CF’s. For production of fibre based concrete, initially a solution having mix of surfactant and water (required for casting) was prepared by churning these two using a shear mixer for twenty minutes. Carbon fibre was subsequently added and mixed in the solution with the same mixer for twenty minutes for even distribution of CF’s in the solution. The afore obtained mix is then blended with dry concrete ingredients (that were already mixed in dry state and kept in mixer) with a super plasticizer of 1 percent to obtain SCC. The obtained fresh concrete mixture is then decanted in metal moulds and left at room temperature for 24 hours. After 24 hours the samples have been demoulded and preserved in fresh water for 28 days. Mix proportion of SCC along with material properties for 0.5% CF is shown in Table 2, keeping all the ingredients constant, only fibre volume has been changed for 1%, 1.5% and 2% CF samples. All the mixtures for slump flow in fresh state have been checked and are tabulated in table 3 along with its allowable limits as per EFNARC code, to ensure that the concrete used is self-compacted.

| Table 2. Mix proportion for SCC (0.5% CF mix) |
|---------------------------------------------|
| S. No. | Materials | Remarks | Quantity in kgs /m³ of concrete |
|-------|-----------|---------|--------------------------------|
| 1     | Cement   | 43 Grade OPC | 475 |
| 2     | Carbon Fibre | Electrically conductive | 2.37 |
| 3     | Fine Aggregate | FM-2.56 and Zone-III | 653.4 |
| 4     | Water     | Tap water having pH 7.1 | 203.4 |
| 5     | Coarse Aggregate( of maximum size 10 mm) | FM- 6.88 | 1174 |
| 6     | Surfactant | Dedocyl Benzenesulphonic acid sodium salt (SDBS) | 0.32 |
| 7     | Superplastizer | PCE based | 8.7 |

FM-Fiennes modules, PCE- Polycarboxylic ether
Table 3. Test results of Slump flow

| S. No. | Mix Designation representing % of CF | Obtained slump flow Diameter in 30 seconds (mm) | Allowable range as per EFNARC (mm) | Time for 500mm flow Dia. (T<sub>500</sub>) slump flow (sec) | Allowable limits for T<sub>500</sub> as per EFNARC (sec) |
|-------|-------------------------------------|-----------------------------------------------|---------------------------------|-------------------------------------------------|-----------------|
| 1     | 0                                   | 760                                           | 600-850                         | 2.5                                             | 2-5             |
| 2     | 0.5                                 | 745                                           | 600-850                         | 2.7                                             | 2-5             |
| 3     | 1                                   | 728                                           | 600-850                         | 3.0                                             | 2-5             |
| 4     | 1.5                                 | 702                                           | 600-850                         | 3.2                                             | 2-5             |
| 5     | 2                                   | 688                                           | 600-850                         | 3.6                                             | 2-5             |

2.3. Test Programme

Universal tester/test Machine (UTM) of capacity 1000kN was used for all the tests throughout the experiment. UTM was used to measure load and stress while Digital Multimeter (DMM) evaluated electric resistance changes. For all samples, on the concrete surface, an electrically conductive paint was applied and the wound of copper wire was done perpendicular to the direction of load application over this conductive paint as shown in fig. 1. Further, to record change in resistance upon loading, the DMM was attached to these copper wires.

![Figure 1. Detailing of the specimen](image)

2.3.1 Test setup for stress and damage sensing: During the stress sensing test, every specimen was loaded up to 250 kN and discharged at the same speed. The load was rising slowly at the constant speed of 1.6 kN/ sec. Loading -unloading of the specimen was performed for 3 cycles to track the stress sensing property. The load was registered from UTM and electrical resistance readings by DMM during this experiment.

For damage sensing test, each sample has been loaded to damage/failure at a load rate of 1.6 kN / sec. Stress, resistance and load were documented during the experiment and their behavior. The real laboratory design for damage and stress sensing studies is shown in Figure 2.
3. Experimental Results and Discussions

3.1. Ultimate strength

The compressive strength tests for evaluating peak load carrying capacity of three specimens from each carbon fibre dose were performed. It is done to ensure that, during stress/strain sensing test, applied load is within elastic limit and also to know the effect of addition of CF’s in the concrete. The apex compressive strength of all the cubes is demonstrated in Fig.3. The figure shows that peak stress with a rising quantity of fibre is marginally lower. This is be like due to more carbon fibres presence that lead to lower strength as small air packages are formed. Compared with no fibre specimen, a decrease of 1.67%, 6.4%, 8.6% and 11.6% of strengths was observed for 0.5, 1, 1.5 and 2% CF dosage respectively.

![Ultimate load carrying capacity](image)

**Figure 3** Ultimate load carrying capacity

3.2. Electrical Investigation

Before load application, initial resistance of all cubes was assessed by attaching a digital multimeter to the each concrete cube while holding back for 2 minutes to neutralize the fluctuation in readings. Two probe methods were used to obtain initial electrical resistance of all the samples. The initial resistivity of all specimens shows in Figure 4. The initial resistivity calculated using equation 3, decrements steadily from 0 to 1% fibre dose, decreases in a drastic manner at 1.5%, and decreases slightly at a 2% CF content. Thus a 1.5 percent CF dosage, percolation limit may be drawn from concrete cubes consisting of distinct percentages of fibre, where the fibre is still electrically connected through the specimens. Equation 3 was used to measure the resistivity of all samples. Alessandro et al. [18]
observed the same pattern of decreased resistivity in cement-based cement specimens with different dosages while using MWCNT’s and CF’s.

\[ \rho = \frac{AR}{L} \]  

(3)

**Figure 4** Initial resistivity

3.3. *Results of Stress sensing*

Keeping a constant loading rate of 1.6kN/sec, all the specimens were tested for a peak load of 260kN (elastic range) for 28 days of curing. For each dosage of carbon fibre, plot of FCR and stress is drawn with respect to time. During testing, strain, load on cube was measured using UTM while change in resistance using digital multimeter. Having load and resistance readings, stress was calculated using formula load upon area and FCR values were calculated using equation 2. Time related findings of stress and FCR are shown in fig.5.

**Figure 5** Compressive stress and FCR plot against time under cyclic loading
Results achieved suggest that the co-relation in Figure 5-a between stress and FCR is not very much in similarity in the specimen where CF is absent. The FCR is also much less than other specimens with a maximum order of 4x10^-5 that contain the embedded carbon fibres. Of fig. 5 shown from b to e, the close relation between FCR and stress can obviously be seen in better way in a reversible way during cyclic loading when the fibres dosage keep on increases as previously reported in previous study [23]. The average improvement in electrical resistivity was 4x10^-5, that increased to 200 times in specimen having 0.5 percent fibre, producing a overall increase of 0.007 (in the third cycle) for FCR relative to non-fibre specimens. The multiplication factor for FCR increases by 1.36 from 0.5 to 1%, and from 1 to 1.5% is 2.2 and from 1.5 to 2% is 1.52. Fig. f of figure 5, displays the plot of transition relating all samples on a single scale to FCR. It was observed by Galao et al. [26] that, among fibre based cement specimen cured for 7 and 28 days, the best results can be obtained for samples cured for 28 days.

For cyclic loading, using equation 1, the average GF was also determined. The mean GF values for various carbon fibre measurements are represented in fig.6. It was found that there wasn't a lot of difference between means GF of loading or unloading during the cyclic loading representing that analysis is correct. The GF increases as carbon fibre dose rises and the FCR readings indicate a strong rise.

![Figure 6 Gauge factor](image)

**3.4 Damage sensing study results**

All samples were subject to the same load speed as in the stress sensing check before cube failure. Fig.7 shows the relationship stress strain for all specimens with various dosages of CF's. While the strength didn’t greatly affected by 0.5 and 1% fibre dosing, additional CF decreases strength significantly. The average intensity decline as a result of fibre additions was 1.67, 6.4, 8.6 and 11.6% for 0-2% CF for every 0.5% step increment. Fig.8 shows the plotted stress curve and FCR for various carbon fibre dosages against strain. Fig 8(a) shows no relationship among the stress, strain and FCR in concrete specimens without carbon fibres, since fibres are not present, resulting due to no charging flow. But as the fibre dosage increased, the co-relation gets better and better and from economical point of view the 1.5% CF dosage can be considered as it gives healthy relation among stress and strain.
Figure 7. Stress–strain plot for multiple dosages of CF’s

a) 0% CF dosage

b) 2% CF dosage

c) 1.0% CF dosage
d) 1.5% CF dosage
The sudden increase in fractional resistance curve Fig 8 (a-d) indicates a sample failure because of no conductivity among the fibres because of large crack formation. The greatest increases in resistance from 0.00018 to 0.068 are also noted, as the fibre-dose increase from 0% to 2%. Surprisingly, the smooth curve (fig.8 b & c) in contrast to remaining specimens appears on the cubes with 1.5 and 2 percent fibres. Owing to the consistency of carbon fibres even after cube fracture, before the fracture is big opened up in the sample. The Galao et al.[5] and Yining Ding[24] also saw a sudden rise in FCR) as a cement specimen was loaded cyclically before a load increase failed with each load period. The FCR values of 0.5% and 1% fibre are suddenly increasing, on the other hand and there is no similar correlation between stress and FCR. This is because the fibres are less numerous and poorly or not connected after micro crack formation.

4. Conclusion

For stress sensing and damage detection tests, self-consolidating concrete cubes with distinct carbon fibre dosages have been evaluated in the present study. From this study, the following conclusions can be drawn:

- As carbon fibre dosage rises, electrical resistivity begins to decline and percolation levels are observed at a dose of 1.5 percent carbon fibre cement weight. The initial resistivity measured is 2.5x106 ohm-cm for non-fibre specimens, while 1.5% CF for 1.6x106 Ohm-cm is measured.
- The maximum compressive strength is observed to decrease with the increased carbon fibre dose because more fibres form agglomerates which result in void formation and reduction of strength.
- Properties namely strain and stress sensing are only clearly observed if fibres are embedded in the concrete and not in the conventional concrete.
- Presence of carbon fibres by 1.5% and 2% by weight of cement is observed to give good correlation between properties of concrete (strain/stress) and electrical resistivity (FCR) but from economical purpose, 1.5% CF can be viewed as best.
- Consequently, the findings of stress-damage-sensing tests are seen to provide a new way of SHM as an non-destructive test (NDT) method to detect changes in load/stress/strain acting on structure/structural element knowing electrical resistance.
Notations used:

- $R_0$ - Initial resistance,
- $\Delta L$ - Length change between the probes,
- $\Delta R$ - Electrical resistance change,
- $A$ - Cross sectional area,
- $L$ - Initial distance between the probes,
- $\rho$ - Resistivity.

Declarations

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