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Strain and Damage Sensing Property of Self-compacting Concrete Reinforced with Carbon Fibers

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ABSTRACT

Present paper investigated the strain and damage sensing property on concrete cubes embedded with carbon fibers. Concrete cubes of dimension 150 mm have been casted with different concentration of carbon fibers to study the strain and damage sensing property under cyclic loading that can be further used for health monitoring as non-destructive testing (NDT) approach. All the specimens were tested under cyclic loading within elastic region of the sample for three cycles of loading with a maximum load of 195kN for strain sensing test. During cyclic loading, fractional change in resistance (FCR) is calculated and co-relation with the stress is plotted. During strain sensing test, gauge factors (GF) were also calculated during loading and unloading on the samples. From obtained results, it is found that the concrete sample containing 1.5% of carbon fibers by weight of cement gives best co-relation between stress and FCR that can be further used for health monitoring purpose. Along with strain sensing property, damage sensing property and ultimate load carrying capacities of all the specimens are also reported in present paper with detailed explanation.

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NOMENCLATURE

ΔR	Change in electrical resistance	ΔL	Change in Length
Ro	Initial resistance	L	Length between the probes
ρ	Electrical resistivity	A	Cross section area

1. INTRODUCTION

Traditional concrete is a matrix of cement, fine and coarse aggregates capable of resisting compressive forces/stresses effectively. This concrete being heterogeneous material may have voids/loose/weak packets within the body with drastically reduced strength. Under load, these weak packets are unable to resist stresses and thereby transfer these stresses to surrounding concrete resulting in stress concentration and hence the failure of the section/member/structure. This has enforced the researchers to have regular knowledge about the internal body structure of concrete and the stresses induced in it during loading, reflecting as a study on internal health monitoring of concrete.

It is normal practice to wrap strain gauges on the body of concrete to notice the strain and thereby stress at a particular location on the surface of the concrete or steel [1]. Health monitoring by this process is selective and may not be valid for the internal body of concrete. Therefore, there is a need to observe comprehensively random health monitoring of concrete in a unified manner.

In recent studies, many researchers noticed that unlike other fibers, carbon fibers have very active self-sensing ability/property [2]. When these fibers are randomly distributed in concrete body, they induce resistibility and self sensing property in concrete [3] with improved mechanical properties of concrete/cement composites [4-7]. Any change anywhere (structural) in the body of concrete under load is immediately noticed by these fibers thereby providing a corridor for consistent health monitoring of concrete

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and reinforced concrete structures [3, 4, 8, 9]. Therefore, health monitoring by this process can replace usage of external device, embedded device and attachments [10, 11]. Health monitoring by this process reduces cost and improves the durability of the structure, as no embedded sensors are available.

1. 1. Strain Sensing Principal By addition of carbon fibers to concrete, concrete becomes sensor as it gains electrical sensing property. Electrical sensing property of a material can be defined as response on volumetric electrical resistivity due to its strain state [12]. Researchers observed that, when a cube or prismatic specimen is externally loaded, then there is variation in resistance through the sample due to movement of fibers either towards each other or away from each other. Studies revile that under compressive loading [13], resistance of the specimen increases as load increases [6, 7, 14]. Similarly in case of flexural loading, the resistivity at compression surface decreases because of movement of fibers towards each other and decreases at tension surface due to opposite movement of fibers because of pull in concrete [2, 8, 15, 16].

Strain sensitivity of carbon fiber reinforced concrete can be measured by a factor called as gauge factor (GF).This gauge factor may be defined as the fractional change in electrical resistance per unit strain [17]. Gauge factor can be calculated using Equation (1).

$$GF = \frac{(\Delta R|R0)}{(\Delta L|L)} = \frac{(\Delta R|Ro)}{Strain} \quad (1)$$

$$FCR = \frac{\Delta R}{Ro} \quad (2)$$

In recent years, many researchers [5,10, 11, 19] studied the behavior of cement paste and cement mortar composites, when carbon fibers are added to concrete. Strain-sensing [17] and damage sensing properties [4,12, 13, 20, 21] on cement composites has been studied by adding different percentages of carbon fibers and carbon nano tubes (CNT) and also in combination of both [22]. Few other researchers have also studied real application for traffic monitoring and health monitoring of structures [23, 24] using carbon fibers in concrete.

A recent investigation [25] has been conducted where vibration monitoring of structures is done using carbon fiber and carbon nano tubes as cementitious sensor. Using these cementitious sensors, natural frequencies in the structures can be found, that further helps in vibration monitoring of structures. Another recent study shows that structural health monitoring can be done on reinforced concrete columns that have been casted with CNF concrete and tested under reversed cyclic loading [26, 27]. Same study observed that, concrete embedded with carbon fibers is capable of detecting the level of damage in reinforced columns that can be used for real time structural health monitoring. However, in the above tests on column the author did not established the correlation between electrical resistance and compressive strain [12].

As the major work is done on cement and mortar paste, as compared to concrete, here is an attempt to work on concrete rather than cement or mortar specimens [16,19]. The main objective of this study is to extend the same strain and damage sensing property of cement composites to the conventional concrete for the purpose of health monitoring of concrete structures. Therefore, for the same reason in present study, sufficient concrete cubes embedded with carbon fibers with different dosages were casted and tested in order to obtain different properties like percolation threshold, gauge factor, strain sensing, damage sensing etc,. Percolation threshold may be defined as the state, where there is continues electrical path in the material due to randomly dispersed carbon fibers when they touch each other to give low resistivity. The least number of fibers required to get such conductive pathway is called as percolation threshold [14].

2. EXPERIMENTAL PROCEDURE

2. 1. Materials Concrete mix for all the samples was prepared using 43 Grade OPC cement and potable water with fixed water/cement ratio (w/c) of 0.38. A surfactant namely dedocyl benzenesulphonic acid sodium salt (SDBS) was also mixed in water for effective dispersion of fibers, as it is observed to be a good dispersion medium for carbon fibers [23]. Concrete cubes of 150 mm were prepared using carbon Fibers (CF's) of type SYC-TR-PU with varying percentages from 0 to 2% by cement mass with 0.5% step increment. Varying concentration of carbon fibers were added into concret cubes, in order to study the strain sensing behaviour, damage sensing behaviour and to know percolation threshold for further studies. Self-compacting concrete (SCC) is manufactured in this study in order to obtain good workability of concrete and to attain better dispersion of fibers within the concrete. For obtaining SCC, a polycarboxylic ether (PCE) based super plasticizer was added 1.5% by weight of cement. The specific gravity of super plastizer was 1.08; had solid contents not less than 32% by weight confirming ASTM C494 Type F standards. Fine aggregate of Zone 4 and coarse aggregate of less than 10mm were used with specific gravity of 2.69 and 2.74, respectively.

2. 2. Sample Fabrication Concrete cubes of 150 mm were casted using carbon fibers with different concentration as mentioned above. For uniform distribution and to avoid lumps of fibers, firstly a solution of water required for concrete quantity and the surfactant namely dedocyl benzene sulphonic acid sodium salt (SDBS) was prepared. Later fibers were added to this solution and the amalgam was mechanically churned for about ten minutes. This process ensured effective and uniform distribution of fibers in the solution. The other quantities of concrete mix were then blended in a mixture and the above fiber based solution was added gradually along with addition of 1.5% super plastizer, that resulted in the production of SCC having random but uniform distribution of fibers. The fresh mix is poured into the steel moulds and kept in room temperature (24^{o}C and RH 84%) for 24 hours. These samples were de-moulded after 24 hours and kept for curing in fresh water for 28 days. The mix proportion of SCC for 0.5% carbon fiber concentration is shown in Table 1 and the obtained slump flow test results of SCC mixes for different dosages of CF's are shown in Table 2 along with their permissible limit.

2. 3. Testing Procedure For all the specimens in the elastic regime resistance was measured using two probe methods. Two-probe method was preferred as samples were very small and the equipment used in present study had high accuracy due to omitting of errors even if voltage and current passes through the same path. Though study conducted by Azhar [28] suggests four probe method over two probe method, in present study two probe method was used as there was no response of resistance on loaded sample when four probe method was used.

Strain and damage sensing test was conducted on Universal Testing Machine (UTM). During testing, load and strain was measured in UTM and Keysight 34401A Digital Multimeter (DMM) measured the change in electrical resistance. For measuring electrical resistance, initially electrical conductive paint was applied on perpendicular phase of load application around four phases at a distance of 10mm from its ends as shown in Figure 1. Copper wires were adhered on top of this conductive paint using adhesive tape to ensure that the complete and continuous surface readings were obtained. The ends of copper wires, attached to top and bottom surface of the cube were connected to digital multimeter (DMM) for measuring change in resistance readings.

TABLE 1. Mix proportion of SCC for 0.5% CF specimen

Material	Mass required per m^3 (kg)
Cement	495
Water	188.1
Carbon Fiber	2.475
Surfactant	0.32
Sand	786
Gravel	853
Plasticizer	7.5

TABLE 2 Slump flow test results

Mix DesignationWith % of CF	Flow Dia. (mm) Obtained in 30 seconds	Permissible range as per EFNARC	Time for 500mm Dia. (T500)	Permissible range for T500as per EFNARC
0	672	600-850	2.7	2-5
0.5	668	600-850	3.1	2-5
1	661	600-850	3.4	2-5
1.5	654	600-850	3.8	2-5
2	632	600-850	4.2	2-5

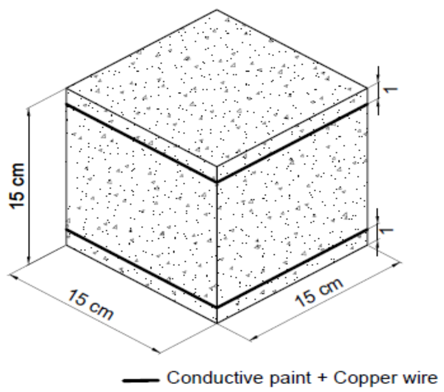

Figure 1. Dimensions of sample

2. 3. 1. Strain Sensing Test In strain sensing test, the cube specimens were loaded up to a maximum load of 195kN and then unloaded with the same speed. Gradually increasing load was applied with a constant loading rate of 1.2kN/s. The loading and unloading of the sample was done for 3 cycles to check its strain sensing behavior. Stress strain readings were obtained from UTM and change in resistance from DMM.

2. 3. 2. Damage Sensing Test In this test, the specimens were loaded up to failure with loading rate of 3kN/s. During this test, load, strain and resistance were noted and its behaviour was studied and explained in results and discussions in further sections.

3. EXPERIMENTAL RESULTS AND COMMENTS

3. 1. Electrical Investigation The initial (without applying load) resistance of concrete cubes was measured by connecting the multimeter to the sample and waiting for 2 minutes so that materials polarization developed. The initial resistance of the samples are shown in Figure 2. From same figure, it can be clearly observed that the resistance diminishes slowly from 0% fiber to 1% fiber concentration and drastically reduced at 1.5% fiber concentration and from there onwards slightly reduced at 2% fiber. Therefore, it can be said that, in samples containing different percentages of fiber, the percolation threshold can be considered at 1.5% carbon fiber, where fibers form the continues electrical link.

3. 2. Mechanical Properties Compressive testing was done on three samples of each carbon fiber dosage in order to get the peak load carrying capasities of the samples. This is done in order to obtain the elastic region of the sample and guarantee an elastic behaviour during strain sensing test. Figure 3 shows the ultimate compressive strengths of samples casted with different percentages of fiber.

From the figure it can be observed that with increase in percentage of fiber there is slight reduction in strength [29]. This is probably because of over saturation of fiber in the concrete that provides small amount of air packets resulting in strength reduction. The observed reduction in strengths for 0.5, 1, 1.5 and 2% fiber concentrations are 1.3, 4.1, 6.9 and 9%, respectively when compared with no fiber sample.

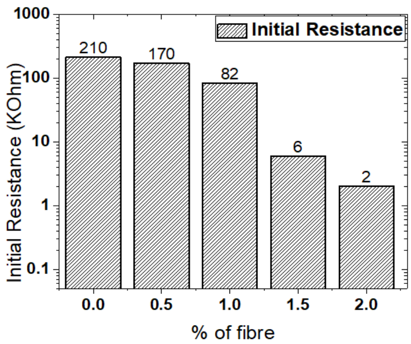

Figure 2. bar diagram showing initial resistance of samples for different percentages of carbon fiber

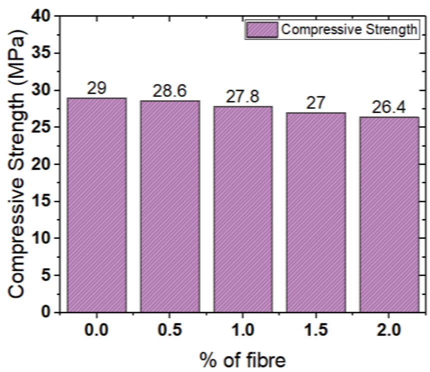

Figure 3. Compressive strengths

3. 3. Strain Sensing Test All the samples were tested for 28 days for a maximum load of 195kN keeping constant loading rate of 1.2kN/s in universal testing machine. Both stress and fractional change in electrical resistance is plotted with respect to time for all dosages of carbon fibers. The load and strain readings were obtained from UTM and readings of change in resistance were obtained from DMM. After obtaining load reading from UTM, stress values were calculated and fractional change in resistance (FCR) values were calculated using equation 2, where ΔR is change in electrical resistance at any point of time (difference of initial resistance and resistance at any time). Both obtained values are plotted with respect to time and are shown in Figure 4.

From obtained results it can be seen that, in Figure 4(a) there is no co-relation observed between the stress and fractional change in electrical resistance in the specimen where carbon fibers are absent. From the same figure it can be also noticed that the value of fractional change in electrical resistance is very less with a maximum order of $3x10^{-5}$ compared to other specimens where carbon fibers were embedded. On the other hand, presence of CF’s in specimens showed good correlation between the stress and fractional change in electrical resistance during loading and unloading in a reversible manner, which no fiber specimen failed to show, as also reported earlier [16]. From Figure 4 (b to e) it can be clearly seen that, as dosage of fibers increases there is good correlation between stress and change in electrical resistance.

In strain sensing test it was also observed that for no-fiber specimen, peak value of FCR is $3x10^{-5}$, for 0.5% fiber concentration it increases by 200 times giving peak change in electrical resistance of 0.006 compared to absence of fiber. This increase is because of presence of fiber in the concrete sample that gave electrical sensiation due to application of load which without fiber specimen fails to show. Similarly the increasing factor for FCR from 0.5 to 1% is observed as 1.3 (peak value increases by 1.3 times), from 1 to 1.5% is 2 and from 1.5 to 2% is 1.47. The best co-relation between stress and change in electrical resistance is observed at 1.5 and 2% fiber concentration. Galao et al. [30] has studied on cement composites (cement paste) casted with carbon fibers for obtaining strain and damage sensing property. It was observed that better strain sensing was achieved in the specimen that was cured for 28 days rather than 7 or 14 days. It was observed that obtained results in the present study followed the same trend as observed by them.

In Figure 4(a) it can be seen that as load changes in a cyclic manner, FCR did not changed in the same manor

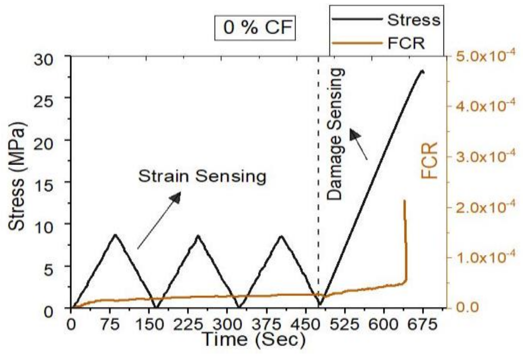

Figure 4(a). Strain and damage sensing of 0% CF sample

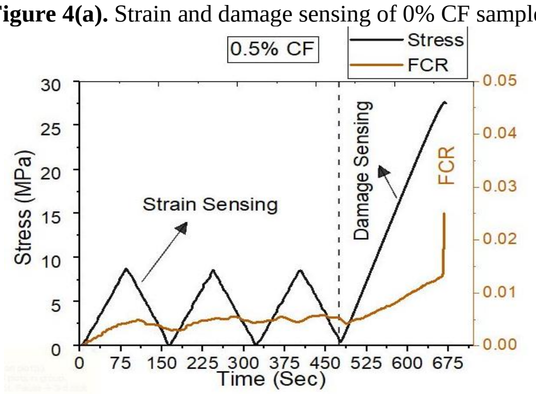

Figure 4(b). Strain and damage sensing of 0.5% CF sample

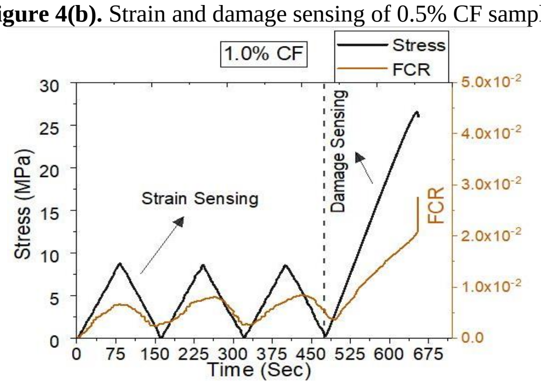

Figure 4(c). Strain and damage sensing of 1% CF sample

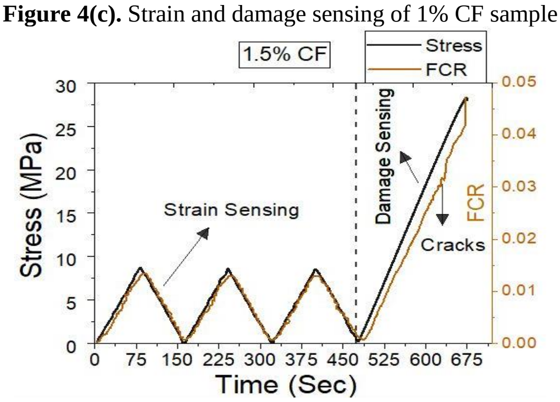

Figure 4(d). Strain and damage sensing of 1.5 % CF sample

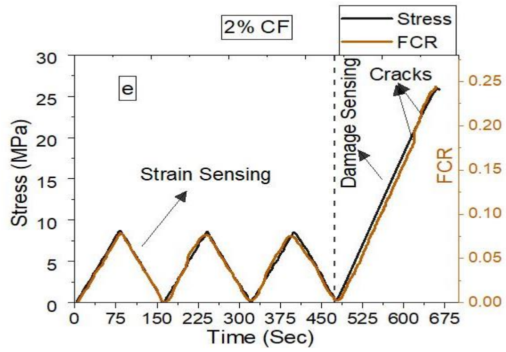

Figure 4(e). Strain and damage sensing of 2 % CF sample

Figure 4 (a)-(e) Results showing strain and damage sensing test on concrete cubes casted with different dosage of carbon fibers by mass of cement. Compressive stress and fractional change in electrical resistance are shown with respect to time

instead it was continuesly increasing. Therefore, it can be said that sample without fiber did not show any strain sensing property under cyclic loading. Similarly from Figure 4(b) it can be observed that as load increases, FCR increases but when the load decreases the FCR curve also decreases and not coming back to its original value. This is because, due to presence of less amount of fibers in sample, there was not much flow of electric charges and due to same reason after unloading the sample, fibers had gap in between them; as a result the resistance was staying within the specimen failing to come back under cyclic loading. This effect is named as polarization effect. This effect is observed to be decreasing as dosage of fiber increases as can be seen from Figure 4(b to e). As fibers concentration increased further from 1% and reached threshold limit, this effect disappears giving better co-relation between FCR and stress under loading and unloading condition.

3. 4. Damage Sensing Test All the specimens were loaded gradually with same rate of loading of 3kN/s until failure. Results of damage sensing test are also shown in Figure 4. From obtained results it is observed that, even in damage sensing test, sample containing carbon fibers by 1.5% by weight of cement shows the better co-relation until failure of the sample. It has also observed that samples containing 1.5 and 2% fibers gave damage sensing property. Damage sensing property is defined as the property of the concrete that can represent the formation of micro cracks within the specimen. From Figures 4(d) and 4(e) it can be observed that there is sudden increase in FCR curve of damage sensing test during loading. The sudden increase in FCR curve is due the formation of micro crack in the sample that resulting in sudden increase in resistance due to reduction of flow of charges through the sample. Similarly, when sample is broken the FCR was abruptly increased because of wide gap in sample without giving further readings of FCR. Therefore, it can be said that concrete containing carbon fibers by 1.5 or 2% by weight of cement can be used for damage sensing also.

4. CONCLUSION

Present work focused on use of carbon fibers in concrete specimen with different dosage percentage. Different tests like Strain sensing and damage sensing test were performed on the concrete samples casted with different concentration of carbon fibers in order to use for health monitoring of concrete structures. From tests and analysis done on all samples, following conclusions can be drawn:

(i) Among different concentrations of carbon fiber, percolation threshold is obtained at 1.5% of carbon fiber concentration, giving very low resistivity and good conductivity making concrete as self-sensing.

(ii) When fibers were absent, the specimens did not show any co-relation between stress and change in electrical resistance.

(iii) Good co-relation is observed in sample containing 1.5% fiber for strain sensing test.

(iv) Concrete containing 1.5 and 2% fiber by weight of cement can be used to evaluate the damage sensing property.

Therefore, this correlation can be used for health monitoring of structures and to know the cracking in concrete by making concrete itself as a sensor so that there is no aid any external or internal sensors.

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چکیده

مقاله حاضر خاصیت سنجش فشار و آسیب در مکعب های بتونی تقویت شده با الیاف کربن را مورد بررسی قرار داده است. مکعب های بتونی به ابعاد ۱۵۰ میلی متر با دوزهای مختلفی از الیاف کربن برای مطالعه کرنش و خاصیت سنجش آسیب تحت بارگذاری چرخه ای قالب گیری شده اند که می توان از آن با استفاده از روش NDT برای نظارت بر سلامت استفاده کرد. تمام نمونه ها تحت بارگذاری چرخه ای در ناحیه الاستیک نمونه به مدت سه چرخه بارگیری با حداکثر بار kN۱۹۵ برای تست سنجش کرنش مورد آزمایش قرار گرفتند. در حین بارگذاری چرخه ای، تغییر کسری در مقاومت (FCR) محاسبه می شود و رابطه مشترک با استرس ترسیم می شود. در حین تست سنجش کرنش ، فاکتورهای سنج (GF) نیز هنگام بارگیری و بارگیری روی نمونه ها محاسبه شد. از نتایج به دست آمده ، مشخص شد که نمونه بتنی حاوی ۱/۵ درصد فیبرهای کربن با وزن سیمان ، بهترین ارتباط را بین استرس و FCR ایجاد می کند که می توان از آن برای کنترل سلامت استفاده کرد. در کنار خاصیت سنجش کرنش ، خاصیت سنجش آسیب و ظرفیت حمل بار نهایی کلیه نمونه ها نیز در مقاله حاضر با توضیحات مفصل گزارش شده است.

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