STRUCTURAL HEALTH MONITORING USING PRESSURE SENSITVE PROPERTIES OF CARBON MICROFIBER REINFORCED CEMENTITIOUS MATRIX

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Structural Health Monitoring Using Pressure Sensitive Properties of Carbon Micro Fiber

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ABSTARCT

The addition of carbon microfibers has proved to be one of the most effective means of improving the electrical conductivity of cementitious matrix. Numerous studies have been conducted toward using this property for measurement of damage, strain and thermal conductance.

In the present study, 5 x 5 x 5 cm carbon fiber reinforced mortar specimens were positioned in a 60 Hz, ± 2.5 V AC circuit with a data acquisition system in order to monitor the changes in its electrical resistivity under the influence of different parameters. The parameters studied included fiber content, water- cement ratio, moisture content, temperature, compressive loading, and cyclic loading.

It was seen that a high fiber fraction and low moisture content makes the specimen act like a pure resistor with negligible capacitance or inductance associated with it. All specimens were moist cured. It was also observed that electronic conduction was dominant over electrolytic conduction in a mix proportion with high fiber volume fraction and low water to cement ratio. The influence of temperature on the electrical resistivity of mortar with large amount of fiber was barely significant. The resistivity was found to steadily decrease under compressive loading and then increase during the formation of micro and macro-cracks. It has long been established that carbon fiber reinforced cement mortar specimens have the ability to monitor its own state under various conditions by exhibiting a variation in its resistivity values.

Percolation phenomena is associated with electrical conductivity. Percolation

network will disintegrate under high compressive loads and detrimental effects such as micro cracks and large strains could dislocate the contentious conduction path, thus lowering the conductivity of cementitious matrix reinforced with conductive fibers. This provides an appropriate basis to monitor the health of structures by measuring the increase in electrical resistivity versus the load during the life time of the concrete structures.

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DEDICATION

Dedicated to our beloved parents whose prayers, best wishes and support is always with us during the course of this project.

AND

Our respectable, sincere and dedicated instructors who were always willing to put in their best to guide us throughout the tenure of the studies.

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Chapter 1

INTRODUCTION

Structural health monitoring (SHM) is the most modern development in the field of civil engineering. It aims to develop automated systems for the continuous monitoring, inspection, and damage detection of structures. In general sense it is a process aimed at providing accurate and timely information about the condition and performance of a Structure for the purpose of warning impending abnormal states or accidents at an early stage to avoid casualties as well as giving maintenance and rehabilitation advice.

Civil engineering infrastructure is generally the most expensive national investment and asset of any country. In addition, civil engineering structures have long service life compared with other commercial products, and they are costly to maintain and replace once they are erected. Further, there are few prototypes in civil engineering, and each structure leads to be unique in terms of materials, design, and construction. The most important structures include bridges, high-rise buildings, power utilities, nuclear power plants, and dams. All civil structures age and deteriorate with time. The deterioration is mostly the result of aging of materials, continuous use, overloading, aggressive exposure conditions, lack of sufficient maintenance, and difficulties encountered in proper inspection methods. All of these factors contribute to material and structural degradation as internal and external damages emerge and coalesce, and then evolve and progress.

Innovations like fiber-reinforced polymers are being increasingly used to strengthen and repair civil infrastructures. But instead of repairing damages it is wiser to prevent these damages from happening and causing causalities. SHM involves constant monitoring of a structure's condition or change in its condition through smart sensing technologies, which includes the application of fiber optic smart materials, piezoelectric smart materials, self-diagnosing fiber reinforced composites, transmitting device, data acquisition systems and etc. possess very important capabilities of monitoring various physical or chemical parameters related to the health and therefore, durable service life of structures, which make SHM to be an active monitoring system. Thus, smart sensing technologies are now currently available, and can be utilized to the SHM of civil engineering structures. These developments have led to the coinage of a new term - "civionics"[1]. Civionics is to civil engineering what avionics is to aerospace engineering.

Commonly used SHM devices in bridges and structures are very costly. And it is also required to install a large number of such devices in a structure. The need for an inexpensive method for monitoring infrastructure in situ as it responds to various stresses, temperature variation, changes in ionic concentration within the system, and vibrations have been the key factor in the development of self-monitoring materials. Self-monitoring materials can be considered as smart materials. However, in contrast to smart materials such as optical fibers, piezoelectric smart materials, etc., self-monitoring materials are themselves structural materials [2]. A self-monitoring structure should be able to sense the changes in strain, stress, temperature and chloride content that take place within itself and respond in a particular manner without the need for embedded smart materials. Such materials are also known as intrinsically smart structural materials [2]. The study of their responses helps understand the behavior of the structure and even foresee damages that might occur. Presently various fiber optic smart materials and strain gauges are embedded in the structure to monitor these responses. But with intrinsically smart structural materials there are a number of advantages like [2]:

- low cost,
- great durability,
- large sensing volume, and
- Absence of mechanical property degradation due to the embedding of smart materials.

Plain cement mortar is a semiconductor or insulator with resistivity of the very high order. Conductivity of a cement based specimen depends on the pore structure and the chemistry of the pore solution [3]. Introduction of carbon fibers into cementitious matrix significantly increases the electrical conductivity enabling one to monitor changes in resistivity under varying degrees of strain. There are also other factors that bring about variation in electrical resistivity of the mortar like change in temperature, presence of chlorides, shrinkage, etc. Hence the measurement of variation in resistivity helps one to monitor the response of smart material structures under these varying conditions.

The objective of this research was to develop smart self-sensing cementitious matrix for SHM by subjecting it to different loading conditions that exist in field. The results were then examined to propose modifications to make a more effective smart material. Tests were also aimed at determining the best mix proportion for the smart material. One major topic that this study focused on is the way in which such a smart material responded to direct loading.

This study consists of 8 chapters. In Chapter 2, a review of the literature in the field of resistivity of carbon fiber reinforced cement specimens and concrete is given. In Chapter 3, the experimental program including the materials as well as the method used is described. The effect of various factors like carbon percentage and loading, are discussed in detail in Chapters 4 to 6. In Chapter 7 the final results of the experiments are detailed and modifications are proposed. Chapter 8 suggests few recommendations for future research.

Chapter 2

LITERATURE REVIEW

2.1 CARBON FIBERS

Use of carbon fibers as reinforcement in concrete is gaining momentum because of the need for superior structural and functional performance. Carbon fiber reinforced mortar exhibits superior tensile strength, flexural strength, tensile ductility, flexural toughness, impact resistance, and freeze thaw durability [4]. Drying shrinkage is also reduced by the addition of fibers [4]. Short carbon fibers approximately 5mm in length are used more than continuous fibers because short fibers can be added directly into the concrete whereas continuous one cannot be and short fibers are less costly than continuous ones [5]. However continuous fibers have an advantage over short fibers of providing better bond with the cement matrix because of their high aspect ratio. Since the interface bond between carbon fibers and cement matrix is crucial in determining the performance, surface treatment methods like using ozone, silane, $Si0_2$ particles or hot NaOH solution are often employed to overcome this drawback of short carbon fibers. Ozone and silane treatments improve the wettability by water because of the oxygen containing functional groups in the interfacial layer created by the treatment [6]. These treatments also increase the active specific surface area [5], the number of bonding sites on the fiber surface [7], and the surface roughness [7]. Admixtures such as latex, methylcellulose and silica fume also help the bond.

Increase in fiber volume fraction enhances the properties of concrete. However too great a fiber volume fraction can deteriorate the concrete properties because high fiber content produces large amount of air voids which in tum decreases the compressive strength of concrete. Hence a proper dispersing agent and addition of superplasticizer become necessary when using fiber volume fractions greater than 3% [8]. When compared with the conventional steel fiber composites with 0.3-1.0 diameter steel fibers, at equal fiber volume fractions, the carbon-cement composites have almost three orders of magnitude more fibers, with the number of fibers per square unit exceeding a few Thousands [8]. Most of the studies conducted so far on the electrical resistivity of carbon fiber cement mortar have used an optimum fiber content of 0.2 vol. % [9], [10], [11].

To fully utilize the advantages that carbon fibers offer as a construction material, fibers have to be properly dispersed. Using silica fume of about 15-20% by weight of cement assists dispersion. The reduction in porosity by the addition of silica fume also presents better chances of improving bonding [4]. Methylcellulose of about 0.4% by weight of cement is added along with silica fume to enhance dispersion as well as workability. Addition of methylcellulose produces foam and so a defoamer must also be used [4]. In general, the slump of carbon fiber reinforced cement tends to decrease with increasing carbon fiber content. Therefore, certain amount of water reducing agent should be added in order to maintain the mortar at a reasonable flow value.

Instead of methylcellulose, latex may be used as a dispersant. But due to its less effectiveness a large amount (20% of the weight of the cement) is required. This increases the cost [4]. In spite of its inefficacy as a dispersant, latex is known to improve the flexural strength, flexural toughness, impact resistance, frost resistance and acid resistance [12]. The fact that the ease of dispersion increases with decreasing fiber length is a major incentive for using shorter carbon fibers.

The advantages of adding carbon fibers cannot be restricted to these.

Researchers have discovered that the properties of carbon fibers can be exploited to a much greater extent. These discoveries are believed to be a curtain raiser for a great breakthrough in civionics. The functional properties brought about by the addition of carbon fibers are [5]:

1. Strain sensing ability for smart structures.
2. Damage sensing ability.
3. Temperature sensing ability.
4. Increased flexural strength.
5. Increased flexural toughness (area under the curve of flexural stress versus displacement).
6. Increased durability under cyclic loading.
7. Improved freeze-thaw durability.
8. Decreased drying shrinkage.
9. Thermoelectric behavior.
10. Thermal insulation ability to save energy for buildings.
11. Vibration reduction [13].
12. Electrical conduction ability to facilitate cathodic protection of embedded steel and to provide electrical grounding or connection.
13. Radio wave reflection/absorption ability for electromagnetic interference or EMI shielding, for lateral guidance in automatic highways, and for television image transmission.
14. Improved resistance to earthquake damage

The dual characteristic of carbon fibers of being electrically conducting and having small diameter makes it the best choice for use in smart materials. Carbon fibers are conductive and more resistant to alkaline environment than glass or polymer fibers, which are non-conductors. Steel fibers are conductive but they have a large diameter (60µm) when compared with carbon fibers (15µm).

Although carbon fibers are thermally conductive, addition of carbon fibers decreases the thermal conductivity of concrete due of the formation of air voids [14]. The electrical conductivity of carbon fibers is higher than that of the cement matrix by about 8 orders of magnitude, whereas the thermal conductivity of carbon fibers is higher than that of the cement matrix by only one or two orders of magnitude [5]. As a result, the electrical conductivity is increased upon carbon fiber addition in spite of the increase in air void content, but the thermal conductivity is decreased upon fiber addition.

2.2 METHODS OF MEASURING ELECTRICAL RESISTIVITY OF CONCRETE

Any one of the three methods mentioned below can be used to measure the electrical resistivity of concrete.

2.2.1 Two-Probe Resistivity Measurement Technique

In this method a known D.C/A.C current (I) is applied between two electrodes embedded in concrete at a specific distance and the voltage (V) is measured or vice versa. The resistance (R) is determined by using Ohm's law:

$$R = \frac{V}{I}$$

The resistivity is obtained by multiplying the measured resistance by a conversion factor, called the cell constant (A/L):

$$\rho = R\frac{A}{L}$$

Where A is the specimen cross-sectional area and L is the length of the specimen.

2.2.2 Four-Probe Resistivity Measurement Technique

This is one of the most commonly used methods for measuring electrical resistivity. This method was originally developed by Wenner (1916) to measure earth resistivity. This measurement setup consists of four electrodes, which are equally spaced, and a small alternating current is applied between the outer electrodes. The potential is then measured between the inner electrodes. The resistivity is determined using the following formula:

$$\rho = \frac{2.\pi.a.V}{I}$$

Where, ρ = resistivity (ohm .cm)

a = distance between inner electrodes (cm)

V = voltage (volts)

I = current (amperes)

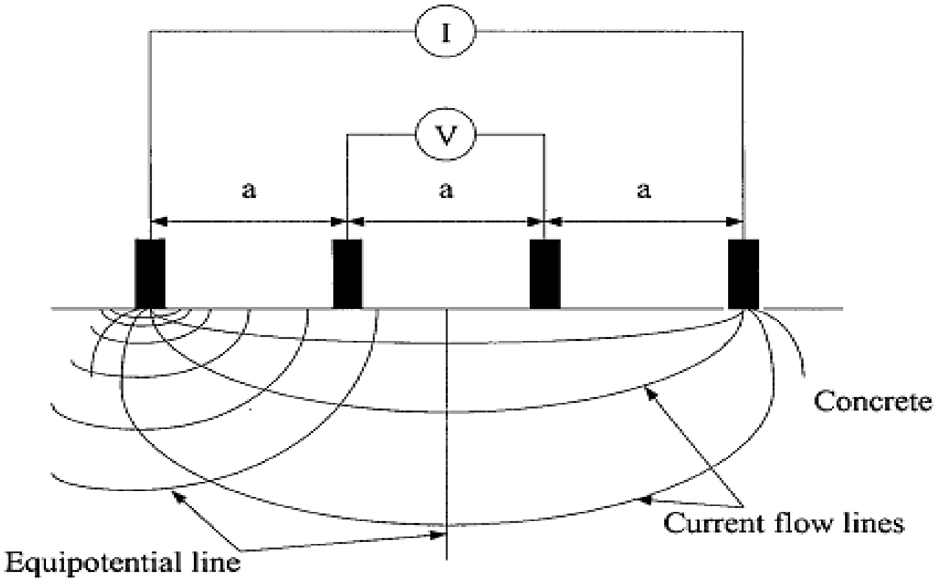

Fig.2.1 Four Probe Method

A conducting liquid is used to improve the contact between the concrete and the electrode tips. However the presence of steel rebars too near to the electrode tip might become a source of error. This is because rebars conduct current much better than concrete; they will disturb homogeneous current flow. While measuring with four electrodes over bars at 10 or 20 mm depth, errors can be made by as much as a factor of 2. So none of the measuring electrodes should be placed above rebars.

Even though electrical resistivity can be measured using the four-probe method, ohmmeter measurements are normally made with just a two-point measurement method. However, when measuring very low values of ohms, in the milli- or micro ohm range, the two-point method is not satisfactory because test lead resistance becomes a significant source of error.

2.2.3 Disc Method

Disc (one electrode) method involves an electrode disc placed on the concrete surface over a rebar and measuring the resistance between the disc and the rebar. It requires a connection to the reinforcement cage and full steel continuity. The method is illustrated in Fig.2.2. The resistance can be converted to resistivity using a cell constant that depends on the cover depth, which varies over the surface and the rebar diameter.

Precise calculation of the cell constant is not possible, because the exact current flow cannot be predicted. For maximum precision, the cell constant can be determined empirically using concrete slabs of known resistivity. Alternatively, the cell constant can be estimated. For usual cover depths, disc and bar diameters being 10 -50 mm, the cell constant is approximately 0.1 m. So the resistivity measured using a small disc electrode is approximately [15]:

$$\boldsymbol{\rho}_{(\boldsymbol{disc})} = \mathbf{0.1}\boldsymbol{R}_{(\boldsymbol{disc-bar})}$$

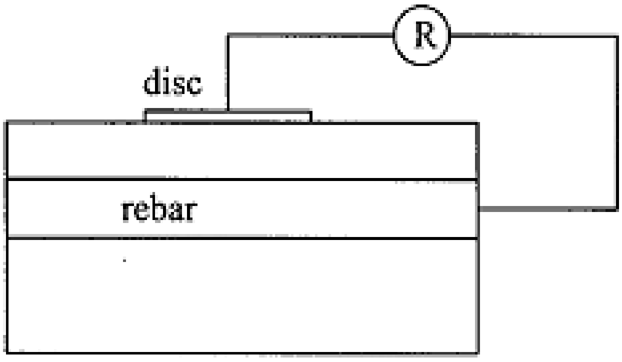

Fig.2.2 Disc Method

2.3 PROBLEMS ASSOCIATED WITH DIRECT CURRENT MEASUREMENTS

Although direct current (D.C.) can be used for the measurement of electrical resistivity of concrete, its use is restricted due to the effects of polarization. Concrete conducts through the movement of ions in pore solution. When chemical reactions take place at the electrodes and hydrogen and oxygen gases are liberated and get deposited around the electrodes in the form of a thin film a polarization potential or back e.m.f. is created [16]. Current cannot be accurately measured because of these polarization effects.

However in most of the experiments conducted by Chung et. al. [2] [17] [10], direct current has been used because it is believed that polarization is appreciable only when the resistivity measurement is continuously performed over a long time (D.D.L. Chung, Composite Materials Research Laboratory, SUNY, Buffalo, NY, USA, .pers.comm.). If so, it can be corrected using the formula [16]:

$$I = \frac{V - V_P}{R}$$

Where V = applied voltage

V_P = polarization potential

It follows that if DC measurements are made, at least two different values of the applied voltage, V, have to be used to determine the two variables Vp and R.

AC provides both resistance and reactance information and AC is relevant to data acquisition by wireless methods. However AC measurement also requires more expensive electronics than DC measurement.

2.4 THE NEED FOR CEMENT BASED CARBON FIBER SMART MATERIAL

There are mainly three reasons for which cement based carbon fiber smart material are being developed. They are:

1. To keep a track of strains and stresses developed in a structure under the influence of dynamic and static loading.
2. To determine the temperature variation of a structure.
3. To determine the chloride content of the structure and hence the possibility of rebars to corrosion.

Many studies have been carried out to determine the response of carbon fiber reinforced cement-based composite to compressive and tensile forces, chloride content and temperature variation. What is required is to compile these findings together with a deeper understanding of the mechanisms involved, develop a cement-based carbon fiber smart material, which can display the values of electrical resistivity of the concrete into which it is integrated. These values can then be calibrated to determine the stresses, strains, chloride content, and temperature of the structure at different locations enabling engineers to get first-hand knowledge of the behavior of a structure and act quickly in case of an emergency.

2.5 STRAIN MONITORING ABILITY

In one of the earliest studies of concrete as a self-monitoring material Chen and Chung [18] studied how electrical resistivity varies during crack generation or propagation. They observed that concrete's volume resistivity decreased during crack closure. On application of stress up to failure, the following observations were noted:

For mortar without fibers

1. It was observed that in plain mortars with no fibers the changes in volume

resistivity were insignificant or negligible up to fracture.

2. The resistivity increased abruptly when the mortar fractured; this is because of the widespread cracking which accompanied fracture and the fact that the mortar was more conductive than air.

For mortar with fibers

1. All mortar with fiber showed an increase in volume resistivity on compression up to fracture.
2. It was seen that fiber-reinforced mortar containing latex, a polymer, exhibited a higher resistivity when compared with fiber-reinforced mortar containing either silica fume or methylcellulose. This was attributed to the insulating property of latex.
3. For all mortars with fibers, the resistivity decreased when the mortar fractured.

Next, on application of a cyclic compressive loading equal to 1/3 of the fracture stress, the following observations were made:

For mortar without fibers

1. All mortars without fibers showed no change in the resistivity during the stress cycling.

For mortar with fibers

All mortars with fibers exhibited:

1. *Irreversibly increasing resistivity during the first loading* - The irreversibly increasing resistivity during the first loading is attributed to flaw generation.
2. *Reversibly increasing resistivity during unloading in any cycle* - The

reversibly increasing resistivity during unloading in any cycle is attributed loading to crack opening, which was hindered under compressive

3. *Reversibly decreasing resistivity during the second and subsequent loadings.* The reversibly decreasing resistivity during the second and subsequent loadings is attributed to the crack closure under compressive loading.

2.6 DAMAGE SENSING ABILITY

If the mechanism of interface degradation is considered then in a composite material with carbon fibers resistivity increases during damage. However interface degradation occurs only during the first cycle of fatigue testing. Hence it is not possible to monitor resistivity variation in more advanced stages of damage. We notice a noticeable increase in resistivity when cracks are plentiful and damage occurs. This limits us to obtain results only in the very initial cycles of fatigue testing. Even during the first cycles, damage can be monitored only after the cracks are plentiful.

In experiment conducted by Chung [10] using self-monitoring material it was noticed that when damage occurs (probably in the form of micro cracks in the case of a brittle matrix such as cement) it increases the chance of adjacent fibers to touch each other hence decreases the electrical resistivity of the material. In this way it is possible to monitor the slight damage mechanics as long as up to 350 cycles.

Testing was performed under cyclic loading (tensile or compressive) at stress amplitudes equal to 0.3 0.5 and 0.70 of the fracture stress. For compressive testing each cycle took 38.1 seconds and for tensile testing it took 52.2 seconds.

The following points were noted:

1. Δ.R/Ro decreased during loading and increased during unloading.
2. Δ.R/Ro had a baseline which monotonically decreased as cycling progressed.

This decrease is because of the adjacent fibers coming in contact with each other. The decrease was limited to a certain number of cycles only probably because the damage was stabilized. The number of cycles up to which Δ.R/Ro decreased depended mainly on the stress amplitude. It occurred only in the early fatigue life, i.e., 5.8% of compressive fatigue life at stress amplitude of 0.07 of fracture stress, or 9.2% of tensile fatigue life at stress amplitude of 0.07 of fracture stress. The baseline decrease was not linear with cycle number. This decrease provides an indication of the extent of damage in the regime of slight damage.

Δ.R/Ro baseline increased slightly during few cycles prior to fracture providing an indication of the impending fracture. However due to the slightness of this increase the warning is not reliable. This slight increase is attributed to cracking. At fracture, Δ.R/Ro greatly increased due to cracking. It can be concluded that damage results in an irreversible resistivity change.

Chapter 3

MATERIALS AND METHODS

3.1 MATERIALS

3.1.1 Cement

The cement used was a Type 1 Normal Portland Cement obtained from Best Way Cement Pvt. Ltd. (fineness of blaine 452 m^2/kg). The chemical composition of the cement is given in Table 3.1.

Table 3.1: Chemical Composition of Cement

C_3S (%)	C_2S (%)	C_3A (%)	C_4AF (%)	CaO (%)	$Si0_2$ (%)	Al_2O_3 (%)	Fe_20_3 (%)	MgO (%)	$S0_3$ (%)	Loss on ignition (%)	Alkalies (%)
63	13	6	11	65.4	21.1	4.44	3.68	0.9	2.7	1.61	0.38

Table 3.2: Properties of Cement

LAB TEST	VALUES	ASTM SPECIFICATIONS
Standard Consistency	24	20-26%
Initial Setting Time	120	60 Min (min)
Final Setting Time	480	375 Min (max)
Fineness	99	90% (min)
Soundness	5.33	10mm (max)
Specific Gravity	3.12	3-3.15

3.1.2 Silica Fumes

Silica fume with bulk density 550 kg/m^3 from Sika, Pakistan Pvt. Ltd. was used. The chemical composition of the silica fume used is presented in Table 3.2.

Table 3.3: Chemical Composition of Silica Fume

$Si0_2$ (%)	Al_30_2 (%)	$Ti0_2$ (%)	P_20_5 (%)	Fe_20_3 (%)	CaO (%)	MgO (%)	Na_20 (%)	K_2O (%)	$S0_3$ (%)	Loss on ignition (%)
88.9	0.0065	0.002	0.08	0.85	0.93	0.54	0.52	0.60	0.25	4.5

3.1.3 Carbon Fibers

TC-36S 12K Polyacrylonitrile (PAN) TC-36S 12K based carbon fibers from Formosa Plastic, Inc. were used. The properties of the fiber are presented in Table 3.4.

Table 3.4: Properties of Carbon Fibers

Length (average) (mm)	Diameter (µm)	Yield Tex (g/1000m)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation (%)	Density (g/cm^3)
5	7	800	4,900	250	2	1.81

3.1.4 Superplasticizer

Two different water reducer i.e. Ultra High Range Sika ViscoCrete-20HE and High Range Sikament 512PK having bulk densities 1.08 kg/lt and 1.18 kg/lt respectively were used. Both water reducers were polycarboxylate-based superplasticizer.

3.1.5 Sand

Dry Jalbai sand graded between 0.5 mm (No.35) sieve and 0.074 mm (No.200) was used for all samples. The sieve analysis was performed in accordance with ASTM C136 – 04. Physical properties of sand are listed in table 3.5 below.

Table 3.4: Physical properties of sand

PROPERTIES	JALBAI SAND
FINENESS MODULUS	2.83
BULK SPECIFIC GRAVITY (SSD)	2.655
BULK SPECIFIC GRAVITY OVEN DRY	2.612
WATER ABSORPTION	1.5
APPARENT SPECIFIC GRAVITY	2.23

3.1.6 Water

Ordinary water of Risalpur was used in specimen preparation and their curing.

3.1.7 Mix Proportions

Mix proportions given in Table 3.4 is the final mix used for making specimens for different sets of experiments, this mix was finalized while aiming for compressive strength above 6000 Psi, for that different combination of mixes were used i.e sand, w/c ratio, superplasticizer and silica fumes. Silica fume added at a relatively high dosage in all mixes acted as a dispersant as well as a densifier. Superplasticizer was added to obtain the desired workability.

Table 3.4: Mix Proportions

Water/cementitious ratio, by weight	Silica fume/cement ratio, by weight	Sand/cement ratio, by weight	Carbon fiber ratio by, weight (%)
0.40			**0**
0.40			**1**
0.40	**0.2**	**1.5**	**2**
0.40			**3**
0.40			**4**
0.40			**5**

3.2 METHODS

3.2.1 Mixing Procedure and Specimen Preparation

The mixing was performed using a Hobart mixer (12 L) to obtain the better consistency of mix and the following mixing sequence was employed.

1. The superplasticizer was added to the water.
2. The silica fume and cement was mixed thoroughly in the mixer.
3. The fibers were gradually introduced into the silica fume cement mix.
4. Once all fibers were added, water was slowly introduced and the mix was allowed to form into slurry.

5. A small amount of water was kept aside.
6. To obtain the better consistency material was mixed at three different speeds i.e. 3 min at each speed.
7. Finally after making sure that the constituents have mixed well the remaining amount of water added and mixed once again for few minutes.

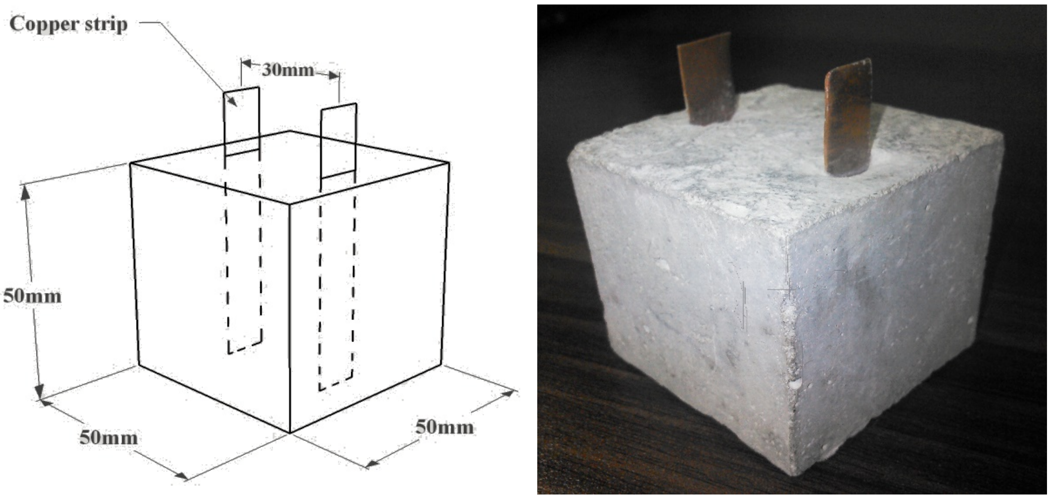

Fig.3.1 Specimen for Resistivity Measurements

Specimens were casted with dimensions 5 x 5 x 5 cm. Two copper electrodes of thickness 0.35 mm and width 10 mm were inserted through the entire depth of the specimen as shown.

The inter-electrode spacing was 3 cm. For each experiment a set of nine specimens were casted, three out of them were used for electrical measurements and the graphs were plotted for the average of their results. Rest six specimens were used for compression and split tensile strength. Twenty-four hours after casting, the specimens were carefully de-molded and shifted to curing room where electrical measurements were begun. The measurements were made up to an age of 28 days. After each measurement, the specimens were immediately transferred to the curing room.

3.2.2 Measurement Technique

The two-probe resistivity measurement technique was adopted. Electrical resistivity measurements were made by applying a known AC voltage of ± 2.5V across the electrodes using a function generator at a frequency of 60 Hz. This frequency was selected because it was observed that at higher values there was a great fluctuation in the resistivity reading, owing to the incongruence in the frequencies of the excitation signal and sampling rate of the system. The reason for selecting an AC voltage has been cited earlier in Chapter 2.

Due to the high percentage of fiber volume present in the specimen it was seen that the setup used for specimen behaved more like a pure resistor. Fig.3.2 and Fig.3.3 show resistivity measurement.

A known resistance of 100 ohms and the specimen are connected in series in the circuit (Fig.3.2). Since the current flowing through the entire circuit is constant, based on Ohm's law the following equation holds true:

$$\frac{(V_T - V_X)}{R} = \frac{V_X}{X}$$

Where, V_R = voltage across known resistor R,

V_T = voltage across circuit,

R = known resistor = 100 ohms,

V_X = voltage across unknown resistor, and

X = unknown resistor.

The value of X is thus calculated by the software MATLAB and the resistances versus time values are plotted in the display unit. Resistivity ρ is calculated as follows:

$$\rho = X\frac{A}{L} \qquad \text{Eq. 3.1}$$

Where, X = resistance of specimen, now known

A = cross-sectional area of specimen

L= gauge length = inter electrode spacing

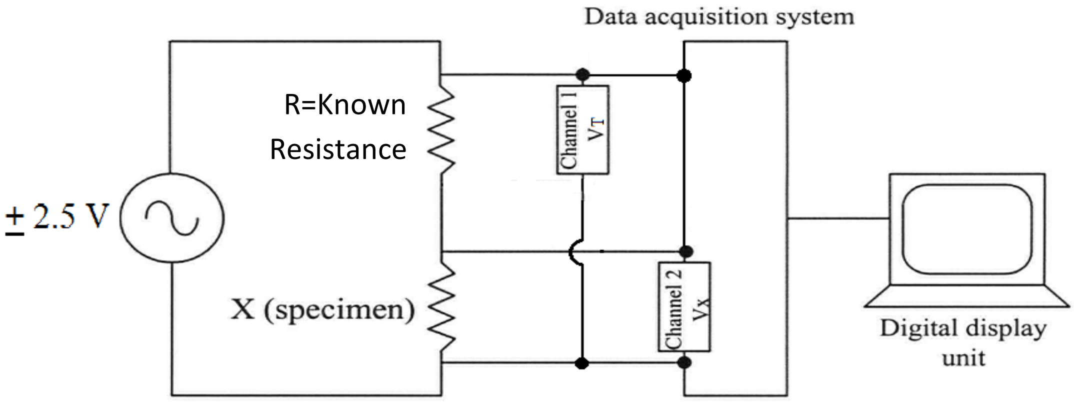

Fig.3.2 Simplified circuit diagram Resistivity Measurements

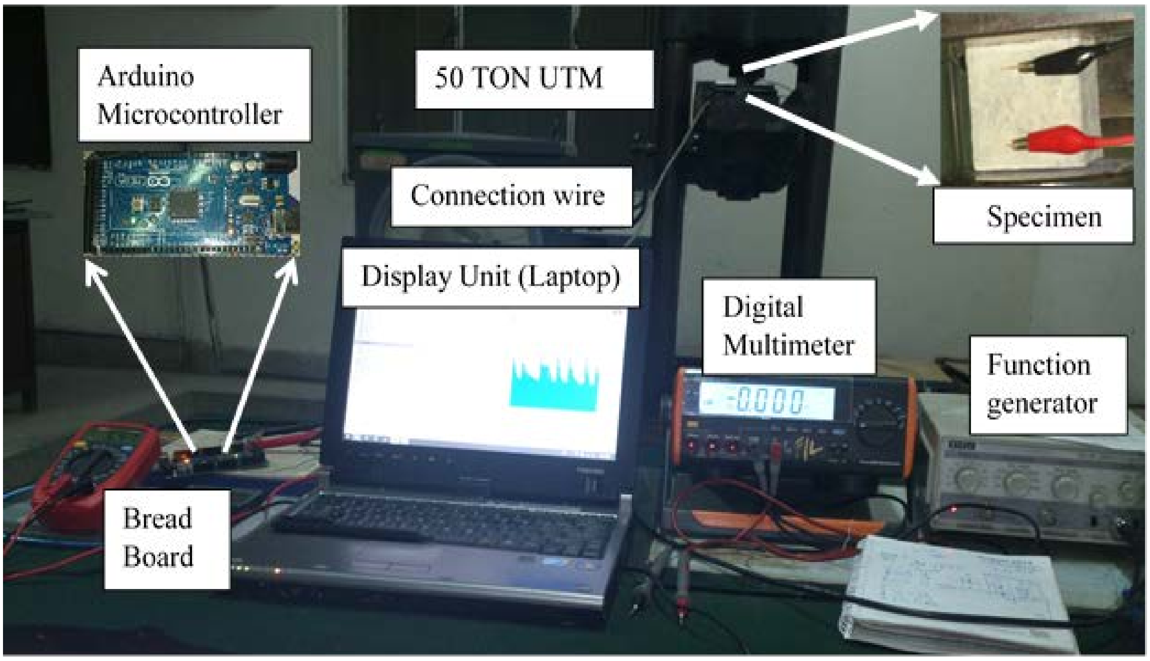

Fig.3.3: Setup for Resistivity Measurement

Chapter 4

INTERNAL FACTORS AFFECTING ELECTRICAL RESISTIVITY OF CARBON FIBER REINFORCED CEMENT MORTAR

All systems in this universe are in a state of entropy. There are always elements at work that bring about changes in a system. In a system like carbon fiber reinforced cement mortar specimen, there are various factors that play a critical role in changing its resistivity. This chapter enumerates the internal factors that affect the electrical resistivity of such a system.

There are basically two mechanisms of electrical conduction in moist specimens: electronic and electrolytic [19]. Electronic conduction is through the motion of free electrons in the conductive phases, e.g. carbon fibers, and electrolytic conduction is through the motion of ions in the pore solution. The conductivity of mortar can be attributed to mainly three media: carbon fibers, the pore solution within the matrix and the physical interface between the fibers and matrix.

Carbon fibers are known to reduce the electrical resistivity of cementitious composites. The conductivity of the mix is directly proportional to the volume fraction of carbon fibers and can be visualized as shown in Fig.4.1. The plot of resistivity vs. time (Fig.4.2) for mixes with different fiber fraction volume further asserts this fact.

The conductivity in a carbon microfiber reinforced mortar specimen follows the phenomena of percolation theory. Percolation theory is basically a geometrical theory that describes the structure of random particles or filaments in a matrix as a function of their volume fraction [20].

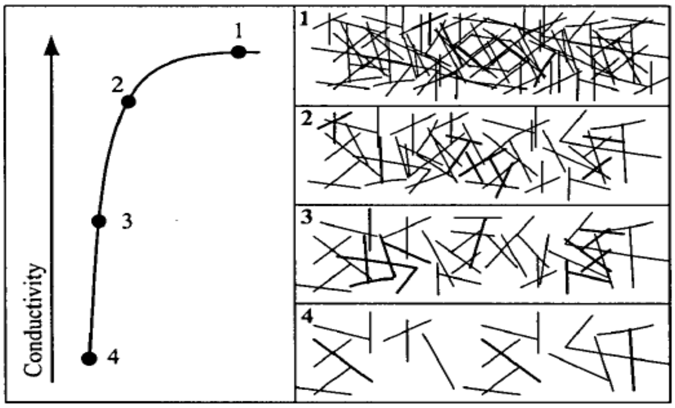

Fig 4.1: Percolation Theory [20]

It postulates that it is only when the volume fraction of the particle or filament exceeds a certain critical value that the particle or filament can come into contact and form clusters. As a result, electrical conduction can occur due to the connection of the clusters. Percolation threshold thus is the critical fraction of lattice points that must be filled in order to create a continuous path of nearest neighbors from one side to another. Thus the electrical conductivity of the specimen also largely depends on the fiber's aspect ratio and material.

A higher volume fraction ensures that there exists more fiber-to-fiber contact thus allowing easy passage of current. Moreover a high volume percentage and low w/c ratio makes the specimen act like a pure resistor with negligible capacitance and inductance values.

The influence of w/c ratio on the resistivity of mortar is pretty significant. On comparing different combinations of fiber percentage and w/c ratio, it can be seen that the set with 5% volume of carbon fiber and 0.40 w/c ratio offers the least resistance. The combination of 5% fiber volume and 0.6 w/c ratio has lesser resistivity than 5% fiber volume and 0.5 w/c ratio.

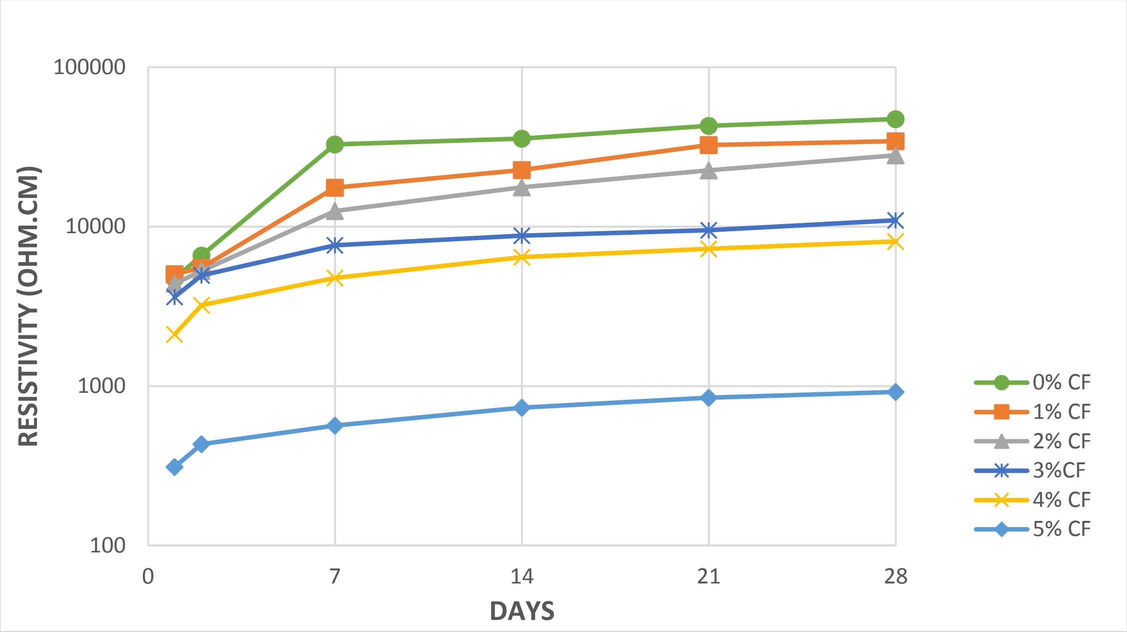

Fig 4.2: Resistivity as a Function of Percentage of Fiber Volume

This can be attributed to the large amount of pore solution available in the capillary pores of the mix with 0.5 w/c ratio. However the combination of 5% fiber volume and 0.4 w/c ratio has a lesser resistivity value than the one with 0.5 w/c ratio and is lower than even the mix with 0.5 w/c ratio. This is because the former most has larger amount of fines and lesser pores with respect to both the latter ones thus allowing denser packing and more fiber-to-fiber contact. Moreover the large amount of superplasticizer that was added to obtain the desired workability can bring about finer packing of different phases. A lower w/c ratio can also assist in better contact between the electrode and matrix. It can be concluded that on decreasing the w/c ratio from 0.5 to 0.3 the conduction transfers from electrolytic to electronic and fiber-to-fiber contact starts playing a prominent role.

Chapter 5

COMPRESSIVE LOADING

Compression test was conducted on all the samples according to ASTM standard C109 to determine the behavior of smart material under compressive loading. A significant increase in the maximum strain achieved prior to failure was observed. The basic objective of conducting compressive test on smart material is to observe the change in electrical resistivity with increase in load to develop an effective SHM mechanism. The reaction to loading of such materials has been discussed in detail by Chung [2], Fu[IO, 11], Wang [11]. However, in this chapter the load versus resistivity graph has been discussed once again as a preface for the following chapters. A diagram of the experimental setup is shown in Fig. 6.1

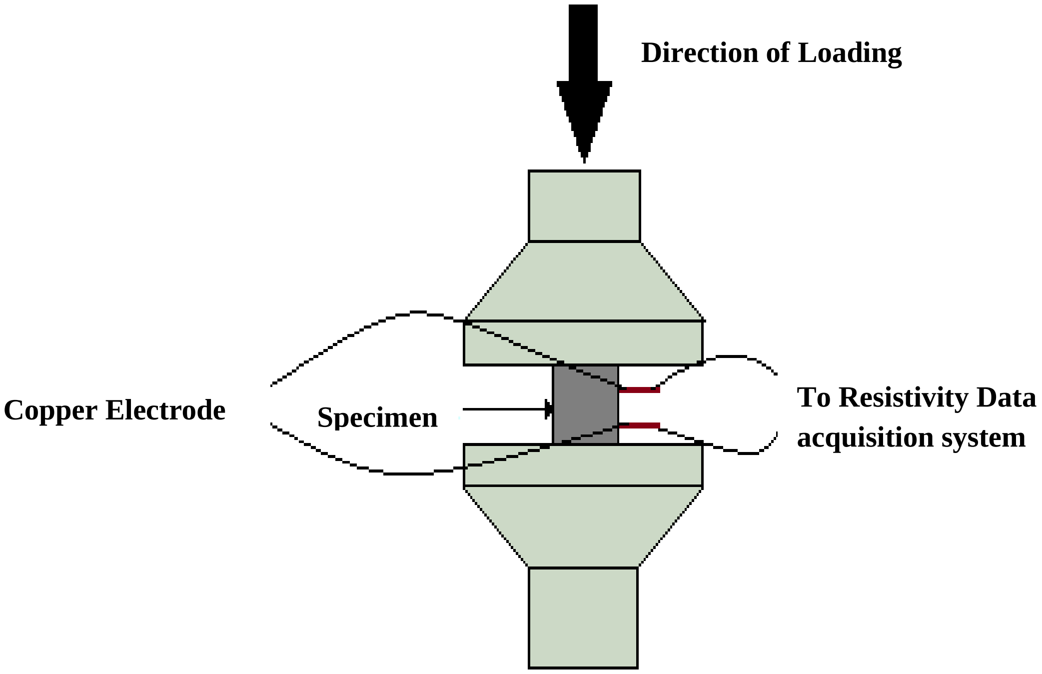

Fig.6.1 Experimental Setup for Compressive Loading of Specimen

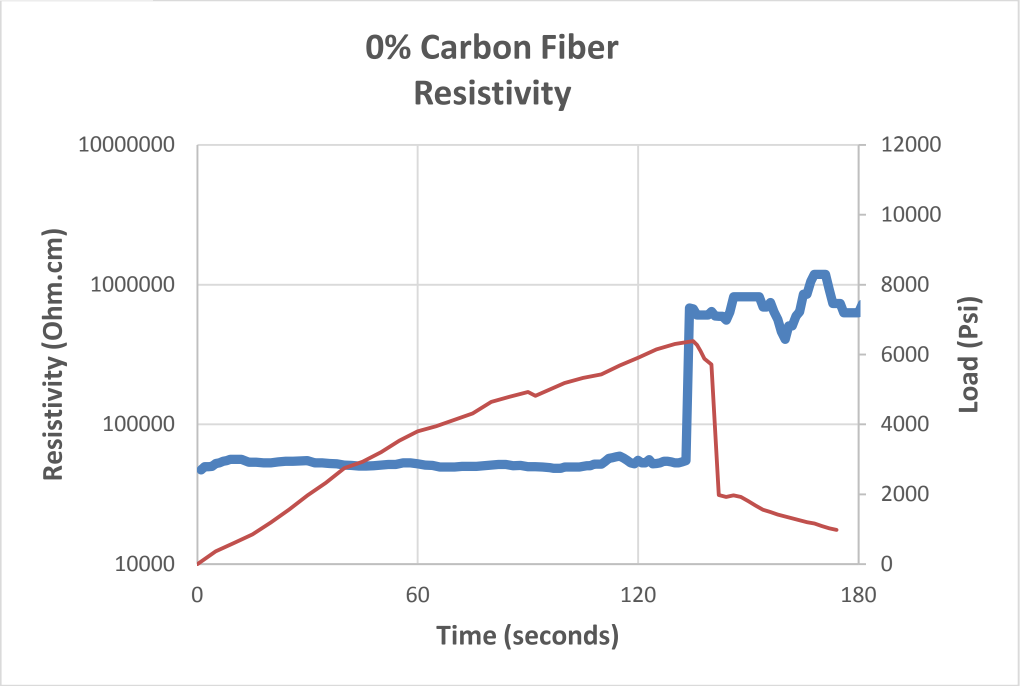

Fig.5.2: Variation of Resistivity under Compressive Load for plain CF Specimens

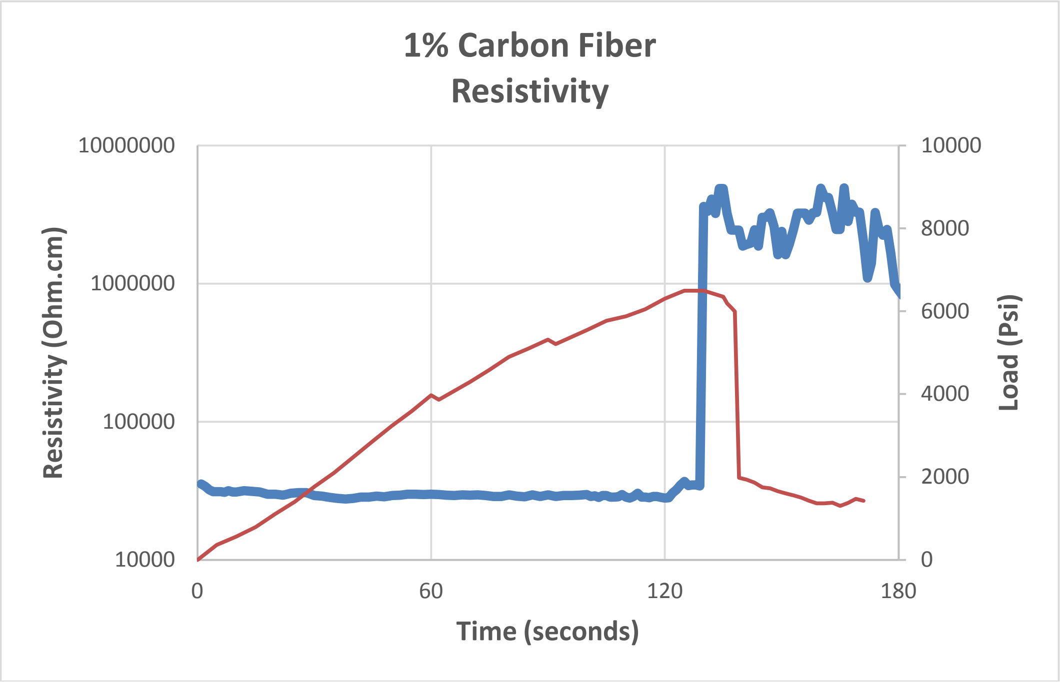

Fig.5.2: Variation of Resistivity under Compressive Load for 1% CF Specimens

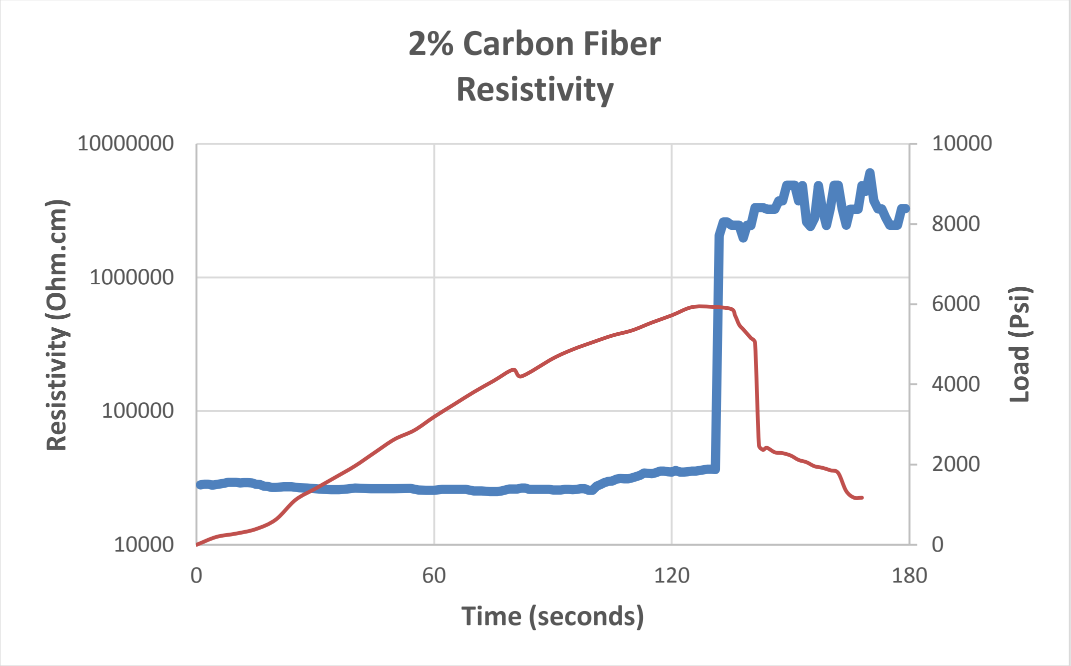

Fig.5.3: Variation of Resistivity under Compressive Load for 2% CF Specimens

All the specimens were loaded till failure at constant loading rate. Initially as load increases for specimen having 0 - 3% carbon fiber no change in resistivity observed which is represented by straight line in graph. Finally as the load reaches the full capacity of the specimen there was a sudden rise in the resistivity value. This can be attributed to the complete failure of the matrix. Although there was a significant decrease in resistivity of specimen with the introduction of 1 - 3% carbon fibers in the specimen but results are indicating that percolation network was not established resulting in failure to detect any change in electrical resistivity under loading.

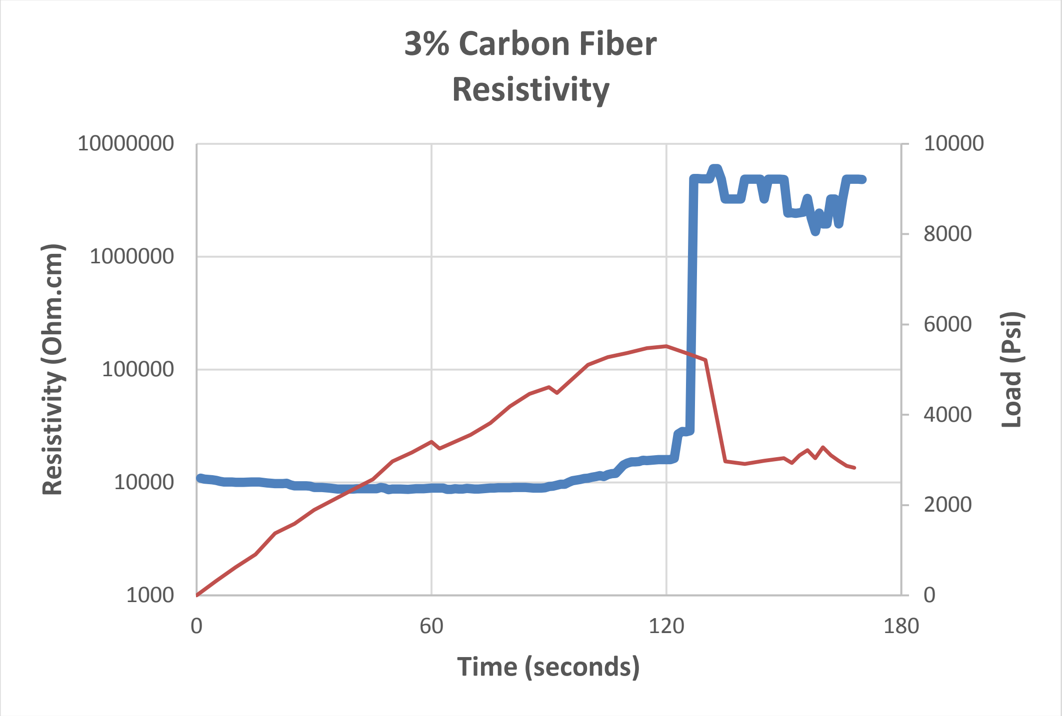

Fig.6.4: Variation of Resistivity under Compressive Load for 3% CF Specimens

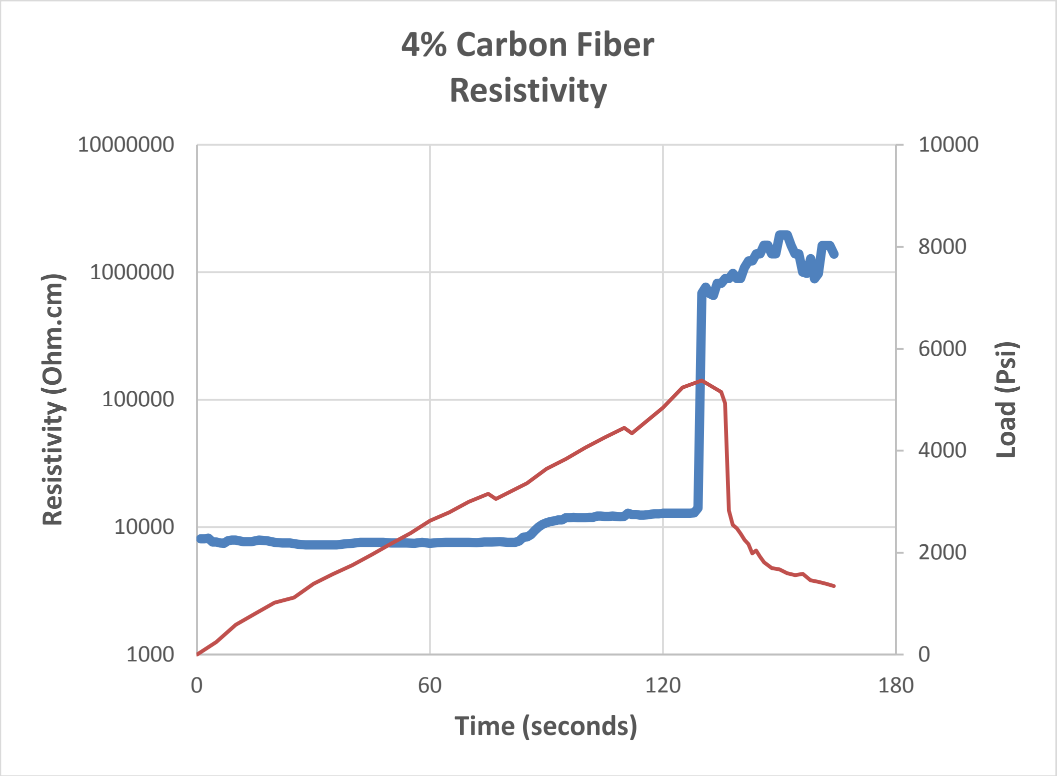

Fig.5.5: Variation of Resistivity under Compressive Load for 4% CF Specimens

As we increase the fiber percentage further to 3 and 4% the resistivity decreases five times of plain matrix. And when placed under compression, initially there was no resistivity change observed but as the load reached 70% of ultimate strength it was seen that the resistivity too started increasing. This increase in the resistivity was a clear sign of formation of micro cracks in matrix. Finally as the load reached the full capacity of the specimen there was a sudden increase in the resistivity value which shows the complete failure of specimen.

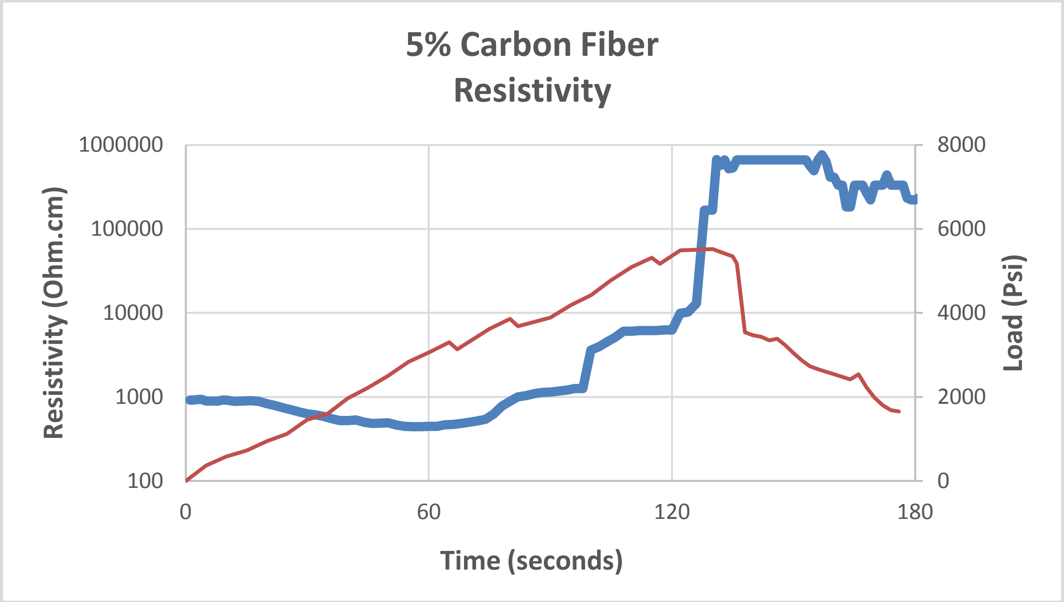

Fig.5.5: Variation of Resistivity under Compressive Load for 5% CF Specimens

Finally on adding 5% fibers the resistivity decrease 52 times of plain matrix clearly indicating the development of percolation network within the specimens. When placed under the compressive loading, initially as load increases there is a steady fall in the resistivity value. This can be attributed to the increase in contact between carbon fibers by the closing of voids and thus decrease in the distance between the matrix and the copper plates. Then there is a relatively flat portion, which indicates that the closing of original micro cracks and opening of new ones reached a dynamic balance [24]. Gradually as the load increased it was seen that the resistivity too started increasing. This increase in the resistivity was a clear indication of formation of new micro cracks within the matrix, which created distance between the fibers and weakened the fiber-matrix interface. Finally as the load reached the full capacity of the specimen there was a sudden ascend in the resistivity value. This can be attributed to the complete failure of the matrix thus resulting in air pockets within the matrix. The resistivity of air being higher than that of the matrix, increases the resistivity of the specimen.

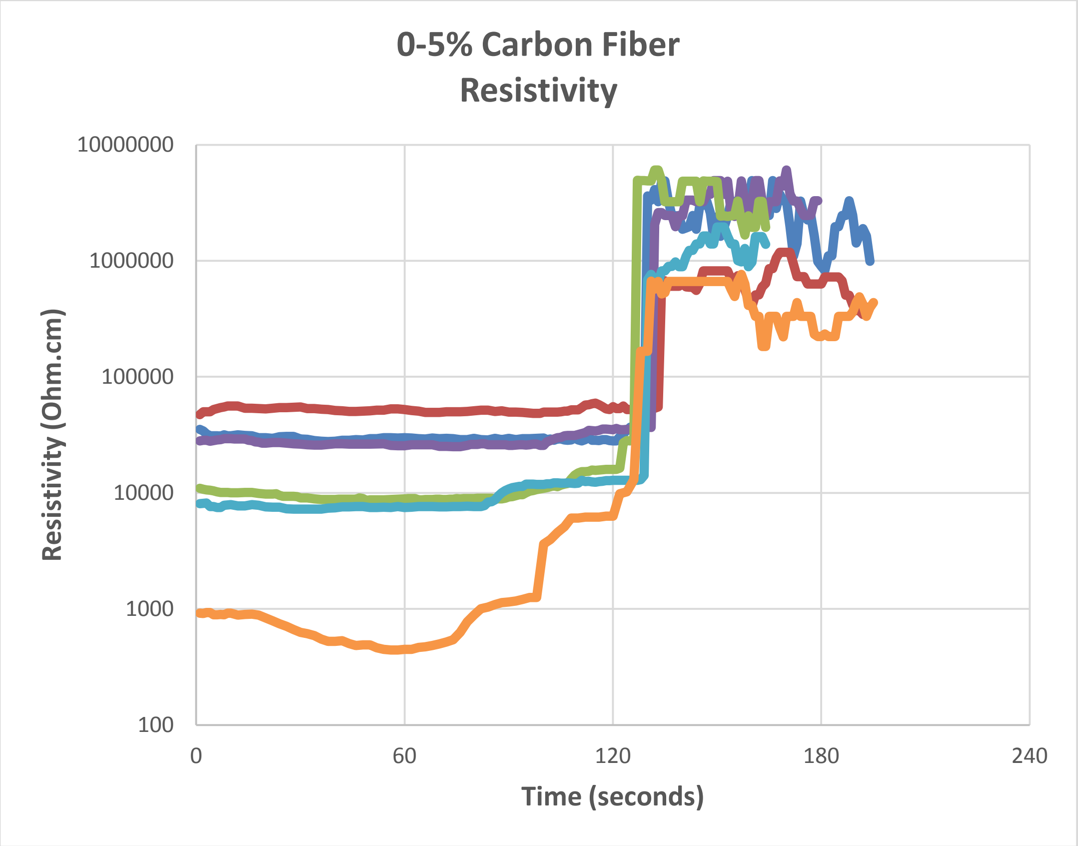

Fig.5.6: Variation of Resistivity under Compressive Load for 0-5% CF Specimens

The Fig: 5.6 shows the comparison of change in resistivity under compressive loading for 0 to 5% fiber reinforced mortar samples. It can be clearly seen from the graph that as the fiber content increases resistivity decreases. Lowest value of resistivity corresponds to the 5% fiber reinforcement. Another important observation was the similar trend of 1% and 2% fiber reinforced mortar samples and same can be observed for 3% and 4% fiber reinforced samples. Samples with 5% fiber reinforcement clearly stand out showing the formation of percolation network.

However when used to monitor strain the resistivity changes before the formation of micro cracks are relevant or in other words the resistivity changes that are reversible on load removal are the values that can really tell what is happening in the structure. During the experiment it was noted that the initial resistivity changes only in the range of 5 - 10 % of ultimate load was irreversible. The resistivity changes during load values higher than 10 % of maximum load and up to 45 % of maximum load were reversible to a great extent. This contradicts with the findings of Chen and Chung [18] where they noticed an irreversible change in the resistivity values in the initial phase of loading due to flaw generation and then a reversible decrease in the resistivity values till larger cracks were formed. The reason for this could be the low resistivity of the specimen itself, which makes the resistance changes too small to be conveniently detected.

From the graphs it can be seen that the slope of the resistivity in the elastic range in greater than the slope in the strain hardening and softening regions. Thus, indicating that such a smart material can more efficiently monitor strains in the elastic range of compressive stress application than in the post crack period.

Chapter 6

CYCLIC LOADING

While reversible changes in electrical resistance upon dynamic loading relates to dynamic strain, irreversible changes in resistance relate to damage. It has been reported that the resistance of carbon fiber-reinforced cement mortar decreases irreversibly during the early stage of fatigue (the first 10% or less of the fatigue life) due to matrix damage resulting from multiple cycles of fiber pull-out and push-in. The matrix damage enhances the chance of adjacent fibers to touch one another, thereby decreasing the resistivity. Beyond the early stage of fatigue and up to the end of the fatigue life, there is no irreversible resistance change, other than the abrupt resistance increase at fracture [25]. The absence of an irreversible change before fracture indicates that the mortar is not a good sensor of its fatigue damage.

Fatigue damage is to be distinguished from damage under increasing stresses. The former typically involves stress cycling at a low and fixed stress amplitude [6], whereas the latter typically involves higher stresses. The former tends to occur more gradually than the latter. Thus, the failure to sense fatigue damage [25] does not suggest failure to sense damage in general.

In this work, the sensing of damage under increasing stresses was demonstrated in carbon fiber-reinforced mortar. The damage was found to be accompanied by a partially reversible increase in the electrical resistivity of the mortar. The greater the damage, the larger was the resistivity increase. As fiber breakage would have resulted in an irreversible resistivity increase, the damage is probably not due to fiber breakage, but due to partially reversible interface degradation. The interface could be that between fiber and matrix. This behavior was observed within the elastic regime.

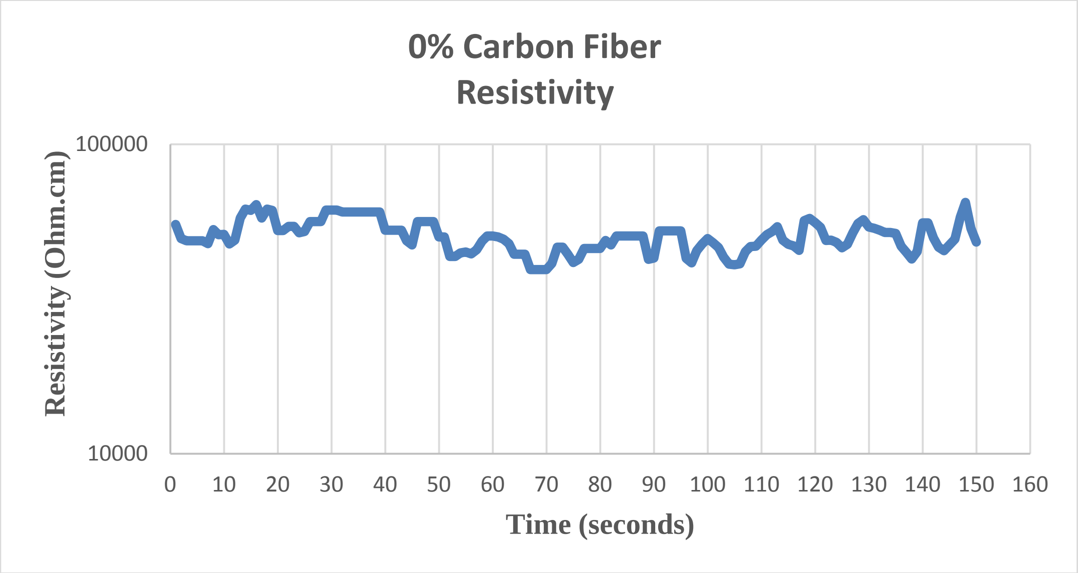

Fig.6.1: Variation of Resistivity under Cyclic Loading for Plain Specimens

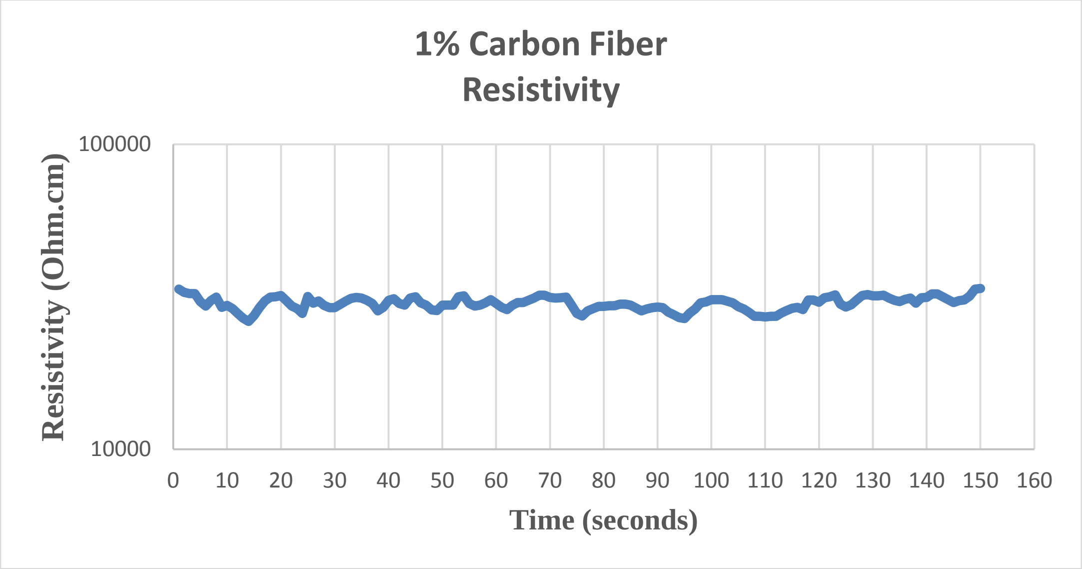

Fig.6.2: Variation of Resistivity under Cyclic Loading for 0% Specimens

In order to study the response of the cyclic loading, samples were cast using different percentage of carbon microfibers. All samples were cured for 28 days before testing. The samples were subjected to cyclic loading. The load during each cycle was gradually increased to 75 % of the ultimate capacity of the sample.

Resistance readings were taken across mortar sample during loading. Resistivity was calculated using Eq. 3.1. All samples were tested and the average value of variation in resistivity with load of each smart material was plotted. Figures in this chapter show the variation in resistivity for each sample with change in load. The behavior of the specimen cyclic loading was found to be similar to that under compressive loading. Resistivity decreased in the initial phase till it reached a relatively flat phase after which it increased. An increase in the resistivity towards the end, indicate that micro cracks were beginning to form at higher load values.

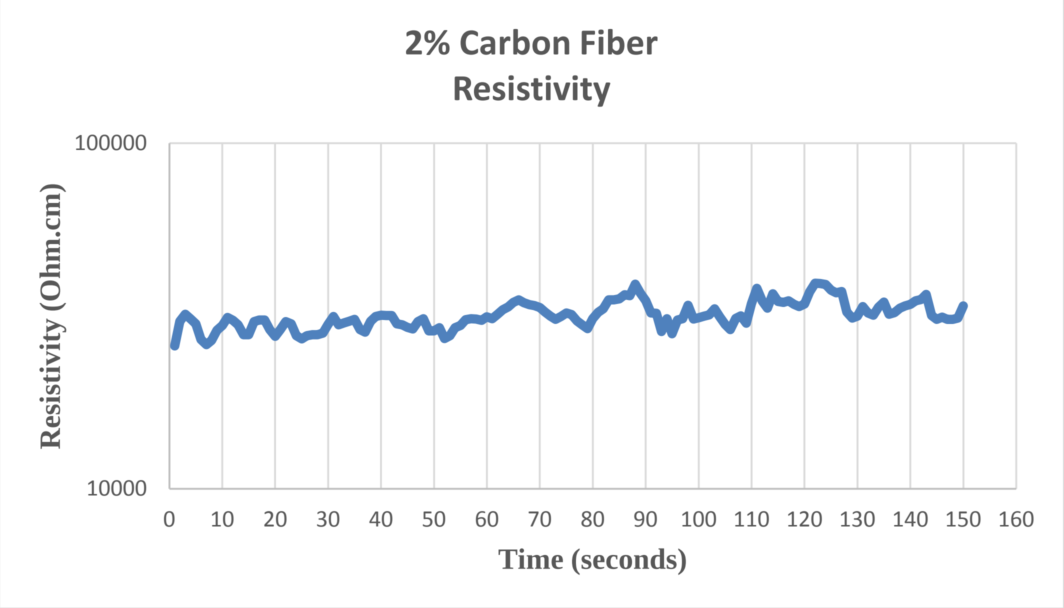

Fig.6.3: Variation of Resistivity under Cyclic Loading for 2% Specimens

Specimens having 0 - 3% carbon fiber reinforcement under cyclic loading were unable to observe any significant change in resistivity and data was very noisy for lower fiber (0-3%) content. At a fiber content of 0% by weight of cement, the data was too noisy to be meaningful which can be very clearly seen in fig.6.1. This noisy data attributes that at lower carbon fiber percentage no percolation network was formed thus resulting in distorted data.

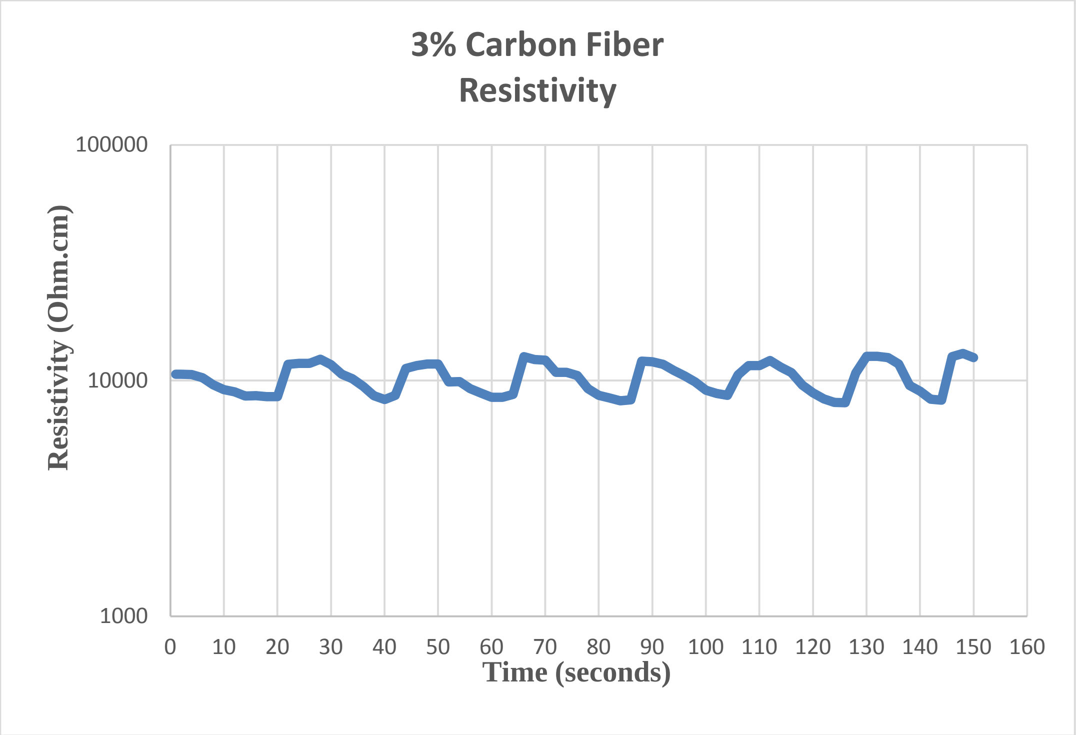

Fig.6.4: Variation of Resistivity under Cyclic Loading for 3% Specimens

As we increase the carbon fiber percentage to 3-5% specimen shows significant change in resistance,. The stress returned to zero at the end of each loading cycle. The higher the stress, the greater was the extent of resistance decrease. The strain returned to zero at the end of each cycle. The resistance decreased reversibaly upon loading in each cycle, as in Fig. 6.4 - 6.6. Hence, during loading from zero stress within a cycle, the resistance dropped and then increased sharply on unloading reaching the maximum resistance of specimen. Upon subsequent loading, the resistance decreased and then increased as unloading continued, reaching the maximum resistance of the original resistance at zero stress.

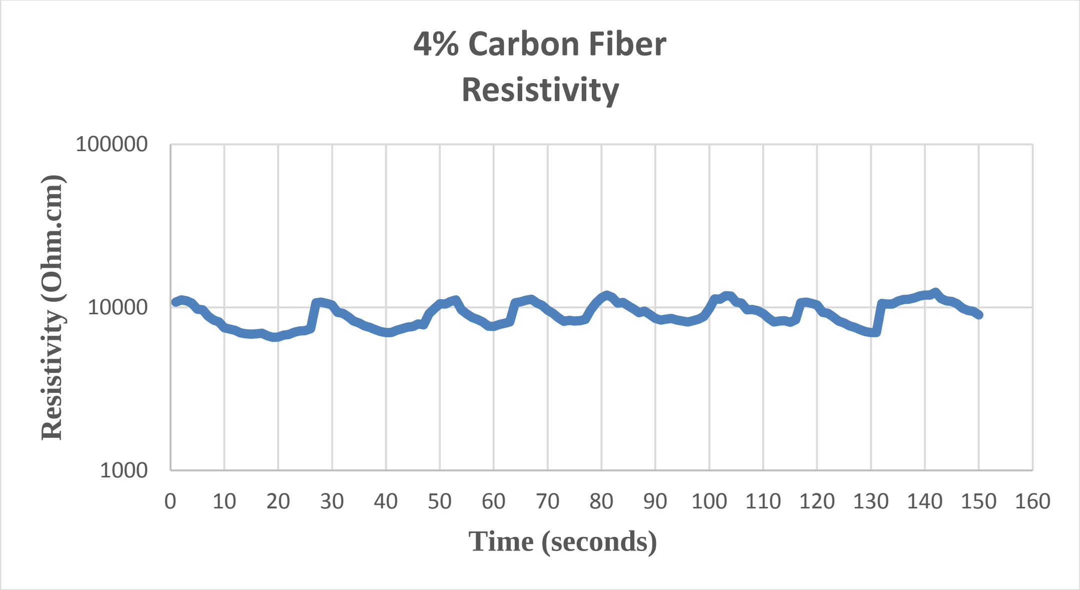

Fig.6.5: Variation of Resistivity under Cyclic Loading for 4% Specimens

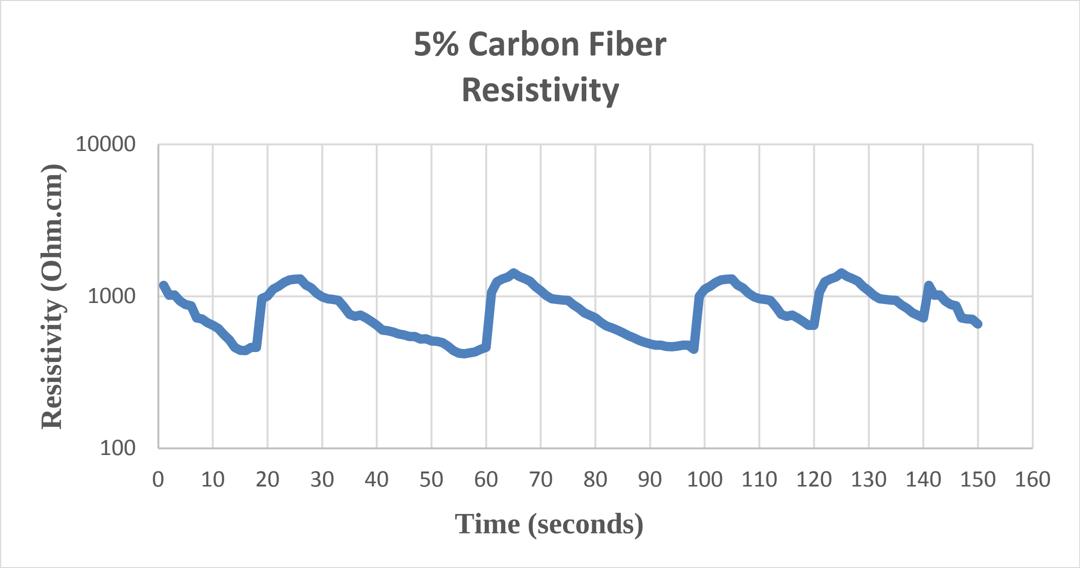

Fig.6.6: Variation of Resistivity under Cyclic Loading for 5% Specimens

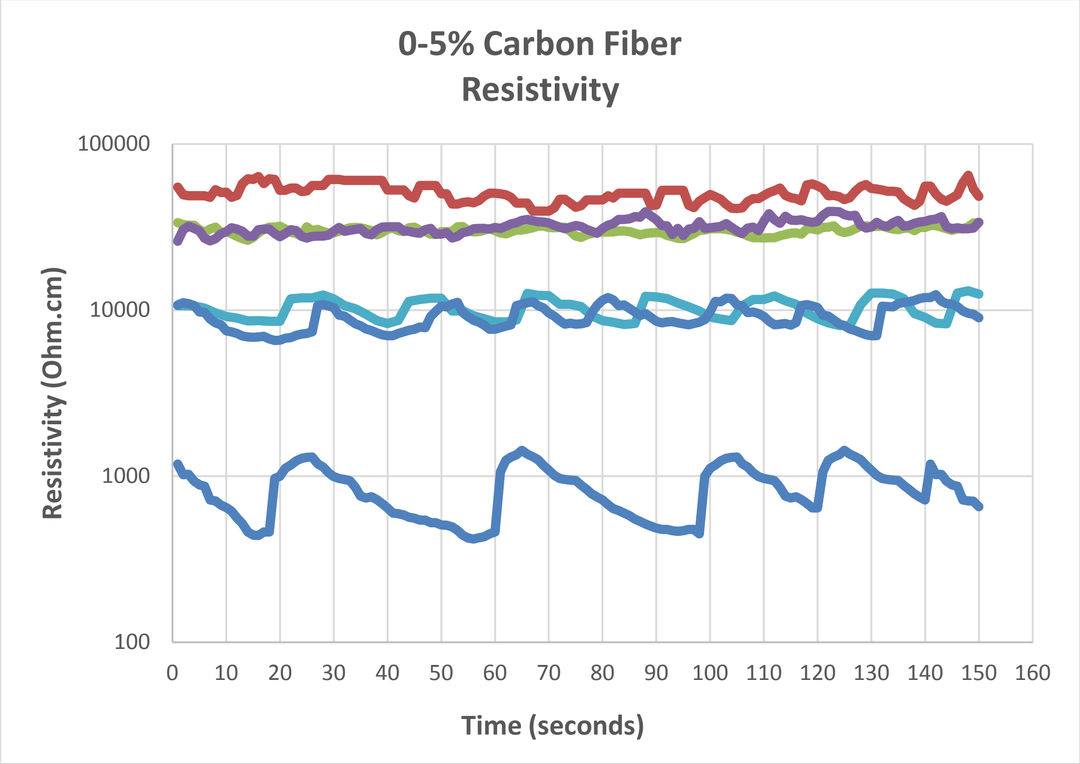

Fig.6.7: Variation of Resistivity under Cyclic Loading for 0-5% Specimens

Fig: 6.7 shows the comparison of different carbon fiber matrix under cyclic loading.

Chapter 7

RESULTS AND CONCLUSIONS

This study was carried out to develop an economic smart material using carbon microfibers that can be used in field of civil engineering for the purpose of structural health monitoring.

It was found that the electrical resistivity of both plain mortar samples and carbon fiber reinforced mortar samples when continuously cured, increased over time. This can be attributed to the overall change in the microstructure of the mortar due to hydration. An increase in fiber volume fraction at constant w/c ratio decreased the electrical resistivity significantly.

Another prominent attribute found in carbon fiber reinforced mortar was reduction in density due to addition of air voids. One advantage of such mortar is resistance against freezing and thawing.

A mix proportion with lower w/c ratio and higher fiber volume fraction had lower electrical resistivity than specimens with higher w/c ratio and lower fiber volume fractions. The samples with 5% fiber content showed lowest values of resistivity. It was found that w/c ratio did not significantly affect the electrical resistivity of samples with higher fiber volume fraction. It could be because the carbon fibers provided the primary conduction path as opposed electrolytic conduction through pore solution in connected capillary pores. It is possible to take advantage of this large fiber to fiber contact for solely monitoring strain since the effect of moisture and temperature on resistivity is relatively insignificant.

On direct compressive loading it was seen that during the elastic range resistivity decreased continuously. This clearly indicated that the fibers were coming in contact with each other. The resistivity then flattened and continued in this phase till the formation of micro cracks after which it increased. On an average, the resistivity changes between 10% and 45% of the ultimate load capacity of the specimen were found to be reversible. Since the slope of the resistivity was always the steepest in the elastic region during compression, it can be said that the smart material works most effectively in the elastic region.

Carbon fiber-reinforced mortar can monitor both strain and damage simultaneously through electrical resistance measurement. The resistance decreases upon compressive strain and increases upon damage.

In the experiment where the specimen were subjected to cyclic loading the samples with higher carbon fiber shows better result, at lower percentage of carbon fiber the results obtained were too noisy and thus making it difficult to make any conclusions. During the cyclic loading from zero stress within a cycle, the resistance dropped on loading and then increased sharply on unloading reaching the maximum resistance of specimen. Upon subsequent loading, the resistance decreased and then increased as unloading continued, reaching the maximum resistance of the original resistance at zero stress. This shows the reversibility of resistivity under cyclic loading which is very use full for SHM in structure subjected to cyclic loading i.e. bridges, high rise buildings, slopes, offshore plarforms etc.

This means that the strain/stress condition during cyclic loading under which damage occurs can be obtained, thus facilitating damage origin identification.

Chapter 8

RECOMMENDATIONS

There is a wide range of potential that can be tapped in the field of structural health monitoring using carbon microfibers. The biggest advantage of this system is its low cost and straightforward mechanism. The development of such a low-cost fiber reinforced matrix can significantly increase the number of structures being monitored throughout the world. However a lot of work has to be done in creating a practical matrix which can be used in field.

It was observed that percolation threshold was achieved at 5% fiber content, this can be achieved at a lower percentage of carbon microfibers by using a dispersant like latex and methylcellulose, by formulating a different mix or using carbon fiber of different lengths which will help in finer dispersion of carbon microfibers.

It was observed that samples with higher percentage of carbon microfibers showed lower compressive strength compared to the samples without carbon microfibers. This decrease is probably due to the formation of a large amount of air voids which are developed due to use of carbon microfibers. The amount of air voids can be decreased by proper use of silica fumes which will make the mix dense and helps in dispersion of carbon fibers, superplasticizer also play a very important role in increasing the workability of mix. Also, steam curing is recommended instead of moist curing.

Our study focused on the electric conduction of carbon microfibers and using this property to evaluate the strain sensing ability and damage sensing ability of mortar samples under compressive and cyclic loading. Further studies can be carried out to study the influence of carbon microfibers on other mechanical properties of mortar such as tensile strength, tensile ductility, flexure toughness, impact resistance and freeze thaw durability etc. Carbon microfiber reinforced matrix can further be used in the field of SHM to study temperature sensing ability, thermoelectric behavior, thermal insulation ability and improved resistance to earthquake.

The contact between electrodes and the matrix was of major concern. This problem was finally resolved by creating a rough surface on the electrode for better bonding.

The effect of steel rebar on the resistivity readings in such a smart material is not known. Experiments that can validate the usefulness of such matrix in steel reinforced structural elements can take this concept to a whole new level.

The results of these experiments are based on work conducted in laboratory environment. Hence future work is required where this matrix is subjected to use in field, where it can be made to function under a combination of different environmental factors that bring about changes in resistivity.

While using such a smart material in the field it is recommended to coat the specimen with a thin layer of water resistant material to prevent an unnecessary increase in the moisture content in the smart material.

Concrete differs from mortar in that it contains a coarse aggregate. Moreover, concrete is a much more common structural material than mortar. Hence further work must be done to observe the behavior of carbon fiber in concrete.

Behavior of smart material under flexural loading must be studied as many elements of structures are subjected to flexural loading.

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PHOTO GALLARY

Copper Strips

2”x 2”x 2” Molds

Silica Fumes

Cement

Sand

Chopped Carbon Fibers

Carbon Fibers Roll

Superplasticizer
Sika ViscoCrete-20HE

Superplasticizer
Sica Sicament 512

Water

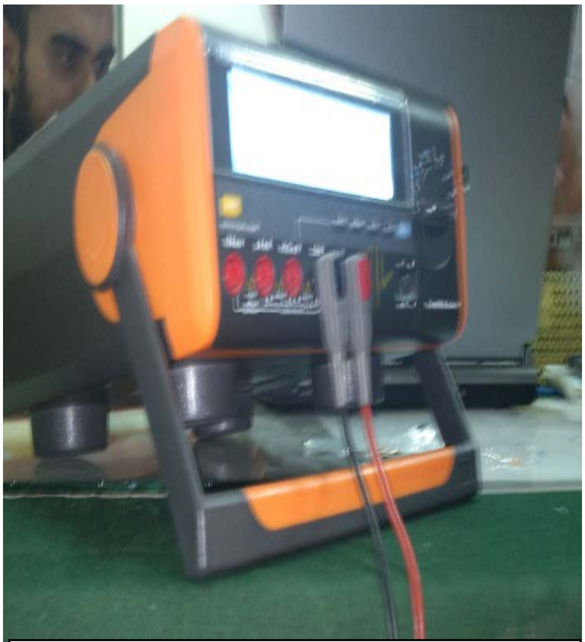
Hobart Mixer

Materials Used

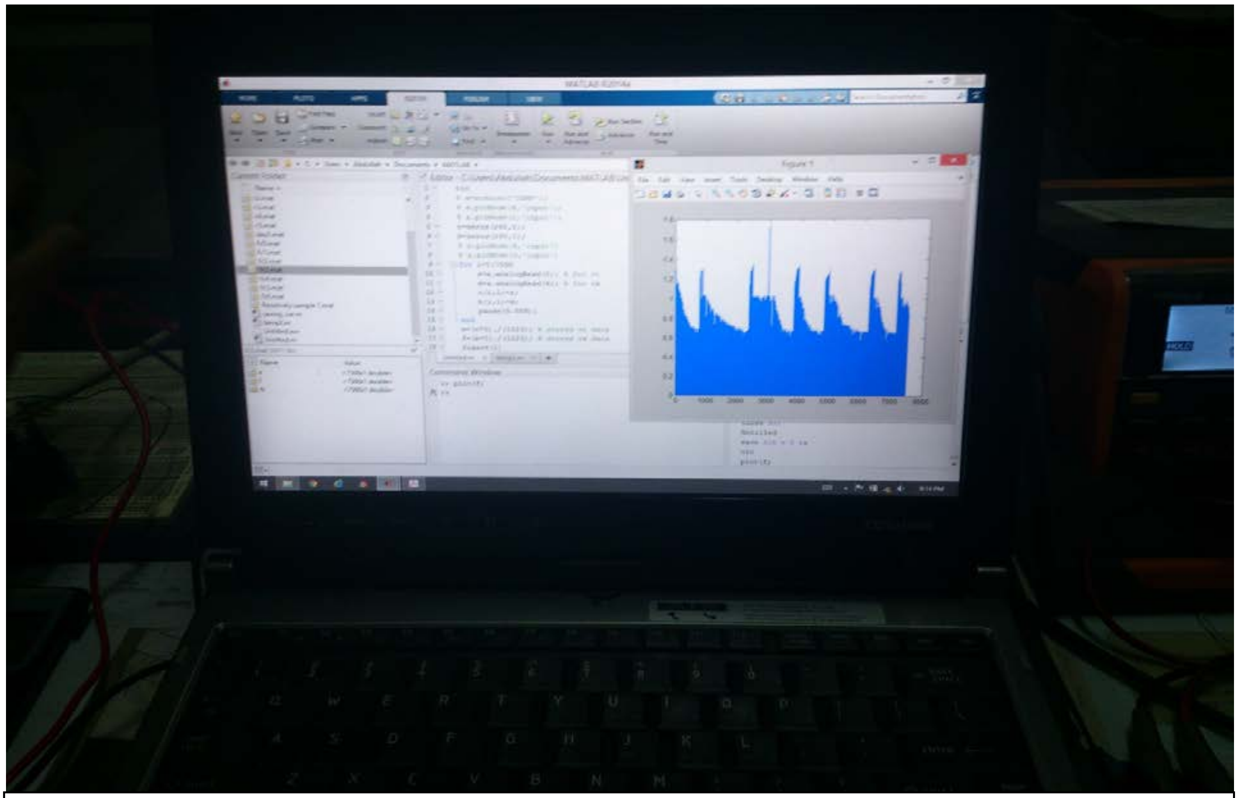
Mortar Mix

Specimen

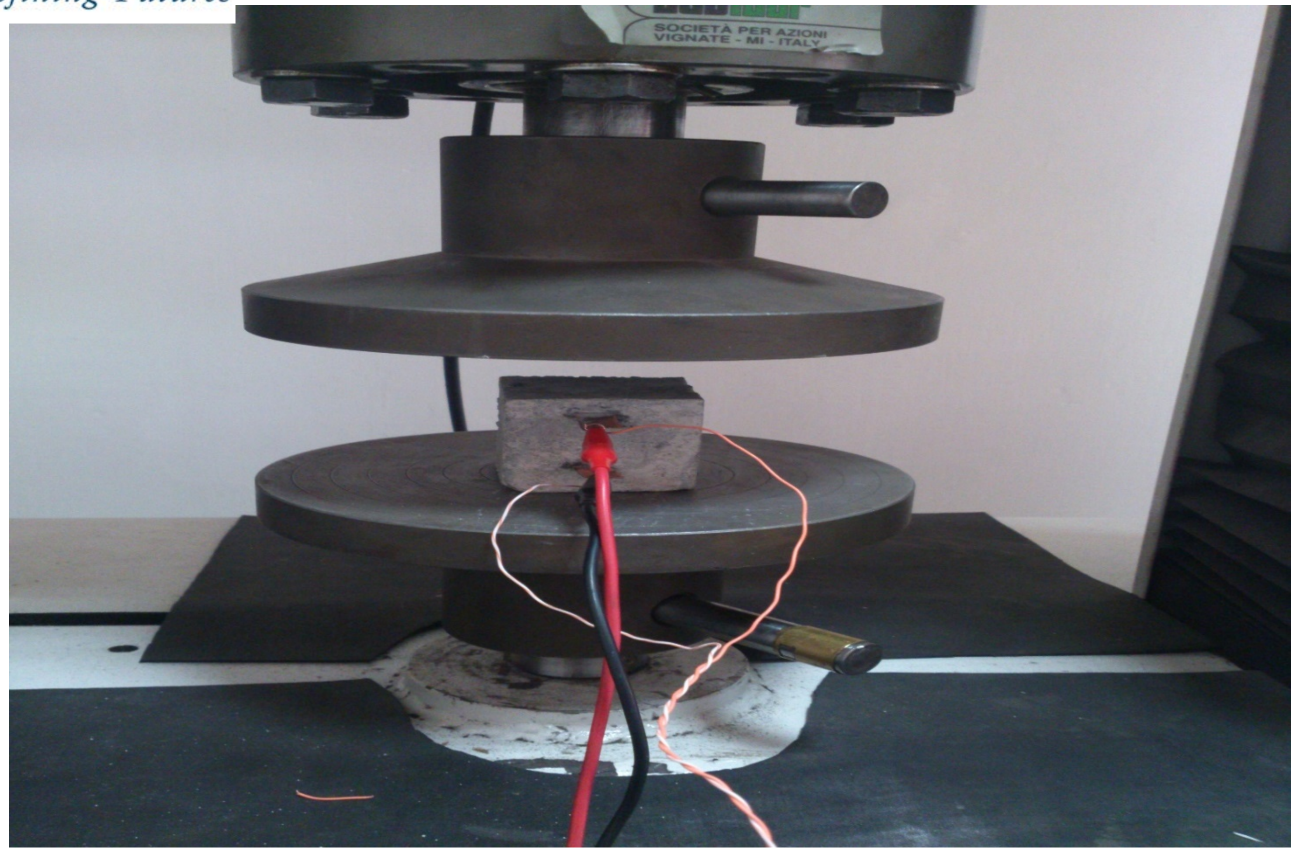
Arduino Microcontroller



Digital Multimeter



Display Unit (Laptop)



Specimen Testing

Complete Testing Setup