

Conductivity-based strain monitoring and damage characterization of fiber reinforced cementitious structural components

Tsung-Chin Hou and Jerome P. Lynch

Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109

ABSTRACT

In recent years, a new class of cementitious composite has been proposed for the design and construction of durable civil structures. Termed engineered cementitious composites (ECC), ECC utilizes a low volume fraction of short fibers (polymer, steel, carbon) within a cementitious matrix resulting in a composite that strain hardens when loaded in tension. By refining the mechanical properties of the fiber-cement interface, the material exhibits high tolerance to damage. This study explores the electrical properties of ECC materials to monitor their performance and health when employed in the construction of civil structures. In particular, the conductivity of ECC changes in proportion to strain indicating that the material is piezoresistive. In this paper, the piezoresistive properties of various ECC composites are thoroughly explored. To measure the electrical resistance of ECC structures in the field, a low-cost wireless active sensing unit is proposed. The wireless active sensing unit is capable of applying DC and AC voltage signals to ECC elements while simultaneously measuring their corresponding voltages away from the signal input. By locally processing the corresponding input-output electrical signals recorded by the wireless active sensing units, the magnitude of strain in ECC elements can be calculated. In addition to measuring strain, the study seeks to correlate changes in ECC electrical properties to the magnitude of crack damage witnessed in tested specimens. A large number of ECC specimens are tested in the laboratory including a large-scale ECC bridge pier laterally loaded under cyclically repeated drift reversals. The novel self-sensing properties of ECC exploited by a wireless monitoring system hold tremendous promise for the advancement of structural health monitoring of ECC structures.

Keyword: piezoresistivity, wireless sensing, strain hardening, strain monitoring, damage characterization, engineered cementitious composites

1. INTRODUCTION

Fiber reinforced cementitious composite (FRCC) is a relatively new civil engineering material that has been under study for several decades. Formed by the addition of an appropriate amount of short fibers within a cement matrix, FRCC provides improved mechanical properties compared to conventional concrete counterparts. The inclusion of short fibers (polymer, steel, or carbon) within a cement matrix enhances the mechanical properties of the composite including its ductility and energy adsorption capacity. Special classes of FRCC termed high performance fiber reinforced cementitious composite (HPFRCC) or engineered cementitious composite (ECC) have been proposed by a number of researchers [1,2]. Fabricated from cement, silica, fine sand, water and a small volume (usually less than 2%) of fibers, ECC is a highly ductile material (tensile strain capacities between 3 and 8%) that exhibits strain hardening in tension. The tensile strength of ECC can be as high as 10 MPa, with compressive strengths on the same order as high strength concrete. The bulk material properties of ECC are tailored through a judicious selection of the fiber's dimensions, material-type, and matrix interface properties [3]. Upon the initiation of matrix cracking, fibers arrest crack growth thereby avoiding damage localization; in contrast, energy is dissipated through the formation of a dense field of microcracks (with widths less than 100 μm) as shown in Figure 1a. Ultra ductility and damage tolerance are achieved through tuning of the fiber-matrix interface. Appropriately designed interface properties ensure the fibers act as inelastic springs that deform freely without pulling out from the matrix. Figure 1b presents a microscopic image of fibers arresting the development of a crack in a cement matrix.

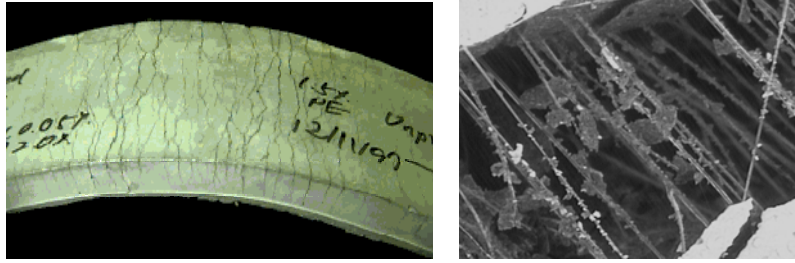


Figure 1 – (a) ECC plate in bending revealing dense field of micro-cracking; (b) microscopic view of fibers bridging a single crack in an ECC specimen (*courtesy Prof. V. C. Li, University of Michigan*)

The mechanical performance of ECC materials has been thoroughly studied in the laboratory. In contrast, non-mechanical properties such as thermal and electrical conductivity have not received as much attention from the research community. While the electrical properties of traditional concrete have been under study since the seminal work of Hammond and Robson [4], little attention has been focused upon the fundamental understanding of the electrical properties of FRCC, and more specifically, ECC materials. Cementitious materials, including concrete and FRCCs, are piezoresistive and experience linear changes in conductivity when mechanically strained [5]. Consistent with other cementitious materials, ECC is piezoresistive thereby allowing the material to be utilized for sensing its strain and potentially, crack damage. Conductivity-based monitoring of cementitious materials is ordinarily performed in the laboratory where large and expensive testing equipment is readily available. However, to translate the potential of utilizing piezoresistivity as a novel mechanism for monitoring the behavior of cementitious materials, low-cost and portable sensors for field deployment are needed.

In this study, a new approach to monitoring the performance and health of structural elements constructed of ECC is proposed. At the core of the study is the use of low-cost wireless sensors that have shown promise in other structural health monitoring applications [6]. In particular, a compact wireless active sensing unit that is capable of emitting electrical signals into ECC materials while simultaneously measuring their voltage output is proposed. This structural monitoring solution is both elegant and low-cost since electricity is a natural and seamless interface that exists between wireless monitoring systems (built from electrical components) and the cementitious material. The electrical properties of ECC are studied during laboratory testing of ECC structural specimens loaded under tension. As ECC specimens are loaded, the wireless active sensing unit is utilized to accurately measure material conductivities. The piezoresistive properties of ECC materials are shown to be an accurate measure of the material strain. In addition, changes in conductivity inconsistent with variations in strain are also shown to be correlated to crack damage in the structural element. The study concludes with validation of conductivity-based strain monitoring by utilizing a 1/3-scale bridge pier constructed from ECC and monotonically loaded in a lateral direction.

2. CONDUCTIVITY OF CEMENTITIOUS MATERIALS

To render concrete an effective construction material, its mechanical properties (e.g. compressive strength) have been thoroughly explored by the structural engineering profession. However, other properties of cementitious materials such as thermal conductivity, electrical conductivity and electromagnetic properties remain largely unexplored. The electrical properties of concrete were first explored systematically in the 1950's, when Hammond and Robson first reported their findings on the electrical properties of plain concrete [4]. Subsequent to their study, the electrical properties of concrete have been important design parameters in the design of unique structural elements such as concrete rail ties, electrical power plant slabs, and hospital operating room floors [7]. For example, in using concrete for rail ties, a material with a very low electrical conductivity is desirable so as to electrically isolate power rail lines attached to the ties. The electrical properties of concrete have also found use in monitoring the curing and in assessing the rate of corrosion of embedded reinforcement steel.

Recently, researchers have begun to explore the electrical properties of FRCC materials [5]. In contrast to those studying the electrical properties of plain concrete, research on the conductivity of FRCC is mainly focused upon utilizing material electrical properties to measure axial strain and tracking the formation of crack damage. Just as the

addition of short discontinuous fibers can enhance the mechanical performance of FRCC and ECC materials, judicious selection of fiber type (steel, carbon or polymer) and fiber volume fraction can lead to desirable electrical properties optimally suited for sensing applications. For example, various studies have found that by adding a small volume of conductive fibers in a cement matrix, the bulk electrical properties of the composite, such as conductivity, can fall within a rational range for practical measurement. In this study, the electrical properties of ECC materials are studied to develop a low-cost method of monitoring strain and damage severity (degree of crack damage) in realistic field applications.

Conductivity is a scientific measure of how easy it is for electrical current (transport of electrons) to flow in a material. By following Ohm's Law, $V = iR$, the electrical resistance, R , of a material can be determined based upon the applied voltage potential, V , and the corresponding electrical current, i , passing through it. In characterizing the natural conductivity properties of a specific material, electrical resistivity, ρ , is generally more widely used because it normalizes resistance (which is dependent upon the size of a test specimen) by geometric dimensions:

$$\rho = \frac{RA}{L} \quad (1)$$

Here, A is the cross section area of the material across which electrical current travels and L is the corresponding traveling length inside the material. Conductivity (σ) is the inverse of resistivity: $\sigma = 1/\rho$.

The electrical conductivity of cementitious materials depends on various parameters including material composition, environment, and time. In general, highly conductive materials such as metals have electrical conductivities above $1 \times 10^{-4} \Omega^{-1} \text{cm}^{-1}$ while insulators, such as paraffin, have electrical resistivity below $1 \times 10^{-8} \Omega^{-1} \text{cm}^{-1}$. In contrast to these two extremes, the electrical conductivity of cementitious materials ranges from 1×10^{-8} to $1 \times 10^{-4} \Omega^{-1} \text{cm}^{-1}$, which is similar to the range of semiconductors. The electrical conductivity of cementitious materials can be varied with the inclusion of conductive fibers such as carbon and steel; conductive fibers effectively raise the bulk material electrical conductivity. The conductive fibers provide additional paths for electrical current to travel through the cement matrix. Unlike the electrical current in metals and semiconductors which is defined by a flow of electrons or holes, current in cementitious materials is the flow of free ions in the porous matrix material. If the material is an FRCC, electrical current in the individual conductive fibers is known to be a flow of electrons. Therefore, electrical properties of FRCC materials are the combination of cement matrix and the conductive fibers within it. The physical interface that lies between the conductive fibers and the cement matrix is also known to play role in the conductive properties of the composite material. Researchers have found that the electrical conductivity of the fiber-matrix interface is current frequency dependent [8,9]. For example, direct current (DC) and low frequency alternating current (AC) tests reveal that the fiber-matrix interface is characterized by high impedance. As a result, the composite conductivity is dominated by the electrical properties of the cement. As the AC frequency is raised, the interface impedance lessens and the composite's electrical properties are strongly influenced by the conductivity of the fibers [8].

It has been found that the mechanical deformation, specifically tensile strain, will induce a detectable change in the electrical conductivity of a cementitious material. Furthermore, research done in the piezoresistivity of FRCC materials has revealed that due to the absence of large aggregates and the presence of conductive fibers, piezoresistive behaviors are fairly linear as well as repeatable [5]. This is mainly due to conductive fibers that bridge the cracks that form during tensile straining. For example, if an FRCC specimen is sustaining crack damage as shown in Figure 2, the electrical current, i , will not travel through region "1" since both the matrix and fibers are separated from each other. In contrast, the fiber bridging mechanism depicted in region "2" allows the electrical current to pass through the matrix crack. As a result, the increased electrical resistivity is partially or even fully reversible once the crack is closed upon compression of the material. For completeness, consider region "3"; the electrical conductivity of the uncracked region is attributed to the cement matrix and the conductive fibers.

High-performance fiber reinforced cementitious composites (HPFRCCs) are one class of FRCC materials that have been developed in recent years. As opposed to strain softening that occurs after the first crack of the cement matrix, HPFRCC materials exhibit strain hardening and ultra-ductile behaviors (tensile strains in excess of 3% are common). To date, the electrical properties of HPFRCC and ECC elements have not been explored. There is much demand to

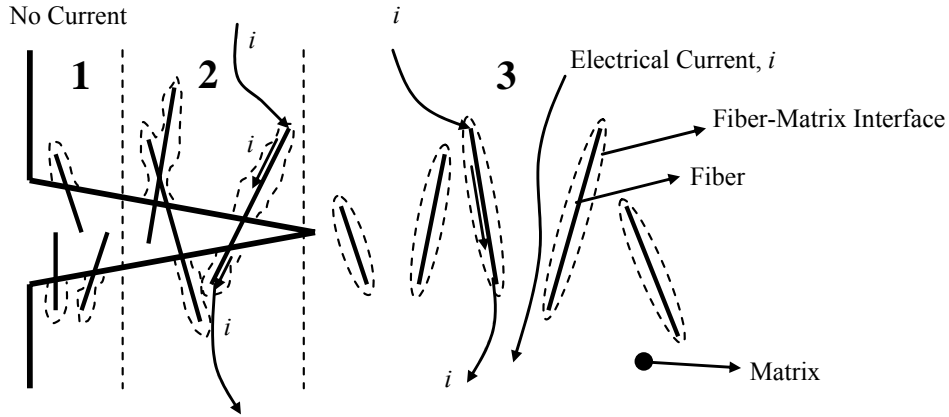


Figure 2 - Electrical current passing through three ECC states: 1) post-fiber pullout, 2) fiber bridged cracks, and 3) uncracked



Performance Feature	Specification
ADC Resolution	10-bit
ADC Channels	32
DAC Resolution	12-bit
DAC Channels	1
Sampling Rate	100 kHz
Microcontroller	32-bit PowerPC
Wireless Radio	MaxStream 9XCite
Radio Frequency	900 MHz
Wireless Range	300 m (Line of Sight)
Radio Encoding	FHSS

Figure 3 – (Left) wireless active sensing unit prototype, (right) performance specifications

monitor the performance of HPRCC materials as they transition from the laboratory to the field. For example, ECC has been proposed for highway bridge slabs [10], bridge piers [11], and concrete-steel beam-column connections [12]. With ECC exhibiting the same piezoresistive properties as FRCC, this study intends to leverage ECC conductivity for monitoring strain and damage in ECC structures.

3. WIRELESS ACTIVE SENSING UNITS

Wireless sensing technology is an emerging field of structural health monitoring that has shown great potential in recent years. In 1998, Straser and Kiremidjian [13] first proposed the concept of wireless communications within a structural monitoring system to eliminate the installation costs associated with installing extensive lengths of coaxial cables. In order to improve upon the functionality of wireless sensors within a structural monitoring system, Lynch *et al.* [6] has integrated powerful microcontrollers into the wireless sensor design so that local data interrogation can be accommodated. Furthermore, as wireless sensors continue to decline in cost, ever higher densities of sensors can be installed in a single structure. As a result, wireless structural monitoring systems are multi-scale in nature with both system- (global) and component-level monitoring possible.

To broaden the role of the wireless sensor within the context of structural health monitoring, wireless active sensors have recently been proposed [14]. In stark contrast to traditional wireless sensors that are passive in nature, wireless active sensors are capable of exciting the structure by using actuators. Active sensing necessitates a wireless sensor that can command an actuator (typically a piezoelectric element inducing Lamb waves within structural elements). In addition to an analog-to-digital converter, microcontroller, and wireless transceiver, the wireless active sensing unit proposed by Lynch *et al.* [14] contains an actuation interface that is capable of emitting actuation command signals ranging from -5V to 5V. Figure 3 summarizes the performance features of the wireless active sensing unit prototype. To date, the

prototype has been validated using piezoelectric actuators epoxy mounted to the surface of aluminum plates. In this study, no actuator is needed. Rather, the wireless active sensing unit is utilized to apply input voltage signals (DC and AC) into ECC structural elements. In the same manner, the sensing interface of the wireless active sensing unit is used to record the corresponding voltage potential of the element away from the voltage input.

4. ELECTRICAL RESISTANCE MEASUREMENT OF ECC TENSILE PLATES

In order to investigate the piezoresistive behaviors of ECC materials under axial strain, a series of ECC plates regularly used for tensile testing are constructed. The ECC material is constructed from a combination of Type III Portland cement (cement to water ratio of 0.53), silica sand, fly ash, and short polyvinyl alcohol (PVA) fibers. In the specimens constructed, only a 2% volume fraction of PVA fibers is included in the cement matrix so as to provide strain-hardening and ultra-ductility. With PVA fibers being non-conductive, additional conductive fibers including carbon and steel fibers are added into the ECC material mixture to allow for the flow of electrical current during cracking of the matrix.

The smallest possible volume fraction of the carbon and steel fibers is desirable to minimize interference with the mechanical performance of the ECC material that has already been optimized assuming only PVA fibers present. At the same time, enough fibers are needed to ensure conductive fibers are present across matrix cracks. Hence, one set of ECC specimens is constructed with a 0.4% volume fraction of carbon fibers while another set employs steel fibers with a volume fraction of 0.1%. Both the volume fractions of carbon and steel fibers used in this study are close to the lower bound of the percolation thresholds reported by Chung [5]. An adequate amount of superplasticizer is also used in casting the ECC specimens so as to increase the workability of the mixtures and guarantee all of the fibers are well dispersed. A third set of regular ECC plates (PVA fibers only) are constructed to serve as control specimens. The control specimens are instrumental in examining the effect of extra conductive fibers on both the mechanical and electrical properties of the bulk material.

Because electrical conductivity is a natural property of the material, the ECC plates of different geometries can be tested. One set of ECC tensile plates has cross sectional dimensions of 13 mm by 76 mm and length of 305 mm. The second set of specimens is much smaller than the first, with cross sectional dimensions of 13 mm by 25 mm and 153 mm long. The reason for introducing a second set of specimens is to ensure specimens do not buckle during cyclic axial load testing. All of the specimens are removed from their molds roughly 7 days after casting and are allowed to cure till the 28th day. To electrically probe the specimens, electrodes attached to laboratory equipment and wireless active sensing units are constructed from copper wire and mounted to the specimens using silver colloidal paste. In this study, two-probe electrical resistance measurements are made.

In measuring the electrical resistance of FRCC materials, several methods have been proposed by various researchers. Among those, the direct current (DC) test method is the simplest with a fixed voltage applied to the test specimen. Unfortunately, ECC materials cannot be viewed as simply being resistive; rather, the material is somewhat capacitive with charge build-up probable. Referred to as the polarization effect, the DC measurement of electrical resistance is technically difficult due to an exponential rise in the measured resistance (as depicted in Figure 4a). One way to nullify the polarization effect of DC electrical resistance measurements is to record the change in resistance due to polarization for an unloaded specimen. Another approach is to apply a DC voltage potential well ahead of loading the material so as to allow the resistance to plateau off due to complete polarization. However, this method is not practical for use in the field. Furthermore, polarization is dependent upon the specimen geometry with large specimens taking more time to fully polarize. An alternative method of applying voltage signals to ECC materials is to employ alternating current (AC) signals with equal magnitudes of positive and negative peaks. Although polarization can still be observed in AC signals, its effect can be lessened to an acceptable range by increasing the applied AC frequency. As seen in Figure 4b, in a very short period of the beginning of the alternated electrical current direction, polarization effect is nearly linear and reversible.

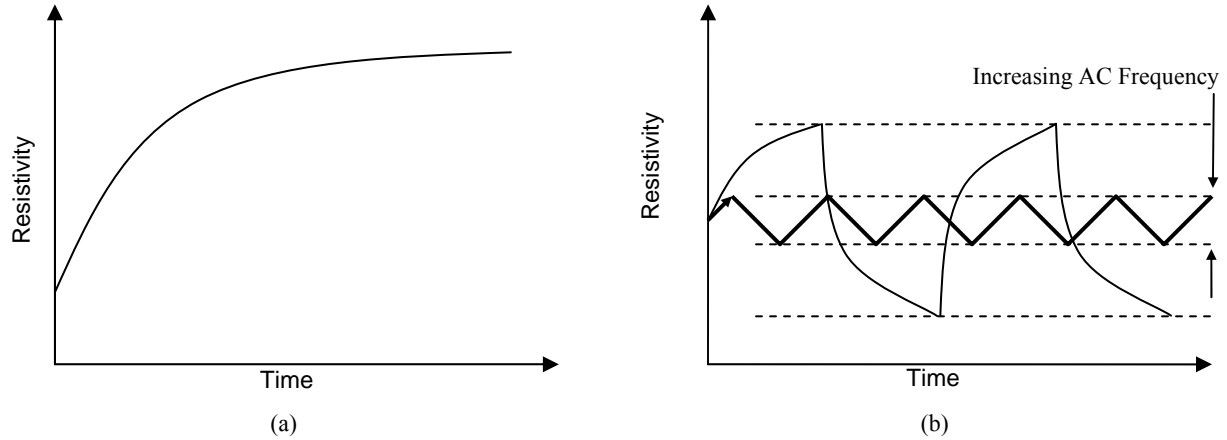


Figure – 4 Polarization effect of cementitious materials when applied with (a) DC, (b) AC

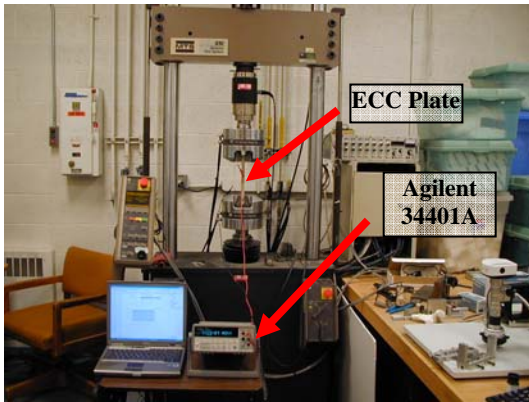
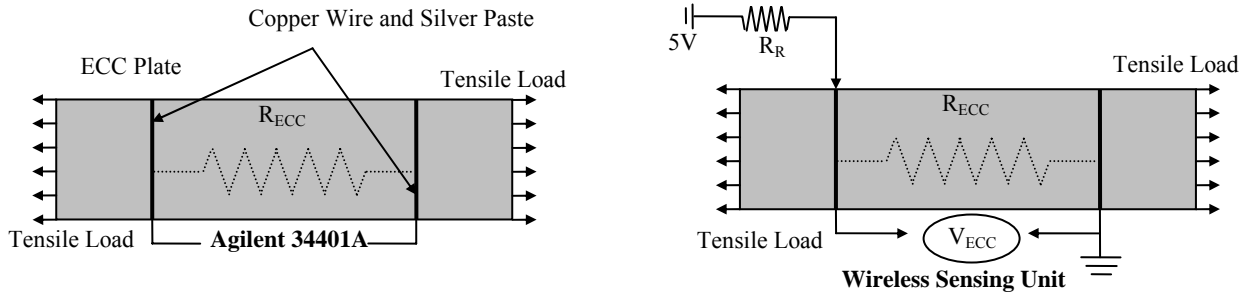
DC Test (Monotonic): When conducting a DC resistance measurement, ECC specimens are pre-charged ahead of the mechanical loading so as to eliminate the effect of polarization. In this type of tests, ECC specimens are monotonically loaded in tension by MTS 810 system at a strain rate of 0.064 mm per second. Changes in the electrical resistance of ECC specimens are directly measured by a traditional digital multimeter (Agilent 34401A) or indirectly calculated from the voltage output acquired by the wireless active sensing units, as shown in Figure 5. The intention of the digital multimeter is to ensure the accuracy of the wireless active sensing unit in calculating material resistance. In measuring the voltage output of the specimens using the wireless active sensing units, the ECC specimen is connected in series to a resistor with a known electrical resistance so as to compose an electrical circuit. An external voltage potential with the magnitude of 5V is provided by the wireless active sensing unit and the induced flow of electrical current travels through the resistor-specimen circuit. As seen in Figure 5(b), electrical resistance of the ECC specimen can be calculated from the voltage output of the resistor-specimen circuit analogy, which can be expressed as:

$$R_{ECC} = \frac{R_R V_{ECC}}{5 - V_{ECC}} \quad (2)$$

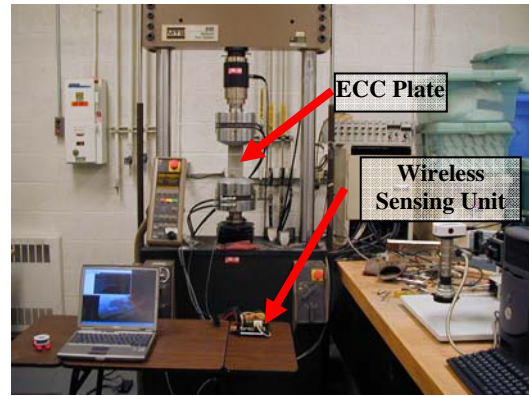
where R_R is the resistor with known electrical resistance. It should be mentioned that rather than having a 1 Hz sampling rate limit as the digital multimeter (Agilent 34401A), the wireless active sensing unit proposed by Lynch *et al.* [14] possesses a much higher data acquisition capacity (100 kHz). In DC resistance tests, the sampling rate of the wireless active sensing units is programmed as 50 Hz. Upon collection of the voltage output of the specimen, the computational core of the wireless active sensing unit calculates the resistance based on Equation (2) and wirelessly transmits the value to a remote data repository (a laptop computer).

As shown in Figure 6a, the presence of additional fibers (steel and carbon) does not severely decrease the strain capacity of ECC materials (approximately 2.5% tensile strain). On the other hand, the tensile strength at the initiation of strain-hardening is slightly increased by around 10% for the carbon fiber ECC specimen and by 18% for the steel fiber ECC. Figure 6b illustrates the changes of electrical resistivity of each ECC plate tested under tensile load. In comparing the resistance behavior of the three different ECC plate specimens (regular, steel-doped and carbon-doped ECC) they all exhibit a similar trend - a strong linear relationship between electrical resistivity and mechanical strain. These curves confirm the piezoresistive property inherent to the three ECC materials tested. As expected, the electrical resistivity of the regular ECC plate, is around $2.5 \times 10^6 \Omega \text{ cm}$ ($\sigma = 4 \times 10^{-7} \Omega^{-1} \text{ cm}^{-1}$) before loading. This is higher than the carbon fiber and steel fiber ECC plates, which are roughly $0.8 \times 10^6 \text{ Ohm-cm}$ ($\sigma = 1.25 \times 10^{-6} \Omega^{-1} \text{ cm}^{-1}$) and $1.9 \times 10^6 \Omega \text{ cm}$ ($\sigma = 5.2 \times 10^{-7} \Omega^{-1} \text{ cm}^{-1}$), respectively. Furthermore, the rate of change in electrical resistivity versus strain (gage factor) is much higher for the regular ECC plate specimens than those with steel and carbon fibers included. The gage factor of the ordinary ECC material is roughly 100 while that for the steel and carbon materials are 18 and 21, respectively. It

should be noted that these gage factors are well above those associated with traditional metal foil strain gages which typically have gage factors of 2 to 3 [15].

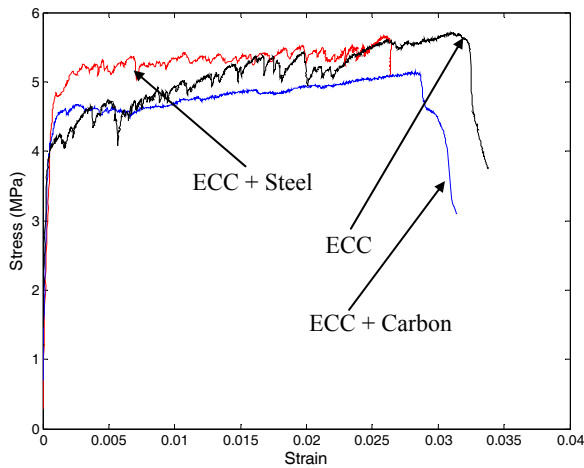


(a)

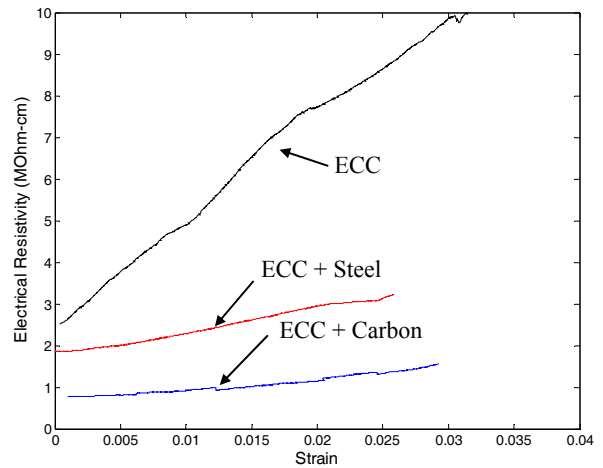


(b)

Figure 5 - DC electrical resistance measurement taken by (a) digital multimeter, and (b) wireless active sensing unit



(a)



(b)

Figure – 6 DC monotonic test (a) stress-strain relationships, (b) electrical resistivity-strain relationship

AC Test (Monotonic): Unlike the DC testing, the AC resistance test has little or no polarization influencing the conductivity measurement, thus resulting in strain measurements with greater accuracy. In order to adjust the voltage output of the resistor-specimen circuit, the specimen dimensions are shrunk to one-sixth of the size of DC test (second set of specimens whose dimensions are 13 mm x 25 mm x 153 mm). A low frequency AC current (5 Hz) is provided by the wireless active sensing unit to the ECC specimens with the voltage potential varying from -5V to 5V. Figure 7 presents the test set-up of an ECC specimen using AC electrical probing. Figure 8 shows the results of the carbon-ECC plate under monotonic axial tensile loading. As seen in Figure 8a, the linear relationship between mechanical strain and electrical resistivity still holds as was the case in the DC case. The specimen ultimately fails due to damage localization in a region near the specimen ends. Since this was beyond the region probed by the electrical leads, this damage goes unnoticed. However, Figure 8b shows three different stages of the linearity that are unique to the progression of damage in a second carbon-ECC specimen tested. Following strain hardening, the change in the resistance of the specimen is observed to behave linearly with strain just as it had done in Figure 8a. Denoted as stage 1, the development of a dense field of microcracks contributes to the slow increase in electrical resistivity. However, damage localization begins to occur at 2.5% strain resulting in strain softening and an observable change in the material gage factor. The damage in this specimen is occurring between the leads. As the damage progresses (further localization resulting in a single macroscopic crack), the gage factor continues to increase through phase 3.

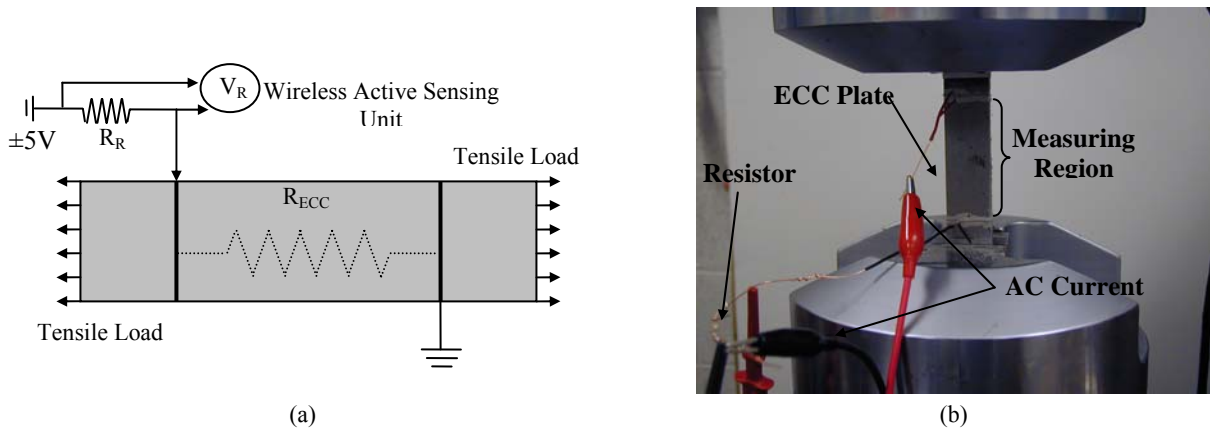


Figure 7 - AC resistance test (a) specimen-resistor circuit, and (b) experimental configuration

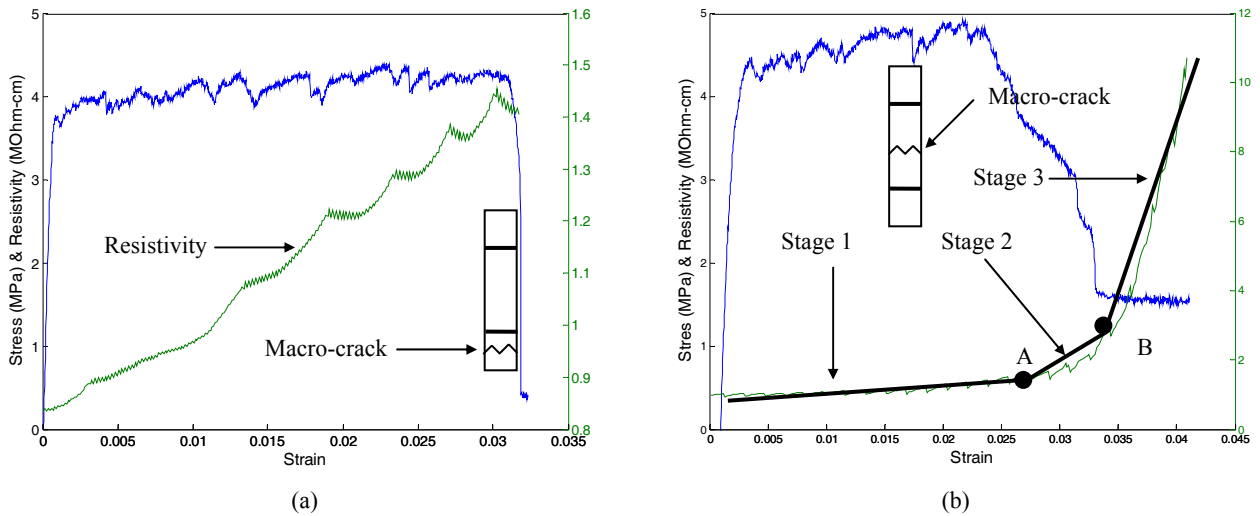


Figure 8 – Stress-strain and resistivity-strain relationship of a carbon-ECC specimen during AC monotonic load testing: (a) specimen in which major cracking occurs beyond the probes and (b) one in which cracking occurs within the measuring region

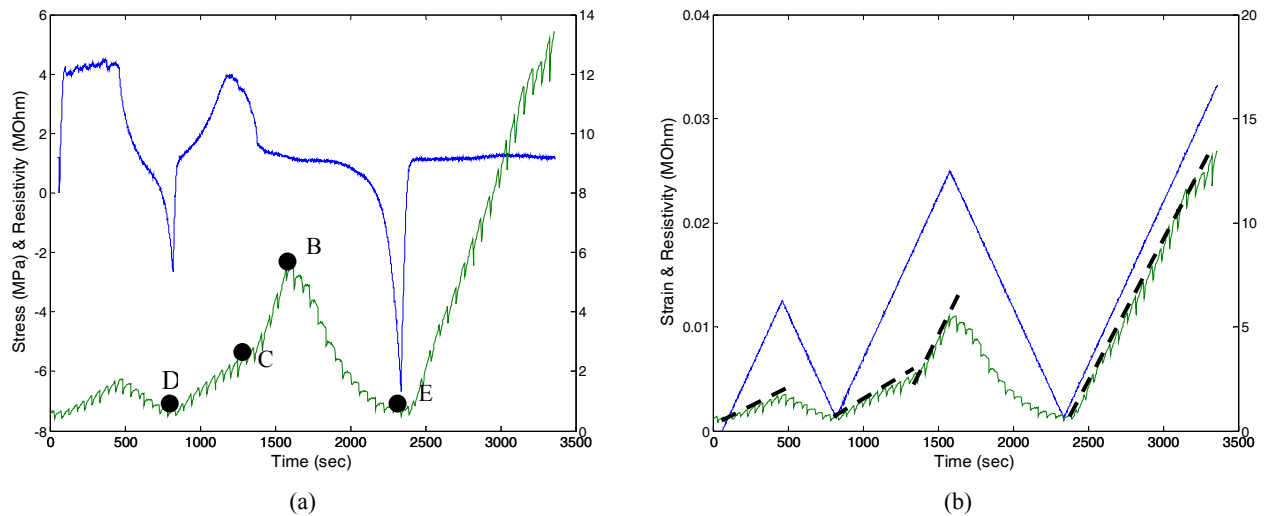


Figure – 9 AC cyclic test (a) stress and electrical resistivity histories, (b) strain and electrical resistivity histories

AC Test (Cyclic): In the previous two sets of tests, the ECC specimens are loaded monotonically. While linear strain-resistivity behaviors of the different materials can be observed, the tests do not reveal if the behavior is reversible during cyclic loading. Reversibility of the piezoresistive phenomena is important if the strain measurement of ECC elements loaded by earthquakes or other cyclic loading scenarios is sought. To observe the change in resistivity under reversed cyclic loading, the smaller set of ECC tests specimens (13 mm x 25 mm x 153 mm) is tested. Figure 9 illustrates the stress, strain and resistivity time-histories of a steel-ECC specimen loaded over one hour through 3 axial load cycles. As shown in Figure 9b, the change in the electrical resistivity is again strongly correlated to the mechanical strain in a linear fashion. However, the change in the resistance of the specimen during the second load cycle can be divided into two portions (DC and CB). Prior to the initiation of strain-softening (point C in Figure 9a), the slopes are generally consistent with the results obtained from the monotonic load tests. However, the slope increases when the ECC plate undergoes strain-softening and damage localization. It can also be noted from Figure 9a that when the ECC specimen is completely unloaded to point E, the resistivity of the specimen is almost fully recovered. After point E, the damage localization is still present so the subsequent slope of the resistivity-strain curve is the same as that of region CB.

5. MEASUREMENT ON CYCLICALLY LOADED BRIDGE PIERS

To explore the feasibility of measuring the strain of ECC within realistic structural elements, a 1/3 scaled bridge pier shown in Figure 10 of ECC materials is laterally loaded. At the base of the pier, the strain in the extreme cross section fiber is measured using a series of LVDT sensors. In order to correlate this longitudinal strain to the change of electrical resistance, two electrical probes are mounted with copper wire and silver paste in the vicinity of the LVDTs (Figure 10a). Figure 10b shows the relationship between the axial LVDT reading and the measured electrical resistance response when the pier is cyclically loaded. A strong linearity exists between the mechanical deformation and the electrical resistance in both the positive and negative direction (tension and compression). It should be noted that below the surface of the ECC material is a dense network of steel reinforcement (longitudinal and transverse). As witnessed by the results presented in Figure 10b, the presence of steel below the ECC cover does not interfere with the piezoresistive properties of the ECC bridge pier.

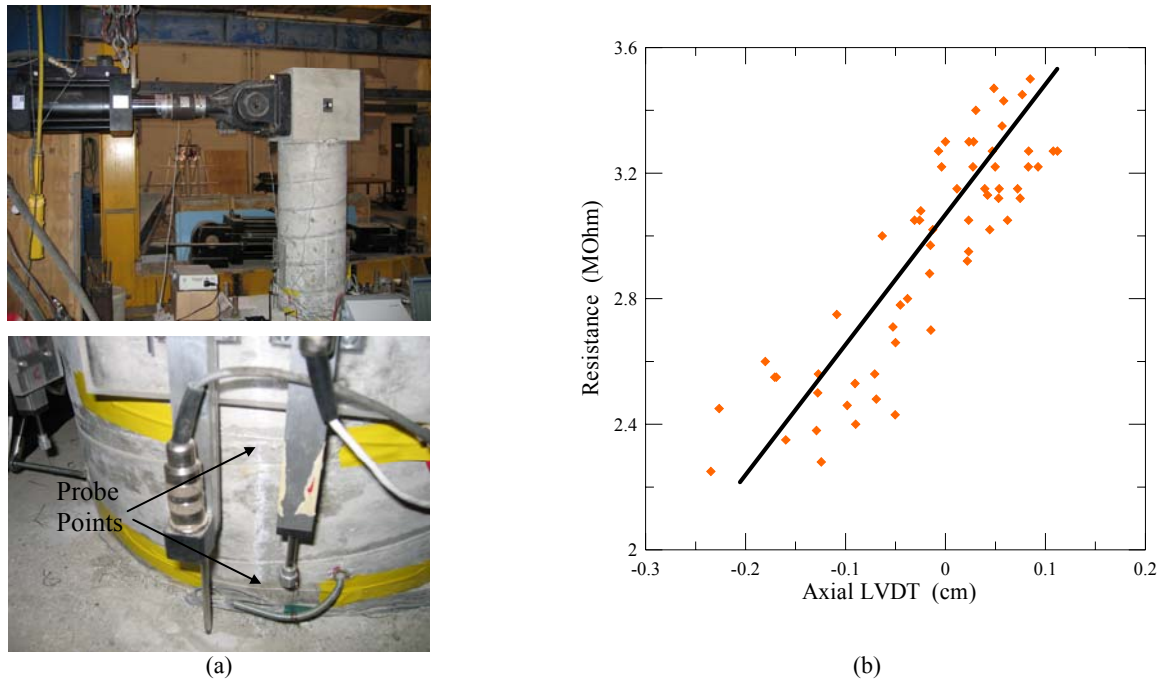


Figure – 10 (a) Cyclically loaded bridge pier and the electrical probe points, (b) axial LVDT-electrical resistance relationship

6. CONCLUSIONS

The piezoresistive behavior of engineered cementitious composites (ECC) has been thoroughly examined in this study. It is found that the presence of small volume fractions of conductive fibers (steel and carbon fibers) results in a decrease in the electrical resistivity of the bulk composite to a range suitable for measurement using wireless active sensing units. Under DC and low-frequency AC voltage inputs, the piezoresistive behavior of the ECC material is witnessed. The presence of conductive fibers has also been observed to effectively decrease the gage factor of the material. The initiation of strain-softening and damage localization is easily identified from a drastic change in the material gage factor. As such, the material is also capable of potentially self-sensing its damage states. The piezoresistive behavior of the bridge pier, even after damage localization, is fully recoverable during extreme cyclic loading. The concluding tests of the study involving a partial scale ECC bridge pier reveals the feasibility of using ECC to self-sense its strain, even when steel reinforcement is included in the structure. Additional work is already underway exploring the theoretical foundation for ECC piezoresistive behavior.

7. ACKNOWLEDGEMENT

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