Smart Structures and Systems, Vol. 7, No. 1 (2011) 27-40
DOI: http://dx.doi.org/10.12989/sss.2011.7.1.027

Experimental evaluation of electrical conductivity of carbon fiber reinforced fly-ash based geopolymer

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(Received June 25, 2010, Accepted October 4, 2010)

Abstract. Geopolymer concrete is finding a growing number of niche applications in the field of civil engineering due to its high compressive strength and strength gain rate, retainage of structural properties in elevated temperature environments, chemical stability in highly acidic conditions and environmental benefits. Combining the above mentioned characteristics with induced electrical conductivity, could enable geopolymer cement to serve as a smart and sustainable cementitious material suitable for health monitoring of civil structures. Carbon fibers were added to fresh geopolymer and OPC (ordinary Portland cement) mixes to enhance their electrical conductivities. AC-impedance spectroscopy analysis was performed on the specimens with fiber fraction ranging from 0.008 to 0.8 with respect to the weight of cementitious binder, to measure their electrical resistivity values and to determine the maximum beneficial fiber content required to attain electrical percolation. Experimental observations suggest that CFR-geopolymer cement exhibits superior performance to CFR-OPC in terms of conducting electrical current.

Keywords: geopolymer concrete; electrical conductivity; carbon fibers; health monitoring; ac-impedance spectroscopy; CFR (carbon fiber reinforced).

1. Introduction

Civil infrastructure systems are prone to a number of deterioration mechanisms including fatigue (e.g., due to repeated live load), environmental degradation (e.g., freeze-thaw effect, corrosion), and extreme natural events (e.g., earth quakes, hurricanes). Coupled with lack of adequate maintenance, these factors could lead to deterioration of strength and reduced service life of the structure. A study conducted by Aketan *et al.* (1998) estimates that deterioration of the nation's infrastructure has a negative impact of up to 1% on the USA national gross domestic product (GDP).

While some defects in structural concrete such as cracks, spalling, and flaking can be detected by visual inspection or by using non-destructive test methods such as ultrasonic and liquid penetration, others, such as delamination, corrosion and failure due to freeze thaw are difficult to detect using commonly employed detection techniques. Electrical measurements of conductive concrete could allow detecting both major and minor damages (Dragos and Chung 2000). This manuscript investigates the development of fly ash based geopolymer binder induced with carbon fibers for producing electrically conductive geopolymer concrete for possible health monitoring applications

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of civil structures.

Geopolymers are a family of cementitious binders that do not require the presence of ordinary Portland cement (OPC). Similarly to OPC concrete, geopolymers also require a source material and a liquid phase for making concrete. Materials with high content of silica (Si) and alumina (Al) can be used as source material, while the liquid phase is provided by alkaline solutions, thus these materials are also known as alkali activated alumino-silicate binders (Davidovits 1994). Source materials in making geopolymer paste include naturally occurring minerals e.g., metakaolin, kaolinite, clays and mica, or certain industrial byproducts such as fly ash, silica fume, slag, and rice husk ash (Hua Xu and Van Deventer 2000, Wallah and Rangan 2006). The choice of source material depends upon availability, cost and type of application (Van Jaarsveld *et al.* 1997, Palomo *et al.* 1999, Cheng and Chiu 2003). Metakaolin is highly suitable for making geopolymer because of its rich silica and alumina content, high reactivity and ease of control. However, it is not economically feasible to use Metakaolin for the mass production of geopolymer (Wallah and Rangan 2006).

An alternative source material for mass production of geopolymer concrete is ASTM class F fly ash, which is preferred over class C due to its lower percentage of calcium. The presence of calcium in elevated levels could result in flash set due to formation of calcium hydrate products (Swanepoel and Strydom 2002, Fernandez and Palomo 2003, Palomo *et al*. 2004, Diaz *et al.* 2010).

Geopolymers have several properties that make them of interest for construction applications including high early strength gain, low permeability, resistance to chemical attack, high thermal resistance and cost efficiency in production (Fernandez and Palomo 2003, Bakharev 2005). These properties offer several advantages over Portland cement. First, it is cost effective to produce geopolymer, because the source material it uses can be naturally occurring minerals (e.g., Kaolinite) or a byproduct of industrial processes, such as fly ash or rice husk. Second, its production is environmental friendly (i.e., CO_2 released during its production is significantly lower than that of OPC). Finally, geopolymer offer higher resistance to harsh environmental conditions due to its stable microstructure. Unlike C-S-H gel in OPC, geopolymer forms 3-dimensional polymeric chains of Si-O-Al, which are credited with the mechanical strength and other micro-structural properties of geopolymer (see Fig. 1).

These mechanical and chemical characteristics make geopolymers potentially suitable for several applications in civil engineering. Defazio *et al.* (2006) investigated the possibilities of using geopolymer composites as a protective coating for transportation structures. Palomo *et al.* (2004) investigate the utilization of fly ash based geopolymer concrete for making railway sleepers. A study involving the utilization of geopolymer composites in high temperature applications was reported by Zhao *et al*. (2007). Hardijito and Rangan (2005) demonstrated that fly ash based geopolymer

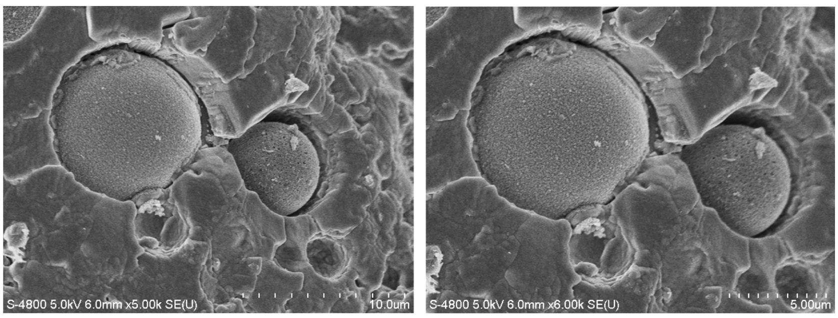


Fig. 1 SEM images of geopolymer showing unreacted fly ash particles surrounded aluminosilicate binder

can serve as potential source for replacing Portland cement concrete in construction. Montes and Allouche (2010) reported the utilization of geopolymer grout in the rehabilitation of manhole structures and pipes.

Reinforcing concrete using fibers is a not a new concept when it comes to improving the strength and ductility of the structures. There are several ways fibers could be used in construction to meet day-to-day demands for sustainable structures. Fiber usage can be classified into three main categories, namely: a) providing internal reinforcement; b) increasing performance of an existing structure by external wrapping and plating; and c) adding short random fibers to increase tensile strength, resistance to cracking and ductility (Banthia *et al.* 2000, Bakis *et al.* 2002, Balendran *et al.* 2002, Uomoto *et al.* 2002). The present work concerns with short fibers reinforced cementitious materials, specifically, exploiting the enhanced electrical conductivity induced by the addition of short carbon fibers to cementitious matrices. A significant amount of research has been done on this topic by Chung and her associates, who suggested that by adding short carbon fibers to a cementitious matrix, the conductivity of the latter could be significantly improved (Chen and Chung 1993, Xuli and Chung 1996, Zeng and Chung 1999, Chung 2003). Work on carbon fiber reinforced conductive cement (CFRCC) was also performed by Reza *et al.* 2003, Chen *et al.* 2004 and Manuela and Raffaelle 2005. The main difference between Chung's initial work and more recent research is the use of alternating current (AC) for electrical interrogation rather than direct current (DC). Chung used DC electrical resistance measurements for the characterization of CFRCC. DC measurements tend to produce false polarization potentials arising from chemical reactions at the electrodes. This false potential is also known as back emf, since it opposes the current flow. To avoid inaccuracies associated with false potential, AC is often preferred over DC for electrical resistivity measurements. Using AC the polarization potential is not completely eliminated, but rather transformed into a capacitive resistance in series or in parallel with the true resistance of the material, and can be accounted for in the calculations. When AC is used electrical resistance measurements are termed as impedance (Z), a term consisting of the real impedance (or "true resistance") and the imaginary impedance (capacitance or inductance). Imaginary impedance (in this case capacitance) is frequency dependent, (i.e., as the frequency of the applied alternating current increases, the capacitance decreases, and the total impedance approaches real impedance). In this way capacitance, or polarization potential, can be eliminated from total impedance measurements. This is numerically expressed in equations 1 through 3 (after Banthia *et al.* 1992)

$$Z = \sqrt{(R^2 + X_C^2)} \tag{1}$$

$$Z = \frac{1}{\sqrt{\left(\frac{1}{R^2} + \frac{1}{X_C^2}\right)}} \tag{2}$$

$$X_C = \frac{1}{2\pi * f * C} \tag{3}$$

Where Z = Total impedance

R = Real part of the impedance

X_c = Imaginary part of the impedance due to capacitance

f = Frequency of current applied

C = Capacitance

Another reason for adopting AC over DC is to make use of the frequency dependent behavior exhibited by the embedded carbon fibers. When carbon fibers are added to a cementitious matrix, a potential barrier (charge transfer resistance) is formed around the fibers that do not allow them to conduct electricity at low AC frequencies or DC measurements. Using high frequency AC causes displacement currents to short circuit the barrier, and the fibers start conducting through the matrix (Torrents *et al.* 2001, Mason *et al.* 2002). Considering the advantages of using high frequency AC when measuring the conductivity of fiber reinforced cementitious composites, many researchers have opted to use AC over DC for the characterization of CFRCC. Farhad *et al.* (2003) studied the changes in electrical resistance of carbon fiber reinforced cement composite under dynamic compressive loading, Wang *et al.* (2002) investigated the influence of fiber volume fraction and length on the electrical conductivity of CFRCC. The piezoelectric behavior of CFRCC was studied by Mingqing *et al.* (2000). Chen *et al.* (2004) and Manuela *et al.* (2005) investigated the effects of fiber volume, size, relative humidity and curing age on the electrical conductivity of carbon fiber reinforced cementitous composite (CFRCC).

This study is focused on the development of conductive carbon fiber reinforced geopolymer composite (CFRGC). AC-impedance spectroscopy was employed to evaluate the electrical conductivity properties of CFRGC.

2. Experimental program

The experimental procedure was divided into two phases. In Phase I mortar specimens were used to evaluate the effect of carbon fibers volume fraction in the cementitious material on the electrical conduction of the matrix. Phase II consists of a study of the effect of curing time on the electrical conduction of the cementitious matrix. Specimens were prepared using the maximum beneficial fiber volume fraction.

2.1 Phase I - electrical conductivity in mortar specimens

2.1.1 Specimen preparation

Rectangular bar specimens were prepared for both Portland cement and geopolymer mortar (Fig. 2). Portland cement of Type II was used in making cement mortar specimens with a water to cement ratio of 0.40 and sand to cement ratio of 1.0. Geopolymer specimens were prepared using

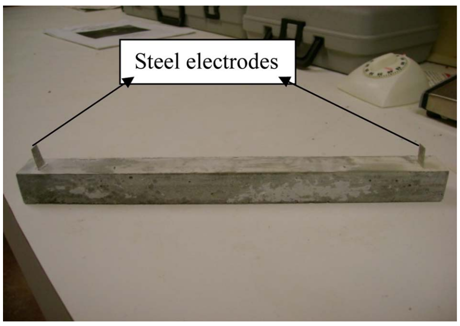
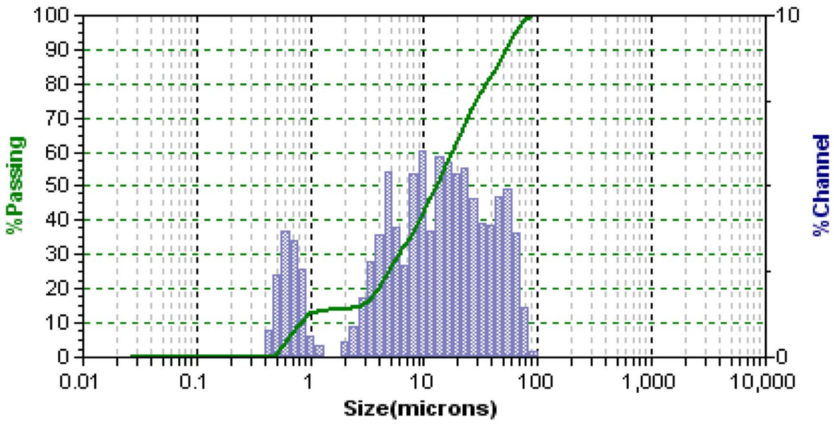


Fig. 2 A rectangular bar specimen with embedded steel electrodes



Size(μm)	Percent Passing
10.00	43.41
20.00	64.27
30.00	76.49
40.00	82.99
45.00	85.71
50.00	88.54
60.00	93.74
70.00	97.40
80.00	99.24

Fig. 3 Particle size distribution of fly ash stockpile

Table 1 Chemical composition of fly ash stockpile (wt,%)

Silicon Dioxide, SiO_2	55.07
Aluminum Oxide, AL_2O_3	28.61
Iron Oxide, Fe_2O_3	6.22
Calcium Oxide, CaO	1.97
Magnesium Oxide, MgO	1.08
Sodium Oxide, Na_2O	0.38
Potassium Oxide, K_2O	2.63
Titanium Oxide, TiO_2	1.56
Manganese Dioxide, MnO_2	0.02
Phosphorus Pentoxide, P_2O_5	0.16
Strontium Oxide, SrO	0.08
Barium Oxide, BaO	0.21
Sulfur Trioxide, SO_3	0.19
Total	98.18
Loss on Ignition	1.82

class F fly ash (FA) obtained from Flyash Direct, OH. Particle size distribution and chemical analysis of the FA used are listed in Fig. 3 and Table 1, respectively. More than 80% of the particles were found to be smaller than 45 μm. For making geopolymer specimens, a 2:1 ratio of sodium silicate to sodium hydroxide was used (liquid phase materials), with an activator to fly ash ratio of 0.50 and fly ash to sand ratio of 1.0. Sodium hydroxide used was 10 M (400 gm of sodium hydroxide mixed in 1 L of water), prepared in the laboratory by dissolving sodium hydroxide pellets in distilled water. The sodium silicate used was a Type N obtained from PQ INC, LA. To induce conductivity through the cementitious matrix, carbon fibers were added while mixing. The properties and dimension of fibers provided by Taho Tanex, TN are shown in Table 2. Two stainless steel electrodes (10 mm x 35 mm × 0.4 mm) were embedded in each bar specimen while placing the fresh cementitious material in the molds. To increase the workability of cementitious material and to improve fiber dispersion throughout the matrix, Rheobuild super plasticizer of 2% and methyl cellulose of 0.4%

Table 2 Properties and dimensions of carbon fibers

Length, mm	Diameter, μm	Tensile Strength, MPa	Tensile Modulus, GPa	Resistivity, Ω-m	Density, Kg/m^3
6	7	3447	0.2	1,670×10^{-8}	1800

Table 3 Mix design adopted in phase I

Materials	OPC	GPC
Sand/cementitious material ratio	1	1
Activator/source material	0.4 (water/cement)	0.5 (($NaOH + Na_2SiO_3$)/fly ash)
Rheobuild super plasticizer	2%*	2%*
Methyle cellulose	0.4%*	0.4%*
Fiber content	0.0% - 0.8%*	0.0% - 0.8%*

*by weight of dry cementitious material

by weight dry cementitious material were added to the mix design. To evaluate the effect of fiber addition on the electrical conductivity of the cementitious composite, fiber percentage was varied from 0.0% to 0.8% by weight of cementitous material in both cases (OPC and Geopolymer). A set of 3 specimens were prepared for each fiber percentage fraction (Table 3 summerizes the mix design used in Phase I). During mixing, first the cementitious material and sand were mixed for a minute, and then fibers and methylcellulose were added and mixed for two additional minutes. Immediately following the addition of fibers, the liquid phase material and super plasticizer were added slowly while mixing continued. Upon mixing, the mortar was taken out of the mixer and placed in bar molds (25.4 mm × 25.4 mm × 279 mm) in two layers. Each layer was tamped and steel electrodes were embedded in the finished specimens. Specimens were left in the molds to set for one day, before they were taken out of the molds for curing. Portland cement specimens were cured in lime water for 3 days while geopolymer specimens were placed in an oven at 60°C for 24 hours to achieve curing.

2.1.2 Electrical conductivity test procedure

Following the curing period, impedance measurements were conducted on the specimens to evaluate the effect of fiber percentage on the bulk resistivity of the cementitious matrix. Portland cement specimens were taken out of the water and surface dried, while the geopolymer specimens were removed from the oven and left at room temperature for at least 2 hrs prior to performing conductivity measurements. High frequency alternating current (AC) was used to perform electrical measurements on the fiber reinforced cementitious matrices. Reasons for choosing high frequency AC over DC were to avoid inaccuracies due to false potential (or polarization potential) and to exploit frequency dependent behavior exhibited by carbon fibers embedded in the cementitious matrices. At high frequency AC carbon fibers began conducting and the value of the imaginary impedance (X_c), due to capacitance approached zero with increasing frequency. Thus, the impedance measured using high frequency AC is the true impedance of the conducting material, minimizing deleterious effects due to polarization potential. However, using very high frequency AC causes current to flow through the outer surface of the material instead of flowing through its cross section (i.e., skin effect). To determine the appropriate maximum frequency at which fibers in the matrix are fully conductive while minimizing skin effect and imaginary impedance, an AC impedance spectroscopy analysis was employed. AC-IS contained a potentiostat in conjunction with an impedance analyzer. The potentiostat provided the necessary voltage while impedance measurements were recorded by the impedance analyzer. Bode plots (i.e., magnitude of impedance vs. frequency and phase vs. frequency) generated by AC-IS were used to analyze the experimentally collected data. Impedance measurements on all specimens were conducted using 1 V voltage amplitude while frequency was swept from 10 MHz to 1 Hz. Two sets of measurements were collected for each specimen, for a total of 6 readings for each fiber fraction.

2.1.3 Analysis of AC-IS data

Bode plots consists of two different plots, namely magnitude of impedance vs. frequency and phase vs. frequency. In magnitude of impedance and frequency plots, the X axis represents the frequency (Hz) in logarithmic scale, while the Y axis represents the magnitude of impedance (Ohm). Experimental data collected suggest that as current frequency increased from left to right, the value of impedance decreased. However, above certain frequency (F_t), the impedance value dropped rapidly, a phenomenon attributed to skin effect (see Fig. 4). In other words, above threshold frequency (F_t), the current instead of flowing through the cross sectional area of the specimen chose to flow only through a zone around the perimeter of the sample. This zone decreased with increasing frequency, reaching a minimum value at very high frequencies. Fig. 5 presents a graphical representation of the skin effect phenomenon. Thus, F_t was chosen as the maximum allowable frequency for the impedance measurements, while the impedance readings above F_t were discarded. In each measurement, the value of impedance at frequency F_t is considered the total impedance of the composite (i.e., including fiber contribution).

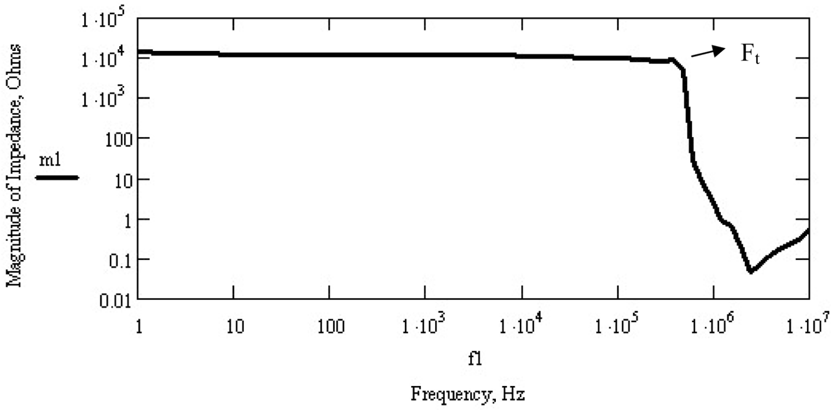


Fig. 4 Magnitude of impedance vs. frequency plot

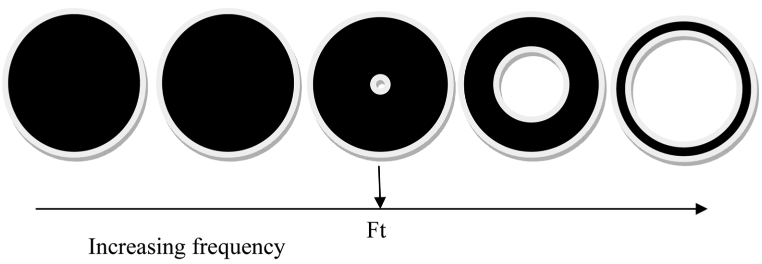


Fig. 5 Illustration of skin effect

2.2 Phase II - electrical conductivity in concrete specimens

To test the hypothesis that conductivity could also be induced into concrete specimens, concrete cylinders were casted from both Portland cement (OPC) and geopolymer (GPC), with and without carbon fibers. AC-IS analysis was performed on all the specimens to obtain their electrical impedance values. Testing was performed follwing one day of curing at 60°C for geopolymer specimens; whereas, concrete specimen were tested after 7, 14 and 21 days to see the effect of the curing period on electrical conduction. The pilot study conducted on mortar specimens provided a basis for selecting the proper combination of fiber percentage ratio and liquid to binder material ratio, to achieve the needed workability for making concrete specimens.

2.2.1 Preparation of concrete specimens and experimental design

Based on experimental results obtained in Phase I, it was determined that fiber content of 0.4% by weight of cementitious material would be appropriate for making concrete samples. For making concrete samples, 101 mm × 203 mm cylindrical plastic molds were used. Type II Portaland cement with water to cement ratio of 0.40 and 1:2:2 ratio of cement to sand to aggregate was used in making the OPC concrete specimens. As for the geopolymer specimens, the fly ash whose properties are listed in Table 1 was used with an activator solution to fly ash ratio of 0.50 and fly ash to sand to aggregate ratio of 1:2:2. Pea gravel (9.5 mm) was used as coarse aggregate in making the concrete samples for both Portland cement and geopolymer. The activator solution for making geopolymer consisted of 2:1 ratio of sodium silicate to sodium hydroxide. A set of six concrete cylinders were poured for each cementitious binder, three with blended carbon fibers (see Table 2 for fiber properties) and three plain (control) specimens. Prior to pouring of the concrete, two stainless steel electrodes (10 mm × 101 mm × 0.38 mm) were inserted into each cylindrical plastic mold by making inserts at its top & bottom (see Fig. 6). The separation distance between the two electrodes was 178 mm. Rheobuild super plasticizer 2% by weight of cementitious material was added while mixing to increase workability and methyl cellulose of 0.4% by weight of cementitious materials was added to increase fiber dispersion (The mix design used in phase II is summarized in Table 5). After preparing the samples, care was taken not to disturb the steel electrodes in the molds. Specimens were left in the molds to set for one day before de-molding. OPC specimens were placed in lime water bath for curing while geopolymer specimens were cured at 60°C for 24 hours in an oven.

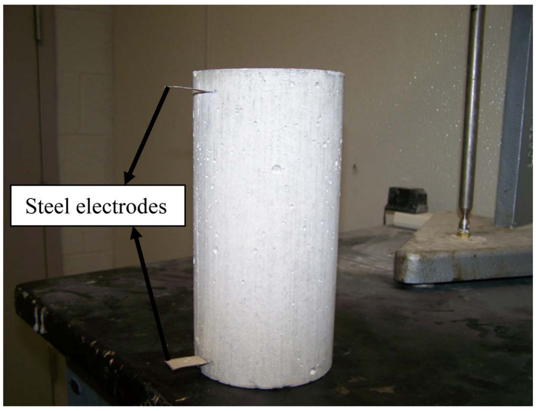


Fig. 6 Concrete cylinder specimen with embedded steel electrodes

Table 4 Summary of results from Phase I experiments (3 specimens per fiber perentage)

Fiber percentage WRT cementitious material	Electrical resistivity, ohms-m	
	OPC specimens (W/C = 0.4, S/C = 1)*	GPC specimens (A/S = 0.5, S/C = 1)*
0	7.229	1.944
0.008	3.975	1.269
0.02	0.753	1.101
0.04	0.554	0.407
0.06	0.241	0.179
0.08	0.125	0.146
0.2	0.086	0.056
0.4	0.071	0.039
0.6	0.0445	0.022
0.8	0.049	0.017

*Average of 6 readings (3 specimens per fiber percentage, 2 readings per specimen)

Table 5 Mix design adopted in phase II

Materials	OPC	GPC
Cementitious material/sand/coarse aggregate ratio	1:2:2	1:2:2
Activator/source material	0.4 (water/cement)	0.5 ((NaOH + Na_2SiO_3)/flyash)
Rheobuild super plasticizer	2%*	2%*
Methyle cellulose	0.4%*	0.4%*
Fiber content	0.4%*	0.4%*

*by weight of dry cementitious material

2.2.2 Experimental procedure - Phase II

Following the curing process, cement specimens were taken out of the water and surface dried while geopolymer specimen were left outside the oven for at least 2 hrs to attain room temperature before performing conductivity measurements. AC-IS analysis was performed on all geopolymer specimens after one day of curing, while in the case of OPC concrete, testing was performed on the specimens after 7, 14 and 21 days of curing. Bode plots generated by AC-IS were used to analyze the results. Impedance measurements on all the specimens were conducted using 1 V voltage amplitude while the frequency was swept from 10 MHz to 1 Hz.

3. Results

3.1 Analysis of results from Phase I

Using AC-IS, Bode plots were obtained for all Portland cement and geopolymer mortar specimens, and the magnitude of impedance was calculated at frequencies F_t in each case as explained above. Results obtained from Phase I are summarized in Table 4, while Figs. 7(a) and 7(b) represent the resistivity of geopolymer and Portland cement mortars with respect to changes in fiber fraction,

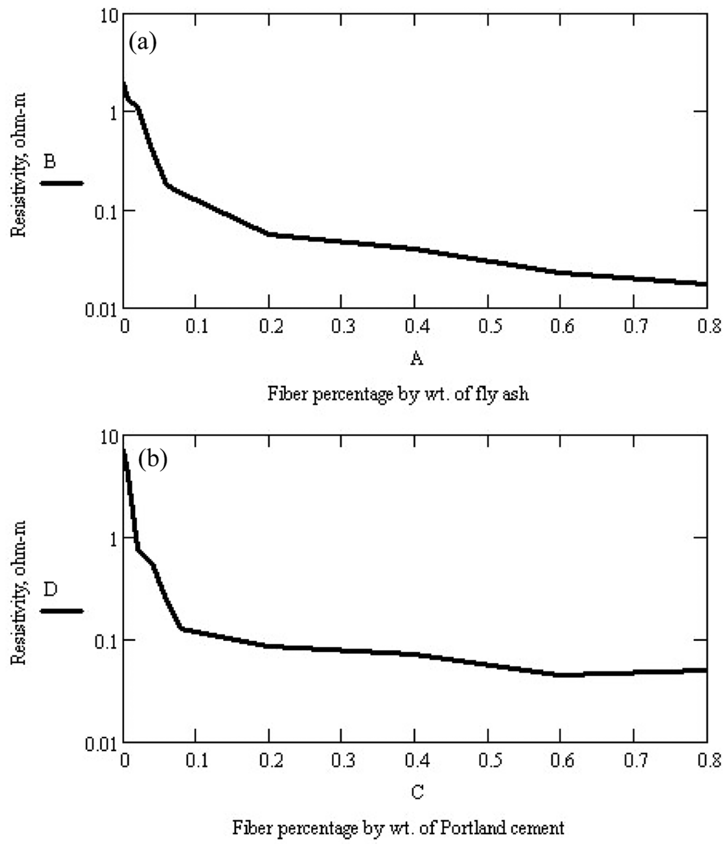


Fig. 7 Resistivity of the specimen vs. fiber percentage by weight of cementitious binder, (a) Geopolymer cement mortar and (b) Portland cement mortar

respectively. In both plots, the X axis represents the fiber percentage while the and Y axis expresses the resistivity of the specimens (Ohms-m). Electrical resistivity of each specimen was calculated using the following expression

$$\rho = \frac{(R*A)}{L} \quad (4)$$

where, ρ = Resistivity (Ohm-m)

R = Magnitude of impedance obtained from bode plots (Ohms)

A = Embedded cross sectional area of electrode (Sq. mm)

L = Distance between the electrodes (mm)

The separation distance between the electrodes and the cross sectional area of the embedded electrodes for all specimens were 254 mm and 258 mm^2, respectively. The value of real impedance (R) for each point on the plot is an average of six readings per fiber percentage (two readings per specimen, three specimens per fiber percentage) obtained at the threshold frequency F_t.

A review of the results obtained from Phase I reveals that in both cases (OPC and geopolymer), resistivity decreased with increase in fiber percentage (as expected). From the plots (Figs. 7(a) and 7(b)) it can be observed that at a fiber percentage value of 0.1, the resistivity if the specimens dropped rapidly. Also, for fiber percentage values greater than 0.1 percent, reduction in the electrical resistivity of the specimens with increase in fiber percentage was limited. This phenomenon suggest that 0.1% fiber fraction (by weight of cementitious binder) is the critical fiber content value required to attain electrical percolation for both OPC and geopolymer grouts.

From the results, it can also be observed that in the case of geopolymer specimens without any fibers, resistivity measured was 1.95 ohm-m after one day of curing at 60ºC, while for Portland cement specimens it was 7.22 ohm-m after curing them in lime water for 3 days. Portland cement after 3 days is not fully cured and there is still significant amount of free water present inside the cementitious gel that contributes towards the specimen's electrical conductivity (specimens were only surface dry). Whereas, geopolymer specimens are fully cured after one day at 60ºC. With full curing, and little to no free water presence, geopolymer specimens exhibited lower resistivity compared with their OPC counter parts. This effect suggests that geopolymer could serve as a better candidate when used as a conductive material.

3.2 Analysis of results from Phase II

Results obtained from AC-IS analysis for all concrete specimens are given in Table 6, which summarizes the resistivity values collected for both Portland cement and geopolymer concretes. Fig. 8 represents the resistivity values vs. curing time for both Portland cement and geopolymer concretes. Each resistivity value in the table is an average of six readings. Resistivity was calculated using Eq. (4), where 'R' is the real impedance obtained from AC-IS at frequency F_t for each specimen, 'A' is the embedded cross sectional area (775 mm^2) and 'L' is the separation distance between the electrodes (178 mm).

The data reveal that conductivity of both OPC and GPC has improved by the addition of carbon fibers. This change in conductivity proves the hypothesis that conductivity can also be induced into concrete, and presence of aggregates does not affect it significantly. From the OPC results it could be inferred that curing of OPC has a detrimental effect on its electrical conductivity during early stages, however, the rate of increase in resistivity diminishes as curing continues. It is expected that as curing becomes substantially complete, the electrical conductivity of the specimen stabilizes. AC-IS testing on all OPC samples were performed shortly after taking them out of the lime water and surface drying them. To isolate the effect of water content on electrical conductivity, three OPC concrete samples with 0.4% fibers were tested after 28 days in lime water and 7 days of open air drying at room temperature. The average electrical resistivity for these samples was found to be 10.4 Ohm-m.

Table 6 Summary of results obtained from OPC-based concrete and GPC-based concrete specimens

<table>
<tr><th rowspan="2">Curing period</th><th colspan="3">Electrical Resistivity of OPC (Ohm-m)</th><th colspan="2">Electrical Resistivity of GPC(Ohm-m)</th></tr>
<tr><th>0% by wt fibers</th><th>0.4% by wt fibers</th><th>0.4% by wt fiber</th><th>0% by wt fibers</th><th>0.4% by wt fibers</th></tr>
<tr><td>24 hrs @ 60ºC</td><td>--</td><td>--</td><td>--</td><td>2.12</td><td>0.68</td></tr>
<tr><td>7 days in water</td><td>5.48</td><td>2.32</td><td rowspan="3">--</td><td rowspan="4" colspan="2">--</td></tr>
<tr><td>14 days in water</td><td>6.31</td><td>2.74</td></tr>
<tr><td>21 days in water</td><td>6.13</td><td>2.86</td></tr>
<tr><td>28 days in water and 7 days in air</td><td>--</td><td>--</td><td>10.41</td></tr>
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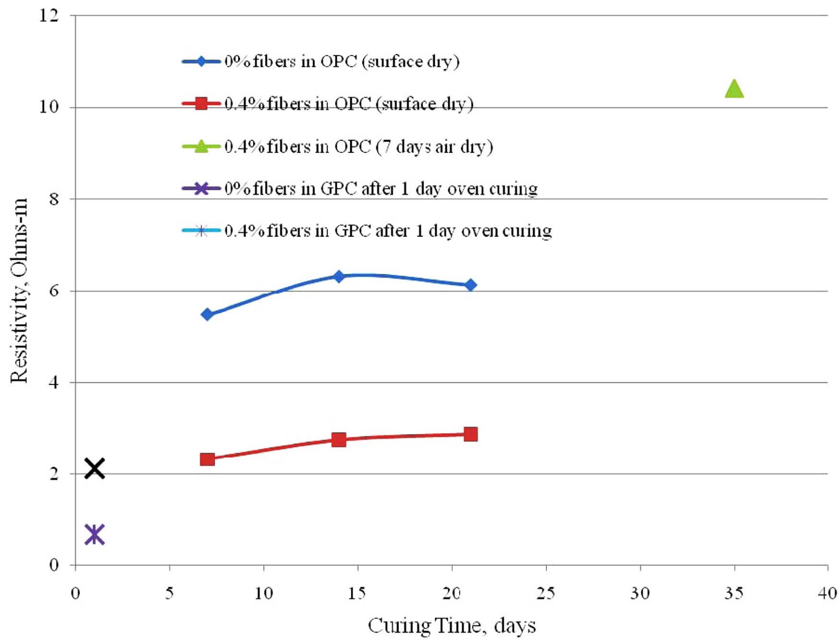

Fig. 8 Resistivity of concrete specimens vs. curing time

A review of the values listed in Table 6 reveals that resistivity measured for air dry OPC samples with 0.4% fibers is significantly higher than that measured for surface dry OPC samples without fibers and nearly 15 times greater than the resistivity of oven dry GPC with identical percentage of carbon fibers. Results suggest that electrical resistivity of OPC is highly dependent on the free water content in the matrix. On the other hand, GPC samples containing no free water exhibit significantly lower electrical resistivity compared with OPC specimens, regardless if fibers present or not.

4. Discussion

Reviewing the results from Phase I of the experimental study, it can be observed that with increasing fiber percentile fraction, the resistivity of the cementitious matrix decreased in both Portland cement and geopolymer mortar specimens. Results also suggest that fiber percentage value of 0.1 (by the weight cementitious binder) is the critical fiber content required to attain electrical percolation in the specimens. Geopolymer mortar specimens exhibited lower resistivity to the passage of electrical current compared with Portland cement mortar specimens, even though little or no free water exists in the geopolymer specimens after curing at 60°C in an oven for 24 hours.

Results from Phase II reveal that electrical conductivity could also be induced in concrete specimens (using Portland cement or geopolymer as binder) by the addition of carbon fibers. In the case of OPC, it was observed that electrical conductivity decreased with age of the concrete (degree of hydration) before approaching a steady value. This decrease was attributed to reduced amount of free water within the cementitious matrix as the hydration process progresses. Results from impedance tests on air dry OPC samples (28 day curing and 7 day air dry) revealed that the moisture content in the OPC composite plays a key role on its ability to conduct electric current. Also, in

OPC the properties of the cementitious binder powder have little influence on the composite conductivity, as free water content and fiber content are the dominant factors determining the conductivity of the OPC composite. In contrast, in geopolymer binder the characteristics of the fly ash and activator solution used contribute in a meaningful way to the conduction of the composite in addition to the fibers. The alkali cation (Na^+ or K^+) present in the geopolymer matrix can freely move within the matrix leading to ionic conduction (Cui *et al.* 2008), which could significantly contribute to the electrical conduction of the geopolymer composite.

5. Conclusions

The research reported herein is a preliminary work aimed at developing a conductive geopolymer concrete to be used in health monitoring applications for civil infrastructure. Experimental measurements suggest that CFR geopolymer features superior electrical conductivity compared with CFR OPC. Further studies on CFR geopolymer should include examination of the effect of moisture content in GPC and effect of ionic conduction (due to different alkaline solutions) on its electrical properties. It is also beneficial to study means to improve the conductivity of GPC such as ion substitutions as well as evaluation of other fiber types such as stainless steel.

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