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Effect of High-Carbon Fly Ash on the Electrical Resistivity of Fly Ash Concrete Containing Carbon Fibers

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ABSTRACT

Two series, each consisting of seven high-volume fly ash concrete mixtures with conductive carbon fibers, were used in this investigation. The first series of the concrete mixtures contained ASTM Class C fly ash and 0, 1, 3, 5, 7.5, 10, and 20 lbs. carbon fibers per cubic yard of concrete. The second series of concrete mixtures contained high-carbon fly ash in addition to the materials used in the first series. The high-carbon fly ash was used as a replacement of fine aggregate in the concrete mixtures. The electrical resistance of the concrete was measured at the ages of 1, 3, 7, 14, 28, 56, and 91 days. The study revealed a reduction in electrical resistance of concrete with an addition of high-carbon fly ash containing conductive carbon fibers. Finally, the study indicated that high-carbon fly ash could be used for making concrete of lower electrical resistance.

INTRODUCTION

Conventional moist and oven-dried concrete can be classified as semiconductor and insulator, respectively [Monfore 1968]. Air-dried concrete has a resistivity of the order of 10^6 ohm-cm [Neville 1995]. Conductivity of moist concrete is influenced by the presence of salts in the electrolytic solution and the ambient temperature [Farrar 1978; Monfore 1968]. However, conductive concrete is a new type of concrete that possesses high electrical conductivity without sacrificing mechanical properties. Concrete is a poor electrical conductor, especially under dry conditions. Hence, electrically conductive particles and/or fibers are added to the conventional concrete to attain stable and conductive properties [Farrar 1978; Yehia et al. 2000; Tuan 2004]. The design formulation of conductive concrete is based on the 'electrical percolation' principle by which the composite conductivity (product of insulating matrix and conductive fiber) increases when the content of the conductive phase reaches a critical 'threshold' value. Additional increase in the conductive phase content boosts composite conductivity only slightly beyond the threshold value. The design of conductive composite specifies an amount of conductive fibers or materials just over the threshold content, assuring high conductivity and mechanical strength, as well as good mixing conditions for conductive fibers with matrix materials. Commonly used additives for making conductive concrete include carbon fibers, steel fibers, carbon black, coke breeze, ferrous compound, steel shavings, high-carbon fly ash, and other similar materials [Farrar 1978; Yehia and Tuan

1999; Banthia et al 1992; Neville 1995; Wen and Chung 2001; Tuan 2004, Kraus and Naik 2006]. In order to increase the conductivity of the concrete, it is essential to provide fiber-to-fiber and/or fiber-to-particle continuity throughout the concrete mixture so that a conductive fiber and/or particle network could be formed in the concrete [Farrar 1978; Yehia and Tuan 1999; Banthia et al 1992]. Addition of additives such as steel fibers, coke breeze, and steel shavings increases the material cost of conductive concrete about five times more than that of the conventional concrete [Yehia and Tuan 1999]. This is mainly due to the cost of the electrically conductive additives.

In the mono-fiber systems, carbon fibers are far more effective in improving the conductivity than steel fibers, although the carbon fibers themselves are much less conductive than steel fibers. This is due to the extremely fine size of carbon fibers, which contributes to the effectiveness of the inter-fiber continuity. In the hybrid-fiber system, carbon fibers and steel fibers are both used together and the electrical resistivity of the concrete reduces drastically [Banthia et al 1992].

Concrete with electrically conductive properties make it a smart material that has many important applications in grounding, self-health monitoring structures, and other similar fields. Along with specially configured electrodes and an electrical power supply, it could be used for de-icing roads, sidewalk, bridges, and runways [Ramme and Tharaniyil 2004]. Electrically conductive concrete attenuates electromagnetic and radio waves; and, therefore, such concrete can be used to shield computer equipment from eavesdropping efforts and to protect electrical installations and electronic equipment from interference [Farrar 1978; Yehia and Tuan 1999; Xie and Beaudoin 1995]. In this study, use of a non-conventional material, for example, high-carbon fly ash, in the manufacturing of economical conductive concrete has been described.

EXPERIMENTAL STUDIES

Materials

Portland cement that met the requirements of ASTM C 150 for Type I cement was used in the study. Natural sand and crushed quartzite stone of maximum size, 3/8- inches (10 mm), were used as a fine aggregate and coarse aggregate, respectively in the concrete. The physical properties of fine and coarse aggregates are given in Table 1.

Table 1. Physical Properties of Aggregates

	Fineness Modulus	Void Content (%)	Bulk Density (lb/ft^3)	Bulk Specific Gravity	SSD Bulk Specific Gravity	SSD Absorption (%)
ASTM Test Designation	C 136	C 29		C 127/C 128		
Fine Aggregate	2.7	36	107	2.69	2.73	1.3
Coarse Aggregate	5.2	35	106	2.62	2.68	2.3

Note: 1 lb/ft^3 = 16.018 kg/m^3

Pan-type carbon fibers, 1/2-inch long, and approximately 0.283 mils (7.2 microns) in diameter were used in this study. Figure 1 shows the carbon fibers used. The density of the fibers was 0.065 lb/in^3. The bundles of fibers are typically separated into individual fibers and were dispersed in the concrete during the mixing process.

Fig. 1. Carbon Fibers Used in Concrete Mixtures

ASTM Class C fly ash and a high-carbon Class F fly ash, as shown in Figure 2, were used in this investigation. These two fly ashes had a distinct color difference; the high-carbon fly ash was darker gray in color. The chemical and physical properties of the fly ashes are given in Table 2 and 3, respectively. The carbon content, as indicated by the Loss on Ignition, was slightly over 21% for the high-carbon fly ash (Table 3).

Fig. 2. ASTM Class C Fly Ash (Left) and High-Carbon Fly Ash (Right)

Table 2. Chemical Analysis of Fly Ash

Analysis Parameter	Material, %		ASTM C 618 Requirements, %		
	High-carbon fly ash	Class C fly ash	Class N	Class C	Class F
Silicon Dioxide, SiO_2	44.8	37.7	--	--	--
Aluminum Oxide, Al_2O_3	18.4	19.4	--	--	--
Iron Oxide, Fe_2O_3	6.8	5.6	--	--	--
SiO_2 + Al_2O_3 + Fe_2O_3	70.0	62.7	70.0 Min.	50.0 Min.	70.0 Min.
Calcium Oxide, CaO	3.9	22.4	--	--	--
Magnesium Oxide, MgO	0.1	4.2	--	--	--
Titanium Oxide, TiO_2	0.6	--	--	--	--
Potassium Oxide, K_2O	1.25	0.5	--	--	--
Sodium Oxide, Na_2O	0.7	1.9	--	--	--
Sulfate, SO_3	0.3	2.0	4.0 Max.	5.0 Max.	5.0 Max.
Loss on Ignition, LOI	21.2	0.6	10.0 Max.*	6.0 Max.*	6.0 Max.*
Moisture Content	0.3	0.1	3.0 Max.	3.0 Max.	3.0 Max.
Available Alkali, Na_2O Equivalent (ASTM C-311)	0.5	N.A.	1.5 Max.**	1.5 Max.**	1.5 Max.**

N.A. – Result not available
* Under certain circumstances, up to 12.0% max. LOI may be allowed.
** Optional. Required for ASR Minimization.

Concrete mixtures

Two series, each consisting of seven high-volume fly ash concrete mixtures, were produced. Details are given in Table 4 and 5. One series of seven high-volume fly ash concrete mixtures were produced without the high-carbon fly ash, containing 0, 1, 3, 5, 7.5, 10, and 20 lb of conductive carbon fibers per cubic yard of concrete. The next series of seven mixtures contained the high-carbon fly ash, as well as 0, 1, 3, 5, 7.5, 10, and 20 lb of conductive carbon fibers per cubic yard of concrete.

Mixing, specimen preparation, and testing

All materials were weighed and added to a concrete mixture following the procedure specified in ASTM C 192. The carbon fibers were added and mixed with the aggregates to ensure a uniform dispersion of the fibers in the mixture. The desired workability of the concrete mixtures was achieved by means of mixing water. Cylindrical specimens of 3 inches x 6 inches (75 mm x 150 mm) were prepared to determine compressive strength and

Table 3. Physical Properties of Fly Ash

Analysis Parameter	Material		ASTM C 618 Requirements		
	High-carbon fly ash	Class C fly ash	Class N	Class C	Class F
Retained on No. 325 Sieve (%)	68.6	17.7	--	34 max.	34 max.
Strength Activity Index with Cement (% of Control)					
7-day	54.0	101	75 min.	75 min.	75 min.
28-day	53.4	99	75 min.	75 min.	75 min.
Water Requirement, (% of Control)	112	94	115 max.	105 max.	105 max.
Autoclave Expansion, (%)	0.01	0.07	0.8 max.	0.8 max.	0.8 max.
Density	2.04	2.57	--	--	--

Table 4. Mixture Proportions of Concrete without High-Carbon Fly Ash

Mixture No.	WE-O-A	WE-1	WE-3	WE-5	WE-7.5B2	WE-10	WE-20
Fly Ash/ [(C+A1)] (%)	50%	50%	50%	50%	50%	50%	50%
Class C Fly Ash (lb/yd^3), A1	373	370	369	367	355	358	358
High-Carbon Fly Ash (lb/yd^3), A2	0	0	0	0	0	0	0
Cement (lb/yd^3), C	373	370	369	367	355	358	358
Water (lb/yd^3), W	336	333	332	331	320	323	323
[W/(C+A1)]	0.45	0.45	0.45	0.45	0.45	0.45	0.45
SSD Fine Aggregate (lb/yd^3)	1465	1455	1450	1445	1455	1405	1405
SSD 3/8" Aggregate (lb/yd^3)	1465	1455	1450	1445	1455	1405	1405
Carbon Fibers (lb/yd^3)	0	1.1	3.1	5.3	7.9	10.3	20.5
Fresh Concrete Density (lb/ft3)	148.5	147.7	146.9	146.5	146.2	143.1	143.5

Note: 1 lb/ft^3 = 16.018 kg/m^3

Table 5. Mixture Proportions of Concrete Containing High-Carbon Fly Ash

Mixture No.	WE-OC-A	WE-1C-A	WE-3C	WE-5C	WE-7.5C	WE-10C-A	WE-20C-A
Fly Ash/ [(C+A1+A2)] (%)	65%	65%	65%	65%	65%	65%	65%
Class C Fly Ash (lb/yd^3), A1	339	337	337	334	335	332	334
High-Carbon Fly Ash (lb/yd^3), A2	291	288	289	287	287	285	287
Cement (lb/yd^3), C	339	337	337	334	335	332	334
Water (lb/yd^3), W	515	511	512	507	469	504	508
[W/(C+A1 +A2)]	0.53	0.53	0.53	0.53	0.49	0.53	0.53
SSD Fine Aggregate (lb/yd^3)	960	935	925	920	945	915	910
SSD 3/8" Aggregate (lb/yd^3)	1225	1200	1185	1180	1210	1170	1165
Carbon Fibers (lb/yd^3)	0	0.9	2.6	4.3	6.6	8.5	16.9
Fresh Concrete Density (lb/ft^3)	135.9	133.6	132.8	132.1	132.8	131.3	131.7

electrical resistance of concrete mixtures. The specimens were demolded 24 hours after casting. After demolding, these test specimens were immediately moved in a curing room with RH not less than 95% and temperature of 20 ± 2 ºC and kept there until the time of testing.

The equipment used has the potential for resistance taken at two different frequencies, 120 Hz or 1000 Hz. The test specimens were evaluated for resistance at the frequency of 1000 Hz. However, it should not make a difference in the resistance readings that were taken. No Variation in the resistance values were not seen during the tests that were conducted, typically less than 10-15seconds for each reading. It is known that the frequency of lightning is very different than normal 60 Hz systems. A test installation using conductive material was implemented at a communications tower that used to be damaged regularly by lightning. Since the construction of the new foundation base for the tower, about five years ago, containing this newly developed electrically conductive materials, there have not been lightning strikes on the tower.

Compressive strength of concrete mixtures

The compressive strength of the concrete mixtures of both series was determined at the 28-day age. The main objective of this test was to record the effect of addition of carbon fibers and high-carbon fly ash on the compressive strength of concrete. The results for both series of mixtures are given in Figure 3 and Figure 4, respectively.

Electrical resistance measurements and resistivity calculations

The electrical resistance of concrete was measurements using a Leader LCR-475-01 multi-meter at one pre-determined location on each test specimens. The test was performed on two cylinders for each mixture up to the age of 28 days. A conductive gel was applied to the ends of the test cylinder to ensure proper contact between concrete surface and the copper plates. Figure 5 shows a typical measurement of electrical resistance of the concrete cylinder. An average from two test cylinders was determined for each type and test age of the concrete. The electrical resistivity was calculated by using average value of the electrical resistance in the following expression:

$$\rho = \frac{R \times A}{L} \qquad (1)$$

where, ρ = Electrical Resistivity (ohm-cm); R = Electrical Resistance (ohms); A = Cross Sectional Area (cm^2); and, L = Length of Electrical Path (cm).

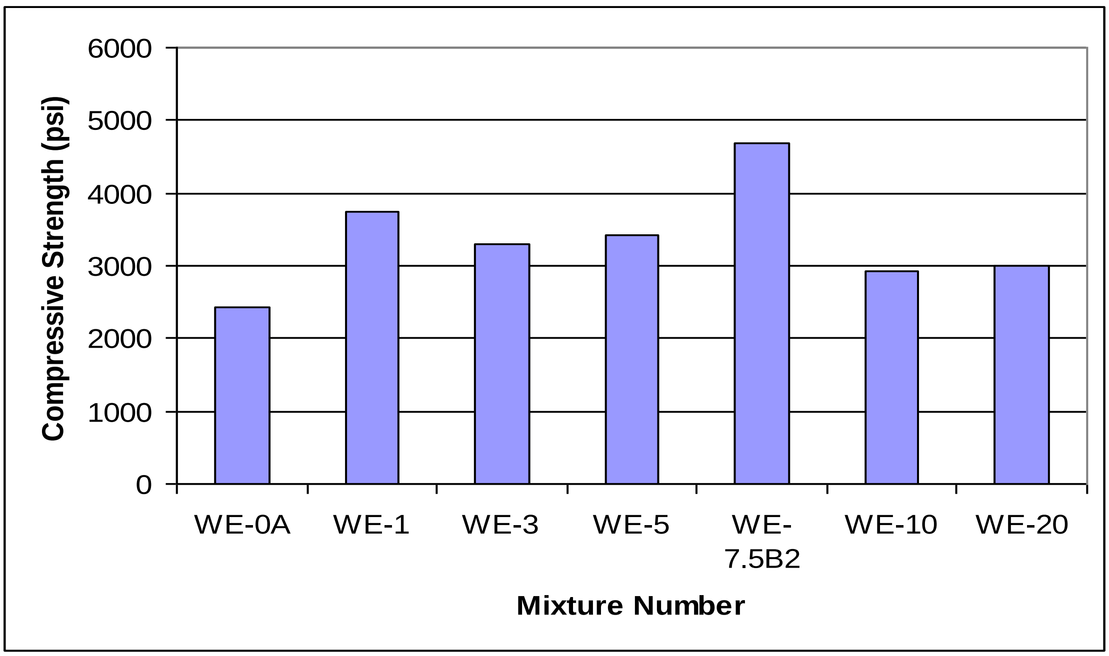

Fig. 3. 28-Day Compressive Strength of Concrete without High-Carbon Fly Ash

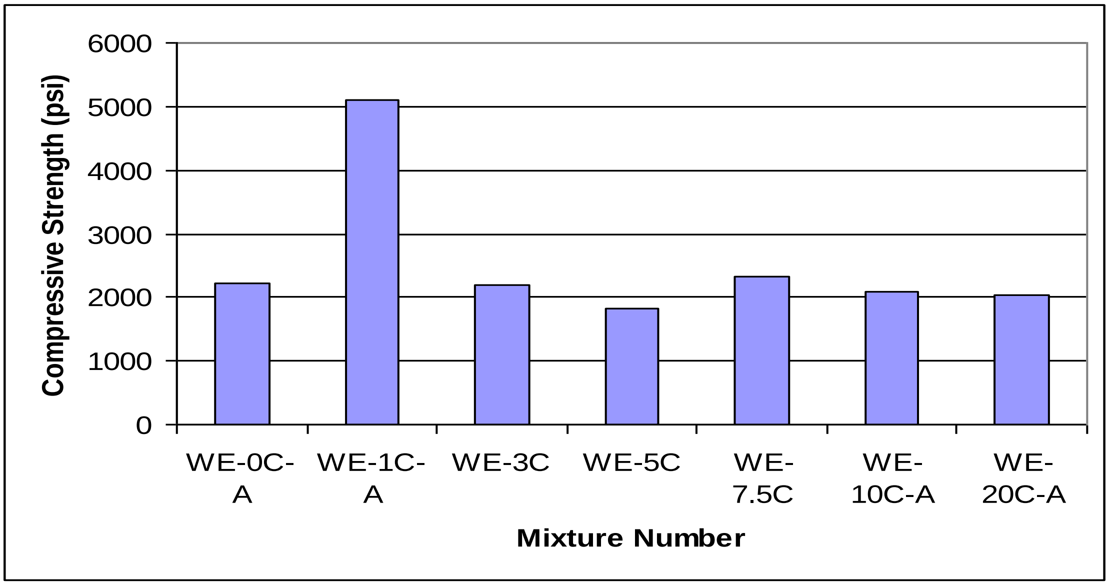

Fig. 4. 28-Day Compressive Strength of Concrete Containing High-Carbon Fly Ash

Note: 1 MPa = 145.038 psi

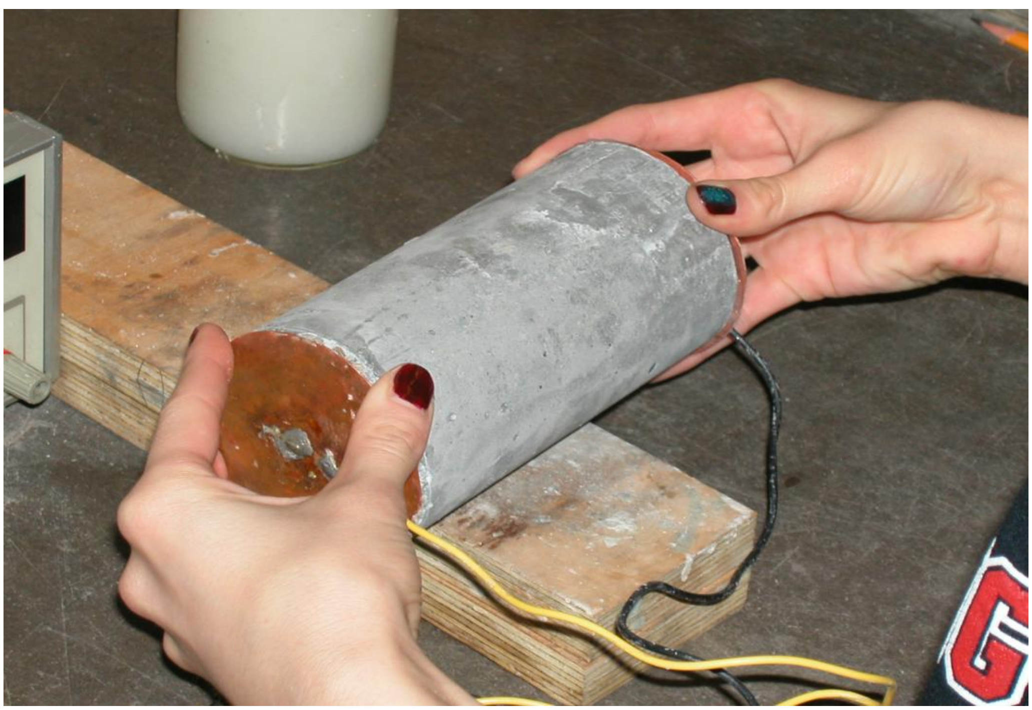

Fig. 5. Measurement of Electrical Resistance of Concrete Test Cylinder

RESULTS AND DISCUSSIONS

Compressive strength

Based on this study, Figure 4 and Figure 5 show that the addition of high-carbon fly ash reduced the compressive strength of the concrete. It is clear from these figures that concrete with high-carbon fly ash developed lower strength than comparable concrete without high-carbon fly ash. This reduction was mainly due to the higher water demand as observed in concrete mixtures using the high-carbon fly ash, and the corresponding increase in the water-to-cementitious materials ratio.

Electrical properties of concrete

The electrical resistivity of concrete mixtures without and with high-carbon fly ash is given in Table 6 and Table 7, respectively. The resistivity of the concrete containing high-carbon fly ash was typically lower than the resistivity of the concrete without high-carbon fly ash. The electrical resistivity ranged from 173 to over 60,000 ohm-cm for concrete mixtures without high-carbon fly ash, and from 131 to over 50,000 ohm-cm for mixtures with high-carbon fly ash. Mixtures containing the high-carbon fly ash had an overall lower resistivity (less than 350 ohm-cm) starting at dosages of carbon fibers at 2.6 lb per cubic yard of concrete (Mixture WE-3c). Concrete mixtures without the high-carbon fly ash achieved this level of resistivity only when at least 10.3 lb per cubic yard of carbon fibers were incorporated into the concrete (Mixture WE-10C-A).This dosage of carbon fiber is nearly four times the carbon fiber content in the high-carbon fly ash mixtures. This indicated that conductive concrete mixtures containing high-carbon fly ash would be much more economical than mixtures without such high-carbon ash. Such conductive concrete could be used for wide-ranging applications, varying from deicing of the walk ways to health monitoring of the structures.

Table 6. Electrical Resistivity of Concrete Mixtures without High-Carbon Fly Ash

Mixture No.	Resistivity of Concrete, (ohm-cm)						
	Test Age, Days						
	1	3	7	14	28	56	91
WE-0-A	1229	1672	2086	15938	58902	66105	59540
WE-1	575	802	920	3022	6121	9727	20891
WE-3	584	733	825	2605	5999	9737	22088
WE-5	569	660	760	2401	4302	4784	8071
WE-7.5B2	284	401	524	569	639	757	716
WE-10	171	184	220	246	171	225	241
WE-20	136	120	144	148	125	161	173

Note: 1 ohm-cm = 0.01 ohm-m

Table 7. Electrical Resistivity of Concrete Mixtures Containing High-Carbon Fly Ash

Mixture No.	Resistivity of Concrete, (ohm-cm)						
	Test Age, Days						
	1	3	7	14	28	56	91
WE-0C-A	466	886	1055	3118	38699	50012	37831
WE-1C-A	377	544	572	1277	13238*	47678	47787
WE-3C	107	124	144	299	306	330	343
WE-5C	88	96	113	185	171	194	204
WE-7.5C	94	102	133	171	192	215	216
WE-10C-A	53	88	96	124	152	153	141
WE-20C-A	45	86	97	122	127	134	131

* Test results at the age of 29 days. Note: 1 ohm-cm = 0.01 ohm-m

CONCLUSIONS

Based on the experimental study the following conclusions emerged:

- Inclusion of high-carbon fly ash in concrete containing carbon fibers reduced the compressive strength due to the increase in water demand.
- An increase in carbon fiber content significantly decreased the electrical resistivity of concrete.
- A combination of high-carbon fly ash and carbon fibers lowered electrical resistivity of concrete drastically, and, at a lower cost.
- The optimum dosage of carbon fibers when used with the high-carbon fly ash was approximately 2.5 lb per cubic yard.
- High-carbon fly ash could be used as an additive for making economical electrically-conductive concrete.

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