Center for By-Products Utilization

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Use of High-Carbon Fly Ash in Manufacturing Conductive CLSM and Concrete

by

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Synopsis: Presented in this paper are results of an experimental work conducted for the study of feasibility of using high-carbon fly ash in manufacturing electrically conductive controlled low-strength materials (CLSM) and concrete. The loss on ignition (LOI) of the fly ash was greater than 12%. For this study, three CLSM mixtures and three concrete mixtures were used. For the CLSM mixtures, high-carbon fly ash content was varied from 22% to 93% of the total solid materials (cement + fly ash + sand + stone). One CLSM mixture was made without aggregates, another contained fine aggregate, and the third contained fine and coarse aggregates. For all the concrete mixtures, the high-carbon fly ash content was kept at 43% by mass of total cementitious materials. In one of the concrete mixtures, steel fibers were also used. In another concrete mixture, taconite (iron ore) pellets were used as coarse aggregate. The CLSM and concrete mixtures did not contain any chemical admixtures. Electrical resistance of moist-cured (saturated) and air-cured specimens of CLSM and concrete mixtures were measured at 3, 7, 14, and 28 days. The CLSM showed approximately 5 to 15 times lower electrical resistance than the concrete. Electrical resistance of concrete reduced by half upon inclusion of approximately 3% steel fibers by mass of concrete or upon replacement of natural coarse aggregate with taconite pellets. This study also shows that high-carbon fly ash can be used in manufacturing conductive flowable slurry (CLSM) and concrete. Such materials can be used for conducting electrical charge from lightening to the ground more safely.

Keywords: conductive concrete, conductive slurry, controlled low-strength materials (CLSM), electrical resistance, high-carbon fly ash

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INTRODUCTION

In response to Phase II of the Clean Air Act Amendments of 1990, many electric utilities operating coal-fired power plants installed low NO_X (nitrogen oxides) equipment to meet new air emissions requirements. As a consequence of employing low NO_X burners, a higher percentage of unburned carbon (greater than 6%) remains in the fly ash, making it no longer acceptable for concrete manufacture [1, 2, 3, 4]. As a result of high-unburned-carbon in fly ash, a number of power plants, which previously were able to market their fly ash, now must truck the fly ash to landfills or use it in non-concrete applications. The physical characteristics of the coal fly ash vary widely and depend on the type of low-NO_X technology employed.

Moist and oven-dried conventional concrete can be classified as semiconductor and insulator, respectively [5]. The resistivity of air-dried concrete is of the order of 10^6 ohm-cm [6]. Resistivity of concrete is directly related to the degree of hydration of the cement paste. There is a linear relationship between resistivity and compressive strength of cement paste and concrete. Resistivity increases as the compressive strength increases [5, 7]. The addition of silica fume to the concrete also increases its resistivity [6]. Any increase in the volume of water and the concentration of ions present in the pore water decreases the resistivity of cement paste. When the cement content is held constant and water is increased, an increase in the water-cement ratio (*w/c*) results. This leads to a decrease in resistivity of the concrete. At a constant *w/c*, an increase in the cement content results in decrease in resistivity of concrete [6]. The salinity of mixing water greatly reduces the resistivity of concrete [6]. Conductivity of concrete can be greatly improved by placing electrically conductive fibers (e.g., steel fibers) and/or particles (e.g., taconite [iron ore] pellets) in close contact with each other in the concrete [8 - 12]. In the case of conductive concrete, the transmission of electric charge occurs mainly through the conductive additives in the concrete and does not require the presence of an electrolyte [10]. The resistivity of conductive concrete is less dependent on the hydration of cement paste than the resistivity of normal concrete [11]. Additives for making conductive concrete include steel fibers, steel shavings, carbon black, coke breeze, ferrous compounds, and other similar materials.

In order to increase the conductivity, it is necessary to provide fiber-to-fiber and/or fiber-to-particle continuity throughout the concrete to facilitate the formation of a conductive fiber/particle network in the concrete [9, 10, 12]. Therefore, the conductivity of concrete depends on the grading of the conductive particles, the particle-to-cement ratio, and the pressure applied to the fresh concrete during its placing stage [10].

Generally, concrete containing conductive fibers has higher mechanical strength but lower conductivity compared with concrete containing conductive aggregates. The lower conductivity of conductive-fiber concrete is attributed to less contact area between fibers. The lower mechanical strength and the higher conductivity of conductive-aggregate concrete are attributed to the high mixing-water demand for offseting the large amount of water absorption by conductive aggregates such as carbon black and coke breeze [11]. An electrically conductive concrete may have important applications in the military, construction industry, and for de-icing roads. In conjunction with an electrical power supply and specially configured electrodes, conductive concrete can be used in de-icing roads, sidewalks, bridges, and runways. When placed as an overlay, conductive concrete with very low resistivity can be used as a secondary anode in existing cathodic protection systems. Also, conductive concrete attenuates electromagnetic and radio waves, hence, can be used to shield computer equipment from eavesdropping efforts and to protect electrical installations and electronic equipment from interference [10 - 13]. There is very limited work on conductive controlled low-strength materials (CLSM) [14]. This paper presents the results of a research project on the use of high-carbon fly ash in manufacturing conductive CLSM and concrete. The unburned carbon content of the fly ash was 12%.

EXPERIMENTAL STUDY

Materials

Materials used in this study consisted of one source each of cement, high-carbon fly ash, natural sand, 19 mm maximum size crushed quartzite limestone, steel fibers, and processed taconite (iron ore) pellets. The carbon content of the fly ash was 12% by the loss on ignition (LOI) test. The ash was obtained from Port Washington Power Plant of We Energies, Wisconsin, USA. The steel fibers were 6 mm wide and 50 mm long crimped fibers. The steel fibers were used in one of the concrete mixtures (Mixture 50) in order to enhance the electrical conductivity of the concrete. The processed taconite pellets were classified as a heavyweight coarse aggregate. They were obtained from upper Michigan, USA.

Mixture Proportions for CLSM and Concrete

Three different CLSM mixture proportions were developed in this study:

- CLSM made with cement, water, and high-carbon fly ash;
- CLSM made with cement, water, high-carbon fly ash, and sand; and
- CLSM made with cement, water, high-carbon fly ash, sand, and crushed stone.

The details about CLSM mixture proportions and fresh properties are given in Table 1.

Three different concrete mixture proportions were used in this study:

- Concrete containing high-carbon fly ash;
- Concrete containing high-carbon fly ash and steel fibers; and

- Concrete containing high-carbon fly ash and taconite pellets as a replacement of crushed stone.

The details about concrete mixture proportions and fresh properties are given in Table 2.

CLSM and Concrete Specimens

All test specimens for CLSM and concrete were cast in accordance with ASTM D 4832 and C 192, respectively. These specimens were typically cured for one day in their molds in the UWM-CBU concrete laboratory at about 23 °C. The specimens were then demolded. Specimens for strength determination were cured in a standard moist-curing room maintained at 100% relative humidity (R. H.) and 23 °C temperature until the time of testing. For each mixture, two groups of specimens were prepared for electrical resistance measurements: one group was moist cured in lime-saturated water, and the other group was cured in air at 60 ± 10% R. H. and 23 °C.

Electrical Resistance Measurements

For the measurement of the electrical resistance of the material under investigation and the reliability of measurements, six 150 x 300 mm cylinders were cast from each CLSM and concrete mixture. Following demolding, a group of three cylinders were cured in air, and another group of three cylinders were cured in water. Both the air-cured specimens and water-cured (saturated) specimens were tested at the same ages for electrical resistance. Resistance measurements were performed using a Leader LCR-475-01 multimeter at the seven pre-determined locations on each of the six cylinders for each mixture. The seven locations used for measuring electrical resistance were (Fig. 1):

Location 1: For measurement of electrical resistance along the 300 mm length of the cylinder using 150 mm diameter copper plates on ends of the cylinder.

Locations 2, 3, 4: For three measurements along the 300 mm length of the cylinder taken using 13 mm diameter copper plates on ends of the cylinder: Location 2, at the center; Location 3, half way between the center and the perimeter; and Location 4, near the perimeter.

Locations 5, 6: For two measurements taken using 13 mm diameter copper plates to determine the characteristics of the surface electrical resistance: Location 5, 100 mm apart; and Location 6, 200 mm apart.

Location 7: For measurement of electrical resistance of the cylinder across its diameter.

For each of the seven locations, an average was determined for each group of test cylinder. The average results are shown in the plots of electrical resistance in this study.

RESULTS AND DISCUSSION

Compressive Strength of CLSM and Concrete Mixtures

The compressive strength data for the CLSM mixtures are presented in Table 3. As expected, the CLSM strength increased with increasing age. In general, the rate of strength gain was high for the mixtures containing aggregates (sand and/or stone). Even with reduced cement content, Mixtures 100S and 100SG showed higher compressive strength than Mixture 100.

The compressive strengths of concrete mixtures are given in Table 4. The 28-day compressive strength of concrete was about 17 MPa.

Electrical Resistance of CLSM Mixtures

The electrical resistance values obtained for the CLSM specimens at location 1 to 7 are shown in Figs. 2 - 8. For Location 1, the electrical resistivity values in ohm-cm were also obtained (Fig. 2) by multiplying the corresponding resistance values in ohm by approximately 6 cm, which is the area/length of the 15 x 30 cm CLSM cylinder. The respective 28-day electrical resistivity values of water-saturated specimens of CLSM Mixtures 100, 100S, and 100SG were

48, 102, and 184 ohm-cm, and the corresponding values of air-dried specimens were 3890, 3421, and 5825 ohm-cm. The electrical resistance values of the air-cured specimens of CLSM mixtures were much greater in comparison with the water-saturated specimens at all the locations. The differences increased as the air-cured specimens continued to dry, while the moist-cured specimens remained saturated with the increase in age. In general, the resistance of CLSM mixtures in saturated condition increased slightly with increasing age. CLSM Mixture 100SG showed the highest electrical resistance value in both saturated and air-dried conditions. Overall, CLSM Mixture 100 showed the lowest electrical resistance value in most of the comparisons. This is most likely due to the increase in cementitious paste volume and the highest amount of high-carbon fly ash without any aggregates.

Electrical Resistance of Concrete Mixtures

Results of the electrical resistance of concrete mixtures measured at different locations in both air-dried and water-saturated conditions are shown Figs. 9 – 15. For Location 1, the electrical resistivity values were also obtained (Fig. 9). The respective 28-day electrical resistivity values of water-saturated specimens of concrete Mixtures 40, 50, and 60 were 4100, 1500, and 1700 ohm-cm, and the corresponding values of air-dried specimens were 27300, 10700, 12800 ohm-cm. Similar to the trend of CLSM mixtures, each concrete mixture showed higher electrical resistance values in air-dried condition than in saturated condition. In general, the resistance of CLSM mixtures in saturated condition increased considerably with increasing age. Among the concrete mixtures, Mixture 50, which contained steel fibers, showed the lowest electrical resistance. In most of the comparisons, Mixture 40 showed the highest resistance both in air-dried and saturated conditions. Mixture 60 containing taconite pellets as a replacement of natural crushed stone showed electrical resistance lower than Mixture 40 but higher than Mixture 50.

CONCLUSIONS

Based on the above experimental study, the following conclusions can be drawn:

1. The electrical resistance value of the air-dried specimens of CLSM mixtures was much greater than the water-saturated specimens at all the locations of measurement.
2. In general, the resistance of CLSM mixtures in saturated condition increased slightly with increasing age.
3. CLSM Mixture 100 containing the highest amount of high-carbon fly ash without any aggregates showed the lowest electrical resistance value in most of the comparisons.
4. Air-dried concrete specimens possessed higher electrical resistance in comparison with saturated specimens.
5. Electrical resistance of saturated concrete increased with increasing testing age.
6. Concrete Mixture 50 containing steel fibers showed the lowest electrical resistance, and Concrete Mixture 60 containing taconite pellets as a replacement of natural coarse aggregate showed the second lowest resistance.
7. High-carbon fly ash can be used in manufacturing conductive CLSM and concrete [15].

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Table 1. Proportions and Fresh Properties of CLSM Mixtures

Mixture No.	100	100S	100SG
Fly Ash Content (FA/[C + FA + S + G]) (%)	93	32	22
Cement, C (kg/m^3)	59	39	27
Fly Ash, FA (kg/m^3)	810	395	392
SSD Fine Aggregate, S (kg/m^3)	0	792	513
SSD Coarse Aggregate, G (kg/m^3)	0	0	848
Water, W (kg/m^3)	620	311	285
w/cm	0.71	0.72	0.68
Air Temperature (°C)	26	26	26
CLSM Temperature (°C)	25	25	29
Flow (mm)	286	260	171
Air Content (%)	1.7	1.2	0.9
Density (kg/m^3)	1489	1537	2065

Table 2. Proportions and Fresh Properties of Concrete Mixtures

Mixture No.	40	50	60
Fly Ash Content (FA/[C + FA]) (%)	43	43	43
Steel Fiber (kg/m^3)	0	62	0
Heavyweight Aggregate (taconite pellets) (kg/m^3)	0	0	1175
Cement (kg/m^3)	211	208	208
Fly Ash (kg/m^3)	157	154	157
SSD Fine Aggregate (kg/m^3)	762	756	751
SSD Coarse Aggregate (kg/m^3)	896	881	0
Water, W (kg/m^3)	231	234	249
w/cm	0.63	0.65	0.68
Air Temperature (°C)	27	26	26
Concrete Temperature (°C)	27	27	24
Slump (mm)	51	83	44
Air Content (%)	1.5	1.0	4.1
Density (kg/m^3)	2257	2296	2539

Table 3. Compressive Strength of CLSM

Mixture No.	Fly Ash Content (FA/[C + FA + S + G]) (%)	Compressive Strength (MPa)					
		3-day		7-day		28-day	
		Ind.	Avg.	Ind.	Avg.	Ind.	Avg.
100	93	0.10	0.10	0.24	0.23	0.41	0.33
		0.10		0.24		0.28	
		0.10		0.21		0.31	
100S	32	0.21	0.21	0.72	0.69	0.93	0.94
		0.21		0.69		0.93	
		0.21		0.66		0.97	
100SG	22	0.10	0.11	0.97	0.77	0.93	0.91
		0.10		0.66		0.79	
		0.14		0.69		1.00	

Table 4. Compressive Strength of Concrete

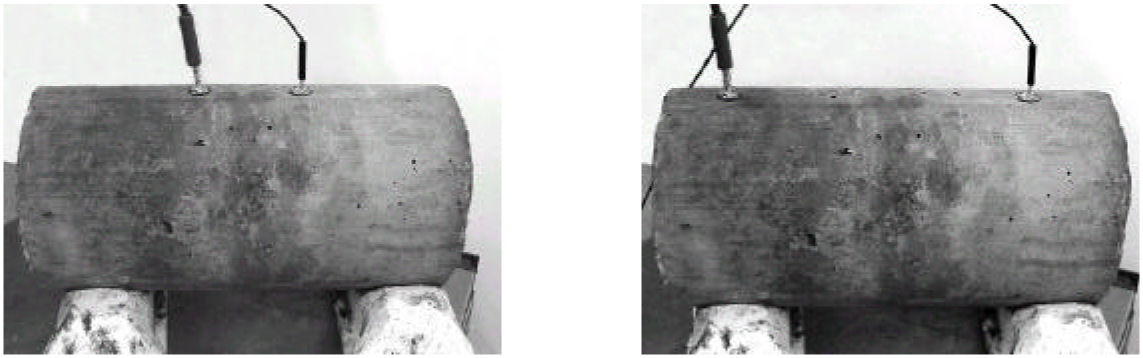
Mixture No.	Fly Ash Content (FA/[C + FA]), (%)	Compressive Strength (MPa)					
		3-day		7-day		28-day	
		Ind.	Avg.	Ind.	Avg.	Ind.	Avg.
40	43	7.69	7.1	9.62	10.0	17.86	17.5
		6.76		10.24		16.97	
		6.83		10.28		17.62	
50	43	6.90	6.7	9.83	9.5	16.48	16.4
		6.66		8.97		16.34	
		6.48		9.79		16.52	
60	43	5.55	5.7	9.38	9.5	16.22	16.1
		5.86		10.07		15.46	
		-		8.97		16.74	

(a) Location 1

(b) Location 2

(c) Location 3

(d) Location 4



(e) Location 5

(f) Location 6

(g) Location 7

Fig. 1. Locations for electrical resistance measurements

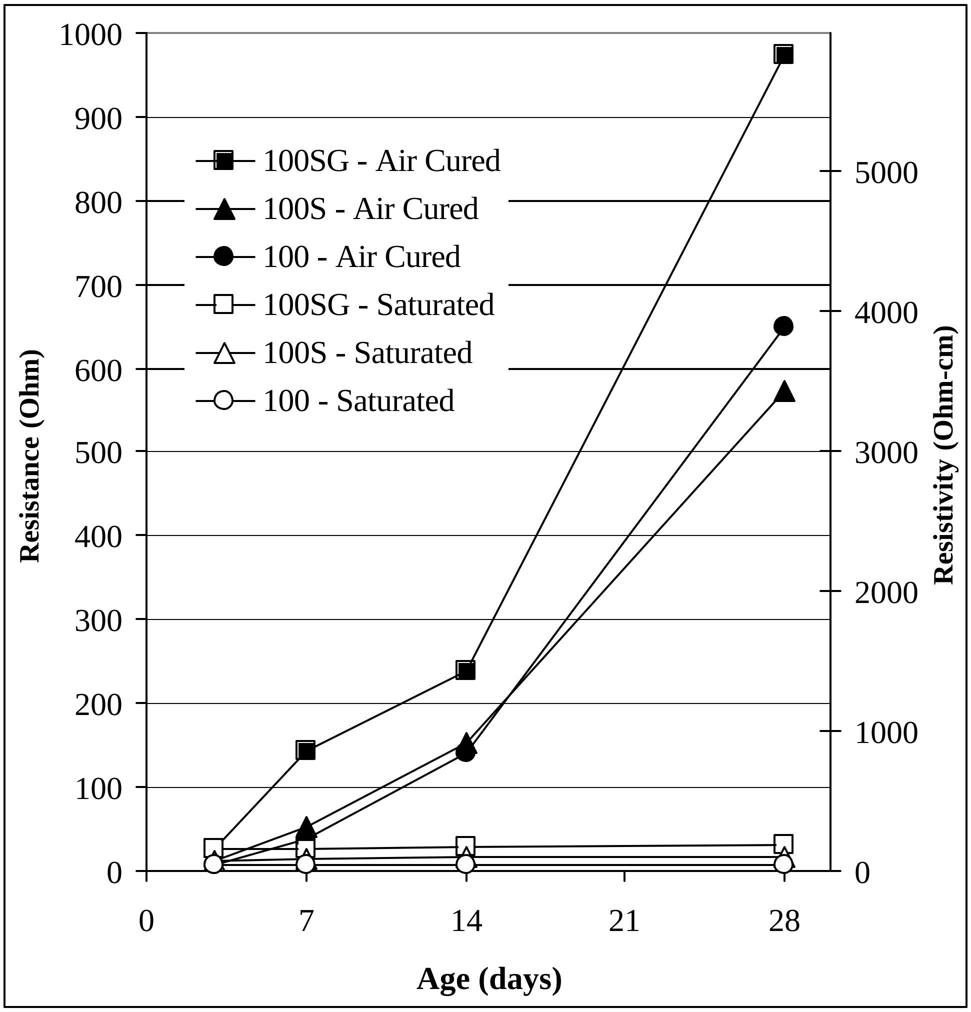


Fig. 2. Electrical resistance and resistivity of CLSM mixtures – Location 1

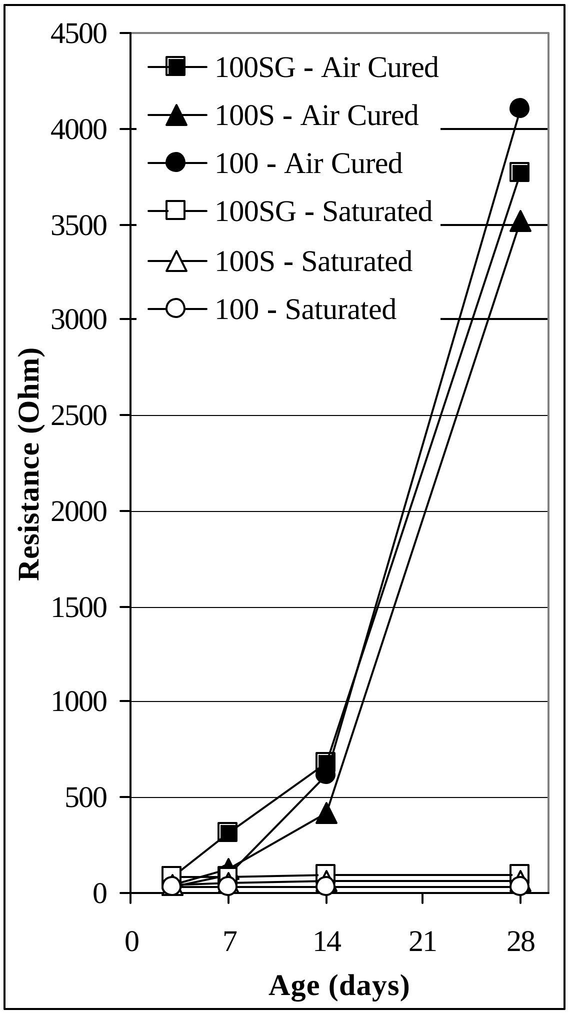


Fig. 3: Electrical resistance of CLSM mixtures – Location 2

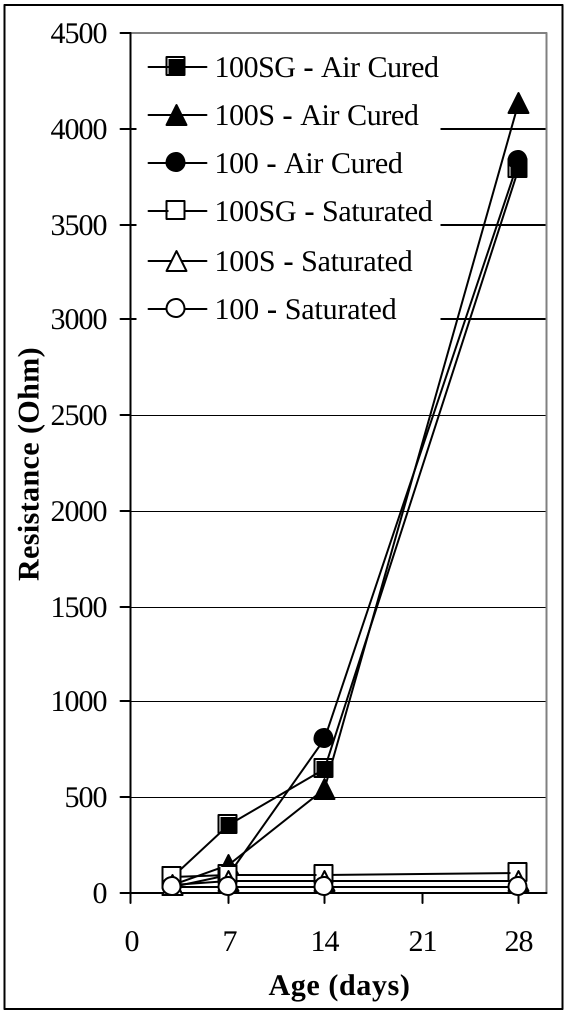
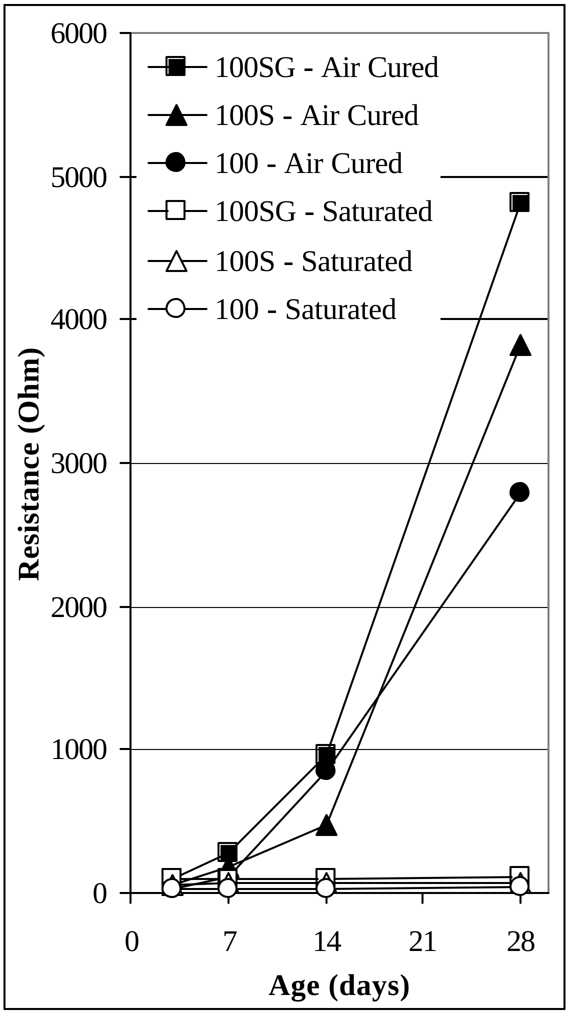


Fig. 4. Electrical resistance of CLSM mixtures – Location 3



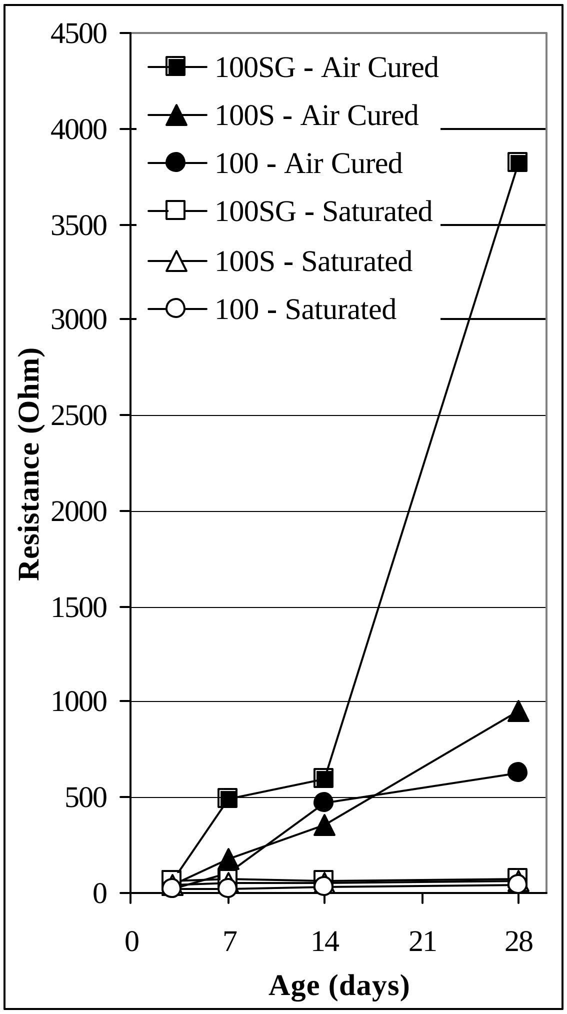


Fig. 5. Electrical resistance of CLSM mixtures – Location 4

Fig. 6. Electrical resistance of CLSM mixtures – Location 5

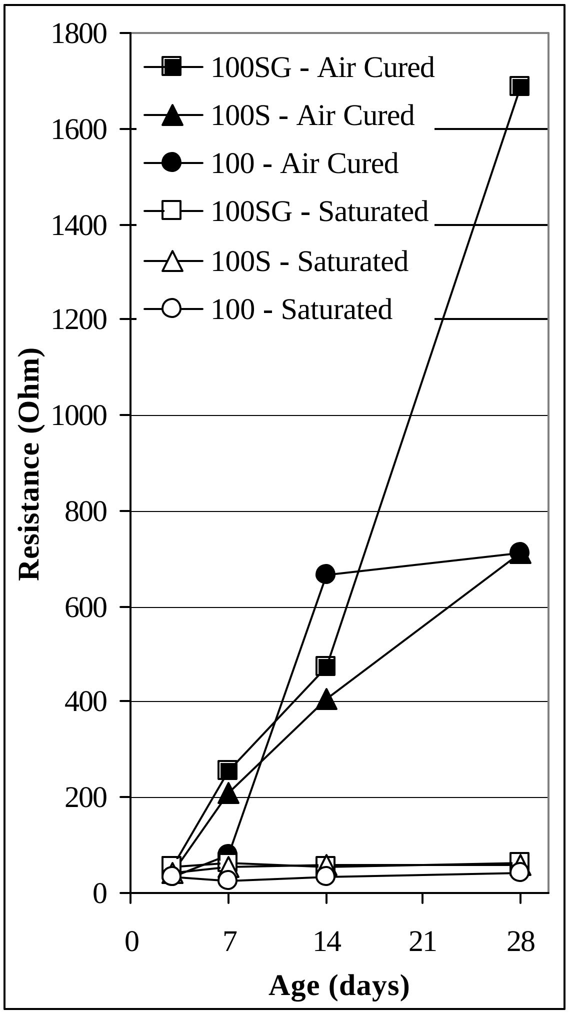


Fig. 7. Electrical resistance of CLSM mixtures – Location 6

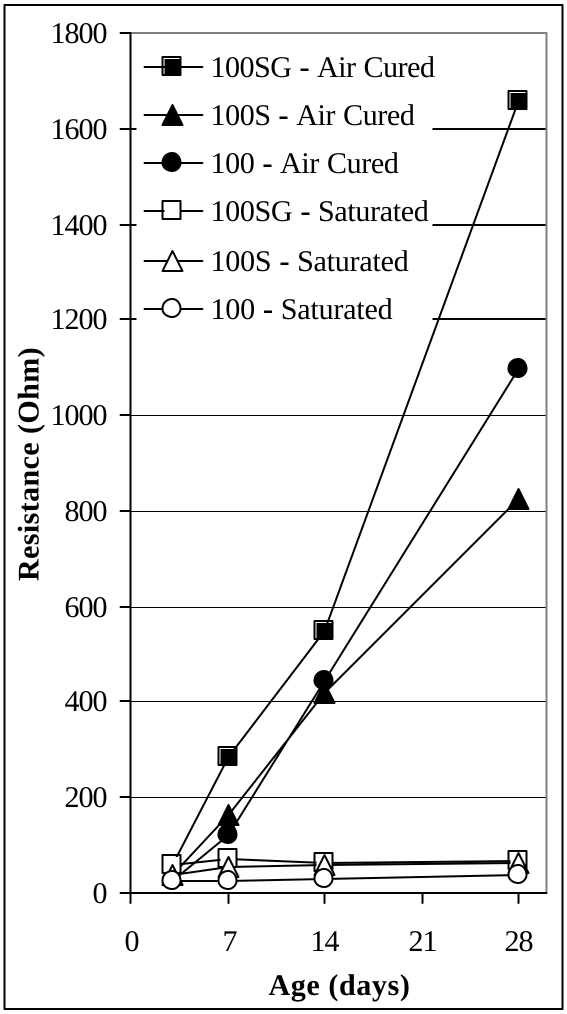


Fig. 8. Electrical resistance of CLSM mixtures – Location 7

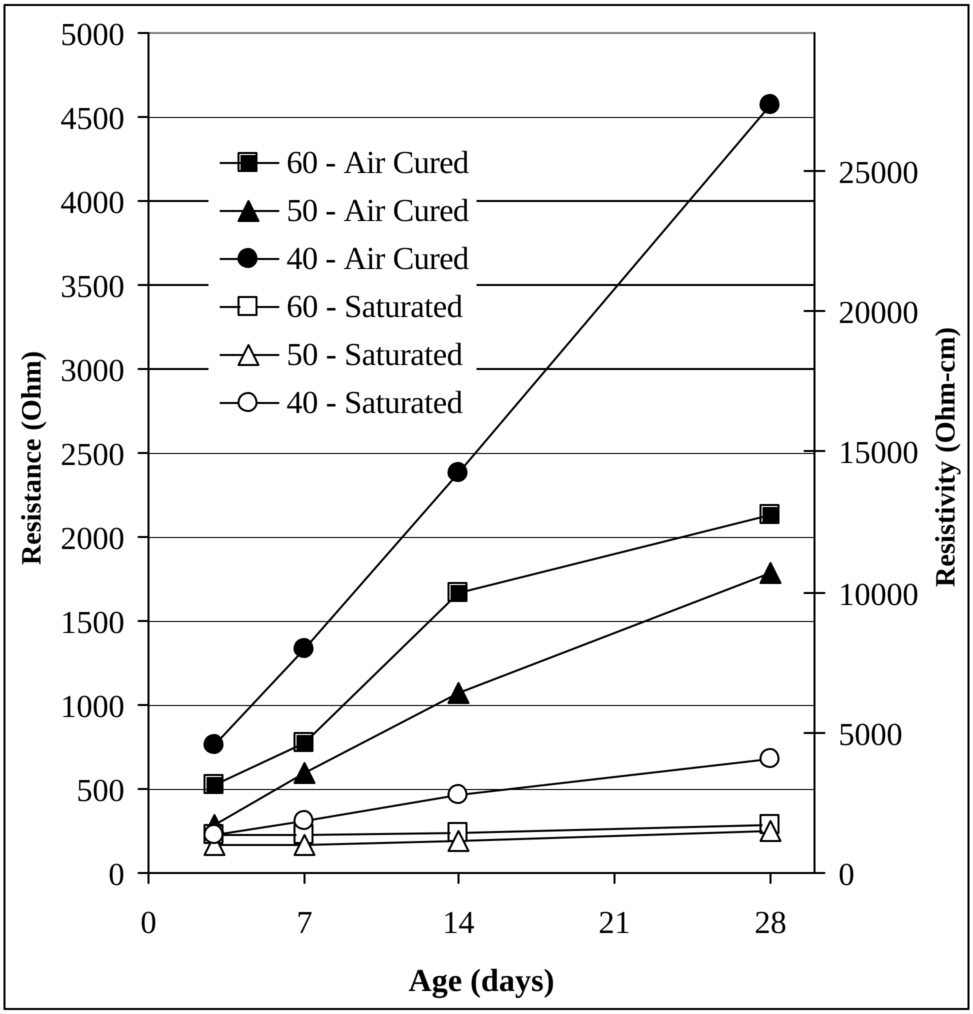


Fig. 9. Electrical resistance and resistivity of concrete mixtures – Location 1

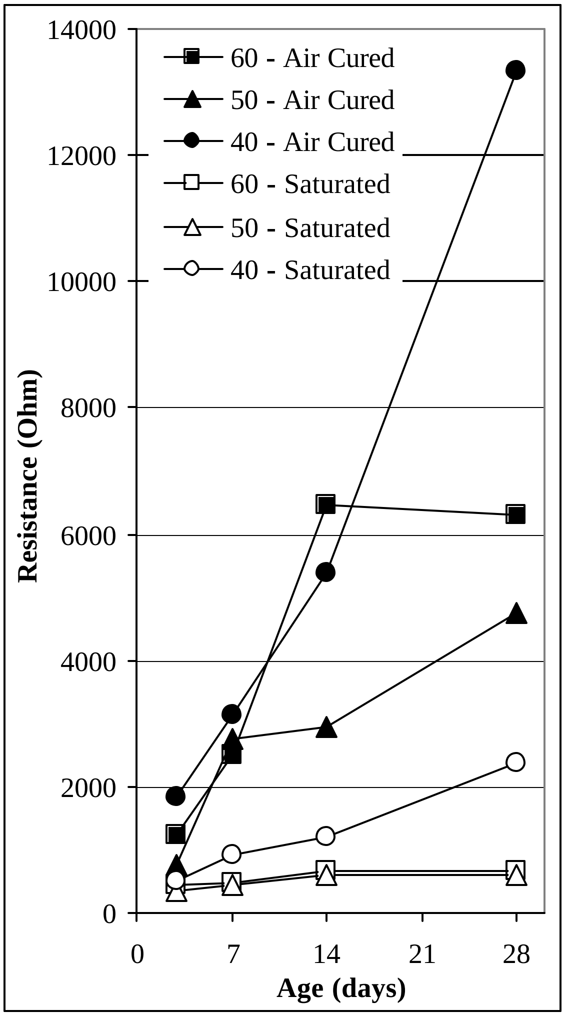


Fig. 10. Electrical resistance of concrete mixtures – Location 2

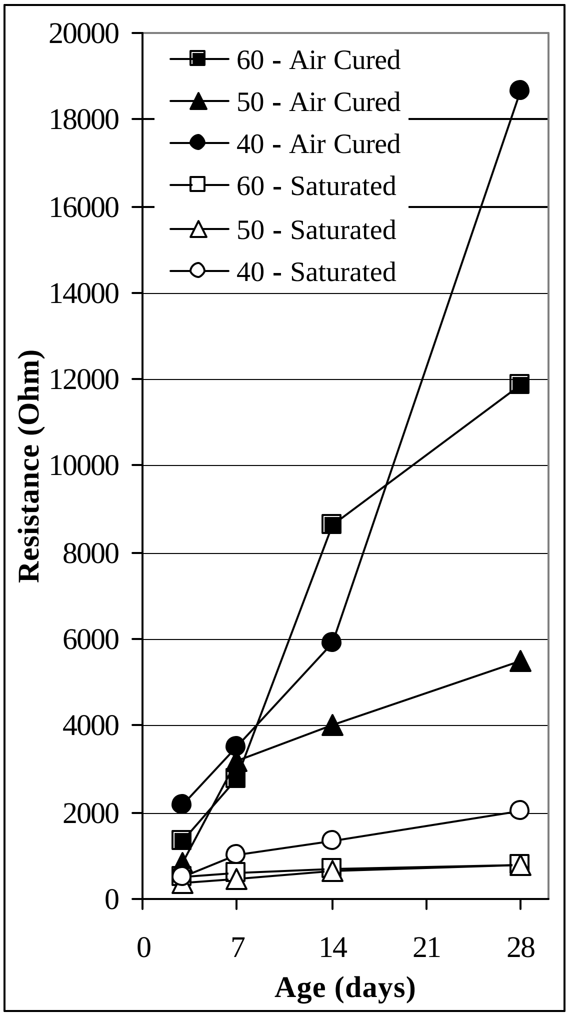


Fig. 11. Electrical resistance of concrete mixtures – Location 3

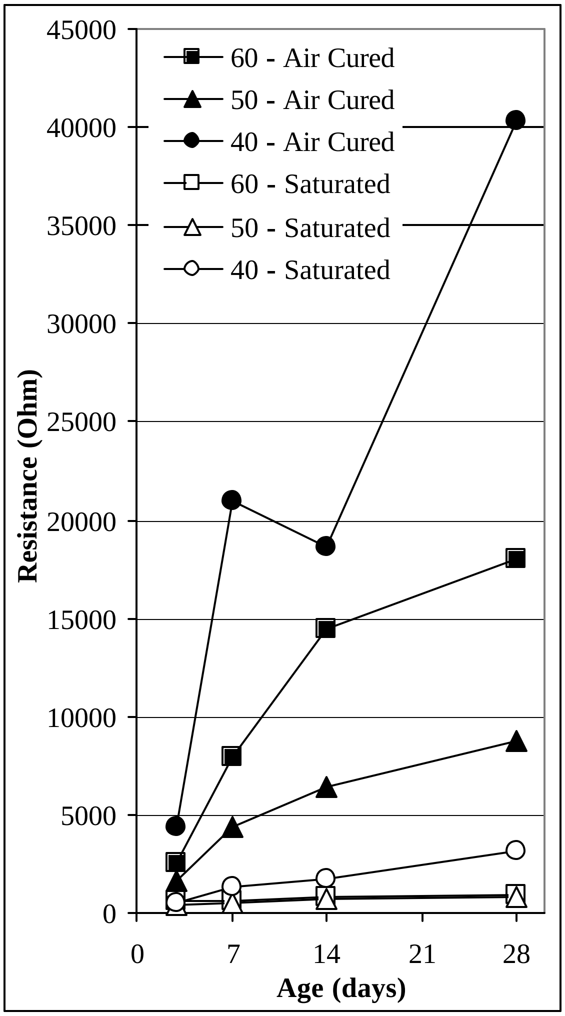


Fig. 12. Electrical resistance of concrete mixtures – Location 4

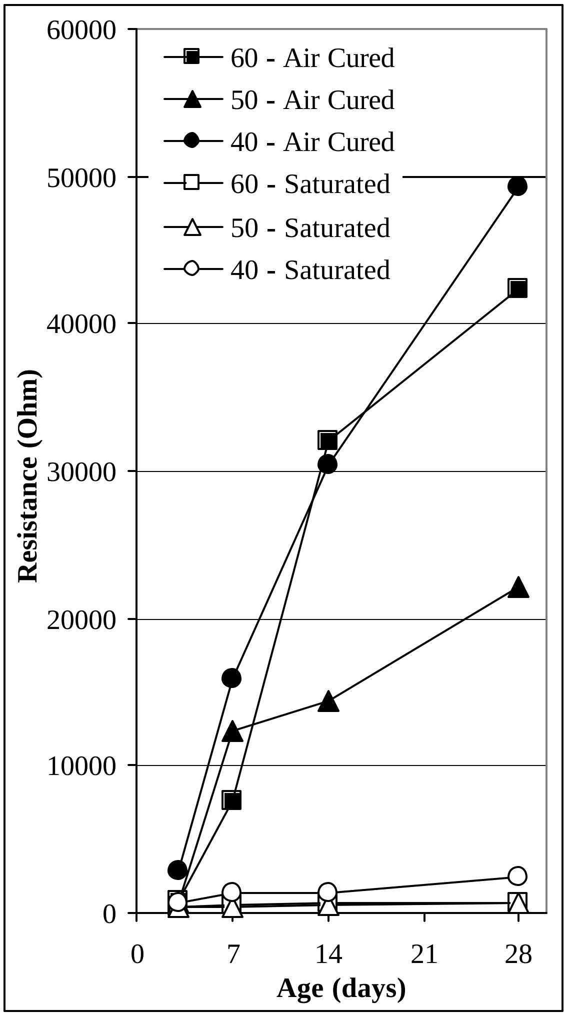


Fig. 13. Electrical resistance of concrete mixtures – Location 5

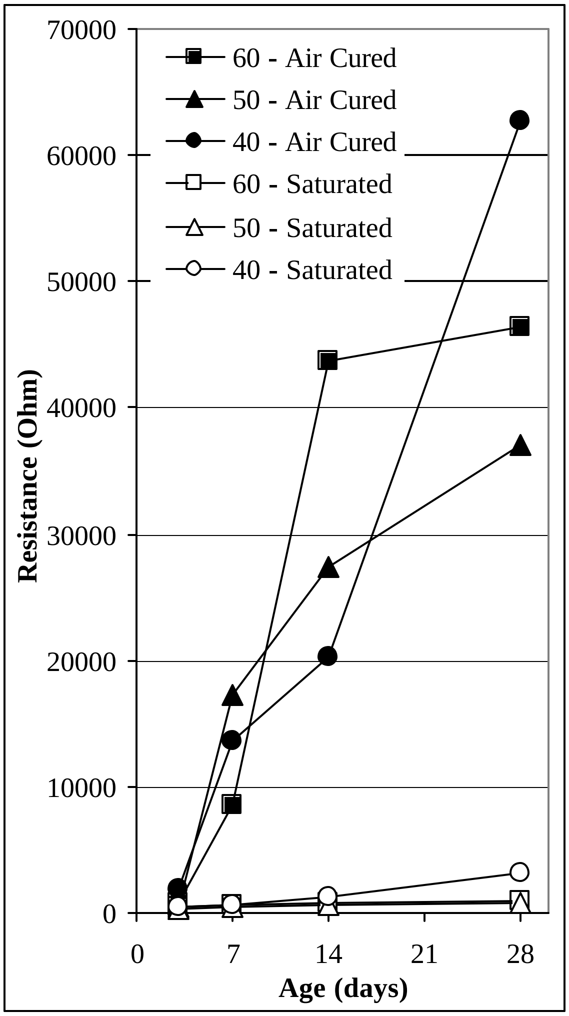


Fig. 14. Electrical resistance of concrete mixtures – Location 6

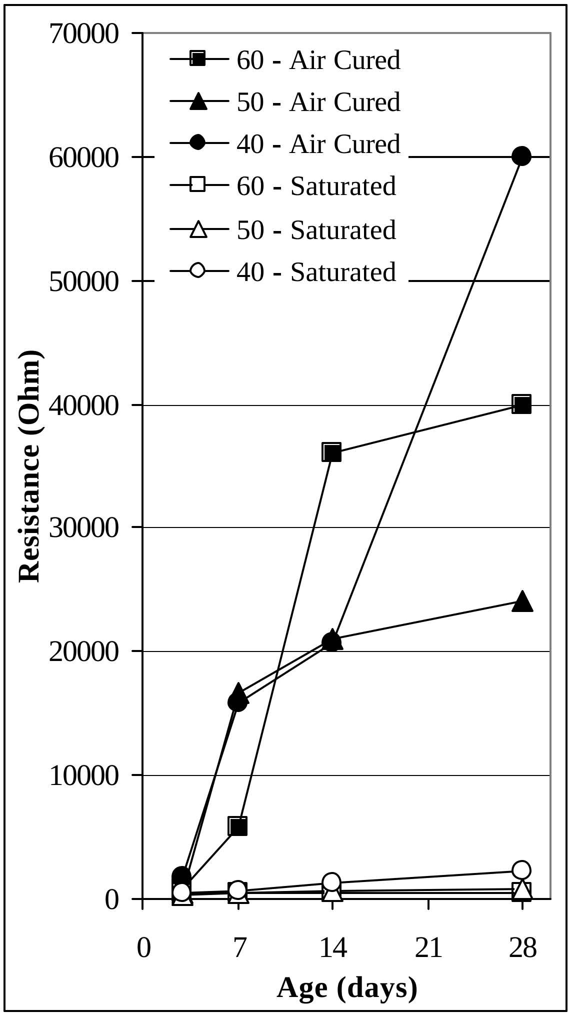


Fig. 15. Electrical resistance of concrete mixtures – Location 7