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Effect of Fly Ash Replacement on Corrosion of Steel in Concrete

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ABSTRACT

Almost 20 years ago, the author was involved in an investigation of the corrosion behavior of steel in concrete made with several chemical and mineral admixtures. These concrete mixes contained different types and amounts of fly ash. Some also contained air entrainment additives and/or superplasticizers. In that investigation, reinforced concrete specimens made using more than 25 mixes were subjected to cyclical saltwater exposure. Exposure was accompanied by corrosion tests that were based on linear polarization resistance measurements for the lollipop specimens and current measurements for the macrocell specimens.

The results of two years of testing showed that there was generally a significant delay in the onset and severity of corrosion with fly ash replacement. At the end of the investigation, selected specimens were sacrificed and subjected to thorough forensic examination. Over the years, some of the remaining specimens have been subjected to periodic exposure, testing, and autopsy. However, to date, more than 80 lollipop specimens still remain.

In this paper, the recent re-exposure and testing of some of the remaining specimens will be examined. The focus is on a comparison of those with and without fly ash. The specimens have taken on new significance due to renewed interest in by-products utilization as well as the role that such utilization can play in corrosion reduction.

INTRODUCTION

In 1988, a research project was initiated to study the effect of certain chemical and mineral admixtures on reinforced concrete. Concrete mixes included mixes with different mix proportions and variables included different types and amounts of fly ash, different amounts of air entrainment, and superplasticizers. The focus of this investigation was corrosion susceptibility and this property was determined by measuring parameters such as chloride permeability, chloride penetration, macrocell current, corrosion potential, and polarization resistance (which is inversely related to corrosion rate). Lollipop specimens (cylindrical specimens having steel reinforcement in the center) and macrocell specimens (based on ASTM G 109) served as the major specimen types for the investigation [Sennour, Zhang, Wheat, and Carrasquillo, 1992]. A complete list of the concrete mixes is given in Table 1. Low or High Fly Ashes are Class F or C and defined based on ACI Specifications. The percentage (%) refers to the amount of cement replacement. The water to cement or water to binder amount is given as w/c. Mixes 1-13 and 20-

26 had approximately 3% air, while Mixes 14, 16, and 18 had approximately 6.5% and Mixes 15, 17, and 19 had approximately 9%.

Table 1 Concrete Mixes, Sennour, Zhang, Wheat, and Carrasquillo, 1992.

MIX	FLY ASH	%	ADMIXTURE	W/C
1				0.66
2	Low F	20		0.60
3	High F	20		0.66
4	Low F	27.5		0.62
5	High F	27.5		0.50
6	Low C	27.5		0.70
7	High C	27.5		0.49
8	Low C	35		0.68
9	High C	35		0.50
10	Medium C	20		0.52
11	Medium F	35		0.69
12	Medium C	27.5	SUPER	0.51
13	Medium F	27.5	SUPER	0.51
14			AIR	0.45
15			AIR	0.40
16	Medium C	27.5	AIR	0.55
17	Medium C	27.5	AIR	0.55
18	Medium F	27.5	AIR	0.43
19	Medium F	27.5	AIR	0.43
20				0.68
21	Medium C	27.5		0.71
22	Medium F	27.5		0.72
23				0.46
24	Medium C	27.5		0.47
25	Medium F	27.5		0.48
26			SUPER	0.46

The experimental procedure involved casting and curing for 28 days, exposure to dry laboratory air for approximately four weeks, followed by cyclical exposure to 3.5% NaCl. For each mix, at least 11 steel-reinforced cylinders or lollipops (7.6 x 15.2 cm) were used. The 15.2 cm steel bars were cast in such a way that the steel protruded 2.5 cm from the top of the concrete cylinder. Cylinders were immersed in the salt solution so that the level of the solution was 2.5 cm below the top of the cylinder. The cylinders were exposed to the solution for 3 days and then they were removed and allowed to dry. This cyclical exposure was repeated every two weeks. Corrosion potential (Ecorr) values and polarization resistance measurements were determined on the third day of exposure, prior to removal from solution.

Macrocell specimens based on ASTM G 109 were also exposed to cyclical wet-dry exposure. Periodically, selected specimens (lollipop or macrocell) were sacrificed and subjected to chloride analysis and microscopic examination.

Average Ecorr and 1/Rp measurements as a function of time are shown for selected specimens in Figures 1 through 4.

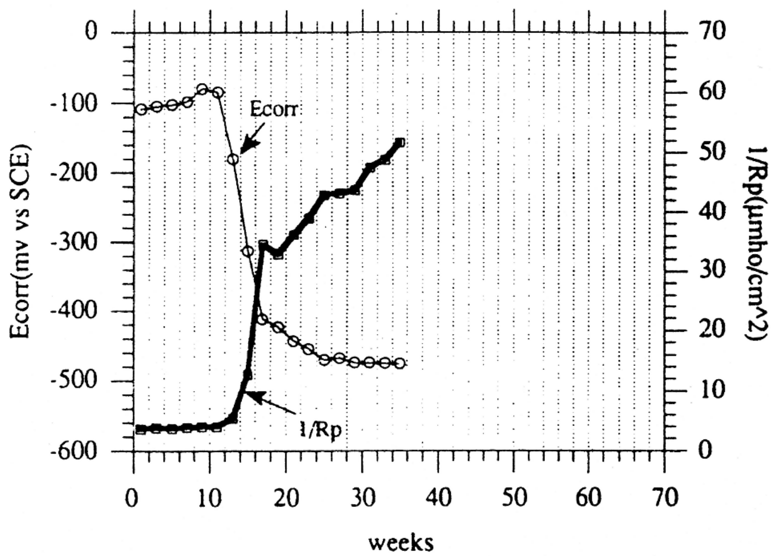

Figure 1 - Plot for Mix 20 (Zhang and Wheat, 1994)

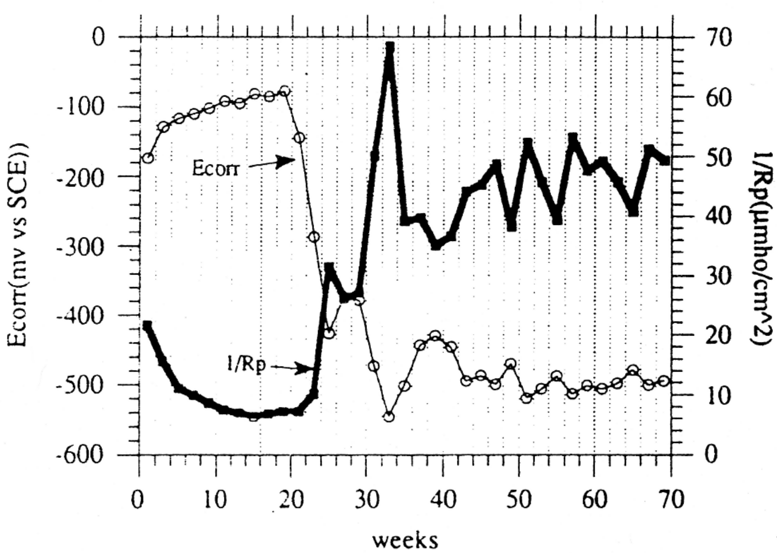

Figure 2 - Plot for Mix 1 (Zhang and Wheat, 1994)

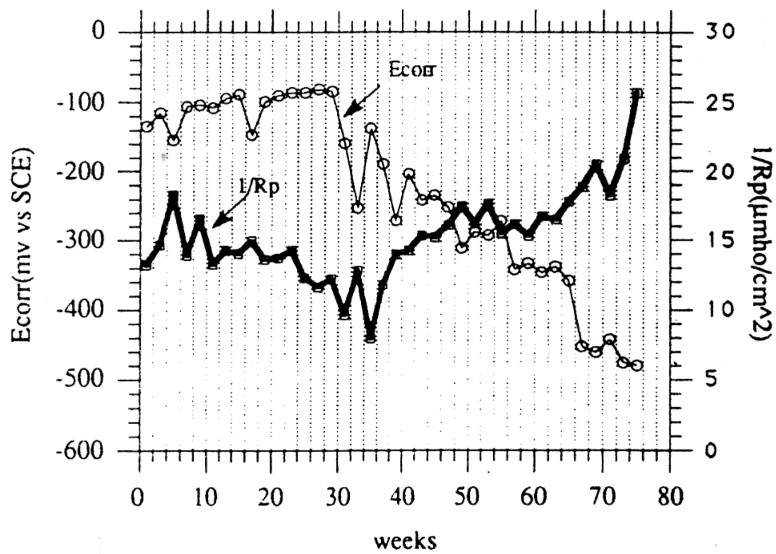

Figure 3 - Plot for Mix 10 (Zhang and Wheat, 1994)

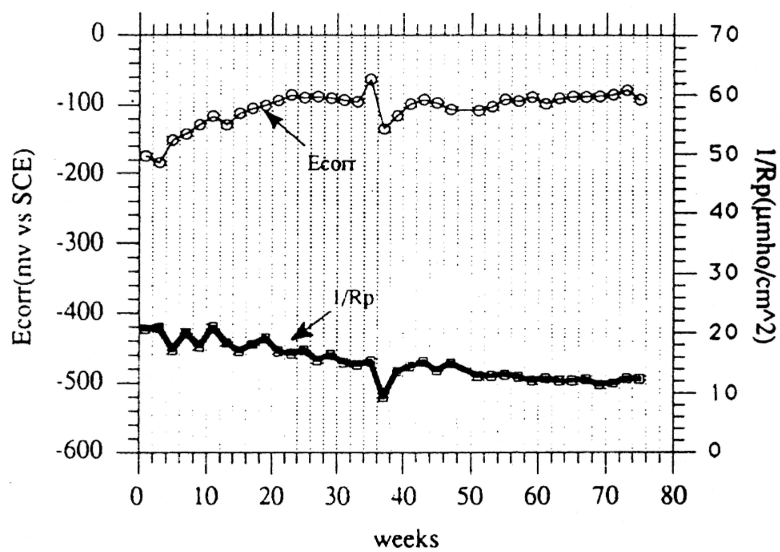

Figure 4 - Plot for Mix 11 (Zhang and Wheat, 1994)

The onset of corrosion activity is generally noted by a decrease in Ecorr (to values more negative than -280 mV vs the Saturated Calomel Electrode (SCE)) and an increase in 1/Rp. Values of 1/Rp in excess of 26 microSiemens per square centimeter have been associated with severe corrosion (Berke, 1987). Therefore, it is interesting to note that specimens from Mix 20 became active early, followed by specimens from Mix 1. Specimens from Mix 10, a mix containing a Class C fly ash and having a w/c = 0.69 became active much later and specimens from Mix 11, a mix containing Class F fly ash and having a w/c =0.43 did not become active during the time of testing.

Average Ecorr, 1/Rp (in terms of microSiemens per square centimeter) for the lollipop specimens and chloride penetration values for the macrocell specimens at depth 1(1.3 cm) and depth 2 (3.2 cm) are shown in Table 2 [Zhang and Wheat,1994].

Table 2 Experimental Data (Data taken at 52 weeks unless otherwise noted)

Mix	Ecorr (mV vs SCE)	1/Rp (μS/cm2)	Ecorr (mV vs SCE)	1/Rp (μS/cm2)	Chloride Penetration	(% of CI ions)
					Depth 1	**Depth 2**
1	-373	26.2	-520	52.2	0.343	0.138
10	-82	11.7	-288	16.2	0.343	0.100
11	-88	15.5	-107	12.9	0.291	0.080
12	-162	5.3	-231	5.4	0.188	0.067
13	-74	11.5	-69	10.1	0.081	0.072
14	-173	3.2	-360	4.2	0.339	0.078
15	-196	4	**-399**	**12.4**	0.363	0.145
16	-106	4.8	**-295**	**9.3**	0.214	0.072
17	-184	4.6	**-317**	**8.3**	0.260	0.072
18	-124	10.9	**-103**	**9.2**	0.148	0.073
19	-83	10.9	**-71**	**11.3**	0.101	0.072
20	-467	43.3	***-476***	***51.7***	0.539	0.211
23	-59	9.5	***-166***	***13.7***	0.221	0.084

Bold represents data taken at 47 weeks
Bold/italics represents data taken at 35 weeks

The results clearly show the effect of fly ash in terms of delaying the onset of corrosion.

EXPERIMENTAL PROCEDURE

Since the conclusion of the testing of the original specimens, remaining specimens from the investigation have been stored in the laboratory. They had been dry from approximately 15 years. The remaining lollipop specimens were reintroduced to cyclical salt water exposure and monitored for at least 4 months. Polarization resistance measurements were carried out on the third day following re-exposure and the previous cyclical exposure and testing conditions were resumed. Specimens from Mixes 1,5,8, 11,13,14,18,19,20,22,24,25, and 26 were used.

RESULTS AND DISCUSSION

It was observed that within about 4 months of re-exposure, almost all specimens had achieved a corrosion potential value more negative than -280 mV vs SCE. Data taken three days after re-exposure to cyclical testing as well as data taken after 4 months of exposure are shown in Table 3**.** It should be noted that in this case, 1/Rp values have been converted to corrosion rates in terms of μm/y.

Table 3. Experimental Data after Re-exposure

	3 days		4 months	
Mix	**Ecorr (mV vs SCE)**	**Cor rate (μm/y)**	**Ecorr (mV vs SCE)**	**Cor rate (μm/y)**
1	-498	14.2	-616	12.8
5	-537	3.6	-343	1.2
8	-500	3.6	-562	8.6
11	-527	6.1	-541	5.0
13	-187	0.2	-403	1.2
14	-282	0.1	-374	1.2
18	-67	0.05	-496	4.1
19	-72	0.03	-390	2.5
20	-581	29.7	-579	24.3
22	-446	7.6	-576	8.6
24	-67	0.04	-443	0.3
25	-419	2.0	-448	3.5
26	-459	0.4	-532	7.3

It is interesting to note that by the fourth month of re-exposure, the corrosion potentials for specimens from all of the above mixes indicated that corrosion activity had initiated. However, there was quite a variation in the corrosion rates. Corrosion rates were lower for specimens made with mixes that contained fly ash; particularly those specimens from mixes with low water:cement ratios and higher air percentages. The influence of the high water:cement ratio for specimens made from Mix 11 is also evident. These specimens performed extremely well in the original investigation.

Nevertheless, when combined with low water:cement or water:binder ratios and air, the positive influence of the addition of fly ash is still very evident.

CONCLUSIONS

Electrochemical testing was used to determine the corrosion behavior of steel in concrete mixes made with and without fly ash. These specimens had been tested in an investigation almost 20 years ago. At that time, it was concluded that the fly ash replacement of cement could significantly delay the onset of corrosion.

Selected specimens from that investigation were re-introduced to cyclical exposure to salt water conditions and corrosion potentials and polarization resistance measurements were determined for at least four months. While the control specimens continued to show relatively high corrosion rates over the four months of exposure, corrosion rates for specimens made using fly ash and additional air, as well as those having low water:cement ratios had much lower corrosion rates.

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