Effect of fly ash and silica fume on time to corrosion initiation for specimens exposed long term to seawater

Francisco J. Presuel-Moreno[1], Eric I. Moreno[2]

1. Florida Atlantic University, Florida, USA

2. Universidad Autonoma de Yucatan, Mexico

Background

- Florida Bridges prone to chloride induced corrosion once chloride threshold is reached
- Silica Fume and Fly Ash are two of the admixtures commonly used to reduce concrete chloride diffusivity
- Studies with binary mixes, low water to cementitious ratio, exposed to fresh seawater in warm weather are rare
- Good correlation chloride diffusivity (D_{app}) vs. resistivity on lab saturated conditions has been reported

Single and Binary Concrete Mixes Prepared
Values are percentages of FA* and SF*,#

Mix Design Designation	Fly Ash percent	Silica Fume Percent	Calcium Nitrate l/m^3
AO	0	0	0
CO	0	0	19.8
FA20	20	0	0
FA35	35	0	0
FA50	50	0	0
FA35-N	35	0	19.8
SF06	0	6	0
SF15	0	15	0
SF27	0	27	0
SF15-N	0	15	9.9

* %FA and %SF content are % of FA/(c+FA) and SF/(c+SF) respectively

Silica fume used was in slurry silica fume

Concrete Composition and Selected Properties

Fly ash type F was used

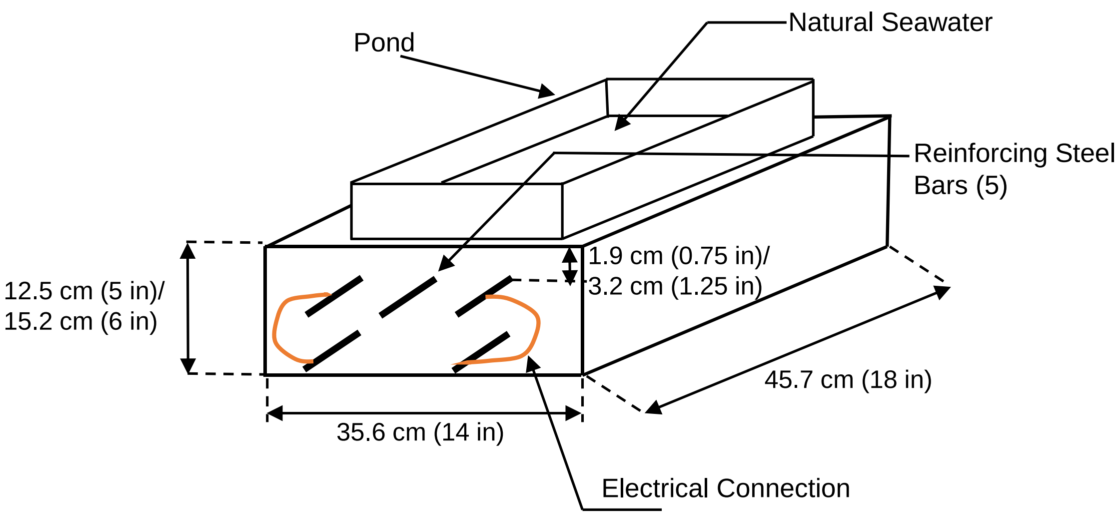
Silica Fume slurry was used. Part of the SF mass counted towards the water

Target cementitious in kg/m^3 was 400 kg/m^3

	FA20	FA35	FA50	FA35N
Cement, kgs	90.8	73.8	56.7	73.8
Fly Ash, kgs	22.7	39.7	56.7	39.8
Calcium Nitrite, kgs	0	0	0	5.2
Water, kgs	27.6	27.8	28.0	24.4
Coarse Aggregates, kgs	287.4	287.4	287.4	288.4
Coarse Aggregates, % excess moisture	2.96	2.3	2.3	2.9
Fine Aggregates, kgs	212.4	206.0	199.6	203.8
Fine Aggregates, % excess moisture	2.68	3.68	3.68	3.0
Unit Weight, kgs/m^3	2,263.6	2,247.6	2,231.6	2,231.6
w/cm ratio	0.367	0.37	0.37	0.363
RCP Avg. 91 Days, C	989	713	731	NA
Strength Avg. 28 days (MPa)	45.5	42.7	36.3	34.2
Strength Avg. 91 days (MPa)	53.2	52.9	45.6	44.5
Cementious per unit volume, kgs/m^3	399	400.4	401	396

	SF06	SF15	SF27	SF15N
Cement, kgs	110.2	104.4	96.6	104.4
Silica Fume, kgs	7.2	19	35.6	19
Calcium Nitrite, kgs	0	0	0	2.68
Water, kgs	25	18.8	10.2	16.6
Coarse Aggregates, kgs	288.4	288.4	288.4	288.4
Coarse Aggregates, % excess moisture	2.65	2.7	2.9	2.9
Fine Aggregates, kgs	217.4	215.2	212.2	215.2
Fine Aggregates, % excess moisture	2.680	2.68	2.68	2.7
Unit Weight, kgs/m^3	2,279.6	2,273.2	2,262.0	*2,265.2*
w/cm Ratio	0.37	0.367	0.368	0.365
RCP Avg. 91 Days, C	2061	720	598	868
Strength Avg. 28 days (MPa)	48.7	50.8	52.6	48.8
Strength Avg. 91 days (MPa)	52.6	52.2	53.0	51.7
Cementious per unit volume, kgs/m^3	397	397.6	399	396

Specimen Geometry and Number of Samples



Rebar 0.95 cm diameter

Number of samples with reinforcements per mix and height/cover

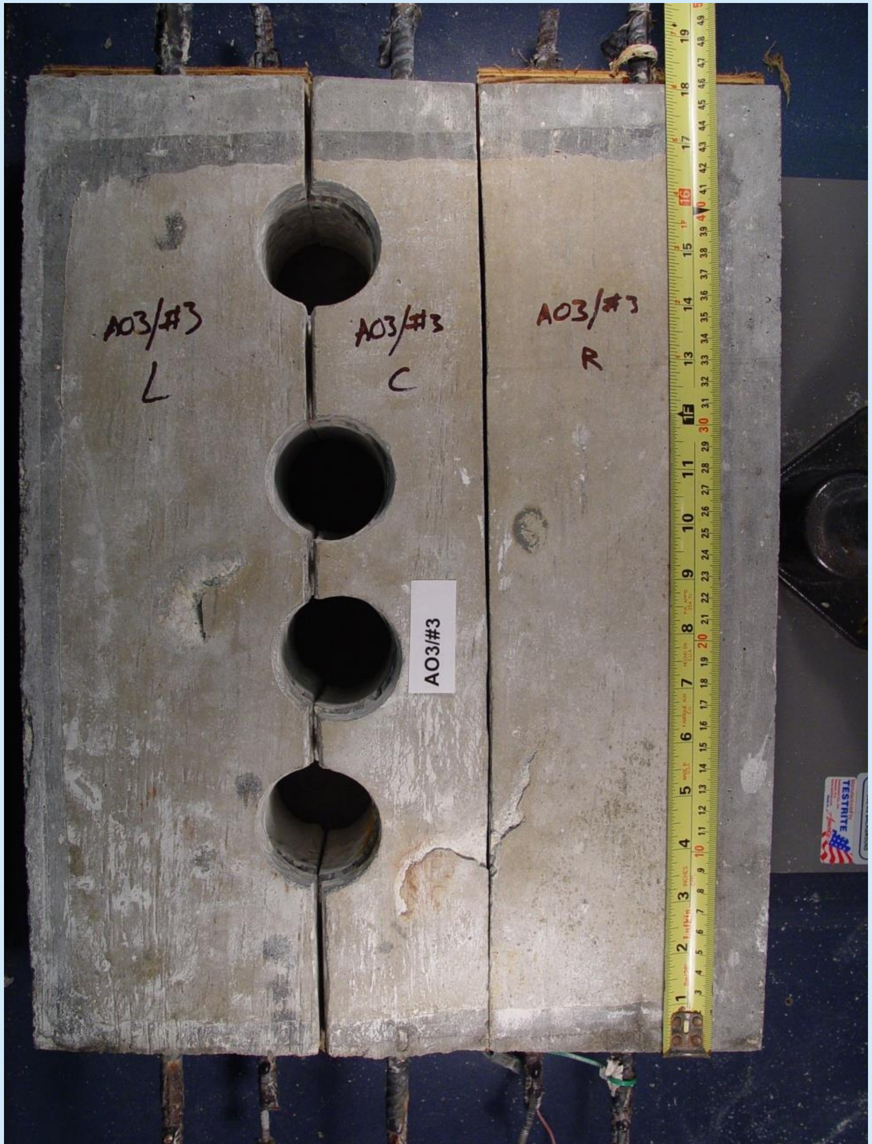
Height/ Cover	AO	CO	FA20	FA35	FA50	FA35N	SF06	SF15	SF27	SF15N
12.7 /1.9 cm	5	4	4	4	4	3	3	3	3	3
15.2 /3.2 cm	3		3	3	3					

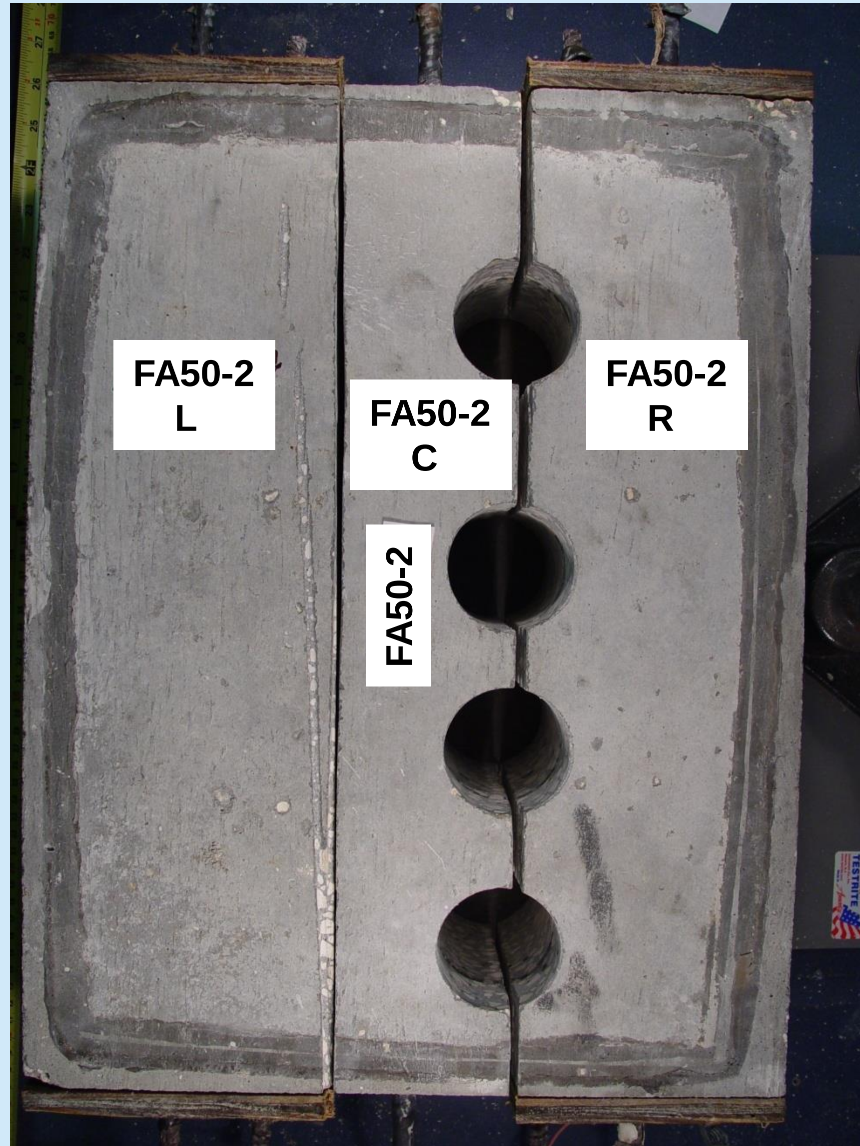
Samples exposed to 1 week with seawater, 1 week no solution
Since 1995, recently reached 7600 days (20.75 years) of exposure

Experimental

- Potential vs. Time
- Selected specimens were terminated (at 5700, 6020 and 6230 days). On day 5700, one sample per mix was terminated.
- Top row of rebars were exposed for visual examination
- Concrete segments above exposed rebars were milled (avoiding corrosion products) and to measure the chloride concentration above the rebar trace (Modified FDOT method - smaller mass)
- Concrete cores obtained from selected terminated specimens (some sliced for chloride profiles others used for resistivity)

Top View – Representative Terminated Samples after coring and segmenting in 3 pieces

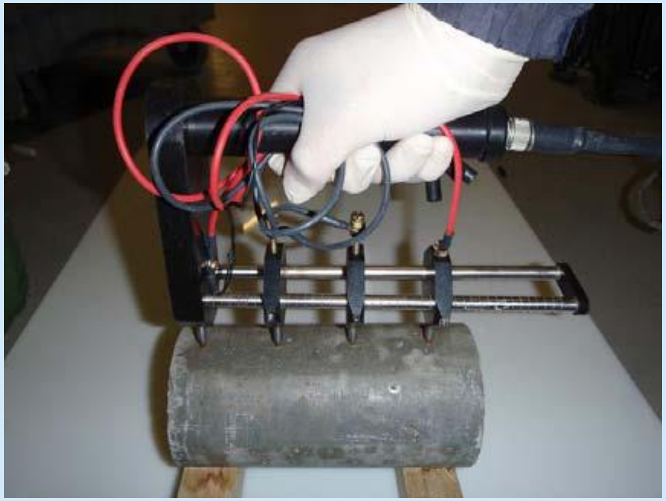


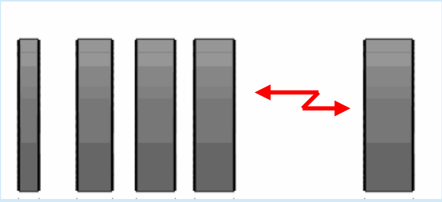


Tests Performed on Concrete Cores

- Resistivity vs. Time (as moisture increased)
- Chloride Profiles from concrete cores (FDOT method)
- D_{app} calculated from chloride profiles

Tests performed on obtained concrete cores

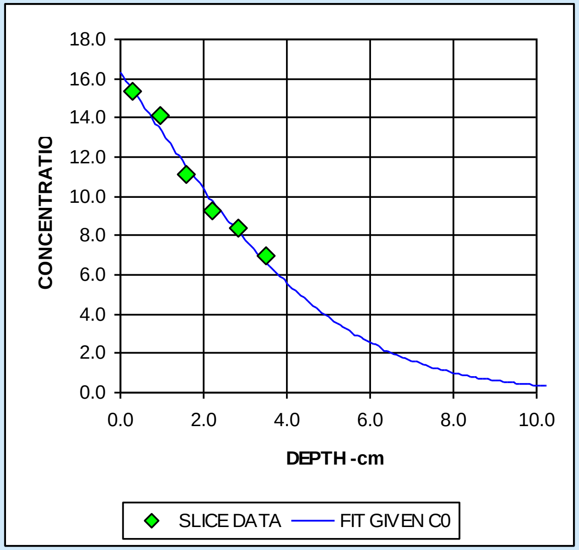


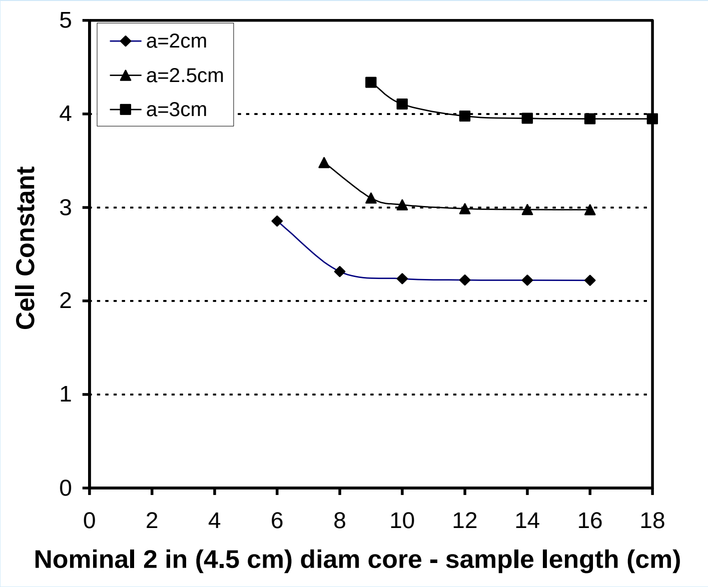


Cores Sliced with wet saw. Six Slices
Cut spacing 0.635 cm (0.25”)
Each slice pulverized and

Chloride titration following FDOT FM5-516
This is total acid soluble chlorides method

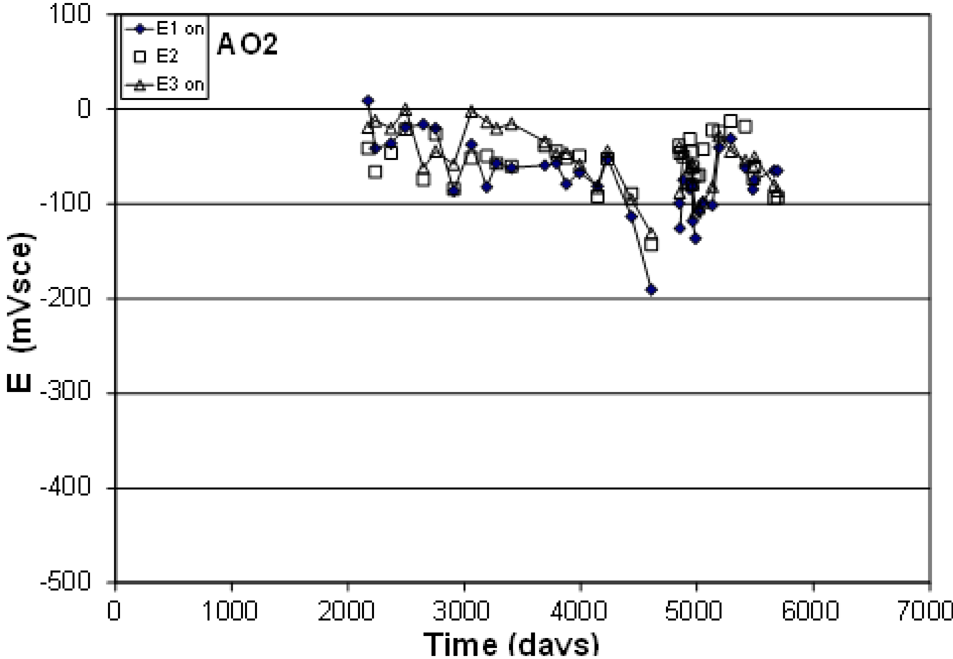
Resistivity as per FM5-578 and values shown include geometry correction

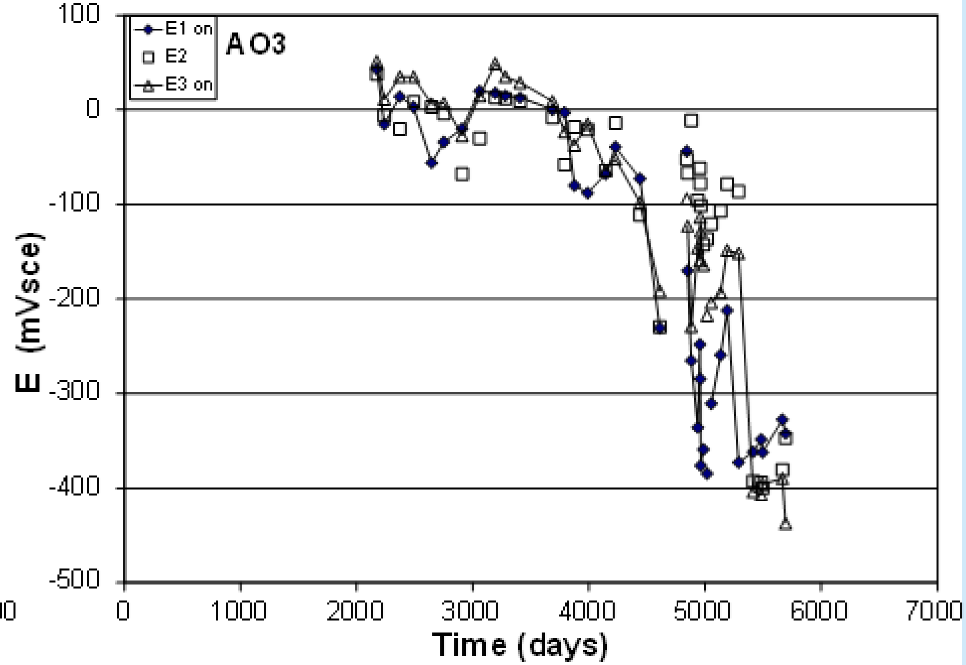


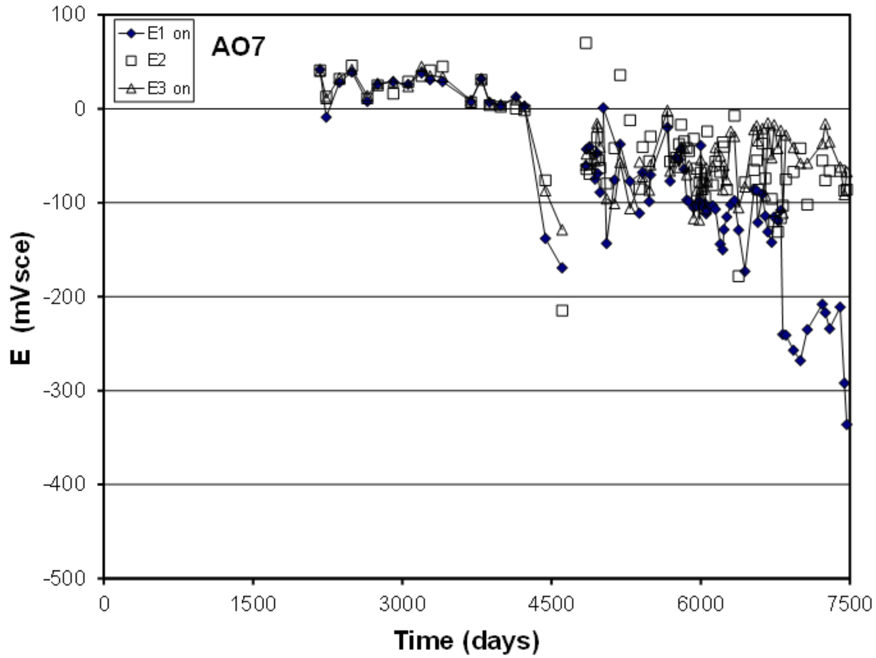


D_{app} fitted from chloride profile

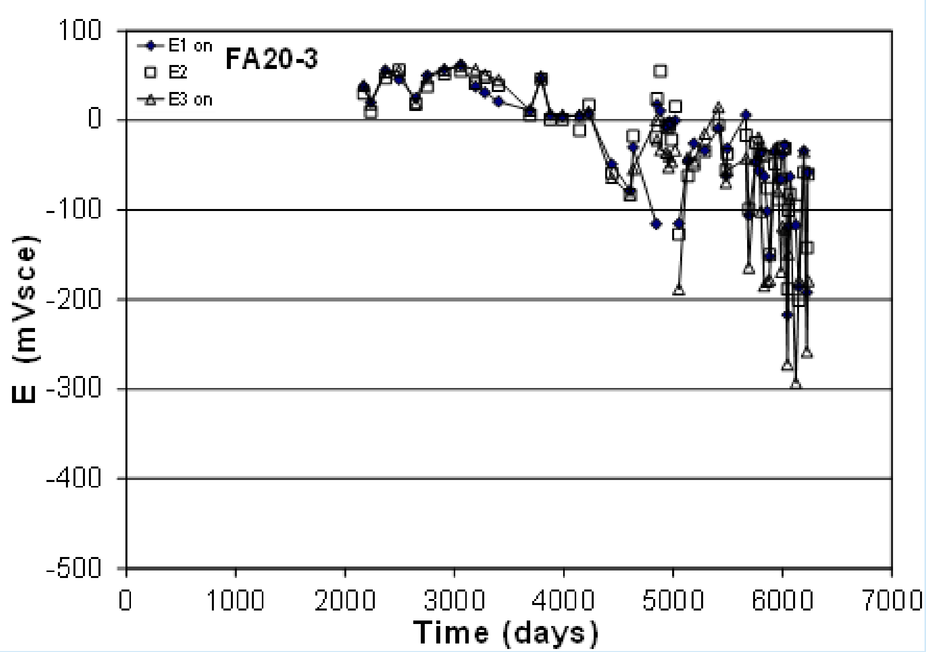
Typical Potential Evolution

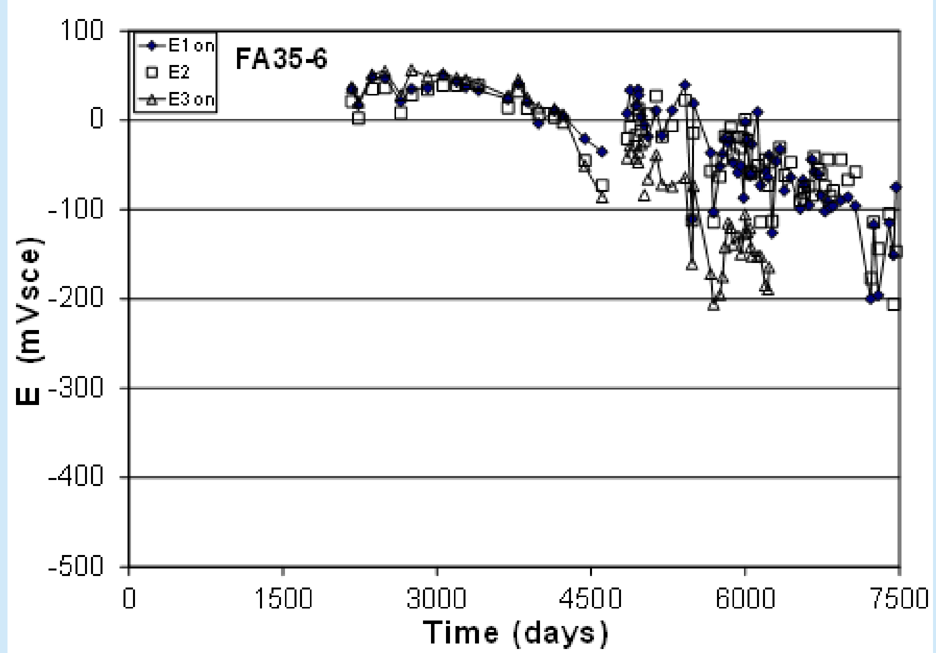


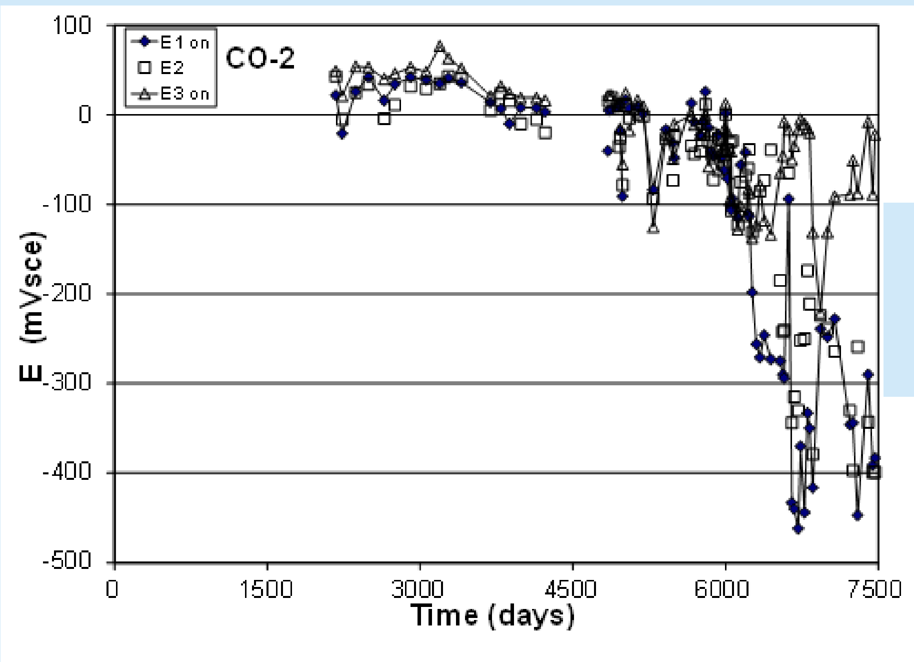


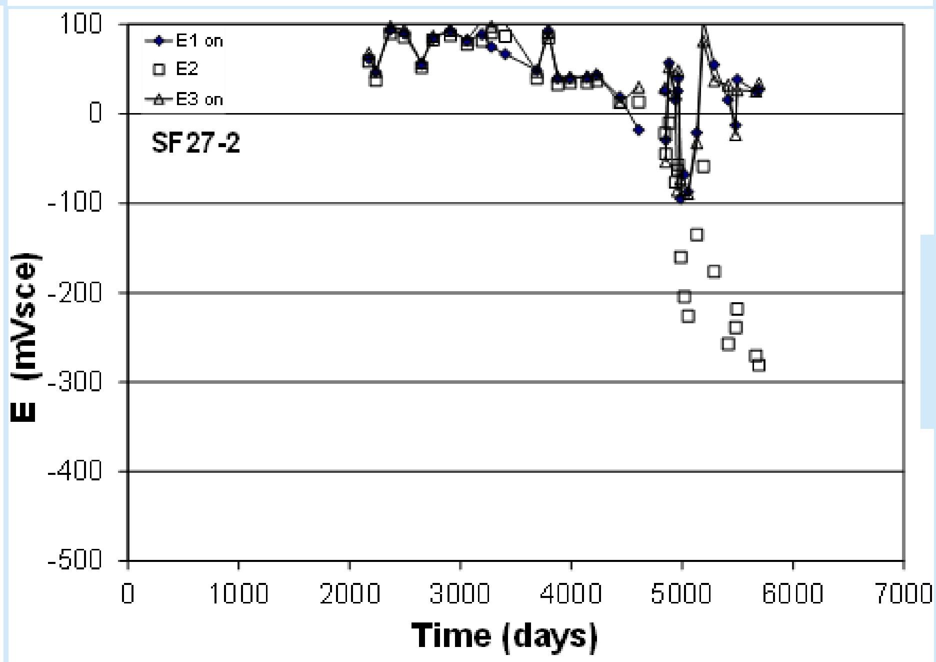


Typical Potential Evolution

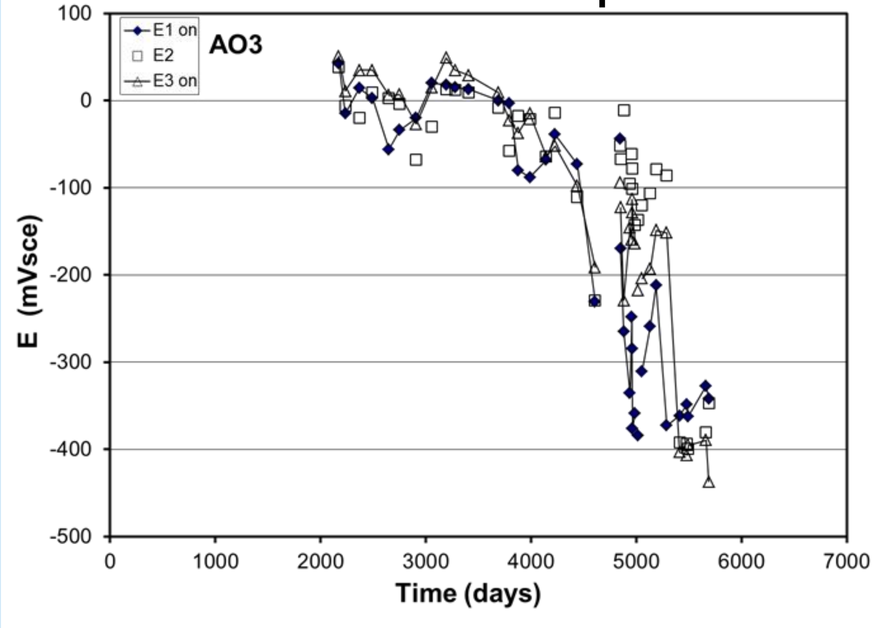




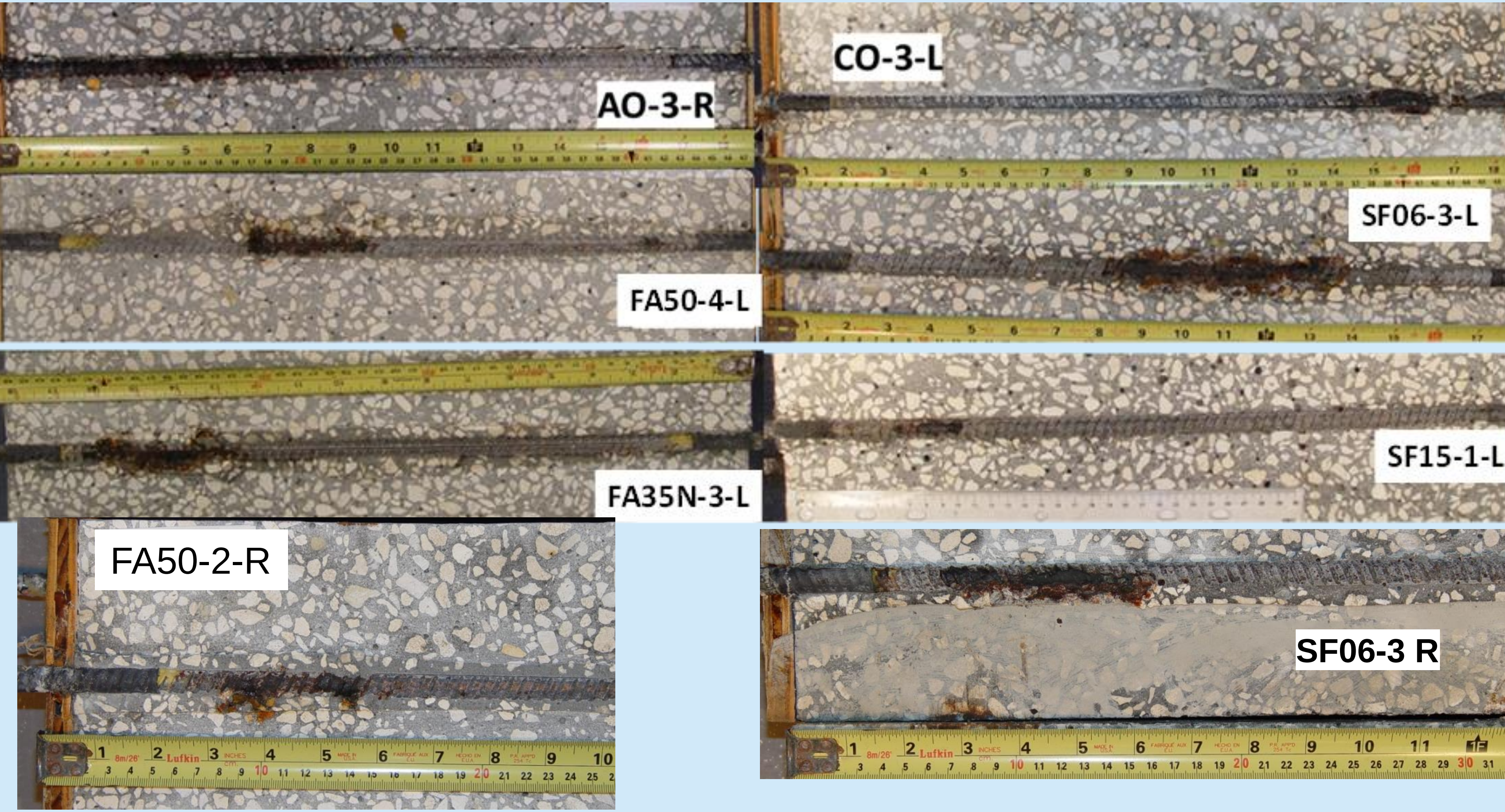




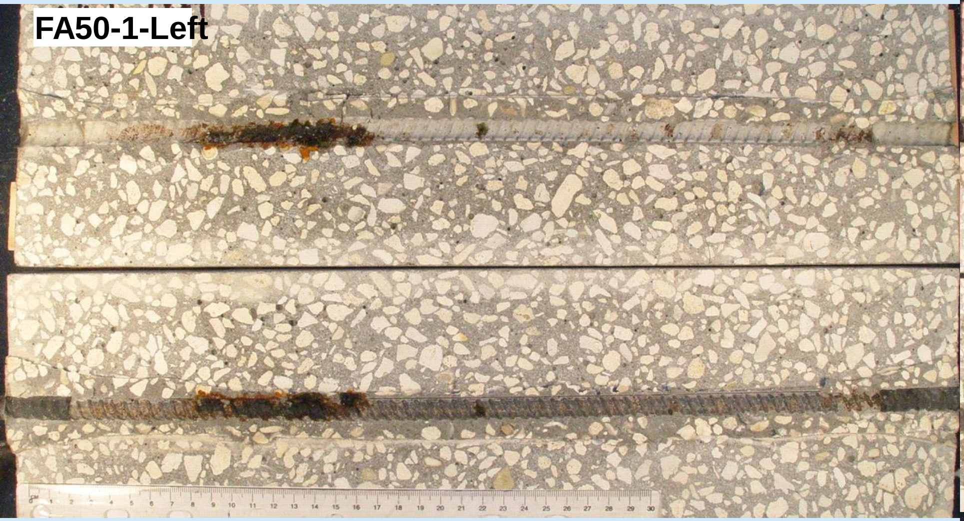
Corrosion Spread on Selected Terminated Rebars

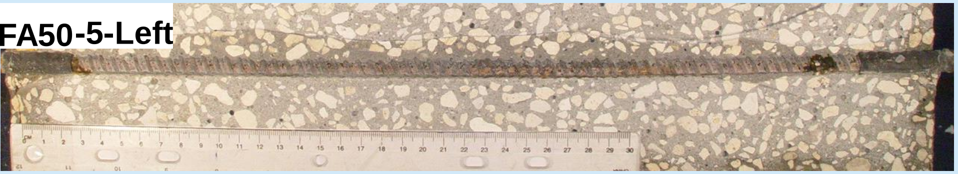


Corrosion Spread on Selected Terminated Rebars

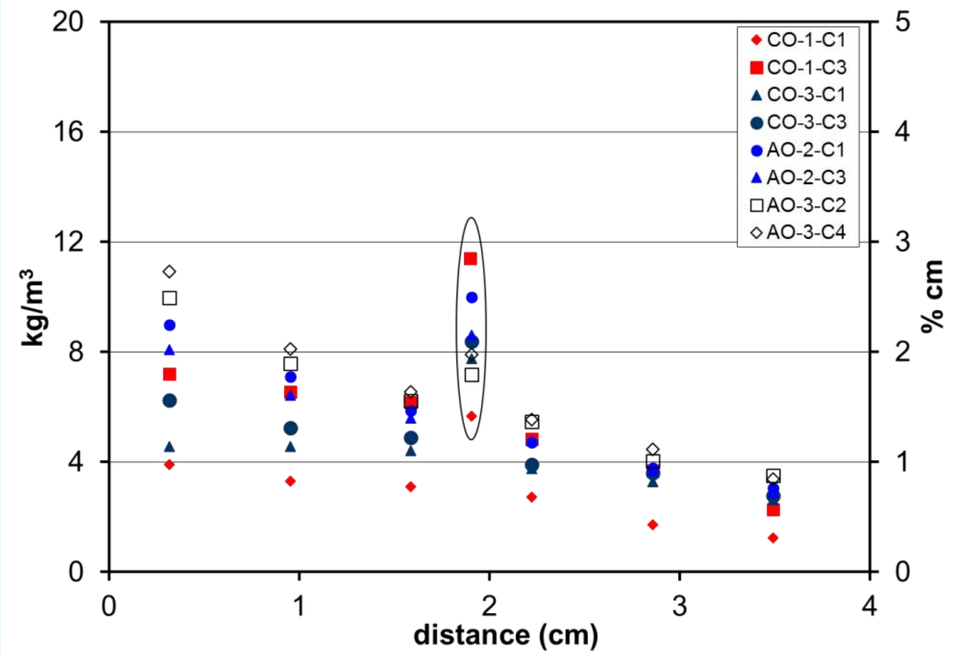


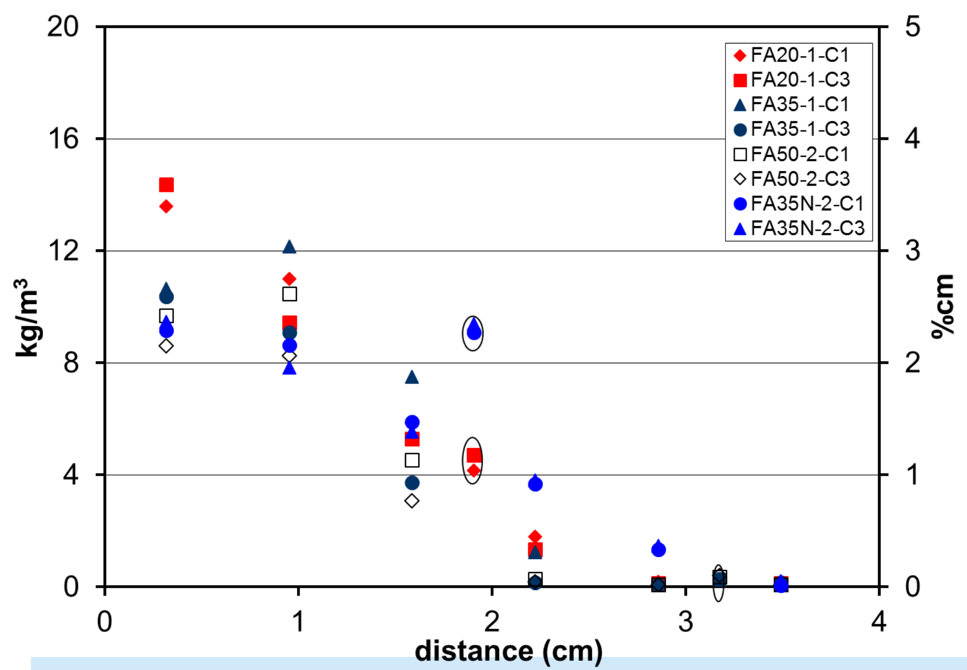
Corrosion Products on Selected Rebars

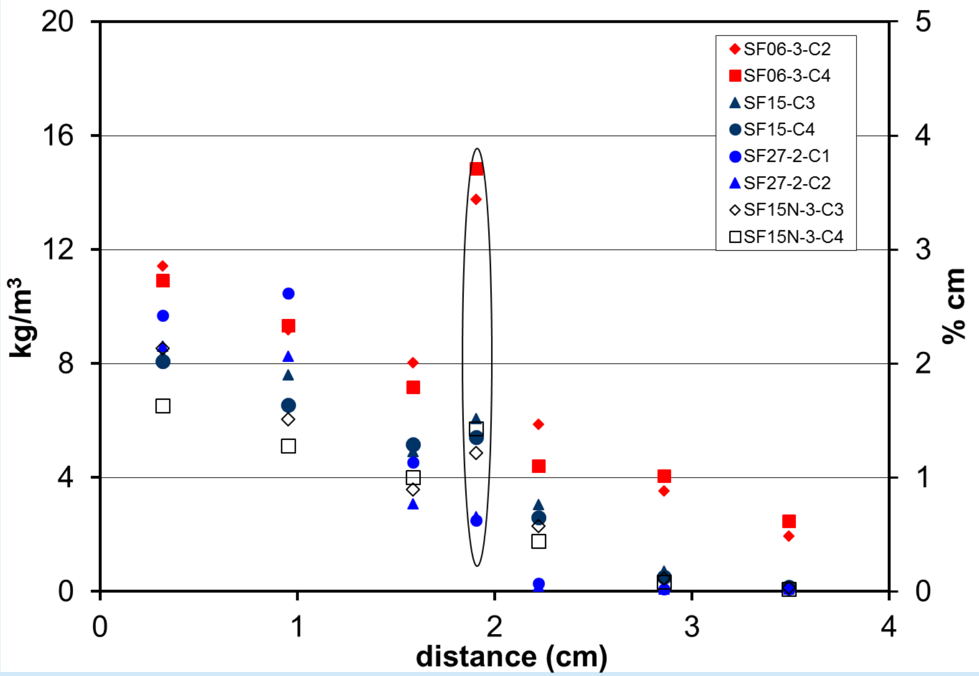




Chloride Profiles and Concentration at the Rebar Surface







Profiles from cores obtained after 5700 days of exposure

Circled values are the chloride concentrations at the rebar trace

Cl^- Concentration measured at the Rebar Trace (kg/m^3)

Specimen	Left		Center		Right	
AO1	NA	Y	NA	NA	NA	Y
AO2	8.0	Y	7.9	Y	10.0	Y
AO3	6.9	Y	7.9	Y	6.7	Y
AO8	5.8	Y	7.4	N	8.9	Y
CO1	6.8	N	4.8	Y	5.4	N
C03	6.4	Y	8.4	Y	8.4	Y
SF06-1	7.2	Y	8.1	N	6.4	N
SF06-3	14.8	Y	14.9	Y	11.6	Y
SF15-1	8.2	Y	7.9	Y	6.8	Y
SF15-2	6.1	Y	5.0	Y	5.2	Y
SF27-2	2.6	N	2.4	Y	2.5	N
SF15N-3	4.1	N	5.7	N	NA	N

Specimen	Left		Center		Right	
FA20-1	4.3	N	3.4	N	4.7	N
FA20-3	6.4	Y	2.9	Y	3.3	Y
FA35-1	0.3	N	0.3	N	0.2	N
FA35-6	C	NA	C	NA	5.5	Y
FA50-1	1.2	Y	NA	Y	1.4	Y
FA50-2	0.4	N	0.4	N	0.3	N
FA50-4	3.1	Y	C	NA	C	NA
FA50-5	2.2	Y	1.6	Y	1.9	Y
FA50-7	3.5	Y	1.3	Y	3.3	Y
FA35N-1	8.9	Y	7.6	Y	6.9	Y
FA35N-2	9.0	Y	8.9	Y	9.4	Y
FA35N-3	9.9	Y	C	NA	C	NA

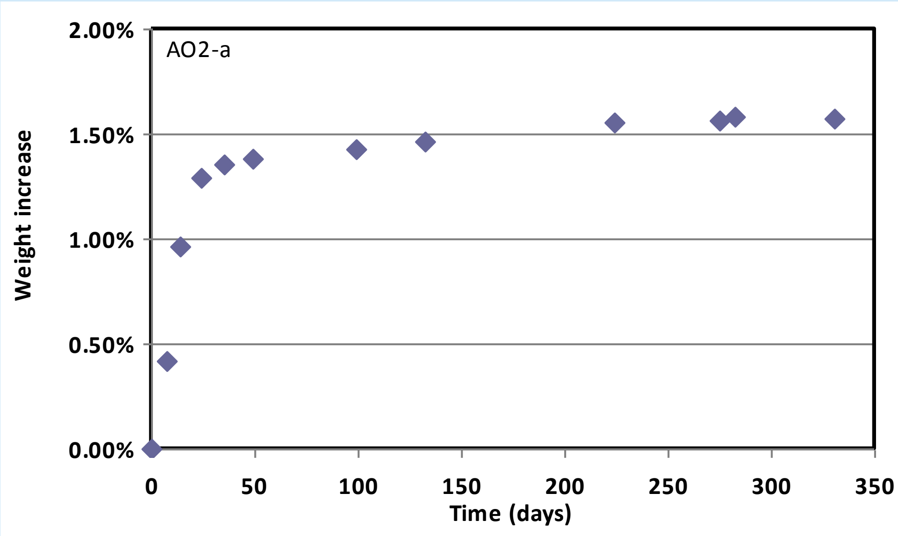
Y- Corroding, N – No Corroding, C – Continue, NA – Not avaliable

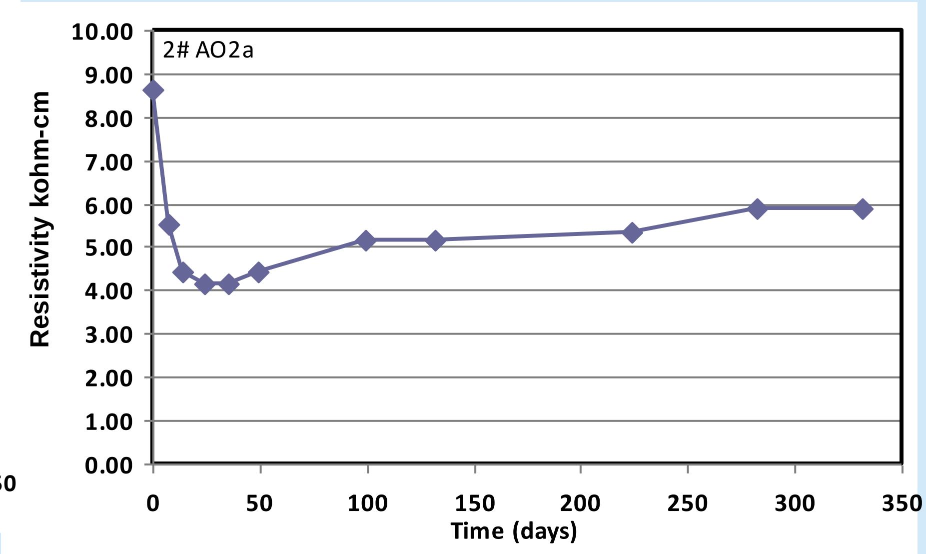
Minimum and average [Cl^-] (kg/m^3) and %cm at the rebar trace on corroding rebars

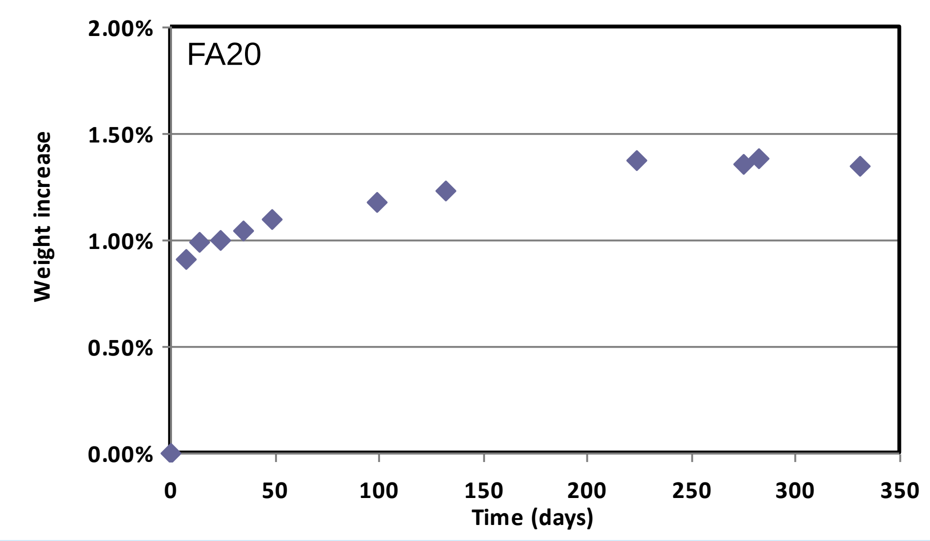
Mix ID	Minimum	Average
AO	**5.8 [1.45%]**	**7.7 [1.92%]**
FA20	**2.9 [0.75%]**	**4.2 [1.05%]**
FA35	**5.5 [1.37%]**	**5.5 [1.37%]**
FA50	**1.4 [0.29%]**	**2.2 [0.54%]**
FA35N	**6.9 [1.74%]**	**8.7 [2.2%]**

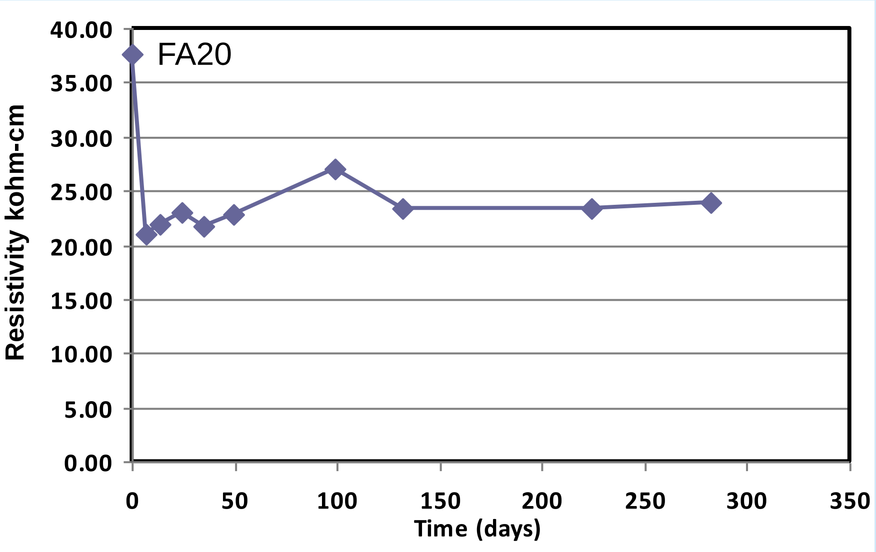
Mix ID	Minimum	Average
CO	**6.4 [1.62%]**	**7.7 [1.95%]**
SF06	**7.2 [1.81%]**	**12.1 [3.04%]**
SF15	**5.0 [1.53%]**	**6.5 [1.63%]**
SF27	**2.4 [0.60%]**	**2.4 [0.60%]**
SF15N	**>5.7 [>1.46%]**	**>5.7 [>1.46%]**

Examples of wt % change vs. time and Resistivity vs. time

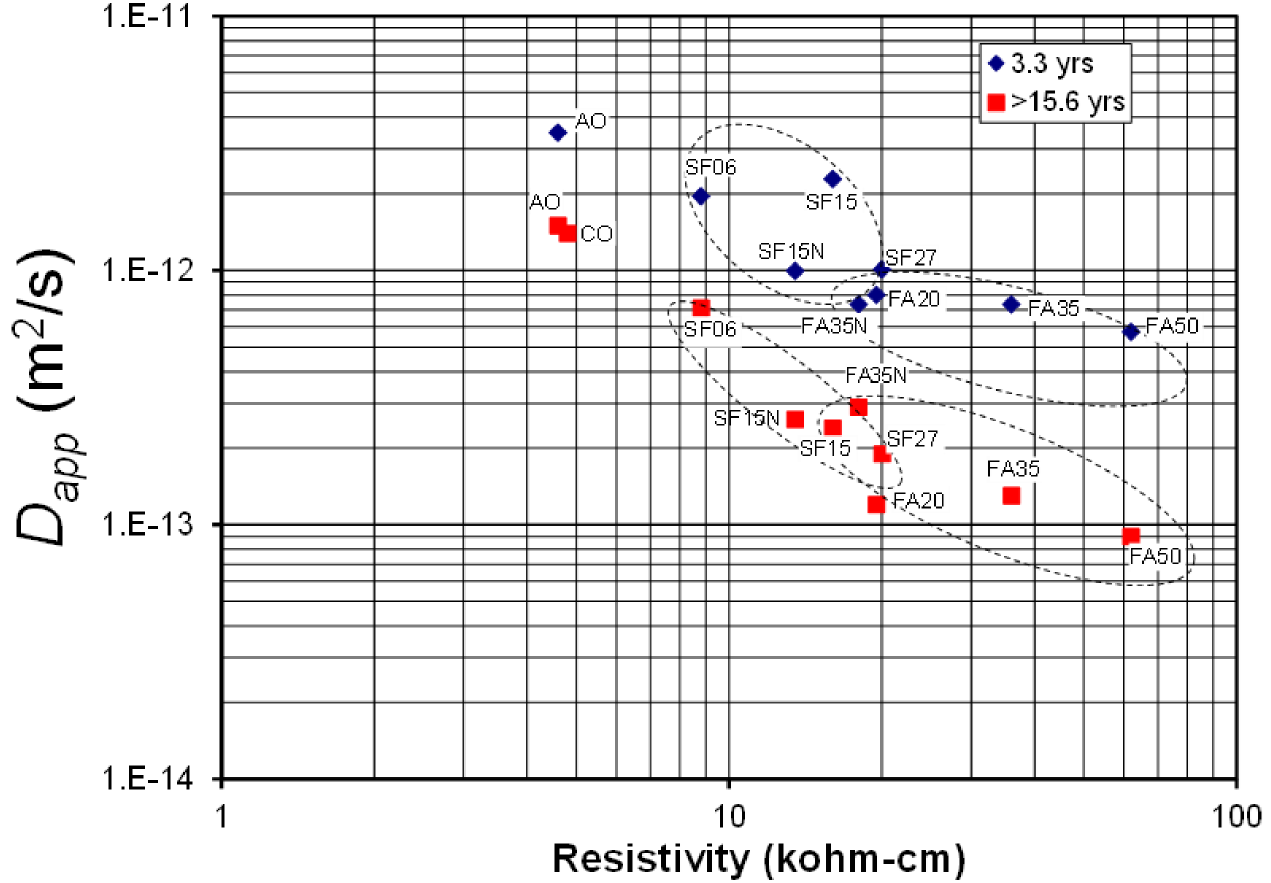








ρ vs. D_{app}



Specimen	Laboratory pH	Admixture pH reduction	N_2 glove box pH	Admixture pH reduction
AO	13.7		13.84	
FA20	13.46	0.24	13.57	0.27
FA35	13.27	0.43	13.39	0.45
FA50	12.57	1.13	13.18	0.66
FA35N	13.27	0.43	13.36	0.48
SF06	13.3	0.4	13.7	0.14
SF15	13.51	0.19	13.51	0.33
SF25	13.27	0.43	13.47	0.37
SF15N	13.42	0.28	13.59	0.25

Effect of C_T, D_{app}, C_S on time to corrosion initiation for more traditional covers and rebar diameter

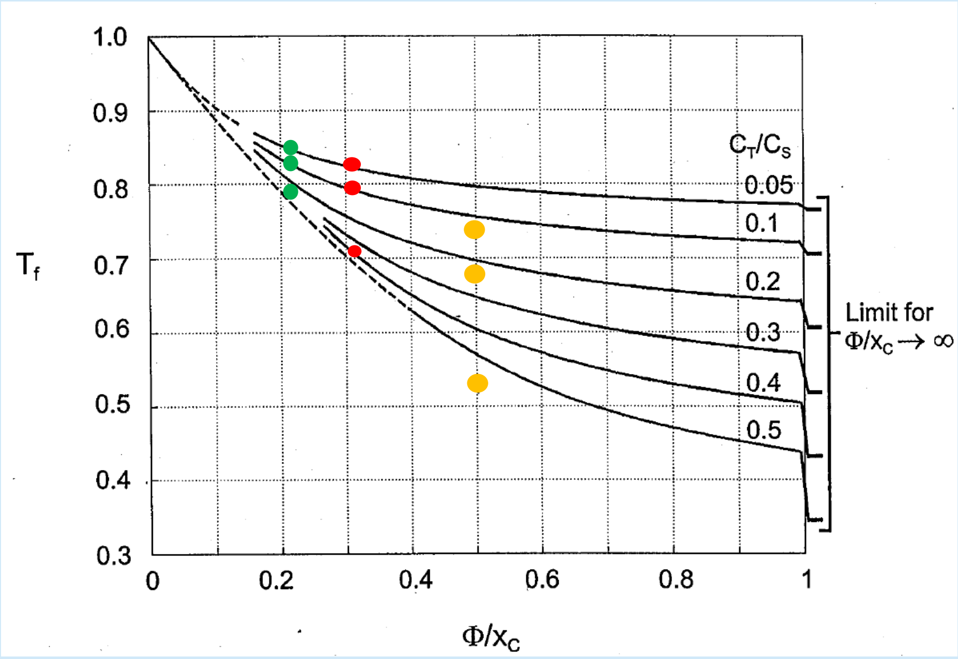
The time to corrosion initiation was calculated for a structure having rebars of 1.6 cm (#5) diameter with a concrete covers of 5 cm (2 inches) or 7.5 cm (3 inches) using the calculated D_{app} and C_s values, and including rebar presence effect.

Assumed parameter based on measured and fitted values

	C_T Kg/m^3	$D_{app} \times 10^{-12}$ m^2/s	Cs Kg/m^3	C_T/C_S
AO	6.2	1.5	15.6	0.40
FA20	3.2	0.13	30	0.11
FA50	1.6	0.09	30	0.05

Derating factors for the geometry and C_T/C_S

Cover	Diameter/cover	OPC	FA20	FA50
5 cm	● 0.32	0.71	0.79	0.82
7.5 cm	● 0.21	0.79	0.82	0.84



Φ=Rebar diameter
Xc=concrete cover

Effect of C_T, D_{app}, C_S on time to corrosion initiation for more traditional covers and rebar diameter

Time to corrosion initiation in years including rebar presence effect

Cover	OPC	FA20	FA50
5 cm	25.9	90.9	90.2
7.5 cm	64.8	211.6	201.6

Time to corrosion initiation in years including rebar presence effect
Model and Experiment

C_T kg/m^3	C_S 1st layer kg/m^3	C_T/C_S	D_{app} m^2/s ×10^{-12}	Derating Factor	Ti (years) Model	Ti (years) Experiment
7.4	12	0.58	1.50	0.53	11	15
3.4	15	0.25	0.13	0.67	21	17
1.6	11	0.15	0.09	0.73	20	17

Left column C_T values in kg/m^3 and %cm

7.4 [1.85%cm], 3.4 [0.85 %cm], and 1.6 [0.4 %cm]

Conclusions

- The *Dapp* of concrete mixture prepared with FA ↓ ~ one order of magnitude (at least 5X) from 3.3 yr to 16 yr. A more modest reduction in *Dapp* was observed on samples with SF.
- The $[Cl\text{-}]_{tmin}$ suggest C_T on FA50 ↓ than other FA groups. Corrosion initiated on more rebars from specimens with 50% FA, than OPC specimens due in part to the lower chloride threshold.
- D_{app} SF mixes are somewhat larger than D_{app} FA mixes
- A good correlation was observed between ρ and D_{app}.
- A reduction in C_T as FA % ↑ needs to be included for service life computations, in addition to the lower *Dapp* that is associated with FA presence. Rebar presence effect if cover is small.

Thank you for you attention, Questions?

Acknowledgments

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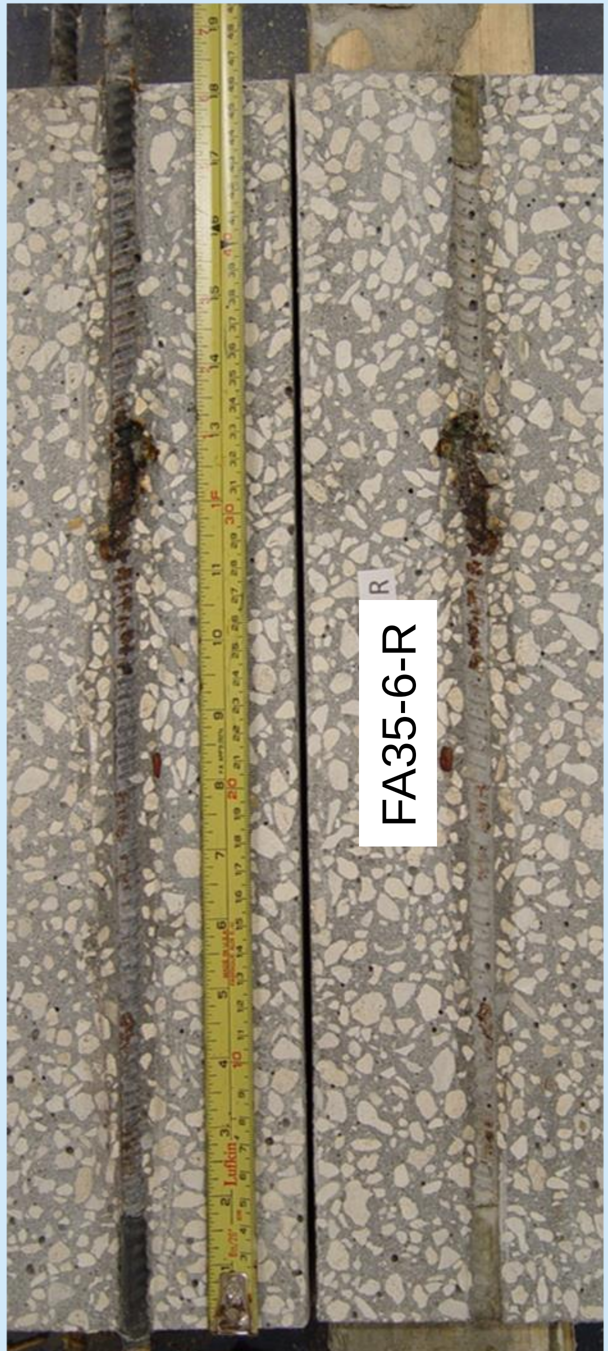
FA20-3-R


FA35-6-R

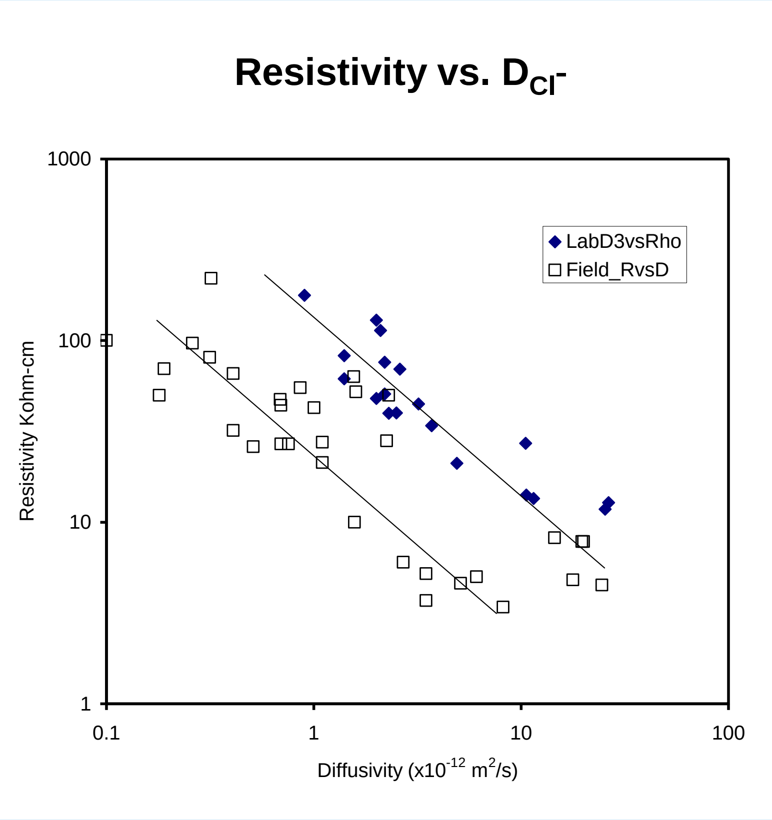

FA50-6-L

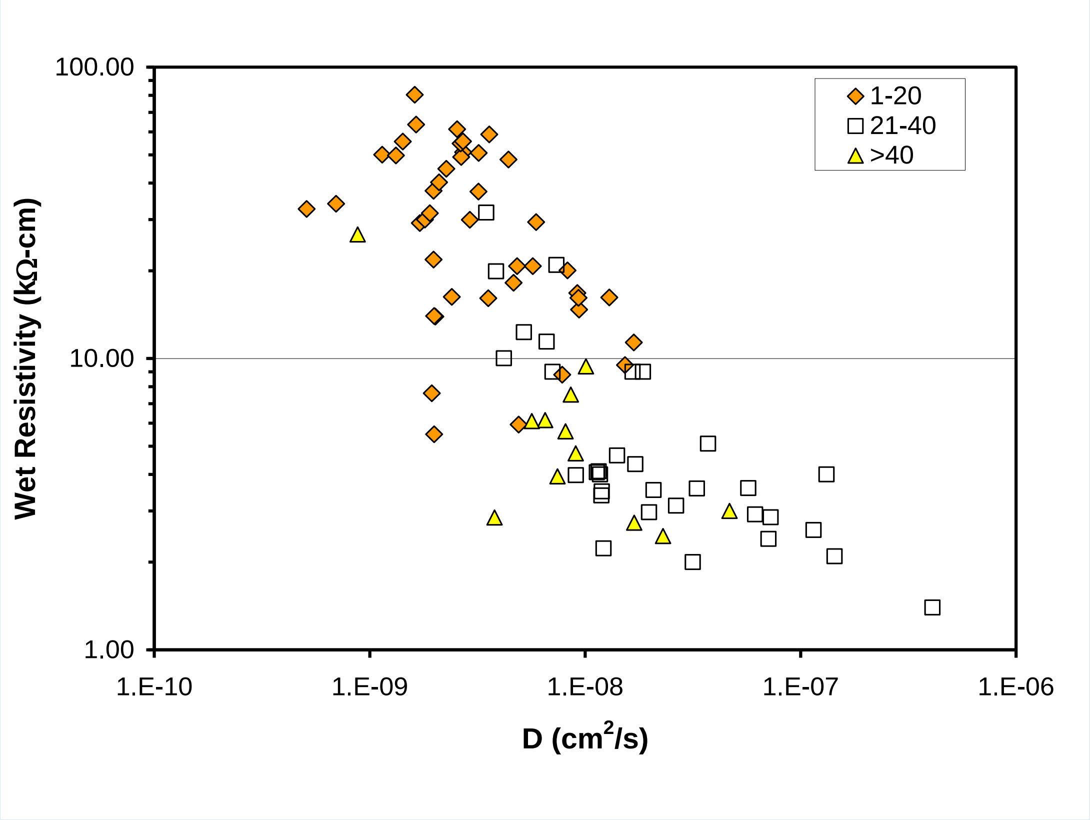

FA35N-1-L


SF06-3-L


SF15-1-R

Resistivity vs. D_{app}





Sagues (2001), Presuel(2010), Paredes(2007)