FHWA/Florida DOT Research on Alternative CRRB's

Corrosion Resistant Alloys for Steel Reinforcement in Concrete

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- **Corrosion Resistant Alloys for Reinforced Concrete** – Six year laboratory and test yard program sponsored jointly by FHWA and FDOT.

  Reports:

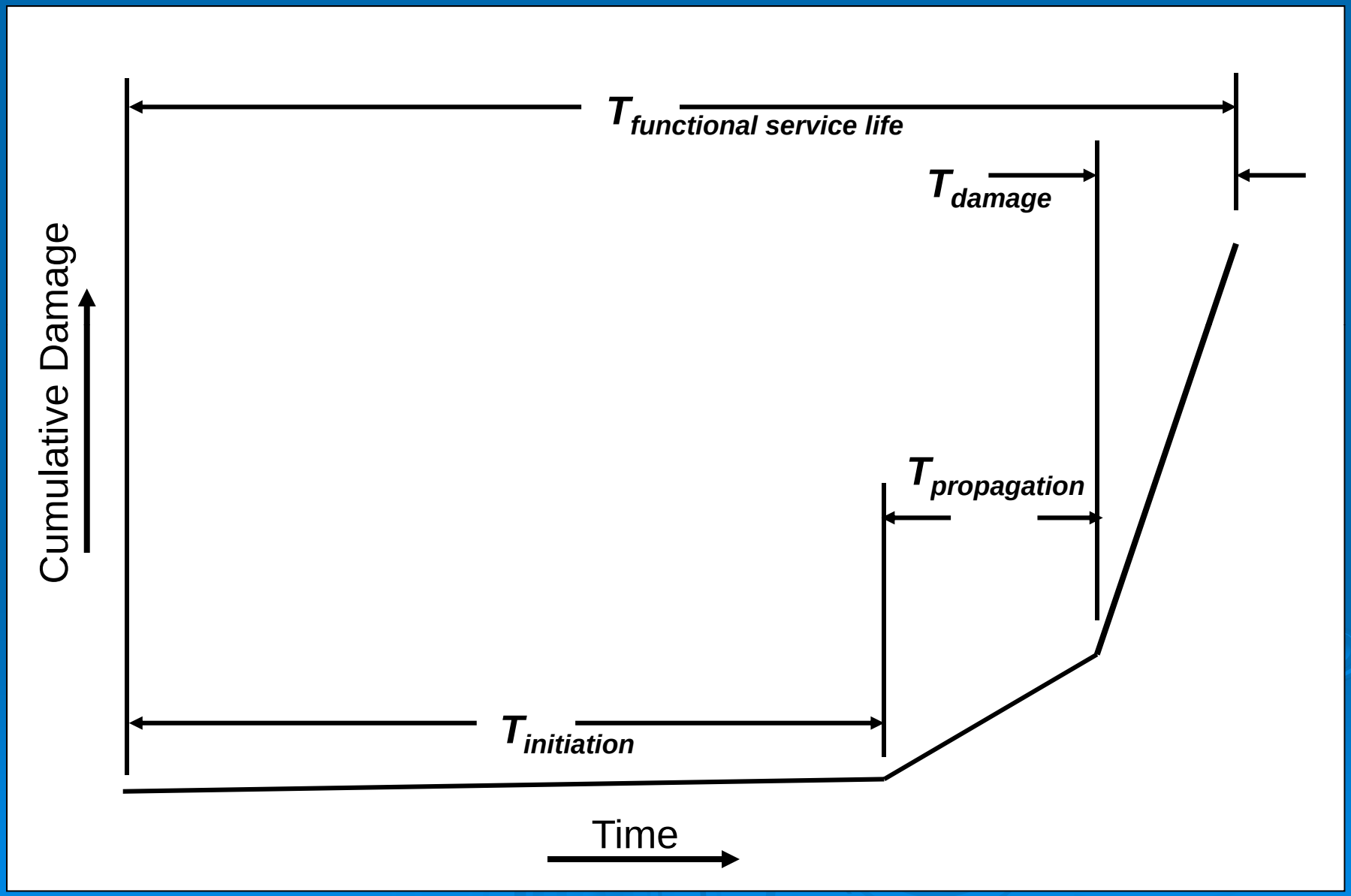
  1. **Critical Review of CRR Literature, FHWA–HRT-04-093.**
  2. **Interim Report, *Corrosion Resistant Alloys for Reinforced Concrete*, FHWA-HRT-07-039.**
  3. **Final CRR Project Report, FHWA-HRT-09-020.**
  4. **Monitor continues - Task under FDOT project 977-02**

- **Job Site Evaluation of Corrosion-Resistant Alloys for Use as Reinforcement in Concrete** – Innovative Bridge Research and Construction (IBRC) program project involving study and documentation of corrosion resistant reinforced concrete bridge projects.

  Job Site Evaluation of Corrosion-Resistant Alloys for Use as Reinforcement in Concrete, FHWA-HRT-06-078

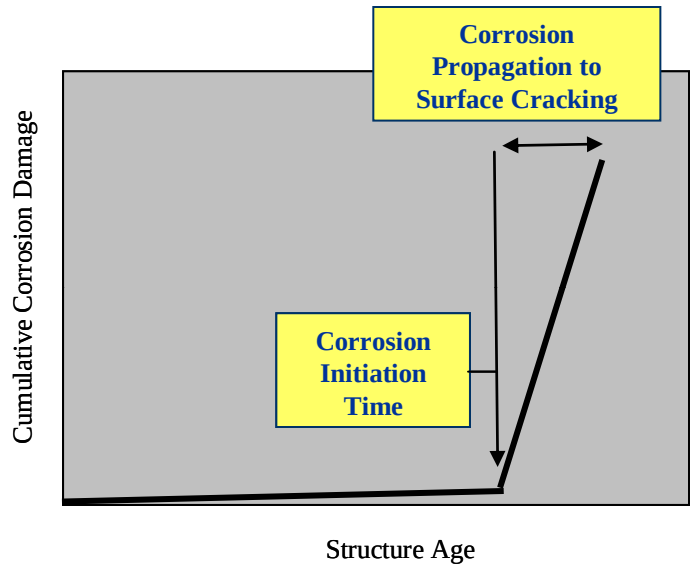
Project Overview

Service Life



Life-Cycle Modeling

Loss of passivity as a consequence of chloride ingress and achievement of a critical concentration, C_T, of this species at the steel depth is generally recognized as the major cause of deterioration for concrete structures.



Fick's second law is widely used to model Chloride diffusion under non steady-state conditions.

$$\frac{\partial^2 C}{\partial T^2} = \frac{\partial}{\partial x}\left[D\frac{\partial C}{\partial x}\right]$$

Projections of Time-to-Corrosion, T_i, are generally based on the solution to Fick's Second Law expressed as,

$$\frac{C_s - C_T}{C_s} = \mathrm{erf}\left[\frac{x}{2\sqrt{D_e \cdot T_i}}\right]$$

C_s = Surface $[Cl^-]$
x = Reinforcement cover
D_e = Effective diffusion coefficient

Accordingly, definition of this critical concentration is an important aspect of maintenance planning and life-cycle cost analysis.

Focus

- Relative corrosion resistance
- Critical Chloride Concentration (C_t)
- Surface condition
- Effects of coupling
- Correlation between short and long-term test

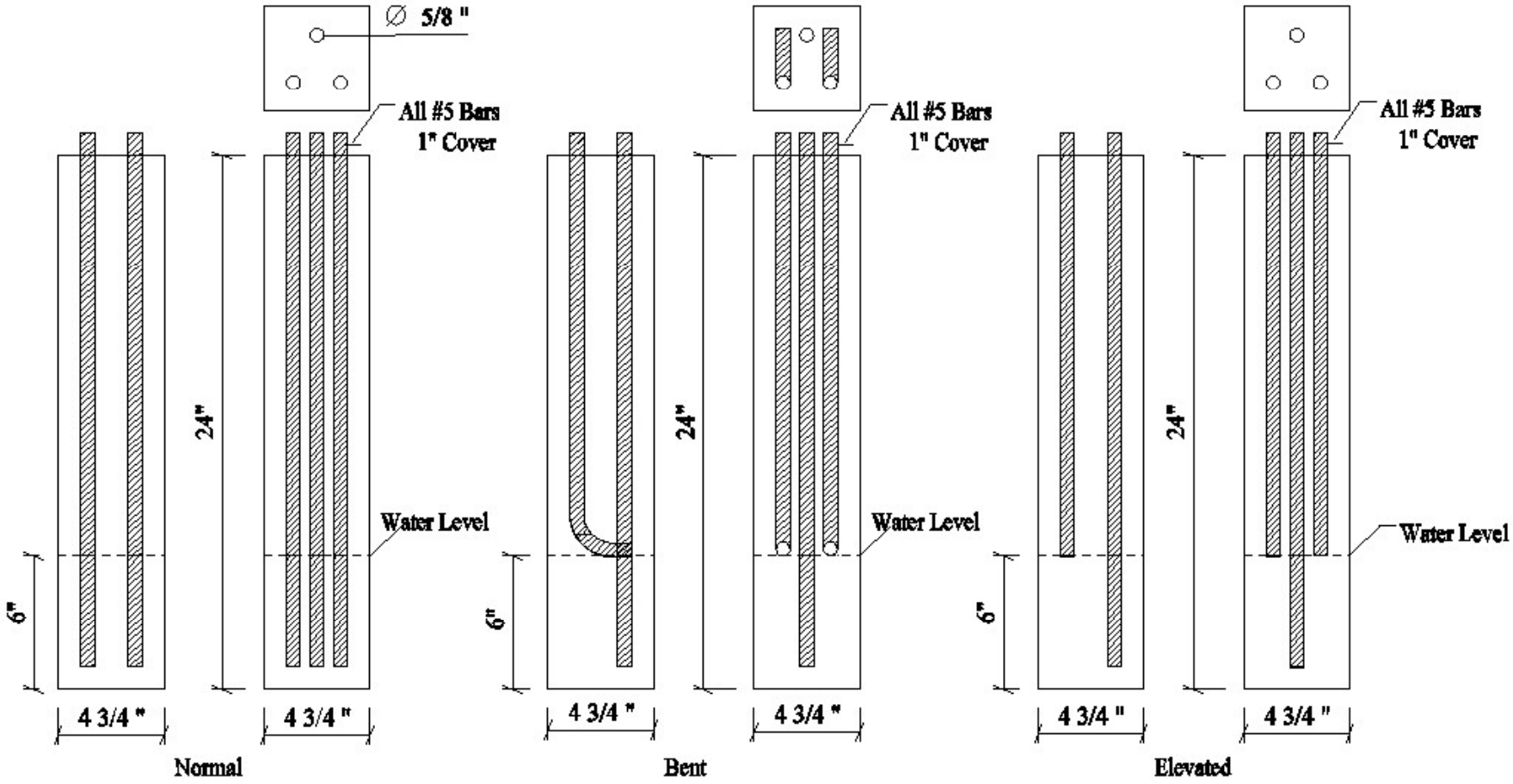
Reinforcing Steel Types

Common Designation	As-Rec'd. Condition	Microstructure
316	Blasted and Pickled	Austenitic
304	Blasted and Pickled	Austenitic
2205	As-Rolled	Duplex (Austenite plus Ferrite)
2201	As-Rolled	Lean Duplex (Austenite plus Ferrite)
A1035	As-Rolled	Micro-composite Austenite-Martensite
Nouvinox	Pickled	316 Clad/Carbon Steel Core
SMI	Pickled	316 Clad/Carbon Steel Core
3Cr12	Blasted and Pickled	Ferritic
Black Bar	As-Rolled	Ferrite/Pearlite

Chemical Composition

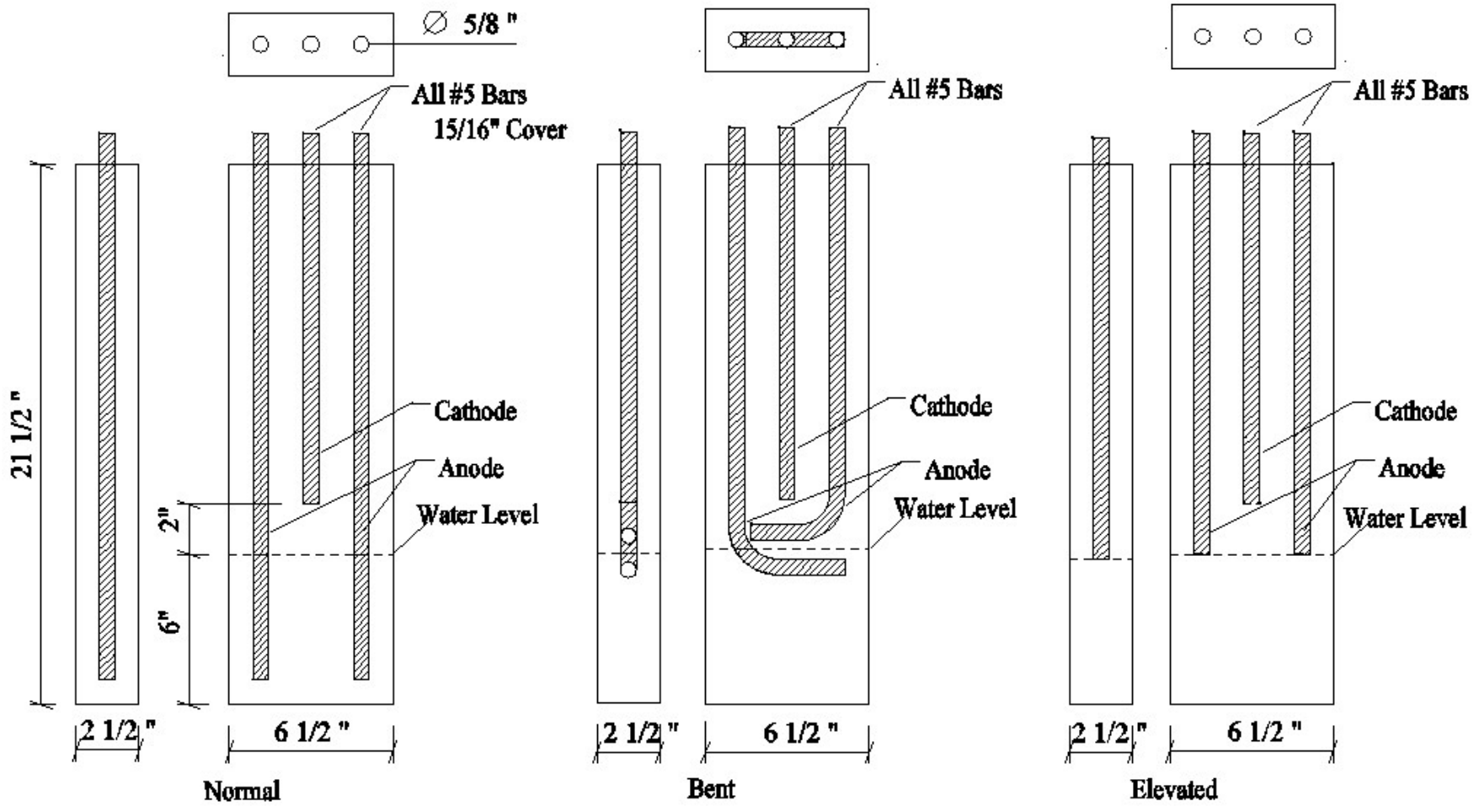
Alloy	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	N	Fe
316 (A)	0.03	1.55	0.025	0.001	0.59	18.43	10.06	2.08	0.42	0.068	Bal.
316 (B)	0.03	1.66	0.026	0.005	0.42	16.97	10.07	2.15	0.85	0.065	Bal.
304	0.07	0.94	0.020	0.001	0.58	18.25	8.12	0.40	0.30		Bal
2205	0.029	1.68	0.028	0.004	0.63	21.58	4.8	2.64	-	0.15	Bal.
2201	0.04	4.70	0.019	0.001	0.80	22.47	1.68	0.24	0.38	0.117	Bal.
A1035	0.05	0.45	0.012	0.015	0.23	9.30	0.10	0.03	0.12	-	Bal.
3Cr12	0.04	0.38	0.018	0.024	0.71	11.69	0.50	0.09	0.02	-	Bal.
Black Bar	0.3	1.22	0.013	0.032	0.26	0.21	0.19	0.04	-	-	Bal.
316-Clad	0.08	1.44	<0.001	<0.001	0.47	16.18	10.34	2.51	0.21	-	Bal.
SMI and Stelax	316 Clad										

3 Bar Square Specimen Geometries

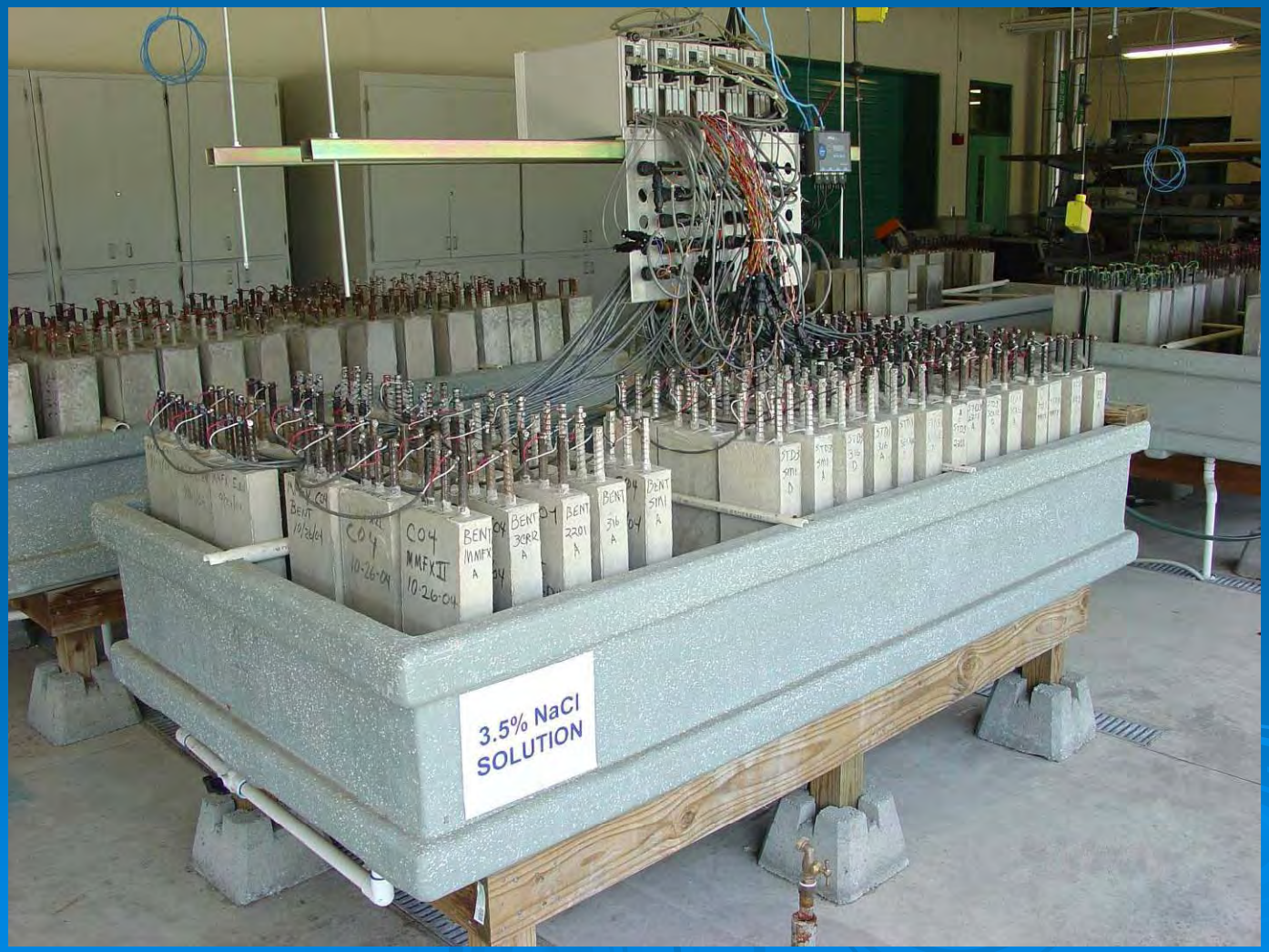


Laboratory Square 3-Bar Specimens

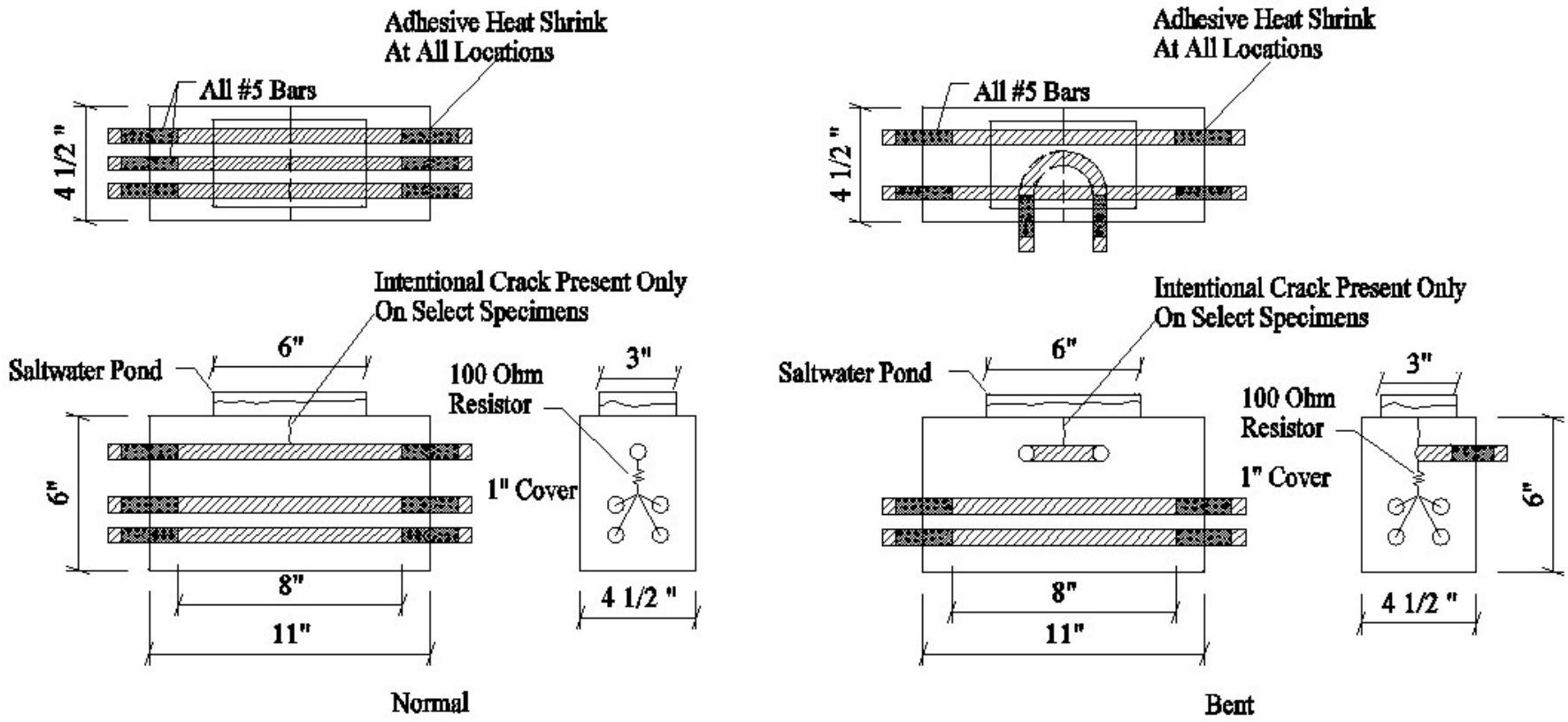
3 Bar Tombstone Specimen Geometries



Laboratory 3-Bar Tombstone Specimens

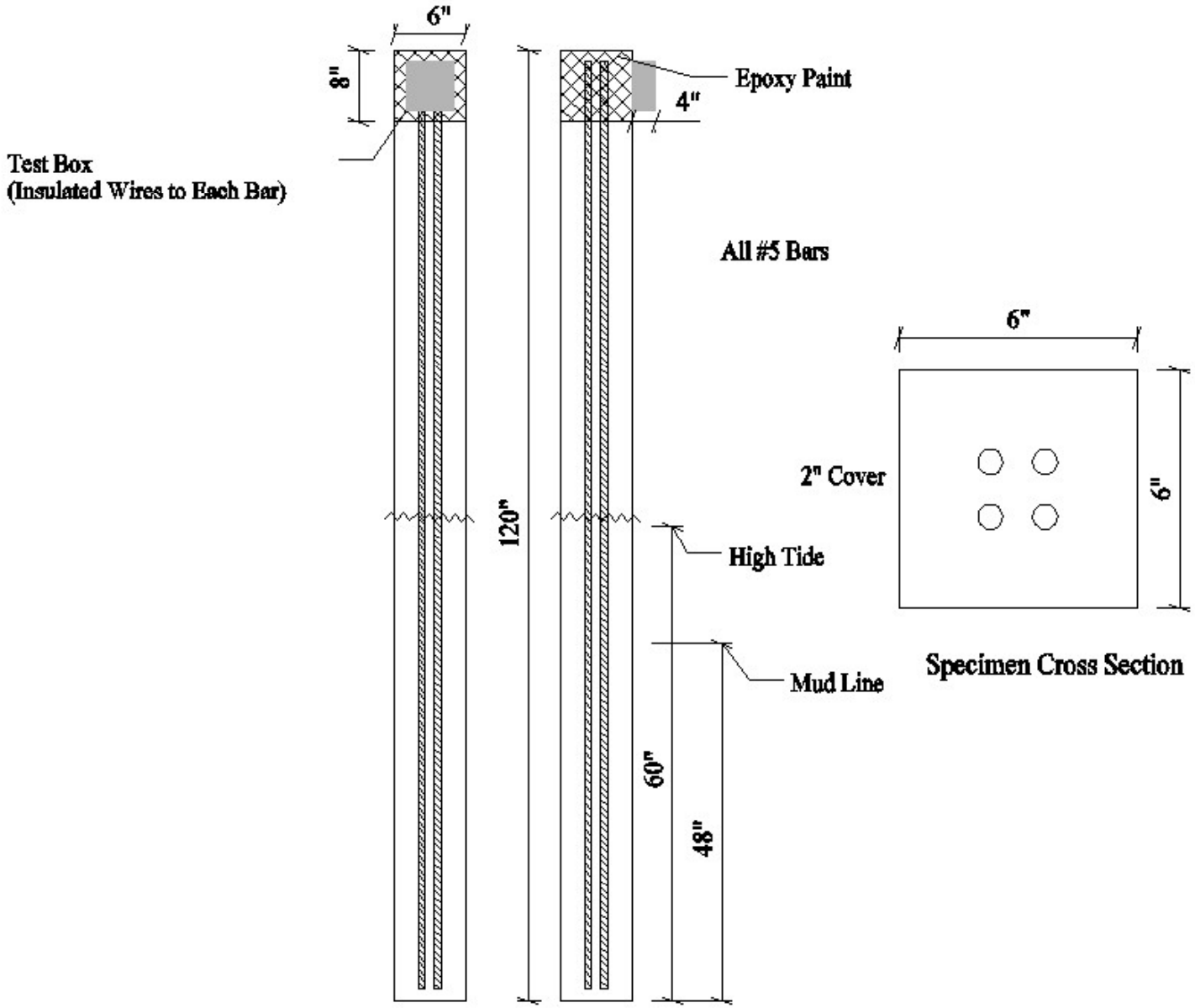


Macrocell Slab Specimen Geometries



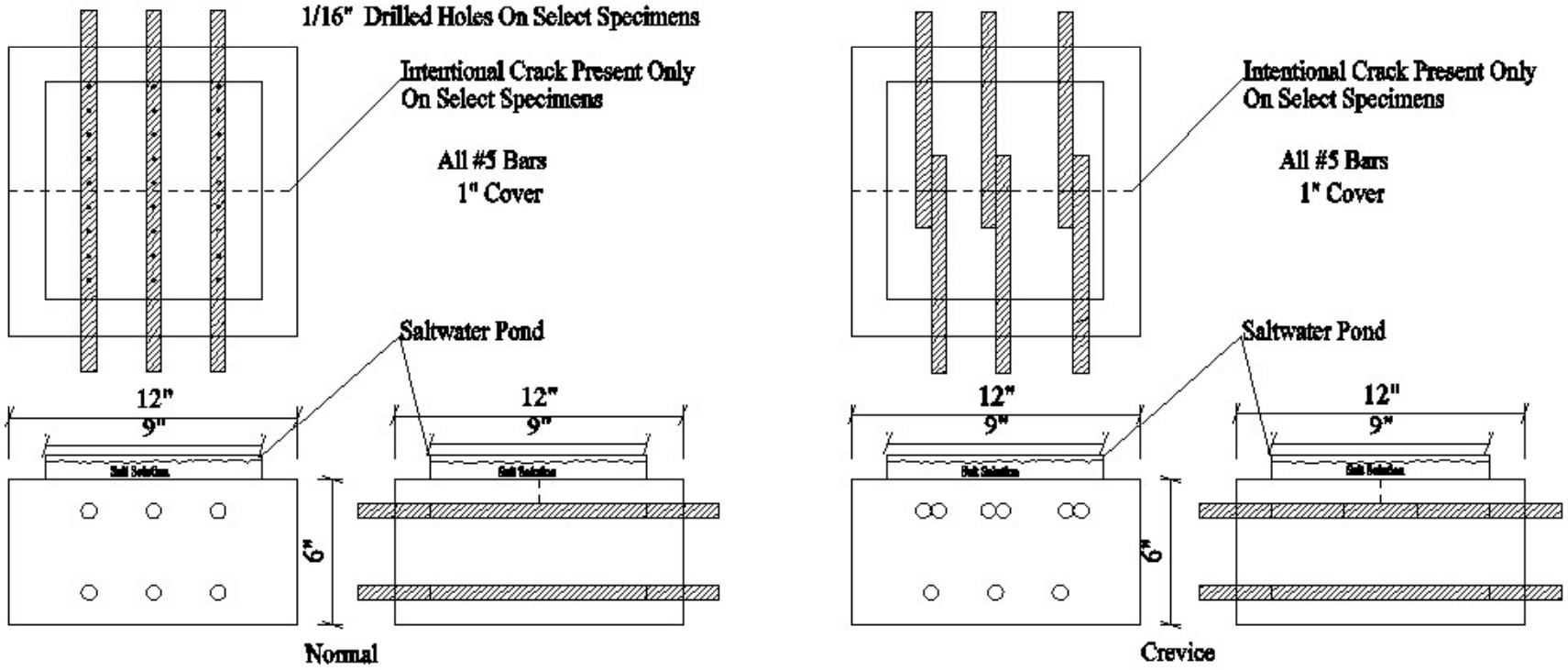
Macrocell Slab Specimens

Field Specimen Geometry



Field Specimens

Simulated Deck Slab without Heat Shrink



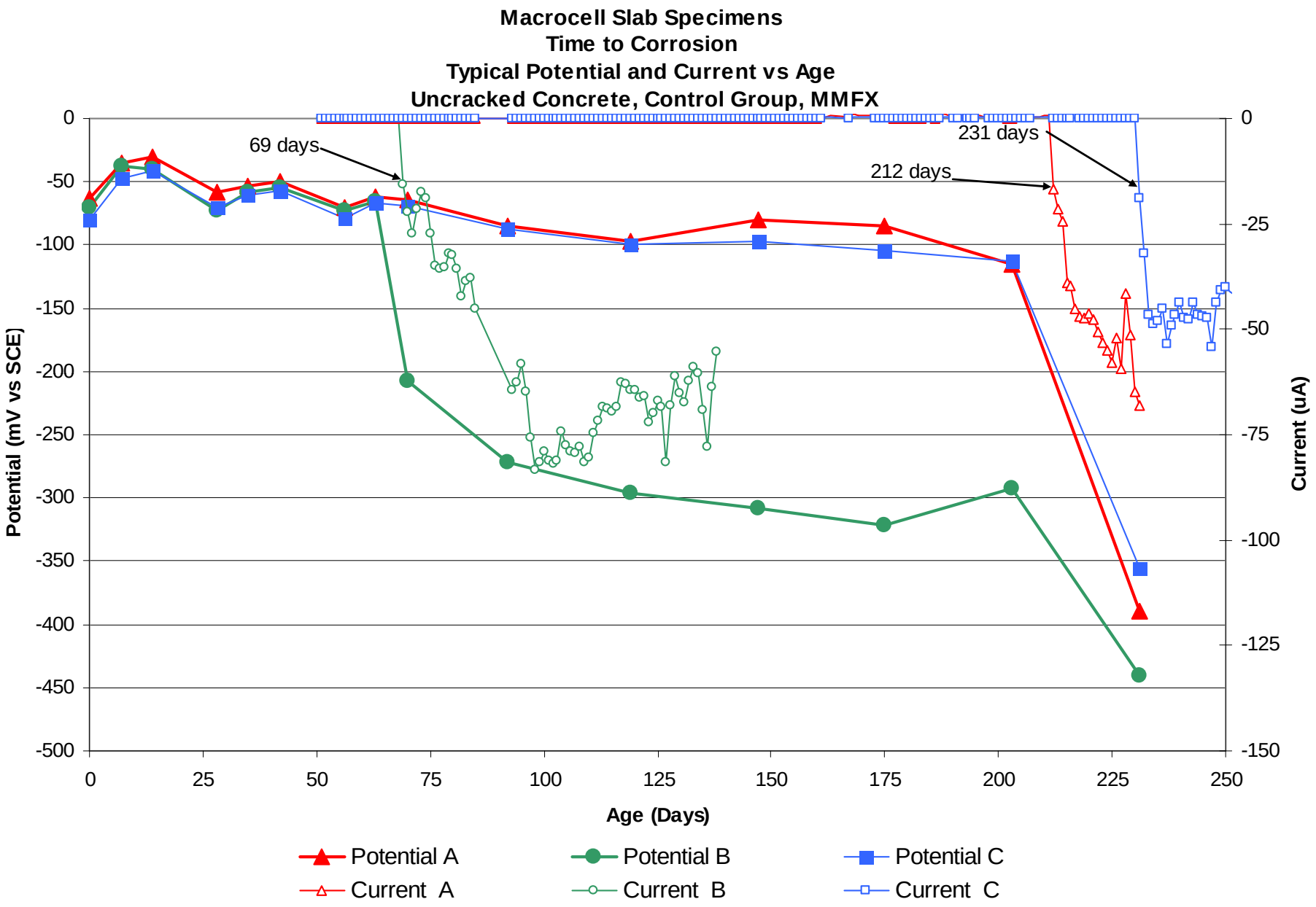
Simulated Deck Slab (SDS) Specimen Test Yard Exposures

Specimen Variables: w/c 0.50 and 0.41 concrete.
Simulated concrete crack.
Black bar lower mat.
Overlapping bars (crevice).
Combinations of variables.

One week wet – one week dry cyclic exposure with 15 wt% NaCl

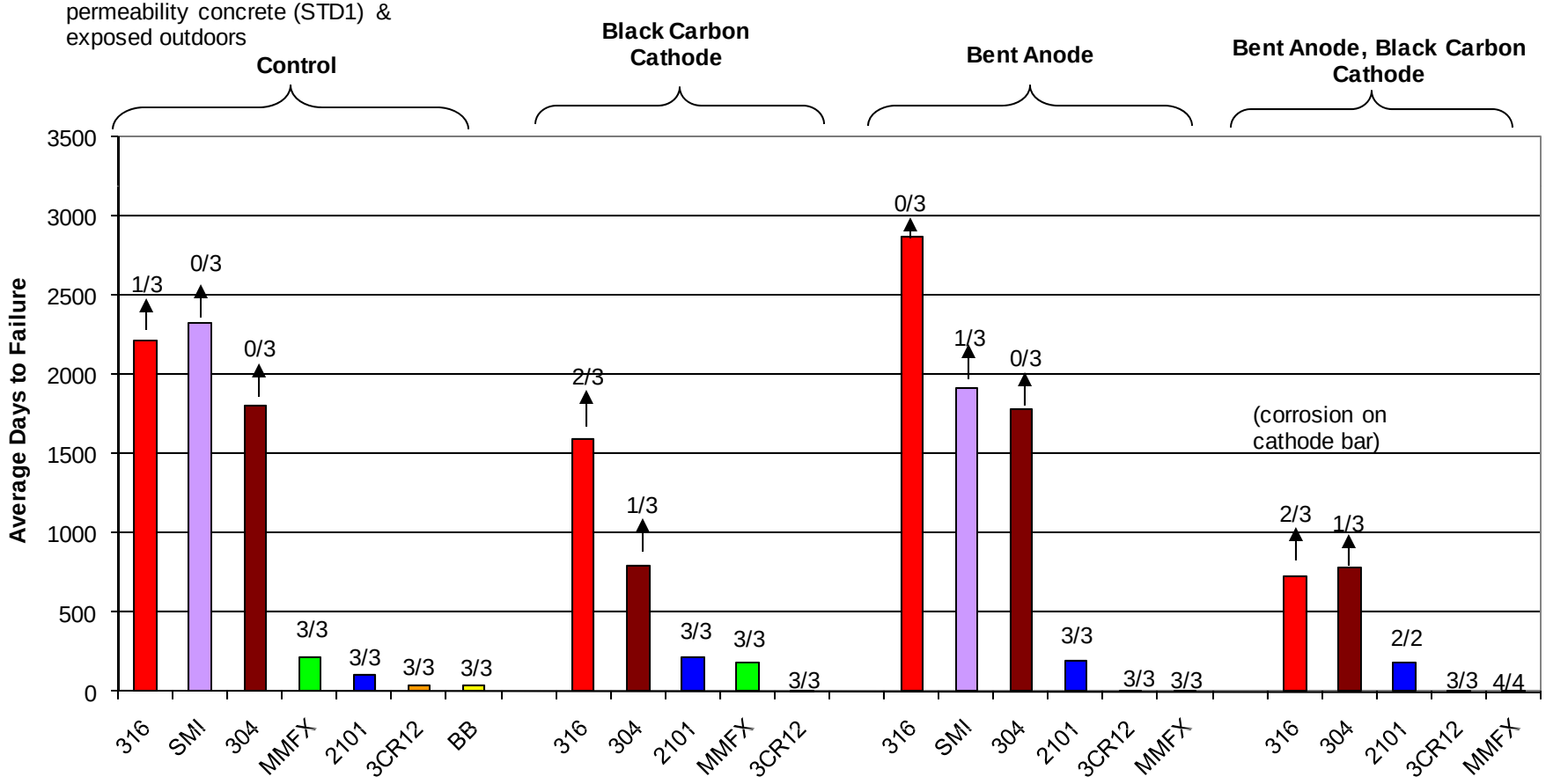
Concrete Mix Proportions

Concrete	Permeability	Cement Bags	Water/Cement Ratio
STD1	Very High	5	0.50
STD2	Moderate	7	0.41
STD3	High	7	0.50


Macrocell Slab Specimens
Time to Corrosion
Typical Potential and Current vs Age
Uncracked Concrete, Control Group, MMFX
69 days
212 days
231 days
Potential (mV vs SCE)
Current (uA)
Age (Days)
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500
-25
-75
-125
0
25
50
75
100
125
150
175
200
225
250
Potential A
Potential B
Potential C
Current A
Current B
Current C

Macrocell Slab Specimens Performance
Effects of Cracked Concrete
on Time to Corrosion

Notes:
- All bars wire brushed
- ↑ Indicates not all samples in the set have shown signs of corrosion
- 1/3, 1 indicates # of active specimens, 3 indicates total # of specimens
- All specimens cast using very high permeability concrete (STD1) & exposed outdoors

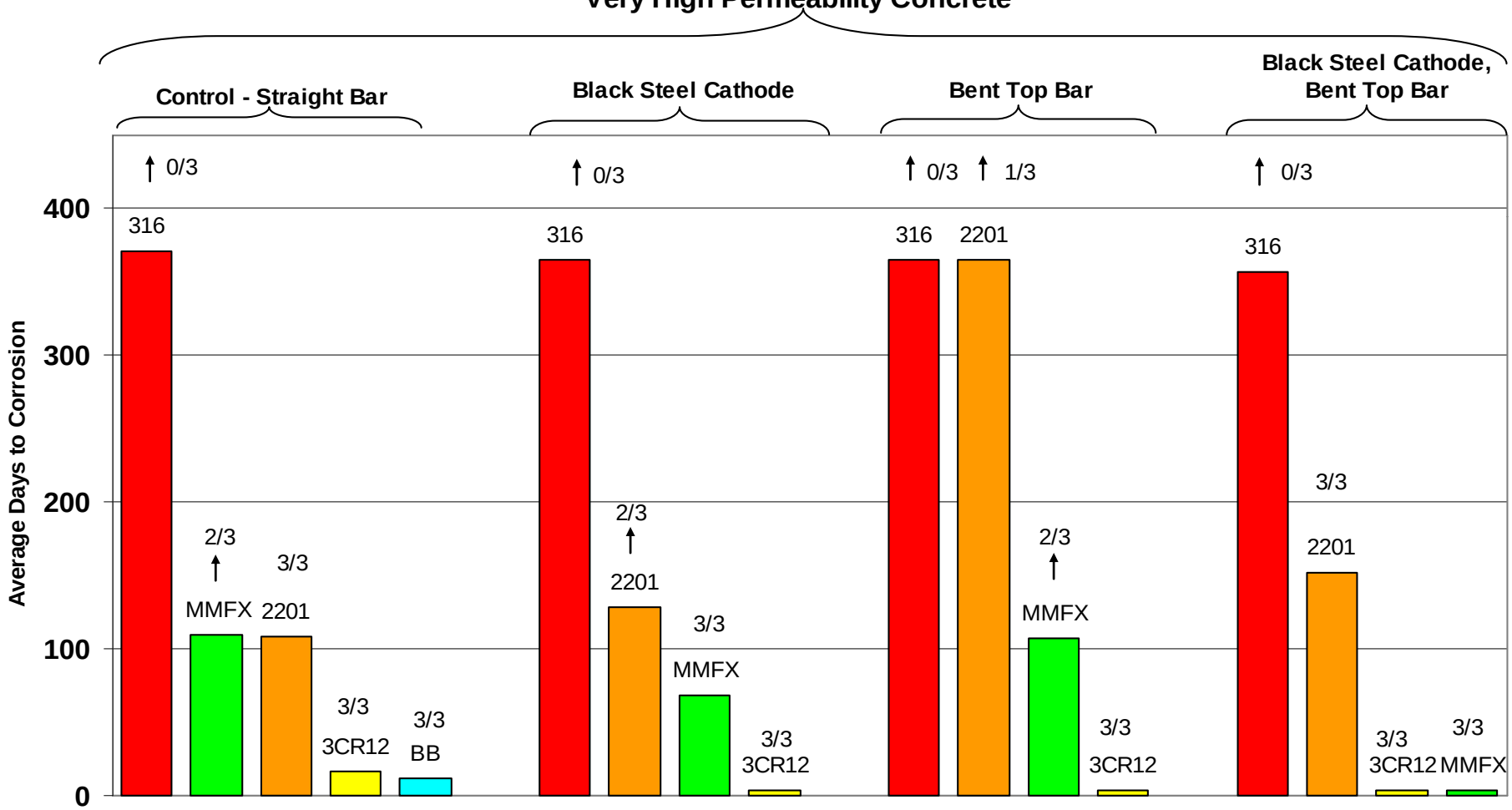


Macrocell Slab Specimens
Time to Corrosion, Cracked Concrete

Notes:
All bars wire brushed.
371 maximum days of total exposure.
Bars present the average performance of 2 specimens or more.
↑ Not all specimens in the set have shown signs of corrosion.

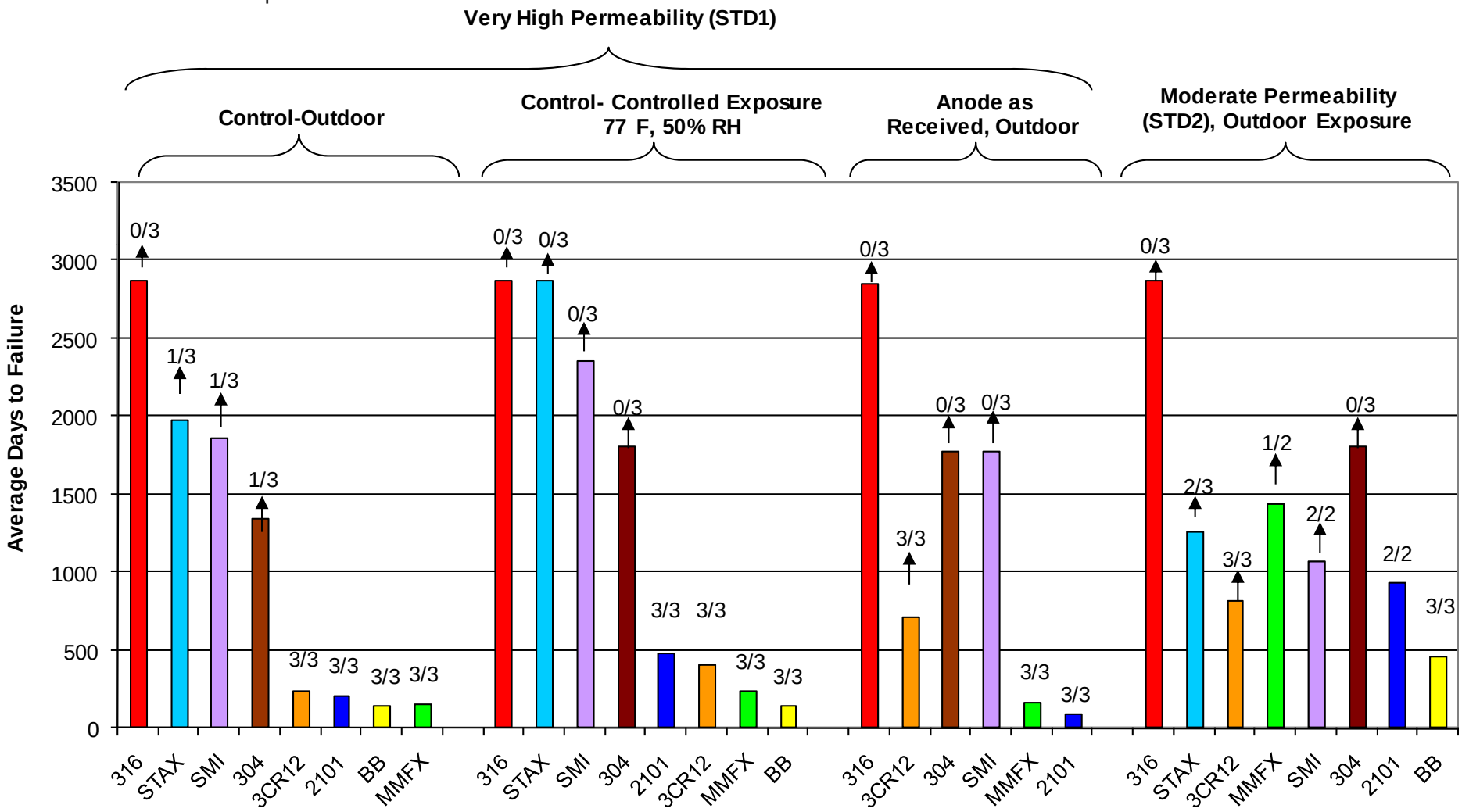
Number of Corroded Specimens → 2/3 ← Total Number of Specimens

Very High Permeability Concrete



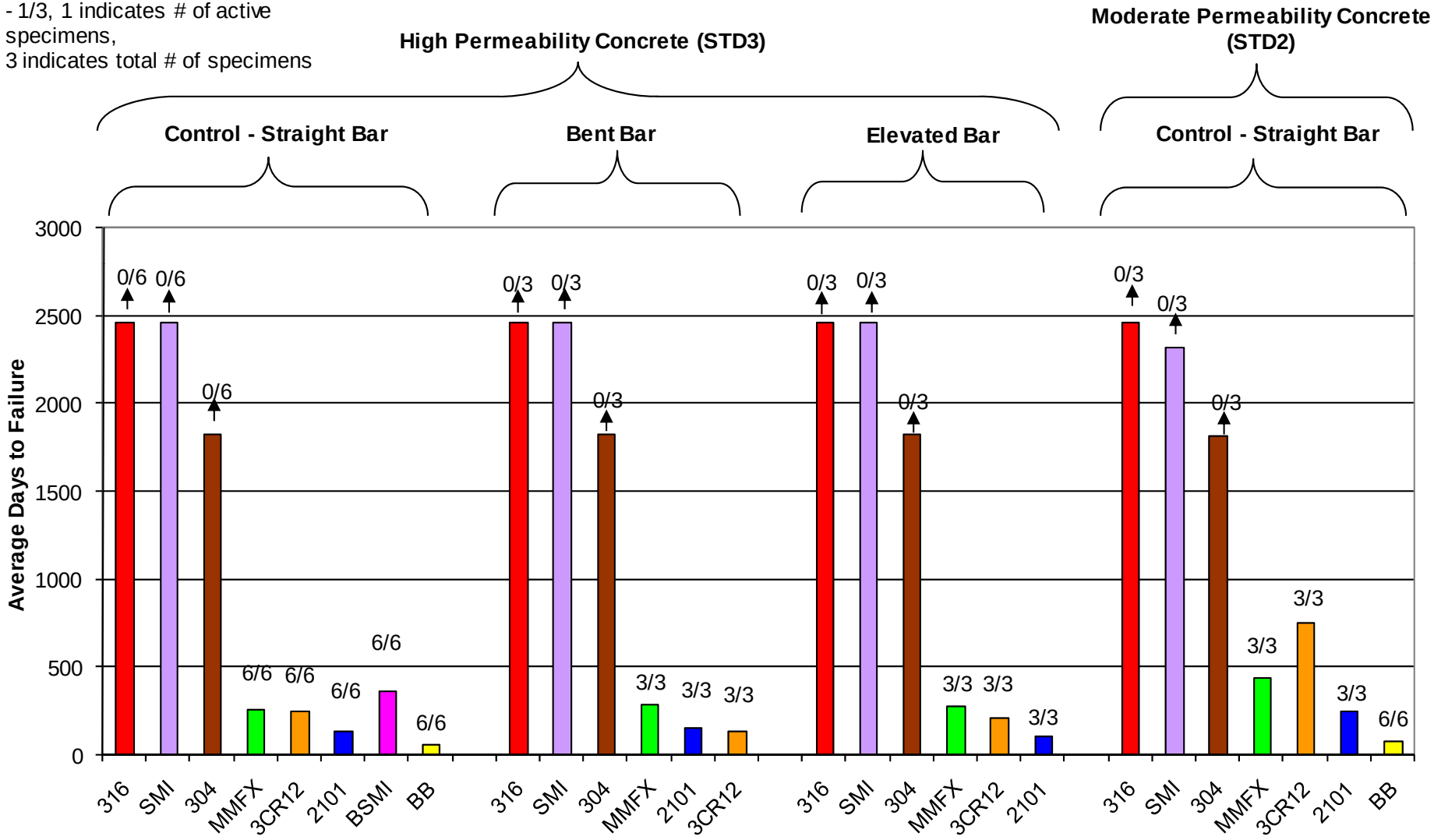
Notes:
- All bars wire brushed
- ↑ Indicates not all samples in the set have shown signs of corrosion
- 1/3, 1 indicates # of active specimens, 3 indicates total # of specimens

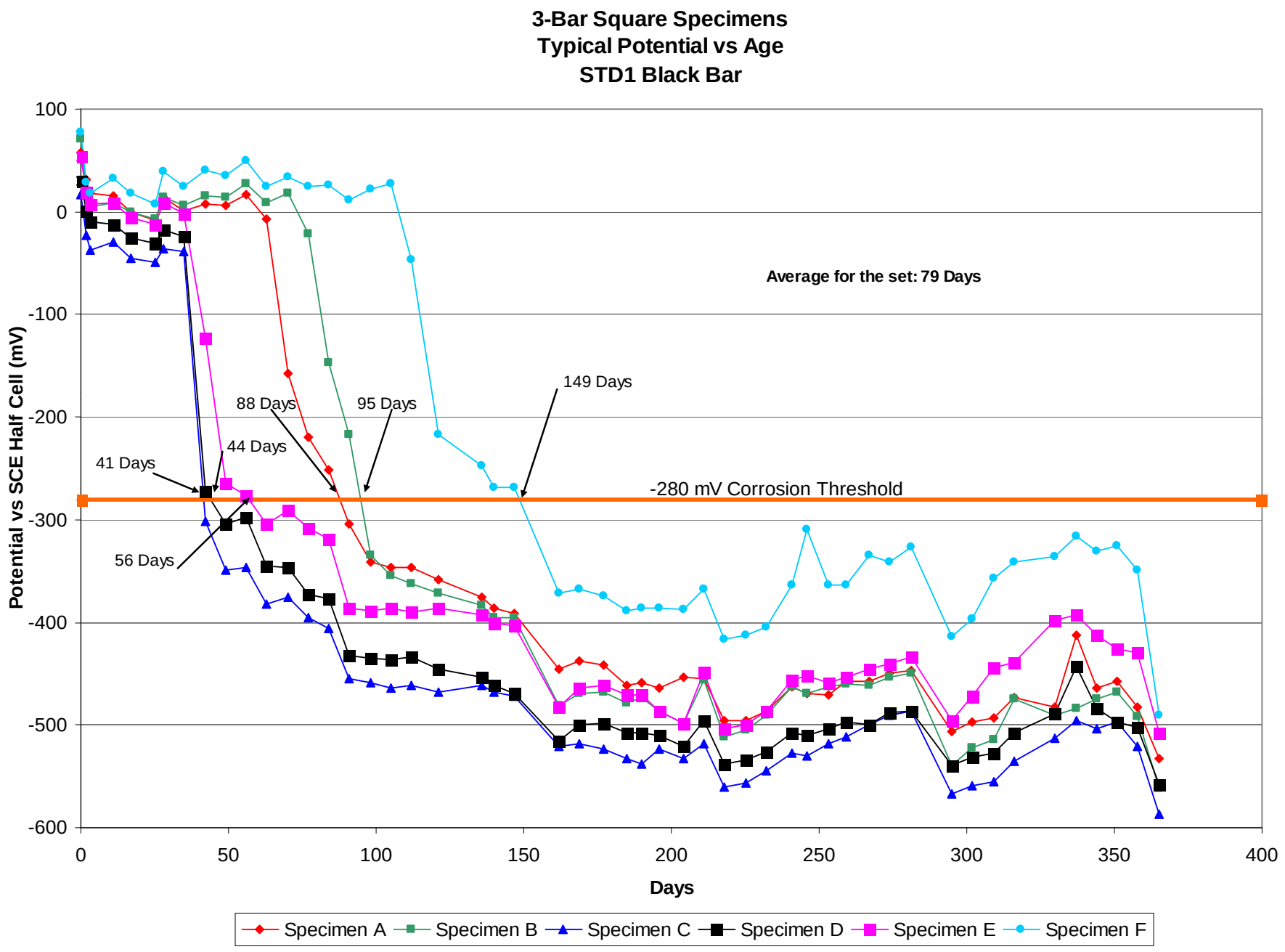
Macrocell Slab Specimens Performance
Effects of Environment, Concrete, & Preparation on Time to Corrosion



3-BAR TOMBSTONE PERFORMANCE

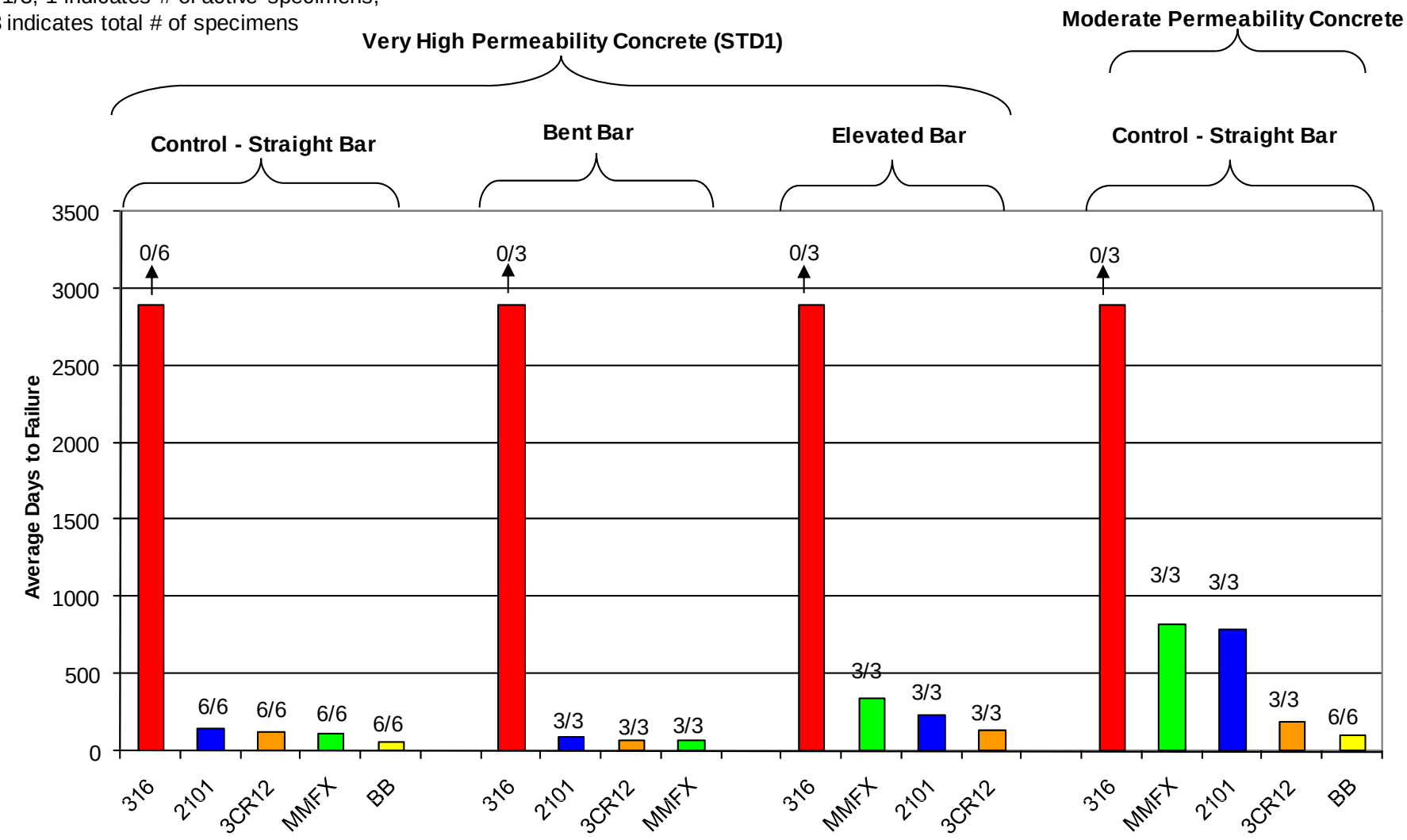
Notes:
- All bars as received.
- ↑ Indicates not all samples in the set have shown signs of corrosion
- 1/3, 1 indicates # of active specimens, 3 indicates total # of specimens




3-Bar Square Specimens
Typical Potential vs Age
STD1 Black Bar
Potential vs SCE Half Cell (mV)
100
0
-100
-200
-300
-400
-500
-600
0
50
100
150
200
250
300
350
400
Days
Average for the set: 79 Days
149 Days
88 Days
95 Days
44 Days
41 Days
56 Days
-280 mV Corrosion Threshold
Specimen A
Specimen B
Specimen C
Specimen D
Specimen E
Specimen F

3-BAR SQUARE SPECIMEN PERFORMANCE

Notes:
- All bars as received.
- ↑ Indicates not all samples in the set have shown signs of corrosion
- 1/3, 1 indicates # of active specimens, 3 indicates total # of specimens

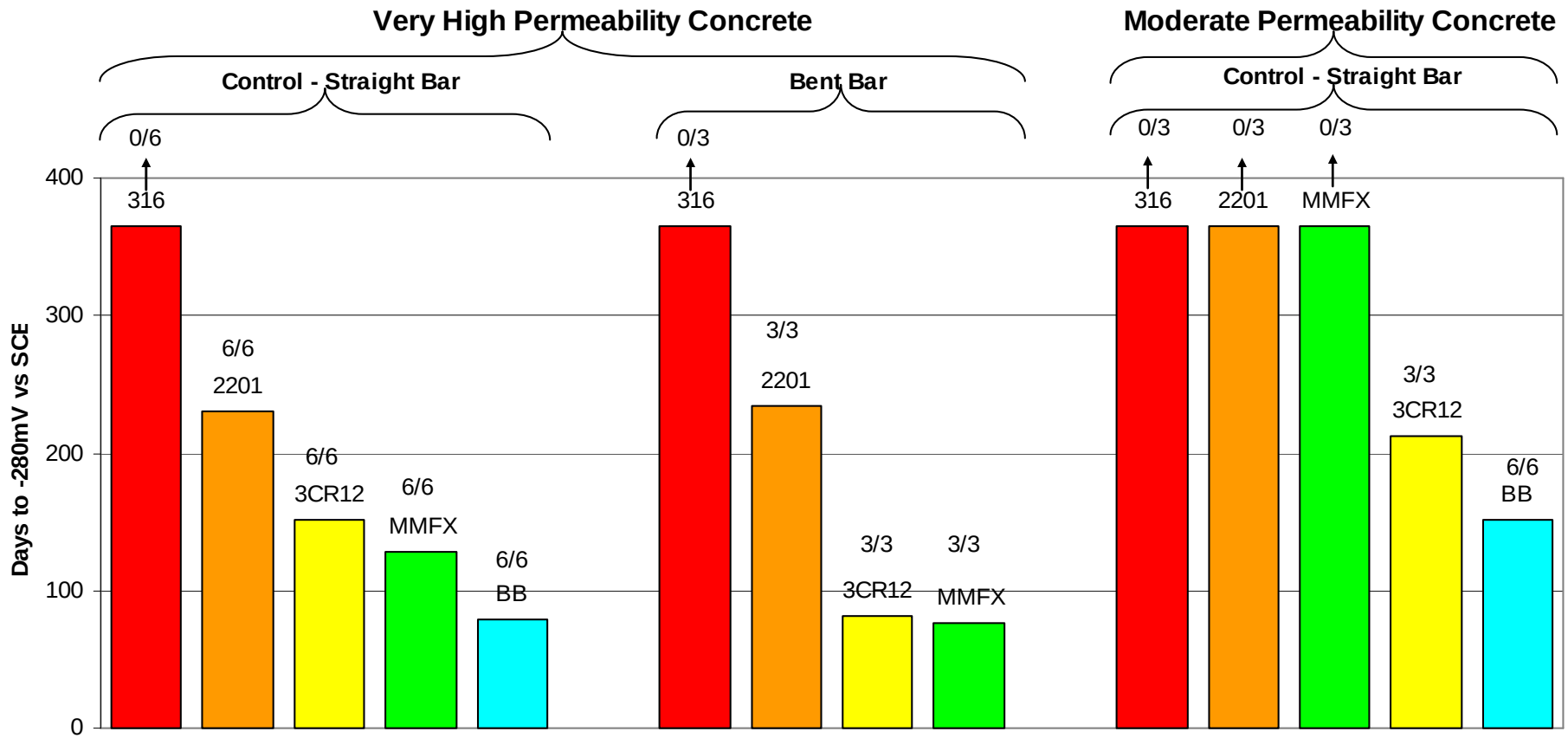


3 Bar Square Specimens

Notes:
All bars as received.
Graph presents time to half-cell potential crossing -280mV vs SCE.
↑ Not all specimens in the set have shown signs of corrosion.

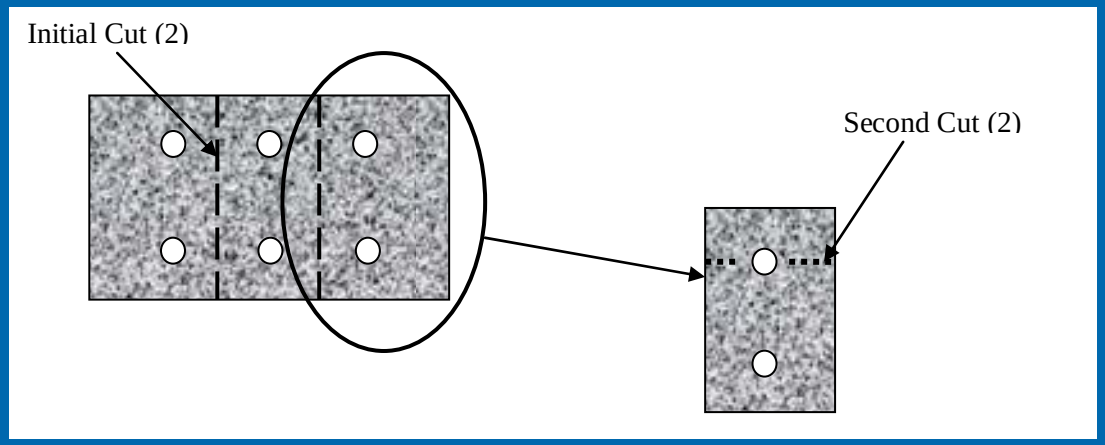
Alloys, as received surface condition
2201, mill scale
316, pickled
3CR12, pickled
BB, mill scale
MMFX, mill scale

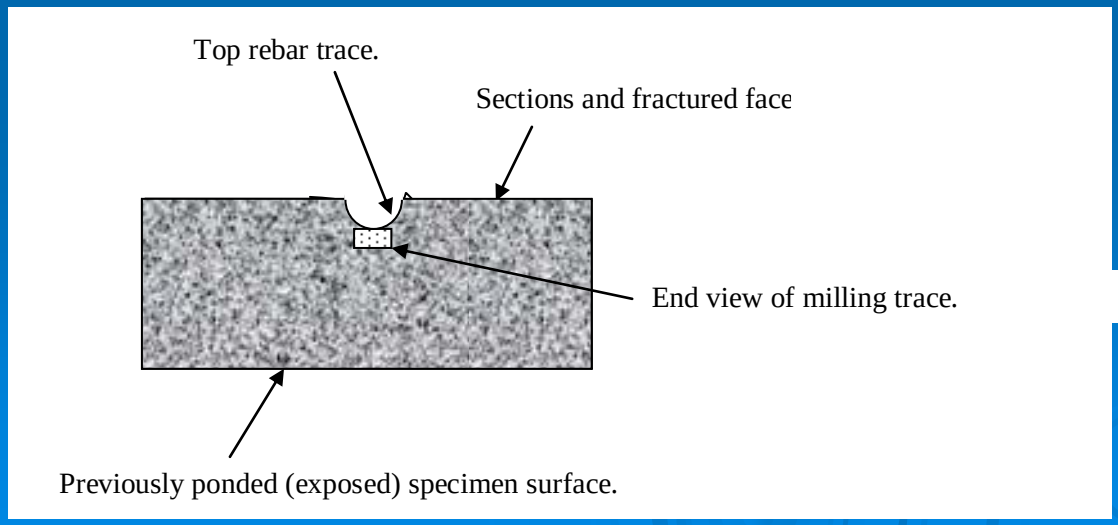
Number of Corroded Specimens → 2/3 ← Total Number of Specimens



SDS - High performance CRRB

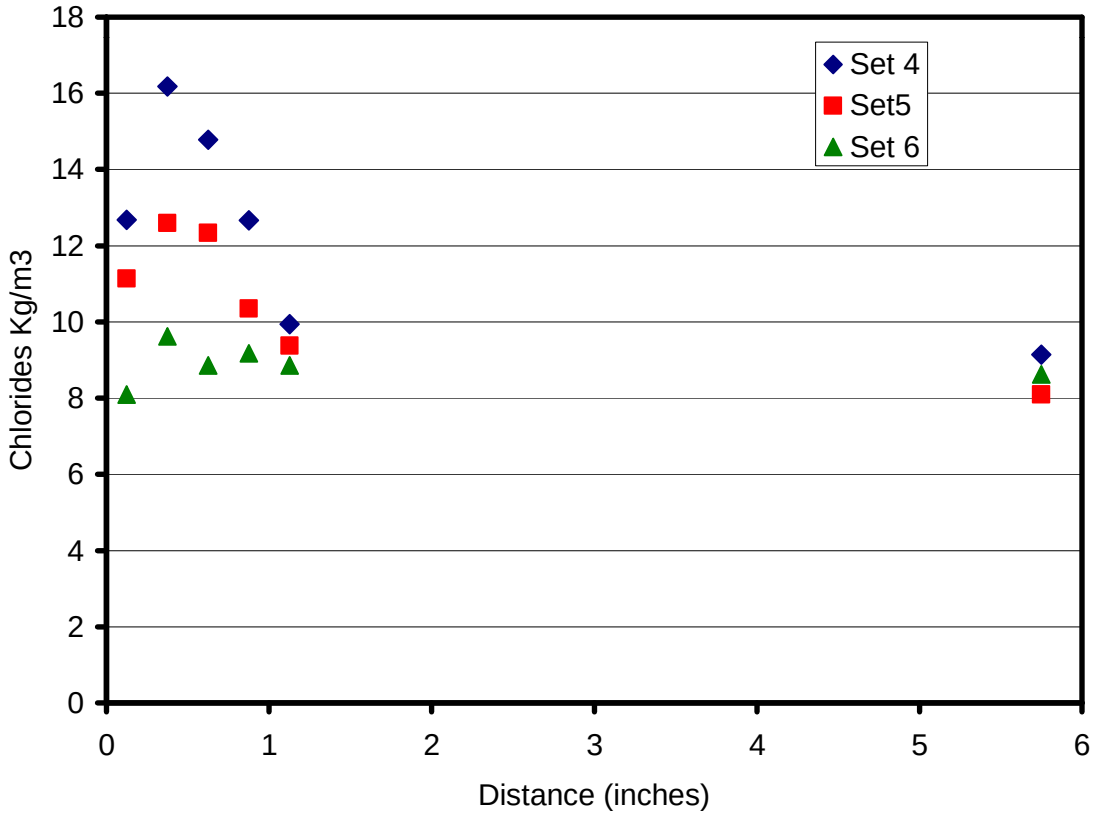
- Summer 2010 – Selected samples were terminated



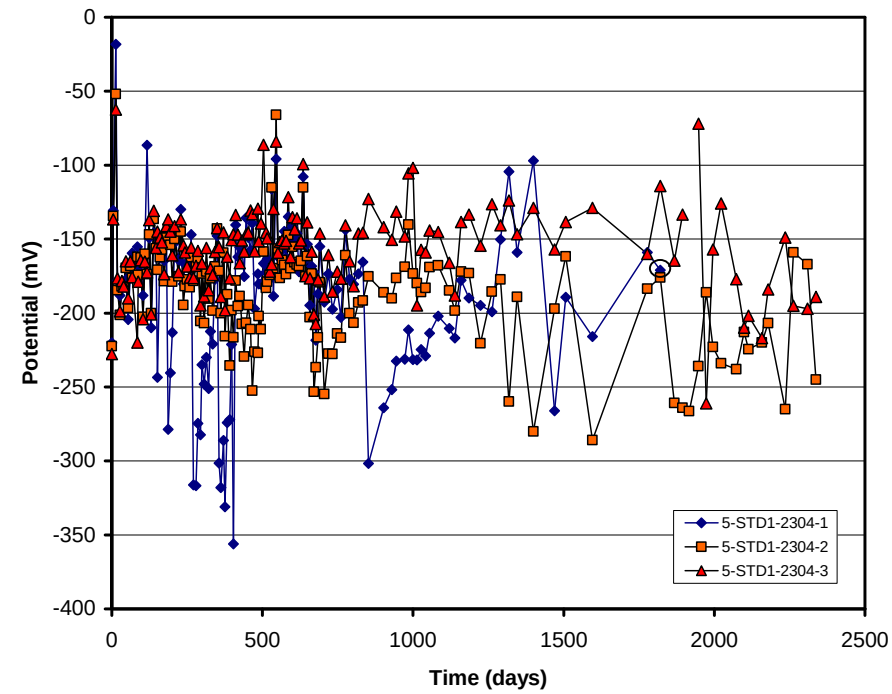


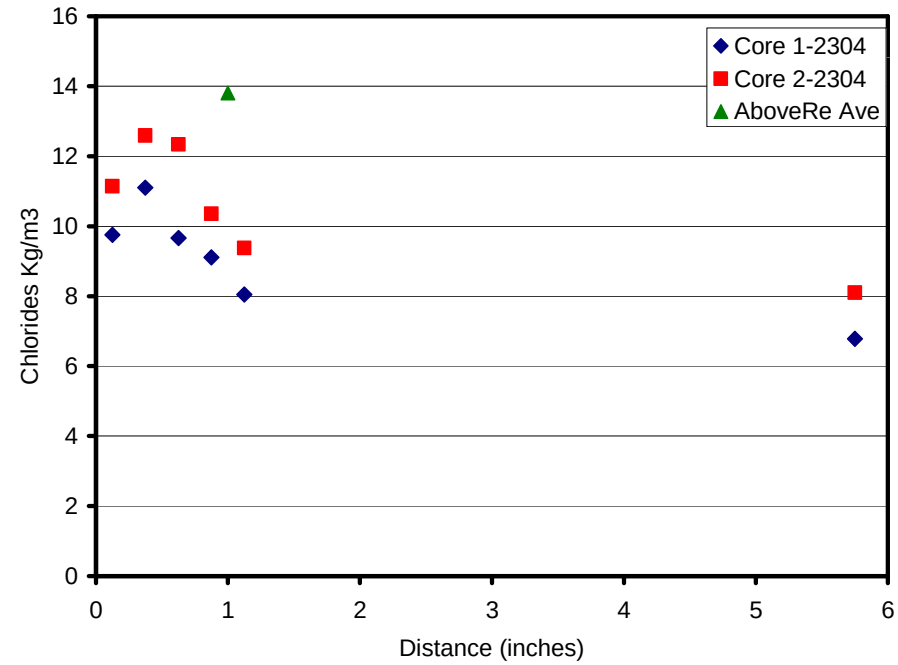
[Cl^-] @ Rebar Trace

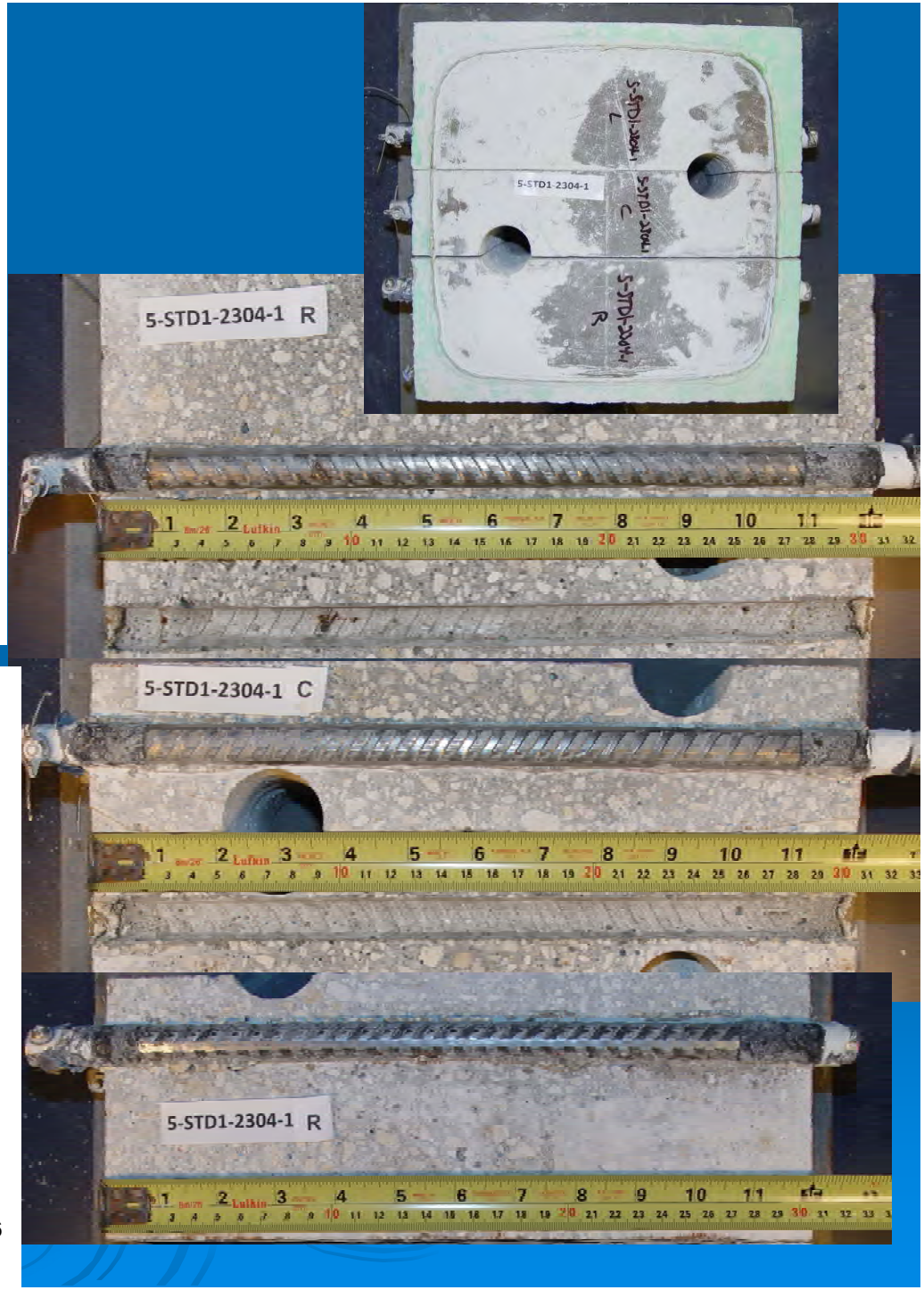
	Average kg/m³	
3-CCRV-316	21.5	
4-CCRV-SMI	22.7	
4-CCRV-3Cr12	15.8	Away from Crevice
5-STD1-2304	13.8	
6-WB-304	11.2	

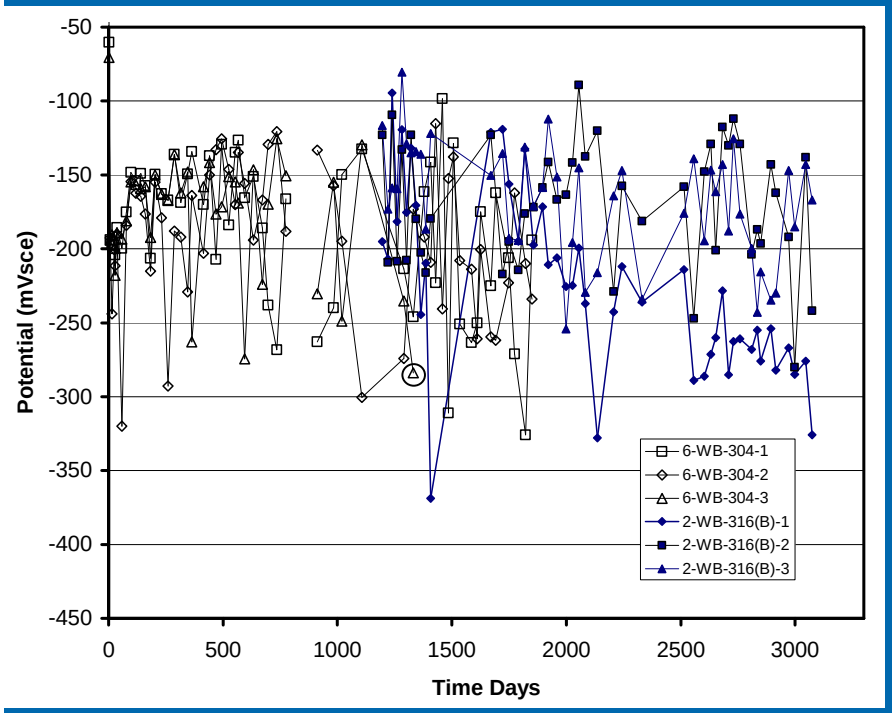


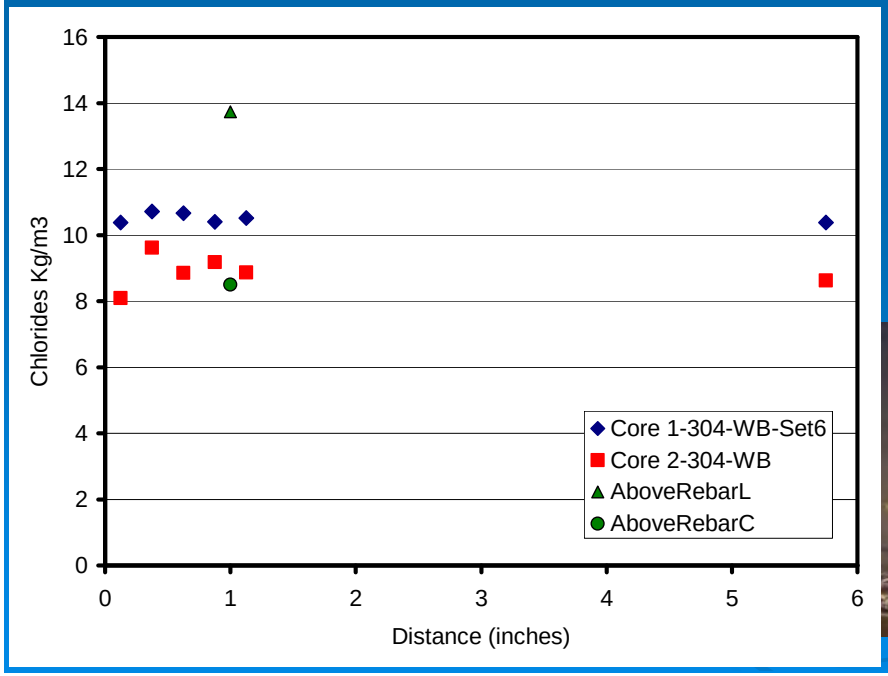
Age @ time of coring
Set 3 ~2500 days
Set 4 ~1900 days
Set 5 ~1820 days
Set 6 ~1300 days

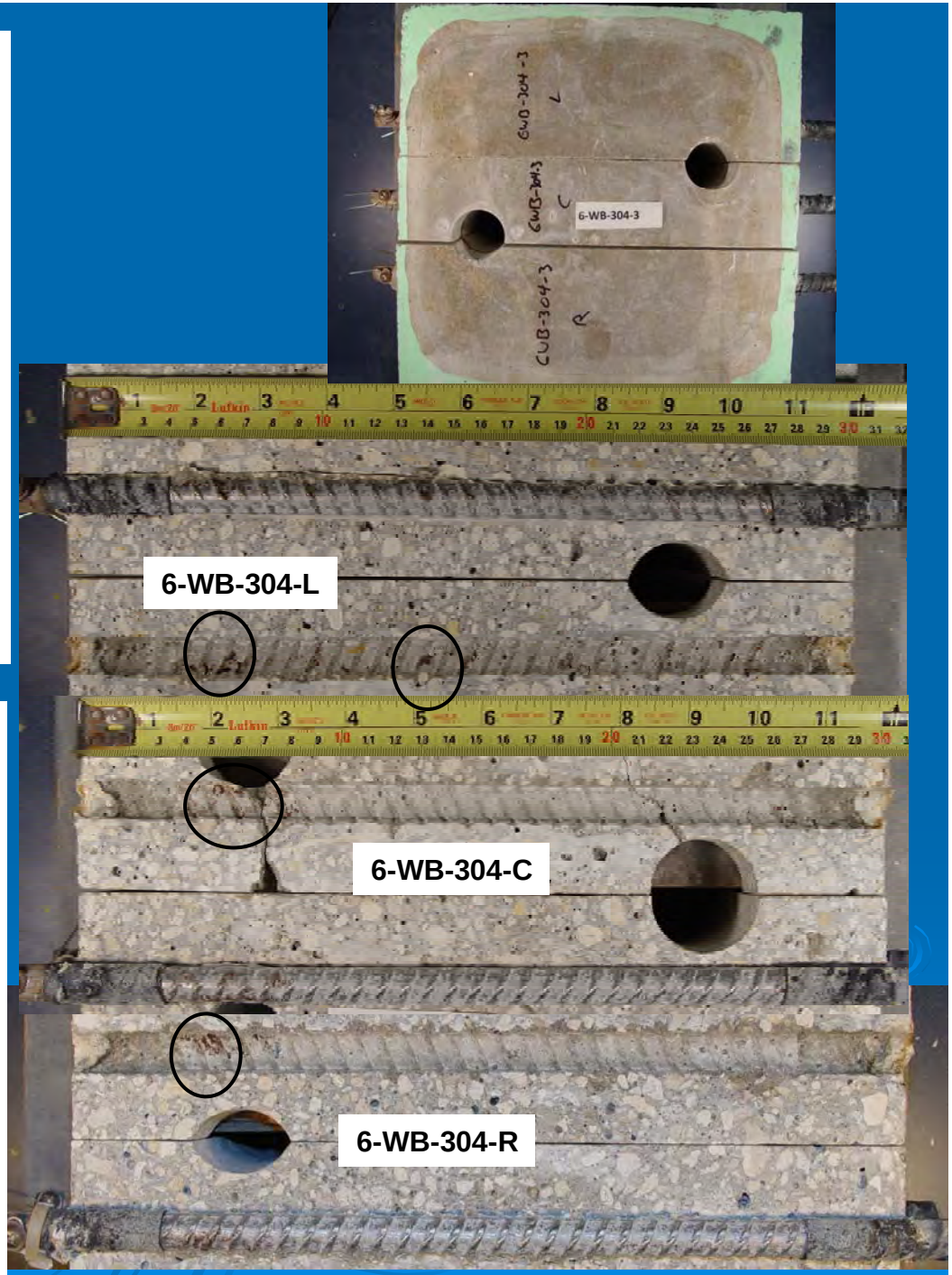

Potential (mV)
Time (days)
5-STD1-2304-1
5-STD1-2304-2
5-STD1-2304-3


Chlorides Kg/m3
Distance (inches)
Core 1-2304
Core 2-2304
AboveRe Ave

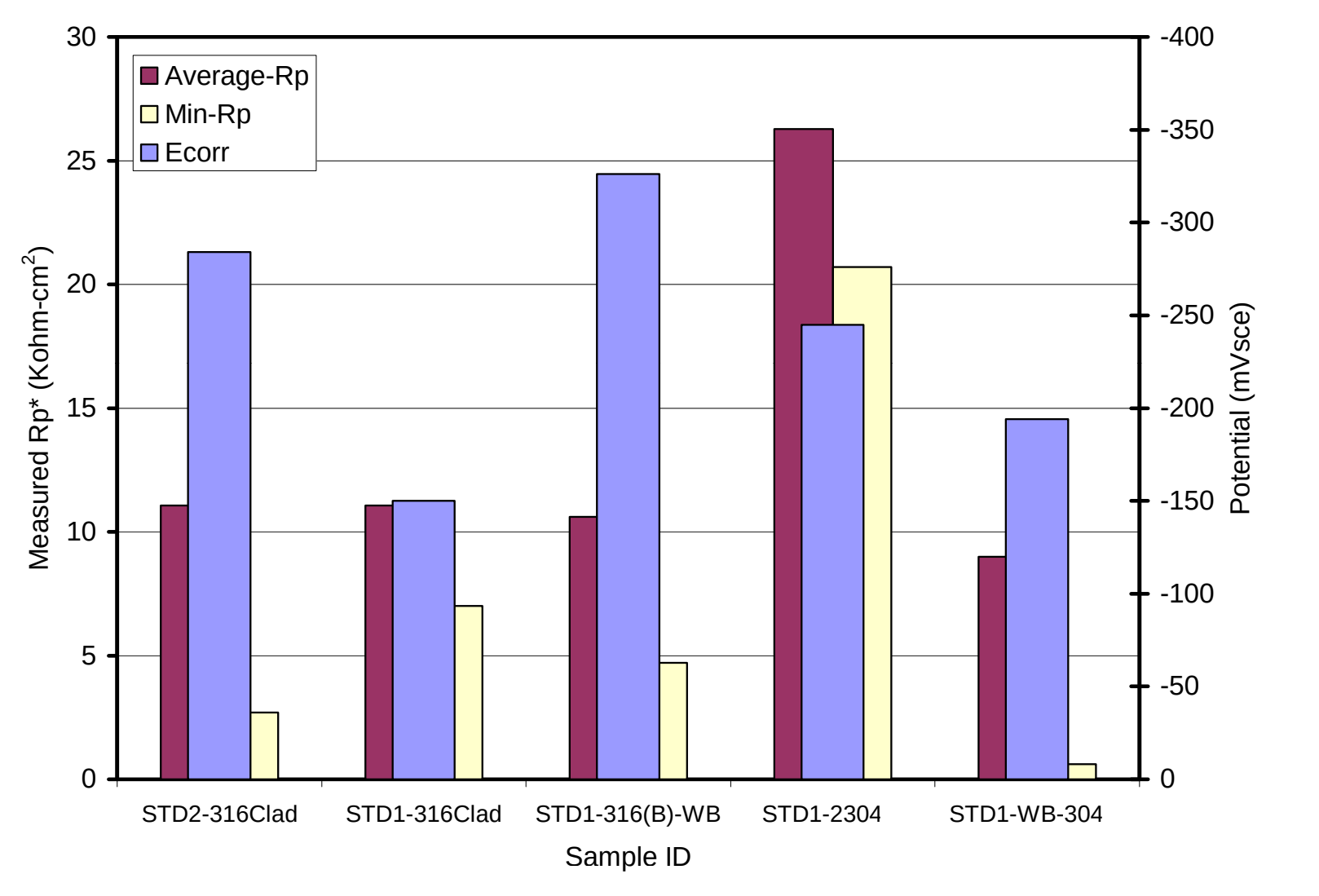

5-STD1-2304-1 R
5-STD1-2304-1 C
5-STD1-2304-1 R


Potential (mVsce)
-50
-100
-150
-200
-250
-300
-350
-400
-450
0
500
1000
1500
2000
2500
3000
Time Days
6-WB-304-1
6-WB-304-2
6-WB-304-3
2-WB-316(B)-1
2-WB-316(B)-2
2-WB-316(B)-3


Chlorides Kg/m3
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
Distance (inches)
Core 1-304-WB-Set6
Core 2-304-WB
AboveRebarL
AboveRebarC

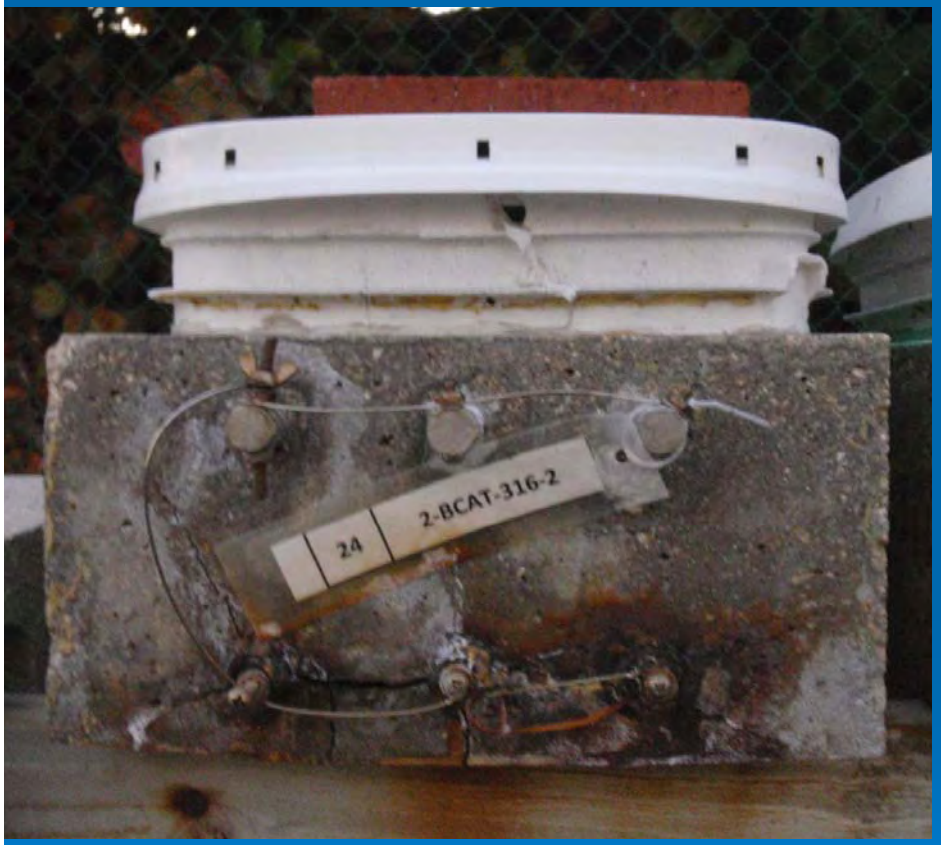

6-WB-304-3
6-WB-304-L
6-WB-304-C
6-WB-304-R

Ecorr and LPR on selected rebars from SDS specimens



* Not area corrected.

SDS with BB in the bottom row



Concrete quality is important!

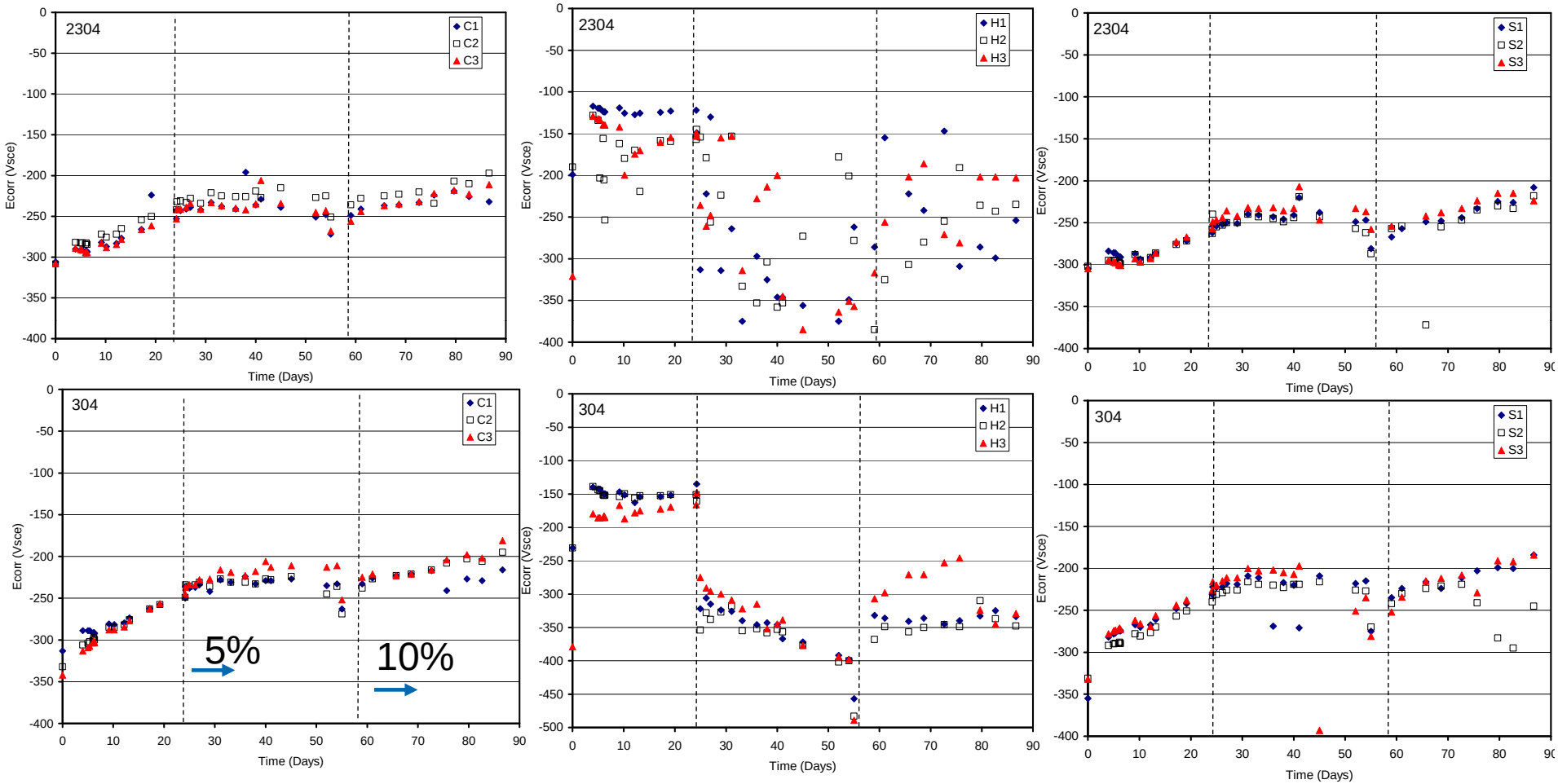
Surface Condition

- Tested Alloys 2304 and 304

3 Surface Conditions
- Pickled (+Sandblasted) – (C)
- Mill scale (H) (after heat treating at 1050°C for 1 hour and air cooling)
- Mill scale + Sandblasted (S)

Test are being conducted in:
a) Simulated Pores Solution with Cl^- additions (0, 5% and 10% so far)
b) Mortar specimens w/c 0.5 (reduced cover 6-8 mm)

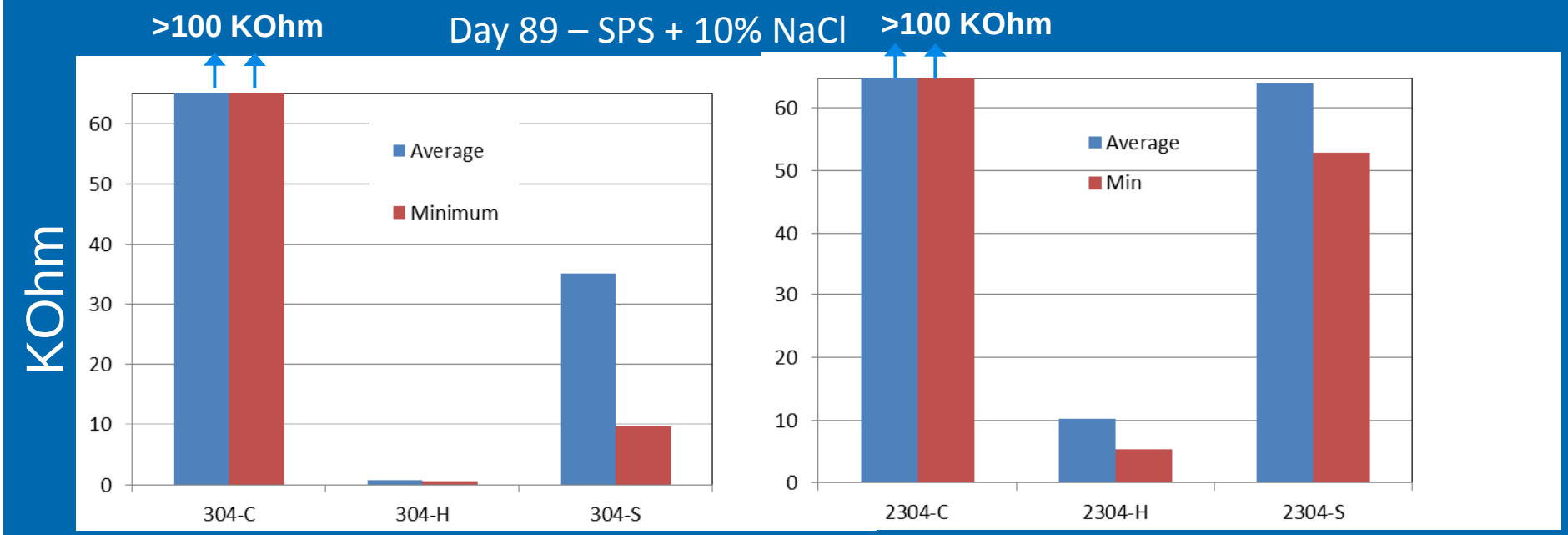
Potential Evolution in Simulated Pore Solution



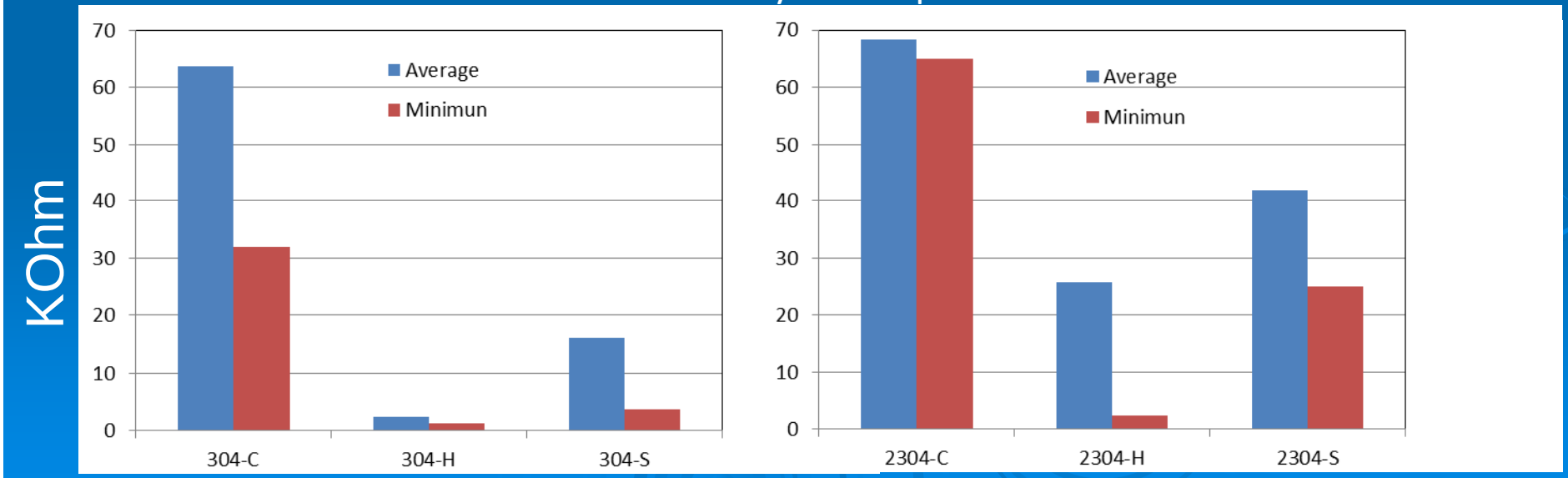
Presence of mill scale is detrimental even on these high Cr & high Ni alloys.

Average and Minimum LPR measured

Day 89 – SPS + 10% NaCl



Embedded in Mortar - Day 74 – exposed to 15% NaCl



Presence of mill scale is detrimental even on these high Cr & high Ni alloys.

Summary

- Tests in high permeability concrete reveal significant performance differences amongst the bars evaluated.
- The relative performance of conventional bars and 316 bars compare favorably with results obtained by others.
- Rebars in Macrocell Slab, 3Bar Tombstone and 3Bar Square specimens in moderate permeability concrete showed corrosion activity after ~3X #days of exposure when compared to high permeability concrete.
- Only the black bar, 3CR12, MMFX, and 2101 samples have corroded in the laboratory columns using moderate permeability concrete.
- Mill scale presence is detrimental to the chloride threshold of CRRB
- Final evaluation will rely primarily on the critical chloride concentration for corrosion in moderate permeability concrete.
- Projected continuation project completion date is June 2013.

Florida DOT Policy

Florida has been looking for alloys that will not corrode even if the concrete is cracked, poorly consolidated, and/or with zero concrete cover.

Florida DOT Policy

- An alloy having a higher chloride threshold is not enough for Florida.
- Some of the cost of the alloy has to be recovered by use of less cover.
- We will still use slag and fly ash regardless. We want to eliminate or quit depending on silica fume, metakaolin, and super fine fly ash.

Florida DOT Policy

If mill scale properly removed

- FDOT will use if needed: 316, 2205, or better. Anything with a good amount of Mo.
- Alloys that show promise pending further tests : 304, 2304, Z-Bar, 2101 (Pickled)
- Items that FDOT have no intention of using at this point: MMFX, Enduramet, 3Cr12, ECR, galvanized, inhibitors

IBRC Projects

Hallmark IBRC Projects (2)

MT-01-01: The IBRC Poster Child

Replacement bridge across the Middle Fork of the Flathead River on U.S. 2 in Flathead County, MT.

Project Aspects and Complexities:

One end terminates on land owned by Glacier National Park and the other on land administered by Flathead National Forest.

The Flathead River that the bridge crosses is under jurisdiction of the United States Fish and Wildlife Service and contains endangered species.

Permitting was complicated because these, as well as the U.S. Army Corps of Engineers and various State agencies, were involved.

Mountainous location with heavy wintertime snow, and numerous deck saltings and freeze-thaw cycles.

Bridge closure involves a 480-km detour.

Hallmark IBRC Project – MT-01-01

- Specification was for either Type 316LN or 2205 stainless steel reinforcement.
- Issues:
  - Preconstruction meetings and supplier cooperation.
    - Fabrication.
    - Pickling.
  - Type of stainless steel.
  - Chairs and steel placement.

Hallmark IBRC Project – SC-00-01

Two lane, five span bridge over Tidal Creek near Charleston, SC.

One span each reinforced with:

1. Type 2205 stainless steel,
2. Type 316 clad black bar,
3. MMFX-2,
4. Black bars, and
5. Black bars with Galvashield XP embedded galvanic anodes.

IBRC Projects Facilitating Comparison of Reinforcement Types

Project with both ECR and MMFX-2

- **OK-01-01 crossing the Chickaskia River on I-35 in Kay County, OK**

Project with both ECR and Galvanized

- **NH-02-03 on I-293 over Frontage Rd. and Brown Ave., Manchester, NH**

IBRC Projects Facilitating Comparison of Reinforcement Types

- FL-01-01 crossing the St. Lucie River at Jensen Beach, FL

Piers 11 and 12 of the Frank A. Wacha Bridge

2101 SS in Footer

2101 SS in Column

Spans 9-16 of the East Relief Bridge, including parapets and barrier walls

MMFX-2

Conclusions

1. The various IBRC projects demonstrated that, in most situations and subject to availability, corrosion-resistant reinforcing steel can be incorporated into bridge construction projects with relative ease. Construction personnel at several job sites indicated that corrosion-resistant reinforcement placement was more straightforward than for ECR because of the care that must be exercised to avoid coating damage on the latter.

2. Attempts should be made to compare results from laboratory and test yard studies, wherein methodologies for projecting long-term performance of corrosion-resistant reinforcement from short-term tests are being developed, with data from the IBRC bridges as the latter become available. This will require, however, that states maintain records for the respective bridges and commit to a long-term monitoring and data acquisition program that extends for decades into the future.

… END

Questions?