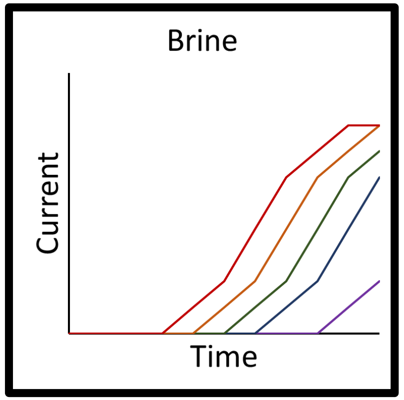
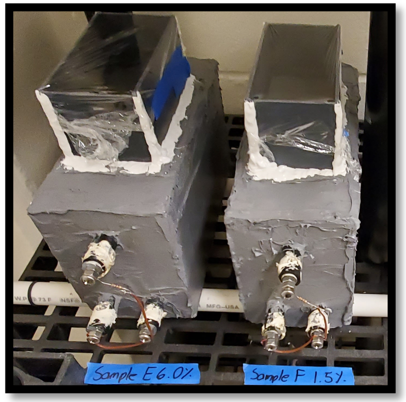
INFLUENCE OF CRACKING AND BRINE CONCENTRATION ON CORROSION AND CHLORIDE CONTENT





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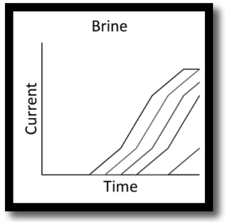
NJDOT Research Showcase: Lunchtime Edition
21st April 2022

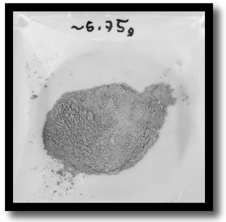
OUTLINE

Introduction to Bridge Corrosion

Testing Procedure



Macrocell Current Results

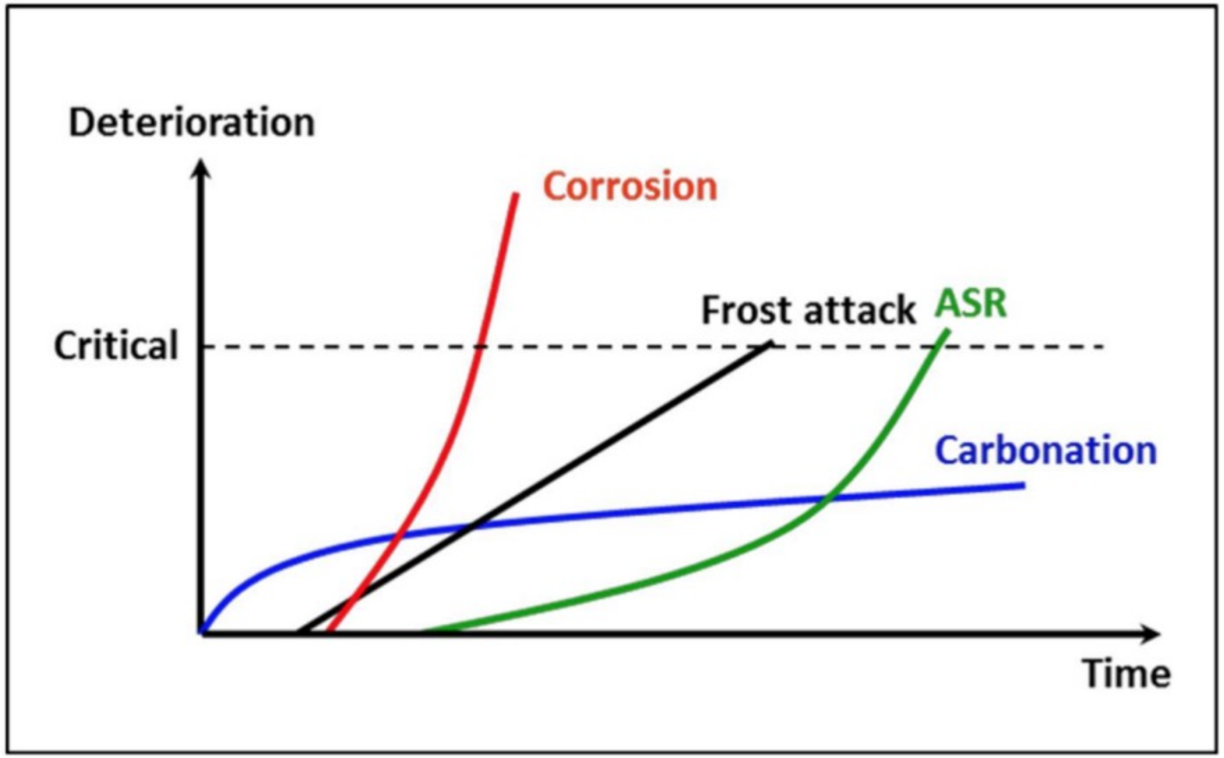


Chloride Profiling Results

Corrosion of Concrete Structures

- 2002 Study: Corrosion cost and preventative strategies for highway bridges was **$8.3 Billion**

- In reinforced concrete bridges primary cause is **chloride-induced corrosion**



Simplified deterioration mechanism (Aboutaha, 2004)

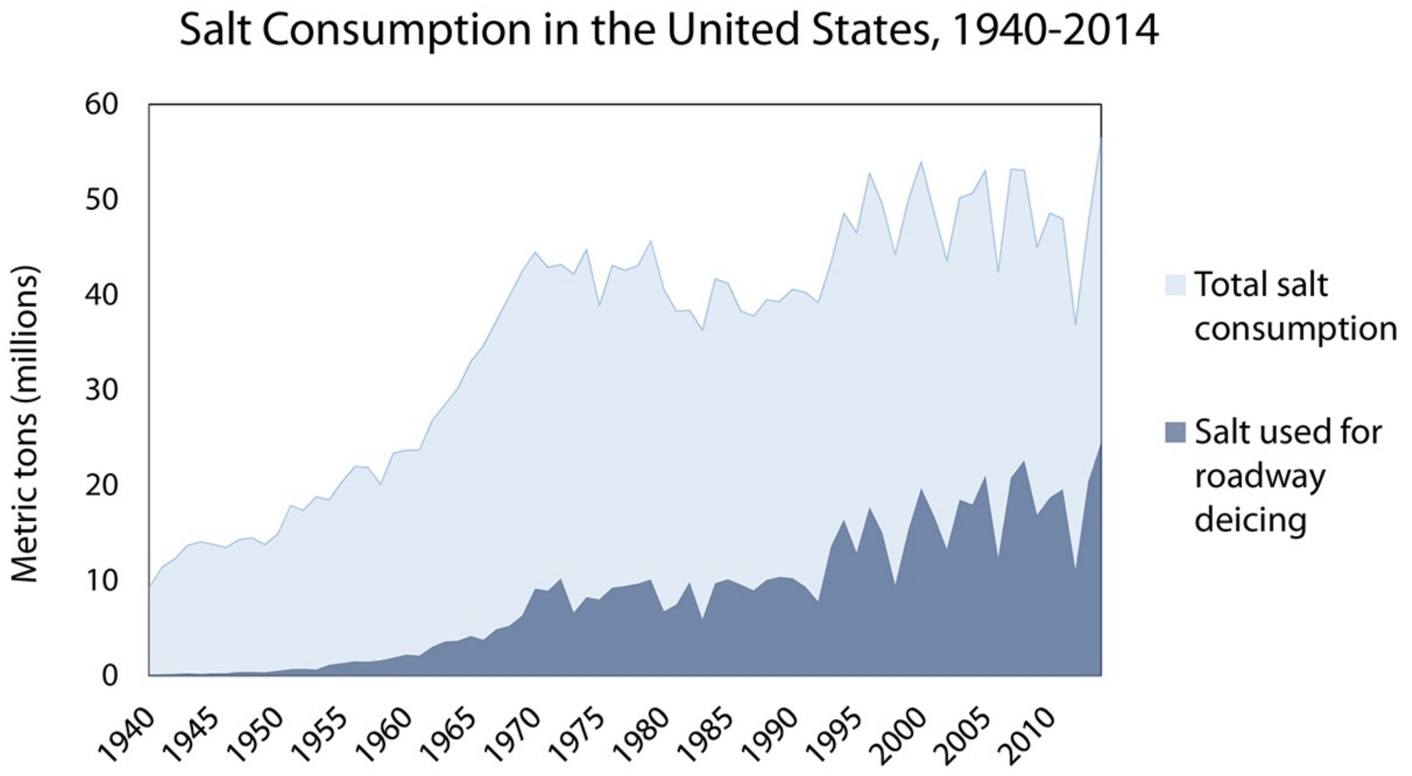
Causes of Corrosion of Steel in Concrete

- Causes of Corrosion of Steel in Concrete
  - Chlorides
    - Cast-In Chlorides
    - **Surface-Applied Chlorides** — Focus of this project
  - Carbonation
  - Dissimilar Metals

Source: Design Guide for Bridges for Service Life 2014

ROAD SALTING

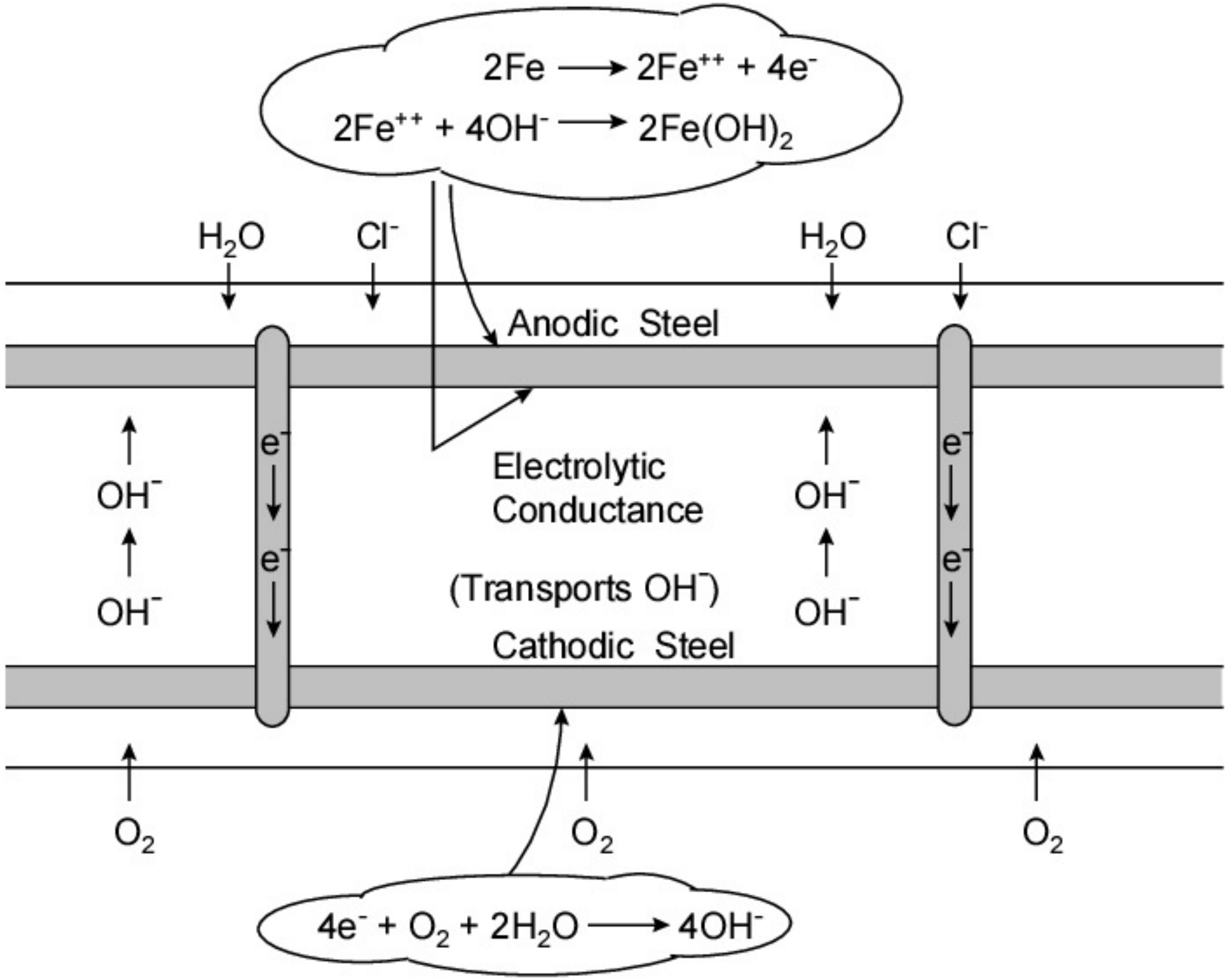
- 2014 road consumption
  - 24.5 million metric tons
- Forms of salt used
  - Rock Salt
  - Brine (23.3% for -6°F freezing)
- NJDOT Winter 2018-2019 Material Usage
  - Salt - 391,447 tons
  - Liquid calcium chloride – 803,709 gallons
  - Brine - 687,370 gallons



Sources: Winter Readiness, *NJDOT*;
Minerals Yearbook 2014 Salt, *U.S. Geological Survey*;
Special Report 235: Highway Deicing, *National Research Council*

MACROCELL CORROSION

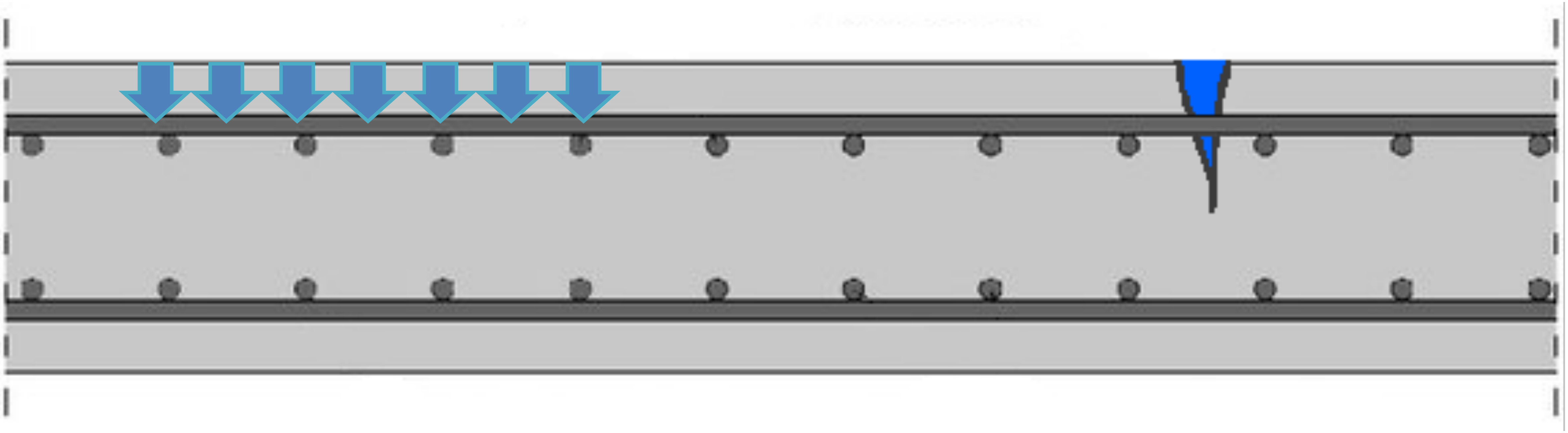
- Local anode and large cathode
- Macrocell forms between upper layer reinforcement and lower mat
- Frequently occurs in chloride induced corrosion
- In bridge decks this form is accelerated due to large cathode/anode area ratio



Source: Kahhaleh 1998

CHLORIDE INGRESS

- Diffusion
  - Chlorides need to penetrate concrete to reach reinforcement
  - Concentration gradient
- Direct access
  - Chlorides have concentrated path to reinforcement



Sources of Bridge Deck Cracking

- Plastic Shrinkage
- Drying Shrinkage
- Surface Tears (Finishing)
- Flexure/Deflection of the Deck
- Reflection of Underlying Cracks and Joints
- Temperature Related Mechanisms

Source: Missouri Department of Transportation

Governing Question

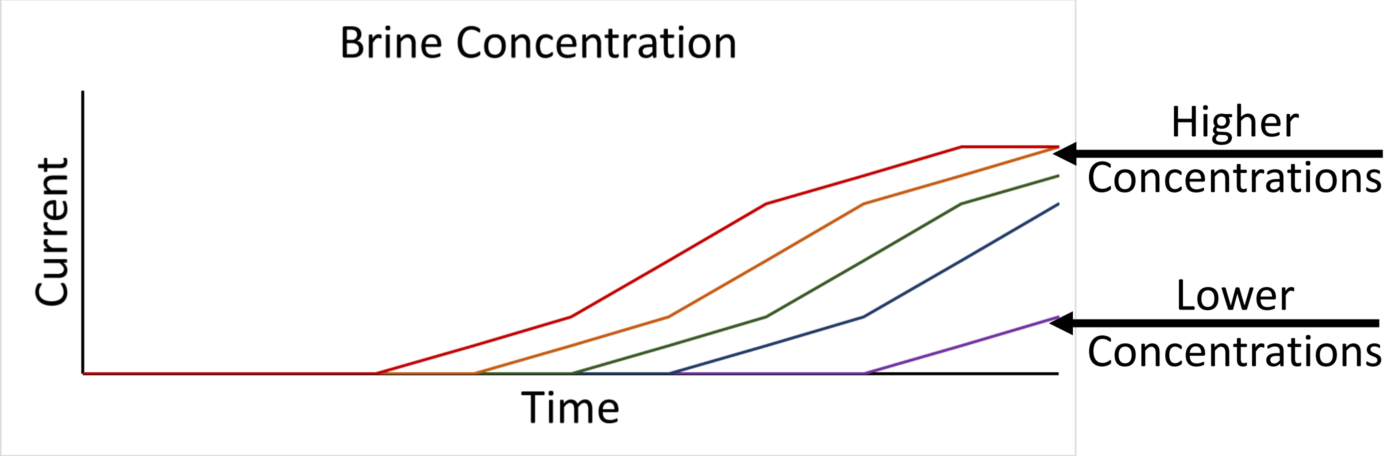
- Does current testing take into account possible real world considerations?

- Amount of salt placed on roads
- Salt placement cycles
- Integrity/condition of bridge deck

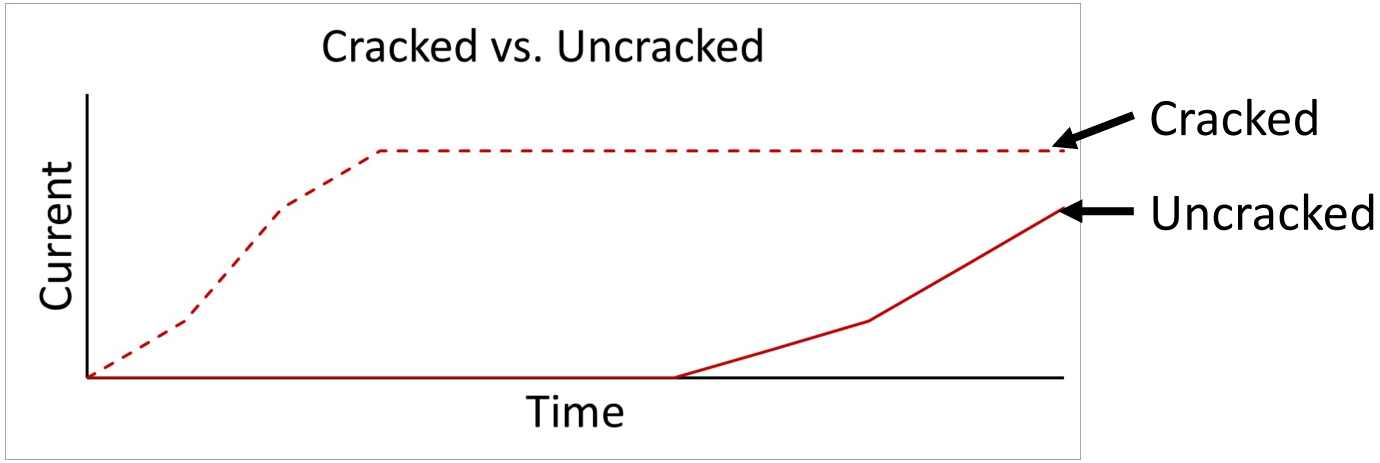
Image Sources: Indiana Department of Transportation, and theconstructor.org

Variables of Interest

- Impact of **salt brine concentration**
  - How does the concentration of the chloride brine impact the time to corrosion?



- Impact of **cracking**
  - How does the presence of cracks to the reinforcing steel impact the time to corrosion?



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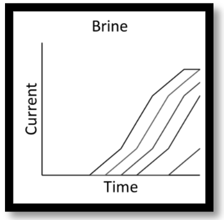
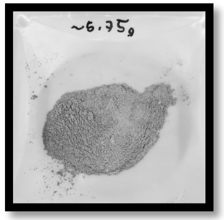
Testing Procedure



Macrocell Current Results



Chloride Profiling Results

Specimens for Laboratory Testing

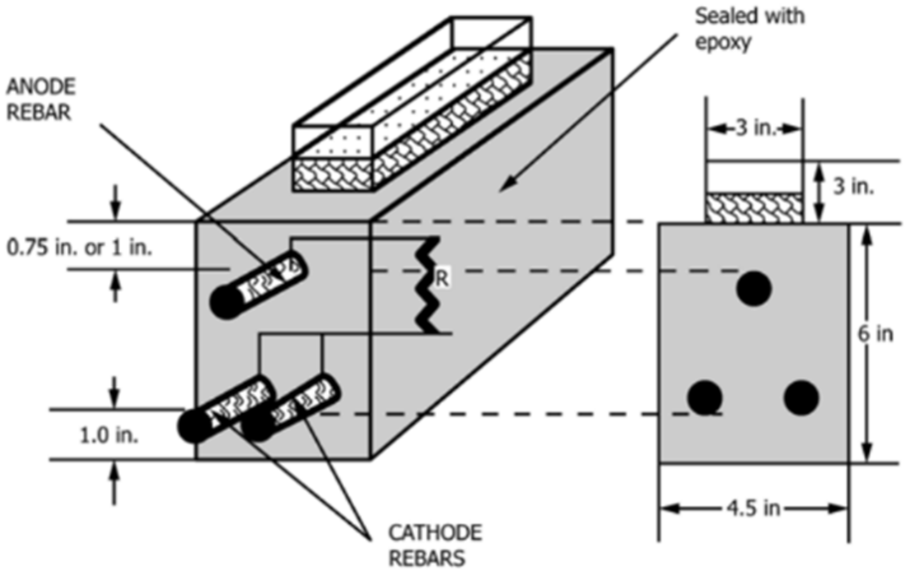
- ASTM G109 for macro-cell current
  - Assumed no initial chlorides in concrete
  - Corrosion only from chloride ingress

- Design compressive strength of 4500 psi

- Tested compressive strength:
  - Set 1 Specimens - 5620 psi
  - Set 2 Specimens - 6660 psi

ASTM G109

- Been previously used to study corrosion in steel of:
  - Ordinary portland cement [1,2]
  - High performance concrete[1]
  - Surface applied corrosion inhibitors[3]
  - Corrosion resistance of microalloyed steels[4]



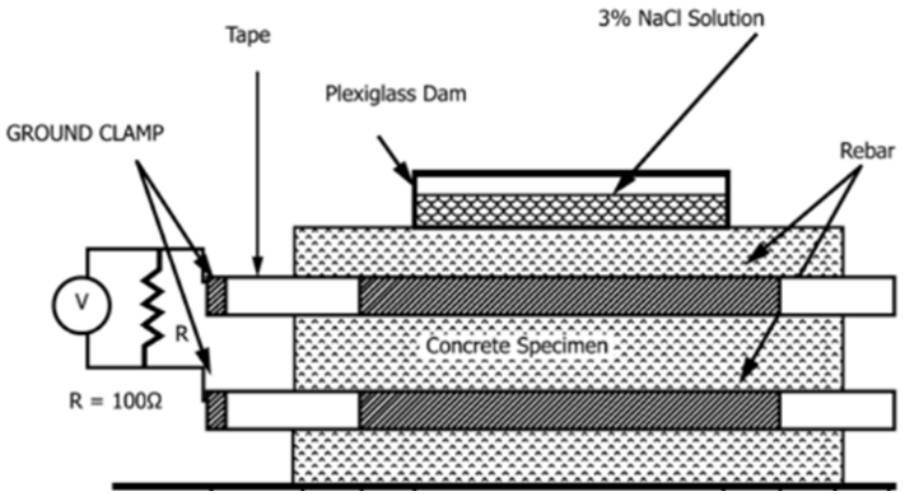
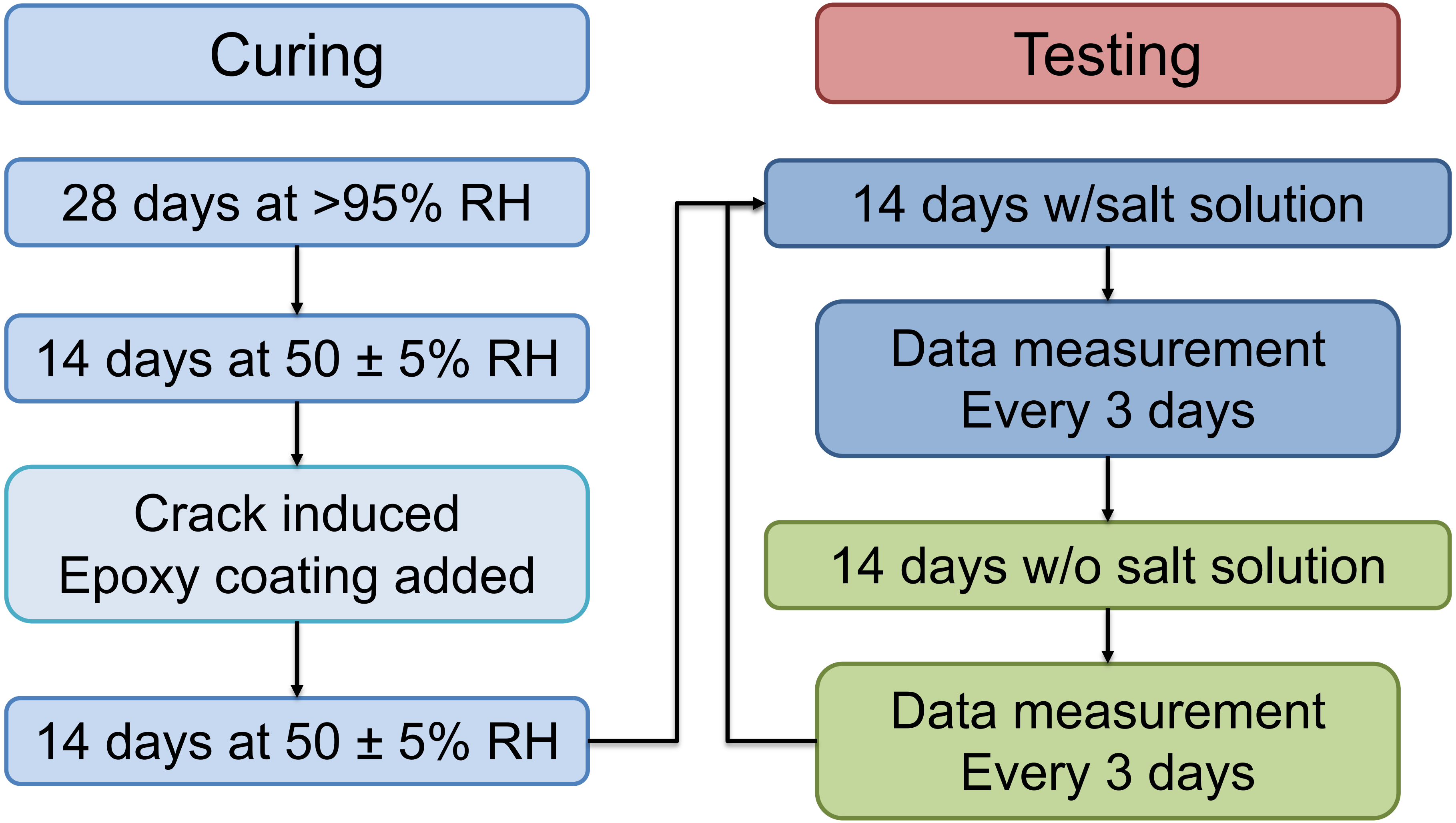


Image Source: ASTM G109

[1] Hansson CM, Poursaee A, Laurent A. (2006); [2] Trejo D, Halmen C, Reinschmidt K. (2009). [3] El-Hacha R, Mirman A, Cook A, Rizkalla S (2011); [4] Balma J, Darwin D, Browning J, Locke Jr CE. (2002)

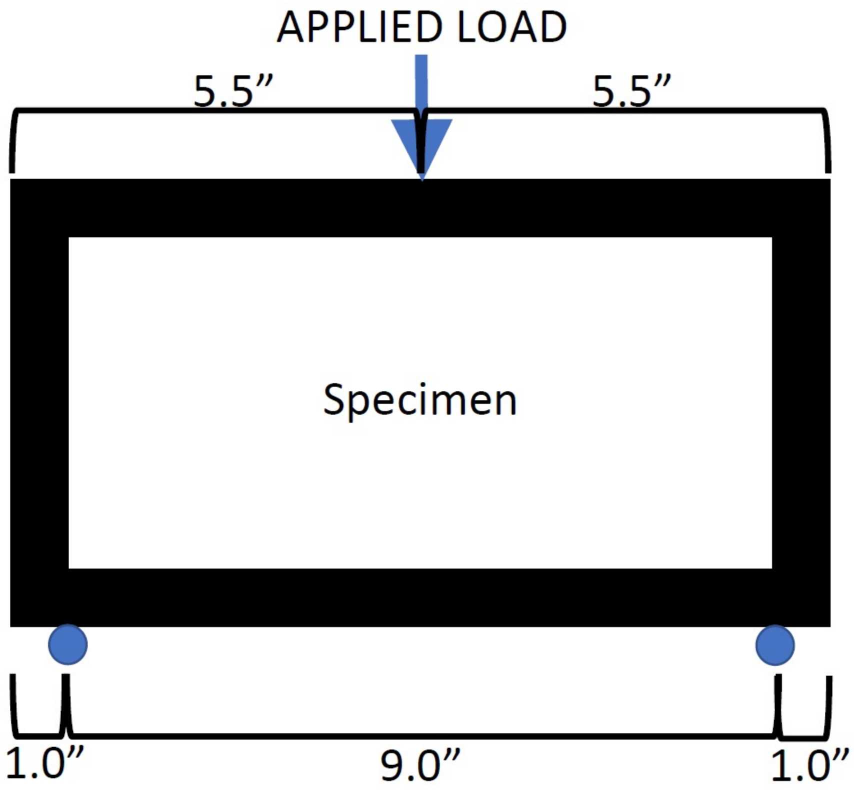
Lab Specimen Testing

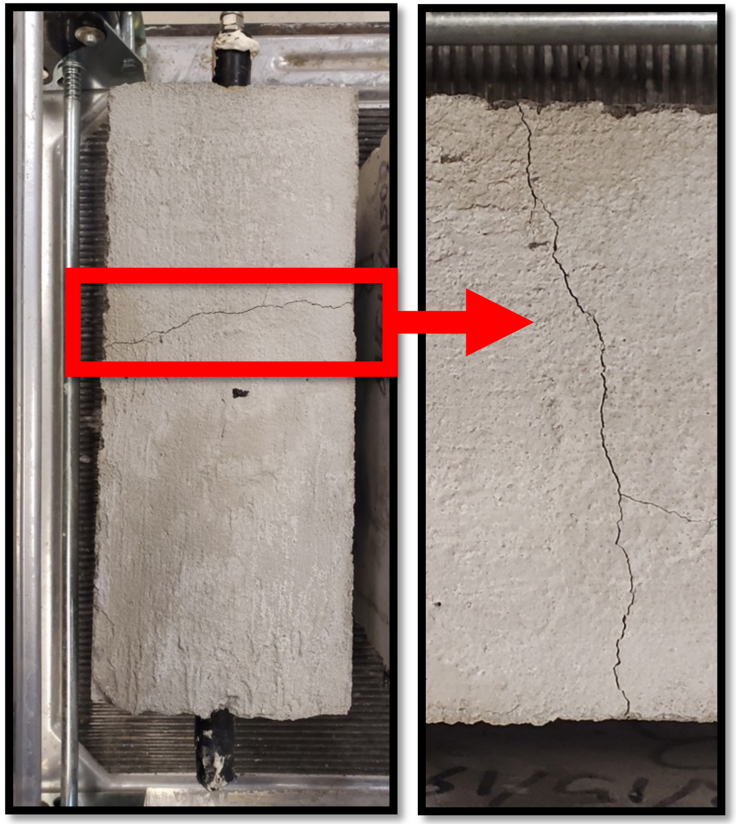


Lab Specimen Casting & Final

Loading Specimens to Form Crack

- Single Point load
  - Load at mid-span
- Loaded until 14.5 kips (M_{cr} 2.75 k-ft)
  - Stopped if cracking was observed
  - Loaded at 5000 lb./min
- Crack widths
  - 0.004 – 0.012 in.
  - 0.15 – 0.30 mm





Lab Specimen Testing Modifications

- Five salt brines used
  - 1.5, 3.0, 4.5. 6.0, and 9.0% NaCl
- Cracking conditions
  - One un-cracked
  - One flexure cracked
- Current measurements collected more frequently

Image Source: indiamart.com, FHWA-RD-03-047

Macrocell Corrosion Measurement

- Measure voltage across resistor
- Threshold values
  - Integrated macrocell current of **75 C**
  - Macrocell current greater than **10 µA**

$$I_j = V_j/100$$

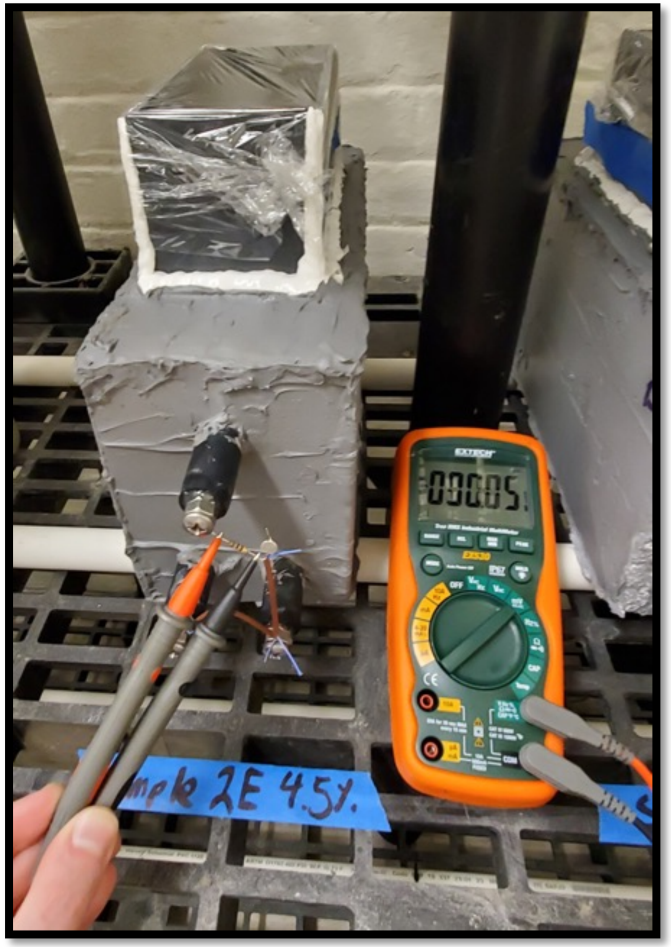
$$TC_j = TC_{j-1} + \left[\left(t_j - t_{j-1}\right) * \left(i_j + i_{j-1}\right)/2\right]$$

Where TC is Total Corrosion (coulombs),

t_j is time (seconds) to test,

I_j is macrocell current,

V_j is measured voltage across 100 Ω resistor in volts



Large Scale Bridge Deck Specimen

- Full size bridge deck (25 ft. wide x 50 ft. long)
- Exposed to 6.0% brine, freezing-thawing, and moving load
- No macrocell corrosion testing on deck
- Chloride content tested through coring of deck

Image Source: Dreamstime

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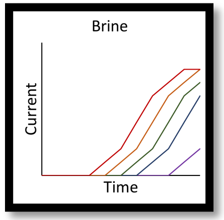
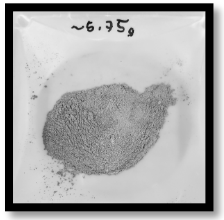


Macrocell Current Results



Chloride Profiling Results

Macrocell Current Results

Selected Representative Data

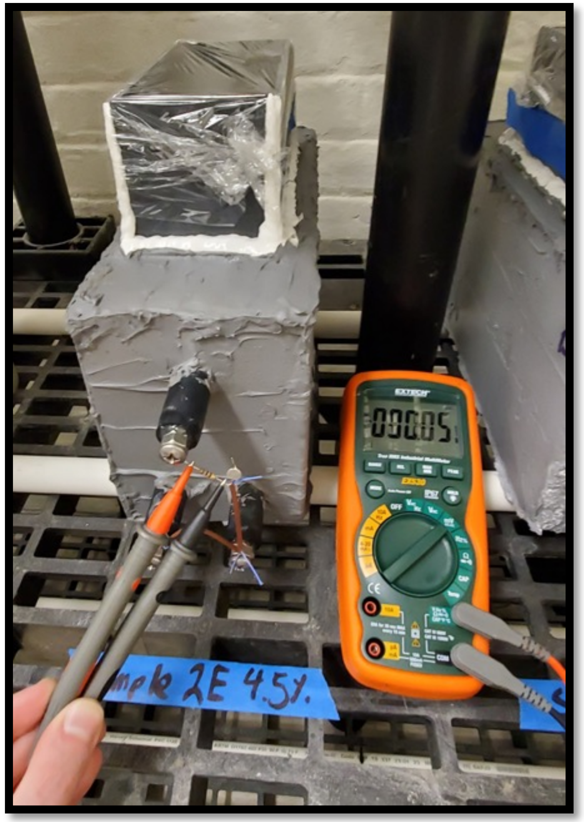
Set 2 Ponding Cycle 1			
Time of Exposure (Days)	4.50%		6.00%
	Uncracked	Cracked	Cracked
Day 0	0.4	0.5	0.5
Day 3	0.6	**154.9**	**129.7**
Day 6	0.6	**116.1**	**87.5**
Day 9	0.5	**103.5**	**76.5**
Day 12	0.0	**83.8**	**67.9**
Day 14	0.3	**77.5**	**68.3**
Day 17	0.6	**42.5**	**60.3**
Day 20	0.0	**40.4**	**47.7**
Day 23	0.5	**64.3**	**34.4**
Day 26	0.4	**59.5**	**34.5**
Day 28	0.0	**57.8**	**31.9**

Brine Solution Added

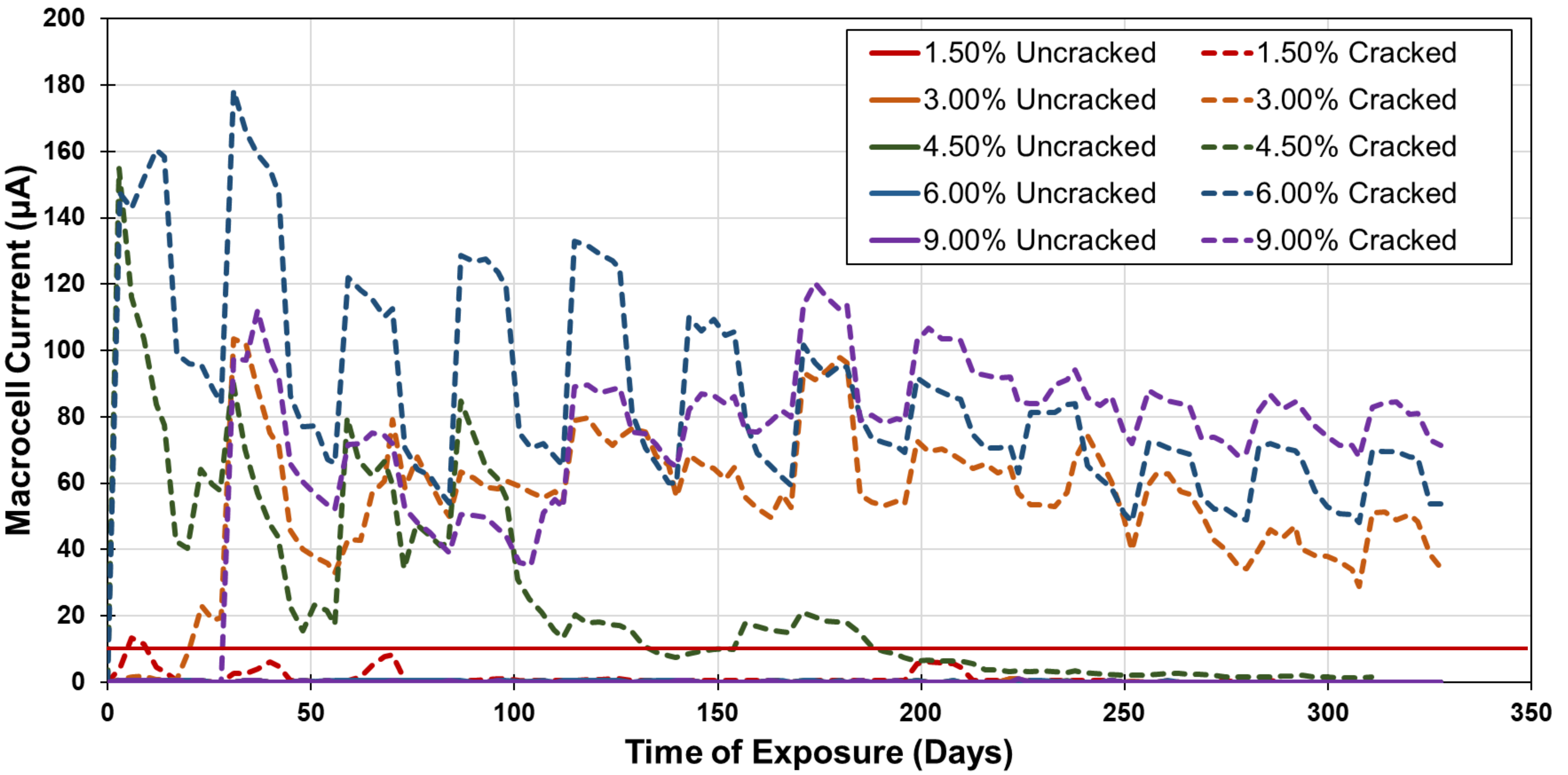
Brine Solution Removed

Set 2 Ponding Cycle 2			
Time of Exposure (Days)	4.50%		6.00%
	Uncracked	Cracked	Cracked
Day 31	0.5	**91.2**	**142.0**
Day 34	0.0	**70.0**	**150.1**
Day 37	0.0	**56.9**	**179.5**
Day 40	0.0	**47.5**	**173.8**
Day 42	0.0	**43.8**	**177.3**
Day 45	0.0	**22.7**	**96.4**
Day 48	0.0	**15.4**	**93.8**
Day 51	0.5	**23.3**	**89.8**
Day 54	0.5	**21.6**	**84.0**
Day 56	0.0	**17.4**	**76.9**

*Note: Bolded values represent current values above 10 µA (specified in ASTM G109), indication of chlorides reaching reinforcement steel



Macrocell Current Over Time



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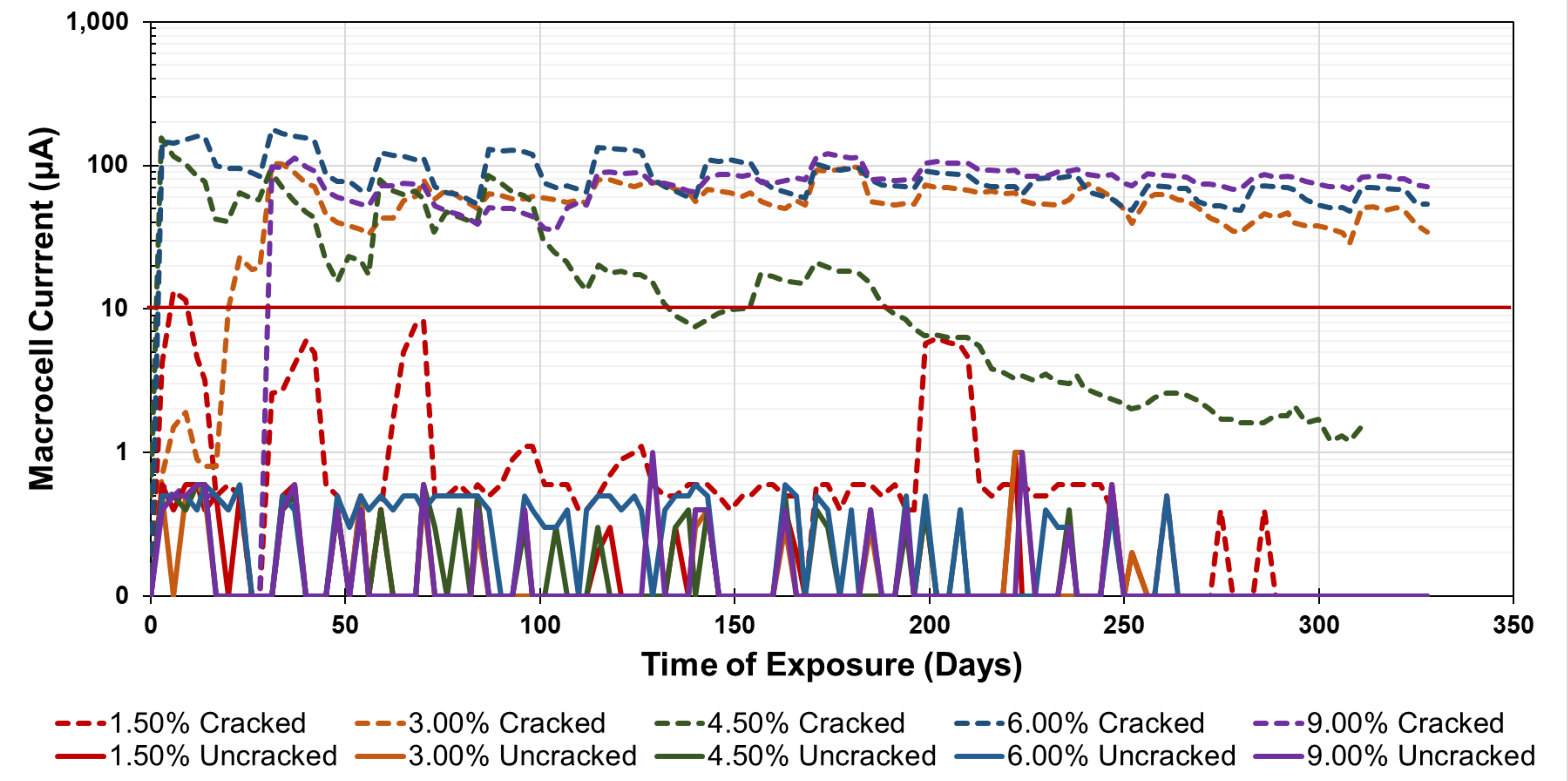
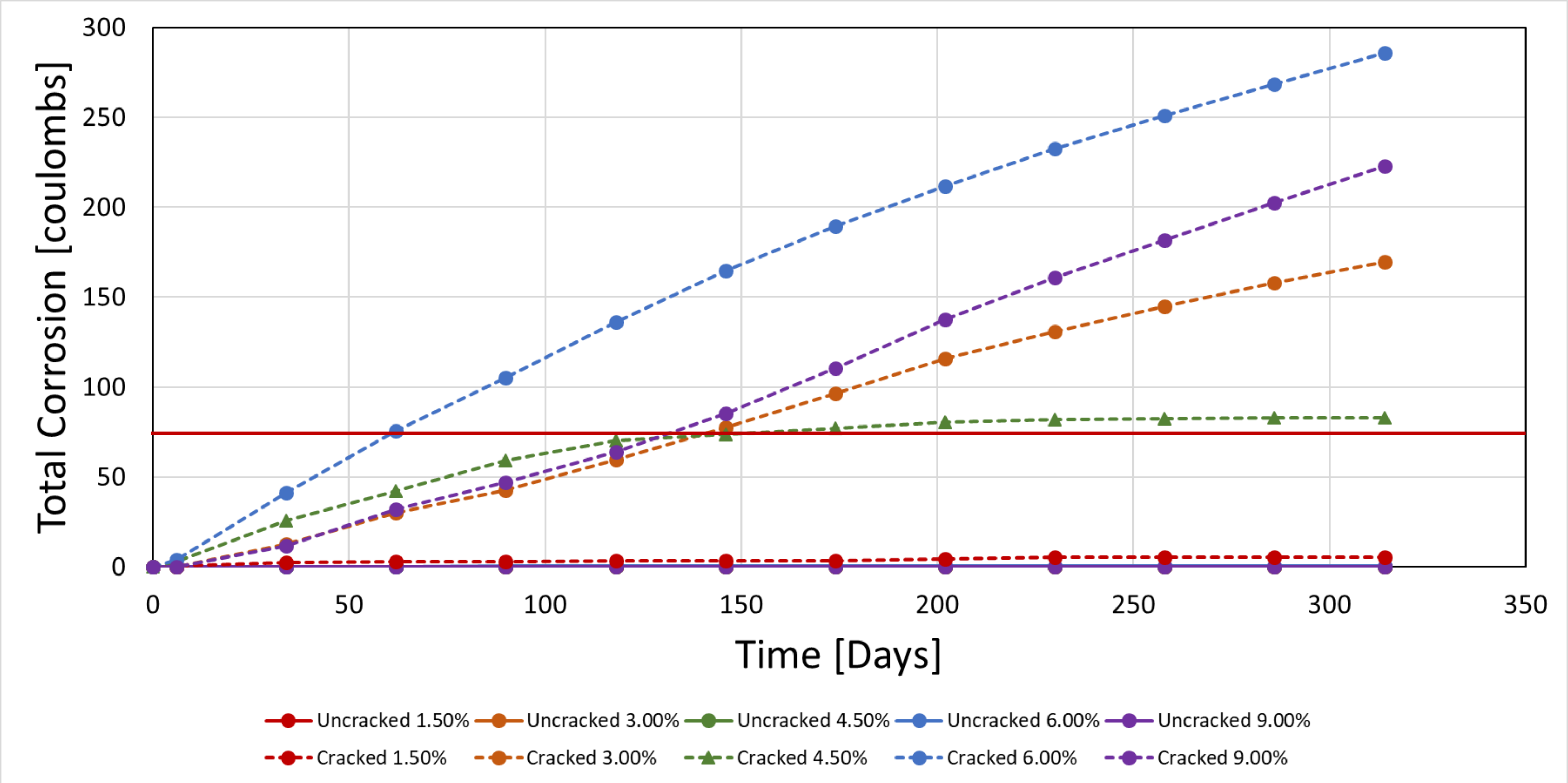
MACROCELL CURRENT SEMI LOG



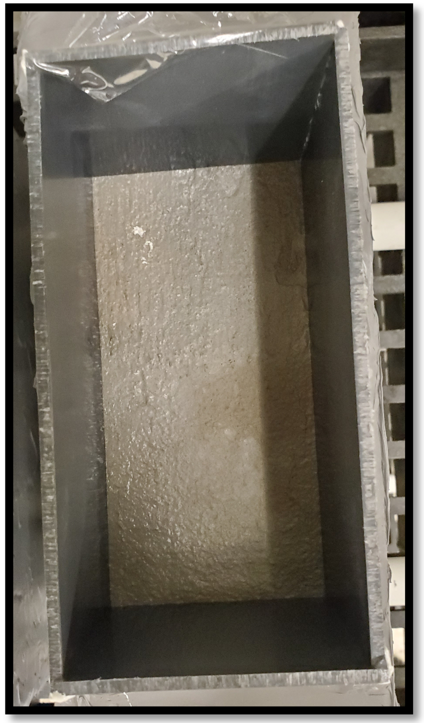
TOTAL CORROSION



Cracking and Brine Concentration Findings

- For **cracked** specimens:
  - Threshold met for solutions **greater than 3%.**
  - Reached at a **greatly accelerated rate**
- For **un-cracked** specimens:
  - At **all** chloride levels no corrosion appears to have initialized
- Presence of brine larger factor than brine concentration
- **No difference** in current results for un-cracked during testing time

Cracked



Uncracked

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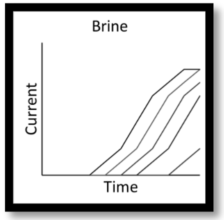


Macrocell Current Results

Chloride Profiling Results

Profiling of Specimens

- Using ASTM C1556 for profile layer depths
  - All specimens are profiled until reinforcement is reached
  - Intervals for 0.40 w/cm for lab cast blocks
  - Intervals were 1mm thicker starting on layer 2 than in C1556 for deck cores due to smaller sample cross section area
- Using ASTM C1152 for Acid-Soluble Chloride Testing

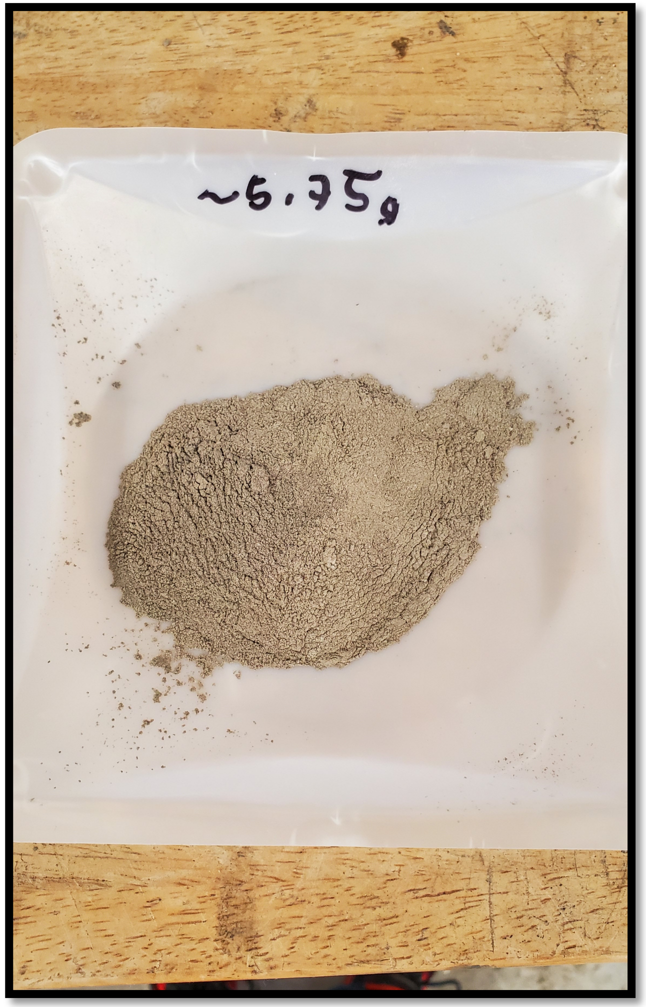
Layer 1 (0.5mm)

Layer 3 (4mm)

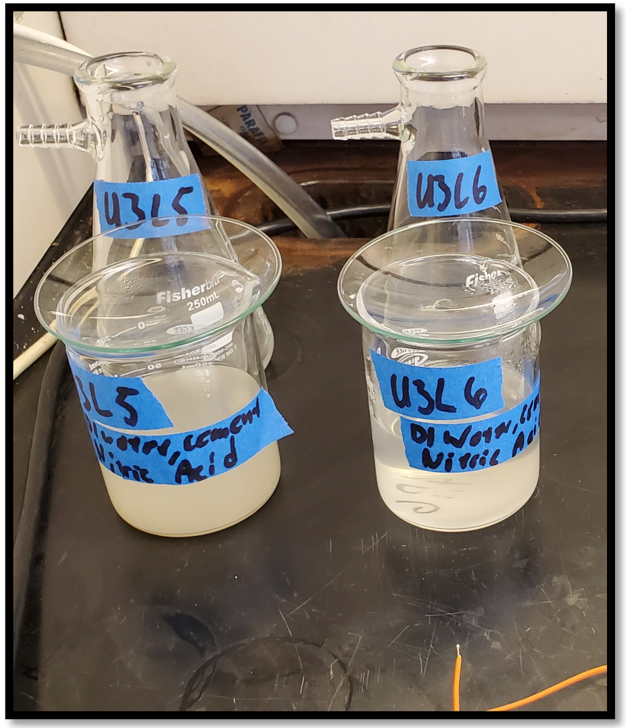
Layer 8 (18mm)

PROFILING SETUP

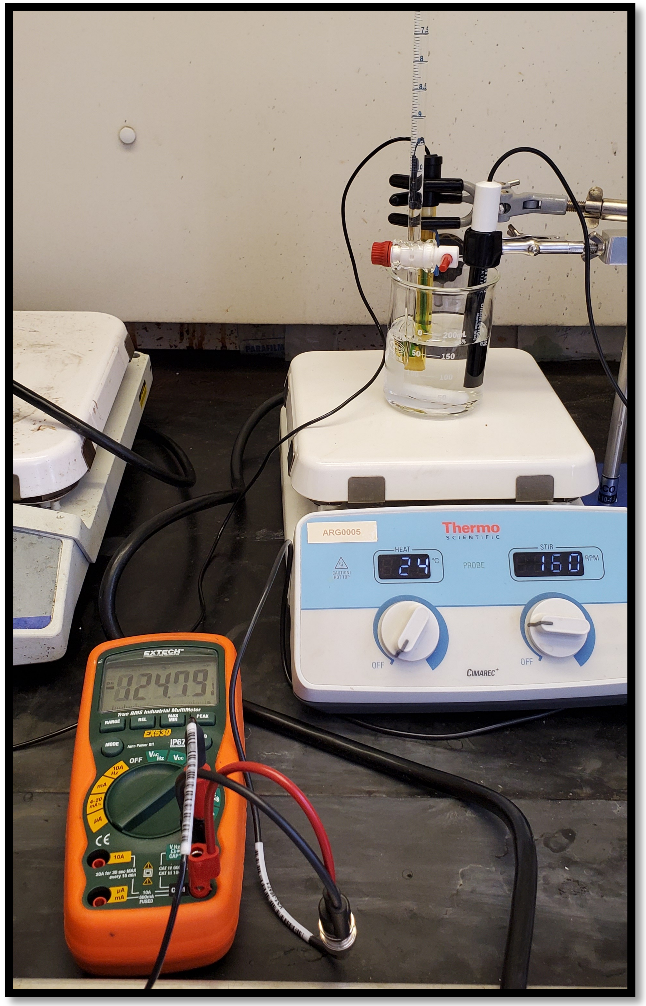
Titration Process/Setup



Collected Powder Sample*



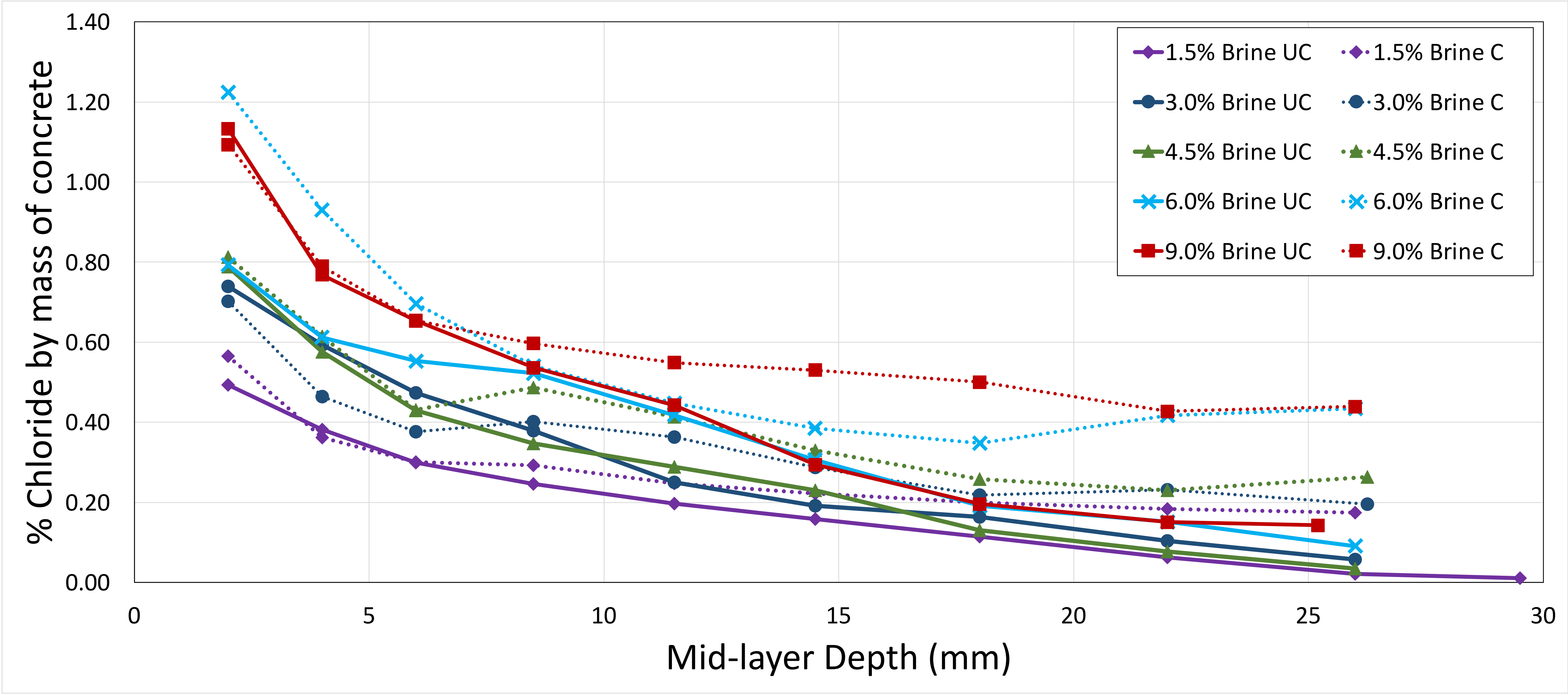
Acid-Chloride solution after boiling and filtering out powder



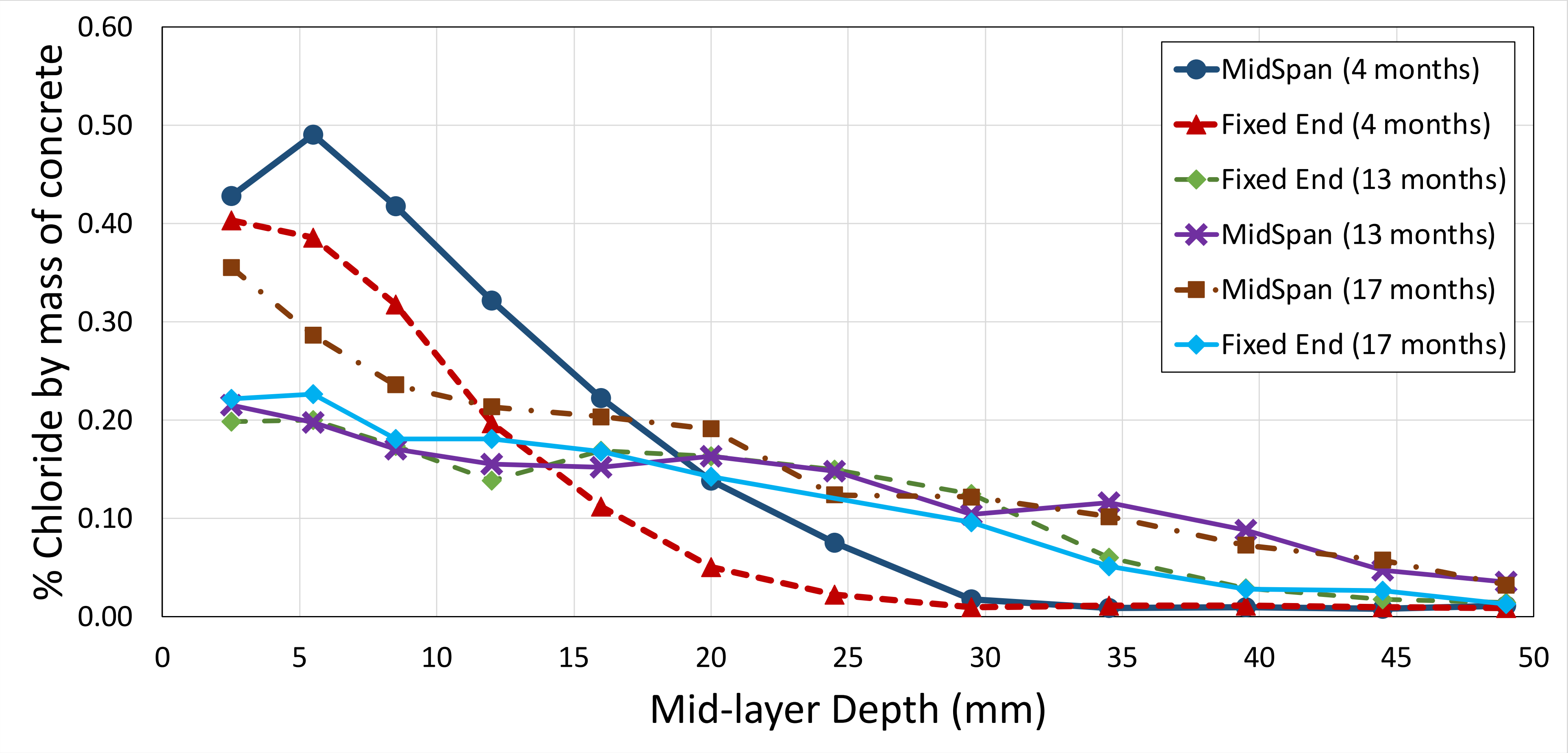
Titration Setup

* Mass value seen is tray mass used to determine approximate mass of powder collected from profiling

Lab Specimen Chloride Profile

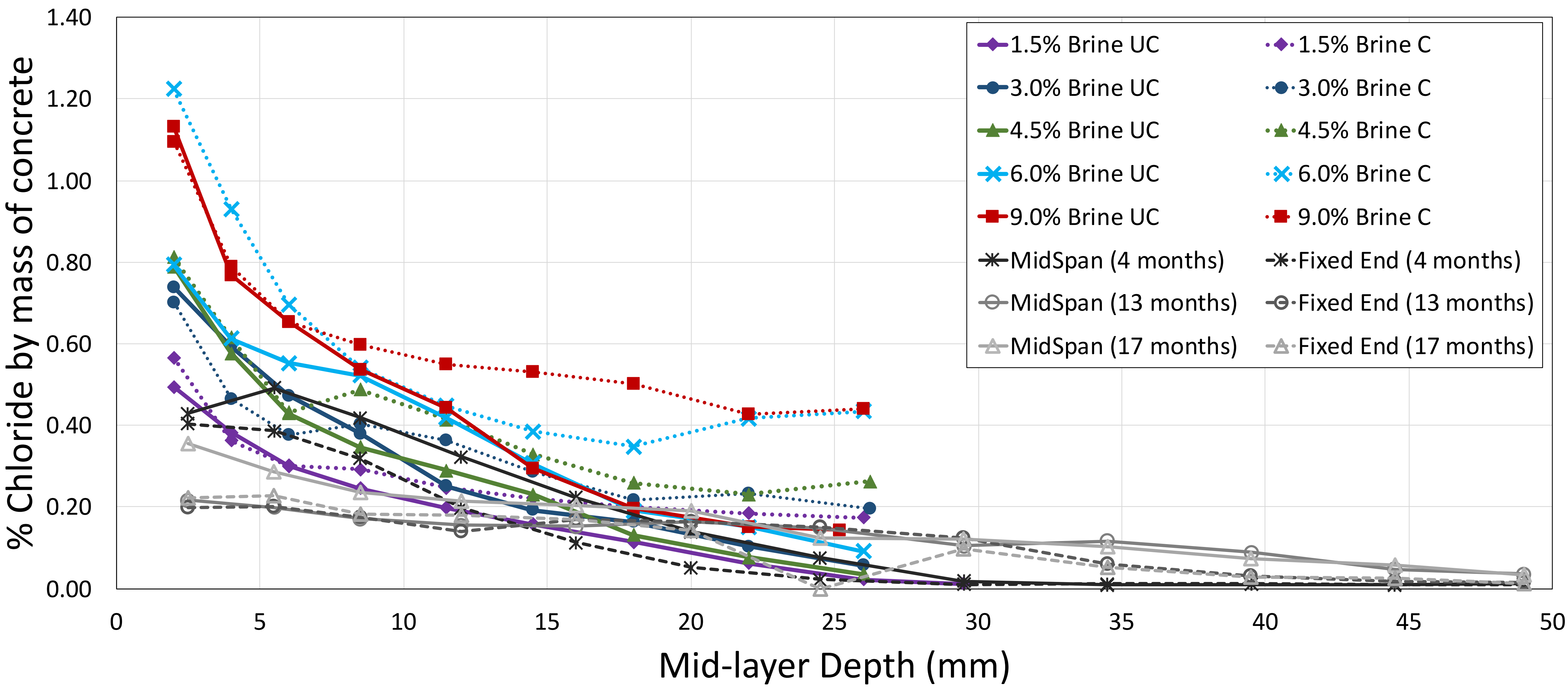


Core Samples Profile Analysis



- Recent cores show greater chloride ingress but less at layers closer to the surface
- By reinforcement chloride values for both are below 0.1%

Combined Chloride Profiles



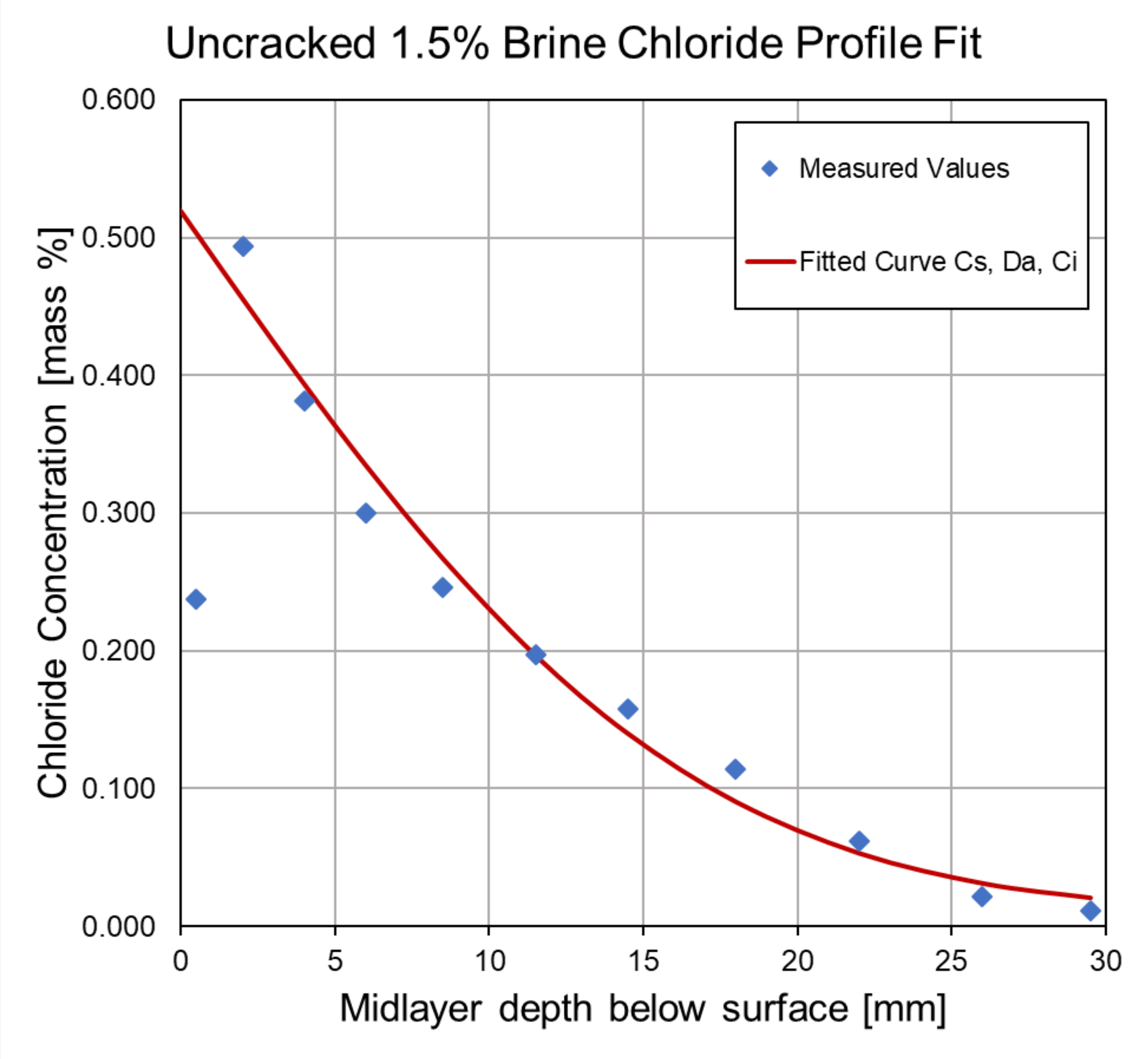
DIFFUSION COEFFICIENTS

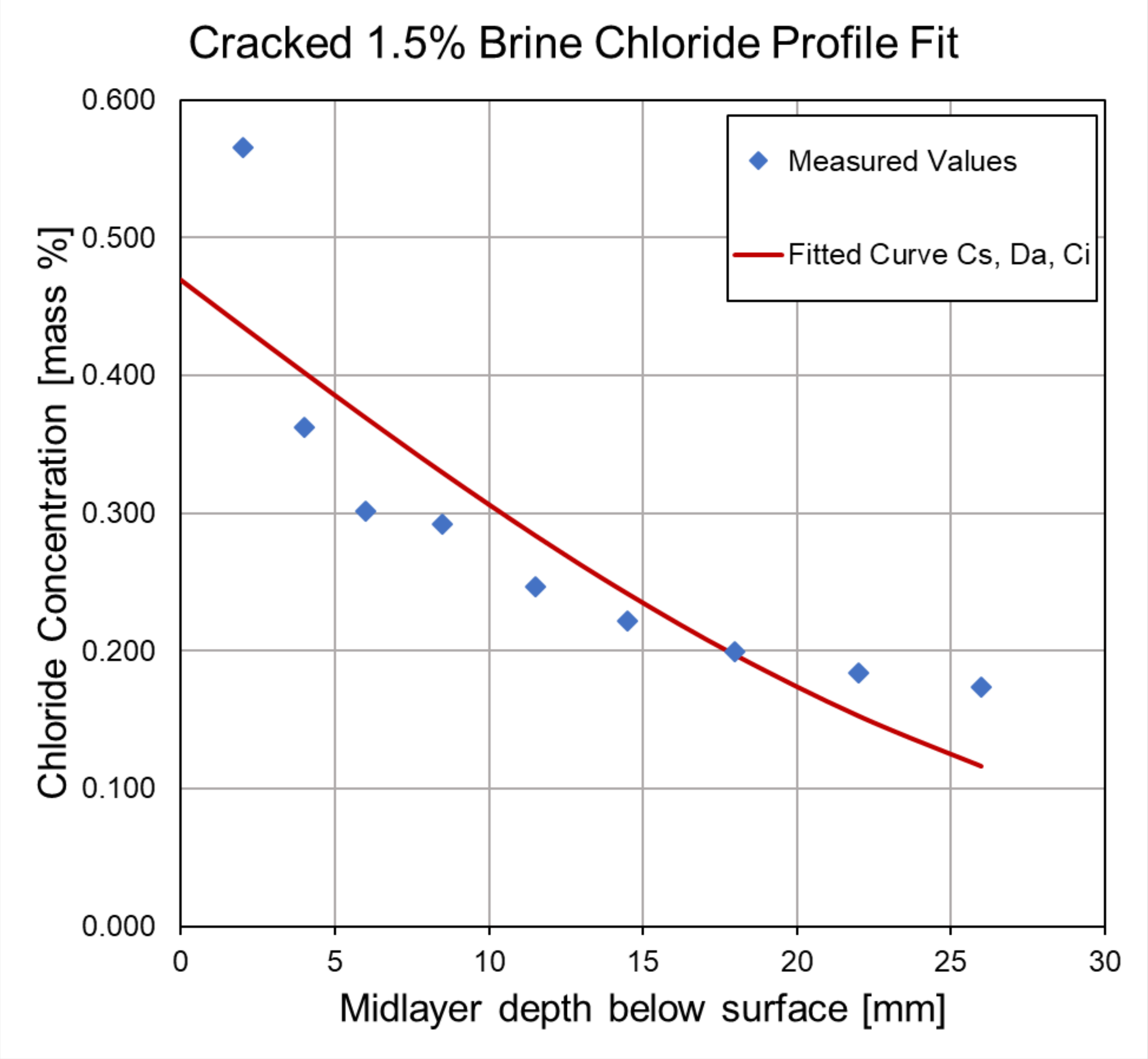
Uncracked Lab Specimens Diffusion Coefficient and Surface Chloride Content						
		1.5% Brine	3.0% Brine	4.5% Brine	6.0% Brine	9.0% Brine
$C_{s;}$ Chloride content at exposed face	[mass %]	0.520	0.804	0.823	0.830	1.140
$D_{app,C;}$ Apparent coefficient of chloride diffusion	[mm^2/yr]	89.037	81.336	74.645	136.302	87.950
	[m^2/s]	2.82E-12	2.58E-12	2.37E-12	4.32E-12	2.79E-12

Cracked Lab Specimens Diffusion Coefficient and Surface Chloride Content						
		1.5% Brine	3.0% Brine	4.5% Brine	6.0% Brine	9.0% Brine
$C_{s;}$ Chloride content at exposed face	[mass %]	0.469	0.606	0.732	1.072	0.918
$D_{app,C;}$ Apparent coefficient of chloride diffusion	[mm^2/yr]	259.201	249.788	232.969	199.418	435.382
	[m^2/s]	8.22E-12	7.92E-12	7.39E-12	6.32E-12	1.38E-11

Deck Cores Diffusion Coefficient and Surface Chloride Content							
		MidSpan (4 months)	Fixed End (4 months)	MidSpan (13 months)	Fixed End (13 months)	MidSpan (17 months)	Fixed End (17 months)
Chloride content at exposed face	[mass %]	0.706	0.626	0.221	0.231	0.293	0.257
Apparent coefficient of chloride diffusion	[mm^2/yr]	350.94	206.71	750.07	487.07	281.21	272.59
	[m^2/s]	1.11E-11	6.55E-12	2.38E-11	1.54E-11	8.92E-12	8.64E-12

1.5% Brine Chloride Fit





Chloride Content Findings

- Chloride content was **greater** in lab specimens subjected to **higher** brine concentrations
- **Similar** chloride content near surface, **greater** in cracked at depth
- Apparent coefficient of diffusion was **similar** for all uncracked specimens
- Apparent coefficient was **greater** for tested cracked specimens
  - Chloride profile fit equation not representative
- Deck cores show **high** chloride ingress at earlier testing times
  - Cores taken from similar but different locations

Ongoing Work

- Testing other concrete mixture designs
- Testing other rebar types
- Model developed from experimental data for chloride content and corrosion current

THANK YOU / QUESTIONS?