Corrosion in CSA and Other ACM Reinforced Concrete

Neal S. Berke, Ph.D., FACI

Tourney Consulting Group, LLC
Kalamazoo, MI

Outline

- Introduction
- Project Scope
- Durability Issues
- Results on Corrosion/Crack-Related Testing
- Conclusions

Introduction

- Work was part of a FHWA BAA exploring the use of:
  Novel Alternative Cementitious Materials
  for the Development of Sustainable Infrastructure
- The additional people on the Research Team:

  Kimberley Kurtis, Lisa Burris, Prasanth Alapati
  Georgia Tech

  Tyler Ley, Jacob Peery, Mehdi Khanzadeh Moradllo, Amir Hajibabaee
  Oklahoma State University

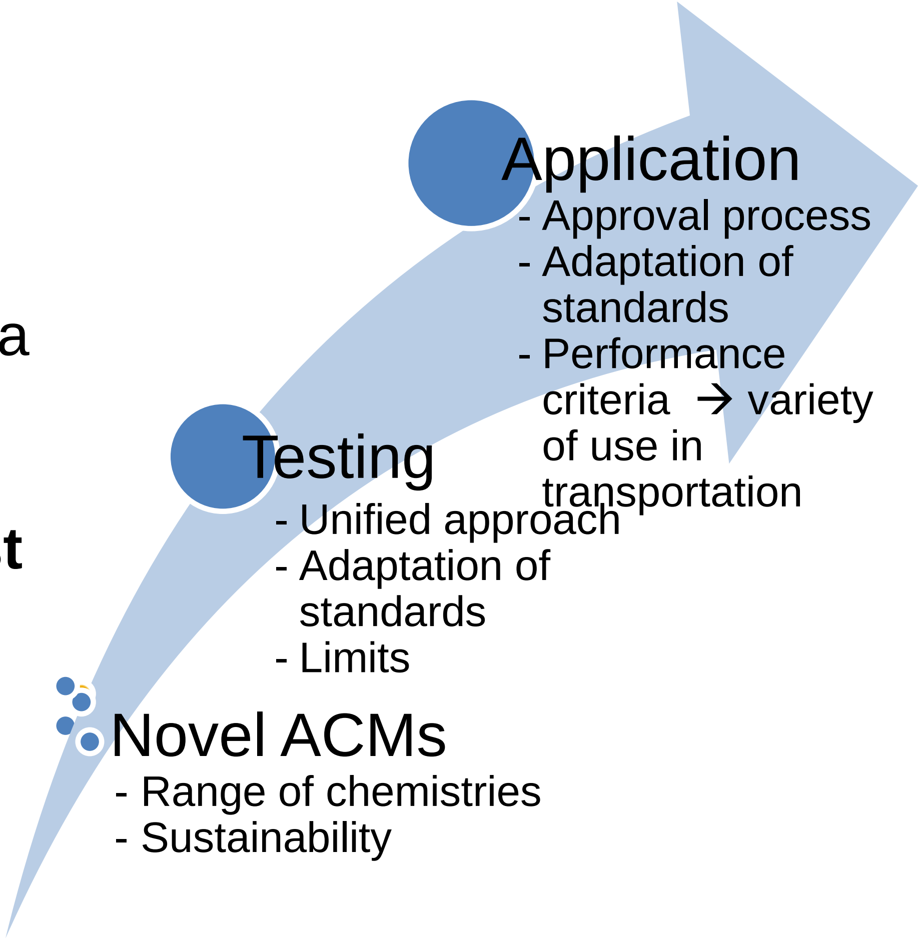
  Robert Moser, Sarah Williams
  USACE

What are Alternative Cementitious Materials (ACMs)?

- ACM – Hydraulic or chemically-activated binding material other than ordinary portland cement (OPC)
- Typical ACMs include:
  - Calcium aluminate cement (CAC)
  - Calcium sulfoaluminate cement (CSA)
  - Chemically-activated binders (AA)
  - Magnesium phosphate cement (MPC)
- ACMs can be used as binders alone, whereas supplementary cementitious materials (SCMs) are used in combination with OPC

Project Scope: Overview

- “We propose a **systematic and comprehensive investigation of novel ACMs** for application in sustainable transportation infrastructure, including evaluation of early-age material properties, long-term material properties, and a multi-scale durability investigation.
- From this, we will provide **guidelines for recommended test methods** and, when relevant, test limits for acceptance of ACMs for transportation infrastructure, including highway structures and rigid pavements along with **preliminary specifications for use**.”



Durability issues investigated

- Freezing and Thawing
- Salt Scaling
- Dimensional Stability
- **Chloride Ingress**
- **Corrosion of Reinforcing Bar**
- Sulfate Resistance
- ASR

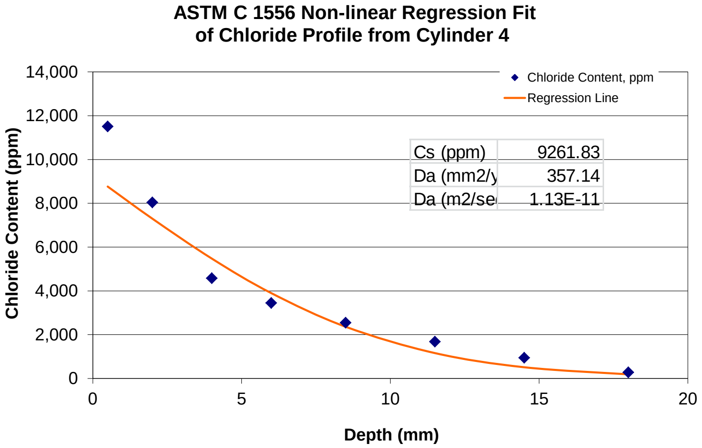
Ones in **Bold** to be covered today

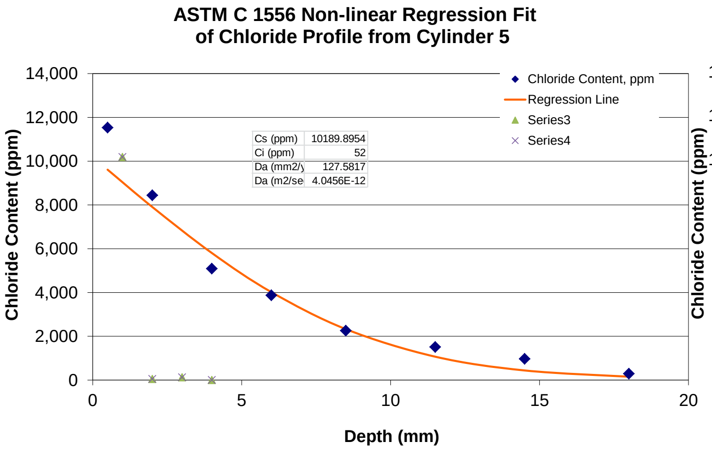
Concrete Transport

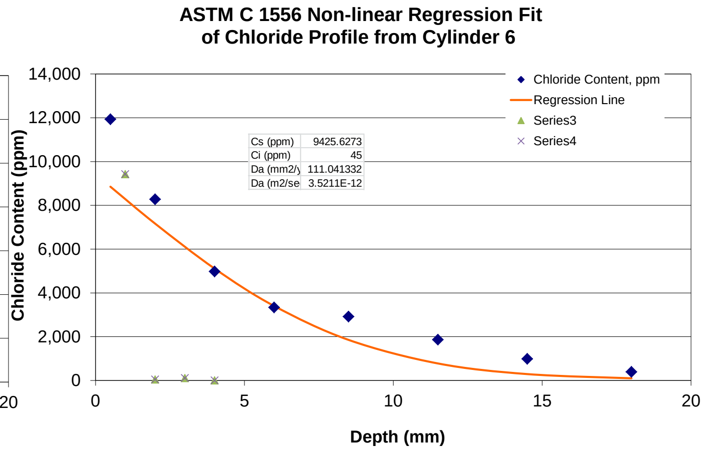
- Concretes produced at w/c or w/ACM of 0.41 except for AA1 which is at lower w/ACM content
- In addition to transport properties chloride profiles from
  - Corrosion Testing
    - At and away from crack in reinforced beams
    - Mortar specimens at same w/c or w/ACM from corrosion testing (some shown in comparison to µXRF measurements performed Oklahoma State).

OPC Concrete ASTM C1556, 28 Days

Non-Linear Regression Analysis Result	
C_s, ppm	9630
D_a, m^2/s	4.0E-12



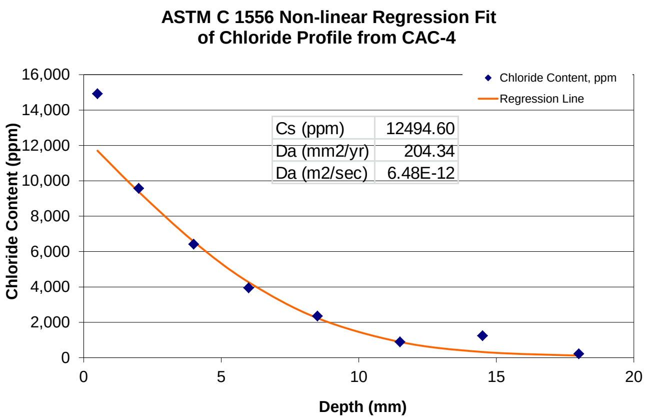


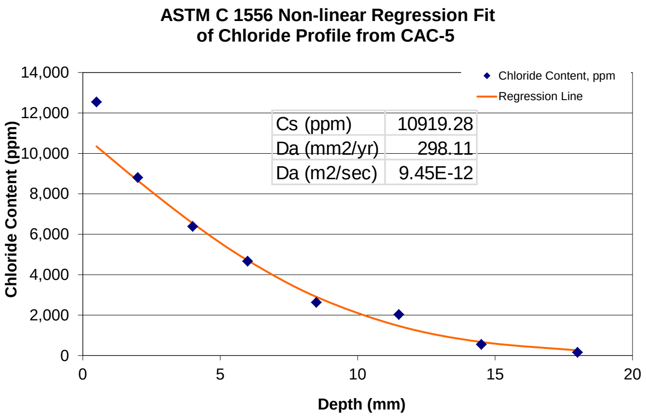


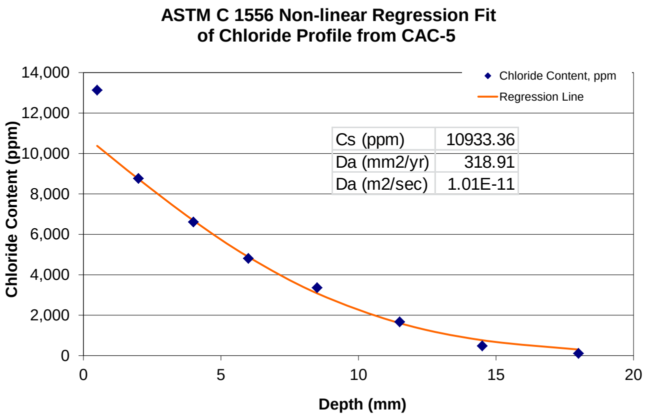
Good fit to data

CAC2 Concrete ASTM C1556, 28 Days

Non-Linear Regression Analysis Result	
C_s, ppm	11449
D_a, m^2/s	8.7E-12



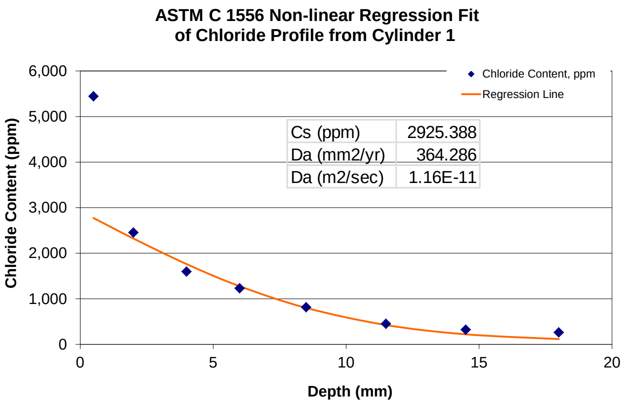


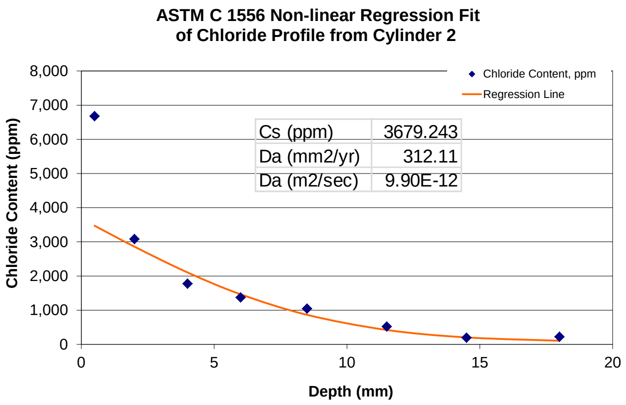


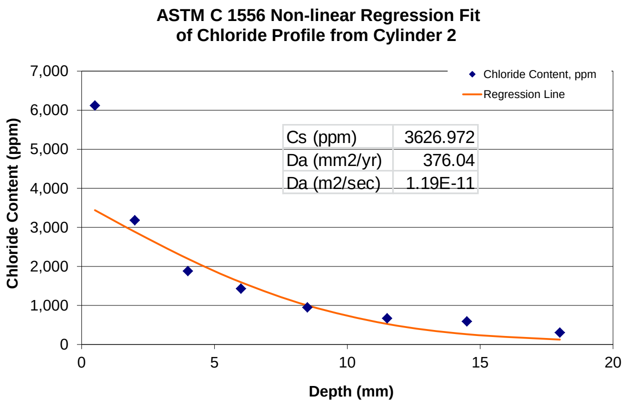
Similar to OPC with better fit to surface concentration

CSA1 Using All Points From C1556, 28 Days

Non-Linear Regression Analysis Result	
C_s, ppm	3411
D_a, m^2/s	1.1E-11

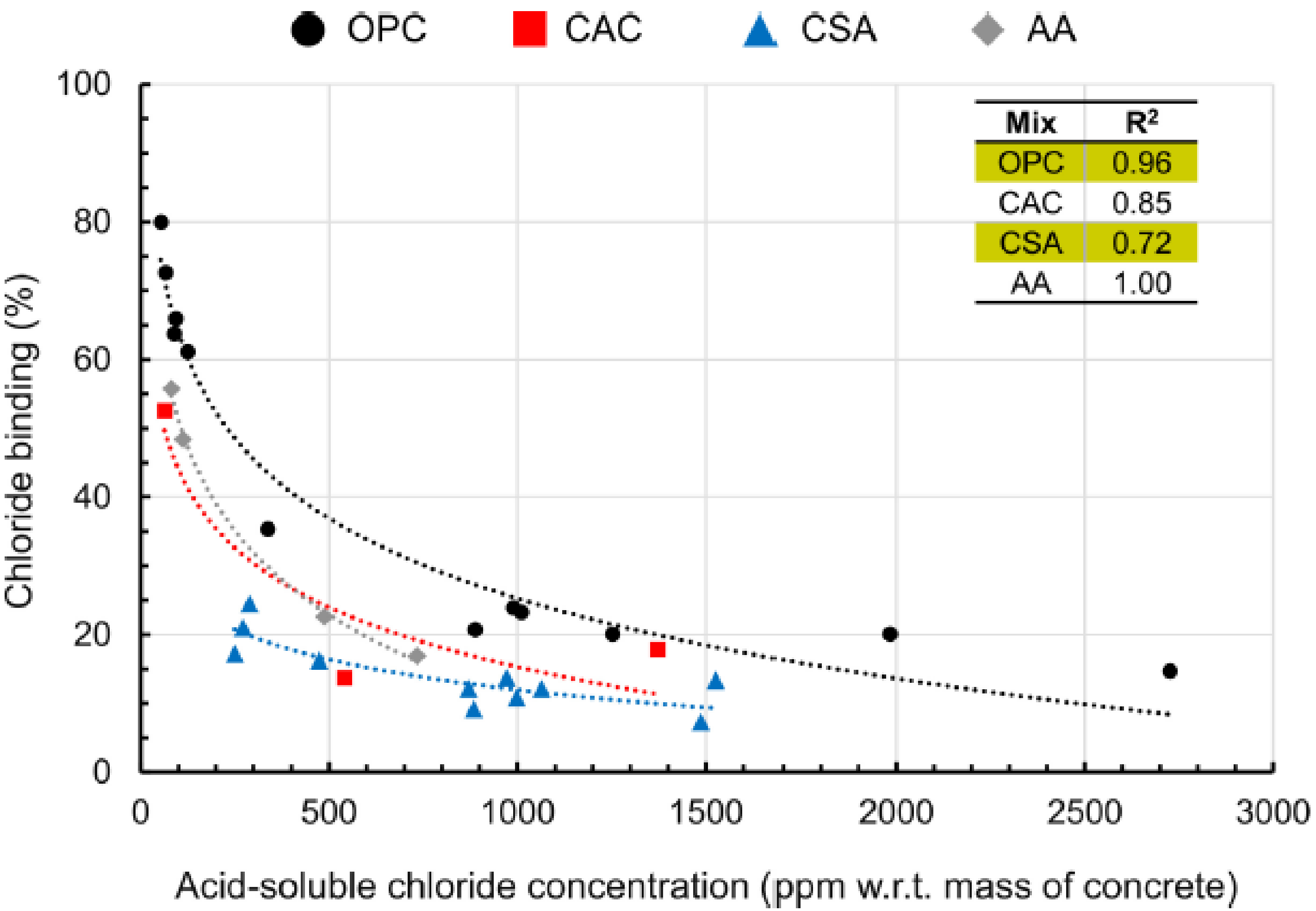




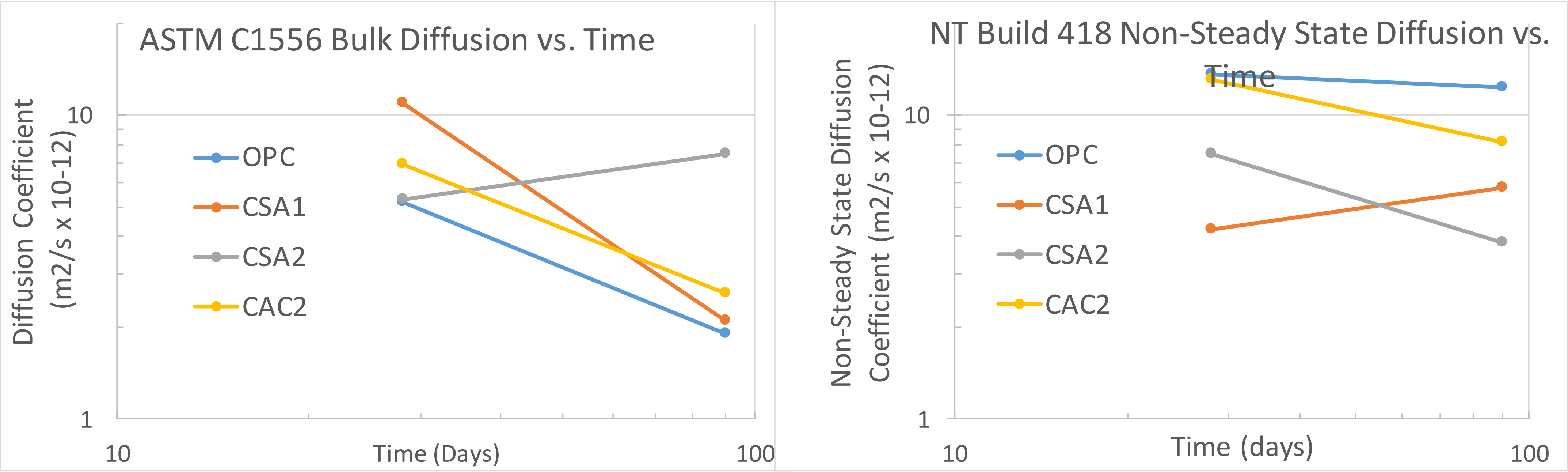


0-1 mm chloride content is high and plays minimal role in data fit

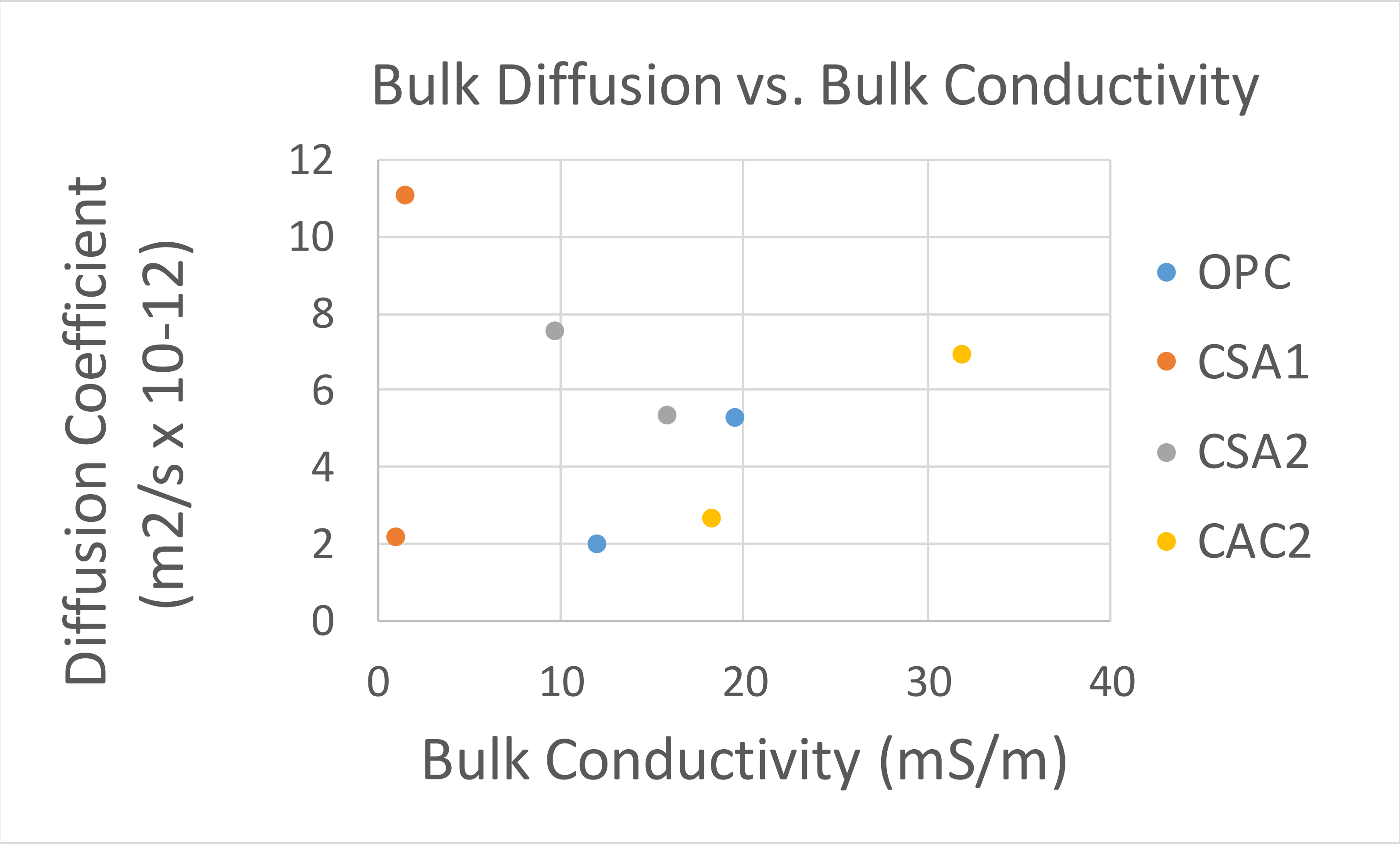
Bound Chloride as a Percentage of Total Acid Soluble Chloride



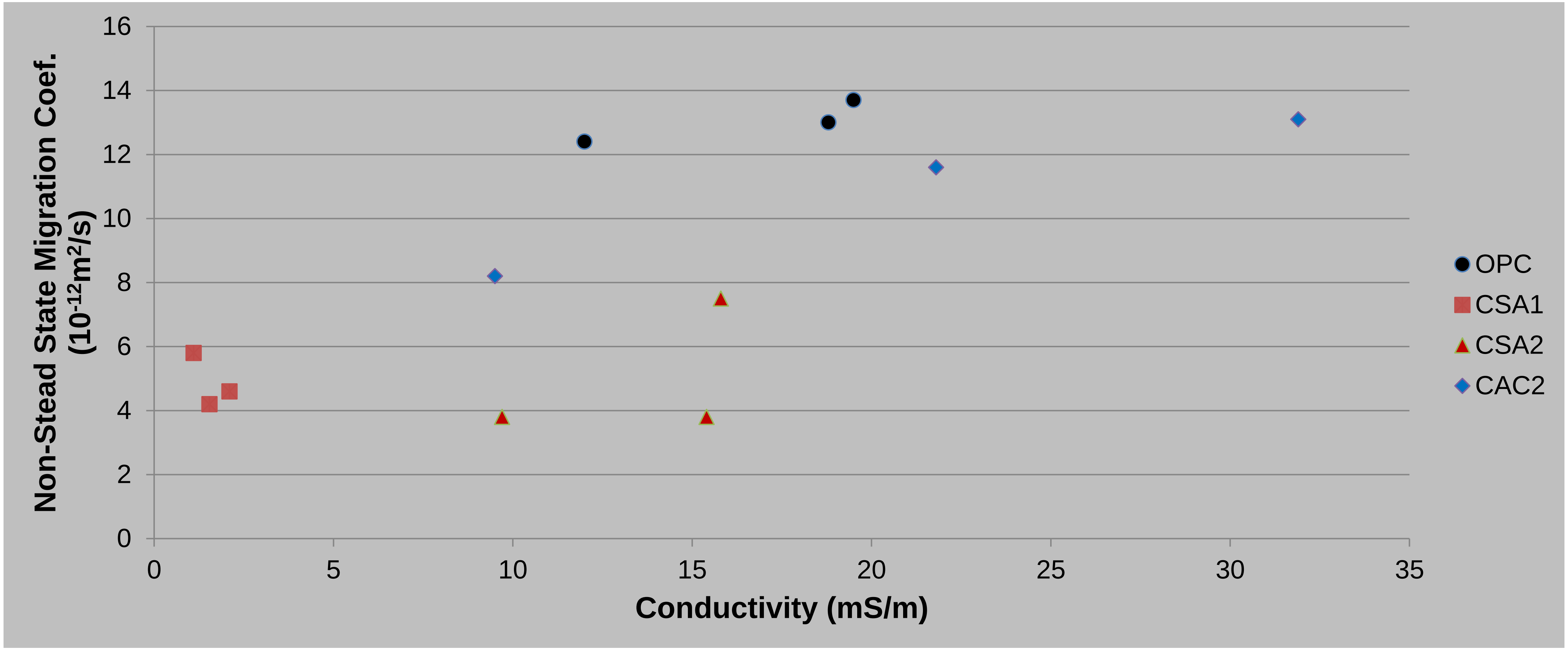
Comparison of ASTM C1556 and NT Build 492



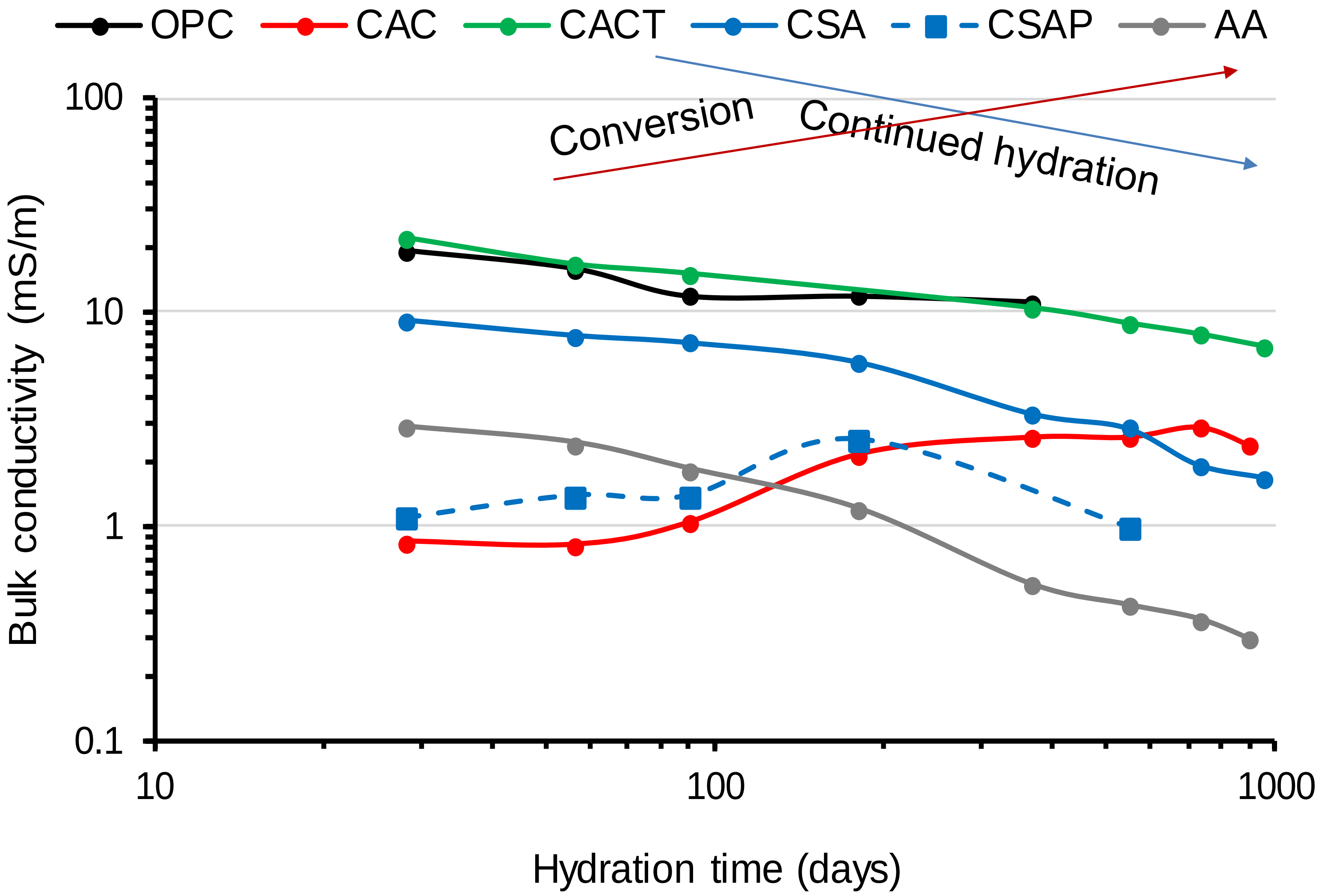
ASTM C1556 Bulk Diffusivity vs. ASTM C1760 Bulk Conductivity



Comparisons of NT Build to Conductivity



Bulk Conductivity vs. Time



Bulk Conductivity to 1/Surface Resistivity

Time	Ratio of Bulk to Surface Conductivity				
	TCSA1	TCSA2	TCAC2	TCAC3	TAA1
28	-	-	-	-	-
29	-	-	1.45	-	-
31	-	1.17	-	-	-
56	1.47	1.09	1.35	1.63	1.35
90	-	-	-	1.53	1.33
97	1.49	1.05	1.61	-	-
180	1.63	1.25	-	1.40	1.67
365	1.68	1.43	1.64	-	-

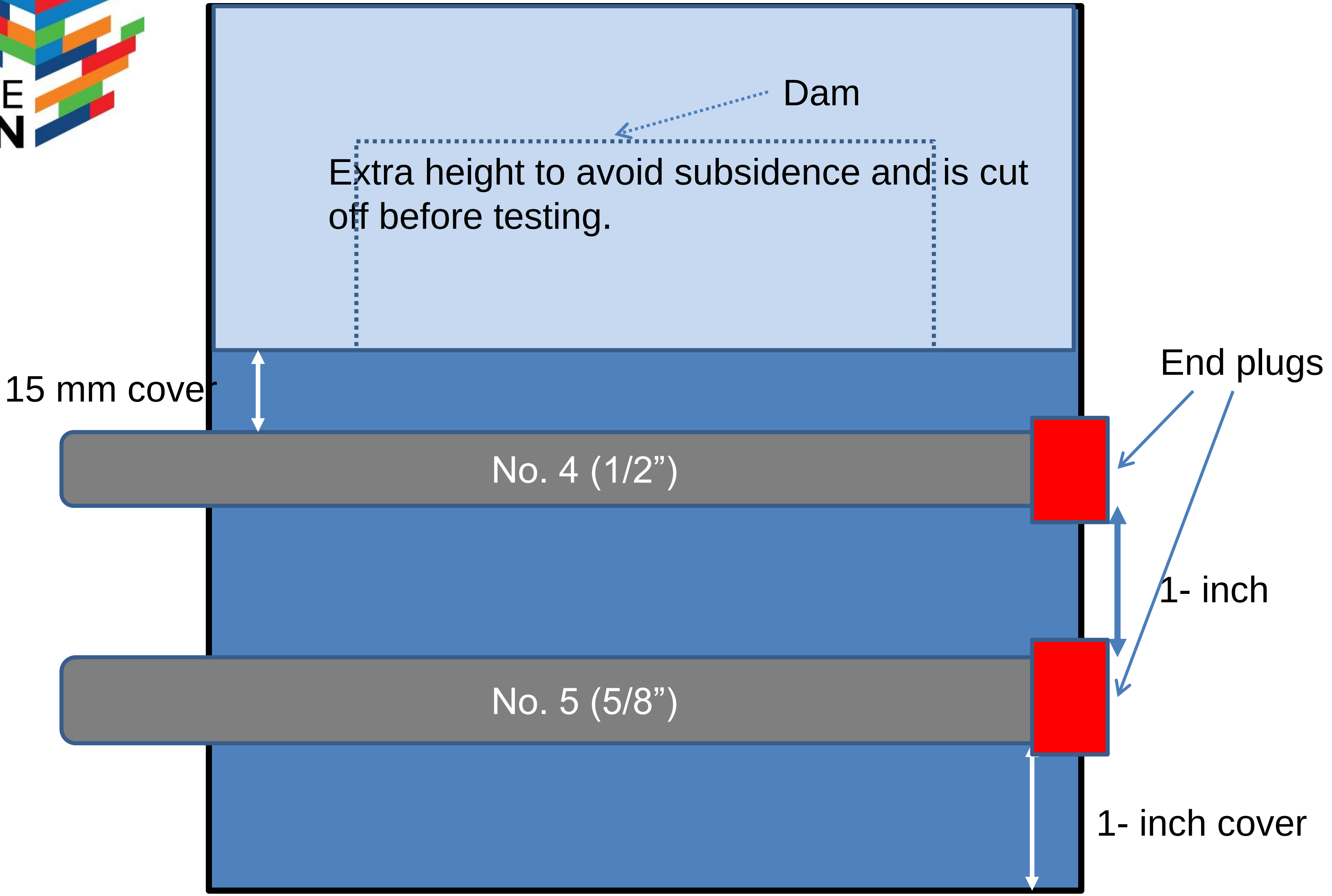
A decrease in the ratio implies that the outside is becoming less permeable relative to the bulk over time.

Data imply that the CAC3 concrete is deteriorating in time from the outside in. It is only concrete with increasing conductivity and the surface is increasing faster than the bulk.

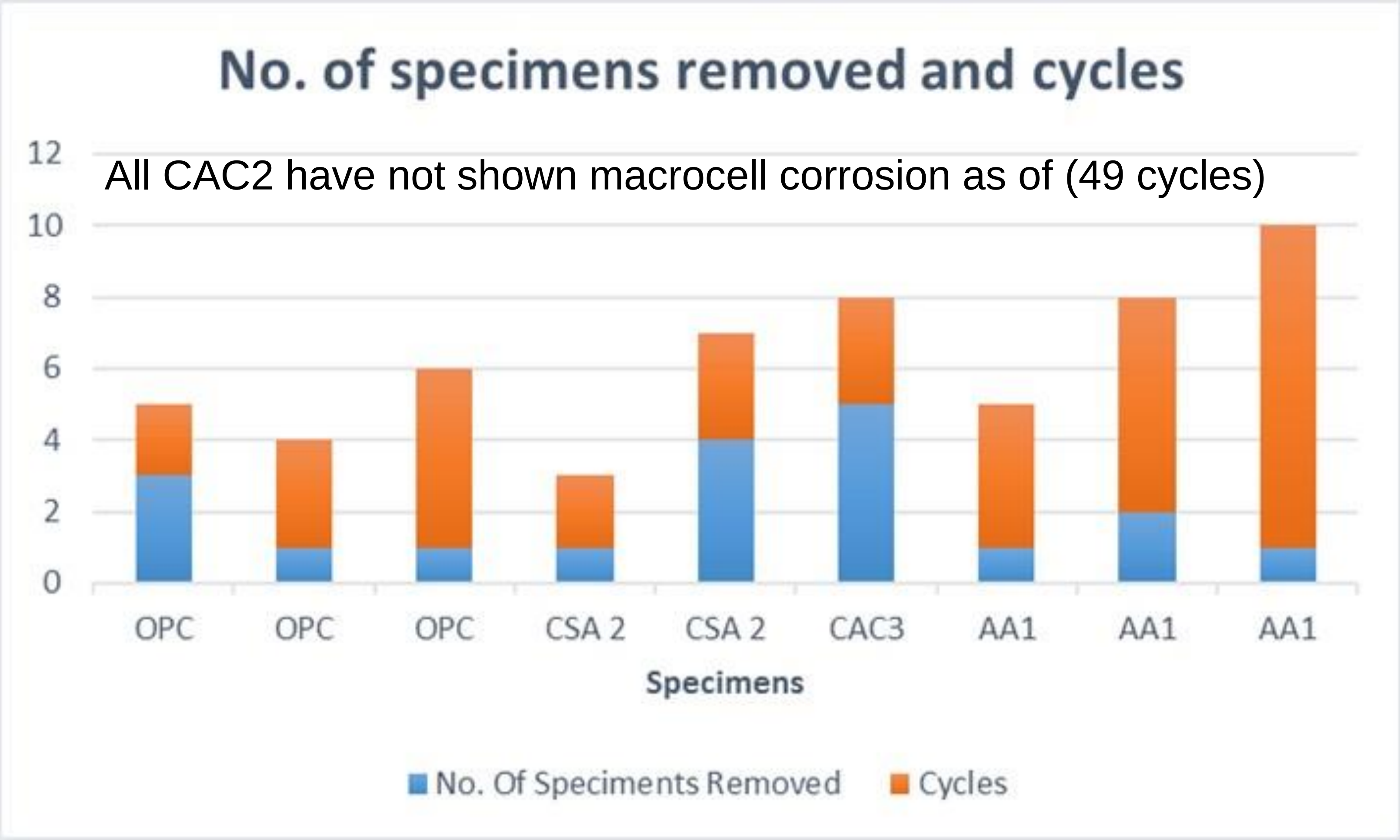
Corrosion Testing of ACMs

- Concrete Cracked and Fatigued Beams (Started in December 2016)
  - OPC/OPC
  - CSA1
  - CSA2/CSA2/CSA2B
  - CAC2
  - CAC3
  - AA1
- Mortars
  - OPC/OPC
  - CSA2/CSA2/CSA2B/CSA2(without retarder)
  - CAC2
  - CAC3
  - AA1

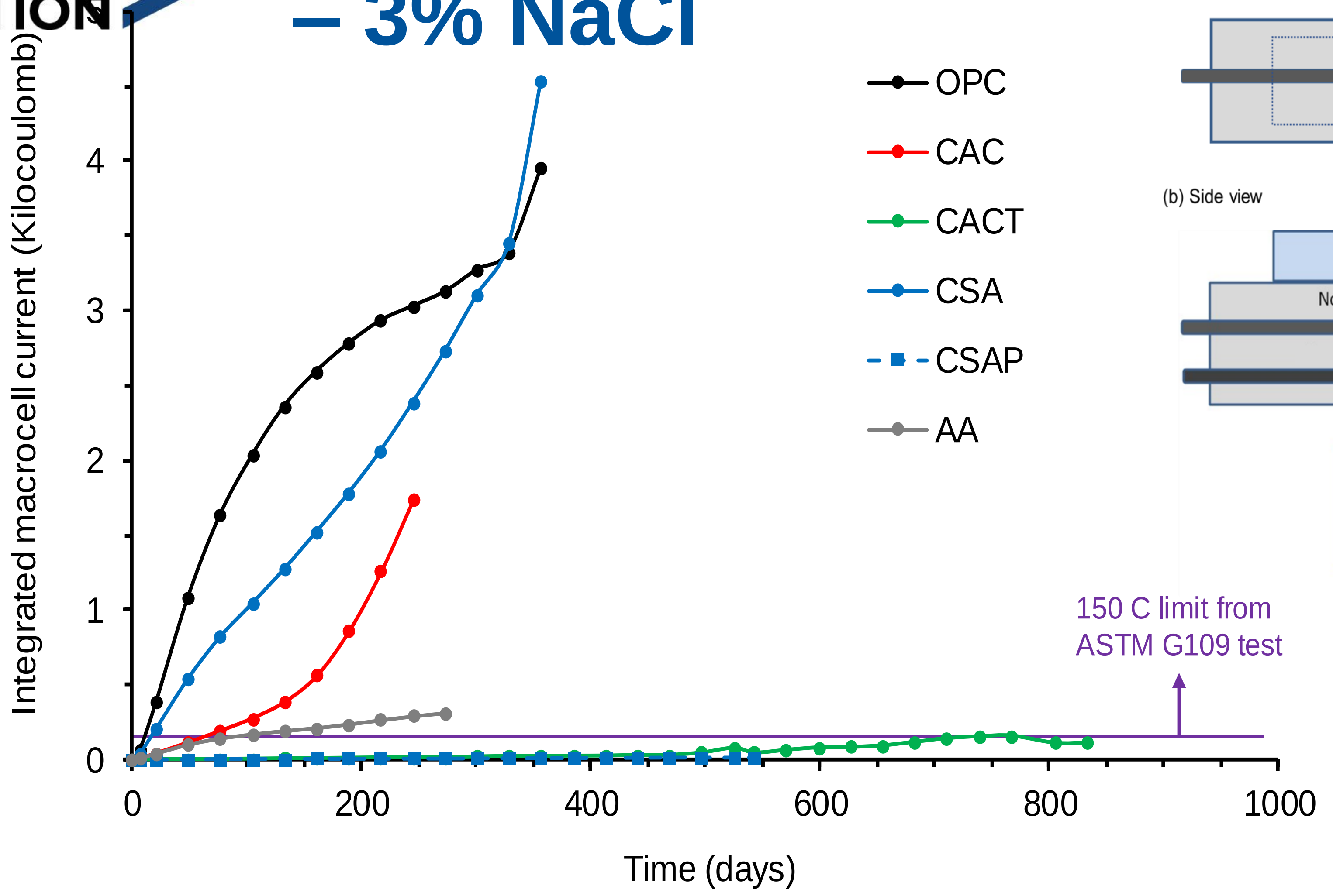
Mortar Specimen Configuration

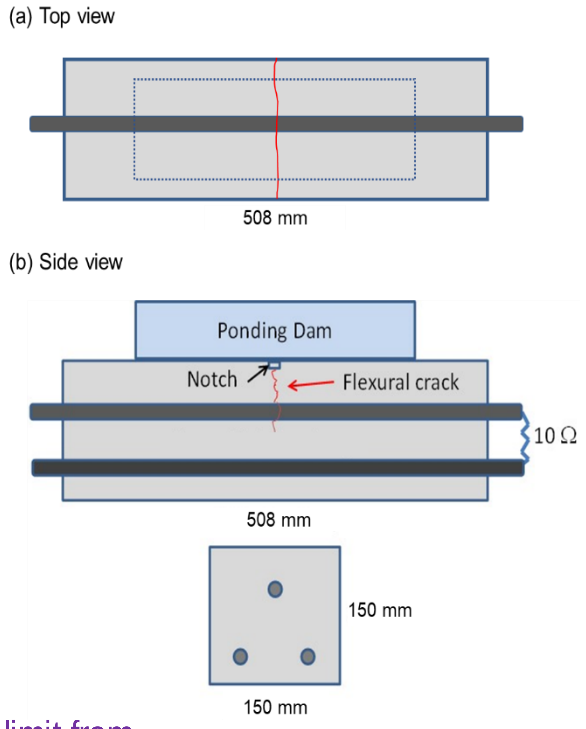


Status of Mortar Corrosion Specimens



G109 Cracked Beam Macrocell Current – 3% NaCl





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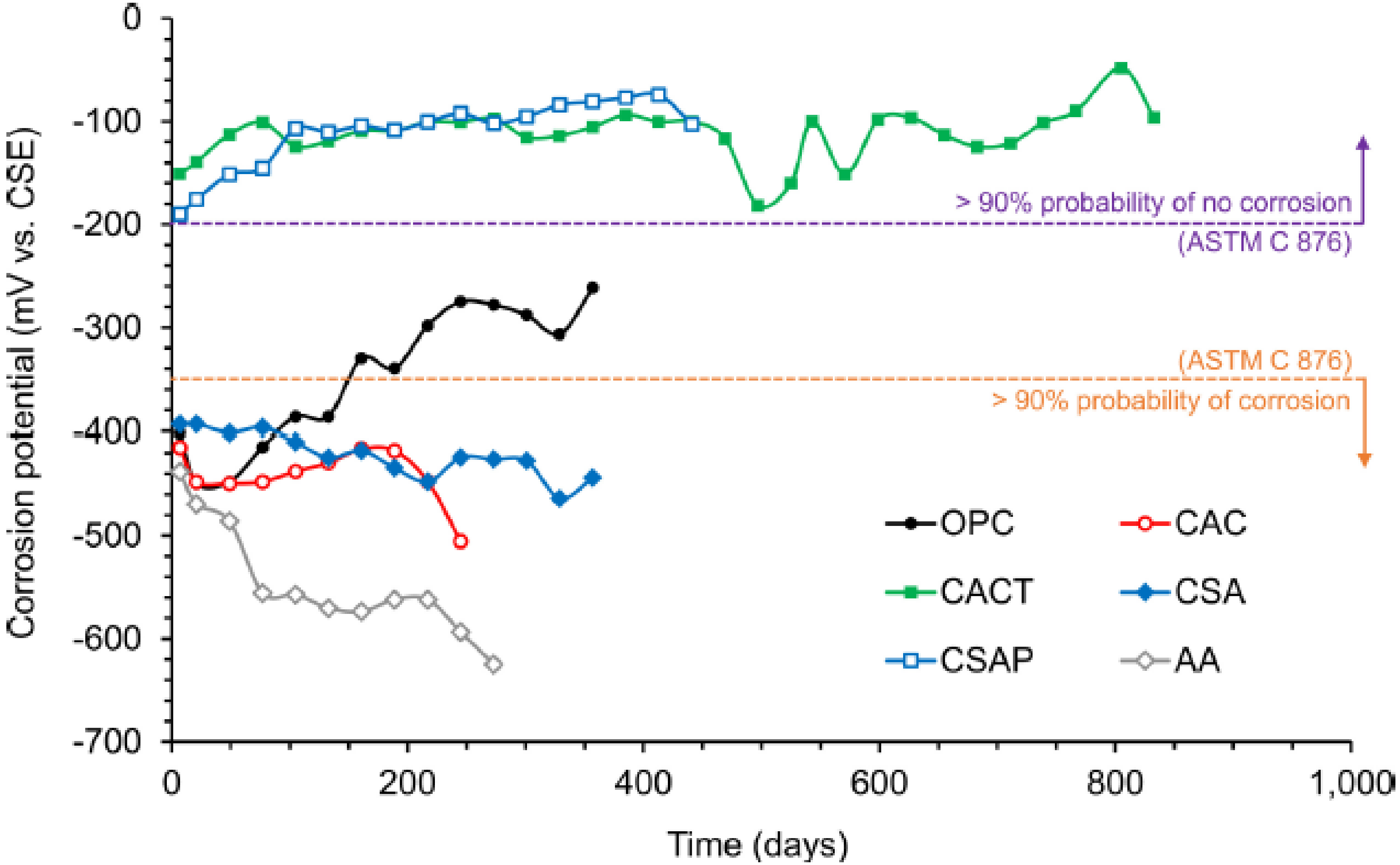
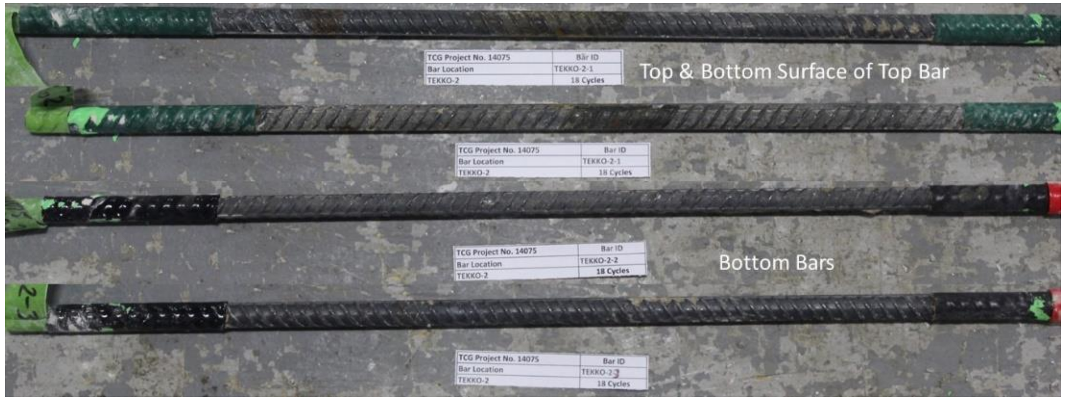
Corrosion Potentials vs. Time



Autopsy Results

Typical OPC showing corrosion on top but minor on bottom bars

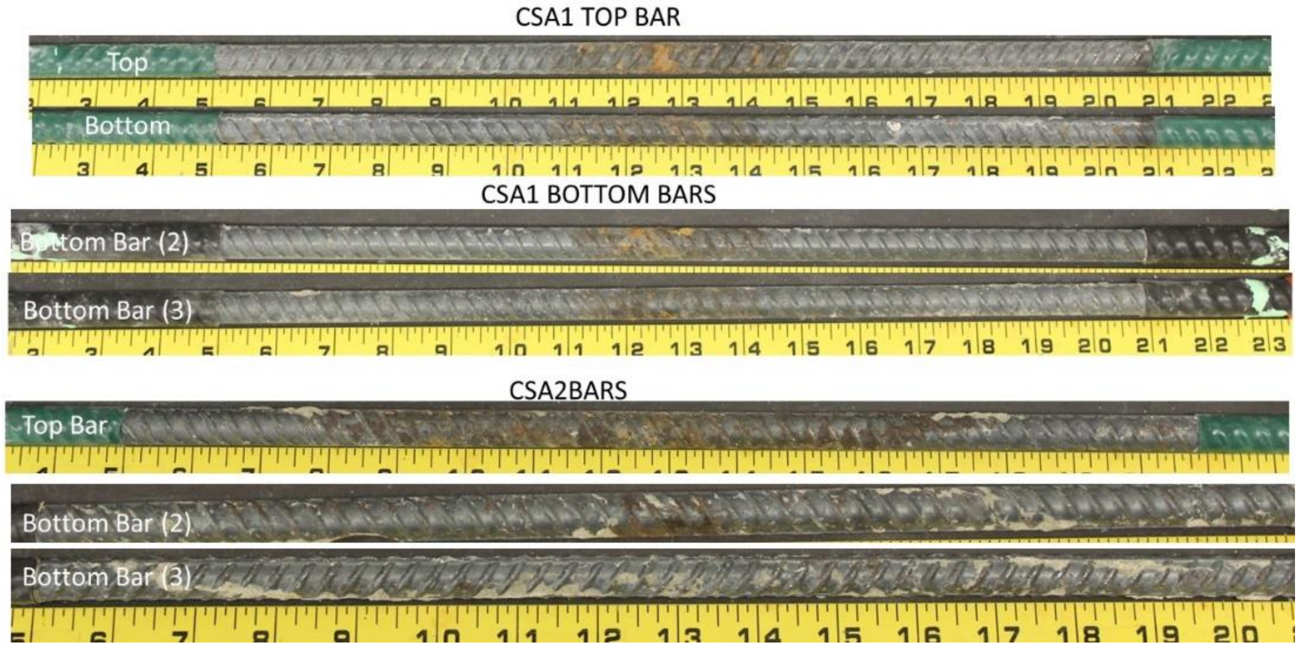
Typical CAC2 showing corrosion on top and bottom bars



Typical AA showing corrosion on top and bottom bars

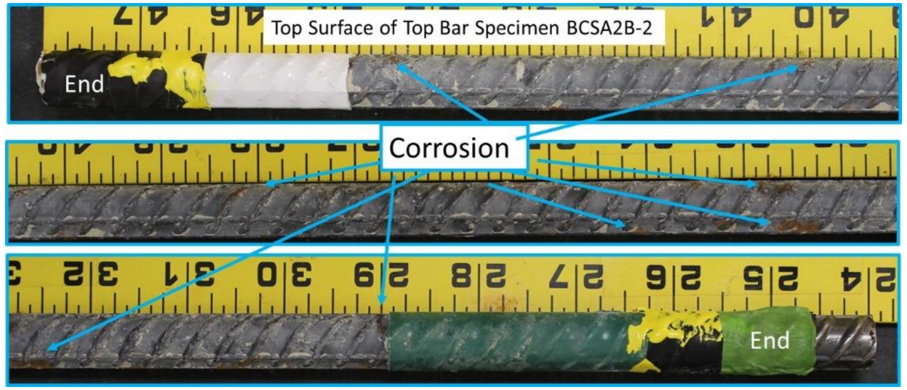
Typical CACT showing corrosion on top but not bottom bars

More Autopsy



Typical CSA1 and CSA 2 showing corrosion on top and bottom bars

More Autopsy

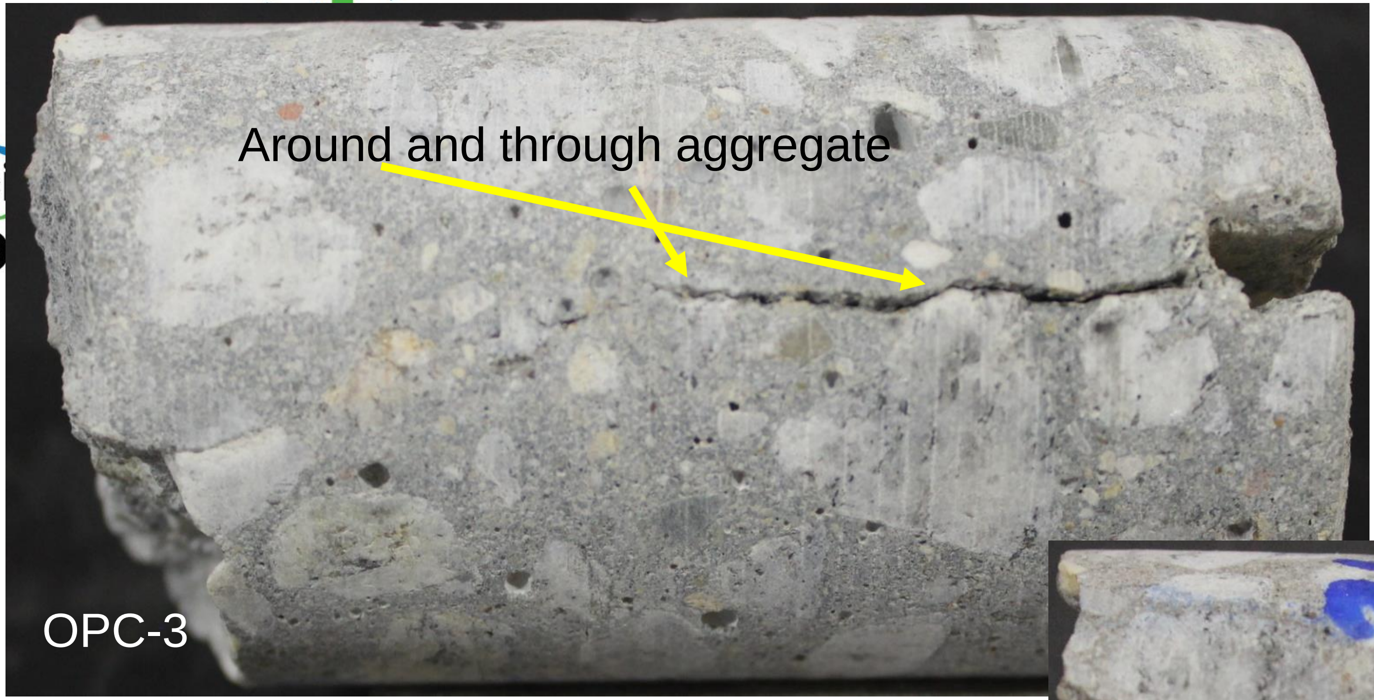


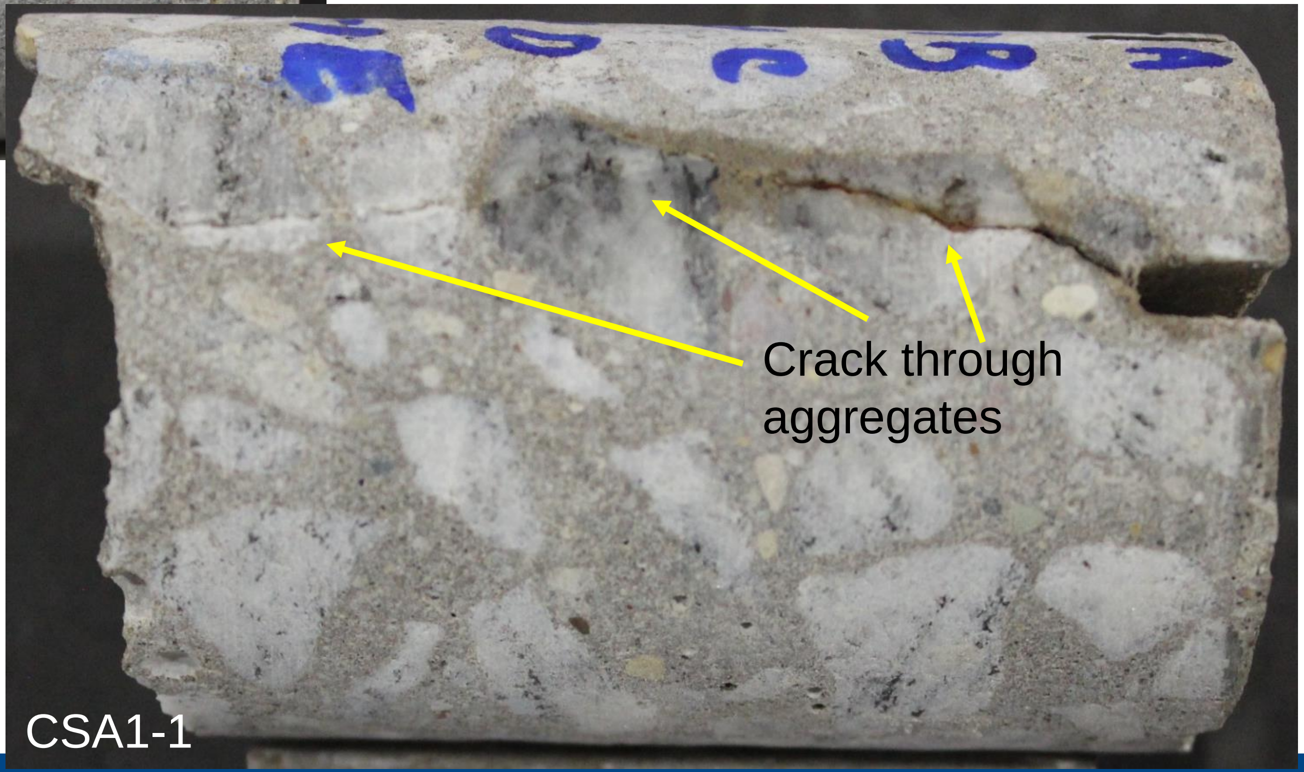
CSA2P showing corrosion near and away from crack on top bars

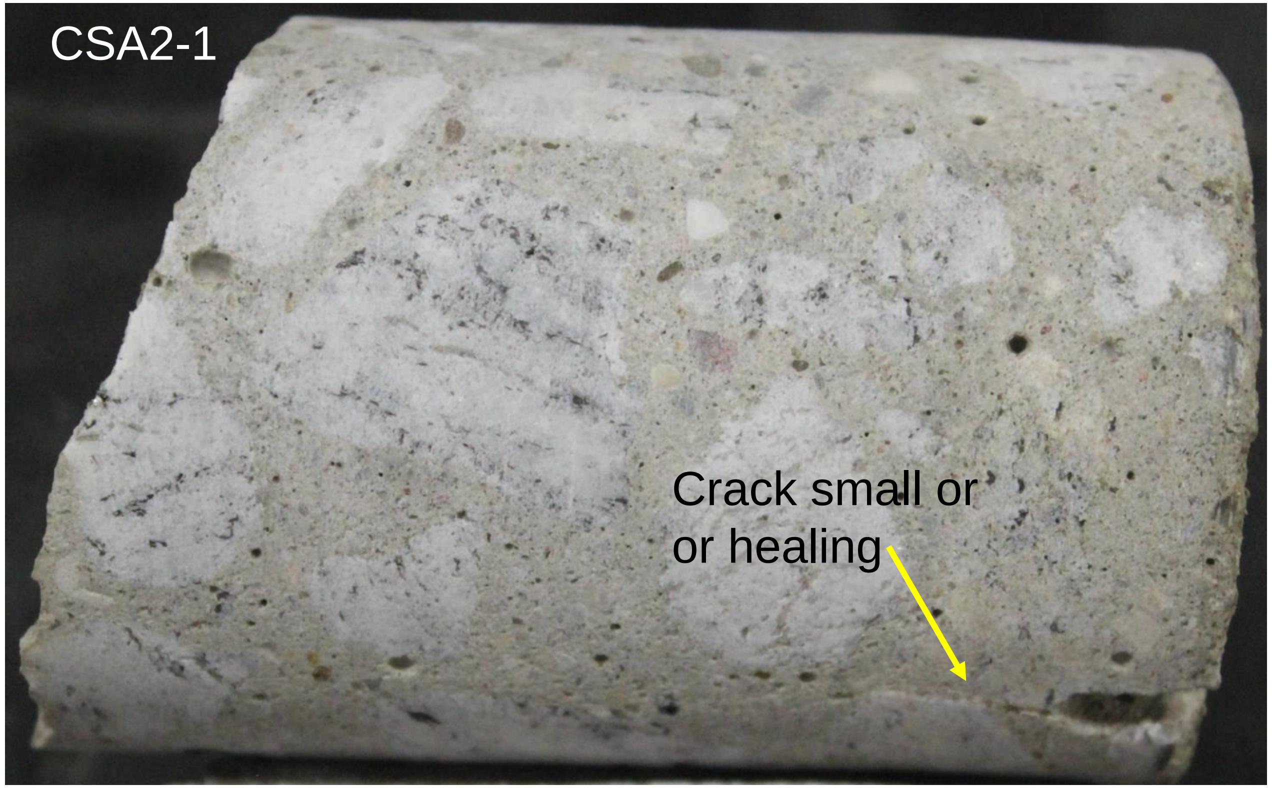
CSA2P showing minor corrosion on bottom bars

Overall Corrosion Results

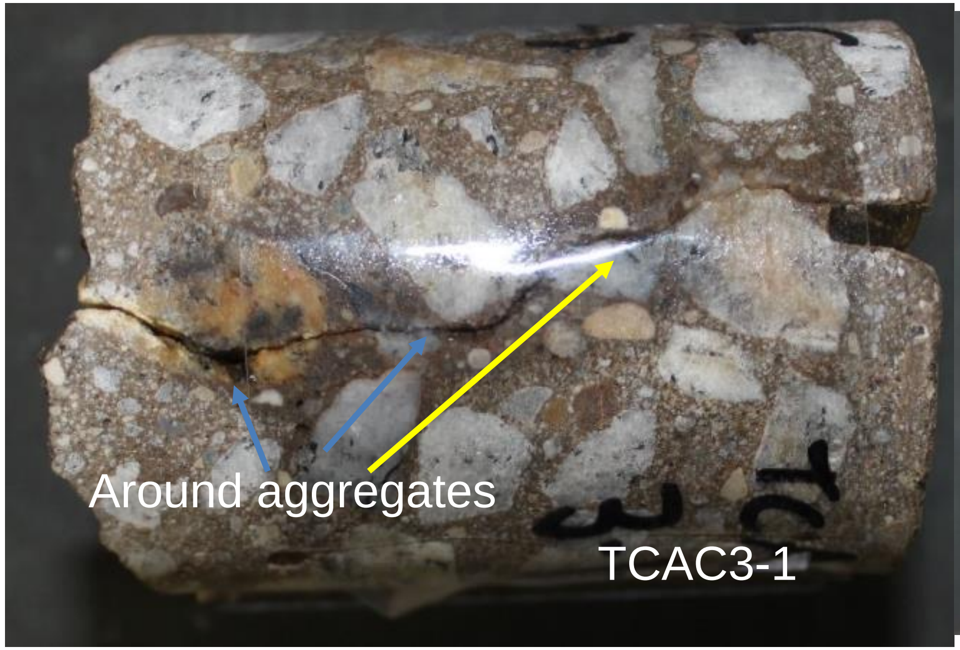
- CACT showed best corrosion performance in macrocell currents and actual corrosion of the bars.
- CSA2P had good macrocell corrosion performance but still had some corrosion. Corrosion on bottom bars would offset some macrocell performance.
- OPC had corrosion on the top bar and high macrocell currents but none to very small corrosion on bottom bars.
- CSA1, CSA2, CAC2 had high macrocell currents somewhat reduced by a large amount of corrosion on bottom as well as top bars.
- AA1 had lower macrocell currents than OPC but more corrosion on the bottom bars.

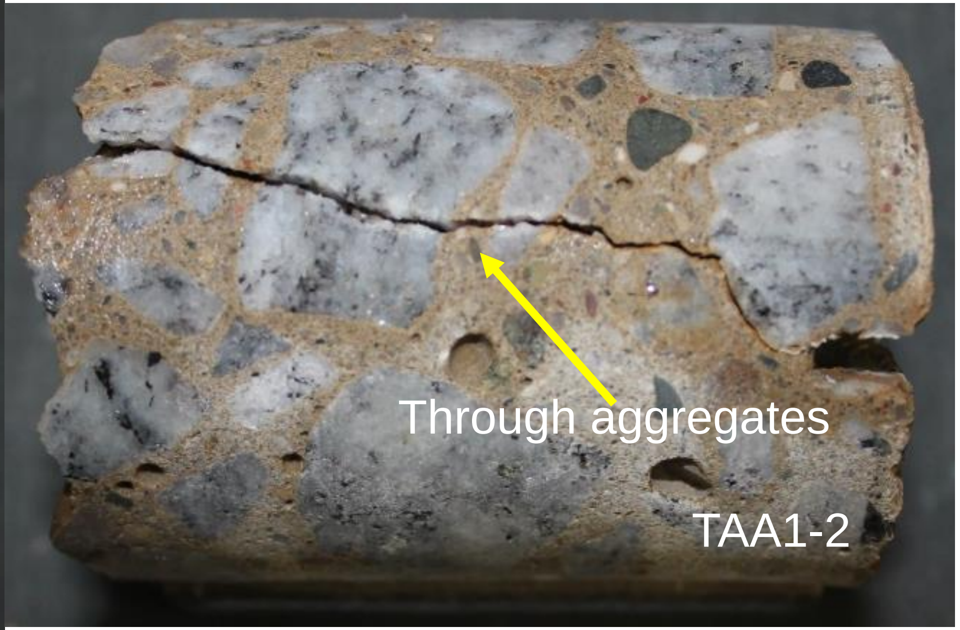

Around and through aggregate
OPC-3


Crack through aggregates
CSA1-1


CSA2-1
Crack small or
or healing

Crack Propagation

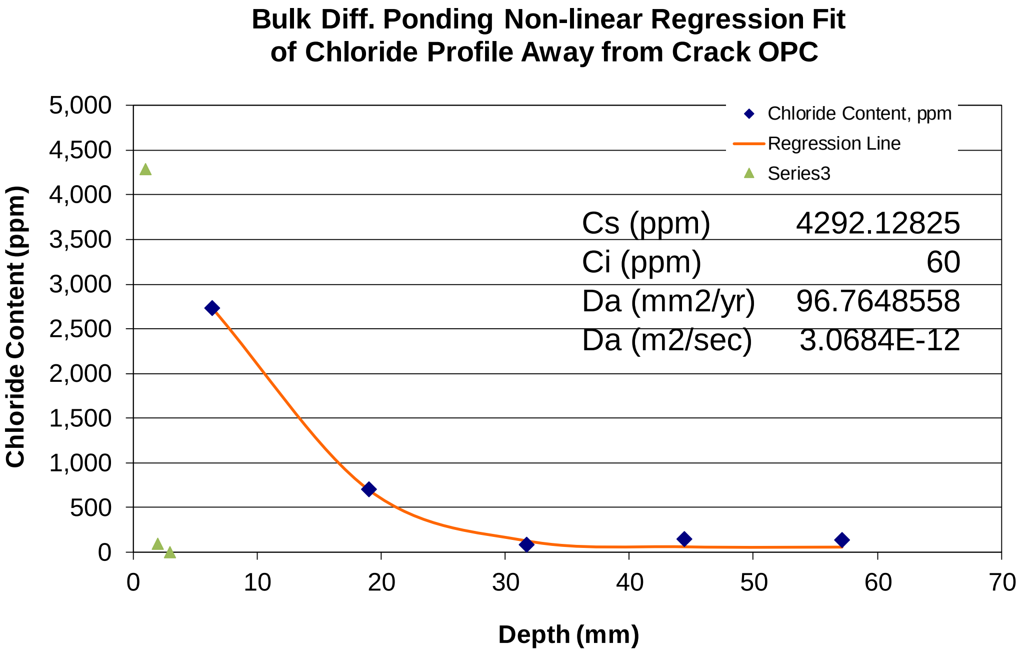


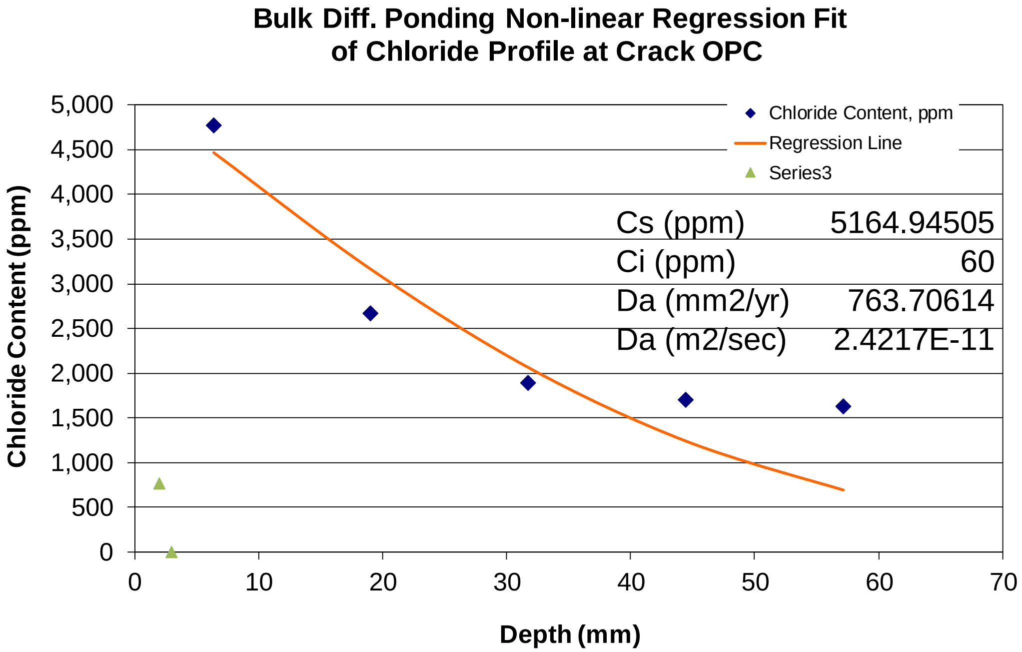


Synopsis of Cracking

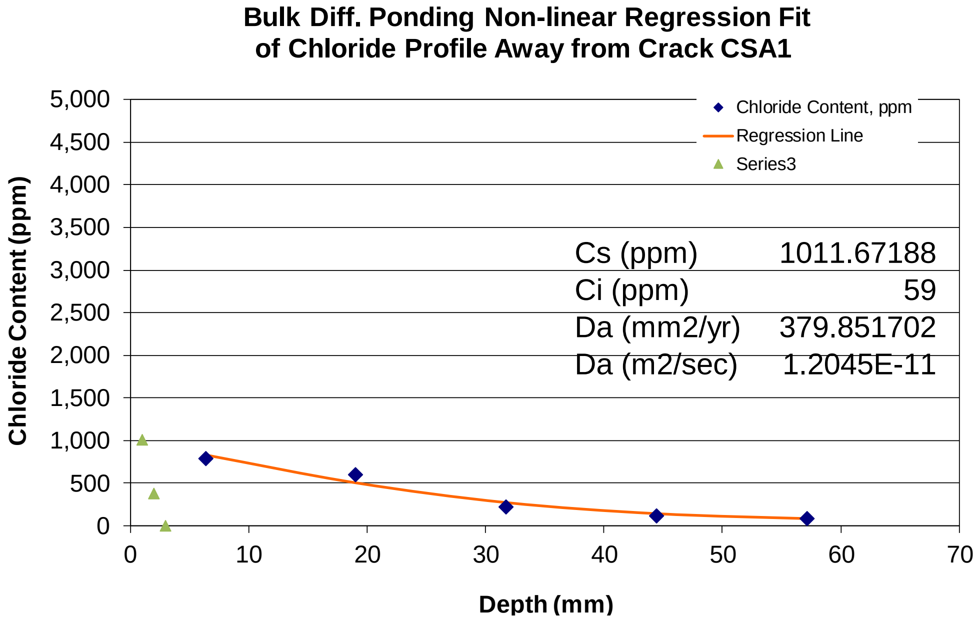
- OPC showed cracking through aggregates and around aggregates
- AA1 and CSA1 had cracking through the aggregates
- CAC3 only showed cracking around the aggregates
- CSA2 specimens had only small crack width
  - Self repaired?
  - As will be shown only ACM showing a reduction in chloride into the crack
- CAC2 (CACT) specimens went into corrosion last and only on the top bar

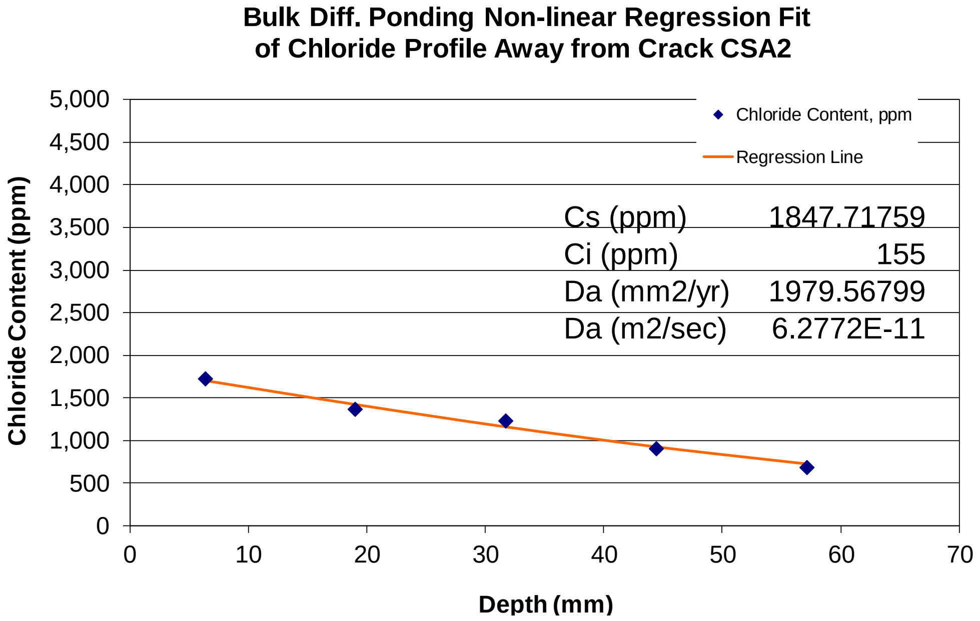
Chloride Profiles for OPC Concrete after 22 Cycles

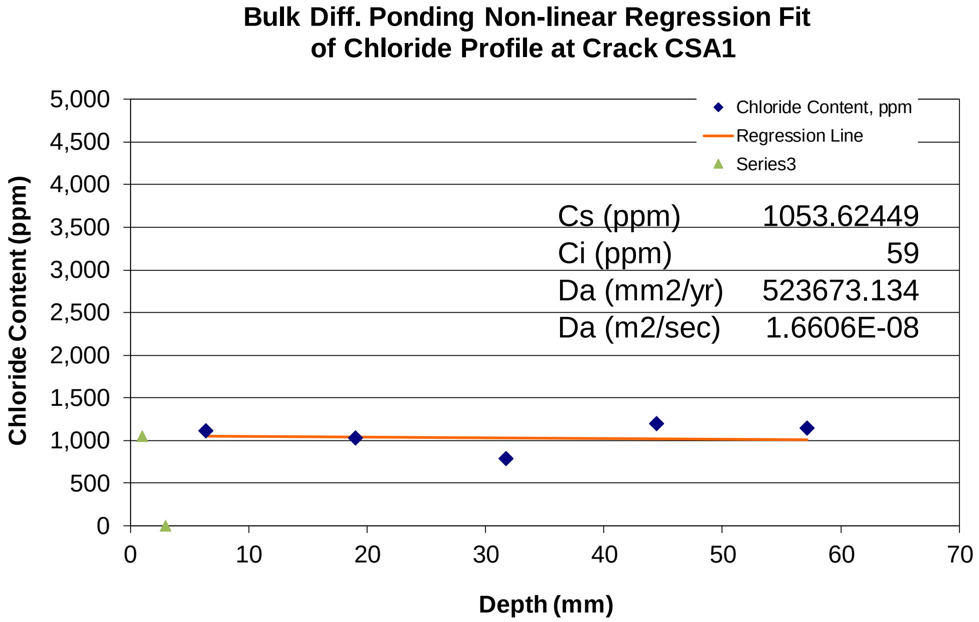


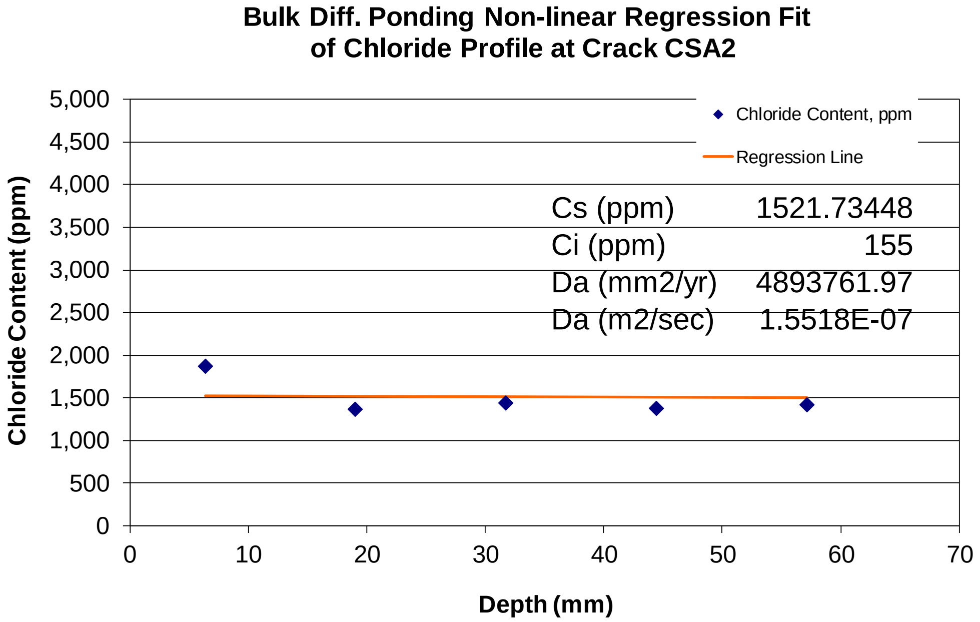


Chloride Profiles for CSA1 & CSA 2 Concretes after 22 Cycles



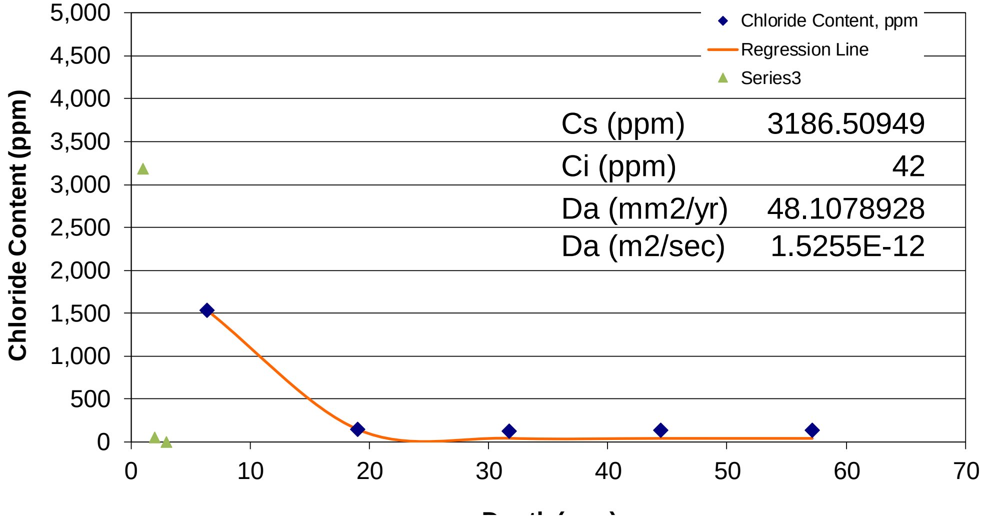




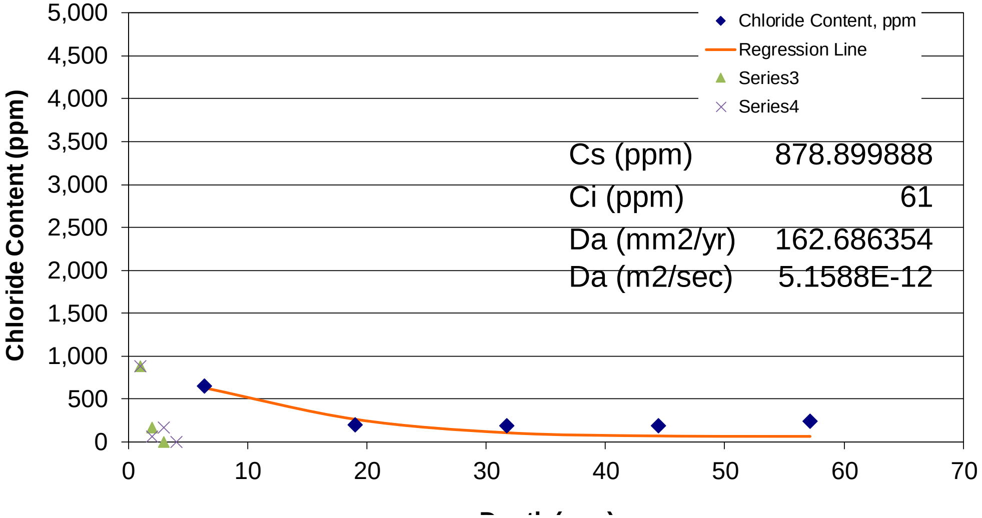


Chloride Profiles after 18 Cycles

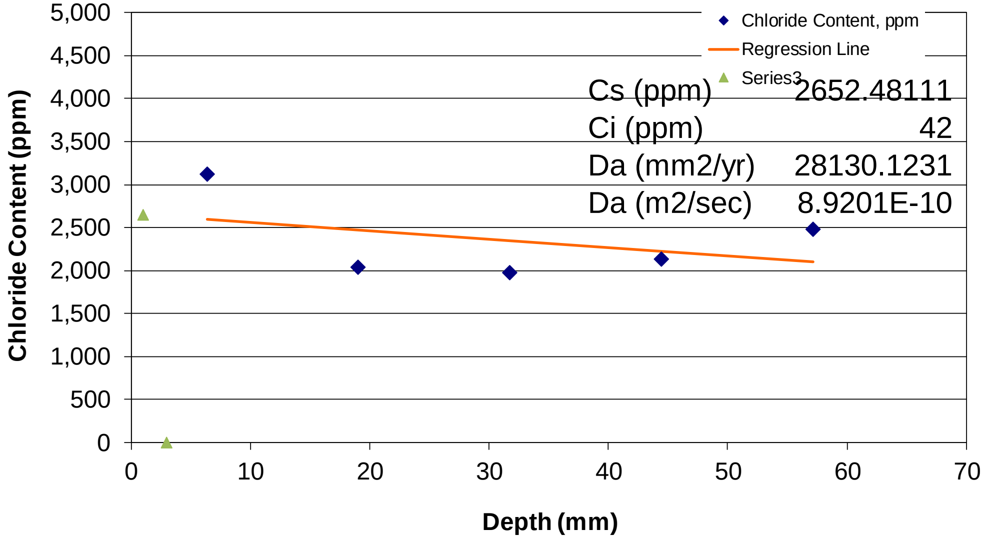
Bulk Diff. Ponding Non-linear Regression Fit of Chloride Profile Away from Crack TCAC3



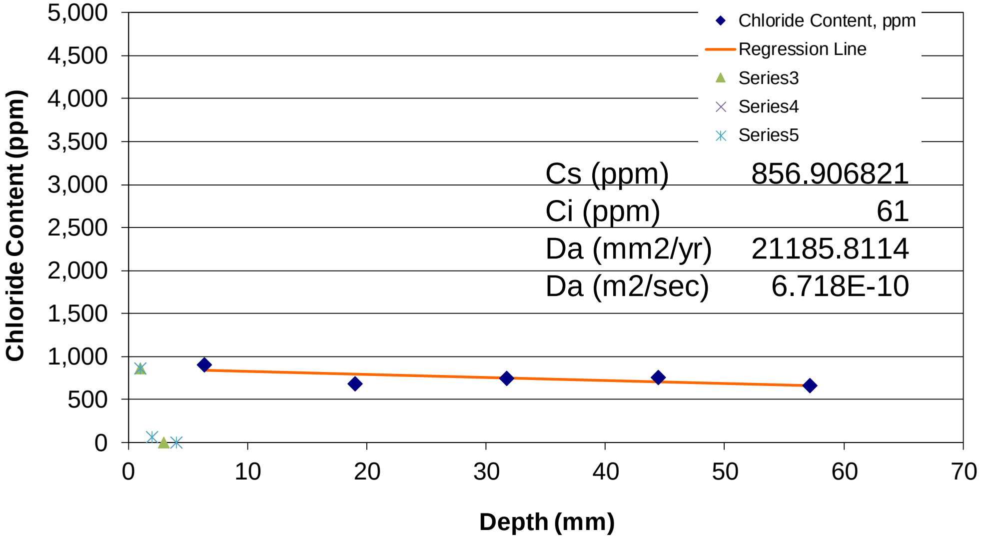
Bulk Diff. Ponding Non-linear Regression Fit of Chloride Profile AA1 Away From Crack



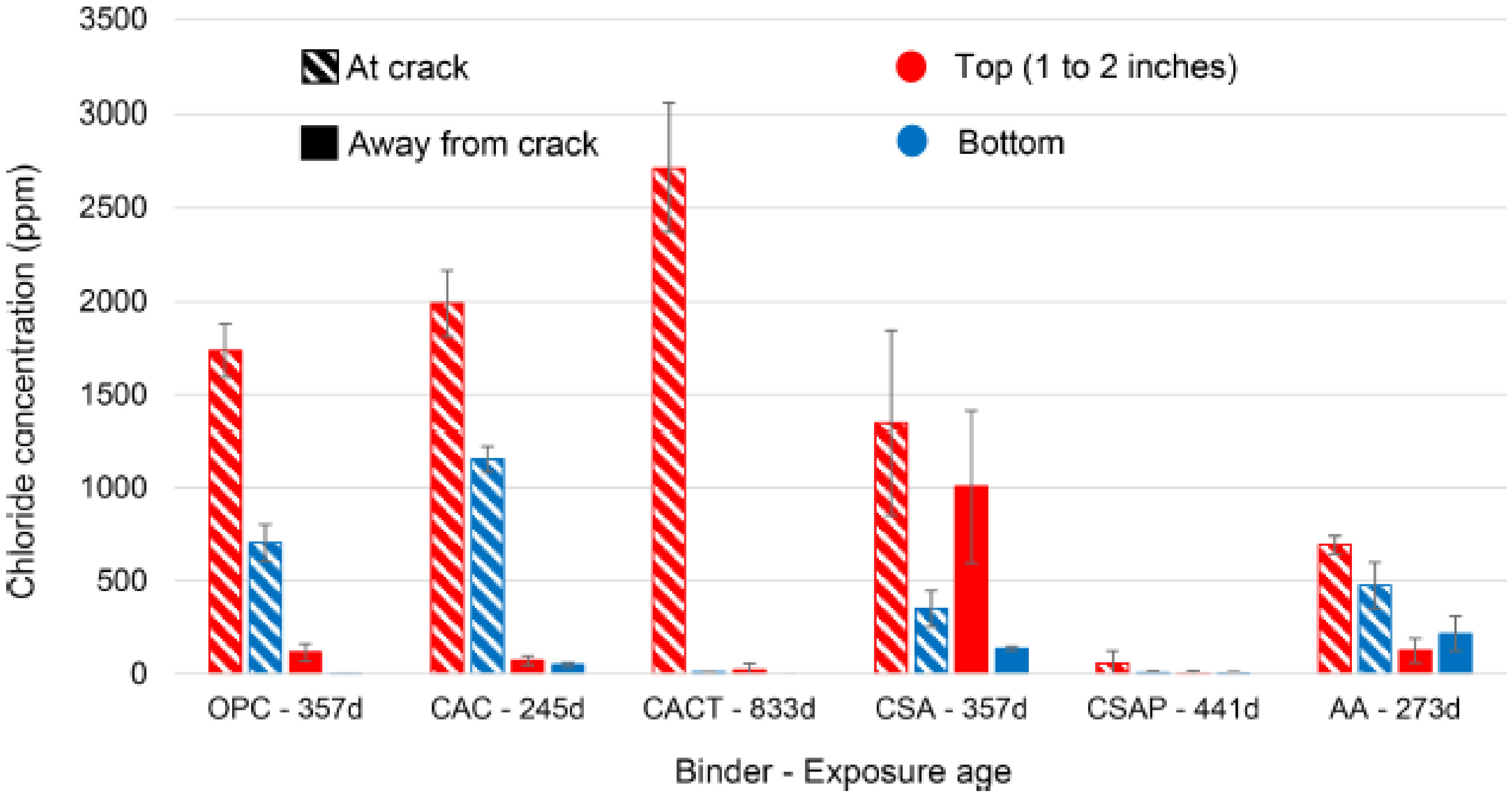
Bulk Diff. Ponding Non-linear Regression Fit of Chloride Profile at Crack TCAC3



Bulk Diff. Ponding Non-linear Regression Fit of Chloride Profile AA1 at Crack



Chloride Distributions at and Away From Cracks



Comparisons of ACMs to OPC

- Bulk pseudo diffusion coefficients compared to OPC
  - Higher for CSA1 and CSA2
  - Approximately the same for AA1 and CAC3
- However, total chloride at the surface and subsequently in the interior is less for the ACMs Could be due to reduced chloride bonding found for CSA and AA1 mixes.
- At cracks all of the ACMs (except CAC2 (CACT)) show no effect of depth on crack, whereas, there is a decrease in chloride with depth for the crack in OPC
- Equivalent corrosion rates at lower chloride levels (except CAC2)

Conclusions

- CAC2 (CACT) and CAC3 shows a decrease in ion penetration over OPC
  - However, CAC3 specimens had expansive cracking in time, increasing chloride ingress.
- AA1, CSA2, CSA2B (P) show almost uniform distribution of chloride ion penetration in the crack vs. OPC
- CAC2 is showed very good performance in the corrosion testing in both cracked concrete and uncracked mortar specimens.
- The corrosion occurring in CSA specimens, at reduced chloride levels is consistent with low chloride binding. A lowering of the pH or more soluble sulfate could be contributing to this. The polymer did help to reduce the overall corrosion and ingress of chlorides.

Thank You!

For more information: nberke@tourneyconsulting.com