Chloride Ingress at Cracks

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Overview of Presentation

- Introduction to Testing
- Concretes/Reinforcement Evaluated
- Tests Performed
- Results
- Conclusions and Future Work

Introduction

- Several models exist to predict chloride ingress into concrete as a function of geometry, concrete composition, and exposure.
- However, the programs do not address ingress at cracking.
- These studies use good quality concrete with cracks formed in flexure to determine chloride ingress at the cracks versus that in sound concrete.
  - Effects of cement type
  - Reinforcement type (alloy and coating)
- Corrosion performance and bottom bar effects determined.
- This presentation concentrates on the chloride ingress results.

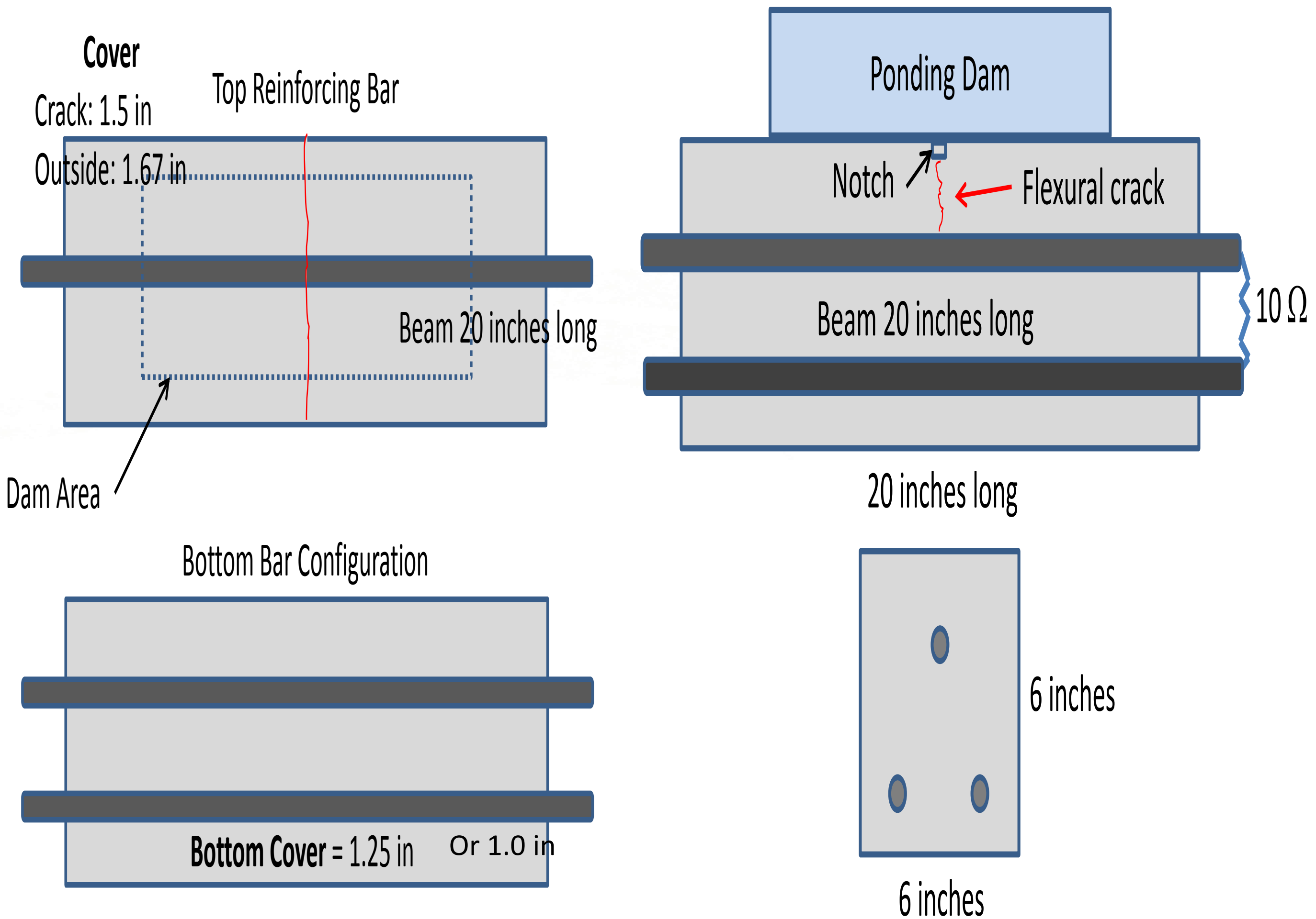
Concretes/Steel Evaluated

- Concrete Base Mixture at 0.4 w/c
- Ordinary Portland Cement (OPC)
  - Black Bar (BB)
  - Galvanized Bar (HDG)
  - Epoxy Coated Bar (EC)
  - Thermal Zinc Diffusion (TZD), With lab applied epoxy (TZE)
  - A1035 Steels with/without Calcium Nitrite Corrosion Inhibitor
  - Stainless Steel SS2304 SS)
- Alternative Cements (BB only)
  - Calcium aluminate (CAC3)
  - Calcium aluminate/OPC blend (CAC2)
  - Calcium sulfoaluminate (CSA2)
  - Type C activated fly ash (AA)

Cracked Beam Macrocell Test

- 0.4 w/c, ¾-in nominal aggregate
- 1.5-in cover over the crack location (bottom of notch)
- Beam Size 20 x 6 x 6-in with one #4 top bar and 2 #4 bottom bars for cathodes
- Bar end treatments—Will be far from salt water so will remain dry.
  - Sealed shrink wrap in production and moist curing
  - Attach ground clamps to make electrical connections
  - Seal ground clamps with liquid electrical tape
- Unreinforced beams to determine flexural strength in third point load
- 0.008-0.01-in crack on top surface to be made and kept open with a spacer after fatigue—Prior experience it works
- Five low frequency fatigue cycles every 3 cycles at 75% of flexural strength
- One cycle is 1 week with 3% NaCl and 1 weeks ambient drying
- Macrocell corrosion
- Corrosion potential when ponded
- Corrosion potential when liquid removed
  - over crack
  - 3-in each side of crack

Macrocell Crack Beam Schematic



Results

- Effect of reinforcement
- Effect of cement type

Chloride Distributions (ppm on concrete) at 52 Cycles*

Beam Rebar	Sample Location	Depth Increments in Inches				
		0 to 1/2	1/2 to 1	1 to 1-1/2	1-1/2 to 2	2 to 2-1/2
BB	1- Top Center Crack	5662	4052	3226	2976	2251
	2- Top Offset	4039	1778	639	891	650
	3- Bottom Center Crack			1600		
	4- Bottom Offset			901		
HDG	1- Top Center Crack	6394	4010	3574	2861	3058
	2- Top Offset	3944	1648	828	735	700
	3- Bottom Center Crack			1635		
	4- Bottom Offset			652		
TZD	1- Top Center Crack	6312	4364	3326	2823	2580
	2- Top Offset	4214	1802	771	688	824
	3- Bottom Center Crack			1296		
	4- Bottom Offset			668		
X-35	1- Top Center Crack	5434	3586	2940	2709	2232
	2- Top Offset	3646	1479	841	688	767
	3- Bottom Center Crack			1498		
	4- Bottom Offset			688		
EC	1- Top Center Crack	6389	3946	3295	2825	2567
	2- Top Offset	3669	1787	869	815	800
	3- Bottom Center Crack			1565		
	4- Bottom Offset			798		
SS	1- Top Center Crack	5844	3872	3139	2721	2523
	2- Top Offset	2913	1500	830	777	791
	3- Bottom Center Crack			1793		
	4- Bottom Offset			637		
TZE	1- Top Center Crack	5818	3751	3305	2890	2687
	2- Top Offset	3907	1669	720	621	650
	3- Bottom Center Crack			1840		
	4- Bottom Offset			776		

Significant at 80% C.L. (± 150 ppm)

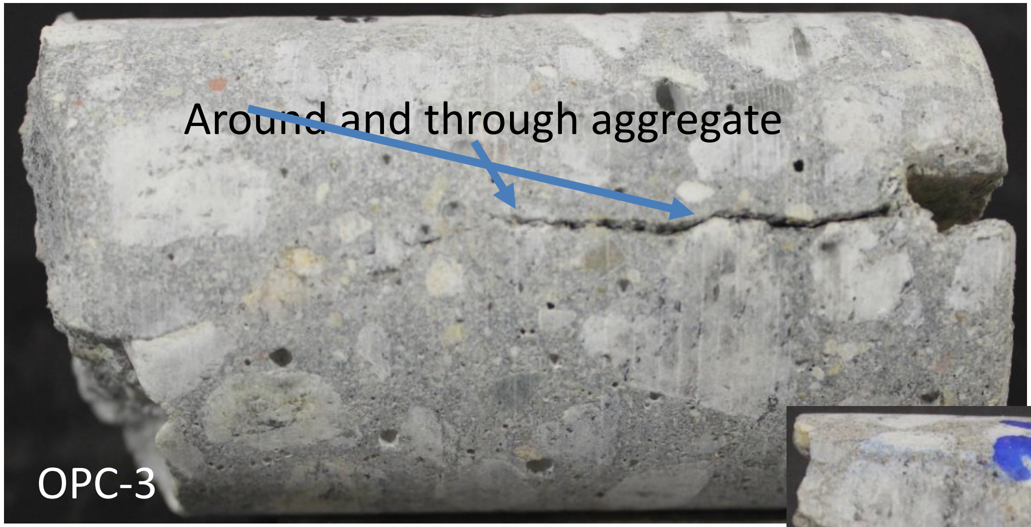
*Average values for three specimens in each group

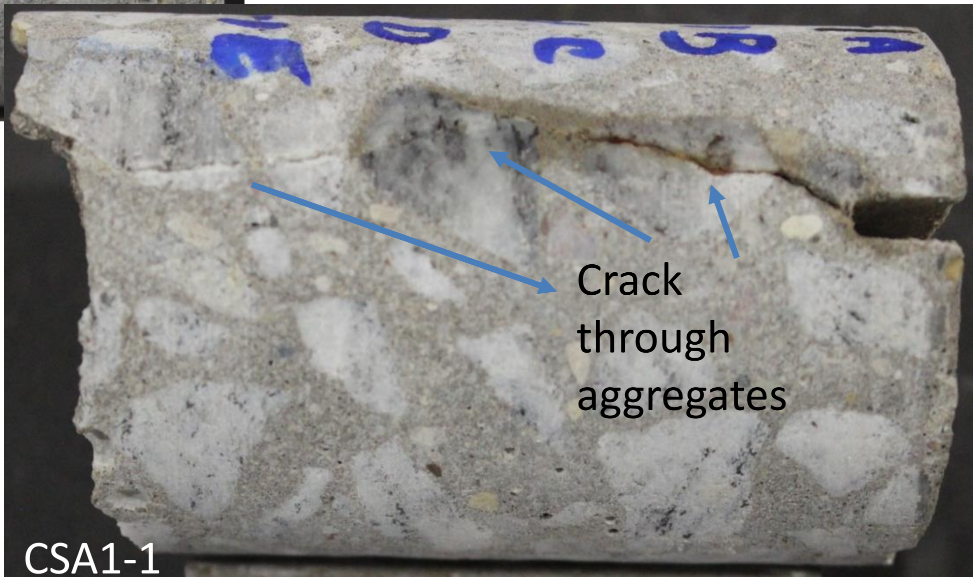
Average Chlorides (ppm on Concrete) 52 cycles (2 Years) X35 Alloys with CNI Compared to BB

Bar	Top Center		Bottom Center	
	Average	SD	Average	SD
BB	3151	134	1561	67
X35 (4% Cr) +4 gpy CNI	3165	289	1079	137
X35 (9% Cr) +3 gpy CNI	2822	278	1207	62

Synopsis of OPC Results with Different Reinforcement

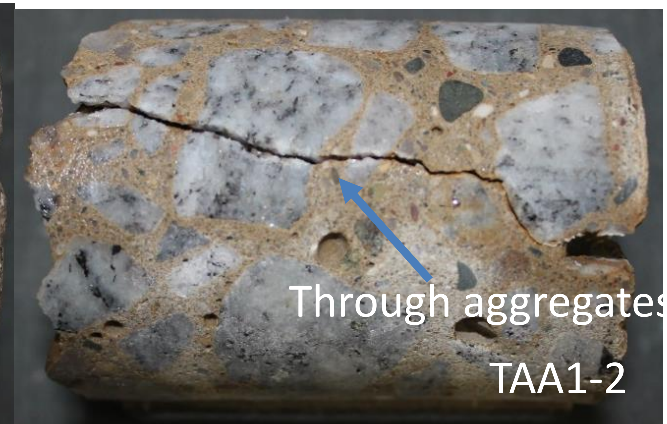
- Chloride levels were 3 to 4 times higher at the crack than away from the cracks at the top reinforcing bar level (1.5-2 inches).
- Chloride levels at the bottom rebar level were approximately two times higher in the region of the crack versus away from the crack.
- Chloride values were similar in all specimens except for the chloride below the crack at the level of the bottom reinforcement.
  - In this case there was a reduction of chloride for the TZD beams at a 80% C.L. indicating that enhanced bond was helping to reduce crack width with depth.
  - X-35 beams had a lower average chloride value at the bottom bar level than the controls, but more specimens would be needed to determine if this is significant.
  - Addition of CNI to concrete with X35 bars resulted in a significant reduction in chloride at the bottom bars below the crack


Around and through aggregate
OPC-3

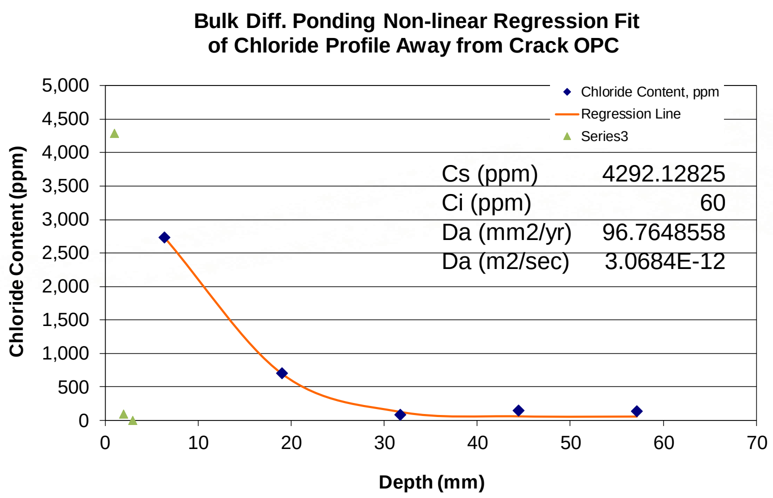

Crack through aggregates
CSA1-1

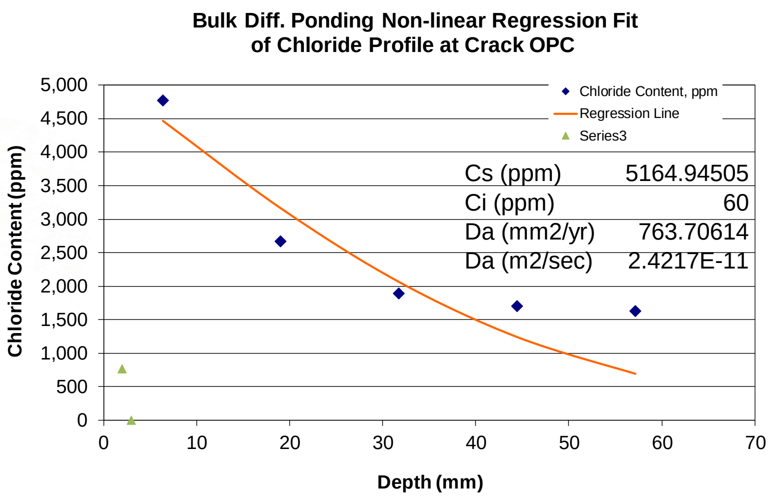

CSA2-1
Crack small or
or healing

Crack Propagation



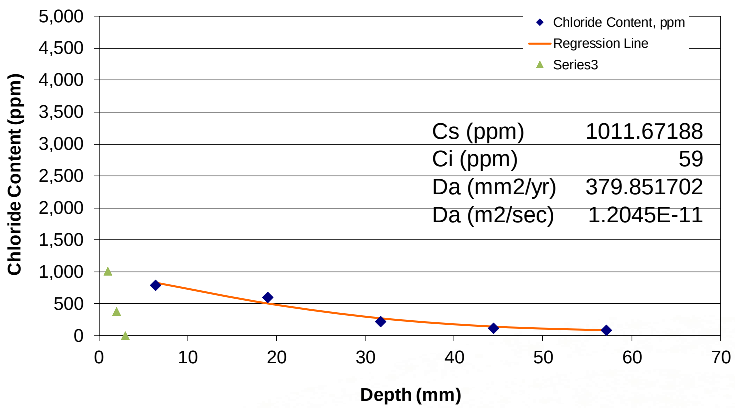
Chloride Profiles for OPC Concrete after 22 Cycles



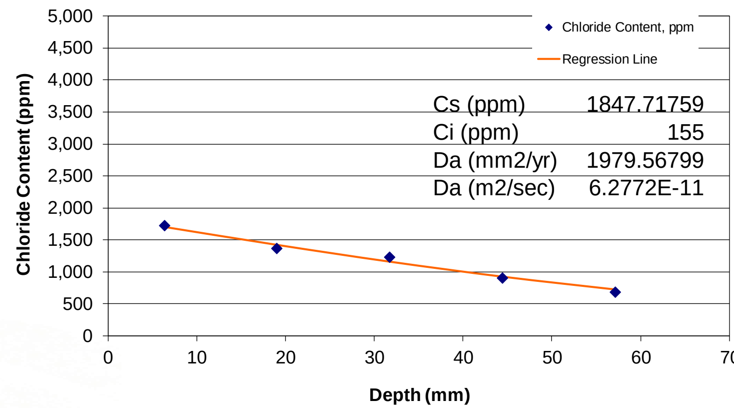


Chloride Profiles for CSA1 & CSA 2 Concretes after 22 Cycles

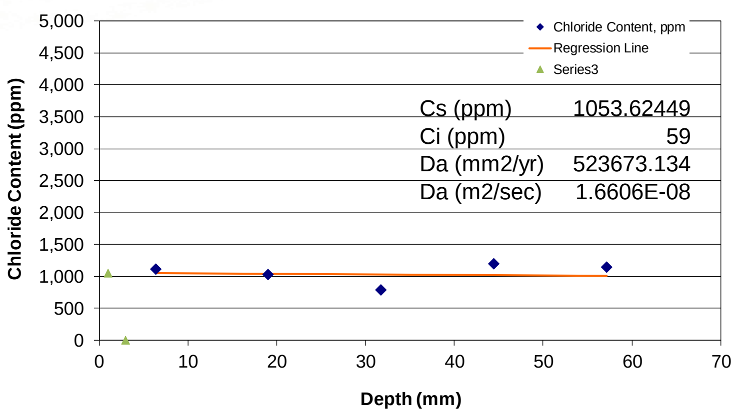
Bulk Diff. Ponding Non-linear Regression Fit of Chloride Profile Away from Crack CSA1



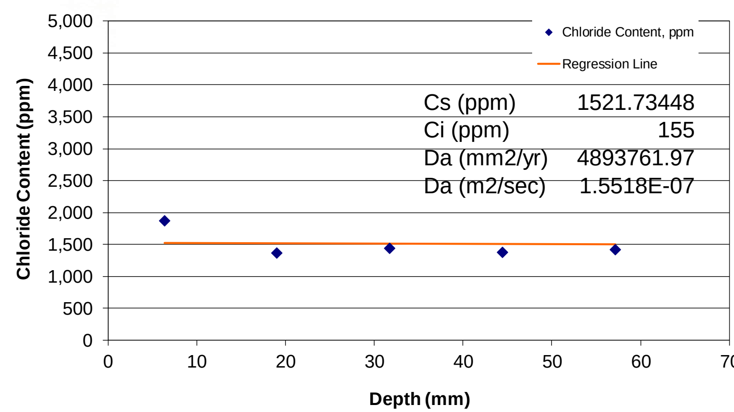
Bulk Diff. Ponding Non-linear Regression Fit of Chloride Profile Away from Crack CSA2



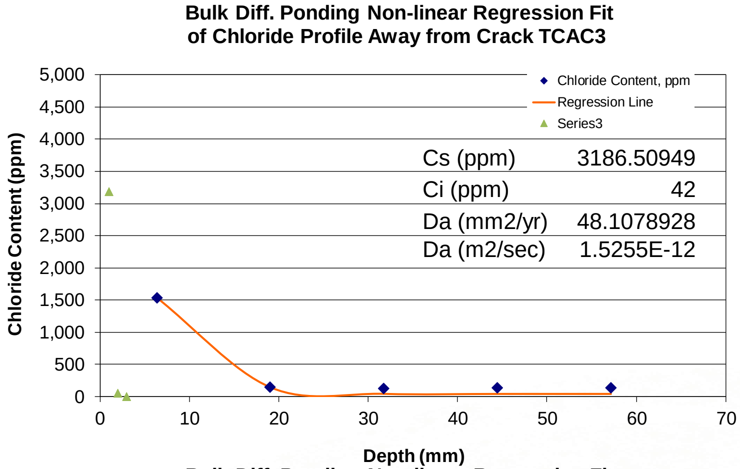
Bulk Diff. Ponding Non-linear Regression Fit of Chloride Profile at Crack CSA1

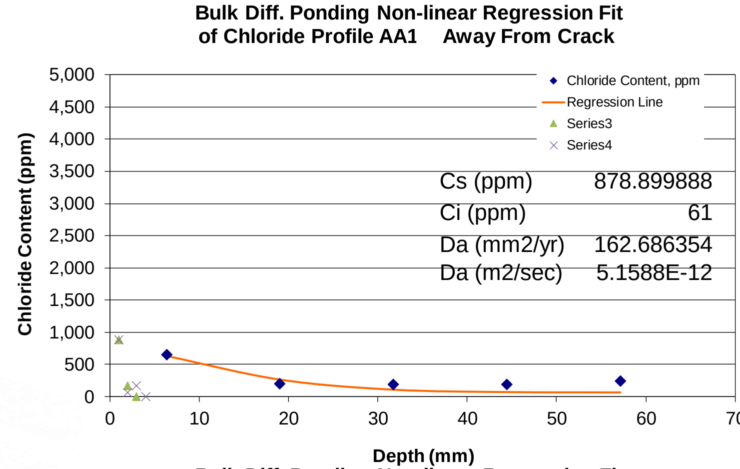


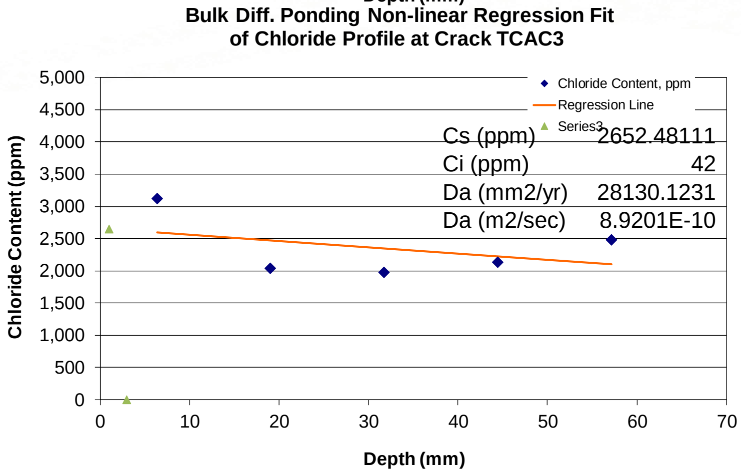
Bulk Diff. Ponding Non-linear Regression Fit of Chloride Profile at Crack CSA2

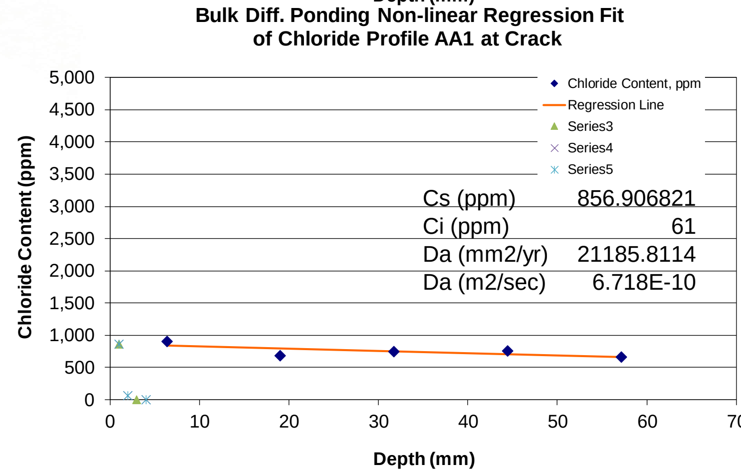


Chloride Profiles after 18 Cycles









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 (not CAC2 which is to be determined)
  - Could be due to reduced chloride bonding reported elsewhere
- At cracks all of the ACMs (except CAC2) show no effect of depth on crack, whereas, there is a decrease in chloride with depth for the crack in OPC

Conclusions

OPC concrete at a w/c of 0.4, 1.5 inch of cover and flexural cracks at 0.01 inch showed the following behavior.

- Reduction in chloride as a function of depth
- Increased chloride ingress at the reinforcement of approximately 3-4 times that in the sound concrete. Apparent bulk diffusion increase of approximately 1 order of magnitude.
- Reinforcement can effect chloride ingress to the bottom level bars 5-inches from the surface.
- CNI with A1035 bars reduce chloride ingress at the bottom bar level.
- Coefficients of variance are in the 10% range for chloride contents at reinforcement level.

Conclusions Continued

Alternative Cements Studied Showed

- Significantly larger chloride ingress at cracks relative to sound concrete than OPC.
- Chloride was not reduced as depth increased.

Next Steps

- Complete analysis of ACMs that were not included here.
- Model chloride transport in cracks.
- Determine effects of SCMs.

Thank You