Performance Criteria for Concrete Resistant to Chloride Ion Penetration

Anna Maria Workshop
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An Evaluation of Performance-Based Alternatives to the Durability Provisions of the ACI 318 Building Code

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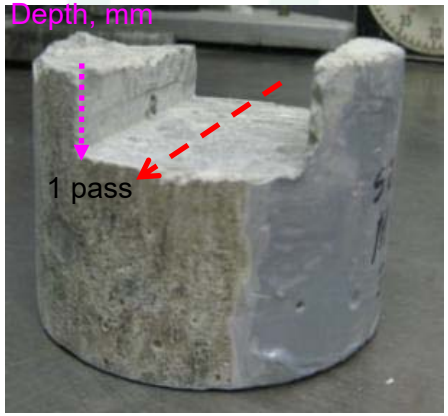
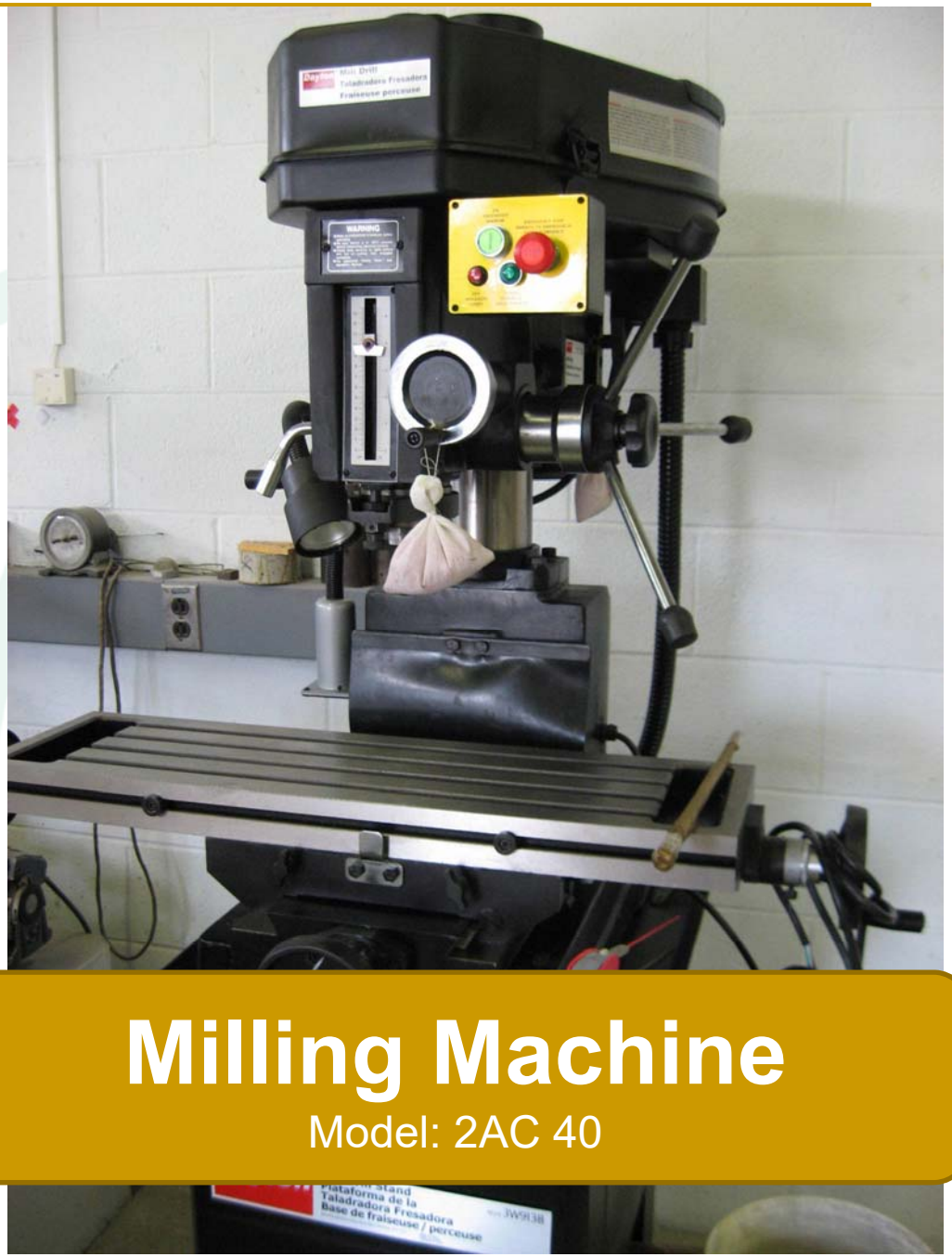
Research Approach

- Correlate rapid index tests with (D_a) chloride diffusion test (ASTM C1556)
- Recommend rapid Index tests and criteria (at <56 days) that classify mixtures based on the chloride penetrability (D_a) level
  - Alternative to w/cm in ACI 318

Diffusion (C1556)





Milling Machine

Model: 2AC 40

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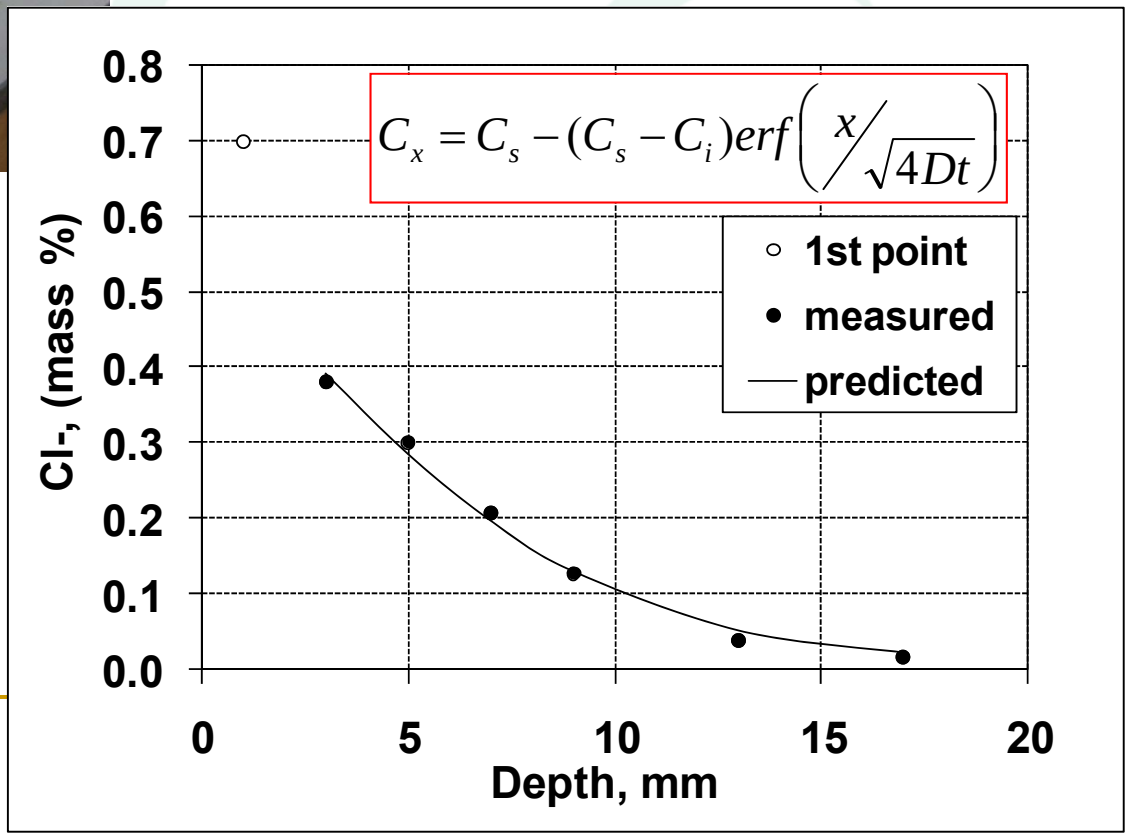
Auto-Titrator

Model: 848 Titrino plus



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Tests Conducted

Fresh properties, strength

- RCPT (ASTM C1202)
  - RCPT/(Model calculated PSC)
- Conductivity
- Rapid Migration Test (AASHTO TP 64)
- Sorptivity Test (ASTM C1585)
- Absorption test BS 1881:122

Test age - 28 day accelerated, 56 day

Mixtures Evaluated

- 13 non air entrained mixtures
  - 6 in Phase I and 7 in Phase II
  - Designation 0.39FA30

w/cm	PC	15% FA	30% FA	25% SL	50% SL	7% SF	40% SL+5%SF
0.29	x						
0.34							x
0.39	x	x	x	x	x	x	
0.49	x	x		x			
0.62			x		x		

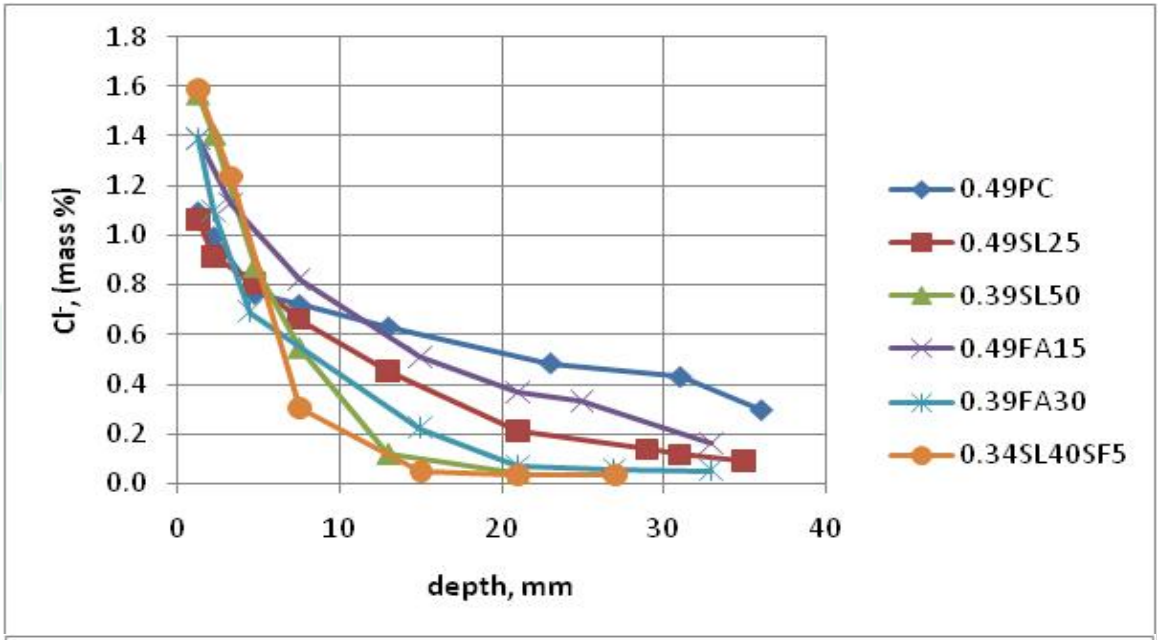
ASTM C1556 Specimen Conditions

Standard cured

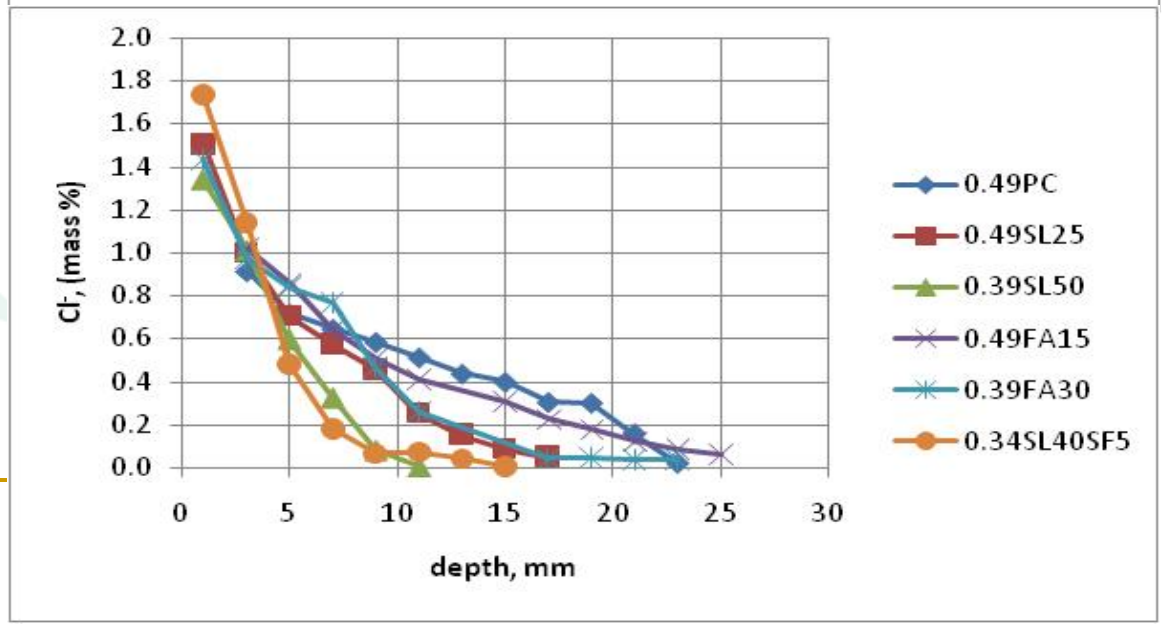
- Immersed (in chloride solution)
  - Primarily diffusion controlled – submerged marine, bridge decks in regions of high precip, humidity
- Cyclic (weekly dry/chloride soltn. immersion)
  - Combination of diffusion and sorption – more arid conditions
- Varying exposure periods

Chloride Profile

Phase I imm. (16 m)



Phase I cyclic (4 m)



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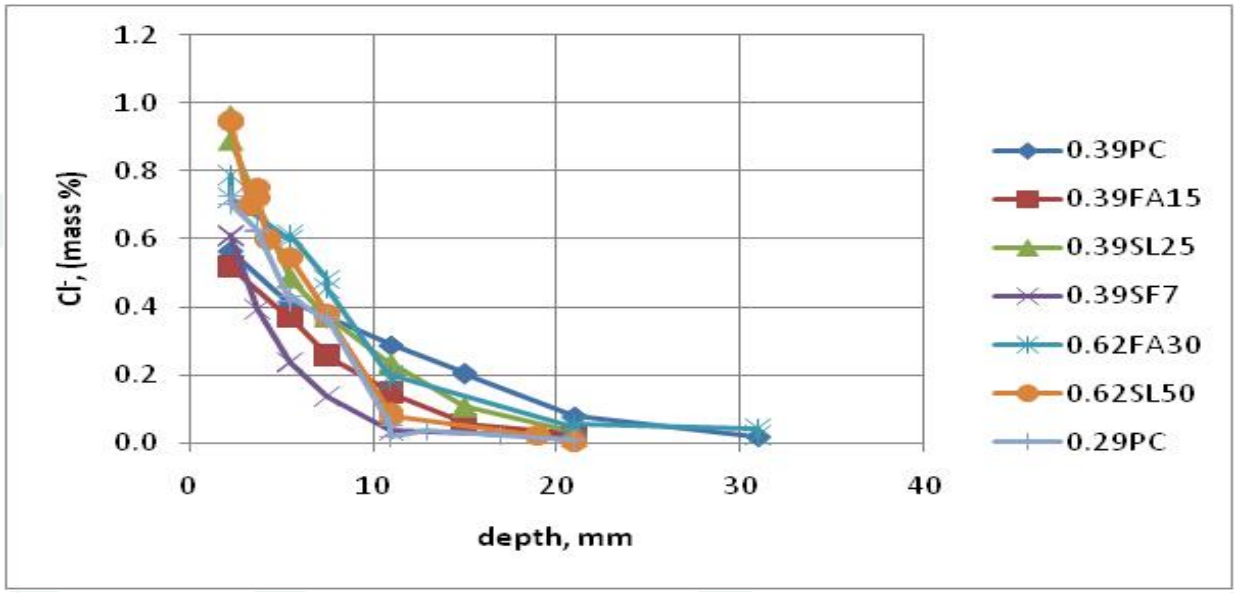
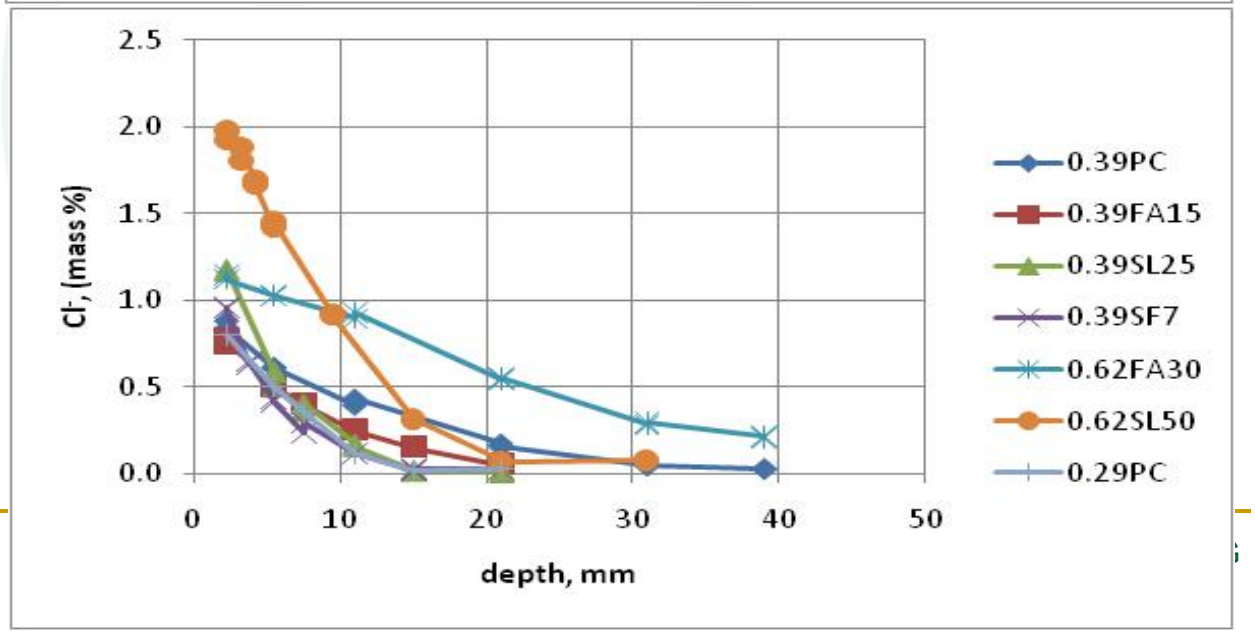
Chloride Profile

Phase II imm. (15 m)



Phase II cyclic (18 m)



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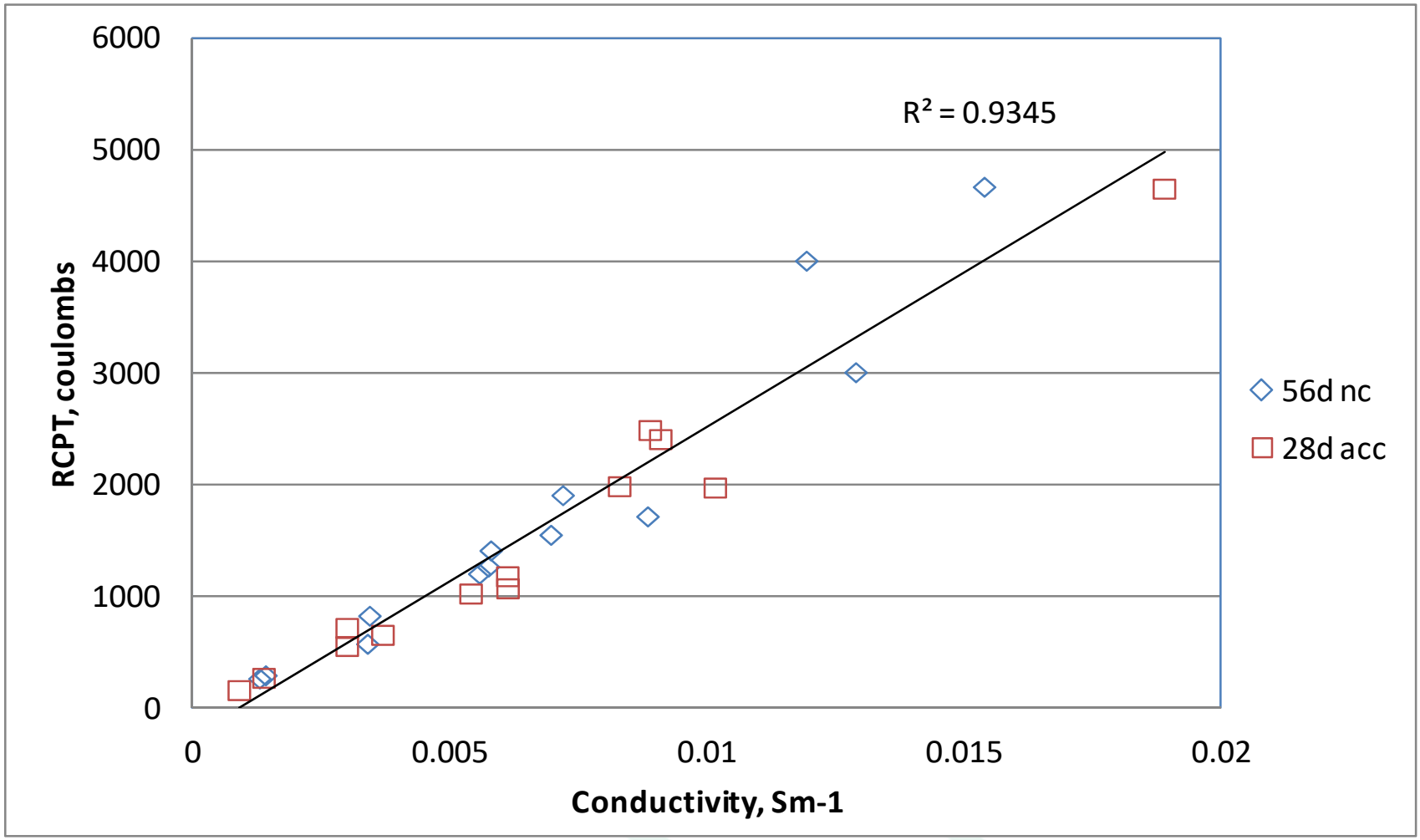
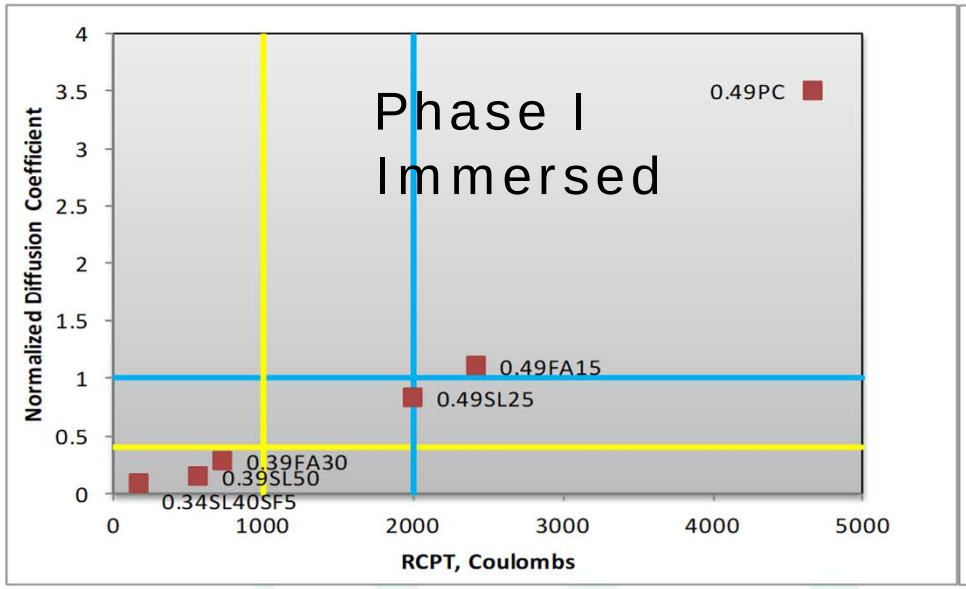
RCPT vs Conductivity

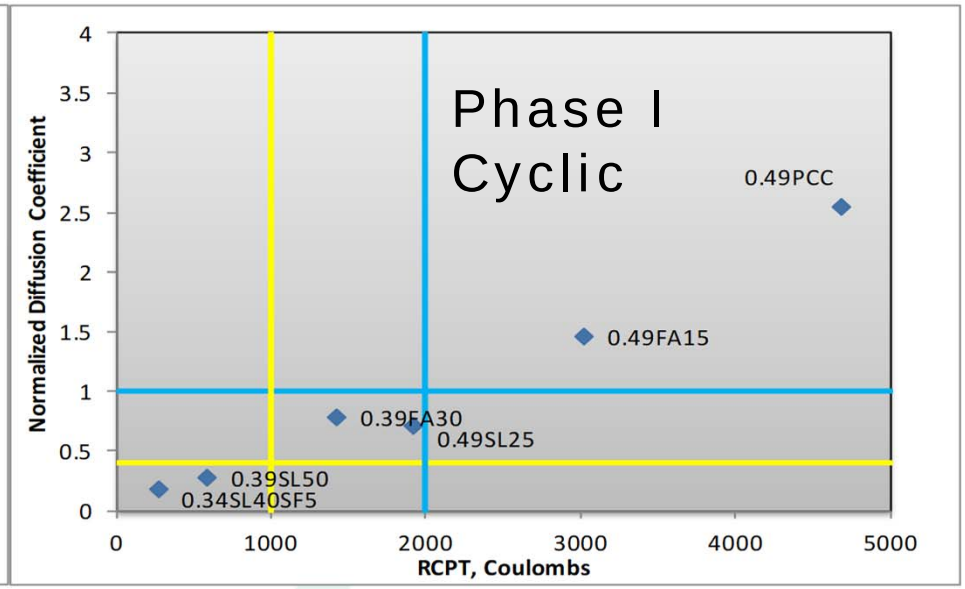


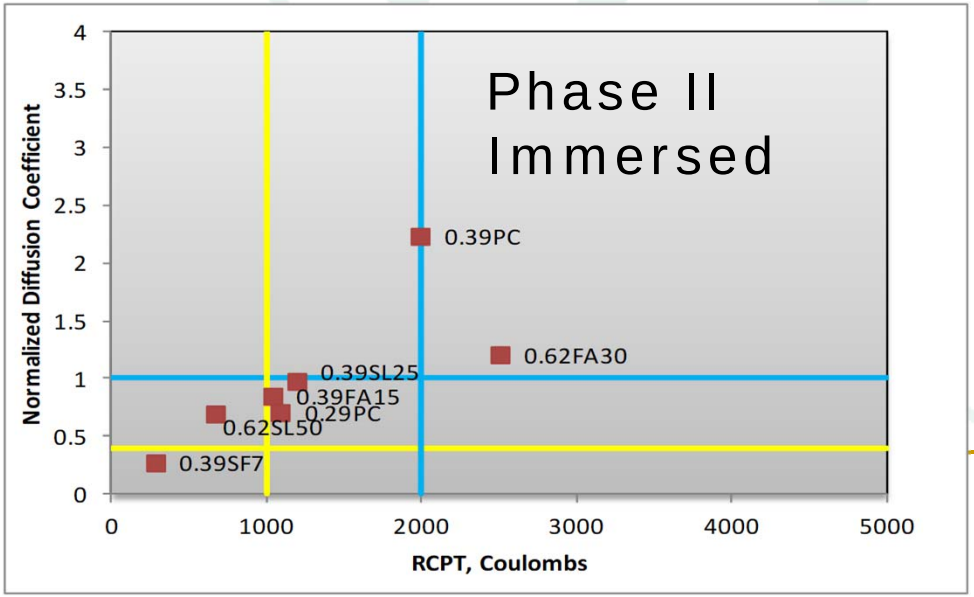
Correlation - Rapid Index Test Vs Chloride Diffusion

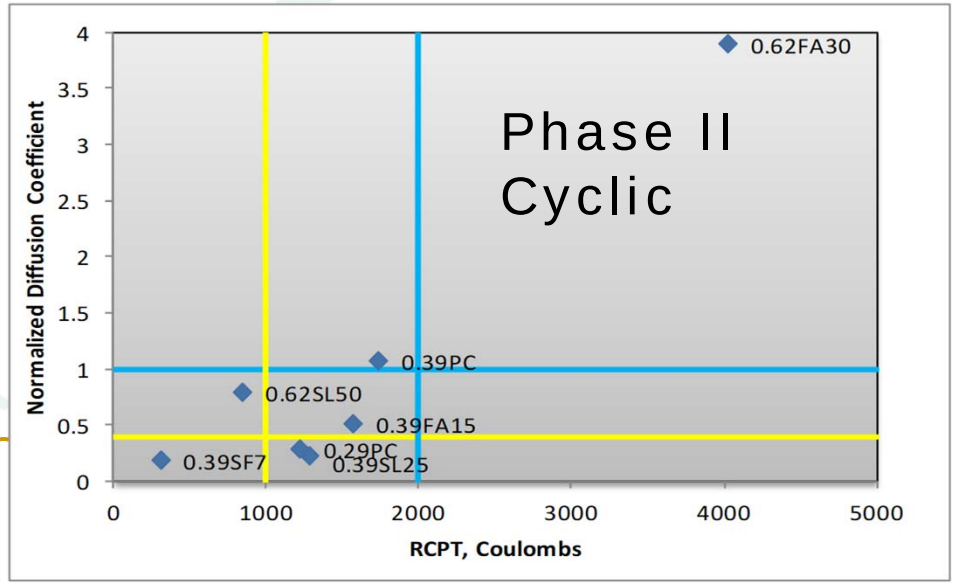
Rapid Index Test	R^2 with Diffusion Coefficient	
	Avg. immersed 28 d acc	Avg. Cyclic 56 d moist
Conductivity	0.88	0.78
RCPT	0.76	0.93
RCPT/PSC	0.55	0.92
RMT	0.62	0.85
Absorption	NA	0.63
Initial Sorptivity	0.65	0.74
Secondary Sorptivity	0.86	0.71

RCPT Vs Apparent Chloride D_a

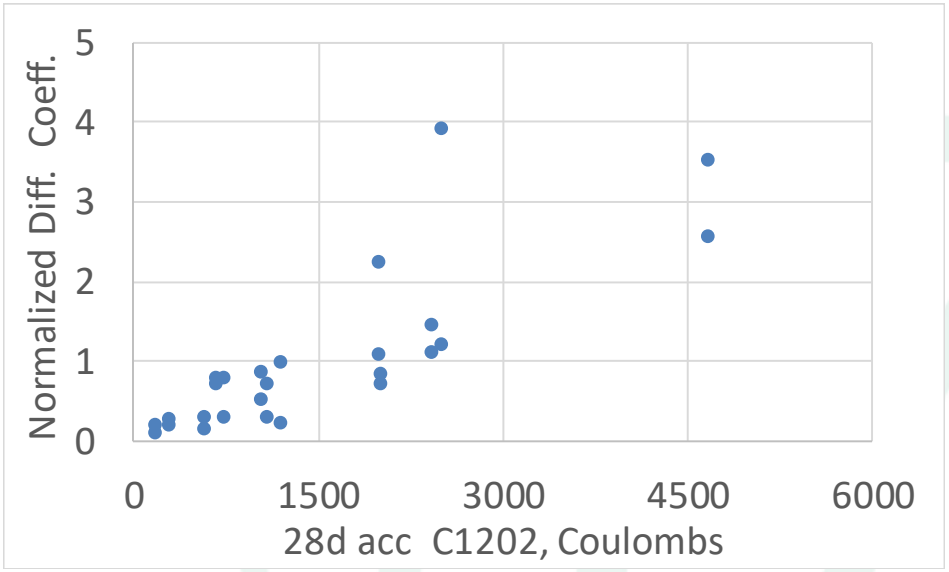


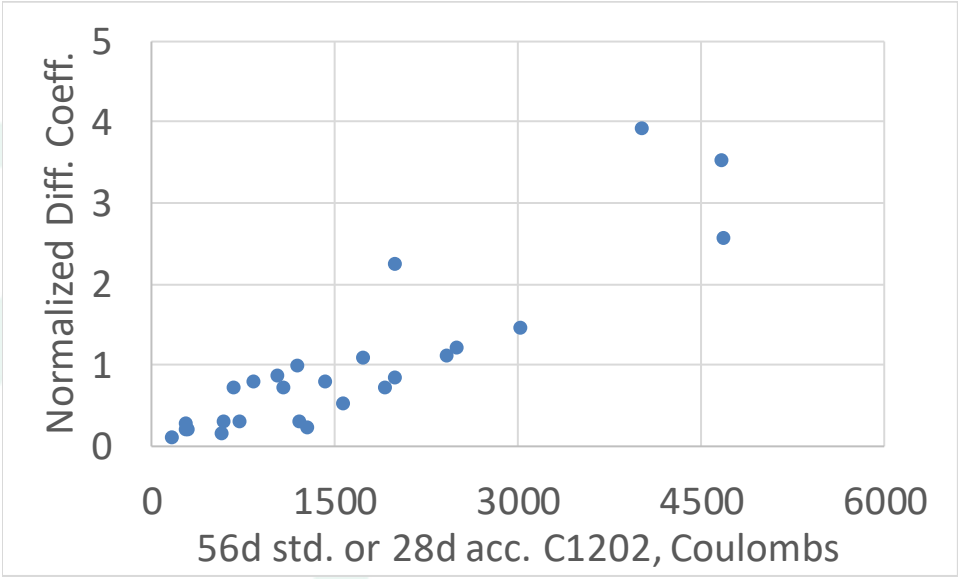


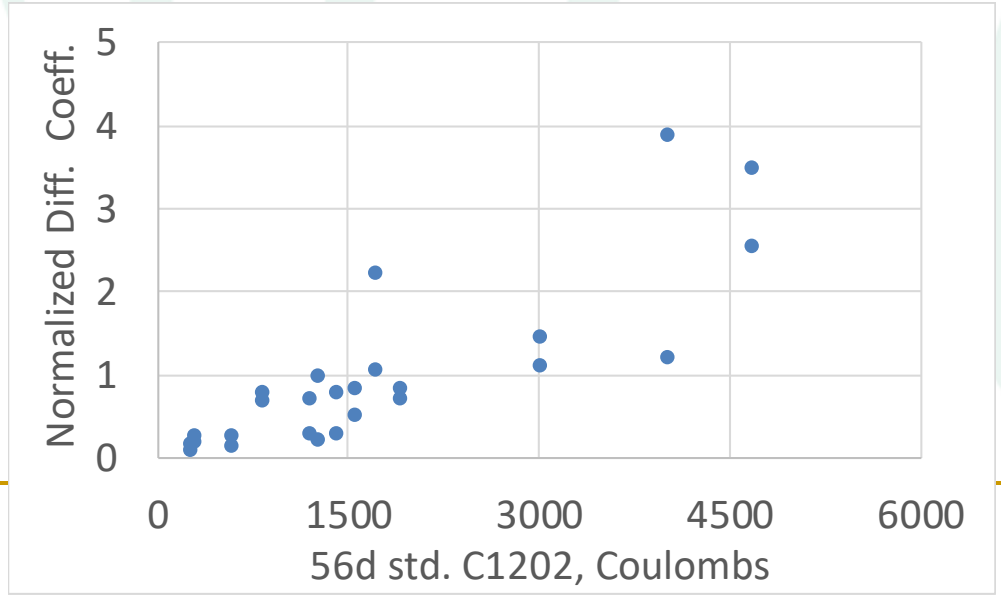




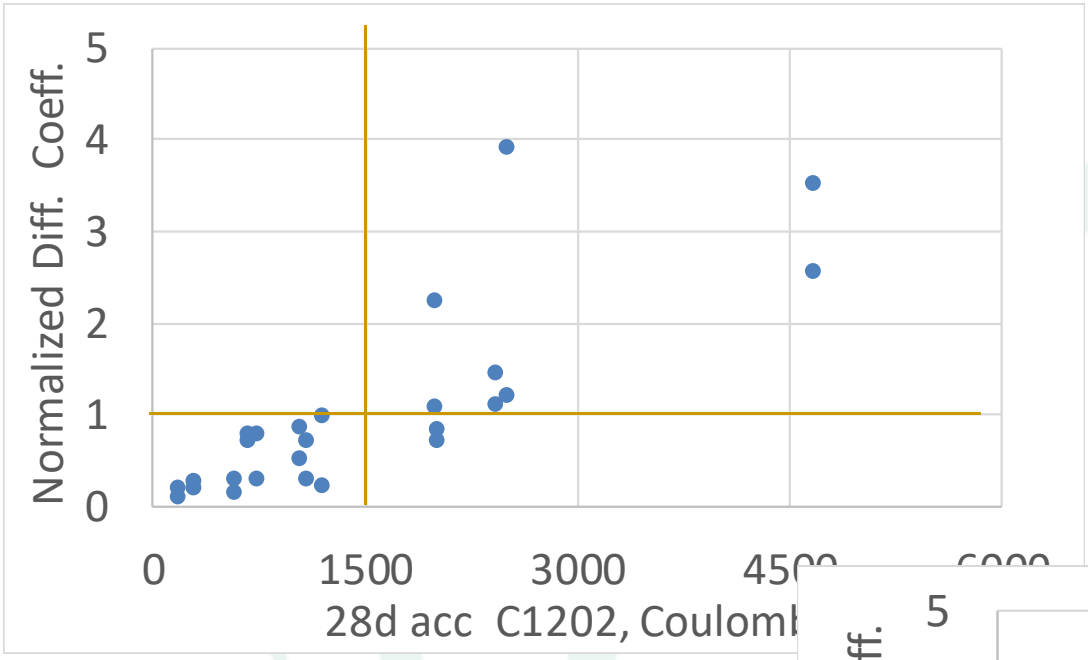
RCPT Vs Apparent Chloride D_a

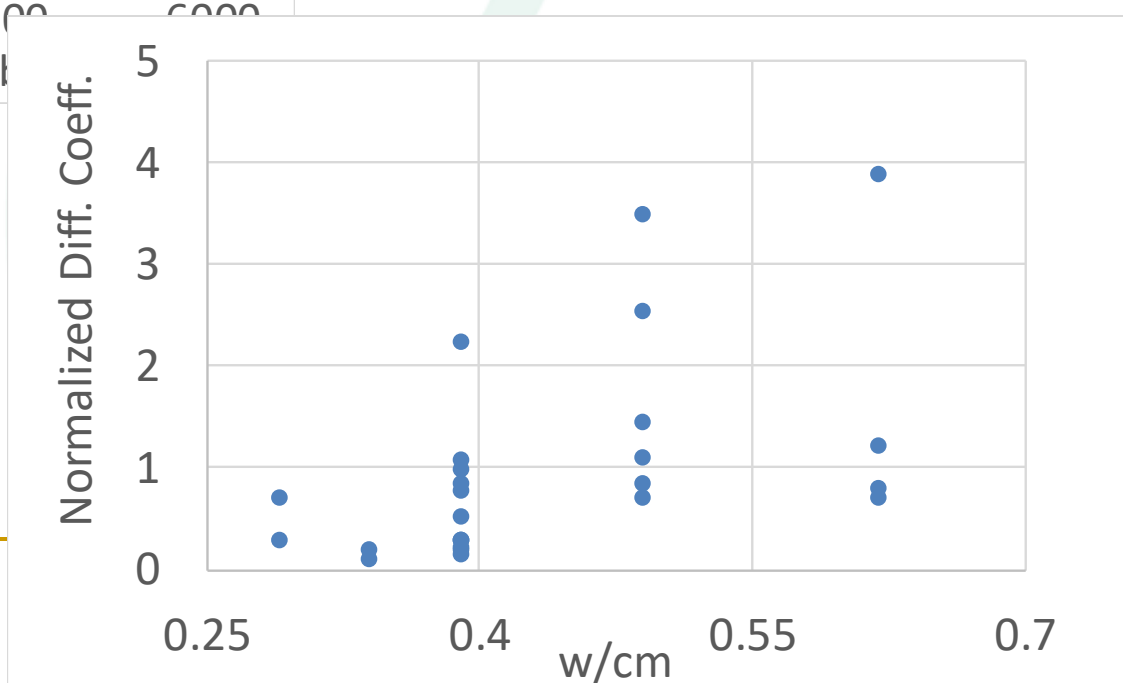






RCPT, w/cm Vs Normalized Chloride D_a





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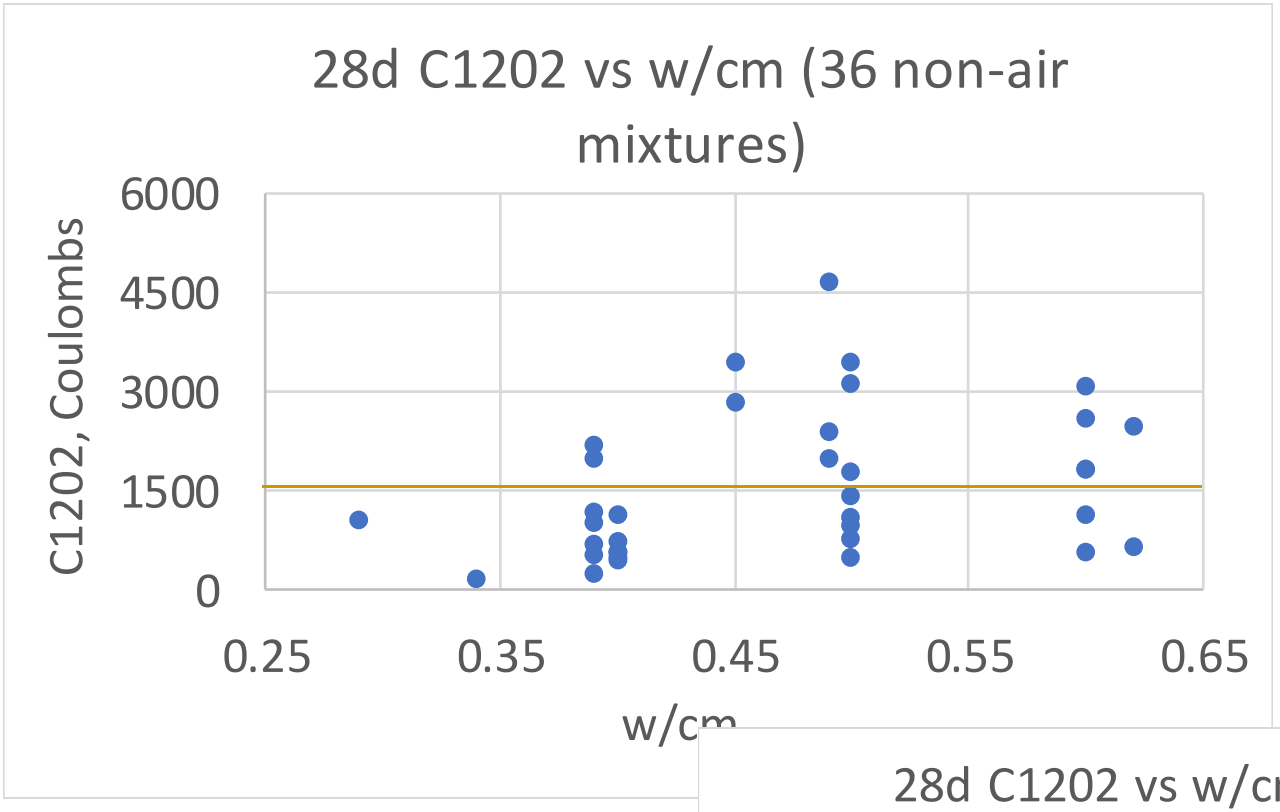
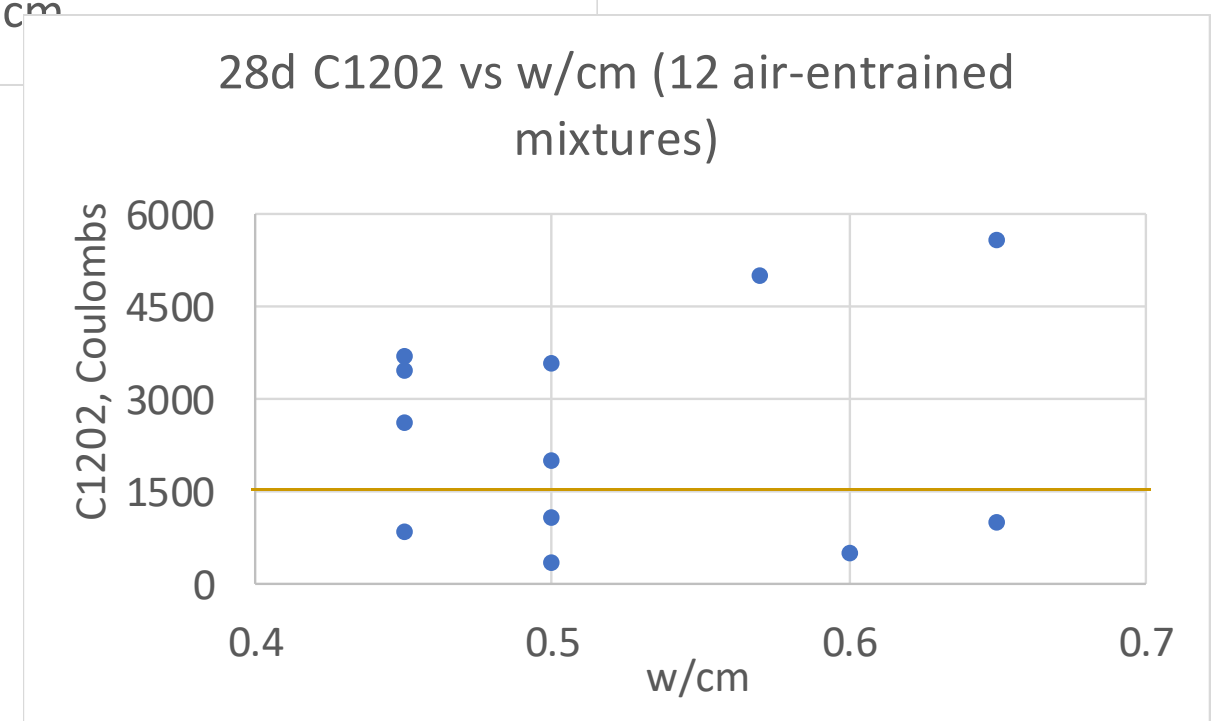
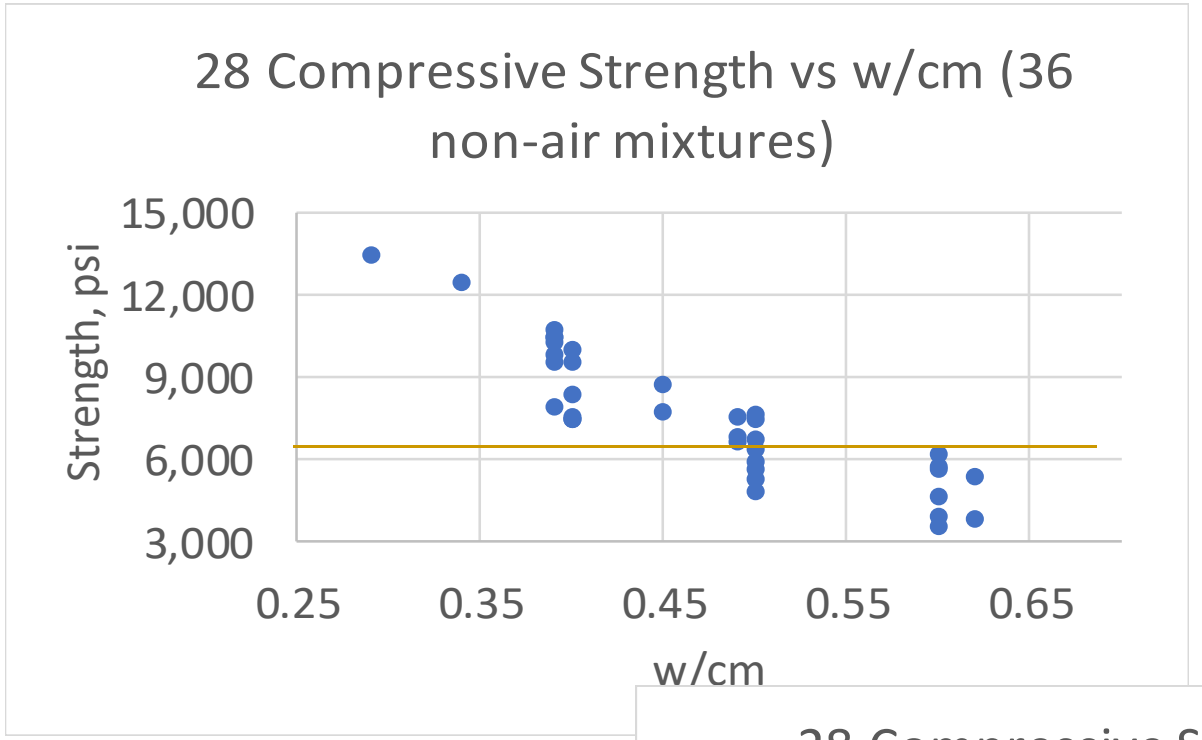
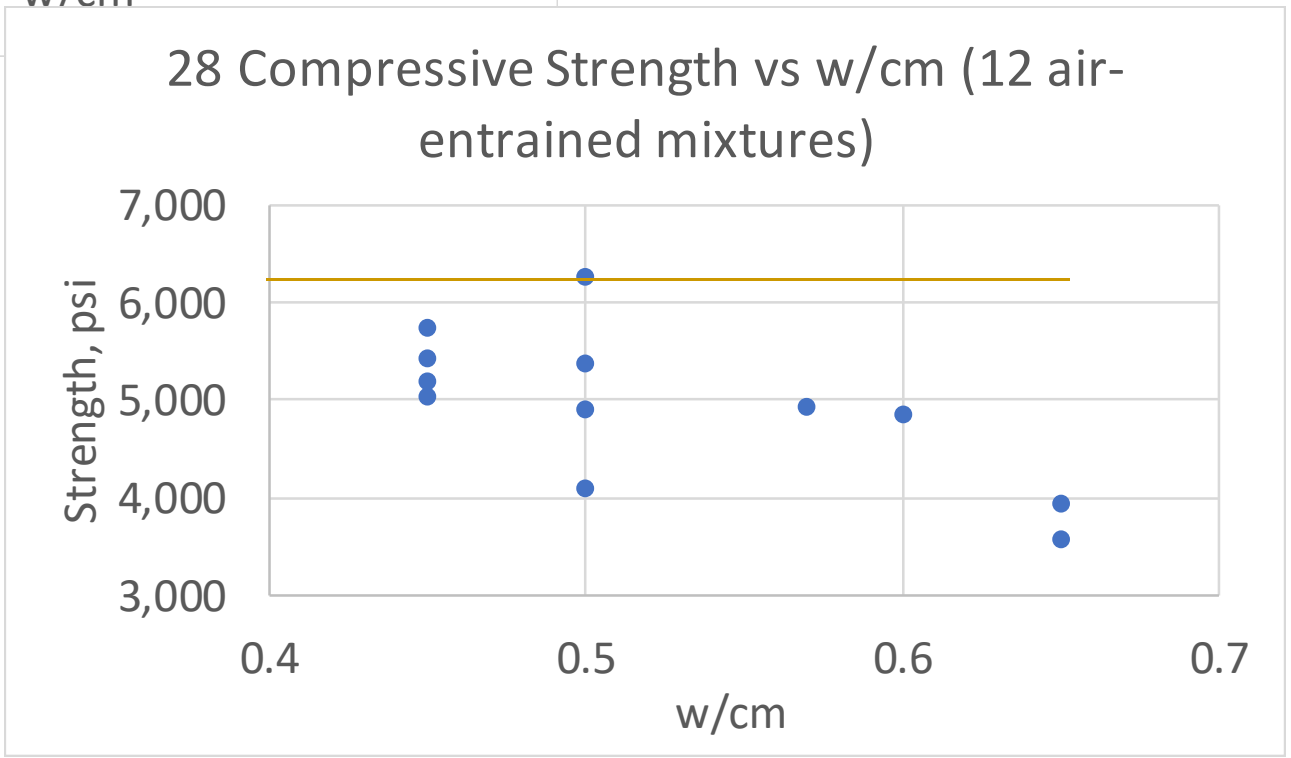
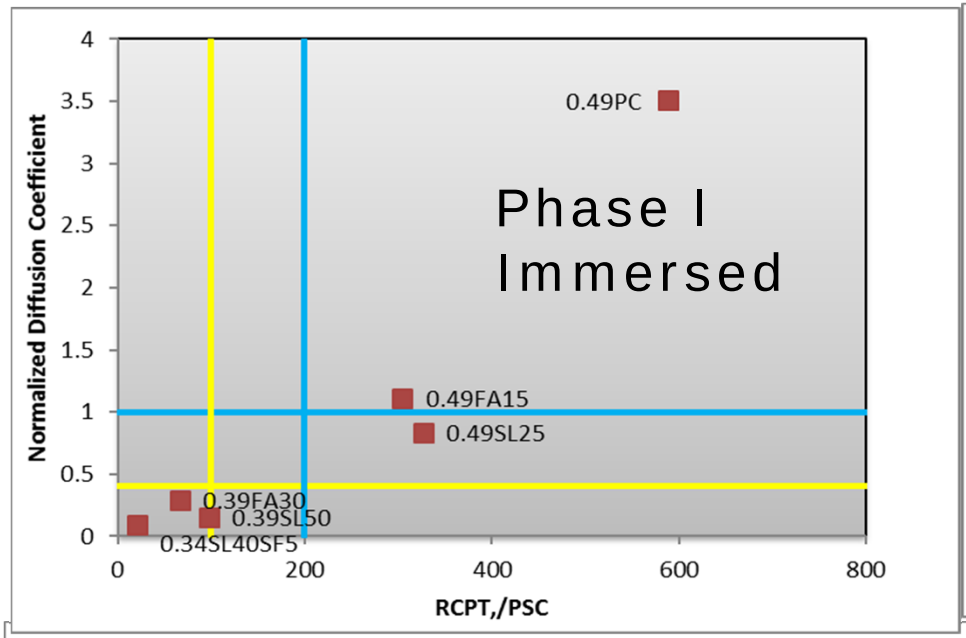

28d C1202 vs w/cm (36 non-air mixtures)
C1202, Coulombs
6000
4500
3000
1500
0
0.25
0.35
0.45
0.55
0.65
w/cm

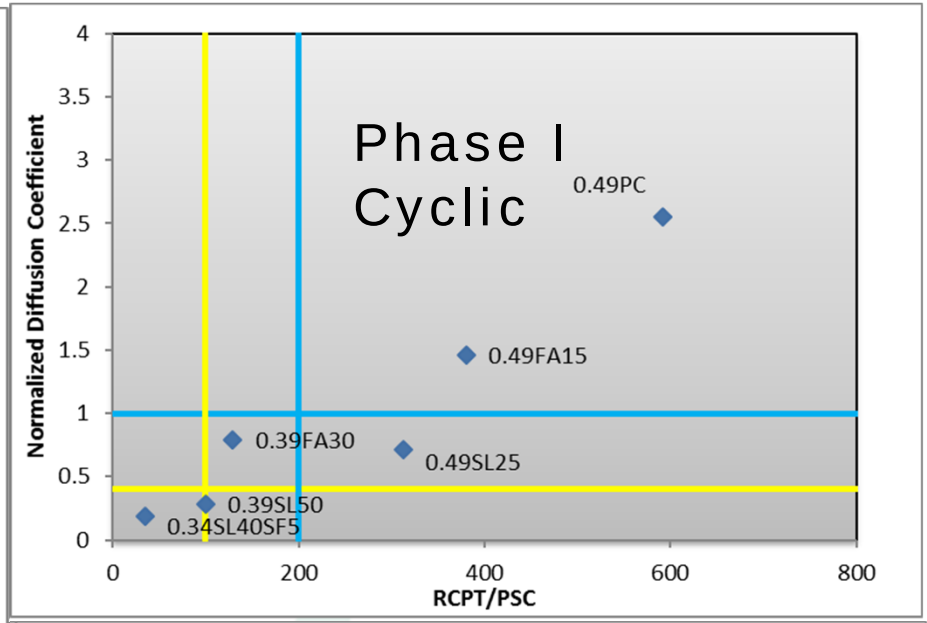

28d C1202 vs w/cm (12 air-entrained mixtures)
C1202, Coulombs
6000
4500
3000
1500
0
0.4
0.5
0.6
0.7
w/cm

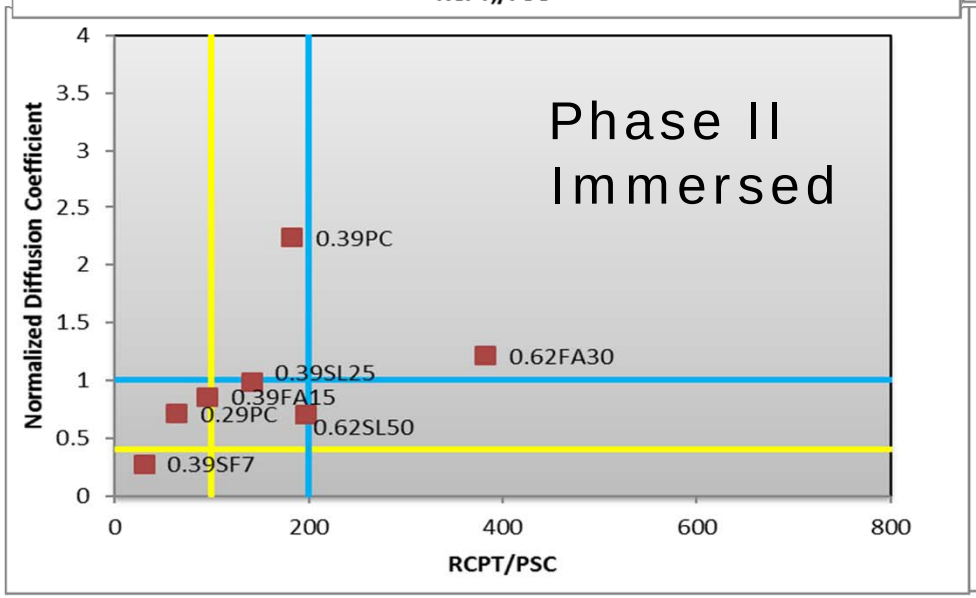

28 Compressive Strength vs w/cm (36 non-air mixtures)
Strength, psi
15,000
12,000
9,000
6,000
3,000
0.25
0.35
0.45
0.55
0.65
w/cm

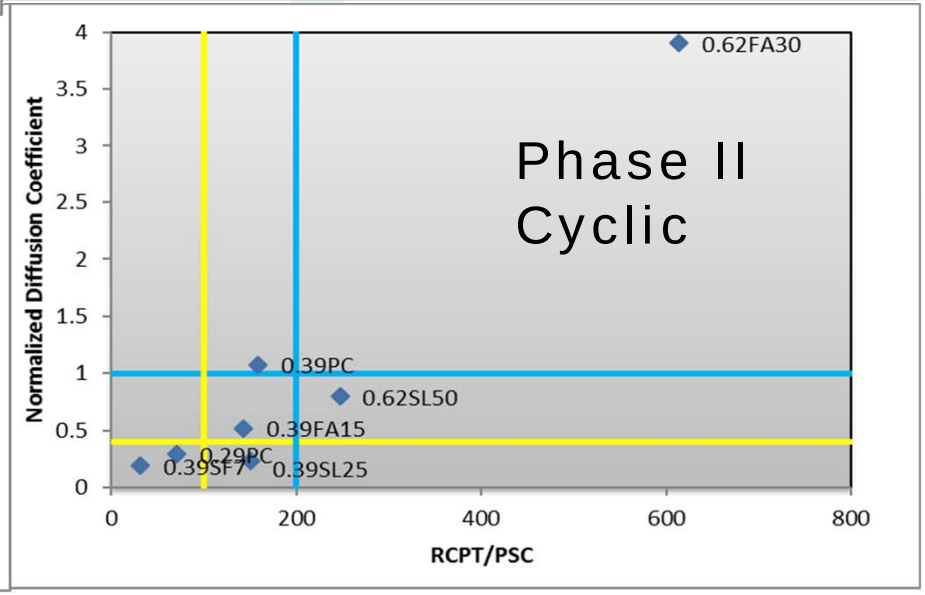

28 Compressive Strength vs w/cm (12 air-entrained mixtures)
Strength, psi
7,000
6,000
5,000
4,000
3,000
0.4
0.5
0.6
0.7
w/cm

RCPT/PSC Vs Apparent Chloride D_a









Rapid Index Test Vs Chloride Diffusion for Phase II mixtures

Mix ID	D_a, Cyclic	56 day RCPT	56 day Initial Sorpt	D_a, Immersed	28 d acc RCPT	28 d acc Initial Sorpt
0.62FA30	7.10	4012	9.9	0.95	2495	9.6
0.39PC	1.96	1722	8.3	1.75	1980	8.3
0.39FA15	0.94	1557	6.1	0.67	1031	3.1
0.29PC	0.53	1209	2.1	0.56	1078	3.1
0.39SL25	0.42	1272	NA	0.77	1186	4.7
0.62SL50	1.45	832	7.1	0.55	661	7.6
0.39SF7	0.35	299	3.8	0.22	276	3.3

Rapid Index Test Vs Chloride Diffusion

Mix ID	D_a, Cyclic	56 day RCPT	D_a, Immersed	28 d acc RCPT
0.29PC	0.53	1209	0.56	1078
0.39SL25	0.42	1272	0.77	1186
0.39SF7	0.35	299	0.22	276

Chloride Penetrability Level for Test Criteria

Chloride Penetrability Level	ND_a	RCPT, Coulombs	RMT, mm/(V-hr)	Conductivity, S/m	Sec. Sorptivity, $\times 10^{-4}$ mm/s$^{0.5}$
Very Low	≤ 0.4	≤ 1000	≤ 0.012	≤ 0.0045	≤ 2.20
Low	0.4 to 1.0	1000 to 2000	0.012 to 0.024	0.0045 to 0.0084	2.20 to 4.40
Moderate	≥ 1.0	≥ 2000	≥ 0.024	≥ 0.0084	≥ 4.40

Combination of Rapid Index Test Criteria

Chloride Penetrability Level	ND_a	RCPT, Coulombs (28 d A or 56 d M)	Comp. Strength, psi	Mixtures
Very Low	≤ 0.4	≤ 1000	≥ 5400	0.34SL40SF5, 0.39SF7, 0.39SL50, 0.39FA30
Low	0.4 to 1.0	1000 to 2000	NA	0.29PC, 0.39FA15, 0.39SL25, 0.39PC, 0.62SL50, 0.49SL25
Rest	≥ 1.0	> 2000	NA	0.62FA30, 0.49PC, 0.49FA15

Evaluating Criteria for Robustness

- 30 additional mixtures (Total = 43)
  - Varying w/cm (0.4 to 0.6)
  - SCM
  - Cement type (I, II, V)
  - With and without air
- RCPT, strength
- Mixtures classified
- Adequacy of classification evaluated

Evaluating Criteria for Robustness – Air-entrained Very Low

	≥6000 psi, ≤800 coulombs
% of all cases that meet criteria for very low chloride penetration	21
% of all cases that meet criteria but not expected to give very low chloride D_a level	5 0.50SL25SF5, 0.40SL25-I, 0.40FA15-I

- If only 56 day moist cure is allowed only 0.50SL25SF5 mixture met the strength/RCPT criteria for very low chloride penetration

Evaluating Criteria for Robustness – Non air-entrained Very Low

	≥6000 psi, ≤1000 coulombs
% of all cases that meet criteria for very low chloride penetration	24.4
% of cases that meet criteria but not expected to give very low chloride D_a level	8.1 0.50SL25SF5, 0.60SL25SF5, 0.40SL25-I, 0.40FA15-I, 0.5SL35-II, 0.60 SL50-V1

- If only 56 day moist cure is allowed only 0.50SL25SF5 mixture met the strength/RCPT criteria for very low chloride penetration
- If NAE concrete requires 6500 psi only 0.50SL25SF5, 0.40SL25-I, 0.40FA15-I passes

Evaluating Criteria for Robustness

	≥4800 psi (any one of the following 2): 800 < L ≤ 2000 coulombs + < 800 coulombs < 5700 psi	≥ 4800 psi (any one of the following 3): 800 < L ≤ 2000 coulombs + ≤ 4.4 x10^{-4} < 800 coulombs + < 5000 psi + ≤ 4.4 x10^{-4} < 800 coulombs + 2.20 x10^{-4} < L ≤ 4.4 x10^{-4}
% of all cases that meet criteria for low chloride penetration	32.6	32.6
% of all cases that meet criteria but not expected to give low chloride D_a level	0	0

Evaluating Criteria for Robustness

	≥5000 psi (any one of the following 2): 800 < L ≤ 2000 coulombs < 800 coulombs + < 5700 psi
% of all cases that meet criteria for low chloride penetration	33
% of all cases that meet criteria but not expected to give low chloride D_a level	7 0.60SL25-I, 0.50FA15-I, 0.60SL35-II

- If NAE concrete requires 6000 psi no false positives

Specification Criteria for Chloride Penetrability

Chloride Penetrability Level	RCPT (for submittal), Coulombs	f'_c, psi
Very Low	≤ 1000	≥ 5000
Low	≤ 2000	≥ 4000

RCPT measured at 56 days of standard moist curing

Proposed Code change to ACI 318 C2 in lieu of w/=0.40

- Option 1 w/cm=0.40
- Option 2 ASTM C1202 = 1500 coulombs[1]

[1] Measured after 28 day of accelerated curing (7 day standard and 21 day 100F lime water). Prequalified

Proposed Code change to ACI 318 C2

Exposure Class	Max w/cm [1]	Min f'_c, psi	Max R, Coulombs	Additional Requirements		
				Maximum water-soluble chloride ion (Cl^-) content in concrete, percent by weight of cement [7]		Additional provisions
				Nonprestressed concrete	Prestressed concrete	
C0	N/A	2500		1.00	0.06	None
C1	N/A	2500		0.30	0.06	None
C2 (Opt 1)	0.40	5000	N/A	0.15	0.06	Concrete cover [8]
C2 (Opt 2)	N/A		1500 [9]			

Determined on an average of at least two specimens subjected to accelerated curing and measured at an age of 28 days in accordance with ASTM C1202

Conclusions – Chloride Ingress

- RCPT best predictor for selecting mixes for chloride penetrability in saturated and cyclic
  - NG for high w/cm and high SCM mixtures
- RCPT + strength criteria works well
  - Can reduce strength and add sorptivity
  - RCPT ages – 28 d acc (immersed), 56 d moist (cyclic)
- Replaces prescription - w/cm, SCM etc.
- RCPT and conductivity show good correlation

Thank you