TPF-5(179) **QPR #09**

Evaluation of Test Methods for Permeability (Transport) and Development of Performance Guidelines for Durability

Quarterly Progress Report

To the

Pooled-Fund Research Program

(The participating states are: FHWA, Indiana, Michigan, Minnesota, Illinois, Kansas, Montana, Pennsylvania, Iowa, New York, Wisconsin, and Colorado)

For the Period of

January 1st, 2011
to
March 31st, 2010

Limited Use Document

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Prepared by Indiana Department of Transportation, Purdue University, and the National Ready Mixed Concrete Association

Figure 1: Overall Project Schedule

		Project Months																								Estimated
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Completed
Phase I:	**Literature Review of Concrete Permeability (Transport) Test Procedures and Models that Link Tests with Performance**																									
	Task 1: Literature Review	15	30	45	75	80	90	90	90	90	90	90	90	90	90	90	90	95	95	95	95	95	95	95	99	99
	Task 2: Prepare a Description of Each Procedure		5	15	25	30	90	90	90	90	90	90	90	90	90	90	90	95	95	95	95	95	95	95	99	99
	Task 3: Develop a Summary Document					10	30	50	70	90	90	90	90	90	90	90	90	95	95	95	95	95	95	95	99	99
Phase II:	**Evaluate of Promising Concrete Permeability (Transport) Tests and Recommend Procedures For Further Use**																									
	Task 1: Prepare Reference Concretes	15	25	40	60	60	60	80	80	80	80	80	80	80	80	80	80	80	80	90	90	90	90	90	99	99
	Task 2: Describe Constituent Materials			10	20	40	40	80	80	80	80	80	80	80	80	80	80	80	80	90	90	90	90	90	99	99
	Task 3: Develop Reference Material			15	15	20	40	40	40	50	50	50	60	60	65	80	80	80	80	90	90	90	90	90	95	95
	Task 4: Perform Tests					20		10	20	30	40	40	50	50	60	80	80	80	80	90	90	90	90	90	95	95
	Task 5: Evaluate Testing Procedures					20						20	25	30	35	35	35	35	35	50	50	50	50	50	60	60
	Task 6: Recommedations to Existing Procedures													10	10	35	35	35	35	50	50	50	50	50	60	60
Phase III:	**Develop New or Improve Existing Permeability (Transport) Testing Procedures. Develop Protocols to Use these Tests, Evaluate the Precision and Bias of Tests**																									
	Task 1: Develop Modified Tests					10							10	10	10	20	20	20	20	20	20	20	20	20	30	30
	Task 2: Evaluate Modified Tests															10	10	20	20	20	20	20	20	20	20	20
	Task 3: Develop a Report of Modified Tests																			15	15	15				15
	Task 4: Develop New Testing Procedures														10	10	10	10	10	10	10	10	10	10	10	10
	Task 5: Perform New Testing Procedures																								5	5
	Task 6: Evaluate New Testing Procedures																									~
	Task 7: Develop a Summary Document with Recommendations																									~
Phase IV:	**Correlate Permeability (Transport) Tests with Laboratory Tests that Evaluate Durability**																									
	Task 1: Prepare Specimens	5	15	25	45	65	65	70	75	80	85	90	90	90	90	90	90	90	90	95	95	95	95	95	95	95
	Task 2: Condition Specimens			10	25	30	30	35	40	45	50	50	55	60	65	65	65	65	65	95	95	95	95	95	95	95
	Task 3: Expose Specimens													60	65	65	65	65	65	80	80	80	80	80	80	80
	Task 4: Evaluate Specimens													60		65			70			80			80	80
	Task 5; Perform ASTM Tests								20	20	20	40	50	50	55	55	55	75	75	75	75	75	75	75	75	75
	Task 5: Evaluate Field Structures																									~
	Task 6: Develop Recommendations																									~
	Task 7: Develop a Summary Document																									~
Phase V:	**Develop Performance Criteria Guidelines that Link Permeability (Transport) Tests with Exposure Conditions and Anticipated Performance**																									
	Task 1: Prepare Draft of Criteria																									~
	Task 2: Address SAC Comments																									~
	Task 3: Prepare Revised Draft of Criteria																									~
Phase VI:	**Preparation of Techonology Transfer and Educational Materials**																									
	Task 1: Prepare Materials																									~
Deliverables								1																		~
Study Advisory Committee Meetings							1																			~

Continued

1 - Phase I draft report
2 - Phase III draft report
3 - Phase IV draft report
4 - Phase V draft report
5 - Phase VI draft report

		Project Months																								Estimated
		25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	Completed
Phase III:	**Develop New or Improve Existing Permeability (Transport) Testing Procedures. Develop Protocols to Use these Tests, Evaluate the Precision and Bias of Tests**																									
	Task 1: Develop Modified Tests	30	35	50	60	70	75																			30
	Task 2: Evaluate Modified Tests	25	40	50	50	60	50																			20
	Task 3: Develop a Report of Modified Tests	15	25	40	40	50	50																			15
	Task 4: Develop New Testing Procedures	10	20	30	30	50	50																			10
	Task 5: Perform New Testing Procedures	5	10	15	15	25	40																			5
	Task 6: Evaluate New Testing Procedures																									~
	Task 7: Develop a Summary Document with Recommendations																									~
Phase IV:	**Correlate Permeability (Transport) Tests with Laboratory Tests that Evaluate Durability**																									
	Task 1: Prepare Specimens	95	95	95	95	95	95																			95
	Task 2: Condition Specimens	95	95	95	95	95	95																			95
	Task 3: Expose Specimens	80	80	80	80	80	95																			80
	Task 4: Evaluate Specimens	80	80	80	80	80	95																			80
	Task 5; Perform ASTM Tests	75	75	75	75	75	75																			75
	Task 5: Evaluate Field Structures																									~
	Task 6: Develop Recommendations																									~
	Task 7: Develop a Summary Document																									~
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	Task 1: Prepare Materials																									~
Deliverables											2						3				4			5		~
Study Advisory Committee Meetings																										~

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Figure 2: Estimated Project Expenses

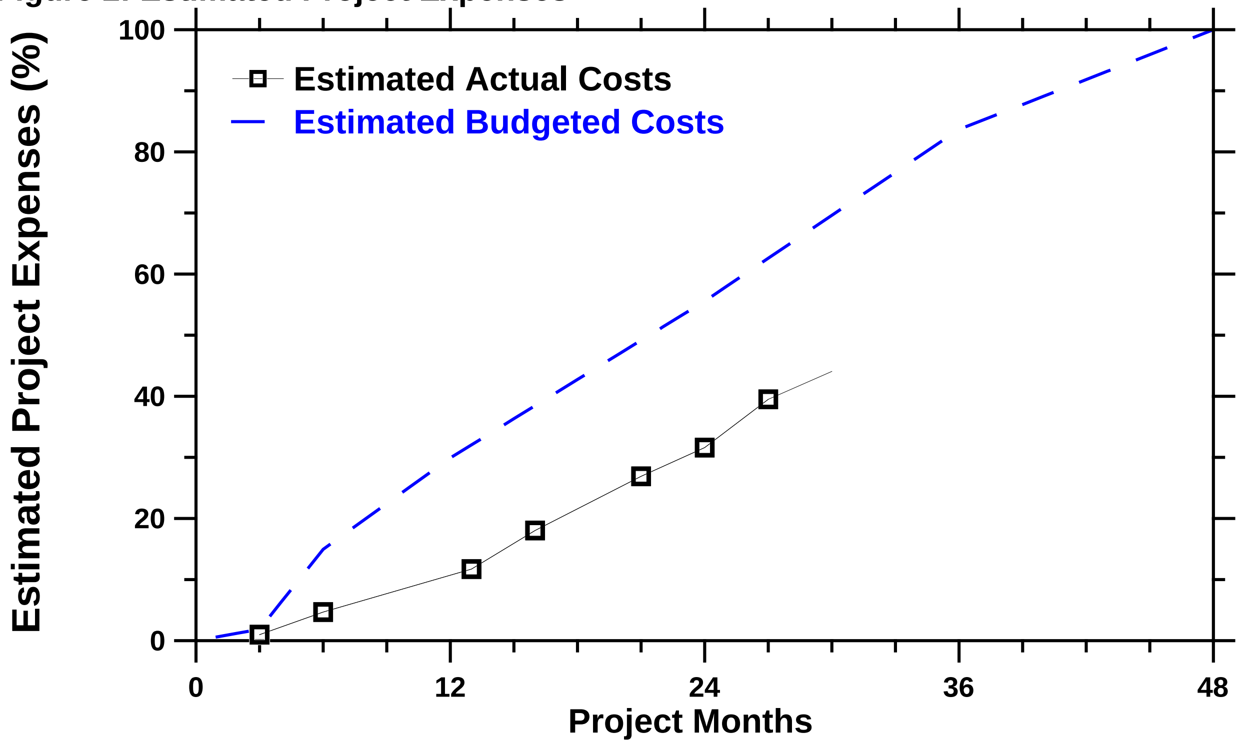


Figure 3: Project Budget and Expenses

Category	Detailed Description	Budgeted Cost	Billed Expense Through 12/30/10
Personnel			
	INDOT Staff (Tommy Nantung*)	~	~
	Purdue Faculty (Jason Weiss and Jan Olek)	$ 121,230	
	Post-Doctoral Research Assistant/Visiting Faculty	$ 168,240	
	Graduate Students	$ 177,848	
	Undergraduate Students	$ 8,679	
	Laboratory Technician	$ 29,343	
Laboratory Expenses			
	Scientific Equipment	$ 62,000	
	Laboratory Supplies/Expendables	$ 13,000	
Travel			$ 283,888
	Domestic Travel	$ 8,400	
Office Expenses			
	Communications	$ 3,000	
	Supplies and Expenses	$ 4,760	
	Printing and Duplication	$ 6,500	
Study Advisory Expenses			
	Participant Travel to SAC	$ 54,000	
	Meeting Expenses	$ 6,000	
Subcontracts			
	NRMCA Consultants	$ 220,000	$ 103,959
Total			
		$ 883,000	$ 387,848

* Costs are estimated on an In-Kind Basis from INDOT

** Note: Subcontractor expensed bills have not all posted to the accounting system

1.0 Summary of Progress

This report provides an update from the tenth quarter of the project. It covers the four month period ending March 31st 2011.

During the reporting period work was performed primarily on Phase II since testing procedures have been analyzed in order to consequently give recommendations. Some work also on phase III, developing a new testing procedure.

The second group of NRMCA samples has been tested: in particular, the remaining sulfate mixes and all the freeze-thawing mixes have been tested.

Moreover, work has been performed to assess the influence of geometry in gas permeability measurement with South African instrument.

NRMCA SAMPLES TESTED TO ACCESS GAS PERMEABILITY and RESISTIVITY

Introduction

The gas permeability of the samples has been measured through the Oxygen Permeability test done according to the procedure originally described by Alexander, Ballim and Mackechnie ('*Alexander MG, Ballim Y, Mackechnie JM, 'Concrete durability index testing manual' Research Monograph no. 4, Departments of Civil Engineering, University of Cape Town and University of the Witwatersrand, March 1999*').

In addition, the resistivity of concrete has been measured and the two parameters (gas permeability and electrical measurement) were finally compared.

Mixture proportions

The samples tested belong to two groups of mixtures from the NRMCA and they are summarized in the following table:

- Sulfate mixtures (Table 1 and 2);
- Freeze-Thaw mixtures (Table 3).

Table 1: Mixture proportion of Sulfate mixes (second NRMCA shipment)

Date Cast	10/25/2010	10/26/2010	10/26/2010	11/1/2010	11/1/2010	11/2/2010	11/2/2010
Calculated Batch Quantities	**SMix9**	**SMix10**	**SMix11**	**SMix12**	**SMix13**	**SMix14**	**SMix15**
	0.4FA20	0.5FA20	0.6FA20	0.4SL35	0.5SL35	0.6SL35	0.4FA30
Tot. Cem.	**609**	**560**	**484**	**601**	**556**	**486**	**613**
Type I/II cement, lb/yd^3	487	448	387	391	361	316	
Type V cement, lb/yd^3							429
Slag, lb/yd^3				210	195	170	
Fly ash, lb/yd^3	122	112	97				184
SCM, %	20	20	20	35	35	35	30
Coarse Agg. (No.57), lb/yd^3	2057	2061	2062	2030	2046	2073	2069
Fine Aggregate, lb/yd^3	1262	1216	1259	1279	1238	1267	1245
Mixing Water, lb/yd^3	244	280	290	240	278	302	245
w/cm	0.40	0.50	0.60	0.40	0.50	0.62	0.40
ASTM C494 Type A, oz/cwt	3	3	3	3	3	3	3
ASTM C494 Type F, oz/cwt	4.67	1.8	0	5.84	2.16	0	4.58
Fresh Concrete Properties							
ASTM C143, Slump, in.	4.5	6.75	5	7	5	4.5	4.75
ASTM C231, Air, %	1.6	1.8	1.7	3.2	2.1	1.7	2
ASTM C138, Density, lb/ft^3	155.3	153.3	152.5	154.5	153.3	153.7	155.3
ASTM C1064, Temperature, °F	74	75	75	72	72	72	70

Table 2: Mixture proportion of sulfate mixtures (second and third shipment)

Date cast	11/3/2010	11/3/2010	11/4/2010	11/8/2010	11/8/2010	11/15/2010	11/15/2010
Calculated Batch Quantities	**SMix16**	**SMix17**	**SMix18**	**SMix19**	**SMix20**	**SMix21**	**SMix22**
	0.5FA30	0.6FA30	0.4SL50	0.5SL50	0.6SL50	0.45PC-V1	0.45PC-V2
Tot. Cem.	**560**	**490**	**600**	**562**	**490**	**577**	**581**
Type I/II cement, lb/yd^3							
Type V cement, lb/yd^3	392	343	300	281	245	577	581
Slag, lb/yd^3			300	281	245		
Fly ash, lb/yd^3	168	147					
SCM, %	30	30	50	50	50	0	0
Coarse Agg. (No.57), lb/yd^3	2062	2088	2028	2070	2086	2049	2065
Fine Aggregate, lb/yd^3	1194	1256	1271	1247	1270	1286	1296
Mixing Water, lb/yd^3	280	294	240	281	304	260	262
w/cm	0.50	0.60	0.40	0.50	0.62	0.45	0.45
ASTM C494 Type A, oz/cwt	3	3	3	3	3	3	3
ASTM C494 Type F, oz/cwt	0	0	1.17	0.72	0	2.5	2.5
Fresh Concrete Properties							
ASTM C143, Slump, in.	6.75	7	7	5.5	6	4.5	6.5
ASTM C231, Air, %	1.5	1	1.7	1.8	1.3	1.9	1.6
ASTM C138, Density, lb/ft^3	152.5	153.7	154.1	154.9	154.5	155.3	156.5
ASTM C1064, Temperature, °F	70	70	71	70	70	72	74

Date cast	10/13/2009	10/13/2009	11/12/2009	10/20/2009	10/27/2009	11/4/2009	11/10/2009	11/10/2009
Calculated Batch Quantities	**FT1**	**FT2**	**FT3**	**FT4**	**FT5**	**FT6**	**FT7**	**FT8**
	0.57PC	**0.50PC**	**0.50FA20**	**0.50SL30**	**0.5SL25SF5**	**0.6SL25SF5**	**0.45PC**	**0.45SL30**
Type I/II cement, lb/yd^3	506	539	442	385	385	353	592	414
Slag, lb/yd^3				165	137	126		177
Fly ash, lb/yd^3			111					
Silica Fume, lb/yd^3					27	25		
SCM, %	0	0	20	30	30	30	0	30
Coarse Agg. (No.57), lb/yd^3	2087	2021	2071	2060	2058	2077	2035	2029
Fine Aggregate, lb/yd^3	1094	1083	1066	1093	1084	1072	1062	1048
Mixing Water, lb/yd^3	290	270	276	275	275	302	267	266
w/cm	0.57	0.50	0.50	0.50	0.50	0.60	0.45	0.45
ASTM C494 AEA, oz/cwt	0.76	0.81	4.26	1.15	0.86	1.39	0.74	1.16
ASTM C494 Type F, oz/cwt		0.57	0.40	0.58	2.59	0.51	1.37	1.87
Fresh Concrete Properties								
ASTM C143, Slump, in.	7	6	6	5	5	6.5	5.25	6
ASTM C231, Air, %	6	7.2	6	6.2	6.5	6.2	7	7.6
ASTM C138, Density, lb/ft^3	148.1	145.7	147.7	148.1	147.7	147.3	147.3	146.5
ASTM C1064, Temperature, F	75	75	73	70	72	70	70	70

Samples preparation and testing

For each mixture, two cylinders (4”x8”) were previously tested for resistivity assessment and gas permeability was then measured.

Resistivity measurements were taken using two techniques:
- Four electrodes method (Wenner probe);
- Two electrodes method (named as “plates” in the report).

The resistivity was directly measured on 4”x8” cylinders.

For OPI testing each specimen consists of a 70 ± 2 mm diameter concrete disc with a thickness of 25 ± 2 mm cored and cut from 4” x 8” cylinders.

Directly after cutting the specimens were placed in the oven at 50 ± 2°C at 30% RH for 3 and 7 days ± 4 hours. The standard procedure considers only a 7 days period in the oven, but we wanted to see the influence of the oven drying on the permeability performance since during this phase micro-cracking might be created and permeability may consequently increase. (Note: the standard procedure does not specify RH conditions).

The samples were subsequently cooled in the desiccator at 23 ± 2°C for at least 2 hours and then the test was performed.

The samples tested in this phase were 91 days old.

Results and preliminary discussion

Resistivity measurements

The results obtained in terms of resistivity are presented in Table 4 and Figure 4 for sulfate mixtures and in Table 5 and Figure 5 for Freeze-Thaw mixtures.

Table 4: Resistivity results – Sulfate mixtures (kΩ cm)

		Wenner Probe	Plates	Wenner Probe	Plates
SMIX 9	**cyl1**	18.24	18.47	18.25	18.97
	cyl2	18.26	19.47		
SMIX 10	**cyl1**	11.67	13.57	11.43	13.13
	cyl2	11.20	12.69		
SMIX 11	**cyl1**	8.09	9.46	8.20	9.64
	cyl2	8.30	9.81		
SMIX 12	**cyl1**	33.78	34.19	32.95	33.79
	cyl2	32.12	33.39		
SMIX 13	**cyl1**	27.13	26.41	26.93	26.95
	cyl2	26.72	27.49		
SMIX 14	**cyl1**	15.87	-	17.14	-
	cyl2	18.41	-		
SMIX 15	**cyl1**	22.87	-	21.94	-
	cyl2	21.01	-		
SMIX 16	**cyl1**	9.76	9.93	10.00	10.25
	cyl2	10.24	10.57		
SMIX 17	**cyl1**	7.63	7.98	7.64	8.24
	cyl2	7.64	8.50		
SMIX 18	**cyl1**	49.96	51.03	47.91	48.12
	cyl2	45.86	45.20		
SMIX 19	**cyl1**	37.50	-	38.84	-
	cyl2	40.18	-		
SMIX 20	**cyl1**	30.92	-	30.90	-
	cyl2	30.88	-		
SMIX 21	**cyl1**	8.01	10.17	7.88	9.80
	cyl2	7.75	9.42		
SMIX 22	**cyl1**	5.75	7.90	6.66	8.48
	cyl2	7.58	9.06		

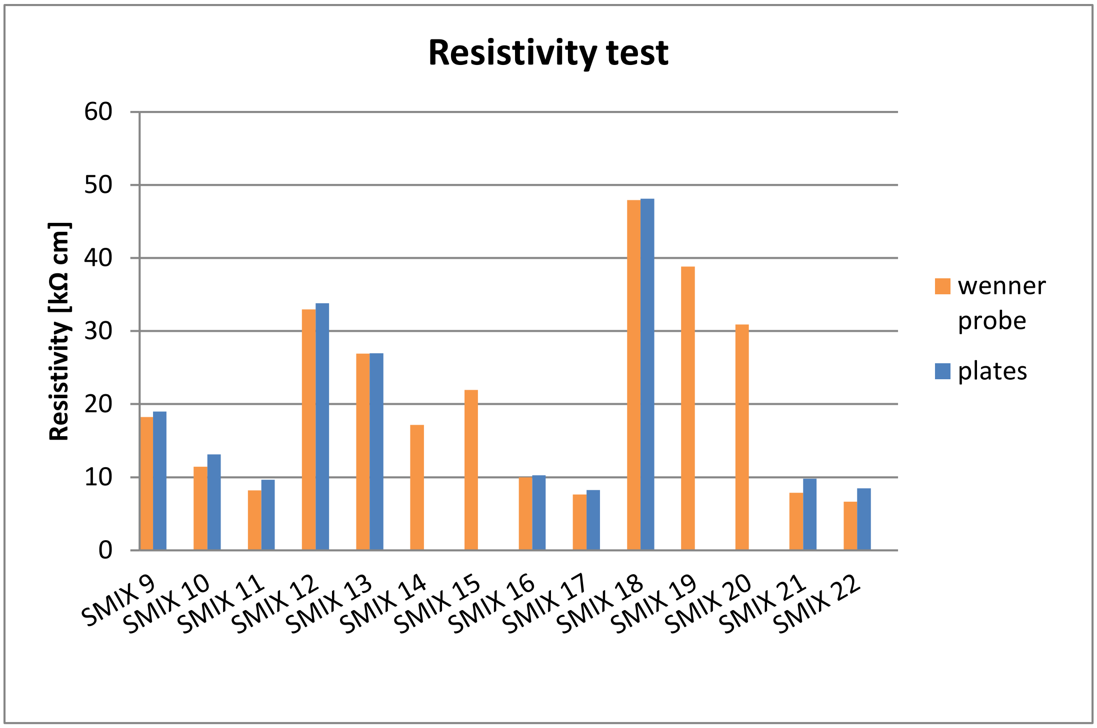
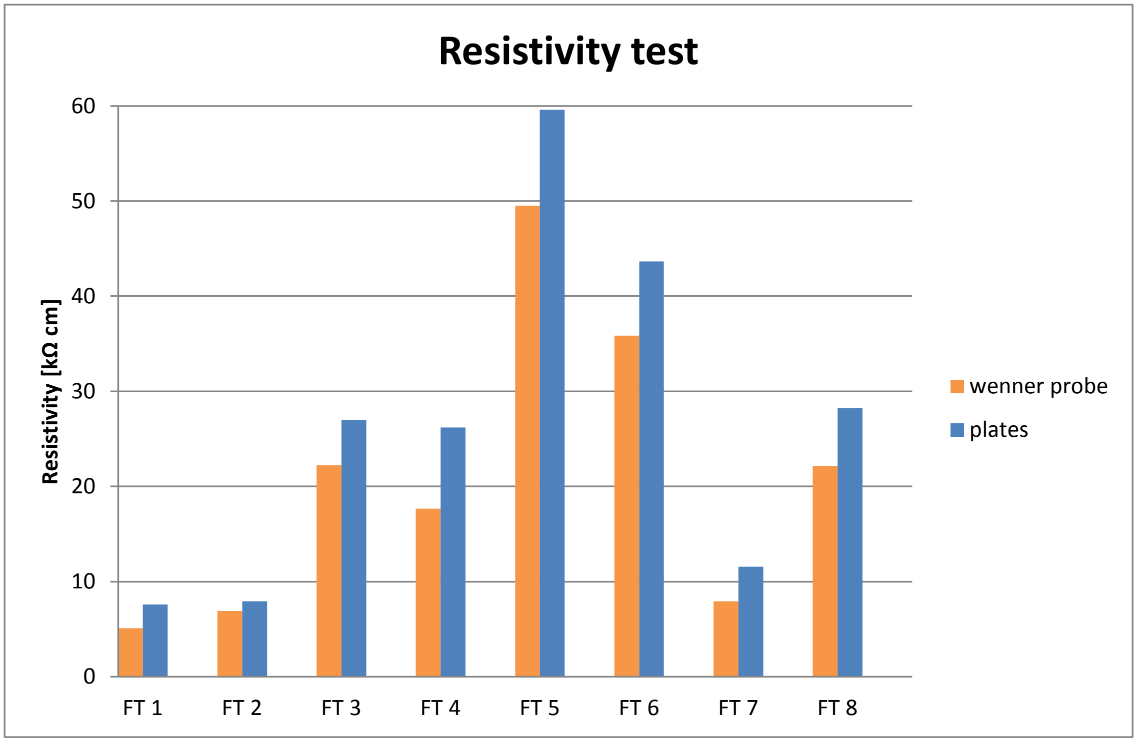


Table 5: Resistivity results – Freeze and Thaw mixtures (kΩ cm)

		Wenner Probe	Plates	Wenner Probe	Plates
FT 1	**cyl1**	4.96	8.06	5.10	7.58
	cyl2	5.24	7.10		
FT 2	**cyl1**	7.09	7.98	6.91	7.92
	cyl2	6.72	7.86		
FT 3	**cyl1**	20.29	24.58	22.24	26.99
	cyl2	24.18	29.40		
FT 4	**cyl1**	17.47	25.85	17.66	26.19
	cyl2	17.86	26.53		
FT 5	**cyl1**	49.07	58.65	49.50	59.61
	cyl2	49.93	60.57		
FT 6	**cyl1**	37.09	46.12	35.86	43.65
	cyl2	34.62	41.17		
FT 7	**cyl1**	7.97	11.45	7.93	11.57
	cyl2	7.88	11.69		
FT 8	**cyl1**	22.36	28.41	22.16	28.23
	cyl2	21.97	28.05		



In order to compare the results of the two measurement methodologies, the conversion from resistance (measured with the two electrodes method) to resistivity has been done. Moreover, it has been taken into account a geometric correction factor assumed to be equal to K=1.9.

Oxygen Permeability measurements

During the Oxygen permeability test the gas permeability is measured by recording the pressure decay with time (from the initial value of 100 kPa). This pressure decay is converted to a linear relationship by plotting the logarithm of the ratio of pressure heads over time. The slope of the linear regression that best fits this trend is then evaluated and the *permeability coefficient* is calculated by:

$$k = \frac{\omega V g d z}{R A \phi} \quad (1)$$

Where:
ω = molecular mass of oxygen (32 g/mol)
V = volume of oxygen under pressure [m^3]
g= acceleration due to gravity [m/s^2]
d = average specimen thickness [m]
R = universal gas constant [N m/K mol]
A = cross sectional area of sample [m^2]
Φ = absolute temperature [°K]
z = slope of linear regression [-] evaluated through:

$$z = \frac{\sum[\ln(P_0 / P_t)]^2}{\sum[\ln(P_0 / P_t)t]} \quad (2)$$

Where P_o is the initial pressure and P_t is the pressure at time t.

The Oxygen Permeability Index is then evaluated through:

$$OPI = -\log_{10} [¼ (k_1+k_2+k_3+k_4)]$$

The results obtained are presented in the following figures (Figure 6, 7, 8 and 9) and tables (Table 6,7).

Table 6: Permeability and OPI indexes – Sulfate mixtures

		OPI index [-]	k [m/s]
SMIX 9	3d	11.96	1.09E-12
	7d	11.85	1.41E-12
SMIX 10	3d	11.71	1.43E-12
	7d	11.76	1.73E-12
SMIX 11	3d	11.84	1.45E-12
	7d	11.72	1.89E-12
SMIX 12	3d	11.86	1.39E-12
	7d	11.88	1.33E-12
SMIX 13	3d	11.72	1.88E-12
	7d	11.71	1.98E-12
SMIX 14	3d	11.64	2.31E-12
	7d	11.52	3.04E-12
SMIX 15	3d	11.77	1.70E-12
	7d	11.50	1.60E-12
SMIX 16	3d	11.56	2.77E-12
	7d	11.62	2.39E-12
SMIX 17	3d	11.42	3.82E-12
	7d	11.43	3.72E-12
SMIX 18	3d	11.66	2.18E-12
	7d	11.68	2.08E-12
SMIX 19	3d	11.49	3.26E-12
	7d	11.51	3.12E-12
SMIX 20	3d	11.40	4.01E-12
	7d	11.44	3.64E-12
SMIX 21	3d	11.66	2.18E-12
	7d	11.61	2.48E-12
SMIX 22	3d	11.63	2.35E-12
	7d	11.61	2.45E-12

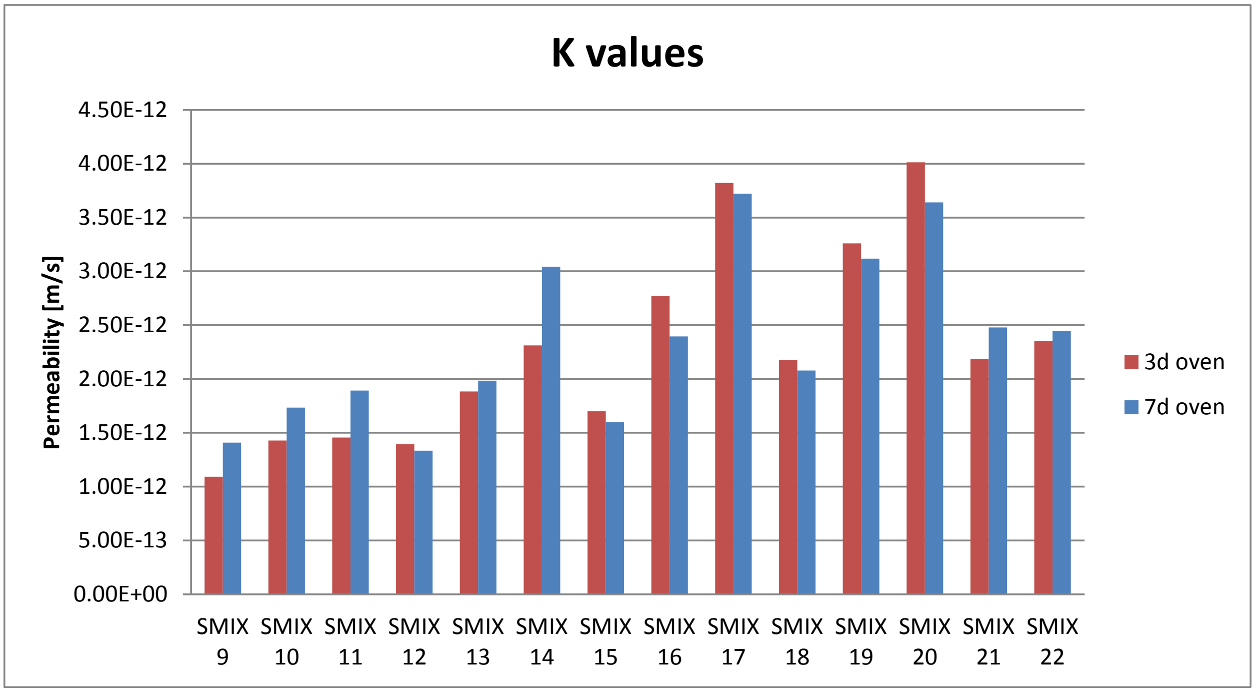


Figure 6: Permeability – Sulfate mixtures

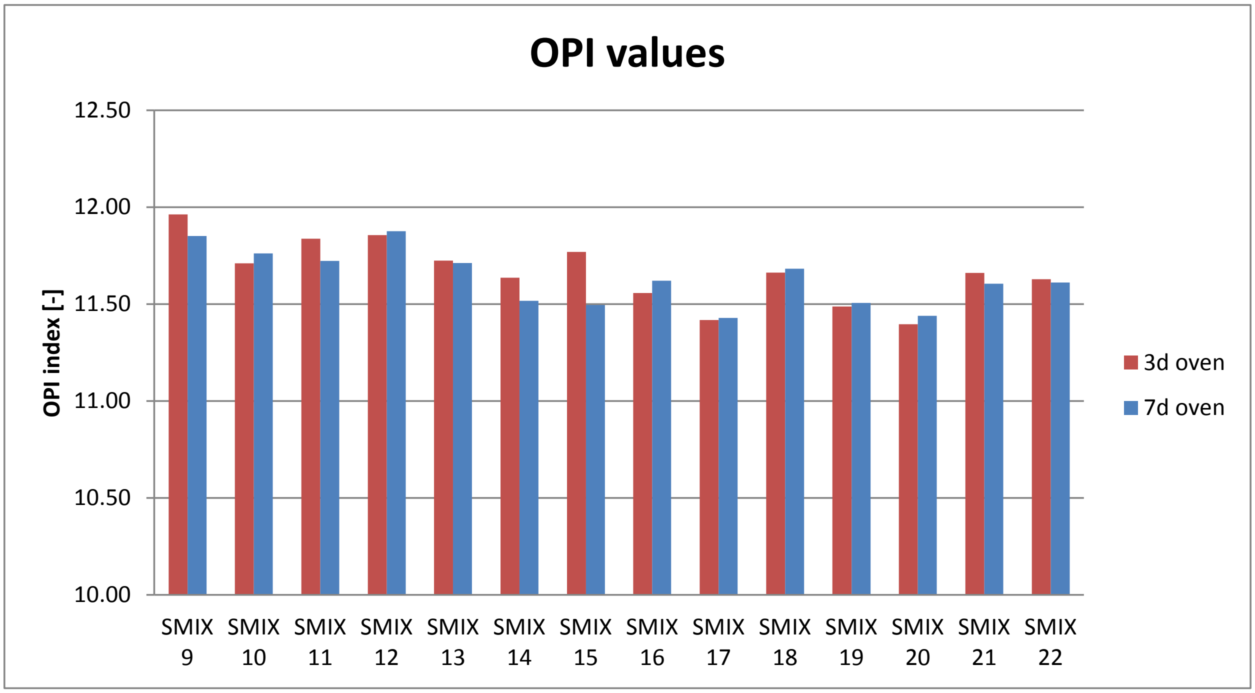


Figure 7: OPI index – Sulfate mixes

Table 7: Permeability and OPI indexes – Freeze and Thaw

FT 1	3d	11.47	3.40E-12
	7d	11.40	3.97E-12
FT 2	3d	11.60	2.51E-12
	7d	11.68	2.08E-12
FT 3	3d	11.48	3.28E-12
	7d	11.46	3.43E-12
FT 4	3d	11.53	2.94E-12
	7d	11.42	3.83E-12
FT 5	3d	11.70	2.02E-12
	7d	11.54	2.90E-12
FT 6	3d	11.40	4.01E-12
	7d	11.38	4.20E-12
FT 7	3d	11.02	9.64E-12
	7d	10.97	1.08E-11
FT 8	3d	11.52	3.01E-12
	7d	11.57	2.68E-12

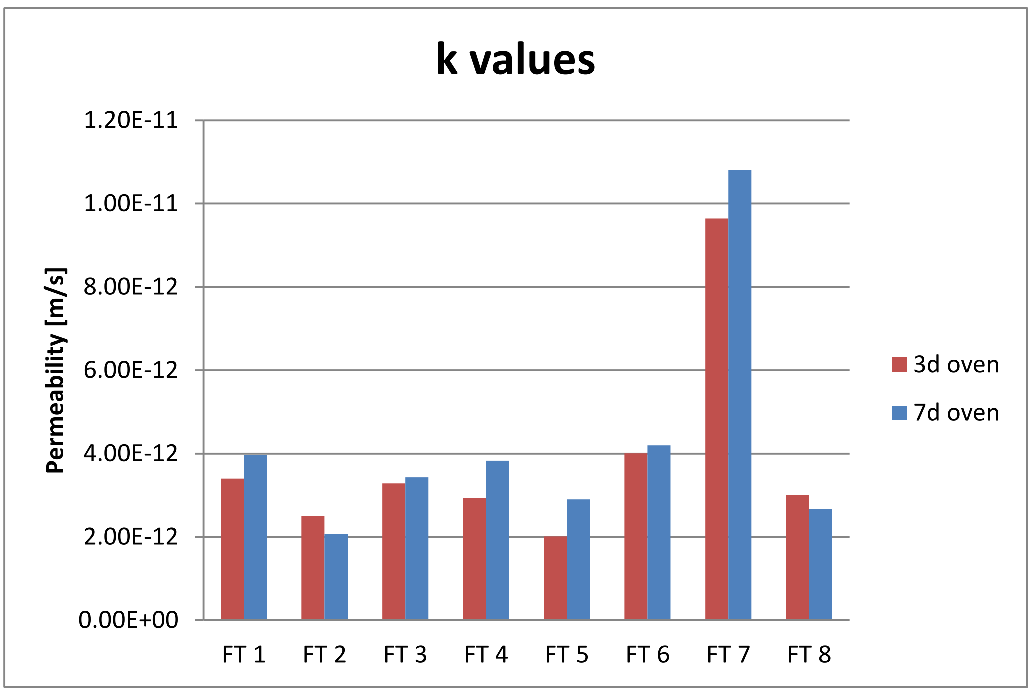


Figure 8: Permeability – Freeze and Thaw mixtures

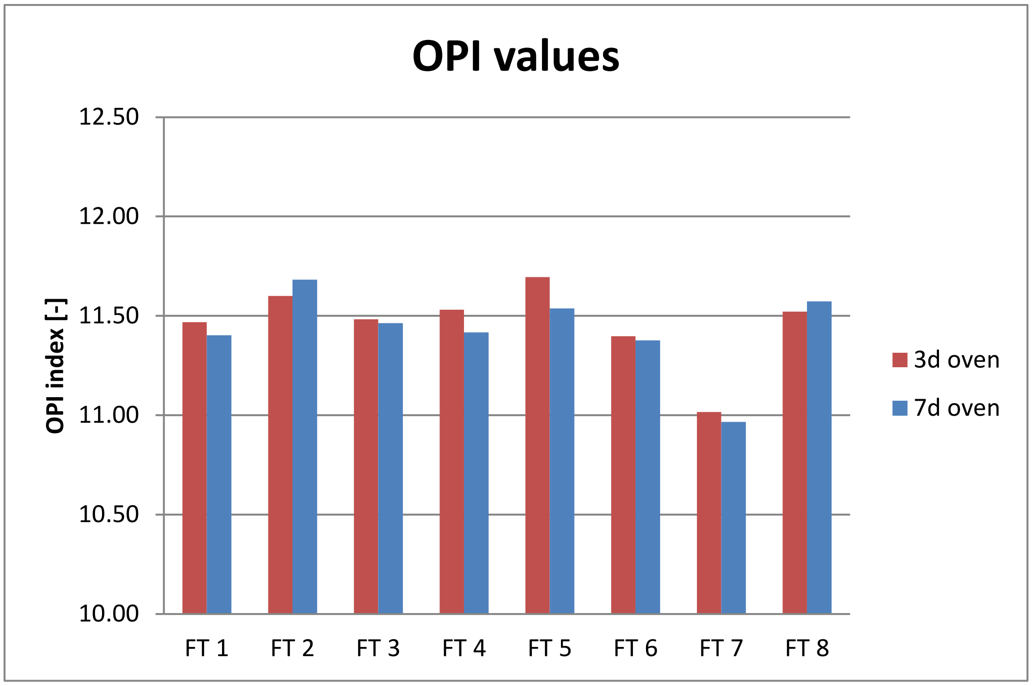


Figure 9: OPI index – Freeze and Thaw mixtures

Observation

We should note, at first, a good general trend between resistivity and gas permeability measurements: obviously, higher values of resistivity correspond to lower values of gas permeability and higher values of OPI.

The results, concerning the gas permeability, have been presented in terms of permeability and OPI index: the choice to show also k values is because we think OPI index does not emphasize enough the difference among the mixtures analyzed. The presence of logarithm, indeed, smoothen the differences among the results and this might hide important changes in terms of permeability.

Looking at sulfate mixes results we should notice that:

- The usage of SCM in general improve the quality of concrete in terms of permeability;
- The addition of slag has a more positive effect then the addition of fly ash;
- Type V cement performs slightly worse than Type I/II cement;
- And obviously increasing w/b ratio, the permeability increases.

From freeze and thaw mixes, similarly:

- Increasing w/b ratio, the permeability increases as well;
- The addition of slag has a positive effect for permeability performance;
- The addition of fly ash, in this case, seems to have little effect, if compared to the system with only cement.

More in general:

- resistivity values from Wenner probe are slightly lower than those from plates measurement;
- samples tested after 7 days of conditioning in the oven showed a slightly higher permeability.

STUDY OF THE INFLUENCE OF GEOMETRY ON GAS PERMEABILITY MEASUREMENT

Introduction

In this preliminary study, the aim is to see the influence of geometry on gas permeability measurements: in particular, samples with different height have been tested with the South African instrument.

Sample and mixture proportions

The mixture proportions of the samples used in this study are presented in Table 8.

Table 8: Mixture proportions

Material	*Quantity*
gravel [lb/m^3]	1800
sand [lb/m^3]	1200
cement [lb/m3]	658
air [%]	0.6
water [lb/m3]	245
Adm 1 (reducer) [%]	2
Adm 2 (retarder) [%]	4

The preparation of samples started when the sample were about 180 days old, sealed at 28 days until the date of testing.

For OPI testing each specimen consists of a 70 ± 2 mm diameter concrete disc with a thickness of 25 ± 2 mm cored and cut from 4" x 8" cylinders.

Directly after cutting the specimens were placed in the oven at 50 ± 2°C at 30% RH for 3 and 7 days ± 4 hours. The standard procedure considers only a 7 days period in the oven, but we wanted to see the influence of the oven drying on the permeability performance since during this phase micro-cracking might be created and permeability may consequently increase. (Note: the standard procedure does not specify RH conditions).

The samples were subsequently cooled in the desiccator at 23 ± 2°C for at least 2 hours and then the test was performed.

The geometry dimensions of the samples tested are presented in Table 9.

Table 9: Geometry

		D [mm]	H [mm]
0.5 in	**sample 1**	68.25	14.0
	sample 2	68.2	15.3
	sample 3	68.35	14.4
	sample 4	68.35	14.8
1.0 in	**sample 1**	68.3	28.2
	sample 2	68.7	28.4
	sample 3	68.65	29.2
	sample 4	68.3	28.8
1.5 in	**sample 1**	68.4	37.3
	sample 2	68.405	39.9
	sample 3	68.425	38.8
	sample 4	68.485	38.8

Results

The calculation of permeability and OPI index has been done following the same procedure previously.

The results are presented in Table 10 and Figure 10 and 11.

Table 10: OPI index and permeability values

	OPI index [-]	k [m/s]
0.5 in	11.79	1.61E-12
1.0 in	11.86	1.39E-12
1.5 in	11.93	1.19E-12

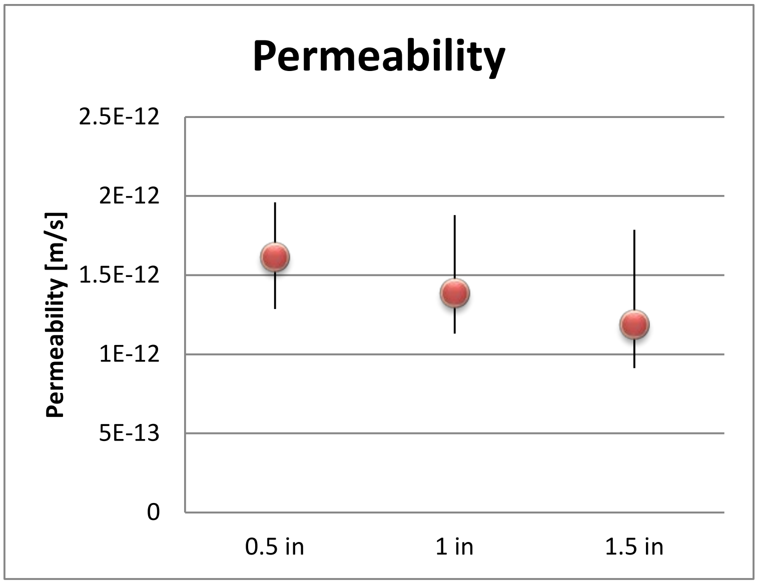


Figure 10: Permeability values and variation

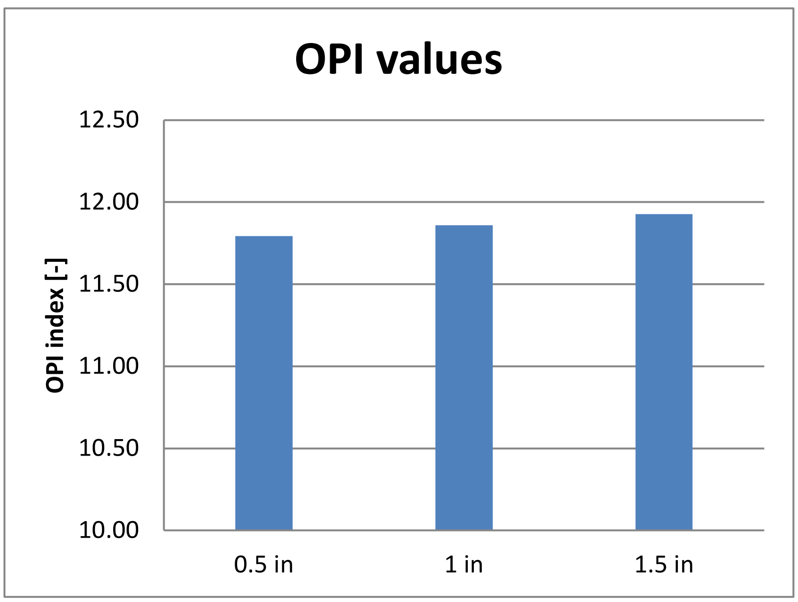


Figure 11: Permeability values and variation

Observation

It can be seen from the plots previously showed that the geometry dimensions of the samples affect the permeability evaluation. In particular, permeability seems to decrease increasing the height of the samples.

Further studies will be performed in order to better understand this effect.

2.0 Proposed Activities for the Next Period

2.1 Phase II – Testing samples

Other mortar samples casted previously will be tested using the south African These samples have been conditioned in three different temperature controlled room (50%, 65% and 80% at 23 C).

Additional samples will be tested to prove the influence of geometry in gas permeability measures.

2.3 Phase III – Development or improvement of existing permeability tests

A further investigation to confirm what it has found in terms of influence of RH on gas permeability measurement will be performed. Four conditions will be tested (30% - 50% - 65% and 80% RH at 50 C).

65% RH condition has been created in an existing oven (50 C) through the usage of a saturated solution of potassium iodide.

The setting of the Swiss permeability instrument is proceeding. Hereafter are presented some pictures of the instrument during the assembling phase (Figure 12).

Figure 12: Swiss Permeability instrument

2.3 Phase IV NRMCA

It is understood that concrete can fail due to chloride induced corrosion, sulfate attack, freeze thaw attack and ASR. In this phase rapid index test criteria suitable for specifications will be developed that correlate well with slower performance tests for concrete exposed to chlorides, sulfates, and freeze thaw.

Chloride Ingress - Test Methods, Curing Conditions and Test Ages

Chloride ingress can occur from deicing salts applied in bridge decks in Northern regions as well as concrete exposed to marine conditions. It is well known that when the chloride concentration at the steel rebar exceeds the chloride threshold corrosion can initiate. The chloride diffusion test (ASTM C1556) is understood to be a good performance test. However, that is a very slow test and applicable only for sophisticated laboratories. So rapid index tests were evaluated as follows:

Table 4 : Mixture Proportions and Variables

w/cm	PC	15%FA	30%FA	25%SL	50%SL	7%SF	40%SL+5%SF
0.29	Yes - l						
0.34							Yes - n
0.39	Yes - m	Yes - l	Yes - vl	Yes - l	Yes - vl	Yes - vl	
0.49	Yes - h	Yes - m		Yes - m			
0.62			Yes - h		Yes - h		

where

H – High chloride permeability (>5 x 10^{-12} m^2/s) – 3 mixtures
M – moderate chloride permeability (3 to 5 x 10^{-12} m^2/s) – 3 mixtures
L – low chloride permeability (2 to 3 x 10^{-12} m^2/s) – 3 mixtures
VL – very low chloride permeability (0.7 to 2 x 10^{-12} m^2/s) – 3 mixtures
N – negligible chloride permeability (<0.7 x 10^{-12} m^2/s) – 1 mixture

The above mixtures were selected keeping the following in mind:

1. Cover a predicted (based on Life 365 computer program) 2 year chloride diffusion coefficient range that is broad – 6.8x10^{-12} to 0.62x10^{-12} m^2/s
2. To be able to use rapid index test criteria to choose mixtures with desired classification as indicated above and at the very least rapid index test criteria should help eliminate mixtures with high diffusion coefficients (>5 x 10^{-12} m^2/s)
3. Look at common SCMs like fly ash, slag, silica fume to see if correlation between the rapid index tests criteria and diffusion coefficients are independent of SCM types and dosages
4. w/cm, SCM dosages chosen must cover the ranges normally used in HPC
5. Also some mixtures that would yield high chloride diffusion coefficients (containing high w/cm, high pozzolan) should be made and the rapid index tests

should yield high values so that such mixtures will not be selected. Also some mixtures that would yield low chloride diffusion coefficients (containing low w/cm, low or no pozzolan or conductive aggregates) should be made and the rapid index tests should yield low values so that such mixtures will be selected.

Mixture Prepared and Tested Thus Far

All the 13 concrete mixtures have now been cast in 2 phases. Phase I looked at 6 mixtures and the test results are provided in Table 1 where as Phase II looked at 7 mixtures and the test results are provided in Table 2. The common elements of the two phases are:

Crushed coarse aggregate (1.0 in. nominal maximum size) ASTM C33 No. 57, natural sand FM=2.88

Adjusted water reducer or high range water reducer (if any) for desired slump = 5 to 7 in.

Non air entrained concrete mixtures – even though most of these mixtures in practice will contain air our aim here is to determine the validity of the rapid index tests and criteria in classifying mixtures based on their chloride diffusion coefficients. This validation will also hold for air entrained concrete mixtures. Also the use of air entrainment will make the comparisons between mixtures more challenging

Planned Test Methods, Curing Conditions and Test Ages

Normal Curing – Standard moist room curing starts immediately after making the specimens

Accelerated Curing – 7 days of normal curing followed by 21 days of curing in 100F water

For all mixtures measure the following:
Slump, temperature, air content, density, Strength (28 days), Shrinkage (7 days moist curing followed by 90 days of air drying). Shrinkage test is for reference and may be discontinued for future mixtures.

The following durability tests will be conducted for all the mixtures

Durability Tests

- **Rapid Chloride Permeability test – RCPT (ASTM C1202)**

i) 28 day accelerated
ii) 56 day normal curing
iii) 26 week (182 d) normal curing
iv) 78 week (546 d) normal curing

- **5 minute Conductivity Test (ASTM C1202 based)**

i) 28 day accelerated

ii) 56 day normal curing
iii) 26 week (182 d) normal curing
iv) 78 week (546 d) normal curing

- **Rapid Migration Test - RMT (AASHTO TP 64)**

i) 28 day accelerated
ii) 56 day normal curing
iii) 26 week (182 d) normal curing
iv) 78 week (546 d) normal curing

- **Chloride Diffusion Test (ASTM C1556)**

i) 59d week normal curing + 186d in solution. For Phase II this condition was replaced by 56d normal curing + cyclic exposure (75 week using 3d in solution/4d at 73F-50%rh cycle) in solution - 2
ii) 59d normal curing + 490d in solution till 78 weeks. For Phase II this condition was replaced by 6months normal curing + 12 months in solution - 1
iii) 59d normal curing + cyclic exposure (18 week using 4d in solution/3d at 100F-20%rh cycle) in solution
iv) 59d normal curing + 59d in solution
v) 26 weeks normal cure +35 days in solution

- **Sorptivity Test (ASTM C1585)**

i) 28 day accelerated + 18 d specimen conditioning (C1585)
ii) 56 day normal curing + 18 d specimen conditioning (C1585)
iii) 26 week (182 d) normal curing + 18 d specimen conditioning (C1585)

- **Absorption test BS 1881:122 (ASTM Draft)**

i) 10 day normal curing + 3 d in oven
ii) 28 day accelerated + 3 d in oven
iii) 26 week (182 d) normal curing + 3 d in oven

For Phase II only the 56 day normal curing condition was tested. For Phase I the oven temperature was maintained at 105C where as for Phase II it was 60C. The difference followed the development of the ASTM drafts. It was felt that the high oven temperatures will lead to internal micro-cracking of concrete leading to misleading high results that are not reflective of the absorption characteristics of the concrete specimen being tested.

Rapid index tests need to correlate with chloride penetration levels for two real life situations:

a. when the structures are in a complete or near complete saturation state such as in a submerged marine exposure or possibly bridge decks in high humidity regions where chloride ingress is primarily diffusion controlled. The ASTM C1556 would be the correct comparison test here and the aim would be to observe which of the rapid index tests correlates well with diffusion coefficient (at oldest age).
b. when the structures are not completely saturated such as bridge decks in low humidity regions where the chloride ingress could be due to sorption and diffusion. ASTM C1556 conducted in a wet/dry scenario would be the correct comparison test here and the aim would be to observe which of the rapid index tests correlates well with the ingress coefficient (at oldest age).

Table 5. Yield Adjusted Mixture Proportions and Test Results

Calculated Batch Quantities						
	0.49Ctrl	**0.49SL25**	**0.39SL50**	**0.49FA15**	**0.39FA30**	**0.34SL40SF5**
Type I/II cement, lb/yd^3	554	416	306	472	431	382
Slag, lb/yd^3		139	306			277
Fly ash, lb/yd^3				83	185	
Silica Fume, lb/yd^3						35
SCM, %	0	25	50	15	30	45
Coarse Agg. (No.57), lb/yd^3	2075	2074	2070	2081	2081	2086
Fine Aggregate, lb/yd^3	1303	1293	1314	1273	1267	1264
Mixing Water, lb/yd^3	272	272	239	273	240	236
w/cm	0.49	0.49	0.39	0.49	0.39	0.34
ASTM C494 Type A, oz/cwt	4.0	4.0	4.0	4.0	4.0	4.0
ASTM C494 Type F, oz/cwt	2.5	2.9	4.3	2.4	5.0	7.8
Fresh Concrete Properties						
ASTM C143, Slump, in.	7 1/2	4 1/2	8	7	6 3/4	9
ASTM C231, Air, %	1.4	1.7	1.3	1.5	1.6	1
ASTM C138, Density, lb/ft^3	156.5	156.1	157.7	155.7	156.5	159.3
ASTM C1064, Temperature, °F	76	76	75	76	75	75
Hardened Concrete Properties						
ASTM C39, Compressive Strength, psi						
28 days	6,830	7,550	10,520	6,640	7,970	12,440
Draft ASTM Standard, Water Absorption Test at 105 °C, %						
10d normal cure	2.89	2.24	1.69	3.25	2.33	1.43
28d accelerated cure	2.52	1.77	1.34	2.44	1.63	1.26
196d normal cure	2.30	1.80	1.29	2.29	1.44	1.49
ASTM C1202, Rapid Chloride Permeability, Coulombs						
28d accelerated cure	4657	1992	561	2414	723	166
56d normal cure	4674	1912	581	3013	1417	270
196d normal cure	3356	1581	496	1551	340	147
550d normal cure	3891^{-}	1465^{-}	394^{-}	1070^{-}	174^{-}	166^{-}
Draft ASTM Standard, 5 minute Conductivity, Sm^{-1}						
28d accelerated cure	0.019	0.009	0.003	0.009	0.003	0.001
56 normal cure	0.015	0.007	0.003	0.013	0.006	0.001
196d normal cure	0.010	0.005	0.002	0.006	0.002	0.001
550d normal cure	0.008^{-}	0.005^{-}	0.002^{-}	0.005^{-}	0.001^{-}	0.001^{-}
AASHTO TP64, Rate of Penetration (RMT), mm/(V-hr)						
28d accelerated cure	0.065	0.030	0.004	0.046	0.015	0.003
56d normal cure	0.044	0.025	0.006	0.043	0.024	0.002
196d normal cure	0.047	0.016	0.006	0.025	0.006	0.002
550d normal cure	0.048^{-}	0.017^{-}	0.003^{-}	0.017^{-}	0.005^{-}	0.001^{-}
ASTM C157, Length Change (Drying Shrinkage), %						

28 days[+]	0.035	0.039	0.031	0.029	0.028	0.028
56 days[+]	0.046	0.048	0.037	0.039	0.036	0.032
90 days[+]	0.055	0.054	0.044	0.048	0.043	0.039
180 days[+]	0.062	0.060	0.049	0.054	0.049	0.044
ASTM C 1585, Rate of Water Absorption (Sorptivity), $x10^{-4}$ $mm/s^{1/2}$						
28d accel. cure (Initial/Secondary)	10.0 / 7.5	3.1[*] / 2.8	1.8[*] / 1.7	7.5 / 4.6	4.8[*] / 2.1	2.6[*] / 0.86
56d normal cure (Initial/Secondary)	9.9 / 6.9	6.8 / 2.4[*]	2.6[*] / 1.4	20.0 / 13.0	7.1[*] / 3.3	4.1[*] / 1.9[*]
196d normal cure (Initial/Secondary)	6.8[*] / 6.8	4.1[*] / 1.3	4.9[*] / 1.3	4.1 / 2.4	3.6[*] / 1.8	1.2[*] / 0.82[*]
28d accel. cure (Initial/Secondary), g	1.77 / 6.85	0.82 / 2.59	0.66 / 1.75	1.48 / 4.93	1.20 / 2.71	0.51 / 1.13
56d normal cure (Initial/Secondary), g	1.78 / 6.74	1.06 / 2.94	0.67 / 1.62	2.62 / 12.2	1.4 / 3.76	0.87 / 2.17
196d normal cure (Initial/Secondary), g	1.34 / 5.74	0.96 / 1.81	1.13 / 1.94	1.09 / 2.73	0.95 / 2.12	0.64 / 1.14
ASTM C 1556, Chloride Diffusion, x 10^{-12} m^2/s						
Case 4	5.28	2.24	0.84	8.64	4.81	0.36
Case 3	11.8	3.20	1.02	6.45	4.01	0.64
Case 1	2.28	1.37	0.47	1.74	0.14	0.26
Case 5	2.36	1.32	0.68	3.91	2.02	0.30
ASTM C 1556, Surface Chloride, % by weight of concrete						
Case 4	1.12	1.77	1.03	0.96	0.75	3.02
Case 3	1.02	1.37	1.93	1.23	1.39	2.65
Case 1	1.01	1.90	2.11	1.26	5.62	1.90
Case 5	0.78	1.29	1.87	1.19	2.41	2.14

[+] Curing period in 70°F, 50% RH environment NOT included 7 days initial wet curing period in water bath
[*] a correlation coefficient less than 0.98 indicating that the rate cannot be determined according to ASTM C1585
[-] Result of only one specimen

Rapid index tests results were compared with chloride diffusion test data. Research results were presented at the 2009 Concrete Technology Forum in Cincinnatti, OH as “Early Age Tests and Criteria for Predicting Long Term Chloride Penetration into Concrete”. Preliminary observations show promising correlations between the early age RCPT results and chloride diffusion coefficients for scenarios Case 1, and Case 3. For Cases 4, and 5 fly ash mixes appear to be more prone to show higher Da’s than what the early age RCPT results would have suggested.

Table 6. Yield Adjusted Mixture Proportions and Preliminary Test Results

Calculated Batch Quantities								
	0.39PC	**0.39FA15**	**0.39SL25**	**0.39SF7**	**0.62FA30**	**0.62SL50**	**0.29PC**	**0.39PC[**]-R**
Type I/II cement, lb/yd^3	612	520	462	565	349	249	803	612
Slag, lb/yd^3	-	-	154	-	-	249	-	-
Fly ash, lb/yd^3	-	92	-	-	149	-	-	-
Silica Fume, lb/yd^3	-	-	-	43	-	-	-	-
SCM, %	0%	15%	25%	7%	30%	50%	0%	0%
Coarse Agg. (No.57), lb/yd^3	2066	2068	2081	2052	2094	2093	2069	2066
Fine Aggregate, lb/yd^3	1331	1296	1331	1307	1216	1258	1183	1331
Mixing Water, lb/yd^3	238	239	240	237	287	290	236	238
w/cm	0.39	0.39	0.39	0.39	0.58	0.58	0.29	0.39
ASTM C494 Type A, oz/cwt	4	4	4	4	3	3	5	4
ASTM C494 Type F, oz/cwt	8.8	8.3	6.9	8.2	-	-	11.7	8.4
Fresh Concrete Properties								
ASTM C143, Slump, in.	5	6 1/2	7 3/4	6	6 1/2	7	8 3/4	7
ASTM C231, Air, %	1.8	1.6	1.2	1.8	1.6	1.4	1.1	1.7
ASTM C138, Density, lb/ft^3	158.1	156.9	158.9	156.5	152.5	154.1	159.7	158.1
ASTM C1064, Temperature, °F	75	75	75	75	75	75	76	76
Hardened Concrete Properties								
ASTM C39, Compressive Strength, psi								
28 days	10,460	9,590	10,300	10,740	3,880	5,380	13,480	9,890
Draft ASTM Standard, Water Absorption Test at 60 °C, %								
56d normal cure	1.03	1.02	1.00	0.82	1.88	1.75	0.91	-
213d normal cure	0.85	0.79	0.91	0.76	1.55	1.40	0.70	-
ASTM C1202, Rapid Chloride Permeability, Coulombs								
28d accelerated cure	2180[-]	1031	1186	276	2495	661	1078	1980
56d normal cure	1722	1557	1272	299	4012	832	1209	-
213d normal cure	1607	563	873	252	1177	572	936	-
Draft ASTM Standard, 5 minute Conductivity, Sm^{-1}								
28d accelerated cure	0.010[-]	0.005	0.006	0.001	0.009	0.004	0.006	0.010
56 normal cure	0.009	0.007	0.006	0.001	0.012	0.003	0.006	-
213d normal cure	0.006	0.003	0.004	0.001	0.004	0.002	0.004	-
AASHTO TP64, Rate of Penetration (RMT), mm/(V-hr)								
28d accelerated cure	0.034[-]	0.017	0.013	0.004	0.047	0.007	0.012	0.029
56d normal cure	0.027	0.017	0.011	0.004	0.046	0.012	0.011	-
213d normal cure	0.021	0.009	0.009	0.002	0.033	0.006	0.007	-
ASTM C157, Length Change (Drying Shrinkage), %								
28 days[+]	0.032	0.037	0.032	0.028	0.041	0.044	0.024	-

56 days[+]	0.039	0.047	0.038	0.034	0.054	0.052	0.029	-
90 days[+]	0.042	0.054	0.047	0.043	0.064	0.053	0.030	-
180 days[+]	0.049	0.056	0.052	0.045	0.066	0.061	0.038	-
ASTM C 1585, Rate of Water Absorption (Sorptivity), x10^{-4} mm/$s^{1/2}$								
28d accel. cure (Initial/Secondary)	-	3.1 / 2.1	4.7 / 2.0[*]	3.3 / 2.1	9.6 / 3.8	7.6 / 2.8	3.1 / 2.6	9.5 / 5.2
56d normal cure (Initial/Secondary)	5.9 / 3.3[*]	6.1 / 4.1	3.1[*] / 1.5[*]	3.1 / 1.9[*]	9.9 / 7.0	7.1[*] /2.8[*]	2.1[*]/ 2.9	-
213d normal cure (Initial/Secondary)	4.7[*] / 3.0	3.2[*] / 2.2	3.6[*] / 1.9	2.6[*] / 0.7[*]	4.6 / 3.7	5.6[*] / 1.6[*]	1.6[*]/1.3[*]	-
28d accel. cure (Initial/Secondary), g	-	0.5 /1.9	0.9 / 2.2	0.6 / 1.9	1.8 / 4.4	1.9 / 3.7	0.5 / 2.2	1.6 / 5.1
56d normal cure (Initial/Secondary), g	1.1 / 3.2	0.9 /3.8	0.8 / 1.7	0.6 / 1.7	2.3 / 6.9	2.1 / 3.9	0.5 / 2.4	-
213d normal cure (Initial/Secondary), g	0.8 / 2.5	0.5 / 2.0	0.7 / 1.8	0.5 / 1.0	1.3 / 4.0	1.4 / 2.7	0.3 / 1.2	-
ASTM C 1556, Chloride Diffusion, x 10^{-12} m^2/s								
56d nc + 35d in solution	4.58	2.89	2.21	1.18	6.99	2.90	1.32	-
6m nc + 35d in solution	2.72	1.34	1.12	0.67	7.10	2.31	1.04	-
6m nc + 12m in solution	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
56d nc + 21w cyclic exposure (3d solution+ 4d air)	1.59	1.24	0.87	0.66	8.33	2.33	0.67	-
56d nc + 75w cyclic exposure (3d solution+ 4d air)	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
ASTM C 1556, Surface Chloride, % by weight of concrete								
56d nc + 35d in solution	0.96	1.17	1.50	1.23	1.11	1.40	1.10	-
6m nc + 35d in solution	0.94	1.46	1.60	1.27	1.00	1.20	1.46	-
6m nc + 12m in solution	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
56d nc + 21w cyclic exposure (3d solution+ 4d air)	1.01	1.29	1.57	1.32	1.54	1.71	1.42	-
56d nc + 75w cyclic exposure (3d solution+ 4d air)	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-

[-] Tested at 21d instead of 28d
[+] Curing period in 70°F, 50% RH environment NOT included 7 days initial wet curing period in water bath
[*] A correlation coefficient less than 0.98 indicating that the rate cannot be determined according to ASTM C1585
[**] Exact repeat of designated mixture

Preliminary Observations

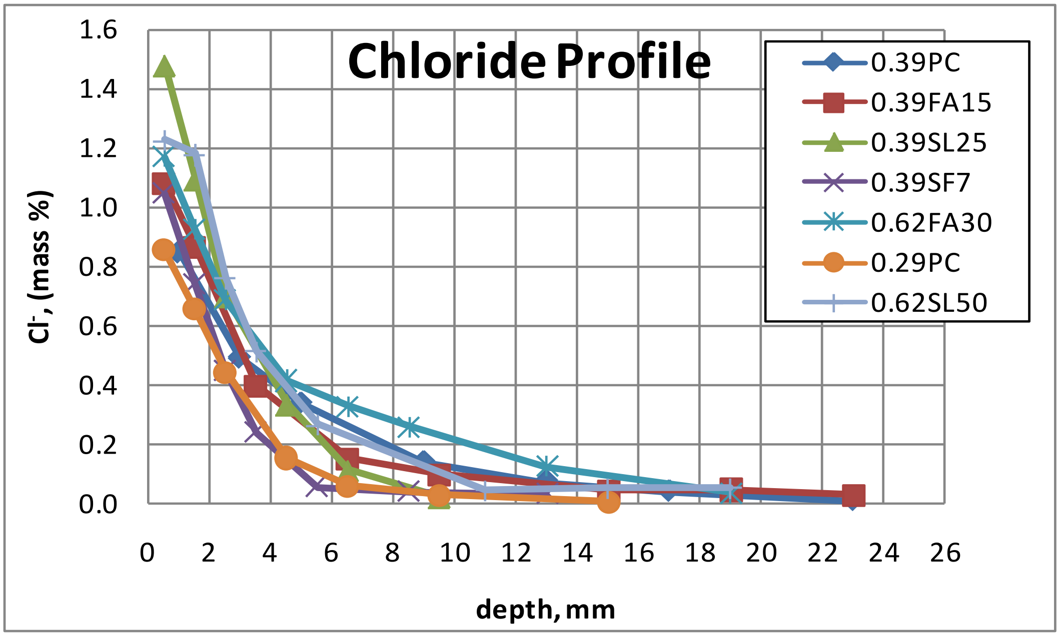


Figure 7. Chloride profile for 56d normal curing followed by 35d in solution

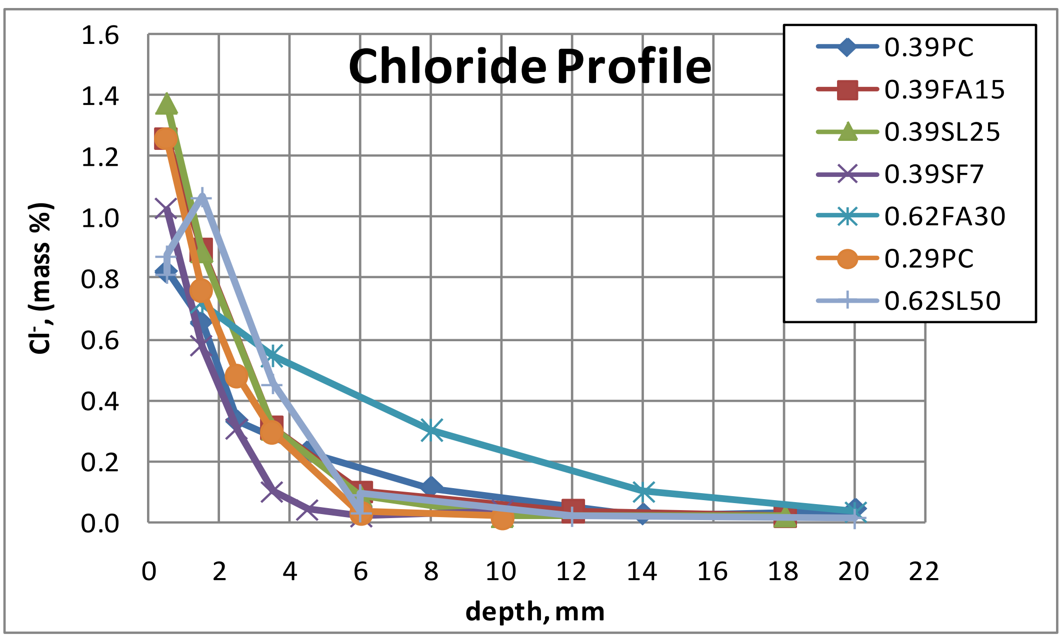


Figure 8. Chloride Profile (ASTM C1556) for 180d (6 month) normal curing followed by 35d in solution

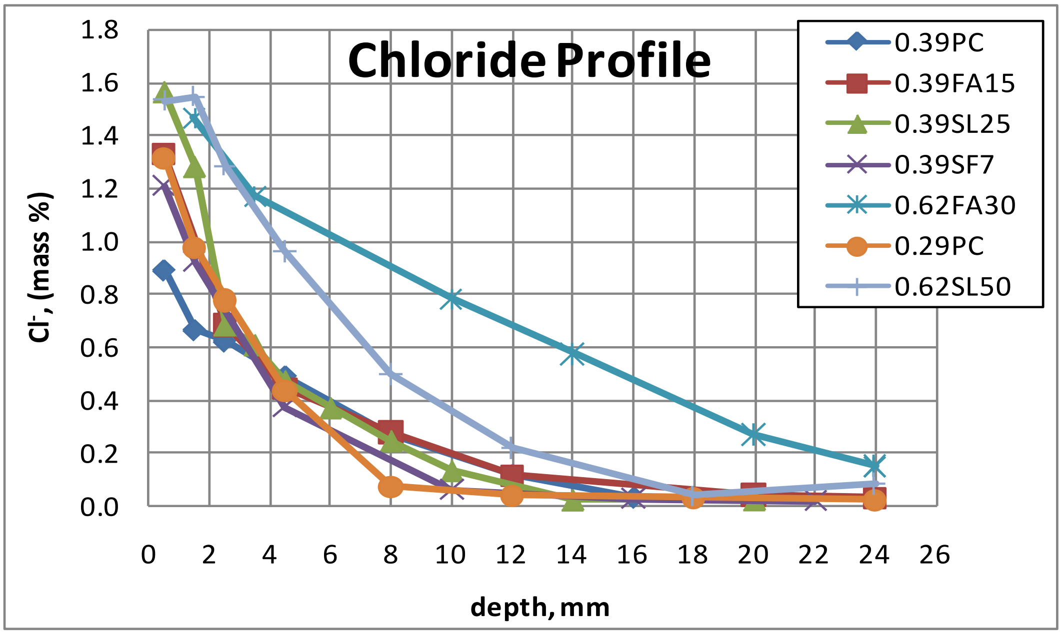


Figure 9. Chloride Profile (ASTM C1556) for 56d normal curing followed by 21 week in cyclic exposure

Preliminary Discussions on Chloride Diffusion Coefficient Test Results

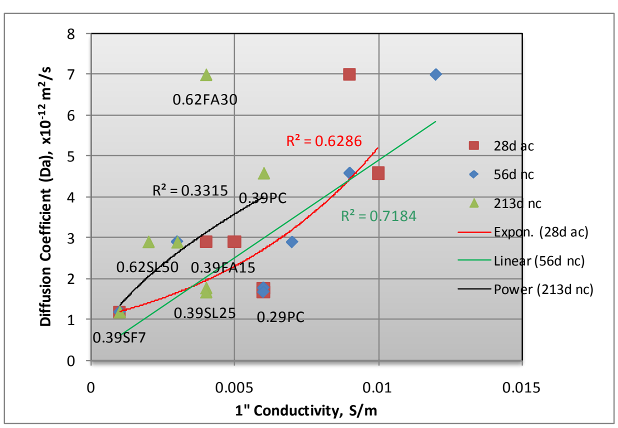
1. Chloride profiles suggest that chloride ingress for all the mixtures followed the order: Cyclic>56 day moist curing>180 day moist curing. This is understandable since cyclic exposure involves the longest exposure to chlorides and therefore should have the highest chloride ingress. Also the 180 day moist cured specimens are at a higher maturity as compared to the 56 day cured specimens and so will have lower chloride ingress.
2. Judging by the chloride profiles shown in Figures 1 and 2 as well as the calculated chloride diffusion coefficients shown in Table 2 it can be concluded that the performance of different mixtures is typically consistent between the two cases. In the 56 day cured condition the best performing mixes (showing low chloride ingress) in order were 0.39SF7=0.29PC<0.39SL25<039FA15=0.62SL50<0.39PC<0.62FA30. In the 180 day cured condition it is 0.39SF7<0.29PC=0.39SL25=0.39FA15<0.62SL50<0.39PC<0.62FA30. The only difference between the 2 conditions is in the order of the fly ash mix and the 0.62 w/cm slag mix with the fly ash mix performing better after longer curing. This is understandable because the fly ash mixture tends to perform poorer early on and continues to get better with age. In the cyclic condition it is 0.39SF7=0.29PC<0.39SL25<0.39FA15=0.39PC <0.62SL50<0.62FA30. The cyclic condition shows more changes as compared to the other two conditions. The 0.39PC mixture had lower chloride ingress as compared to the 0.62SL50 mixture. The two 0.62 w/cm mixtures had much higher chloride ingress when compared to all other mixtures. The 0.29PC mixture had the same chloride ingress as the best performing 0.39SF7 mixture. The cyclic condition is a little different as compared to the other two conditions. For one it involves a much longer chloride exposure and also it involves chloride ingress into a partially saturated concrete surface. From the difference in performance between the 3 conditions it appears that a lower w/cm is

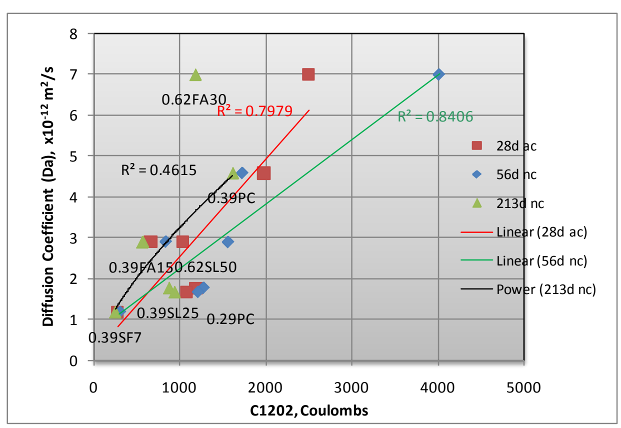
more favorable for a cyclic case possibly due to the tighter pore structure it entails at the concrete surface and also difference in drying rates.

3. Judging by the chloride diffusion coefficient values reported in Table 2 for the 56 day curing condition the best performing mixes (lowest diffusion coefficient) in order were 0.39SF7=0.29PC<0.39SL25<039FA15=0.62SL50<0.39PC<0.62FA30. In the 180 day cured condition it is 0.39SF7<0.29PC=0.39SL25=0.39FA15<0.62SL50<0.39PC<0.62FA30. In the cyclic condition it is 0.39SF7=0.29PC<0.39SL25<0.39FA15<0.39PC<0.62SL50<0.62FA30. The ranking differences between visual observation based on chloride profile and diffusion coefficient estimation is negligible except for one instance that can be explained by the differences in the surface chloride content. The surface chloride contents did not vary substantially between the mixtures. It is the chloride diffusion coefficient value that is used for service life estimation and hence attention would be paid to that. However it is useful to look at the raw chloride profiles to make sure the order of mixtures is generally similar.
4. The chloride diffusion coefficient values vary as follows:
    1. 56 day moist cured - between 1.18 to 6.99 x10^{-12} m^2/s
    2. 180 day moist dured - between 0.67 to 7.10 x10^{-12} m^2/s
    3. Cyclic - between 0.66 to 8.33 x10^{-12} m^2/s

There is nearly an order of difference between the lowest and highest values in each condition and it encompasses the broad range of chloride diffusion coefficients. If the two 0.62 w/cm mixtures are excluded then there are is only a 4 fold difference (between the lowest and highest values) for the first two conditions and only a 2 fold difference for the cyclic condition. The lower difference in the cyclic case is primarily because the cyclic condition seems to be influenced more by the w/cm and less by SCM content. For the continuous moist cured condition even at the same w/cm SCMs show a greater reduction in chloride ingress where as for the cyclic case they show a lesser reduction.

The correlation between the diffusion coefficient results and various rapid index test results (conducted at various ages) are provided in the figures below.





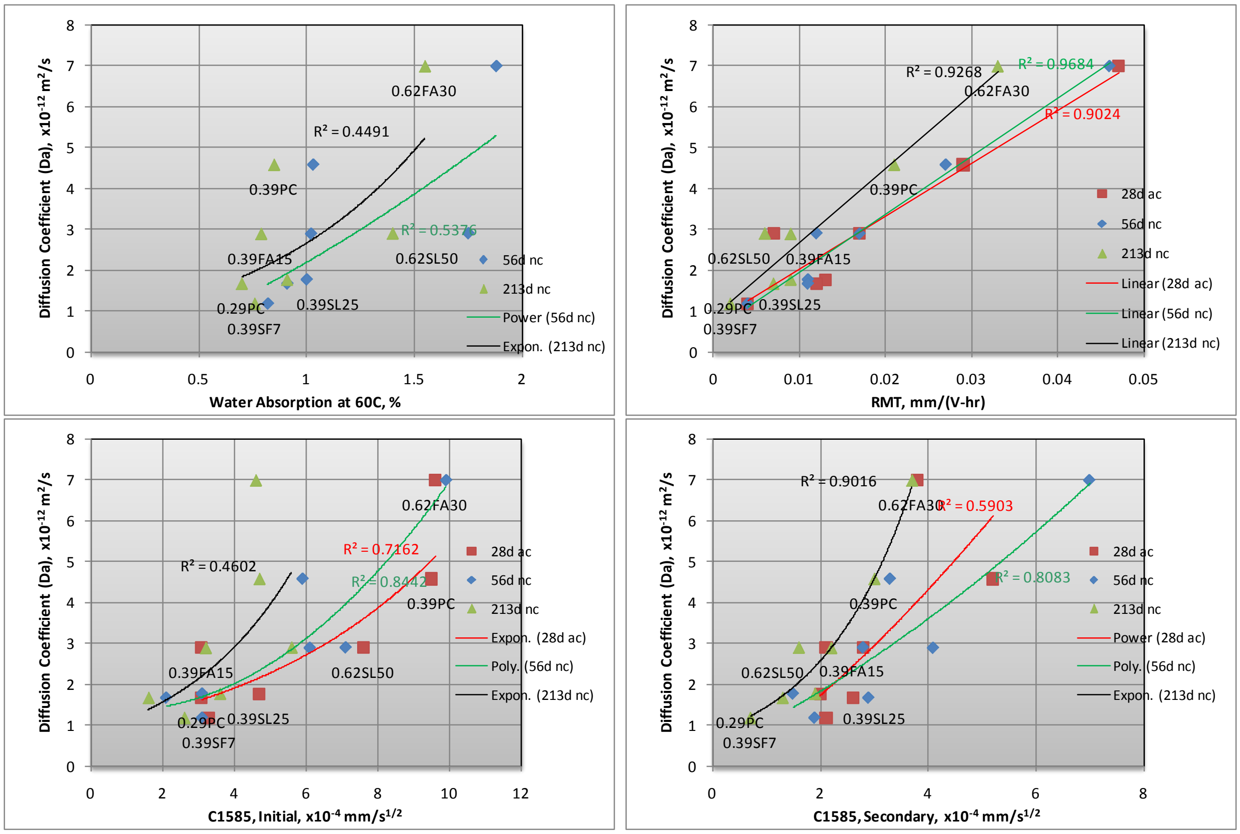
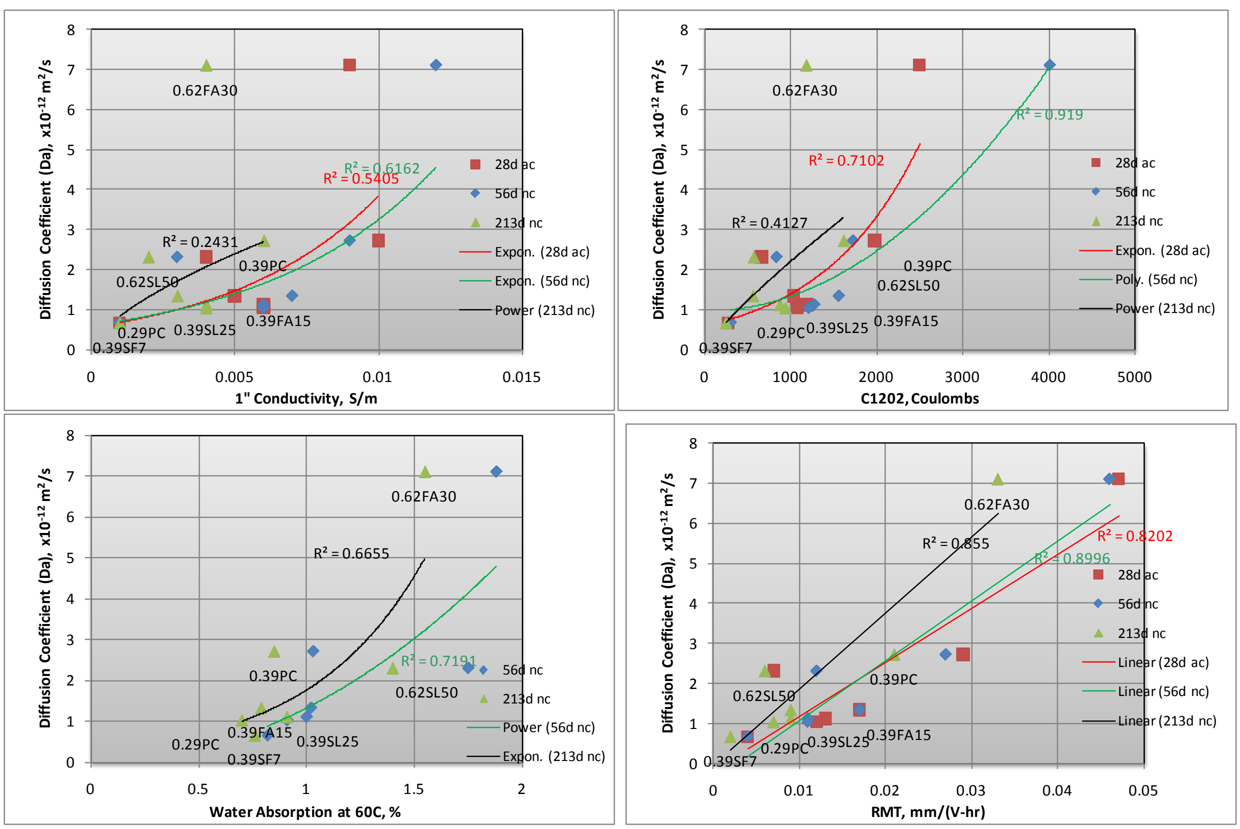


Figure 10. (a) – (f) for 56d normal curing followed by 35d in solution



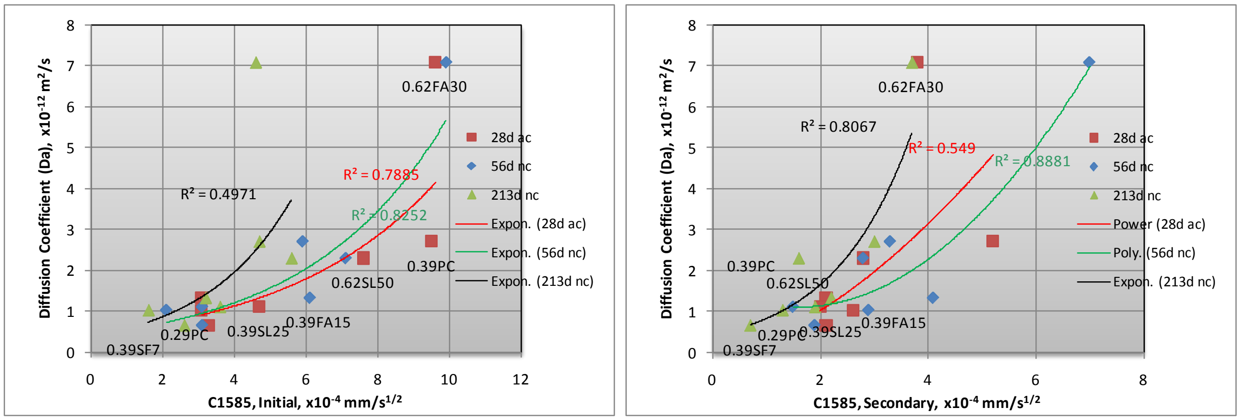


Figure 11. (a) – (f) for 180d normal curing followed by 35d in solution

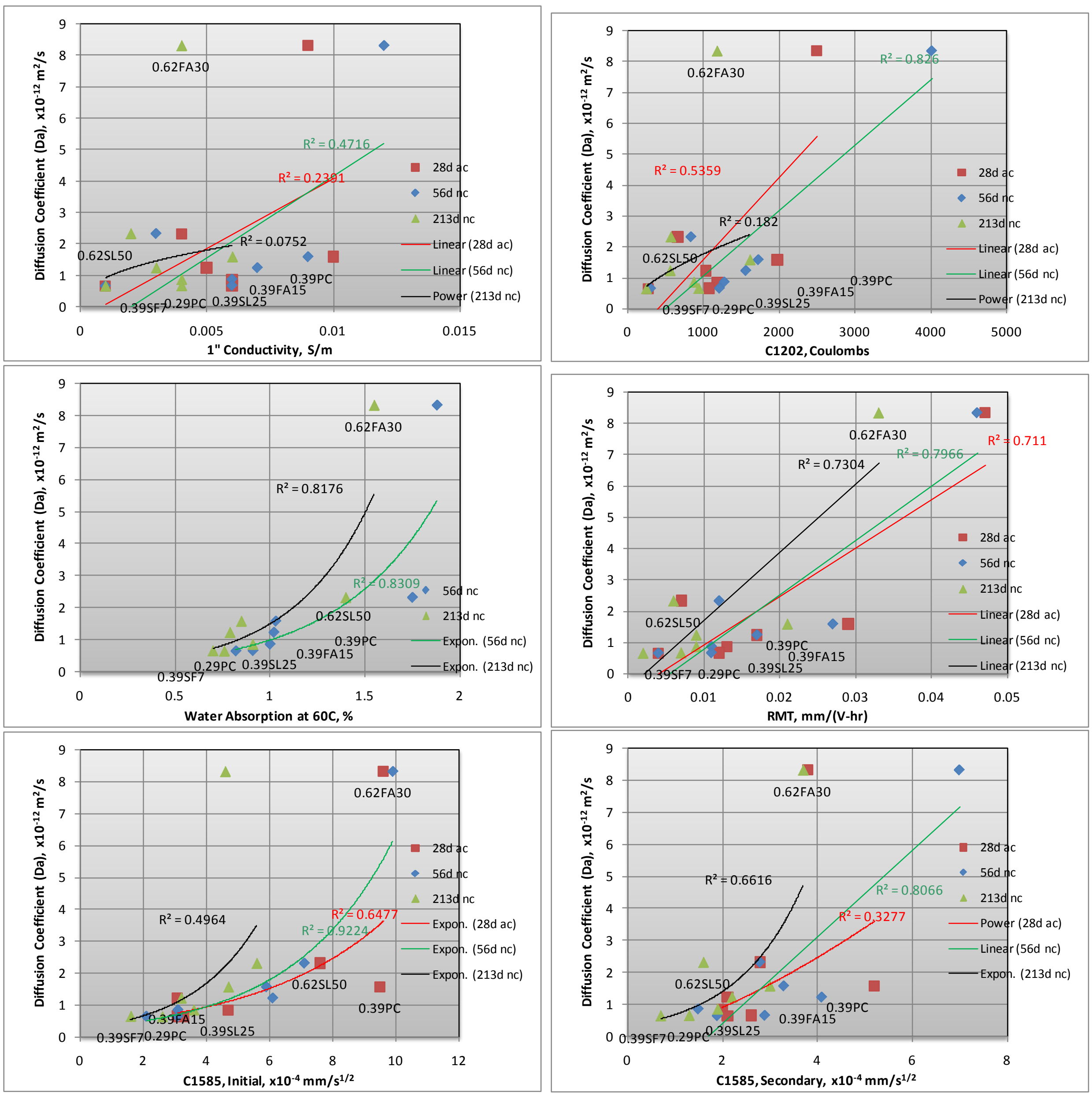


Figure 12. (a) – (f) for 56d normal curing followed by 21 week in cyclic exposure

Choride Diffusion Coefficient and Rapid Index Test Results Comparisons

A quick look suggests that the Rapid Migration Test appears to be the only test that consistently appears to give good correlations to the diffusion coefficient test results. Detailed review of the data is currently ongoing. On the basis of the chloride diffusion test results the mixtures can be classified as follows

Table 7

Classification based on Chloride Diffusion Coefficient	180d normal curing followed by 35d in solution	56d normal curing followed by 21 week in cyclic exposure
Level 1 ($\leq 1.0x10^{-12}$ m^2/s)	0.39SF7	0.39SF7, 0.29PC, 0.39SL25
Level 2 (1 to $2x10^{-12}$ m^2/s)	0.29PC, 0.39SL25, 0.39FA15	0.39PC, 0.39FA15
Level 3 (2 to $3x10^{-12}$ m^2/s)	0.39PC, 0.62SL50	0.62SL50
Level 4 ($\geq 3.0x10^{-12}$ m^2/s)	0.62FA30	0.62FA30

It will be interesting to observe if the rapid index test results can classify mixtures based on the different levels. Given that the different conditioning requirements lead to different mixtures it is clear that more than one rapid index test result may be required.a

2.5 Field Core Testing Program (PROPOSED NO COST ADDITIONAL WORK BY NRMCA)

In addition to that lab experimental program it would be useful to get concrete cores from un-cracked areas from 10-30 years old structures in bridge deck (low relative humidity), bridge deck (high relative humidity), marine - submerged, tidal, spray zones. These samples would be used by NRMCA to measure sorptivity, chloride profile on top 2 in., discard the next 1 inch and conduct ASTM C1556 chloride diffusion test on next 2 inches. Do 2 rapid index test results (RCPT, gas permeability) from sample just below that. So a 7 to 10 in. core thickness of 4 in. diameter may be required for this program. The aim would be to see if there is a unique relation between measured rapid index test result and calculated chloride diffusion coefficient from the chloride profiles. Also it would be worthwhile to compare those diffusion coefficients with mixture proportions and the 56 day rapid index results attained during quality assurance or mix qualification stage (if such is available). The core test program can account for a wide range of field conditions such as moist curing durations, wet/dry chloride exposures, chloride loadings and temperature exposures and is therefore an useful extension of this lab based experimental program.

Freeze Thaw - Test Methods, Curing Conditions and Test Ages

Freeze thaw (F-T) attack is another major concrete deterioration mechanism. Capillary sorption and water vapor diffusion are the two principal transport mechanisms that cause critical saturation of capillary pores which is necessary for freeze thaw damage. An air content of 5% to 7% with an air voids spacing factor less than 0.2 μm is typically necessary to maintain adequate freeze thaw resistance. While the air entrainment requirement is acceptable an attempt will be made to develop test and performance criteria as an alternative to the maximum w/cm requirement. ACI 318 states that for F1, F2, F3 categories max w/cm=0.45, min strength=4500 psi, and air content limits. It is clear that a low w/cm is required to ensure low water penetration and potential for critical saturation. By conducting mixes with different w/cm and various SCM dose and contents we will examine if F-T performance (as measured by no. of cycles for 15% mass loss or relative dynamic modulus of elasticity after 300 cycles) is better correlated with a rapid index test such as sorption or gas permeability criteria than w/cm. If at each w/cm, F-T performance varies widely depending on the test criteria the importance of the test criteria as opposed to w/cm is established. Also it would be determined whether some mixes with low w/cm and higher sorptivity/gas perm can have poorer F-T performance as compared to mixes with higher w/cm and lower sorptivity/gas perm which can again establish the importance of the test criteria as opposed to w/cm.

ACI 318-08 F classes

Moderate F1: Concrete exposed to freezing-and thawing cycles and occasional exposure to moisture
Severe F2: Concrete exposed to freezing-and thawing cycles and in continuous contact with moisture
Very severe F3: Concrete exposed to freezing-and thawing and in continuous contact with moisture and exposed to deicing chemicals

From the test results plots Concrete class F2 can be suggested to have RDM of 60-80% while F3 can have RDM>80% after 300 F-T cycles. It is hoped that these RDM and mass loss correlates with rapid index test criteria such as sorptivity and we can use those test criteria rather than RDM.

For C672 Y axis will be mass loss or visual rating

Table 8: Mixture Proportions Planned

w/cm	PC	20%FA	30%SL	25%SL+5%SF
0.40	Yes-m			Yes-vl
0.45	Yes-m	Yes-m	Yes-m	Yes-vl
0.50	Yes-h	Yes-m	Yes-m	Yes-l
0.60	Yes-h			Yes-m

May add some more mixes with different cement and aggregates

Crushed coarse aggregate (1.0" max) no. 57, natural sand FM=2.88
Adjust water reducer or high range water reducer (if any) for desired slump = 5 to 7 in.
Air entrained concrete mixtures – Target 5 to 6% air. Use AEA from same admix manufacturer

Normal Curing – Standard moist room curing starts immediately after making the specimens
Accelerated Curing – 7 days of normal curing followed by 21 days of curing in 100F water

For all mixtures measure the following: Slump, temperature, air content, density, Strength (28 days of moist curing followed by 28 days of air drying), Shrinkage (7 days moist curing followed by 90 days of air drying).

Durability Tests

For all tests at all ages, make 2 cylinders unless otherwise stated. Make 6 extra cylinders for each mix, moist cure for 28 days and then ship 4 to Purdue/UT for gas permeability testing and keep the other 2.

- Rapid Chloride Permeability test (ASTM C1202)

v) 28 day accelerated
vi) 56 day normal curing
vii) 26 week (182 d) normal curing

- ASTM C666. Test 2 replicate specimens as recommended by C666 standard. 28 day moist curing followed by 28 day air drying in 50% RH and 70F and then start C666. Do dynamic modulus, mass change tests as required by C666. Do test until 1000 cycles or visible differences between mixtures which-ever occurs first. Also mixtures should not be tested for >25% mass reduction or 50% relative dynamic modulus of elasticity.

- ASTM C672. Test 2 replicate specimens as recommended by C672 standard. 28 day moist curing followed by 28 day air drying in 50% RH and 70F and then start C672. Do test until 150 cycles or visible differences between mixtures which-ever occurs first. Measure mass loss and visual rating every 5 cycles.

- Sorptivity Test (ASTM C1585) after:

iv) 28 day accelerated + 18 d specimen conditioning (C1585)
v) 38 day normal curing + 18 d specimen conditioning (C1585)
vi) 26 week (182 d) normal curing + 18 d specimen conditioning (C1585)

- Absorption test BS 1881:122 – use latest ASTM draft which states 50C.

iv) 28 day accelerated + 3 d in oven
v) 56 day normal curing + 3 d in oven
iii) 26 week (182 d) normal curing + 3 d in oven

Table 9. Yield Adjusted Mixture Proportions and Preliminary Test Results

	0.57 PC	0.50 PC	0.50 FA20	0.50 SL30	0.50 SL25SF5	0.60 SL25SF5	0.45 PC	0.45 SL30	0.57 PC**-R	0.50 PC**-R	0.50 SL30**-R
Calculated Batch Quantities											
Type I/II cement, lb/yd^3	506	539	442	385	385	353	592	414	505	541	382
Slag, lb/yd^3				165	137	126		177			164
Fly ash, lb/yd^3			111								
Silica Fume, lb/yd^3					27	25					
SCM, %	0	0	20	30	30	30	0	30	0	0	30
Coarse Agg. (No.57), lb/yd^3	2087	2021	2071	2060	2058	2077	2035	2029	2082	2026	2043
Fine Aggregate, lb/yd^3	1094	1083	1066	1093	1084	1072	1062	1048	1118	1086	1084
Mixing Water, lb/yd^3	290	270	276	275	275	302	267	266	293	270	273
w/cm	0.57	0.50	0.50	0.50	0.50	0.60	0.45	0.45	0.58	0.50	0.50
ASTM C494 AEA, oz/cwt	3.8	4.4	23.5	6.3	4.4	7.0	4.4	6.9	3.8	4.4	4.8
ASTM C494 Type F, oz/cwt		3.1	2.2	3.2	5.5	2.6	8.1	11		6.7	12.8
Fresh Concrete Properties											
ASTM C143, Slump, in.	7	6	6	5	5	6.5	5.25	6	5.5	4.75	7
ASTM C231, Air, %	6	7.2	6	6.2	6.5	6.2	7	7.6	5.8	7.2	7.2
ASTM C138, Density, lb/ft^3	148.1	145.7	147.7	148.1	147.7	147.3	147.3	146.5	148.9	146.1	146.9
ASTM C1064, Temperature, °F	75	75	73	70	72	70	70	70	70	70	68
Hardened Concrete Properties											
ASTM C39, Compressive Strength, psi											
28 days	4,918	4,895	4,101	5,376	6,249	4,844	5,427	5,182	4,738	4,454	5,312
Draft ASTM Standard, Water Absorption Test at 50 °C, %											
28d accelerated cure	-	-	1.41	-	1.24	1.56	1.61	1.2	2.28	1.81	1.47
56d normal cure	1.85	1.65	1.81	1.36	1.44	1.74	1.76	1.39	-	-	-
182d (26w) normal cure	1.67	1.47	1.19	1.45	1.29	1.51	1.49	1.20	-	-	-
ASTM C1202, Rapid Chloride Permeability, Coulombs											
28d accelerated cure	-	-	2014	-	332	516	2630	851^{-}	5015	3578	1077
56d normal cure	4876	3633	4287	1554	469	848	2957	1143^{-}	-	-	-
182d (26w) normal cure	5297	3879	2193	1340	532	622	2722*	1094	-	-	-
ASTM C157, Length Change (Drying Shrinkage), %											
28 days^{+}	0.045	0.039	0.041	0.049	0.053	0.063	0.036	0.039	-	-	-
56 days^{+}	0.061	0.046	0.050	0.052	0.056	0.069	0.049	0.049	-	-	-
90 days^{+}	0.069	0.054	0.057	0.058	0.065	0.075	0.055	0.055	-	-	-
180 days^{+}	0.076	0.059	0.057	0.063	0.065	0.077	0.058	0.058	-	-	-
ASTM C 1585, Rate of Water Absorption (Sorptivity), x10^{-4} mm/s$^{1/2}$											
28d accelerated cure (Initial/Secondary)	17.6*/6.7*	10.8*/4.7*	8.7*/ 3.0	5.7*/ 1.5	5.6*/ 2.8	7.1*/ 3.3	5.9*/ 4.1	6.7*/ 2.0*	-	-	-
56d normal cure (Initial/Secondary)	13.7 /3.7*	8.2*/ 3.4	14.1/9.8	13.1*/ 4.3	6.0/ 3.2	6.3/ 3.5	9.4/ 5.9	5.1/ 3.0*	-	-	-
196d normal cure (Initial/Secondary)	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
28d accel. cure (Initial/Secondary), g	3.1/ 7.6	2.3/ 5.0	2.0/ 3.7	2.0/ 2.7	1.8/ 3.7	1.4/ 3.8	1.4/ 4.0	1.8/ 2.6	-	-	-
56d normal cure (Initial/Secondary), g	2.5/ 5.3	1.6/ 3.8	2.4/ 8.9	2.8/ 5.9	1.6/ 4.1	1.6/ 4.1	2.0/ 6.0	1.5/ 3.5	-	-	-
196d normal cure (Initial/Secondary), g	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
ASTM C 666, Freezing and Thawing Resistance											
Durability Factor	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
Mass loss	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-

ASTM C 672, Salt Scaling Resistance											
Visual Rating (0 – 5)	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-

** Exact repeat of designated mixture
+ Curing period in 70°F, 50% RH environment NOT included 7 days initial wet curing period in water bath
- Result of only one specimen

The freeze thaw tests and scaling are ongoing. Even after 200 F-T cycles most of the mixtures appear to be in excellent condition. Scaling tests are ongoing as well. Some of these results would become available in the next quarter.

Sulfate Resistance - Test Methods, Curing Conditions and Test Ages

Sulfate attack is another major concrete deterioration mechanism. Water soluble sulfates penetrate concrete by a combination of capillary sorption and diffusion. Three mechanisms are recognized:
1 Physical sulfate attack – generally by salt crystallization of certain sulfate salts
2 Chemical attack of aluminate phases in to form calcium sulfo-aluminate hydrates and gypsum.
3. Chemical attack on the calcium silicate hydrate matrix at cooler temperatures (thaumasite formation)
Note: The thaumasite sulfate attack mechanism is less common and is not addressed in this test program.
Concrete resistance to sulfate attack is governed by 2 factors:
1. Cementitious type – Increasing C3A in portland cement portion in concrete decreases its sulfate resistance. Aluminate phases from SCMs can also sometimes contribute to this effect – more likely in some Class C fly ashes or some higher alumina content slags from off shore.
2. Low permeability – that reduces the rate of penetration of sulfates into the concrete.
The ACI 318 building Code recognizes 3 exposure classes of sulfate exposure in increasing severity based on concentration of water soluble sulfates in soil or water – S1, S2, and S3 and establishes the following (Table A) minimum requirements for concrete mixtures for adequate sulfate resistance:

Table A. ACI 318 Building code Requirements for Concrete Exposed to Sulfate

Category	CM type or Performance Equivalent	w/cm, strength
S0	None	None
S1	Type II or ASTM C1012 <0.1% at 6 mos	0.50, 4000 psi
S2	Type V or ASTM C1012 <0.1% at 12 mos	0.45, 4500 psi
S3	Type V+pozz or slag or ASTM C<1012 < 0.1% at 18 mos	0.45, 4500 psi

In ACI 318-08, ASTM C1012 expansion criteria are recognized as an alternative to the prescriptive requirements for the allowable types of cementitious materials.
The maximum w/cm limit is invoked to control the permeability of concrete. Besides w/cm, however, the permeability of concrete is also impacted by the composition of the cementitious materials. The aim of this task to develop rapid index test and performance criteria as an alternative to the maximum w/cm requirements. It is clear

that a low w/cm is required to ensure low sulfate ingress by sorption and diffusion. Low permeability of concrete is an important factor to control both the physical and chemical forms of sulfate attack.

By testing concrete mixtures with different w/cm and cementitious types (including SCM types and contents) we will examine if concrete performance against sulfate attack (as measured by USBR 4908 method B) is better correlated with ASTM C1012 and a rapid index test alternative to w/cm criteria. Rapid index tests that will be evaluated include rapid chloride permeability (and conductivity), sorption or gas permeability.
USBR4908 is a test that was used by the US Bureau of Reclamation on historical research on sulfate resistance. It is a long term test on concrete and is not suited for inclusion in code or specification criteria. The evaluation of rapid index test results relative to performance in the USBR4908 will allow establishment of such required performance criteria. The test involves immersing 3x6 in. cylindrical concrete specimens in 10% sodium sulfate solutions for an extended period and measuring expansions periodically. An expansion of 0.5% is considered as failure and the test is expected to last at least 12-18 mos.
It is proposed that all concrete mixtures be subjected to an immersion period of 18 mos with the expansions recorded. Mixtures that show higher resistance to sulfate attack will result in lower expansions in the USBR test. By separating out mixtures into 3 categories based on their USBR expansion levels it will be possible to select mixtures that will perform in the different sulfate exposure classes S1, S2, and S3 – mixtures with the lowest USBR expansion levels could be used for S3 exposure category and so on. Additionally, partially submerged specimens in test solutions will be performed at the same sulfate concentration. This is intended to simulate sorption and wicking of sulfates in structures and the condition of physical sulfate attack.

The results will be interpreted as follows:

It is expected that two mixtures with different composition of cementitious materials could have the same performance in the USBR test due to different levels of sulfate ingress (permeability) into the concrete. It is proposed to tie the rapid index test criteria that measures a permeability property to the C1012 expansion levels (see Table B). The process of developing these rapid index criteria is proposed to be accomplished by the following 3 plots.
Plot 1 will have 12 mo or 18 mo USBR expansions on the Y axis and rapid index test results on X axis. Plot only those mixtures (from the 30 mixtures tested as per Table C) that satisfy the ASTM C1012 expansion criteria for the S1 exposure class but that fail that for exposure classes S2, and S3. Three different USBR expansion levels as suggested in column 2 of Table b will be used to delineate expansions in the USBR test on concrete specimens for the 3 exposure classes (these may need to be revised later based on the test results). Record the corresponding rapid index test criteria.
Plot 2 should have mixtures that satisfy the ASTM C1012 expansion criteria for the S2 exposure class but that fail that for exposure class S3. The same three expansion criteria for the USBR expansions will be used. Record the corresponding rapid index test criteria.

Plot 3 should have mixtures that satisfy the ASTM C1012 expansion criteria for S3 exposure class. The same three expansion criteria for the USBR expansions will be used. Record the corresponding rapid index test criteria.

The final outcome is expected to be along the following lines
This allows the two criteria to offset each other and can be established based on the USBR concrete performance testing – a more conservative result in the C1012 might permit a less conservative criteria in the rapid index for permeability and vice versa.

Table B. Interpretation of USBR expansion Results and Development of Rapid Index test Criteria

Category	USBR expansion	C1012	Rapid index (assume RCPT coulombs)
S1	0.4 to 0.6%	<0.1% at 6 mos	3000
		<0.1% at 12 mos	4000
		<0.1% at 18 mos	4000
S2	0.2 to 0.4%	<0.1% at 6 mos	2000
		<0.1% at 12 mos	3000
		<0.1% at 18 mos	4000
S3	<0.2%	<0.1% at 6 mos	NA
		<0.1% at 12 mos	1500
		<0.1% at 18 mos	2000

Table C. Mixture Proportions Planned

Category	w/cm	Cement	No SCM	15%FA	20%FA	30%FA	25%SL	35%SL	50%SL
	0.50	Type I	1 cement						
S1	0.50	Type II	2 cements						
	0.40	*Type I*		*Yes*			*Yes*		
	0.50	*Type I*		*Yes*			*Yes*		
	0.60	*Type I*		*Yes*			*Yes*		
S2	0.45	Type V	2 cements						
	0.40	Type II			Yes	Yes*		Yes	
	0.50	Type II			Yes			Yes	
	0.60	Type II			Yes	Yes*		Yes	
S3	0.40	Type V				Yes			Yes
	0.50	Type V				Yes			Yes
	0.60	Type V				Yes			Yes

For S1, 0.50, test 2 Type II control mixes
For S2, 0.45, test 2 Type V control mixes
So there are a total of 25 mixtures – 20 with SCMs and 5 without. Some of these mixtures may be optimized if possible without losing research objective.
* These mixtures have higher SCMs and Type I cement and so may satisfy S2 exposure category

Crushed coarse aggregate (1.0" max) no. 57, natural sand FM=2.88
FA will be Class F fly ash.
Adjust water reducer or high range water reducer (if any) for desired slump = 5 to 7 in.

Non air entrained concrete.
Need a Type I with relatively high C3A so its not too similar to the Type II

Planned Test Methods, Curing Conditions and Test Ages (Lab)

Mortar
ASTM C1012. Conduct C1012 tests. C1012 is normally done on mortar at a constant w/cm = 0.485. Therefore there will be a total of 12 mixtures - 7 SCM mixtures (2 with Type I, 3 with Type II, 2 with Type V) and 5 PC only mixtures. Consider 2 for replication at high and low expansion level. Conduct C1012 for 18 mos – some of mixtures with lower SCMs may be stopped earlier. Take periodic expansion readings as per C1012.

Concrete
Normal Curing – Standard moist room curing starts immediately after making the specimens
Accelerated Curing – 7 days of normal curing followed by 21 days of curing in 100F water

For all concrete mixtures measure the following: Slump, temperature, air content, density, Strength (4x8 cyl at 28 days of moist curing).

Durability Tests
For all tests at all ages, make 2 cylinders unless otherwise stated. Make 6 extra cylinders for each mix, moist cure for 28 days and then ship 4 to Purdue/UT for gas permeability testing and keep the other 2.

- Rapid Chloride Permeability test (ASTM C1202)

i) 28 day accelerated
ii) 56 day normal curing
iii) 52 week normal curing

- USBR4908 fully immersed method B. Test 3 prisms per mix. Start after 28 days of moist curing and 28 days of air drying (everything else similar to USBR 4908 requirements). Conduct test for 18 mos. Take periodic expansion readings. Follow USBR test method for other requirements.

- USBR4908 partially immersed (same 10% solution as above). Test 3 cylinders per mix. Start after 28 days of moist curing and 28 days of air drying (everything else similar to USBR 4908 requirements). Conduct test for 18 mos. Take periodic expansion readings. Follow NIST report (page 28) for half way specimen immersion – paraffin coating for reducing evaporation etc. Limit these to high and low w/cm and PC only mixes. Also need to measure mass change if there is surface spalling at the wet zone.

- Sorptivity Test (ASTM C1585) after :

i) 28 day accelerated + 18 d specimen conditioning (C1585)
ii) 56 day normal curing + 18 d specimen conditioning (C1585)

iii) 52 week normal curing + 18 d specimen conditioning (C1585)

- Absorption test BS 1881:122 – use latest ASTM draft

i) 28 day accelerated + 3 d in oven
ii) 56 day normal curing + 3 d in oven
iii) 52 week normal curing + 3 d in oven

If at each w/cm, sulfate performance varies depending on the test criteria the importance of the test criteria as opposed to w/cm is established. Also it would be determined whether some mixes with low w/cm and higher sorptivity/gas perm can have poorer sulfate performance as compared to mixes with higher w/cm and lower sorptivity/gas perm which can again establish the importance of the test criteria as opposed to w/cm.

This task does not consider the development of a more rapid index test for C1012. Options include smaller specimen size/paste or higher temperature soln exposure.

Some of the initial concrete mixtures are being cast at the moment. All concrete mixtures will be cast this summer and 28 day results should become available by the next quarterly report.