TPF-5(179) **QPR #07**

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, and Colorado)

For the Period of

January 1st, 2009
to
March 31st, 2010

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
	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
	Task 3: Develop a Summary Document					10	30	50	70	90	90	90	90	90	90	90	90	95	95	95	95	95				95
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	80	80	80	80	80	80	80	80	80	80	80	80	80	90	90	90				90
	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
	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
	Task 4: Perform Tests					20		10	20	30	40	40	50	50	60	80	80	80	80	80	80	80				80
	Task 5: Evaluate Testing Procedures					20						20	25	30	35	35	35	35	35	50	50	50				50
	Task 6: Recommedations to Existing Procedures													10	10											10
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	25	25	25	25	25	25	25				25
	Task 2: Evaluate Modified Tests														10	10	10	10	10	10	10	10				10
	Task 3: Develop a Report of Modified Tests														10	10	10	10	10							10
	Task 4: Develop New Testing Procedures														■	■	■	■	■	10	10	10	■	■	■	10
	Task 5: Perform New Testing Procedures															10	10	10	10	10	10	10			■	10
	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	95	95	95					95
	Task 2: Condition Specimens			10	25	30	30	35	40	45	50	50	55	60	65	65	65	65	95	95	95					95
	Task 3: Expose Specimens													60												60
	Task 4: Evaluate Specimens													60		■			■			■			■	60
	Task 5; Perform ASTM Tests								20	20	20	40	50	50	55	55	55	55	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

		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																									~
	Task 2: Evaluate Modified Tests																									~
	Task 3: Develop a Report of Modified Tests																									~
	Task 4: Develop New Testing Procedures	■																								~
	Task 5: Perform New Testing Procedures	■	■	■	■	■	■																			~
	Task 6: Evaluate New Testing Procedures						■	■	■																	~
	Task 7: Develop a Summary Document with Recommendations								■	■	■															~
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	Task 4: Evaluate Specimens			■			■	■	■	■	■	■	■													~
	Task 5; Perform ASTM Tests	■	■	■	■	■	■	■	■	■																~
	Task 5: Evaluate Field Structures								■	■	■	■	■													~
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	Task 1: Prepare Materials																					■	■	■		~
Deliverables											2						3				4			5		~
Study Advisory Committee Meetings												■													■	~

Figure 2: Estimated Project Expenses

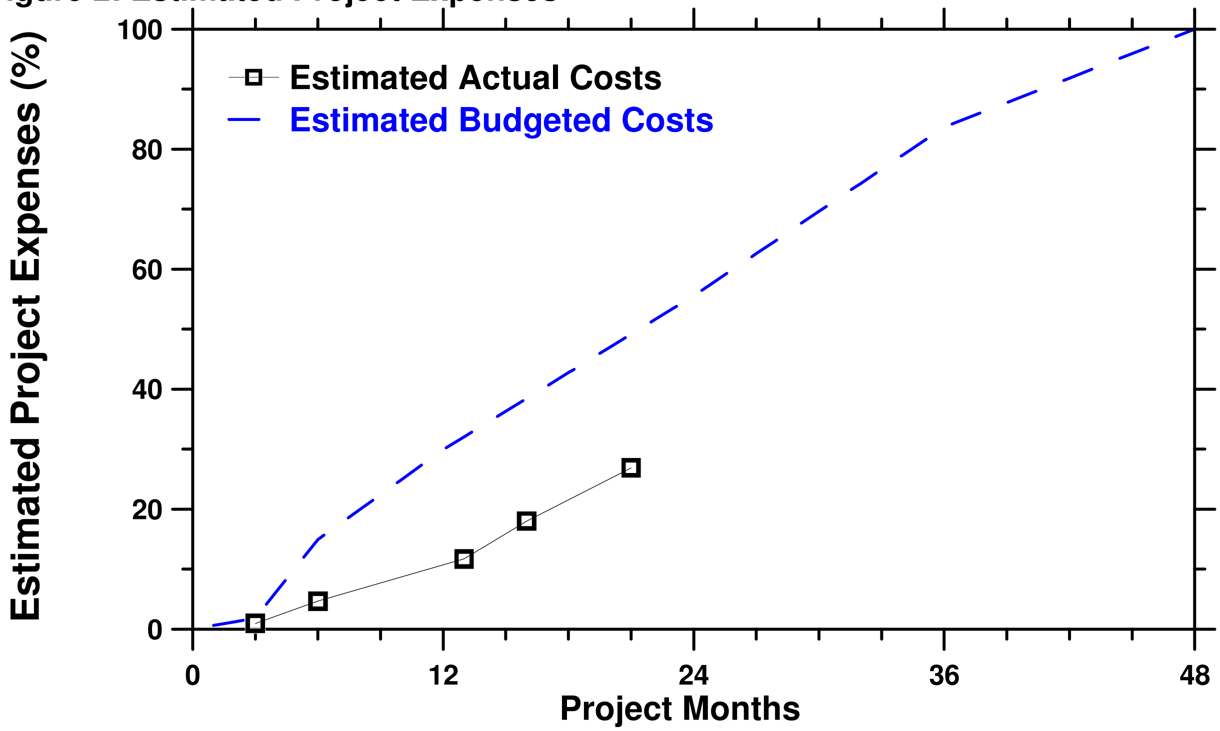


Figure 3: Project Budget and Expenses

Category	Detailed Description	Budgeted Cost	Billed Expense Through 3/30/10
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			$ 166,181
	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	$ 71,790
Total			
		$ 883,000	$ 237,971

* 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 seventh quarter of the project. It covers the three month period ending March 31st 2010.

During the reporting period work was performed primarily on Phases I and II. Additional work was preformed on Phases III and Phase IV.

1.1 Phase I – Literature Review

The research on Phase I is focused on performing an extensive review of literature pertaining to the measurement of permeability (transport) in concrete. To date the research has focused on collecting a complete listing of papers and test methods currently in existence nationally and internationally for determining permeability. The post-doc working on this project, Amir Pourasee, is completing this project as this is the main focus of his current work. To manage the data obtained from this literature review the research team is developing a summary of each existing permeability (or transport) test that includes:

- a description of the scientific principle behind a particular test,
- the application of the test,
- the size and conditioning of the specimens used in the test,
- the testing procedure,
- the methods used to evaluate the test,
- the advantages and disadvantages of a particular test,
- the length of time that a test takes to perform,
- the commercial availability of the test procedure/equipment, and
- an approximate cost and availability of the testing equipment.

The test methods will then be separated according to like scientific principles of operation and the most promising methods will be recommended for further study in phase II.

This data is being gathered from a conventional literature review that will make use of indexes such as the web of science, TRIS, COMPENDEX, NTIS, SHRP concrete and structures program, PCI, ACI, and AASHTO. In addition, surveys are being developed to be distributed to each state or agency to determine which permeability (transport) test procedures they are currently using. Additional surveys will be sent to International countries and test equipment manufactures

At the completion of Phase I, a report will be prepared that provides a review of the literature on permeability (transport) test methods. This will include the summaries as well as a thorough comparison of the methods and recommendations for Phase II.

1.2 Phase II – Evaluate Promising Concrete Permeability (Transport) Tests

The research on Phase II is focused on evaluating several reference concrete mixtures. To fully evaluate the most promising tests, specimen curing, specimen conditioning (duration and relative humidity), sample size, air content, specimen maturity, and variations in mixture proportions that may be anticipated during construction will also be evaluated. This will enable the most promising test methods to be assessed and will indicate the resolution, repeatability, and robustness of these test procedures. Aspects associated with determining the influence of curing procedures, conditioning and curing duration will also be evaluated.

Purdue has assembled materials and prepared samples for conditioning so that the samples can be adequately conditioned. A series of samples have been prepared and are currently conditioning. This includes several of the reference water to cement ratio mixtures. In addition samples have been collected from the field. Testing has begun however additional test methods are still being identified and some samples are still being conditioned. Specific focus has been placed on electrical resistance methods and sorption measures to provide good baseline measurements.

In addition, the research team has placed several samples at in the field at the INDOT test site to evaluate the internal humidity that can be expected in Indiana given five exposures. The exposures will include a 50% environment (indoors), a submerged sample, a vertical surface, a horizontal surface on a drainable base and a horizontal surface on a non drainable base. The team used a series of deployable sensors and have developed an approach whereby this can be done in other locations.

Electrical conductivity is frequently used as a surrogate test method to measure material property development and permeability of concrete and other cement based materials. Electrical impedance spectroscopy (EIS) describes a measurement procedure that measures the electrical resistance of a concrete at different frequencies under an applied potential. By measuring the electrical resistance of concrete over time, information can be obtained about the fluid transport properties that will influence service life predictions for concrete structures.

An automated electrical measurement system (AEMS) for measuring the properties of cementitious materials has been developed and used is this projects. Figure 4 shows a view of the designed system. A copy of the published paper based on the AEMS is attached to the report.

Conductivity of concrete can be attributed to three components: the conductivity of the pore solution as it is the primary conductive phase in concrete, the volume fraction of pore solution, and the connectivity of the system which reflects how well an ion can pass from one place to another within the system. The model can be expressed as following equation:

$$\sigma_t = \sigma_o \ \varphi \ \beta$$

Where,

σ_t = The conductivity of the bulk cement paste (S/m),
σ_o = The conductivity of the pore solution (S/m),
φ = The volume fraction of the liquid that can be found inside the pores (NA),
β = The connectivity of the pore system (Bounds are from 0 to 1)

However, it should be noted that a change in the temperature of a pore solution has a profound effect on the conductivity of the pore solution. Due to the heat of hydration experienced when a cement grain undergoes hydration, the system always undergoes a temperature change in ambient conditions. Therefore, the temperature of the samples needs to be measured simultaneously with the conductivity and then its effect should be compensated.

Cylinders have been prepared with different w/c and their electrical impedance has been continuality monitored. The impedance of the materials will be related to the permeability of the materials. In addition to the electrical impedance measurements on the mortar and concrete, pore solution has been expressed from these materials for use in interpreting the results. Currently, a paper on the effect temperature, pore solution and activation energy of hydration in under preparation and the results will be reported in the next report. Preliminary results from EIS measurements are compared with the Wenner Probe method and are provided as Attachment A.

Figure 4: A view of the new designed system (AEMS) to assess electrical properties in concrete

The research team also visited European laboratories during the fifth quarter (during a separately funded source) and performed a review of techniques that have been used there. Based on this review two test methods are currently being developed which will include a method based on the South African oxygen permeability test and a test based on a test that is utilized by the Swiss. In addition, the Swiss have agreed to assist in using several European tests that they have at EMPA.

In the Swiss system, 100mm X 50 mm disc is used. One side of the samples is exposed to oxygen and the other side is exposed to nitrogen gas. The pressure of oxygen and nitrogen should be kept at ~100 kPa and the trace of oxygen gas will be measured on the side of concrete with is in contact with nitrogen gas. The test specimens were prepared, using mortar with w/c of 0.30, 0.40, 0.42 and 0.50. Samples were cast using 8” X 4 “ (200 mm X 100 mm) cylinder molds. After demolding, samples were sealed for 28 days. After 28 days, cylinders were cut to the required size for the test (50 mm X 100 mm) and kept at different relative humidity (50%, 65% and 80%). In addition, some samples are prepared to be oven dried and test with this device

The South African test method can be used for determining the oxygen permeability index. Figure 5 shows the device for the South African method and Figure 6 schematically shows one of the cell arrangements.

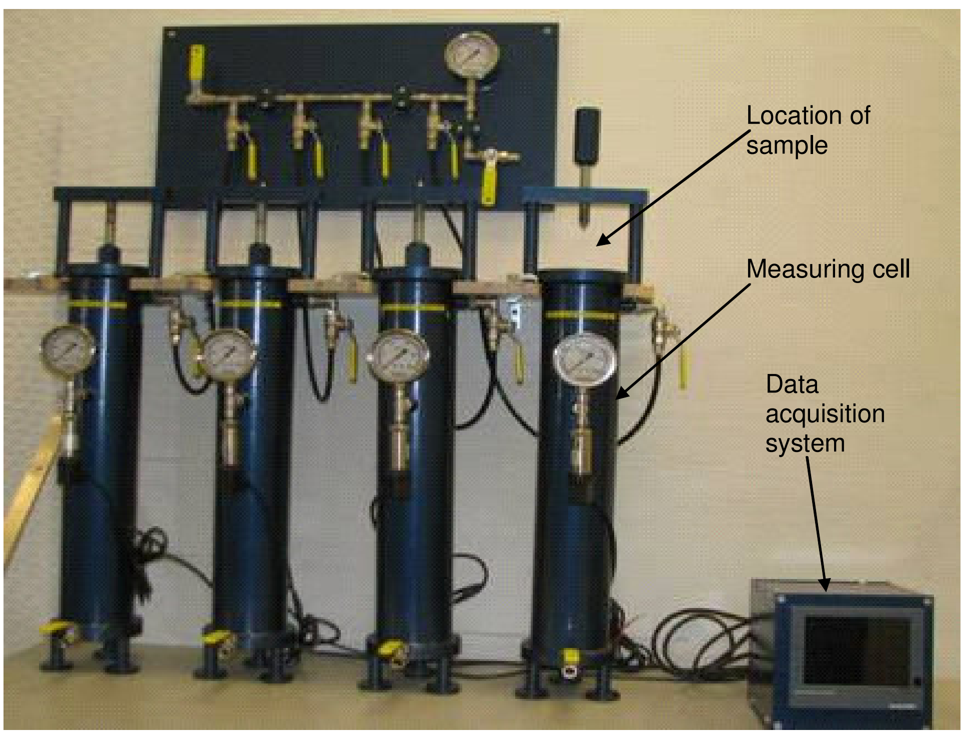


Figure 5: Device used for Permeability Measurement Based on the South African Test Method

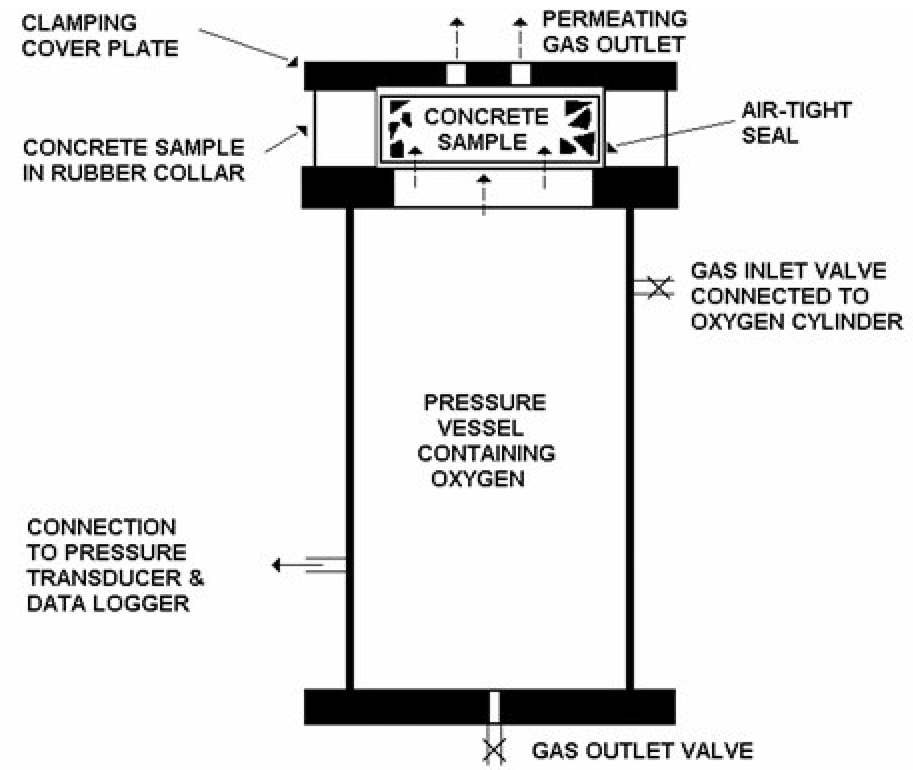


Figure6: South African Permeability Cell

The test specimens considered in this method statement are circular discs prepared by coring and cutting concrete samples in the laboratory. For this purpose, 12” X 9” X 4.5 “ (304 mm X 229 mm X 114 mm) mortar prisms with a w/c of 0.35, 0.40, 0.42, and 0.50 were cast. Prisms were demolded 24 hours after casting, sealed in plastic sheet and kept in 100% humidity for 28 days. After 28 days, two cores with 70 mm diameter were taken from each prism. Each core was cut into several 30 ± 2 mm thick concrete disc by wet saw.

The oven drying procedure has been selected by the South African researchers to result in the minimum degree of micro-structural alteration of the concrete specimens, while still giving minimal uniform moisture content. In addition to study the effect of humidity of permeability, specimens with different w/c are being conditioned at different relative humidifies (50%, 65% and 80%).

In addition to the South African and Swiss system, a Torrent permeability tester was purchased and will be used. The particular features of the Torrent method are a two-chamber vacuum cell and a pressure regulator. This ensures that an air flow at right angles to the surface is directed towards the inner chamber. The cell is placed on the concrete surface and a vacuum is created in both chambers with pump. Due to the external atmospheric pressure and the rubber rings, the cell is pressed against the surface and thus both chambers are sealed. After 1 minute, the inner chamber is insulated. From this moment, the pressure in the inner chamber starts to increase, as air is drawn from the underlying concrete. The rate of pressure raise, which is directly related to the permeability of concrete, is recorded. Meanwhile, the vacuum pump continues to operate on the outer chamber to keep the pressure equal in both chambers. The permeability coefficient can then be calculated. Figure 7, shows the Torrent system (right) and the schematic air flow to the two chambers of the vacuum cell (left).

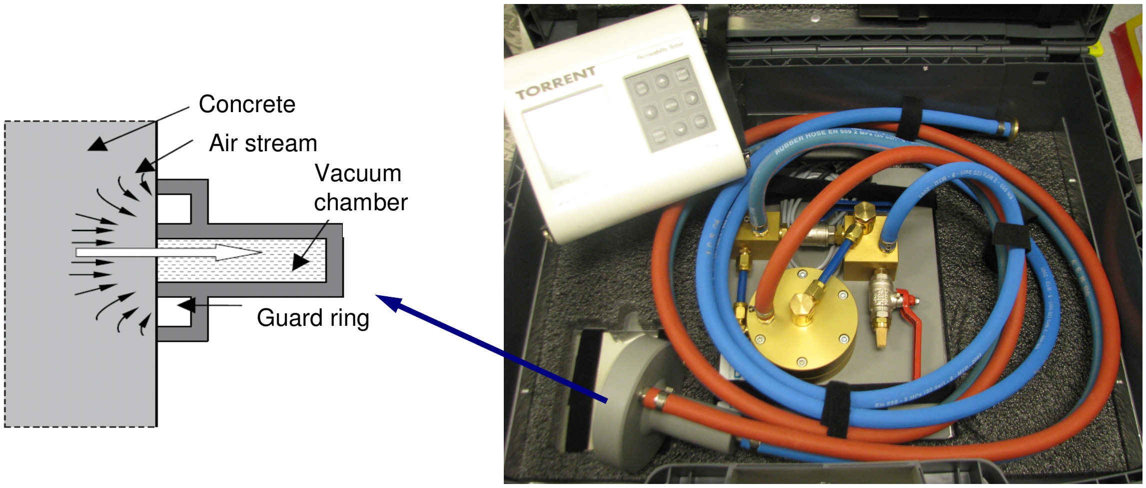


Figure 7: Torrent permeability measurement device

Samples with different w/c of 0.3, 0.42, and 0.50 have been prepared according to ASTM G109, as shown in Figure 13.

Figure 8: Samples Prepared According to ASTM G109

These samples are exposed to 3% sodium chloride solution. The potential difference between top and bottom rebars is monitored every hour, using a new designed automated system. In addition, the potential will be controlled manual to check the accuracy of the new system. The potential difference between top and bottom rebars indicates the macro-cell corrosion of the top rebar. The micro-cell corrosion of the top rebar will also be measured every month by using different electrochemical techniques. Figure 9 shows the macro-cell corrosion current density of the samples. Each curve is the average of three measurements. As can be seen, the samples are in passive state and there is no sign of active corrosion 120 days after casting

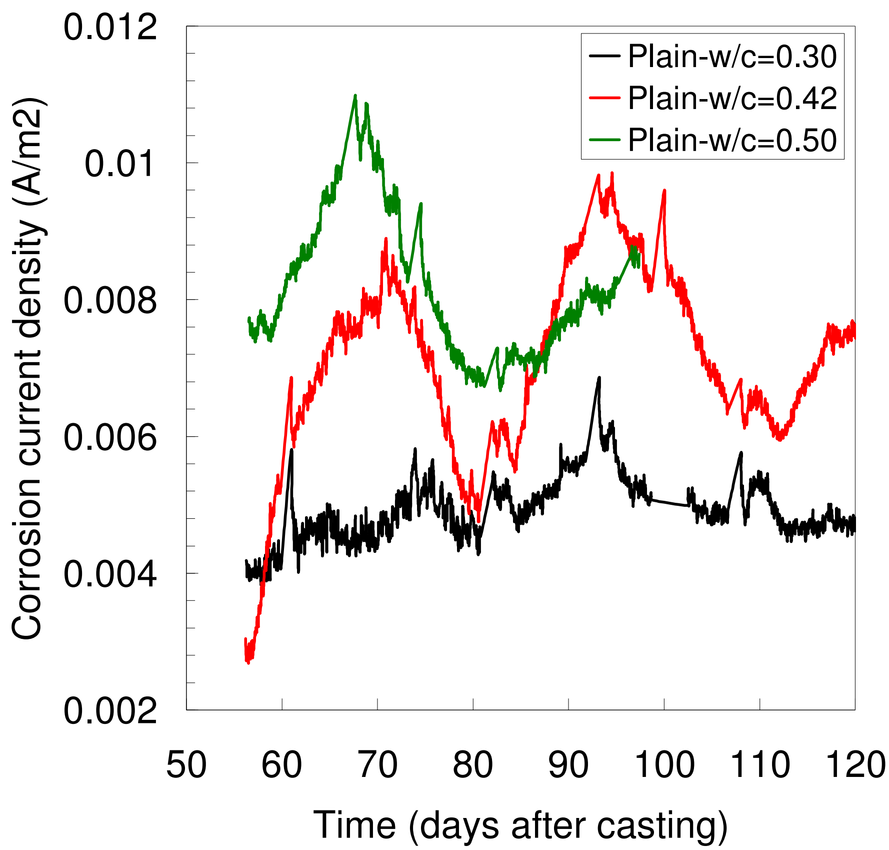


Figure 9: Macro-cell corrosion current density of the ASTM - G109 samples

X-ray attenuation radiography is also being used to study the water permeability and fluid ingress in cementitious materials. X-ray attenuation measurements are based on the concept that as x-rays pass through a material, some of the x-ray's intensity is attenuated by the material while a portion of x-rays passes through the material and is captured using an x-ray camera. The radiation that is attenuated is related to the density of the concrete. This can be used to measure the cracks in concrete since as solution fills the crack and begins to penetrate the pores in the concrete, the concrete becomes more dense.

Additional testing was previously completed using water absorption measurements for the mixtures with the water to cement ratio previously described. In addition to following ASTM C1585, samples were conditioned at 50%, 65%, 80% and oven drying.

The NRMCA Research Laboratory (NRMCA-RL) is currently conducting several tests including

Rapid Index tests in Concrete

- Rapid Chloride Permeability test (ASTM C1202/AASHTO T277)
- 5 minute Conductivity test
- Rapid Migration Test (AASHTO TP 64)
- Sorptivity Test (ASTM C1585)
- Absorption Test (Modification of BS122 being drafted in ASTM subcommittee C09.66)

All the rapid index tests used at NRMCA used a 4” diameter by 2” thick specimen that has been cut from the top of a 4x8 concrete cylinder.

Slower Performance Tests in Concrete

- Chloride Diffusion (ASTM C1556)
- Freeze Thaw (ASTM C666)

The Rapid Index Tests are evaluated to see if they correlate with the slower performance tests. The rapid index tests and criteria that correlate well with the performance tests can be used in performance specifications. More discussions on the mixture proportions evaluated, tests conducted, curing conditions and preliminary results available thus far are provided.

The 5 minute Conductivity (ASTM Draft) test is similar to the Rapid Chloride Permeability test (ASTM C1202) except that it uses a 0.3N sodium hydroxide solution on both sides of the cell and the test is run only for 5 minutes after which the current reading (I) is noted while applying a constant voltage of 60V. Conductivity is calculated as, σ (S-m^{-1})=l/RA, where R=concrete resistance (R-Ω) calculated from Ohm’s Law as R= V/I, A=specimen cross-sectional area, l = specimen length.

After the moist curing period the absorption test (ASTM Draft) involves oven drying at 50°C for 72±2h followed by cooling for 24±0.5h in a dry airtight vessel. Then, the specimen is immersed in the water for 30±0.5 min and immediately the mass is determined for calculation. Absorption is calculated as a percent increase in mass.

2.0 Proposed Activities for the Next Period

The research team had a SAC meeting during Quarter 3. It is anticipate that the next QPR will be held during the Summer/Fall of 2010.

2.1 Phase I - Literature Review

The research team is completing the literature review and providing a draft to the stakeholders for review and discussion. This is near completion and is being completed by Amir Pourasee who is a post-doctoral associate that has been added to this project.

This is the main task that he is currently working on so that this can be brought to completion.

2.2 Phase I - Survey of Permeability Test Methods

A survey of permeability test methods was prepared and sent to DOT, material suppliers and testing labs that evaluates the current state of the practice as it relates to permeability (transport tests). The survey outlined the most common tests used in the US. Data from the survey has been used in guiding the research program. Amir Pourasee is currently completing this phase of the research. Purdue ended up performing this task.

2.3 Phase II - Sample Preparation and Conditioning

Work will continue to prepare the reference concrete for Phase II and IV. The constituent materials will be fully characterized and the samples will be conditioned using both accelerated and natural curing conditions. Javier Castro, a graduate assistant and Phil Kompare a graduate assistant are currently working on this research.

The electrical impedance of the concrete materials is been measured continuously and results will be reported at the next progress meeting

The Swiss gas permeability device has been designed and ordered. The Swiss have also offered to test a small number of samples in a variety of equipment to provide additional data for comparison. It is currently anticipated that the equipment will be in place for testing at the end of the next quarter. The research team has samples conditioning so the research can start as soon as the devices being ready.

Samples with different w/c of 0.30, 0.42, and 0.5) have been prepared according to ASTM G109. These samples will continue to be monitored.

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 2: 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 – 6.8×10^{-12} to 0.62×10^{-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)**

v) 28 day accelerated
vi) 56 day normal curing
vii) 26 week (182 d) normal curing
viii) 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) 56d (8 week) normal curing + 126d (18 week) in solution till 26 weeks. For Phase II this condition was replaced by 56d (8 week) normal curing + cyclic exposure (75 week using 3d in solution/4d at 73F-50%rh cycle) in solution - 2
ii) 56 d (8 week) normal curing + 490d (70 week) in solution till 78 weeks. For Phase II this condition was replaced by 6months normal curing + 12 months in solution - 1
iii) 56d (8 week) normal curing + cyclic exposure (18 week using 4d in solution/3d at 100F-20%rh cycle) in solution till 26 weeks
iv) 56d (8 week) normal curing + 35d (5 week) in solution till 13 weeks
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 3: 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 [A]	5.28	2.24	0.84	8.64	4.81	0.36
Case 3 [B]	11.8	3.20	1.02	6.45	4.01	0.64
Case 1 [C]	2.28	1.37	0.47	1.74	0.14	0.26
Case 5 [C]	2.36	1.32	0.68	3.91	2.02	0.30
ASTM C 1556, Surface Chloride, % by weight of concrete						
Case 4 [A]	1.12	1.77	1.03	0.96	0.75	3.02
Case 3 [B]	1.02	1.37	1.93	1.23	1.39	2.65

Case 1 C	1.01	1.90	2.11	1.26	5.62	1.90
Case 5 C	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 4: 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	4.6* / 2.5	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	0.9 / 2.5	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	3	3.08	0.84	0.63	2.42	1	2.2	-
6m nc + 35d in solution	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
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)	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
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	1.1	1	1.27	1.08	1.10	1.62	0.95	-
6m nc + 35d in solution	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
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)	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
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

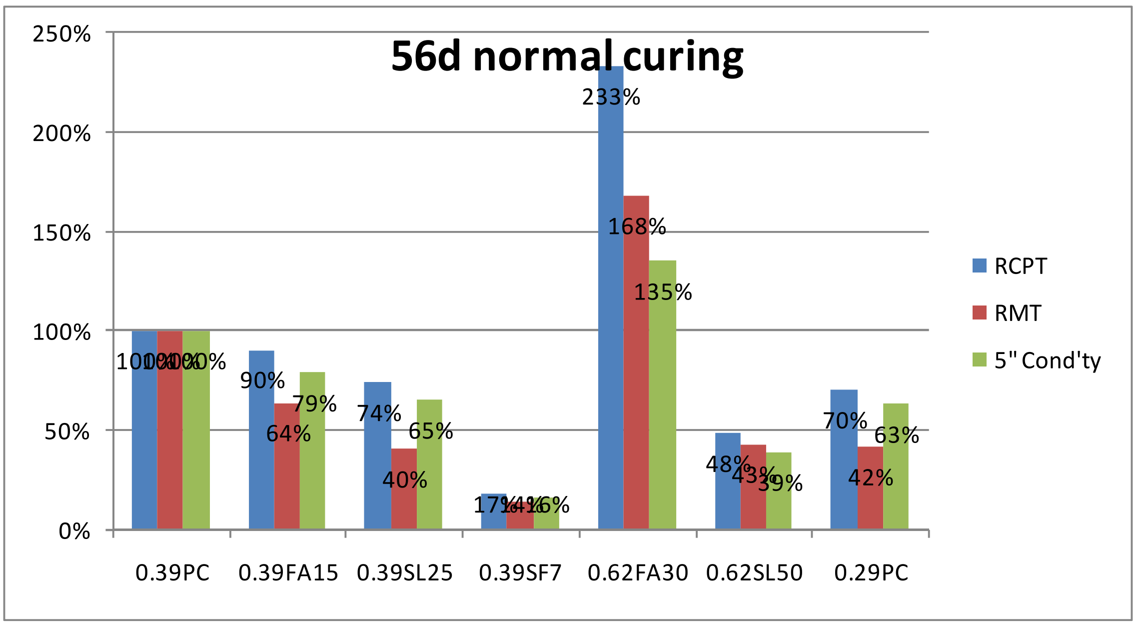
$^{+}$ Curing period in 70°F, 50% RH environment NOT included 7 days initial wet curing period in water bath

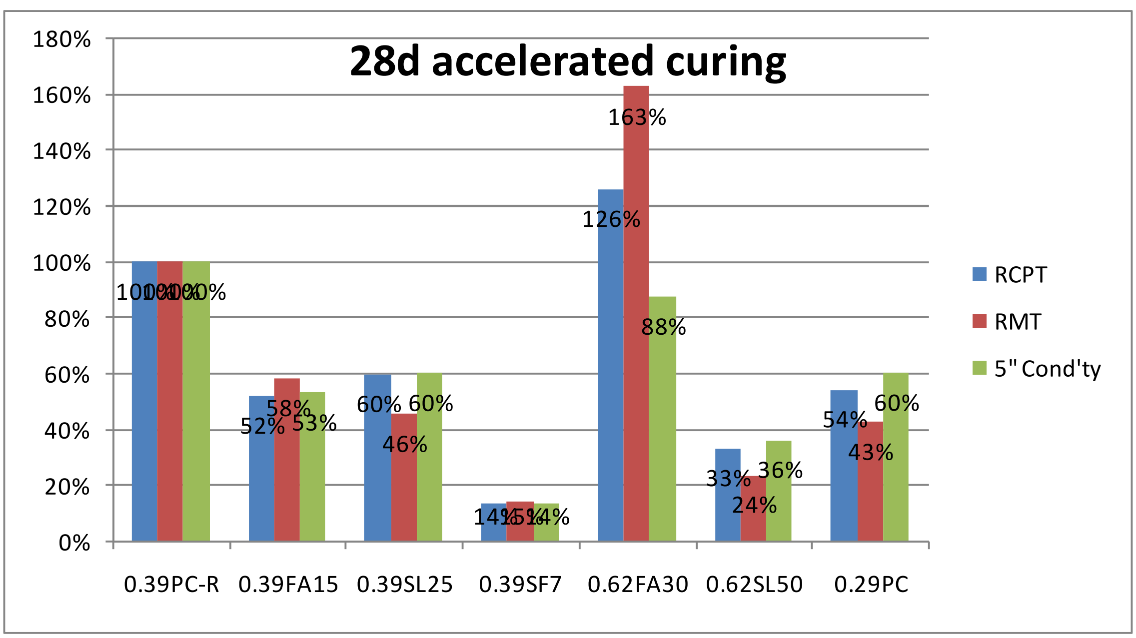
* A correlation coefficient less than 0.98 indicating that the rate cannot be determined according to ASTM C1585

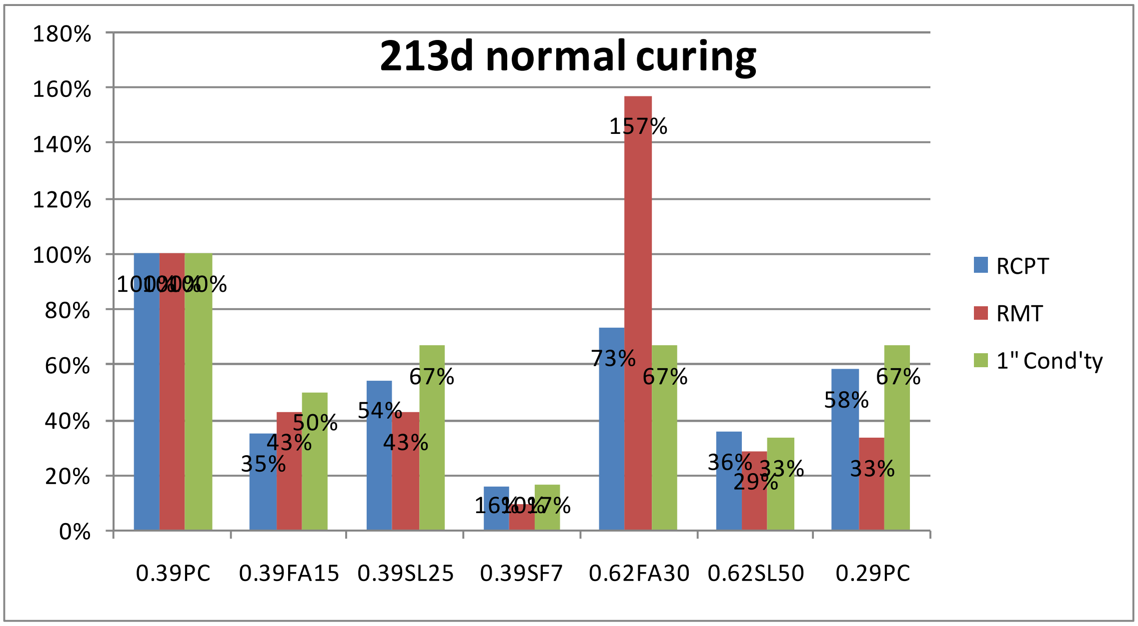
** Exact repeat of designated mixture

Preliminary Observations

1. The 56 day, 28 day accelerated cured, and 213 day RCPT, RMT, and conductivity test results appear to be proportional to each other except for Mix 0.62FA30. This becomes clear from the plot below. Mix 0.62FA30 has high permeability at 56 days (4000+ coulombs) and it is well known that at such levels the RCPT tends to show an increased coulomb value due to over-heating. RMT for those types of mixtures is also questionable because the initial current was at the border line for voltage choice and the chloride had passed throughout the depth. For these high permeability mixes the 5 minute Conductivity results are most dependable as the specimens do not heat up. The 213 day RMT values for the same mixture also appear to be abnormally high.







2. Based on the 56 day 5 minute Conductivity test results the mixtures in the order of chloride penetration (lowest to highest) are as follows:
   0.39SF7<0.62SL50<0.39FA15=0.39SL25=0.29PC<0.39PC<0.62FA30
   This matches the permeability classifications shown in the Table titled "Mixture Proportions and Variables" except for the "very low" measured chloride penetration values of the 0.62SL50 (the expected classification for that mixture was High). It would be interesting to observe if the chloride diffusion coefficient test results would follow the same trend as given above and particularly for the 062 SL50 mixture. It is important to examine if the rapid index vs Cl diff coeff. test result correlations are independent of SCM types, dosage, and w/cm.
3. Water absorption and sorptivity test results did not classify the mixtures so effectively as RCPT, RMT, and 5 min. conductivity. However higher w/cm mixtures gave higher absorption values. If the higher w/cm mixtures showed higher chloride diffusion coefficients it is possible to use the absorption tests to eliminate those mixtures. Also based on all data collected thus far we would try to evaluate if the easier absorption test results can be used for that purpose instead of the more complex sorptivity test results.

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 5: 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)

ix) 28 day accelerated
x) 56 day normal curing
xi) 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 6: Yield Adjusted Mixture Proportions and Preliminary Test Results

Calculated Batch Quantities											
	0.57 PC	**0.50 PC**	**0.50 FA20**	**0.50 SL30**	**0.50 SL25SF 5**	**0.60 SL25SF 5**	**0.45 PC**	**0.45 SL30**	**0.57 PC**-R**	**0.50 PC**-R**	**0.50 SL30**-R**
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	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
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 (22w) normal cure	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
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+	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
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℉, 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	30%FA	25% SL	50%SL
	0.50	Type I	1 cement				
S1	0.50	Type II	2 cements				
	0.40	Type I		Yes	Yes*	Yes	Yes*
	0.50	Type I		Yes		Yes	
	0.60	Type I		Yes	Yes*	Yes	Yes*
S2	0.45	Type V	2 cements				
	0.40	Type II		Yes	Yes**	Yes	Yes**
	0.50	Type II		Yes		Yes	
	0.60	Type II		Yes	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 31 mixtures – 26 with SCMs and 4 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

** These mixtures have higher SCMs and Type II cement and so may satisfy S3 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 14 mixtures - 10 SCM mixtures (3 different cements, and 4 different SCM contents except for the Type V cement that has only 2 different SCM contents) and 4 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)

xii) 28 day accelerated
xiii) 56 day normal curing
xiv) 52 week normal curing

- USBR4908 fully immersed method B. Test 3 cylinders per mix. Start after 56 days of moist curing. Conduct test for 18 mos. Take periodic expansion readings. Follow TXDOT report

- USBR4908 partially immersed (same 10% solution as above). Test 3 cylinders per mix. Start after 56 days of moist curing. Conduct test for 18 mos. Take periodic expansion readings. Follow TXDOT report and NIST report for specimen immersion. 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 :

vii) 28 day accelerated + 18 d specimen conditioning (C1585)
viii) 56 day normal curing + 18 d specimen conditioning (C1585)
ix) 52 week normal curing + 18 d specimen conditioning (C1585)

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

vi) 28 day accelerated + 3 d in oven
vii) 56 day normal curing + 3 d in oven
iv) 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.