TPF-5(179) QPR #02

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, and New York)

For the Period of

October 1st, 2008
to
December 31st, 2008

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																				80
	Task 2: Prepare a Description of Each Procedure		5	15	25	30																				30
	Task 3: Develop a Summary Document																									5
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
	Task 2: Describe Constituent Materials			10	20	40																				40
	Task 3: Develop Reference Material			15	15	20																				20
	Task 4: Perform Tests					20																				20
	Task 5: Evaluate Testing Procedures					20																				20
	Task 6: Recommedations to Existing Procedures																									~
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
	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																									~
Phase IV:	**Correlate Permeability (Transport) Tests with Laboratory Tests that Evaluate Durability**																									
	Task 1: Prepare Specimens	5	15	25	45	65																				65
	Task 2: Condition Specimens			10	25	30																				30
	Task 3: Expose Specimens																									~
	Task 4: Evaluate Specimens																									~
	Task 5; Perform ASTM Tests																									~
	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**																									
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Deliverables											2						3				4			5		~
Study Advisory Committee Meetings																										~

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

Figure 2: Estimated Project Expenses

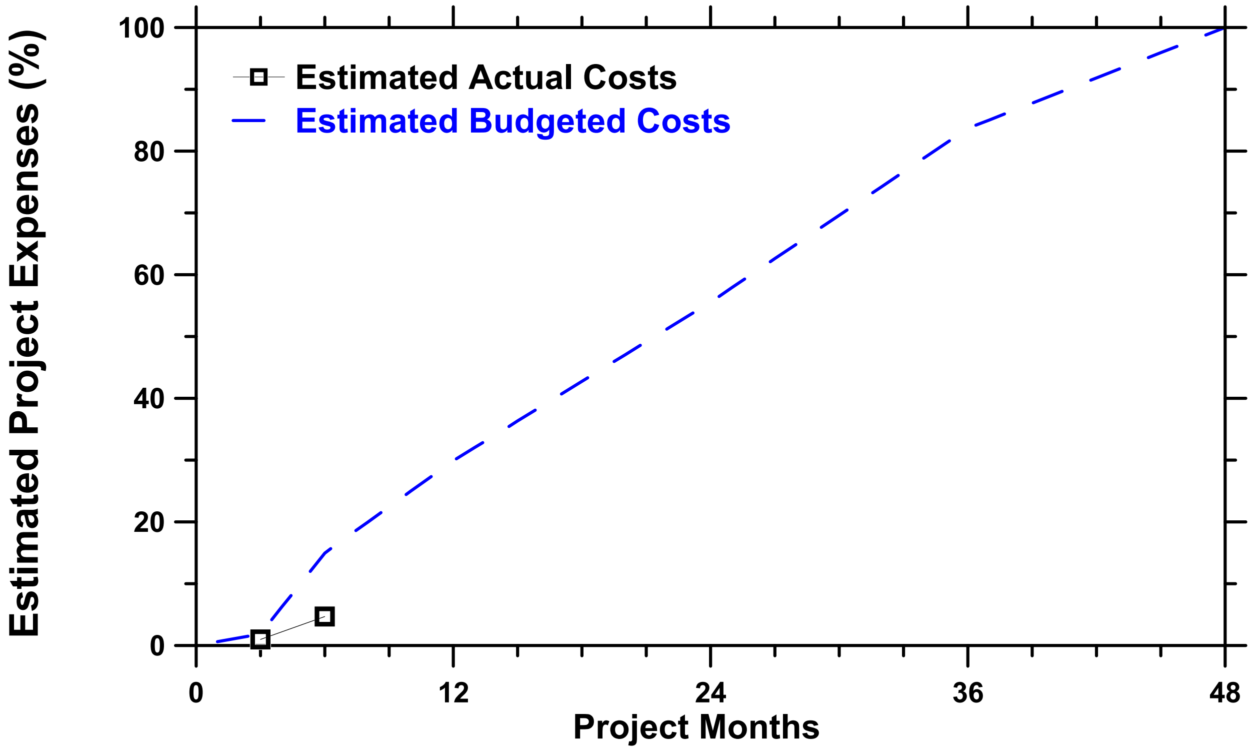


Figure 3: Project Budget and Expenses

Category	Detailed Description	Budgeted Cost	Billed Expense Through 9/30/08
Personnel			
	INDOT Staff (Tommy Nantung*)	~	~
	Purdue Faculty (Jason Weiss and Jan Olek)	$ 121,230	$ 26,145
	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			
	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	$ 15,200
Total			
		$ 883,000	$ 41,344

* 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 of progress from the second quarter of the project. It covers the three month period beginning October 1st 2008 and ending December 31st 2008.

During the reporting period work was performed primarily on Phases I and II. Additional preliminary work was preformed on Phases III and 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. Research has focused on developing a listing of papers and test methods currently in existence nationally and internationally for determining permeability. To manage the data obtained from this literature review the research team will focus on 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, a survey of tests being used by the DOTS is 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. The PI has also become a member of the RILEM committee on performance specifications to gather information from the international community.

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 begun to assemble materials and prepare 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.

NRMCA is using the PFS to broaden the scope of a research project titled "An Evaluation of Performance Based Alternatives to the Durability Provisions of the ACI 318 Building Code" that is being funded by the Portland Cement Association and RMC Research and Education Foundation. An industry review conference call for the PCA/RMC research project was held on May 28th 2008. The industry review committee includes the following individuals:

1. Kevin MacDonald, Cemstone
2. Teck Chua, Vulcan
3. Tim Durning, Grace
4. Emmanuel Attiogobe, BASF
5. Larry Roberts, CTL/Consultant
6. Paul Tennis, PCA
7. Bruce Blair, Lafarge
8. Corresponding member – Ken Rear

Professor Doug Hooton, University of Toronto is currently working as a consultant to NRMCA for the PCA/RMC research project. Several of the materials tested are the same as the materials being tested for Phases II, and IV of the PFS. Mixture proportions, testing conditions and the rationale behind their choice have been summarized below. The mixtures in bold have been prepared and tested to date.

Table 1 Mixture Proportions Planned

w/cm	PC	15%FA	30%FA	25%SL	50%SL	7%SF	40%SL+ 5%SF
0.29	L						
0.34							**N**
0.39	M	L	**VL**	L	**VL**	VL	
0.49	**H**	**M**		**M**			
0.62			H		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 mixture proportions have been chosen to cover different levels of 2 year chloride penetration resistance as predicted by the Life 365 service life computer program. The Life 365 program has a built in data base of chloride diffusion coefficients of concrete mixtures containing various SCMs and w/cm. The Life 365 predictions for 2 year chloride diffusion coefficients (all numbers in x10^{-12} m^2/s) are provided below – with the 6 month numbers indicated after the slash:

Table 2 Two year/Six month Chloride Diffusion Coefficients as Predicted by Life 365

w/cm	PC	15%FA	30%FA	25%SL	50%SL	7%SF	40%SL+5%SF
0.29	2.3/3.9						
0.34							**0.62/1.1**
0.39	3.9/5.2	2.6/4.1	**1.8/3.3**	2.5/4.0	**1.5/3.0**	1.2/1.6	
0.49	**6.8/9**	**4.6/7.2**		**4.3/6.9**			
0.62			6.4/12		5.4/11		

The above mixtures are proposed 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 eliminate mixtures with high diffusion coefficients (>5 x 10^{-12} m^2/s)
3. To be able to use rapid index test criteria to choose mixtures with desired classification as indicated above
4. 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
5. w/cm, SCM dosages must cover the ranges normally used in HPC
6. 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.

The six mixtures highlighted in bold in Tables 1, and 2 were made at the NRMCA Research Laboratory. The mixtures covered 4 permeability levels (1 H, 2 M, 2 VL, 1 N).

Some of the mixture proportioning information is as follows:

- 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

The following section describes the planned test methods, curing conditions and testing ages for the NRMCA mixtures.

For the NRMCA mixtures the term standard curing refers to standard moist room curing starts immediately after making the specimens. The term 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 the NRMCA mixtures.

Rapid Chloride Permeability test – RCPT (ASTM C1202)

i) 28 day accelerated – 2 cyl
ii) 56 day normal curing – 2 cyl
iii) 26 week (182 d) normal curing – 2 cyl
iv) 78 week (546 d) normal curing – 1 cyl

1 minute Conductivity test (ASTM Draft)

v) 28 day accelerated – 2 cyl
vi) 56 day normal curing – 2 cyl
vii) 26 week (182 d) normal curing – 2 cyl
viii) 78 week (546 d) normal curing – 1 cyl

Rapid Migration Test - RMT (AASHTO TP 64)

i) 28 day accelerated – 2 cyl
ii) 56 day normal curing – 2 cyl
iii) 26 week (182 d) normal curing – 2 cyl
iv) 78 week (546 d) normal curing – 1 cyl

Chloride Diffusion Test (ASTM C1556)

i) 56d (8 week) normal curing + 126d (18 week) in solution till 26 weeks – 2 cyl
ii) 56 d (8 week) normal curing + 490d (70 week) in solution till 78 weeks – 1 cyl
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 – 1 cyl
iv) 56d (8 week) normal curing + 35d (5 week) in solution till 13 weeks – 2 cyl to get standard Da value as per Life365 (although 365 uses a 28day Da as baseline).
v) 26 weeks normal cure +35 days in solution – 1 cyl (to get later age Da as per Life365. m-calcs)

Sorptivity Test (ASTM C1585)

i) 28 day accelerated + 18 d specimen conditioning (C1585) – 2 cyls
ii) 56 day normal curing + 18 d specimen conditioning (C1585) – 2 cyls
iii) 26 week (182 d) normal curing + 18 d specimen conditioning (C1585) – 2 cyls

Absorption test BS 1881:122

i) 10 day normal curing + 3 d in oven – 2 cyls
ii) 28 day accelerated + 3 d in oven – 2 cyls
iii) 26 week (182 d) normal curing + 3 d in oven – 2 cyls

The yield adjusted mixtures proportions and some test results are provided in table 3.

Table 3. Yield Adjusted Mixture Proportions and Preliminary 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 standard 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
ASTM C1202, Rapid Chloride Permeability, Coulombs						
28d accelerated cure	4657	1992	561	2414	723	166
Draft ASTM Standard, 1 minute Conductivity, Sm^{-1}						
28d accelerated cure	0.019	0.009	0.003	0.009	0.003	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
ASTM C157, Length Change (Drying Shrinkage), %						
28 days^{+}	0.035	0.039	0.031	0.029	0.028	0.028

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

Durability Tests

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

ix) 28 day accelerated – 2 cyl
x) 56 day normal curing – 2 cyl
xi) 26 week (182 d) normal curing – 2 cyl
xii) 78 week (546 d) normal curing – 1 cyl

- **1 minute Conductivity test (ASTM Draft)**

xiii) 28 day accelerated – 2 cyl
xiv) 56 day normal curing – 2 cyl
xv) 26 week (182 d) normal curing – 2 cyl
xvi) 78 week (546 d) normal curing – 1 cyl

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

v) 28 day accelerated – 2 cyl
vi) 56 day normal curing – 2 cyl
vii) 26 week (182 d) normal curing – 2 cyl
viii) 78 week (546 d) normal curing – 1 cyl

- **Chloride Diffusion Test (ASTM C1556) - due to high manpower need only 6 cylinders will be tested**

vi) 56d (8 week) normal curing + 126d (18 week) in solution till 26 weeks – 2 cyl
vii) 56 d (8 week) normal curing + 490d (70 week) in solution till 78 weeks – 1 cyl
viii) 56d (8 week) normal curing + cyclic exposure (18 week using 4d in solution/3d at 100F-20%rh cycle) in solution till 26 weeks – 1 cyl
ix) 56d (8 week) normal curing + 35d (5 week) in solution till 13 weeks – 2 cyl to get standard Da value as per Life365 (although 365 uses a 28day Da as baseline).
x) 26 weeks normal cure +35 days in solution – 1 cyl (to get later age Da as per Life365. m-calcs)

- **Sorptivity Test (ASTM C1585)**

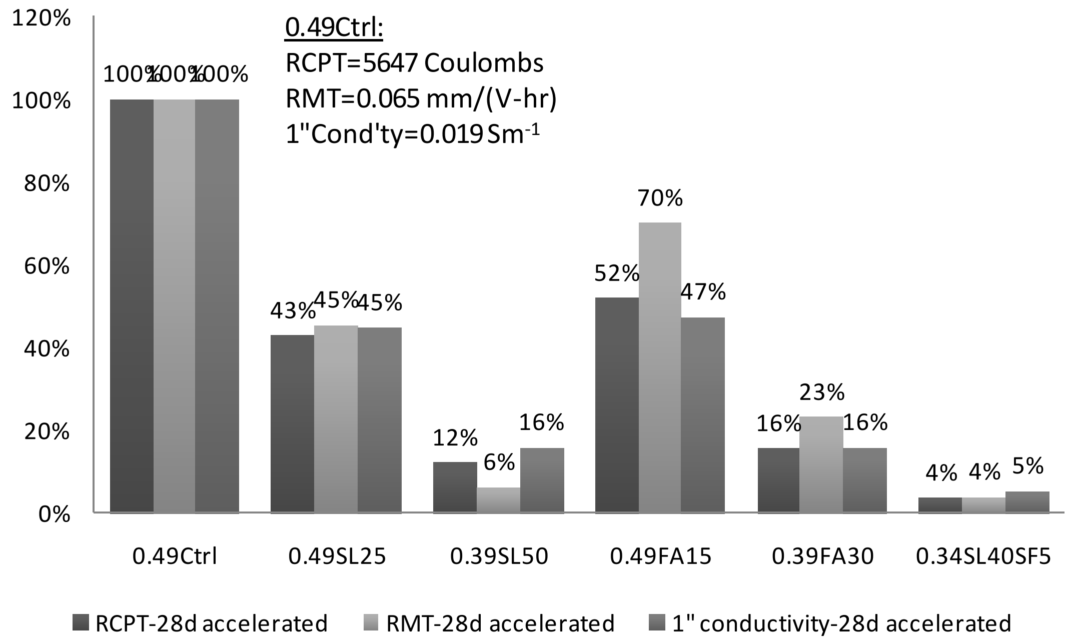
iv) 28 day accelerated + 18 d specimen conditioning (C1585) – 2 cyls
v) 56 day normal curing + 18 d specimen conditioning (C1585) – 2 cyls
vi) 26 week (182 d) normal curing + 18 d specimen conditioning (C1585) – 2 cyls

- **Absorption test BS 1881:122**

iv) 10 day normal curing + 3 d in oven – 2 cyls
v) 28 day accelerated + 3 d in oven – 2 cyls
vi) 26 week (182 d) normal curing + 3 d in oven – 2 cyls

Preliminary Discussions

1. The 28 day accelerated cured RCPT, RMT, and conductivity test results appear to be proportional to each other. This becomes clear from the plot below.



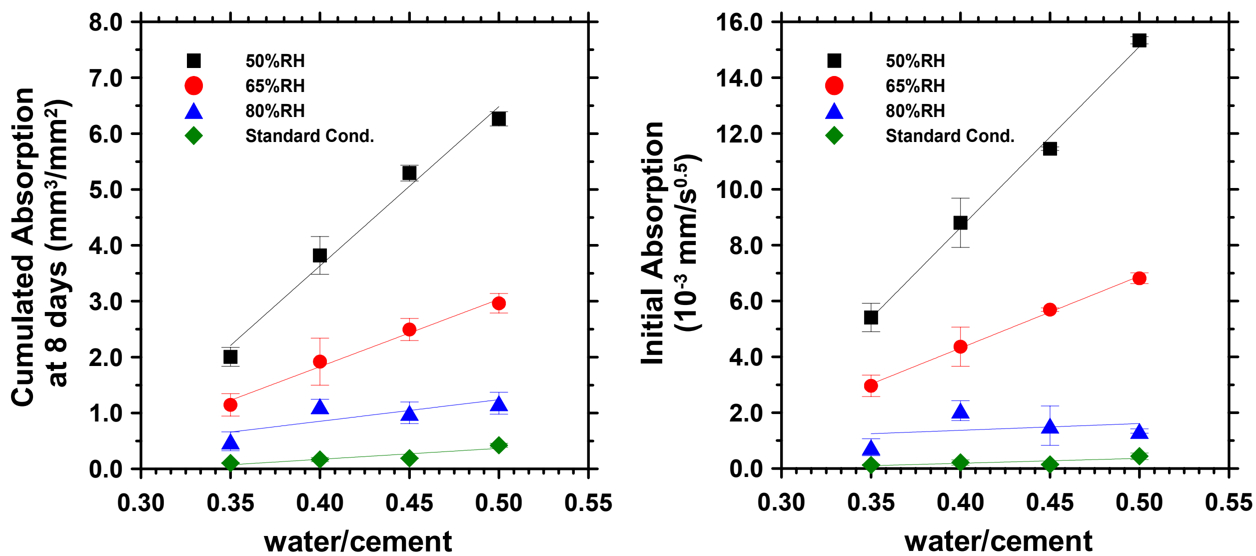
2. The permeability classifications were exactly as expected. 0.49Ctrl was H, 0.49SL25 and 0.49FA15 were M, 0.39SL50 and 0.39FA30 were VL, 0.34SL40SF5 was N. it would be inetersting to see if the chloride diffusion coefficient test results would follow the same trend. If so then it would mean that either one of those three tests are adequate in choosing mixtures based on chloride penetration levels.
3. Water absorption test results are according to expectations. 28 day accelerated test results were lower than 10 day results. Fly ash mixtures that did not perform as well at early ages performed better with later ages. When the later age test data is compared to the early age data fly ash mixtures recorded 25 to 30% reduction in absorption values, slag mixtures recorded 20% reduction where as the control and the slag/silica fume mixture recorded 12% reduction.
4. Water absorption test results do not classify mixtures in the expected permeability classifications. Even after 28 days accelareted curing the 0.49FA15 mixture had the same absorption as the 0.49Ctrl mixture. Clearly this trend is not expected in the chloride diffusion test result. It remains to be seen if the absorption test results play any useful role when chloride diffusion testing is conducted in wet/dry environment (see #5, and #6 below). Also some of the rapid index conductivity test results are known to lead to misleading results (low coulombs but high diffusion coefficients) for high w/cm high pozzolan content mixes (see discussions in Dec 07 prelim report) and it remains to be seen if adding the absorption test would help to weed out such mixtures. Also for future mixtures water absorption test results should be conducted at 60C temperatures since it is known that the 105C curing temperatures lead to internal cracking and hence unrealistic test results.
5. Effect of inadequate curing on chloride diffusion coefficients needs to be investigated. Frequently in the field structures undergo only 7 days of moist curing. In such situations questions are raised whether some of the chloride diffusion test results measured from laboratory moist cured specimens are

accurate – this may be exacerbated for some of the slower acting pozzolans such as fly ash. As a response to this it has been postulated by experts that in the field structures stay at over 80% relative humidity even slightly below the concrete surface and therefore curing continues and so the results are valid. This issue still needs to be addressed. The best way to address is to moist cure the chloride diffusion test specimens only for 7 days followed by laboratory air drying for 21 or 49 days followed by the chloride exposure.

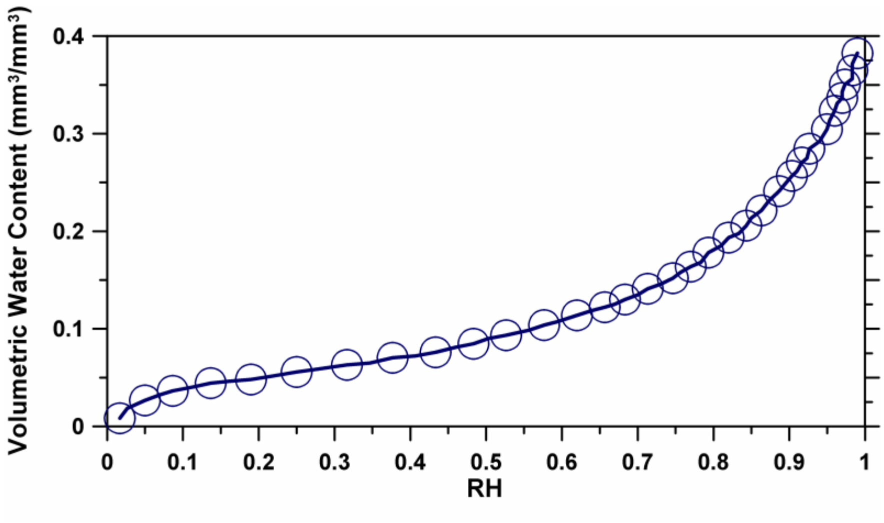
6. Also a continuously moist chloride exposure may be valid only for marine exposures. For bridge deck exposures a wet-dry chloride exposure may be appropriate. This may be even more acute if the humidity levels in the area are low.
7. It should be clearly understood that the rapid index tests should still be subjected to moist curing till the test begins. The final aim is that the rapid index test results should scale with the chloride diffusion coefficient test results.

1.3 Phase III – Develop New or Improve Existing Permeability Transport Testing Procedures. Develop Protocols to Use these Tests, and Evaluate the Precision and Bias of Tests

Testing has been performed to determine water sorption on carefully conditioned samples. The following plot demonstrates the importance of properly obtaining a well conditioned sample. The lines on the figure are just to show general trends.



The research team has also measured sorption-desorption isotherms for use in calculations of unsaturated permeability and fluid transport. A typical plot of the data is illustrated below. Additional samples have been collected and are currently being conditioned.



2.0 Proposed Activities for the Next Period

The research team has met several times to discuss progress.

2.1 Phase I - Literature Review

The research team is focused on summarizing the literature review for discussion with stakeholders at the first study advisory meeting. The team will also work on preparing a summary description of each test technique.

2.2 Phase I - Survey of Permeability Test Methods

A survey of permeability test methods was prepared and sent to DOT personnel, material suppliers and testing labs that evaluates the current state of the practice as it relates to permeability (transport tests). The survey will be sent after TRB.

2.3 Phase II - Sample Preparation and Conditioning

Work will continue to prepare the reference concrete for Phase II, III and IV. The constituent materials will be fully characterized and the samples will be conditioned using both accelerated and natural curing conditions.

2.4 Phase III – Improve Transport Testing Procedures

Work has begun to develop new testing methods. Sorption tests have been tested for reference materials under long-term stable testing. Further testing has been enabled by the development of a multi-channel system for rapid time dependent electrical conductivity testing on multiple samples over a range of times.

2.5 Study Advisory Meeting

The research team will solicited dates for the study advisory committee meeting for the state stakeholders. The meeting will be held February 23rd, 2009.