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

1.0 Introduction

Historically concrete has been specified and placed using prescriptive specifications. As a result, DOT specifications for concrete pavements and bridge decks typically contain a strength requirement as well as prescriptive limitations on water-to-cement ratios, minimum cement contents, air contents, and supplementary cementitious addition rates.

With the support of the FHWA, states and agencies have begun the shift from prescriptive specifications to end result or performance based specifications. Recently completed projects using performance related specifications demonstrate great potential for this approach [1,2,3,4]. The National Ready-Mixed Concrete Association (NRMCA) has recently launched the Prescriptive to Performance initiative (P2P) which proposes the use of performance-based specifications for concrete construction as an alternative to traditional prescriptive specifications [5,6]. Performance specifications provide contractors with incentives to improve their mixture designs and constructions practices by relating the properties of the concrete with anticipated performance and project costs.

Although several states have begun experimenting with performance specifications, rapid advancement is limited by a lack of confidence in testing procedures that can evaluate concrete durability in a rapid, consistent basis for mixture qualification or use in quality control practices. One deficiency is the lack of a test procedure to evaluate the permeability (transport) properties of concrete.

This project will address this deficiency by evaluating existing tests to evaluate the permeability (and resistance to fluid and ion transport) test methods that can be used with performance based/related specifications. In addition, new or revised testing procedures will be developed to enable states and agencies to obtain rapid, reliable material properties for the concrete they are using that are related to long-term performance. A set of guidelines will also be developed that will enable states and agencies to implement these test procedures and to use these test procedures in the specification process.

2.0 Overview of the Research Approach

Performance-based specifications would be expected to provide details of required properties such as strength (or other mechanical properties) along with requirements for durability. While strength can be reliably measured and criteria exist for mixture prequalification, durability issues remain more challenging to measure and specify. Each potential durability issue, including freeze-thaw, chloride penetration and corrosion, alkali aggregate attack, and sulfate attack, can be related in part to water penetration. Therefore, in order to specify concretes that are more durable it is essential that tests are developed that can qualify the resistance of the concrete to water (or aggressive fluid) penetration. This resistance will be referred to in this proposal as permeability (or transport).

There are numerous tests used to provide an indication of the permeability (transport properties) of concrete. This research project will evaluate the applicability of the available test methods (including both test methods from the US and in other countries) and identify those that have the most promise. The research project will assess these tests and develop new and improved methods to measure the permeability of concrete. This project will enable new permeability (transport) testing procedures to be specified. A single operator precision and potentially multi-lab precision will be developed to ensure reliability of the proposed methodology.

To have the greatest value, permeability (transport) tests should be able to be combined with exposure conditions to describe the durability performance of concrete including its response to freeze thaw, sulfate attack, chloride induced corrosion. To establish this link the measured permeability (transport) will be compared with freeze-thaw, sulfate attack, and chloride induced corrosion specimens.

The final outcome expected from this project is the development of performance based criteria for a test or a set of tests that are an alternative to prescriptive requirements in specifications such as minimum cementitious contents, maximum w/c and required supplementary cementitious material quantities. Guidance will be provided as to how to use these tests and performance criteria in QC/QA or performance based/related specifications. In addition, educational materials will be prepared that will enable this material to be transferred to industry and to academia.

3.0 Detailed Research Program

The work described in this proposal is intended to develop standard test procedures for measuring permeability (transport) in concrete and guidelines that relate the measured permeability properties with field exposure and performance. The following section describes the main phases of this work.

3.1 Phase I: Literature Review of Concrete Permeability (Transport) Test Procedures and Models that Link Tests with Performance

In the first task of this study an extensive review of literature pertaining to the measurement of permeability (transport) in concrete will be performed. The main objective of this review is to assemble a complete listing of test methods currently in existence nationally and internationally for determining permeability. This will include investigation in the concrete literature as well as investigations in related fields that may have merit. 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.

In addition to examining permeability test methods, the literature review will be performed to determine methods that have been proposed or methods that are currently in use to relate permeability (transport) and durability performance. Again, analysis methods will be summarized including:

- a description of the scientific approach,
- the material properties needed to establish the relationship,
- the assumptions in the model,
- the advantages and disadvantages of a particular method,
- the methods complexity, and
- the probability of the method of being successful.

This data will be 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 will 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. It is anticipated that valuable information will be obtained from the Duracrete project [7], RILEM Committee Reports [8], FHWA publications [9], PCA publications [10], and ACI Committee reports [11].

Purdue will take the lead in the literature search and summary for Phase I while NRMCA will assist Purdue by polling their member companies with a survey and reviewing the literature summaries. Based on the information obtained during Phase I the tests that are selected for consideration in Phase II will be determined. This initial selection process will be made by Purdue/INDOT/NRMCA and the COTR however this will also be discussed with the Study Advisory Committee (SAC). The primary selection criteria will consist of screening out experimental methods that have a high potential for error, methods that may have a high potential for failure, or methods that are too costly or sophisticated to perform. Further tests will be specifically sought to be included in Phase II that have value to be used to obtain parameters that would be useful for models that relate material properties with performance with the approval of the COTR.

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. A draft of this report will be sent to the SAC Members prior to the first Study Advisory Committee meeting. This report will be discussed at the Study Advisory Committee meeting along with a detailed investigation for use in Phase II of the program. At the end of this phase annotated slides will be prepared for 30 minute presentation summarizing the key findings and submitted to the COTR for possible use by SAC members at their home agencies.

3.2 Phase II: Evaluation of Promising Concrete Permeability (Transport) Tests and Recommend Procedures for Further Use

This main outcome of phase I of the research is to identify potential permeability (transport) tests that are currently in existence. The second phase of this research will be to conduct these tests on a smaller, yet comprehensive, subset of materials. This is essential as only by performing and evaluating the current permeability tests can one truly gain an insight regarding how to improve their shortcomings.

The research team has substantial familiarity with concrete permeability (transport) tests such as the Rapid Chloride Permeability (ASTM C 1202), Rapid Migration Test (AASHTO TP 64), Chloride Diffusion Test (ASTM C 1556), and Sorptivity Test (ASTM C 1585). However there are several other tests that have not been standardized by AASHTO or ASTM but standardized by organizations outside the United States. These include but are not limited to: surface resistivity which has been used extensively at Purdue and at the Florida DOT, Oxygen permeability which has been used by Alexander and Stanish from South Africa in their Durability Index Approach and by Zia, Gas permeability - BS 8500, Water Permeability - The US Corps of Engineers has two tests for water permeability, CRD 48 and CRD 163.

The research team will also investigate the potential use of an engineered material (like a ceramic) with repeatable transport properties that can be used to assess the accuracy and repeatability of the test methods. This material will have the potential for comparing different test methods and being used as a standard reference material for evaluating the precision and bias of test procedures as well as calibrating each test method for use in the field. This will be able to screen out testing procedures with a high variability or materials which can not be used to obtain fundamental transport information.

Where existing standard equipment exists at both laboratories tests will be conducted in parallel to gain rapid assessment of multi-lab variability. For cases where specialized equipment may be needed the samples will be exchanged (or testing devices will be exchanged) to enable the tests will be performed at one laboratory.

3.2.1 Purdue Laboratory - Work at Purdue will focus on four main concrete material compositions. These will focus on three w/c's (0.30, 0.40, and 0.50), a material with a constant w/c (w/c =0.40) with varying water content (i.e., varying paste volume), a material with a constant w/cm (w/cm =0.40) with 20% of the cement replaced with fly ash[†]. 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.

3.2.2 NRMCA Laboratory - Work at NRMCA will focus on examining a wider range of w/cm and required supplementary cementitious material quantities. Three different types of cementitious combinations, each at three w/cm (0.39, 0.49, and 0.62)[‡] as illustrated in Table 9-1 will be investigated in this study. It should be noted that these proportions have been selected to correspond with a larger testing matrix that will enable those materials to be assessed directly in Phase IV.

A complete analysis of the testing results will be performed and summary sheets will be prepared that follow the outline suggested in phase I, however they will also report the average permeability (transport) properties of each test as well as testing variability. The project will evaluate correlations between the results of alternative tests methods to determine if rapid 'index tests' may be used to rank materials or provide indications for mixture jobsite acceptance. The testing will also be used to determine conditions where one test method may provide an incorrect indication of a materials performance such as the RCP test conducted on mixtures with conductive aggregates. The sensitivity and repeatability of each test procedure will be determined to enable the test methods to be properly evaluated so that recommendations can be made for either 1) tests that could be

---

[†] Minor variations in the proposed mixture proportions may be made prior to the beginning of Phase II based on locally available materials and mixture proportions typically used for INDOT specified projects.

[‡] While the w/c in transportation structures is limited to 0.50, the higher w/cm of 0.62 was selected to determine a full range of material compositions. Some rapid index tests may incorrectly suggest low permeability even at the high w/cm of 0.62. This is one way of identifying those tests.

directly implemented or 2) tests that would need to be modified or developed in Phase III of the research.[§] Tables will be developed like those described in Phase I to provide more detail on which test methods provide results that accurately match the behavior of the known materials, In addition, tests will be evaluated based on their time, accuracy, repeatability, robustness, variability, cost, specimen preparation, and training required. Procedures are preferred that measure fundamental material properties or processes that are directly related to transport and aspects of durability. At the end of this phase annotated slides will be prepared for 30 minute presentation summarizing the key findings and submitted to the COTR for possible use by SAC members at their home agencies.

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

At the completion of phase II, the research team will have a much better idea of the characteristics of permeability (transport) tests that have a high probability of being successful as well as permeability (transport) test methods that have a low probability of success. In addition, the research team will be in the unique position of developing new testing procedures or modifying existing procedures to overcome the shortcomings of various permeability (transport) test methods.

At the end of Phase II of the research the team will brainstorm to determine methods that are scientifically correct as well as conducive to mixture prequalification and jobsite acceptance. Test conditions will be developed to assess:

- hydraulic permeability (flow of water in a saturated concrete),
- gas permeability (flow of a gas in an partially saturated concrete),
- water absorption (fluid ingress into a partially saturated concrete), and
- ion diffusion (transport of ions in a saturated concrete under a concentration gradient).

Specifically, the tests will be developed to be rapid, robust, repeatable, and accurate.

Testing protocols will be developed and written in standard AASHTO format. Repeatability of these tests will be assessed as well as their sensitivity to sample size variations, variations in initial moisture, variations in temperature, and variations in mixture proportions (high or low permeability/transport mixtures). Single operator precision and bias data will be developed. Full statistical analysis will be performed to illustrate the influence of testing variability using

[§] It should be noted that not every testing procedure will be tested at both Purdue and NRMCA. Very specialized testing procedures may only be performed at one lab and only if these test procedures yield positive results will they be tested at both labs.

approaches similar to those used for assessing other test procedures [12,13,14]. Concrete acceptance criteria will be developed that illustrates testing variability, production variability, and total measured variability [14].

Evaluations will be performed to determine both the testing variability, the sampling (acquisition, handling, and conditioning) variability, and production variability. This information will be vital in establishing performance criteria described in Phase V of the research.

Results of the new testing procedures will be evaluated with durability tests using mixtures that are under evaluation for use in Phase IV and V of the research as described below. At the end of this phase annotated slides will be prepared for 30 minute presentation summarizing the key findings and submitted to the COTR for possible use by SAC members at their home
agencies.

3.4 Phase IV: Correlate Permeability (Transport) Tests with Tests that Evaluate Durability

To have the greatest value, permeability (transport) test results will need to be combined with exposure conditions to describe concretes response to freeze thaw, sulfate attack, chloride induced corrosion. This phase describe procedures for assessing exposure conditions. In addition, laboratory durability tests will be related to permeability measurements.

To establish this link the permeability (transport) measured in Phase III, results from the permeability tests will be compared with freeze-thaw, sulfate attack, and chloride induced corrosion specimens. NRMCA will lead the effort on correlation between permeability and laboratory measures of durability.

3.4.1 Task 1. Performance Requirements for Corrosion Resistance

Currently the corrosion resistance of steel reinforcement in concrete is frequently specified by imposing a maximum w/cm, restricting chloride content in the concrete, coating the reinforcing steel, and imposing cover limits. While the chloride ion limits and cover requirements appear reasonable, in this study alternative performance criteria to the maximum w/cm requirement will be developed. Concrete will be made with three different types of cementitious combinations, each at three w/cm (0.39, 0.49, and 0.62). Similarly the three different cementitious components reflect a broad range with portland cement mixtures offering high permeability (denoted as HP); 30% GGBFS mixtures offering medium permeability (MP) and 25% fly ash+5% silica fume mixtures offering low permeability (LP).

The research team will develop laboratory tests to simulate chloride ion migration in field structures by a combination of chloride diffusion, capillary sorption and water vapor diffusion mechanisms. This research project will evaluate correlations between the permeability (transport) test methods and the chloride diffusion coefficient obtained from the laboratory test simulation.

3.4.2 Task 2. Performance Requirements for Freeze Thaw Resistance

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 mm 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. Six of the concrete mixtures (0.39HP, all 3 of the 0.49 mixtures, 0.62MP, 0.62LP) evaluated in the previous stage will be recast with 5% to 7% air content. ASTM C 666 freeze thaw testing and rapid permeability (transport) tests will be performed on these materials.

3.4.3 Task 3. Performance Requirements for Sulfate Resistance

Resistance to sulfate attack is typically prescribed by imposing a maximum w/cm, types of cementitious materials, and pozzolans. ACI 201 provides an alternative only to prescriptive cementitious types by recommending performance criteria based on the ASTM C 1012. This project will evaluate the performance based alternatives recommended by ACI 201 along with measured permeability of concrete as an alternative to the maximum w/cm limits and pozzolans. The study proposes to expose concrete beam specimens to controlled sulfate exposure in laboratory simulated field conditions in the more severe partially submerged and completely submerged exposures. This research project will evaluate correlations between the permeability (transport) test methods and the response to sulfate exposure as determined from the laboratory test simulation.

3.4.4 Task 4. Performance Requirements for Alkali Silica Reaction

Alkali silica reaction (ASR) is also a major cause for concrete deterioration. Typically prescriptive requirements such as low alkali cement, specific dosages of supplementary cementitious materials are invoked in concrete specifications to minimize the potential for ASR-related deterioration. The existing ASR tests such as ASTM C 1567, ASTM C 1293 and other tests to develop performance based criteria for mixture qualification purposes have been determined to be satisfactory. ASR will not be explicitly included in the scope of this study however a small methodology will be developed that will help develop performance alternatives to prescriptive ASR specifications. Further ASR is being studied by a significant FHWA supported research project which was initiated in 2006 and some of the results from that project could be used to developed performance guidelines.

3.5 Phase V: Develop Performance Criteria Guidelines that Link Permeability (Transport) Tests with Exposure Conditions and Anticipated Performance

It is anticipated that guidelines may be developed during Phase V of this research that can use measured permeability (transport) test properties and exposure conditions to define grade classifications for concrete elements in the transportation infrastructure. These guidelines will, where possible, use fundamental scientific principles to estimate the anticipated field performance based on fundamental transport material properties (results from the permeability (transport test)) and boundary conditions (exposure conditions). It is anticipated that while these guidelines will be based on first principles they will take the form of a table that could enable a user to use the exposure conditions for their concrete element along with their desired performance to determine the level of permeability (transport) that should be specified for a particular project. These guidelines will also consider the influence of testing variability and production variabilities as determined in Phase III.

For example, an ongoing study for the INDOT is currently examining the link between material tests, exposure conditions, and anticipated service life performance [15]. Similar approaches are being developed by other agencies throughout the world. An example of this approach would be to consider the approach used in LIFE-365 [16] which estimates exposure conditions (temperature and chloride concentration at the surface) and a material property (the diffusion coefficient) to estimate the time to corrosion. Similar approaches have been suggested for other durability problems [17,18]. Despite recent efforts in these areas a more substantial, experimentally based (and validated) approach is needed.

3.6 Phase VI: Preparation of Technology Transfer and Educational Materials

In the final phase of this project the research team will develop presentation materials that can be used for technology transfer and education. At the end of each phase annotated slides will be prepared for 30 minute presentations that will be submitted to the COTR for possible use by SAC members at their home agencies. At the completion of the project two additional 'presentation packages will be developed'.

- The first presentation package will include technology transfer information that can be presented in one day seminars that are specifically prepared for practicing professionals from the departments of transportation, engineering firms, material suppliers, and contractors. Presentations from each phase will be a minimum of 1 hour and cover the objectives of this research and recommendations. Handouts should also be developed as well that include proposed AASHTO test protocol, suggested changes to

existing test methods, and instructional information for training laboratory technicians.
- The second presentation package will focus on the development of educational materials that will be prepared for the development of two one hour presentations that can be used in college classes to prepare the next generation of civil engineering students for this paradigm shift in how materials will be tested, specified, and accepted.

4.0 Study Advisory Committee

A study advisory committee will be formed by the participating pooled fund members with recommendations from the Research Team to oversee progress on this project. This will include approximately 15 members. The co-chairs of the study advisory committee will be Dr. Tommy Nantung of INDOT and the COTR from the FHWA. Each participating state will have the opportunity to be represented on the study advisory committee (SAC) to guide the direction of the study.

The success of this project depends heavily on interaction with the SAC. The research team shall keep the study advisory committee apprised of progress using three main methods plus e-mail or web updates on an as needed basis:

- Monthly research meetings will be held at the INDOT Division of Research or at Purdue University. Researchers from INDOT and Purdue will meet in person while others will be able to join this meeting via video conferencing.
- Quarterly progress reports will be completed and submitted to the COTR and maintained on the secure web site managed by the research team (headquartered at Purdue) for the SAC members. Members of the SAC will be notified when new postings have been added to this website.
- Regularly scheduled progress meetings will be scheduled at the completion of Phase I, Phase III, and Phase VI with the concurrence of the COTR. Each participating DOT will receive a stipend to cover the costs of their participant attending the meetings. Reimbursements will be in accordance with the FHWA Travel policy requirements for the reimbursements of the travel expenses (transportation, lodging, and per diem) for State DOT SAC members.

The SAC will have access to all information produced by this project. Dr. Tommy Nantung will review and the COTR will approve all materials before they are presented or published.

5.0 Project Deliverables

The following list describes the deliverables of this project. It should be noted that each report will consist of both the written text and a short power point presentation that provides an overview of the major findings that can be used by the COTR to report intermediate progress or members of the SAC for briefing their organizations on the progress of this study.

- At the completion of Phase I, Dr. Tommy Nantung will submit a report to the SAC for review and COTR for approval. The materials will be made available that provides a review of the literature on permeability testing.
- At the completion of Phase III, Dr. Tommy Nantung will submit a report to the SAC for review and COTR for approval. The materials will be made available that describes the results of the laboratory phases (Phase II and III) of the permeability (transport) testing. Detailed information will be available in these reports that describe the materials, testing conditions, and experimental results. New testing protocols will be written in AASHTO language for approval by the SAC review and COTR. The testing protocols will be recommended by INDOT and other SAC members to the appropriate committees for consideration.
- At the completion of Phase IV, Dr. Tommy Nantung will submit a report to the SAC for comments and the COTR for approval. The report will be made available that correlates the results of the permeability (transport) tests with observed freeze-thaw, alkali silica reaction, chloride induced corrosion, and sulfate attack tests.
- At the completion of Phase V, Dr. Tommy Nantung will submit a report to the SAC for review and COTR for approval. The report will be made available that provides guidance on how to relate permeability test results and exposure conditions for the use in development of performance based/related specifications.
- At the completion of Phase VI, Dr. Tommy Nantung will submit a report to the SAC for review and COTR for approval. Upon approval by the FHWA a CD will be made available to the SAC that includes project reports, testing protocols, and presentations that will aide in transferring this technology to the field.

6.0 Project Timeline

The proposed work plan is provided in Table 6.1. This Table illustrates the time required for the project has been divided over the 48 month time frame. It can be seen that initially the literature review will be begun however samples will also be prepared due to the long curing and conditioning times that are needed to develop laboratory samples that are representative of field concrete.

Table 6.1: A timeline for the project

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
		Project Months																							
Phase I:	**Literature Review of Concrete Permeability (Transport) Test Procedures and Models that Link Tests with Performance**																								
	Task 1: Literature Review	■	■	■	■																				
	Task 2: Prepare a Description of Each Procedure		■	■	■	■																			
	Task 3: Develop a Summary Document					■	■																		
Phase II:	**Evaluate of Promising Concrete Permeability (Transport) Tests and Recommend Procedures For Further Use**																								
	Task 1: Prepare Reference Concretes	■	■																						
	Task 2: Describe Constituent Materials			■	■	■	■																		
	Task 3: Develop Reference Material						■	■	■																
	Task 4: Perform Tests							■	■	■	■	■	■												
	Task 5: Evaluate Testing Procedures											■	■	■											
	Task 6: Recommedations to Existing Procedures													■	■										
Phase III:	**Develop New or Improve Existing Permeability (Transport) Testing Procedures. Develop Protocols to Use the**																								
	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																								
Phase IV:	**Correlate Permeability (Transport) Tests with Laboratory Tests that Evaluate Durability**																								
	Task 1: Prepare Specimens	■	■	■	■	■																			
	Task 2: Condition Specimens			■	■	■	■	■	■	■	■	■	■	■											
	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									■																

Continued

		25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
		Project Months																							
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								■	■	■														
Phase IV:	**Correlate Permeability (Transport) Tests with Laboratory Tests that Evaluate Durability**																								
	Task 1: Prepare Specimens																								
	Task 2: Condition Specimens																								
	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											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

7.0. RESEARCH TEAM

Tommy E. Nantung, Ph.D., P.E., is active in research in the transportation field. He received his B.S. from Parahyangan Catholic University, a MSCE from the University of Michigan at Ann Arbor, and a PhD from Purdue University. He is currently the section manager of pavement, materials, and accelerated testing in the office of research and development with the Indiana Department of Transportation (INDOT). He is a registered engineer in the State of Indiana and has experience in pavement, materials, and construction for 18 years. He is active in TRB, AASHTO, and numerous INDOT committees.

Jason Weiss, Ph.D., is active in cement and concrete materials research. He earned a B.A.E. from the Pennsylvania State University and a MS and PhD from Northwestern University in 1999. He is currently an associate professor and assistant head for research in the school of Civil Engineering at Purdue University. He is also the associate director of the center for advanced cement based materials. He is a member of the American Concrete Institute (123-chair, 209, 231, 365, 446, 522), American Society of Civil Engineers, RILEM (CCD-chair), Transportation Research Board, and American Society for Testing and Materials (C.09) and is an associate editor of the ASCE journal of Civil Engineering Materials and RILEM journal Materials and Structures. He has twelve years of experience in concrete research and has been involved in the development of testing methods to assess cracking potential, worked in the development of crack resistant materials, developed software to predict the potential for restrained shrinkage cracking, worked in the development of performance related specifications, and recently completed two projects for the INDOT that relate permeability (transport) with concrete performance. Dr. Weiss has authored over 120 publications with over 35 peer-reviewed journal articles or book chapters and over 60 peer reviewed conference proceeding articles.

Jan Olek, Ph.D., P.E., is a Professor of construction materials in the School of Civil Engineering at Purdue University. He is a Registered Professional Engineer in the State of Indiana and has over 25 years of experience in research and teaching in areas of pavement materials and concrete technology with emphasis on durability, use of supplementary cementitious materials and performance of pavements and bridge structures. His work involved various aspects of materials and pavement characterization, including laboratory studies, filed inspection and bridge and pavement instrumentation. In the area of concrete durability, Prof. Olek has been involved in research dealing with corrosion of steel in concrete, scaling and freezing and thawing resistance of concrete, delayed ettringite formation (DEF) and alkali-silica reaction (ASR).

Mark Baker is the Laboratory Manager at the Purdue University Concrete Materials Lab. He has over five years of experience in laboratory testing of construction materials. He holds ACI Level I Field Testing and Laboratory Testing Certification.

Karthik Obla, Ph.D., P.E. is the Senior Director of Research and Materials Engineering at NRMCA. He has over 15 years of experience in concrete research and testing. He oversees NRMCA's concrete laboratory and research program. Dr. Obla is an active participant in several ACI, ASTM and TRB technical committees. Dr. Obla has authored or co-authored over 40 papers concerning concrete and concrete testing. He holds a Ph.D. from University of Michigan, Ann Arbor and is a licensed engineer in the state of Michigan.

Haejin Kim is the Laboratory Manager/Materials Engineer at the NRMCA Research Laboratory. He has over six years of experience in laboratory testing of concrete materials through working on research projects for the Federal Highway Administration, the Maryland State Highway Administration, and the Indiana Department of Transportation. He holds a Masters degree from the University of Maryland. He is currently a Ph.D. Candidate in the School of Civil Engineering at the University of Maryland.

Soliman Ben Barka is the Senior Laboratory Technician at the NRMCA Research Laboratory and has been at the laboratory for 18 years. He has been an integral part of NRMCA, industry and contract research and is competent in planning, scheduling and conducting concrete tests and documenting procedures and reporting test results. He holds ACI Field Testing and Laboratory Testing Certification. He is responsible for conducting the laboratory's reference sample testing program that is required to maintain its accreditation status.

Colin Lobo, Ph.D., P.E. is the Vice President of Engineering at the NRMCA. He holds a Ph.D. from Purdue University and is a licensed engineer in the state of Maryland. Dr. Lobo has been at the NRMCA for 12 years during which time he has been involved in planning, administering and reporting on research projects for the industry and individual companies on contract projects. Dr. Lobo is a member of ACI Committees 318 and 301 and on several key committees on ASTM. He has authored several technical publications and laboratory reports.

Gary Mullings is the Senior Director of Operations and Compliance at the NRMCA. He has authored several technical publications and laboratory reports.

7.0 Equipment and Laboratory Facilities

The following section describes the facilities available to the principal investigators that would be used in performing/completing this research.

Purdue University

Purdue University has several well-equipped laboratories for concrete materials testing (the Charles Pankow Cement and Concrete Laboratory, the Bowen Laboratory for Large Scale testing, and the Materials Sensing and Simulation Laboratory) and is actively involved in concrete/materials research on a daily basis. This Laboratory includes over 11,000 square feet of research space. It is fully equipped with the necessary standard equipment for preparing and testing of cement, concrete, and aggregates. Purdue actively conducts research for material suppliers, material producers, departments of transportation, construction companies, and national research agencies.

NRMCA

The National Ready Mix Concrete Association is the premier industry association representing the majority of the ready mixed concrete produced in the US through its membership. The NRMCA's research facility has a strong history in establishing research programs that have benefited the industry and has established the standards for the production and testing of ready mixed concrete and constructed concrete structures. The NRMCA Research Laboratory is very well equipped to conduct standard and special testing of concrete and concrete making material. The laboratory participates in the Cement and Concrete Reference Laboratory (CCRL) Reference Sample Testing Program and the Laboratory Inspection Program and holds a current accreditation under the AASHTO Accreditation Program. This accreditation ensures that the laboratory maintains requisite procedures and practices in accordance with ASTM C 1077 and has demonstrated proficiency through the above mentioned CCRL sample testing and inspection programs.

8.0 ITEMIZED BUDGET

Tables 8-1 provides an indication of the personnel costs, Table 8-2 illustrate the proposed break down of effort by tasks (hours). Table 8-3 provides an indication of the overall budget. It should be noted that as per the agreement between INDOT, the JTRP, and Purdue University no overhead will be charged to this project.

Table 8-1: Itemized Personnel Costs and Estimated Time Allotted

Name	Role in the Project	Project Cost	Time Allotted (Hours)	Cost Per Hour (Approximate)
Tommy Nantung*	Project Manager and Principal Investigator	~	416	~
Jason Weiss	Co-Principal Investigator Student/Post Doc Supervison	$ 98,890	1150	$ 86
Jan Olek	Researcher	$ 22,340	245	$ 91
Post-Doctoral Research Assistant/Visting Faculty	Researcher	$ 168,240	3824	$ 44
Graduate Students	Graduate Research Assistants	$ 177,848	6587	$ 27
Undergraduate Students	Laboratory Assistants	$ 8,679	789	$ 11
Mark Baker	Technician	$ 29,343	1012	$ 29

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

Table 8-2 Overall Project Budget

Category	Detailed Description	Project Cost
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		
	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
Total		
		$ 883,000

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

The costs will be $264,150 during the first year, $226,530 during the second year, $248,147 during the third year, and $144,173 during the final year.

Table 8-3: Subcontract Itemized Personnel Costs and Estimated Time Allotted

Name	Role in the Project	Total Proejct Value	Time Allotted (Hours)	Cost Per Hour (Approximate)	Cost to Subcontract	Cost Match RMC/PCA	Cost Match NRMCA
Karthik Obla	NRMCA Research Cooridinator	$ 120,000	1200	$ 100	$ 48,396	$ 22,871	$ 48,733
Haejin Kim	Laboratory Manager	$ 111,360	1920	$ 58	$ 44,912	$ 21,224	$ 45,225
Soliman Ben Barker	Technican	$ 82,560	1920	$ 43	$ 33,297	$ 15,735	$ 33,529
Gary Mullings	Researcher	$ 60,000	600	$ 100	$ 24,198	$ 11,435	$ 24,367
Colin Lobo	Researcher	$ 60,000	600	$ 100	$ 24,198	$ 11,435	$ 24,367
Subtotal	~	$ 433,920	5453	~	$ 175,000	$ 82,700	$ 176,220

Table 8:4: Subcontract Overall Budget

Category	Detailed Description	Project Cost	Match RMC/PCA	Match NRMCA*	Value to Project
Personnel					
	NRMCA Personnel	$ 175,000	$ 82,700	$ 176,220	$ 433,920
Laboratory Expenses					
	NRMCA Scientific Equipment	$ -	$ 100,000	~	$ 100,000
	NRMCA Laboratory Expendibles***	$ 35,000	$ 61,000	~	$ 96,000
Travel					
	NRMCA Domestic Travel	$ 5,000	$ 15,000	~	$ 20,000
Office Expenses					
	NRMCA Supplies and Expenses	$ 5,000	$ 10,000	~	$ 15,000
Subcontracts					
	NRMCA Consultants	$ -	$ 86,400	~	$ 86,400
Total					
		$ 220,000	$ 355,100	$ 176,220	$ 751,320

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

Statement of work for the subcontract (NRMCA)

Phase I - NRMCA will work with Purdue to develop a survey to send to State Agencies, Testing Agencies, Test Equipment Developers, and Ready-Mixed concrete suppliers. NRMCA will assume the lead in surveying their member companies and will provide a report of the results to Purdue. NRMCA will also assist in reviewing the literature and reviewing the literature summary developed by INDOT/Purdue.

Phase II – NRMCA will perform a series of prescribed permeability/transport tests on the materials used in Phase IV to enable transport/permeability to be related to durability.

Phase III – NRMCA will perform any of the new or modified permeability/transport tests on the materials used in Phase IV to enable transport/permeability to be related to durability.

Phase IV – NRMCA will be responsible for providing data that relates the permeability tests described in Phases II and III with durability performance. Specifically, NRMCA will be responsible for performing the corrosion resistance tests, the freeze-thaw resistance tests, the sulfate resistance tests,. NRMCA will provide recommendations on the correlation between their measurements of permeability/transport in Phase III and the durability performance of the materials in Phase IV.

Phase V – NRMCA will assist in developing and reviewing the guidelines developed by the research team at INDOT/PURDUE. Purdue will take the lead in describing testing protocols and procedures, testing and production variabilities, and correlation with models. NRMCA will describe correlations between their measurements of permeability /transport in Phase II, III and the durability performance of the materials that they observed in Phase IV.

Phase VI – NRMCA will assist in reviewing the materials developed at INDOT/PURDUE.

9.0 COOPERATIVE FEATURES

In addition to the team of researchers from Purdue University and the National Ready-Mixed Concrete Association, this research plan proposes the establishment of a SAC.

As a result this project proposes that this focus group will meet in person three times during the course of the project to critically discuss the findings.

The research team with the approval of the COTR, work with NCHRP and TRB to host a workshop during the annual meeting of the transportation research board to disseminate the findings of this study throughout the transportation community.

This project will also utilize results from a project being conducted at the NRMCA that is titled An Evaluation of Performance Based Alternatives to the Durability Provisions of the ACI 318 Building Code. This project will be used for cost sharing by NRMCA. This program will evaluate the materials listed in Table 9-1 with respect to corrosion, freeze-thaw, sulfate, and alkali silica resistance.

Table 9-1: Experimental Mixtures to be used in the aforementioned NRMCA project for corrosion resistance and freeze-thaw resistance

	0.62HP	0.49HP	0.39HP	0.62MP	0.49MP	0.39MP	0.62LP	0.49LP	0.39LP
Type I cement	475	550	650	333	385	455	332	385	455
Class F Fly ash	0	0	0	0	0	0	119	137	162
Slag	0	0	0	142	165	195	0	0	0
Silica Fume	0	0	0	0	0	0	24	28	33
Total CM	475	550	650	475	550	650	475	550	650
FA, %	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	25.1%	24.9%	24.9%
Slag	0.0%	0.0%	0.0%	29.9%	30.0%	30.0%	0.0%	0.0%	0.0%
SF, %	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	5.1%	5.1%	5.1%
SCM, %	0.0%	0.0%	0.0%	29.9%	30.0%	30.0%	30.1%	30.0%	30.0%
water (pls adjust)	295	270	255	295	270	255	295	270	255
w/cm	0.62	0.49	0.39	0.62	0.49	0.39	0.62	0.49	0.39
w/c	0.62	0.49	0.39	0.89	0.70	0.56	0.89	0.70	0.56
paste, %	26.46%	26.39%	27.38%	26.69%	26.66%	27.70%	27.36%	27.42%	28.61%
Type A WR	adjust	adjust	4 oz	adjust	adjust	4 oz	adjust	adjust	4 oz
Type F HRWR	0	0	adjust	0	0	adjust	0	0	adjust

2 specimens/test/age for all tests
Crushed coarse aggregate (1.0" max) no. 57, natural sand FM=2.88
Adjust WR or HRWR (if any) for desired slump = 5-7"
Non air entrained concrete mixes
Measure Slump, temperature, air content, density, Strength (28 days), Shrinkage (90 days)
Measure RCPT, RMT, Sorptivity, Gas permeability, Diffusion, Modified diffusion
All specimens will first undergo 7 days moist room curing. Then some of them would be transferred to 70F
This is normal curing. This curing will continue until the test starts or specimen conditioning starts.Some of
Index test specimens will be subjected to to an "Accelerated" curing environment which is 7 days moist room
by 21 days in 100°F water. This is called the 28 day acc. curing environment.
RCPT, RMT test age = 28 d acc., 56 d, 26 weeks, 78 wks - 78 wks only for four mixes
Sorptivity, and Gas Permeability - ages at which specimen conditioning starts will be 28 day acc., 56 d, and
18-day specimen conditioning is started (ASTM C 1585) and test conducted at the end of that period
Diffusion curing = Normal curing till 56 days; Expose to chloride solution till 26 wks and then test
For 4 of the mixtures start chloride solution exposure at 60 wks and then test at 78 wks
Modified Diffusion curing = Normal curing till 56 days; then 2 wks in chloride solution (same concentration a
room till 26 wks at which they will be tested

Table 9-2: Experimental Mixtures to be used in the aforementioned NRMCA project for Sulfate Resistance

Exposure- 5% sodium sulfate solution same as C 1012 - do each specimen submerged vs Half submerged
Mix 0: Type I high C3A cement, Mortar=Do C 1012; Concrete = use w/cm = 0.62
Mix 1 - Class 1 exposure: Type II cement, Mortar=Do C 1012; Concrete, w/cm = 0.50
Mix 1 equivalent - Type I high C3A cement, 30% Slag, Mortar=Do C 1012, modified C 1012; Concrete, w/cm =0.39, 0.49, 0.62
Mix 2 - Class 2 exposure: Type V cement, Mortar=Do C 1012; Concrete, w/cm = 0.45
Mix 2 equivalent - Type I cement, 30% Slag, Mortar=Do C 1012, modified C 1012; Concrete, w/cm =0.39, 0.49, 0.62
Mix 3 - Class 3 exposure: Type V cement, Mortar=Do C 1012; Concrete, w/cm = 0.40
Mix 3 equivalent - Type II C, 25% Class F ash, 5% Fume, Mortar=Do C 1012, Mod. C 1012; Conc., w/cm =0.39, 0.49, 0.62

Non air entrained concrete mixes
Measure Slump, temperature, air content, density, Strength (28 days), Shrinkage (90 days)
Measure RCPT, RMT, Sorptivity, Gas permeability
All specimens will first undergo 7 days moist room curing. Then some of them would be transferred to 70F room in lab
This is normal curing. This curing will continue until the test starts or specimen conditioning starts.Some of the Rapid
Index test specimens will be subjected to to an "Accelerated" curing environment which is 7 days moist room followed
by 21 days in 100°F water. This is called the 28 day acc. curing environment.
RCPT, RMT test age = 28 d acc., 56 d, 26 weeks, 78 wks - 78 wks only for four mixes
Sorptivity, and Gas Permeability - ages at which specimen conditioning starts will be 28 day acc., 56 d, and 26 wks
18-day specimen conditioning is started (ASTM C 1585) and test conducted at the end of that period
Concrete sulfate resistance test = Normal curing till 56 days; Expose to sulfate solution and then test every 2 months
Testing may have to be carried out till 260 wks, but final report for this project wil be made at 78 wks
ASTM C 1012 according to test method
Modified ASTM C 1012 exactly as per test method but with varying w/cm as required. To achive target flows High
range water reducers or viscosity enhancing agents will be used.

11. REFERENCES

[1] Hoerner, T. E., and Darter, M. I., "Improved prediction models for PCC pavement performance-related specifications, Volume II: PaveSpec 3.0 User's Guide", FHWA RD-00-131, Federal Highway Administration, Washington, D. C., September, 2000

[2] Weed, R. M., "Statistical Specification Development", FHWA/NJ-88-017, Trenton: New Jersey Department of Transportation, 1989.

[3] Graveen, C., "Nondestructive Test Methods to Assess Pavement Quality for Use in a Performance-Related Specification," MSCE Thesis, Purdue University, West Lafayette, Indiana , May 2000

[4] Falker, E., "Assessing the Impact of Performance-Related Specifications on Concrete Pavement Construction," MSCE Thesis, Purdue University, West Lafayette, Indiana , May 2003, pp. 177

[5] Bickley, J.A., Hooton, D., and Hover, K.C., "Preparation of a Performance Based Specification for Cast-in-Place Concrete," RMC Research Foundation Report, January 2006

[6] Obla, K, Lobo, C., and Lemay, L., "Specifying Concrete for Durability: Performance Based Criteria offer the Best Solution," NRMCA's Concrete IN-Focus Magazine, December 2005

[7] Brite-Euram III "Compliance Tests State of the Art," (1997)

[8] Report of RILEM TECHNICAL COMMITTEE 189-NEC: Non-destructive evaluation of the 'covercrete' (concrete cover)

[9] Darter, M.I., Abdelrahman, M., Okamoto, P.A. and Smith, K.D., "Performance-Related Specifications for Concrete Pavements: Volume I-Development of a Prototype Performance-Related Specification", FHWA RD-93-042, Washington, D.C., Federal Highway Administration, 1993.

[10] Darter, M.I., Abdelrahman, Hoerner, T., Phillips, M., Smith, K.D., and M., Okamoto, P.A., "Performance-Related Specifications for Concrete Pavements: Volume IIAppendix A, B, and C", FHWA-RD-93-043, Washington, D.C., Federal Highway Administration, 1993.

[11] ACI Manual of Concrete Practice, ACI International, Farmington Hills, MI, 2002

[12] Schmit, T., and Weiss, W. J., (accepted) "Using Monte Carlo Analysis to Quantify how the Number and Arrangement of Sensors Influence the Accuracy of an Insitu Sensing System", Pheonix Transport and Durability Meeting, Accepted to the American Ceramic Society

[13] Qi, C., Weiss, W. J., and Olek, J., (2005) "The Statistical Significance of the Restrained Slag Test to Quantify Plastic Shrinkage Cracking in Fiber Reinforced Concrete," Journal of ASTM International, July 2005, Vol.2, Issue 7

[14] T. Pellinen, J. Weiss, T. Kuczek, and G. Dauksas "Comparison of Various INDOT Testing Methods and Procedures to Quantify Variables in Measured Bituminous and Concrete Properties", SPR 2645, October 2005

[15] M.Cohen, V. Barde, T. Nantung, and J. Weiss, JTRP and INDOT/Modifying the Selection Process of Concrete Mixture Proportions for INDOT

[16] Thomas, M. D. A., and Bentz, E. C., "LIFE-365TM Service Life Prediction Model, Users Manual," Silica Fume Association, 2001.

[17] Fagerlund, G., 1977, The International Cooperative Test of the Critical Degree of Saturation Method of Assessing the Freeze/Thaw Resistance of Concrete, Materials and Structures, Vol. 10, No. 58, pp.231-253.

[18] Bentz, D.P., M. A. Ehlen, C. F. Ferrais, and E. J. Garboczi, 2001, Sorptivity-Based Service Life Predictions for Concrete Pavements, 7th International Conference on Concrete Pavements – Orlando, Florida, USA, Sept. 9-13