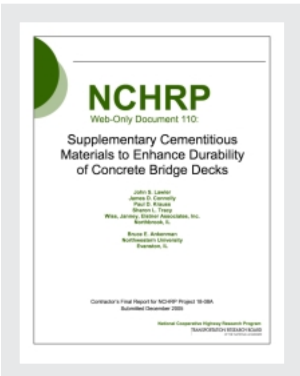
NCHRP
Web-Only Document 110:
Supplementary Cementitious Materials to Enhance Durability of Concrete Bridge Decks

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DETAILS

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ABSTRACT

Performance objectives for achieving durable bridge deck concrete and the properties of locally available concrete raw materials, particularly supplementary cementitious materials (SCMs) like fly ash, GGBFS and silica fume, vary by geographic region. Because of this variation, the optimum concrete mixture proportions for a given application must be determined by experiment. Since durability-related experimental programs investigating the performance of concrete mixtures are expensive and time-consuming, a methodology for designing and conducting an investigation using statistical experimental design concepts has been developed to efficiently identify the optimum concrete mixture proportions for a specific set of conditions. The approach implemented is based on fractional orthogonal experimental design, which supports modeling for a large number of factors (input variables) based on a minimum number of tests. The Methodology, presented in *NCHRP Report 566: Guidelines for Concrete Mixtures Containing Supplementary Cementitious Materials to Enhance Durability of Bridge Decks*, consists of six steps: (1) definition of performance requirements, (2) selection of durable raw materials, (3) construction of an experimental design matrix, (4) testing of concrete mixtures, (5) analysis and empirical modeling to determine the Best Tested and Best Predicted Concretes, and (6) confirmation of predictions and selection of the Best Concrete. This Methodology is flexible and may be applied to a range of performance demands. It was developed to identify optimum contents of SCMs but is also able to select between sources of raw materials. A case study was conducted based on a hypothetical set of service conditions and using concrete raw materials from the Midwest. The performance predictions based on the case study experimental design were verified by confirmation testing. Finally, a computational tool (SEDOC) was developed to support the implementation of this Methodology.

SUMMARY OF FINDINGS

Supplementary cementitious materials (SCMs), like fly ash, GGBFS and silica fume, are included in bridge deck concrete mixtures because they can substantially improve durability performance; however, performance requirements and the properties of SCMs vary from location to location. In addition, the use of SCMs increases the potential for raw material interaction. Because of this variation and because the impact of these materials on performance are beyond our current ability to model mechanistically, the optimum concrete mixture proportions for a given application can be determined only by experiment.

A methodology for designing and conducting an investigation using statistical experimental design concepts has been developed to identify the optimum concrete mixture proportions for a specific set of conditions. The statistical experimental design approach selected for this Methodology is a main-effects method using fractional orthogonal designs that support modeling for a large number of input variables (factors) based a minimum number of tests. Another important feature of this Methodology is the desirability concept, which provides an equivalent framework with which to simultaneously evaluate multiple performance measures. A desirability function is developed for each response (test result) by the user that allows that response to be weighted appropriately in the combined, overall desirability (the single numerical rating that quantifies the performance of a mixture relative to all others).

NCHRP Report 566: Guidelines for Concrete Mixtures Containing Supplementary Cementitious Materials to Enhance Durability of Bridge Deck, available on the TRB website (http://www.trb.org/news/blurb_detail.asp?id=7714), describes and supports the Methodology in detail. The Methodology consists of six steps: (1) definition of performance requirements based on the deterioration mechanisms anticipated for the specific application and selection of tests to evaluate that performance, (2) selection of the locally available raw materials deemed most likely to produce durable concrete, (3) selection of an orthogonal experimental design matrix that investigates the candidate materials of interest, (4) testing of the selected concrete mixtures that represent the range of anticipated performance, (5) analysis of test results and modeling to select the Best Tested Concrete (the tested concrete that produced the best overall performance) and Best Predicted Concrete (the combination of levels for the factors that are expected to produce the best overall performance based on empirically modeled performance in each test), and (6) confirmation of predictions and selection of the Best Concrete.

This Methodology is characterized by great flexibility. It may be applied to a range of performance demands and used not only to identify optimum contents of SCMs, but also to select between sources of similar materials. The input of the user is essential for designing the experimental program and for evaluating the results. Therefore, the outcome of the testing program, i.e., the optimized mixture, will be specifically tailored to the project considered. Users may find the jargon, the large number of worksheets, and computational tool overwhelming at first. However, significant effort has been made to ensure that the Methodology can be easily implemented by users with a wide range of expertise in concrete mixture design and technology.

To test and develop the Methodology, a hypothetical case study was conducted based on the service conditions of a northern bridge deck using real raw materials. The predictions made based on this case study were verified by confirmation testing and agreed well with observed test results. Finally, a computation tool, called Statistical Experimental Design for Optimizing Concrete Mixtures (SEDOC) consisting of two Microsoft® Excel Worksheets, was developed to support the implementation of this Methodology for a limited number of orthogonal experimental designs.

INTRODUCTION AND RESEARCH APPROACH

Problem Statement

Premature deterioration of our nation's concrete bridges has been a persistent and frustrating problem to those responsible for maintaining those bridges as well as to the traveling public. The deterioration typically consists of concrete delamination and spalling due to various mechanisms, including corrosion of embedded steel reinforcement, repeated freezing and thawing, deicing salt-induced scaling, or reactive aggregates. The rate of these mechanisms is primarily dependent on the resistance of the concrete to the ingress of moisture and aggressive substances and on cracking of the concrete.

Since nearly all concrete deterioration processes are driven in some manner by the ingress of water and water-borne agents, such as chloride and sulfate ions, one way to minimize these problems is to make the concrete less permeable. Concrete is primarily made less permeable by densifying the cementitious paste. This is achieved by lowering the water-cementitious materials ratio (w/cm) and by adding supplementary cementitious materials (SCMs), such as silica fume, fly ash, ground granulated blast furnace slag, or metakaolin. However, regardless of how impermeable the concrete cover is, if the concrete cracks, aggressive agents may reach the interior of the concrete and the reinforcing steel and promote deterioration.

Excessive cracking can result from freezing and thawing action, alkali/silica reactions (ASR), corrosion of reinforcement, plastic shrinkage, restrained drying shrinkage, or thermal stress. Early-age cracking became relatively common within the past 30 years as practitioners strived to use less permeable concrete made with extremely low w/cm and high dosages of some SCMs, such as silica fume. These mixtures often produced very high-strength concrete that was prone to thermal, drying, and plastic shrinkage cracking. As these problems have surfaced, researchers and practitioners have developed materials, mixtures, and construction practices to combat these problems and prolong the life of concrete in bridges. It is now better understood that to make durable concrete, high strengths are not necessarily required. High strengths may in fact be detrimental due to the concomitant high modulus of elasticity and low creep, which can result in the development of restraint-induced stresses sufficient to produce cracks. Instead, the mixture performance can be balanced to minimize permeability and shrinkage/thermal cracking while enabling ease of placement, consolidation, and finishing.

The use of SCMs, such as fly ash, silica fume, slag, and natural pozzolans, in concrete bridge decks has become a widely accepted practice by many state highway agencies seeking to maximize durability. This practice is justified by a great deal of research that has been performed on properties of concrete containing one or more supplementary cementitious materials. However, this prior research, necessarily conducted on individual SCM sources, has not provided clear nor universally applicable conclusions concerning the optimum use of these materials. A "one size fits all" approach to concrete mixtures does not achieve the goal of maximizing long-term durability. This is because the quality of local materials used to produce the concrete strongly influences mixture properties and performance. There are large variabilities within, and interactions between, concrete raw materials, and these influence the short-term properties and long-term durability of the concrete. In addition, service environments and the associated deterioration mechanisms vary with geographical location. As a result, concrete mixtures cannot be truly optimized without direct testing of local materials and evaluating the concrete produced with those materials relative to local performance demands. Therefore, research was performed under the National Cooperative Highway Research Program (NCHRP) Project 18-08A to develop a statistically based experimental methodology to efficiently determine the optimum mixture proportions of concretes based on locally available materials and performance requirements.

Scope of Work

The objective of the research was to develop a methodology for designing hydraulic cement concrete mixtures incorporating supplementary cementitious materials that will result in enhanced durability of concrete bridge decks and this objective has been met. The process outlined is based on an experimental program aimed at evaluating the performance relative to an anticipated service environment, using the best materials available and structured around a test matrix that lends itself to statistical analysis. The individual results of the test program are combined based on the desirability-function concept, which provides a consistent framework within which to evaluate various types of performance, and are modeled to predict the optimum combination of materials. Finally, to confirm the model predictions, confirmatory testing is required so that the best concrete for the particular situation and materials can be chosen with confidence.

This Methodology is presented in *NCHRP Report 566*, which outlines the following six step process:

Step 1: Define Concrete Performance Requirements (and appropriate tests for measuring this performance)
Step 2: Select Durable Raw Materials
Step 3: Generate the Experimental Design Matrix
Step 4: Perform Tests
Step 5: Analyze Test Results and Predict the Optimum Mixture Proportions
Step 6: Perform Confirmation Testing and Select Best Concrete

While the testing program (Step 4) is the largest and most time-consuming part of the process, before the testing can be initiated, several other important steps must be completed. The criteria against which the concrete performance will be evaluated must be determined (Step 1), and the range of locally available candidate materials most likely to achieve the performance objectives must be identified (Step 2). A decision-making system for defining appropriate test methods required for the service environment, selecting durable raw materials, and selecting proper ranges and combinations of SCMs was developed to support these processes. This system is based on flowcharts and background guidance summarizing the available literature.

This guidance provides the user with a frame of reference to make intelligent decisions, and it provides sufficient information to allow the Methodology to be adapted to the user's specific application. In the background covering the definition of the service environment and performance requirements, the following topics are covered: cyclic freezing and thawing resistance, salt scaling resistance, chloride penetration resistance, resistance to abrasion, cracking resistance, workability, finishability, and the effects of SCMs on each of these properties. The concrete property requirements most likely to produce durable long-term performance, test methods for evaluating those properties, and target values for those test results are also discussed. Background information on selecting likely candidate raw materials includes topics such as: aggregates (including ASR testing), cement, Class C fly ash, Class F fly ash, ground granulated blast furnace slag (GGBFS), silica fume, metakaolin, and chemical admixtures. Recommendations were also developed for appropriate additional raw materials testing, where needed, as well as target values for these tests.

A range of statistically based experimental approaches was evaluated. The fractional orthogonal design method was chosen for implementation in this Methodology, since this approach provides a means for obtaining useful information over a large test space while testing the minimum number of possible combinations of variables. Guidance has been provided for selecting a feasible number of mixtures to be tested that is consistent with this orthogonal approach. The number of variables (or factors) and levels that can be investigated is governed by the number of mixtures that can be tested within available resources, and a discussion of the significant aspects of this selection is provided.

According to the Methodology, at the completion of Step 4, statistical analysis of the data is performed to identify concrete mixture that performed best relative to the performance requirements and to predict the optimum concrete mixture that will produce the best overall performance relative to those same requirements. (These mixtures are known as the Best Tested Concrete (BTC) and Best Predicted Concrete (BPC), respectively). The method for performing this analysis is presented in detail. The final Step in the Methodology involves confirmatory testing of the BTC and testing the BPC to verify improved mixture performance, as predicted. This is necessary due to the high variability inherent with concrete materials testing, and it provides an assessment of the repeatability of the procedures. From the analysis of the full testing program, the optimum mixture is recommended.

To provide a basis for evaluating the effectiveness of this Methodology and to serve as a tool during its development, a case study was investigated. A hypothetical northern, Midwest environment subject to freezing and thawing and deicing salt exposure, was chosen. Performance requirements were developed, and locally available materials were obtained and used in an experimental program in which eleven concrete mixtures were produced and tested. The results of this test program were analyzed using the process outlined in the Methodology, and the effectiveness of the modeling was evaluated.

Finally, to aid potential users in the implementation of this Methodology, a computation tool called Statistical Experimental Design for Optimization of Concrete (SEDOC) based in Microsoft® Excel was developed. This tool leads the user through each of the Steps in the Methodology and performs the statistical analysis and modeling.

Outline of Project Deliverables

NCHRP Project 18-08A, “Supplementary Cementitious Materials to Enhance Durability of Concrete Bridge Decks,” generated the following products:

- *NCHRP Report 566: Guidelines for Concrete Mixtures Containing Supplementary Cementitious Materials to Enhance Durability of Bridge Decks*
- *NCHRP Web-Only Document 110*, the project report and hypothetical case study appendix
- Microsoft® Excel-based computational tool titled Statistical Experimental Design for Optimization of Concrete (SEDOC) and user’s guide

This document, *NCHRP Web-Only Document 110*, provides a condensed description of the Methodology and the process by which it was developed. It discusses the scope and capabilities of the Methodology and how and where it may be best applied.

To distinguish table and figure numbers in *NCHRP Report 566* from those in this document, *NCHRP Report 566* table and figure numbers are prefaced by an "I" for Introduction or by an "S" followed by the Step number. For example, Table S1.1 indicates Step 1, Table 1 (the first table in Step 1), of *NCHRP Report 566*. Figures and tables discussed in this document are numbered sequentially.

FINDINGS

Statistical Design of Experiments

An experiment that is "designed" is one that is conducted based on a test program laid out to produce results that answer a question or verify a hypothesis. Statistical design of experiments involves selecting the experimental parameters so that the experiment will produce data that supports analysis and modeling with statistical tools. The great advantage of statistical experimental design is that experiments conducted in this way are more efficient, i.e., they allow predictions regarding large numbers of possible variations based on a limited number of tests.

Terminology

Before discussing the details of how statistical experimental design can be applied to the design of concrete mixtures, a review of the relevant terminology is needed. Table 1 summarizes the terminology. The three most common terms are "factor," "level" and "response".

The term "factor" refers to the independent variable, or "x"-variable, to be examined in the experiment. There are multiple kinds of factors. "Type factors" and "Source factors" are factors that describe the type or source of material that is used and are defined discreetly to be either one type of material or another or a material from one source (or supplier) or another, respectively. "Amount factors" vary the amount of a raw material in the mixture and can be defined continuously over the range to be tested. It is also possible to combine two factors in a "Compound factor," to be discussed later.

The term "level" refers to the chosen value of the factor in a particular mixture. For example, if an Amount factor for a given experiment was selected to be w/cm, three levels to test could be chosen as 0.38, 0.40, and 0.44. For a Source factor, the levels are the actual sources used such as Plant A and Plant B. A Type factor is used when it is desired to change the type of cement, SCM, or other raw material. For example, a Type factor might be Type of Fly Ash, and the levels of the Type factor could be Class F and Class C. One could then also have an Amount factor for fly ash (at levels of perhaps 15% and 30%) that would then apply to whichever type of fly ash was used in the mixture.

Another term used is "response." This is the y-variable, or test result, when a mixture is tested for a certain property using a specific test method, such as strength or apparent diffusion coefficient. "Response" means test result.

The "experimental matrix" is the matrix of combinations of factors and levels that is generated by the user with the aid of tables or computational tool. It includes the number of "mixtures" to be evaluated and details how the levels of each of the factors should be set for each mixture.

One of the most important concepts for the analysis process in the Methodology is the "desirability function". The desirability function refers to a plot or equation that rates a given response (test result) on a scale from 0 to 1, where 0 is an unacceptable result, and 1 is a result that cannot or does not need to be improved. The desirability function for a response maps every possible outcome of the test to a desirability value. Through the desirability function, which can vary depending on the application, the relative importance (rating) of each test result (response) is defined.

Table 1. Terminology related to statistical design of experiments

Term	Definition	Example
Factor	X-variable or independent variable	(see below)
Type factor	A factor that varies the type of material used in a mixture	"Type of fly ash"
Source factor	A factor that varies the source or supplier of raw material	"Cement producer"
Amount factor	A factor that varies the amount of a material	"Amount of GGBFS"
Compound factor	Multiple factors where the levels of one factor depend on the level of another factor. (The two factors work together to define the type and amounts of material used in a mixture.)	Factor 1 is a type factor for defining the type of SCM, and its levels are fly ash or slag. Factor 2 is an amount factor whose levels are low and high. The amounts specified for low and high for each type of SCM are different. For example, low and high for fly ash might be 15 % and 40%, but low and high for slag might be 25% and 50%. Thus the levels of the second factor change (from 15% and 40% to 25% and 50%) depending on the level of the first factor (either fly ash or slag).
Factor level	A level associated with a specific factor.	Silica fume content = 5%
Levels	The values of the factor to be tested	Class C or Class F for type of fly ash; Plant A or Plant B for source of cement; 15% or 25% for amount of GGBFS
Response	A measured test result	Strength at 7 days = 5000 psi
Experimental matrix	A list of mixtures to be tested linking specific factors and levels that have been chosen to facilitate the statistical analysis.	See tables in "Selected Orthogonal Designs" at end of Step 3 in *NCHRP Report 566*.
Desirability function	A function that rates the test result from very good, i.e. non-improvable (desirability=1) to unacceptable (desirability=0)	See Figures S1.2 to S1.23 in *NCHRP Report 566*.
Overall desirability	Combined desirability for a single mixture based on all the individual desirabilities. This is calculated as the geometric mean of the individual desirability functions for each response	Overall desirability = 0.984 for Mixture #1

The overall performance or "overall desirability" of a mixture is the combined desirability of each test response and allows a direct comparison of the overall properties of one mixture with another. This comparison is used to decide which mixture is best overall. This is possible because the overall desirability is derived from the individual desirabilities for each response and so reflects the individual properties of the mixture and importance of each of these properties to the overall concrete performance. The concepts of desirability and overall desirability are discussed further in the section titled "Combining Test Results" below.

Methods of Designing Experiments

Through the use of statistical design of experiments, it is possible to obtain useful information without testing every combination of variables at every level. There are several types of designed experiments, including one-factor-at-a-time, orthogonal main-effects designs, mixture approaches, and central composite designs. Each has its advantages and disadvantages.

In this Methodology, a straightforward design method called fractional orthogonal design is used. The biggest advantage of this approach is that it requires a relatively small number of mixtures be tested to cover a large test space. For example, for an experiment of four three-level factors (four materials at three dosages each), careful selection of the combinations of factor levels to be tested would permit conclusions to be made regarding the full test space (all possible combinations within the factor ranges) from tests of only 9 mixtures instead of all 81 ($=3^4$) possible discrete combinations of the factor-levels. This method also permits modeling with non-quantitative factors (such as source of material), which are often important variables to consider in concrete mixture proportioning. Also, there are no limitations on the number of responses or on the form of the desirability functions.

Using the results from only the selected combinations tested, the fractional orthogonal design method is able to provide a prediction of the best level for each of the factors in the experiment. However, the fractional orthogonal approach is a main-effects method. This means that interactions between factors are not modeled as well as by other experiment designs that require a larger number of mixtures. In other words, if the optimum level for any factor substantially changes for different levels of other factors, the optimum level of that factor may be poorly predicted. However, this will not affect the evaluation of the concretes that are actually batched and tested. Since the mixtures in a fractional orthogonal design are quite different from each other, there is an increased chance of finding a good mixture even in the cases where the optimum level for some factors is difficult to predict. A confirmation testing strategy, where the model predictions are tested directly, addresses this issue. The alternative is to test substantially more concrete as in the mixture or central composite design approaches (at least 24 of the 81 possible combinations discussed in the example above would need to be tested for these methods).

Combining Test Results

If only one test were to be performed, the concrete performance can be easily compared based only on the measured value of that test for each mixture. However, since many different tests will be performed, and the selected mixture must perform well in all of these tests, a method of combining the responses (test results) from the different tests is needed. This is done by defining a desirability function for each response (*1*). As previously stated, this function is a rating for all potential values of the test response on a scale from 0 to 1, where 0 means an unacceptable response, and 1 means no more improvement is needed. Each test response has its own desirability function. The advantage of the desirability function is that all test responses are considered using an equivalent scale and can be combined to produce one score or measure of the quality of a given mixture called the "overall desirability function." When maximized, the overall desirability identifies the best possible combination of performance in all the tests.

To build the desirability function for a specific test result, an optimum target for the measured response of each test is specified. At the target, the individual desirability for that test is 1. Then an allowable range for the measured response is specified. Outside of this range, the individual desirability is 0 or totally unacceptable. The shape of the desirability function between the target and the range is also specified to reflect the importance of being near the target. If the measured response of a particular test is to be maximized (or minimized), then the upper (lower) range of the desirability is considered to be perfect and thus any measured value above (below) this level has a desirability of 1. Figure I.1 demonstrates the shape of three possible desirability functions.

Mathematically, the overall desirability is defined for this Methodology to be the geometric mean of the desirability functions for each of the tests. For example, suppose that the desirability functions for three different tests are represented by d_1, d_2, and d_3. The overall desirability, D, is $D = \sqrt[3]{d_1 \times d_2 \times d_3}$. In general for n desirabilities, the overall desirability is the nth root of the product of the desirability functions. Since the desirabilities range between 0 and 1, the overall desirability function also ranges between 0 and 1, where 0 is unacceptable and 1 is desirable.

Another method of calculating the overall desirability is to use an arithmetic mean of the individual desirabilities. When using the geometric mean to calculate overall desirability, the effect of low individual desirabilities is accentuated compared with arithmetic mean-based approaches. However, the big advantage of the geometric mean is that if a single individual desirability is 0, then the overall desirability is 0. As a result, the individual desirability functions can be defined so that a desirability of 0 is assigned to those test outcomes that make the mixture unacceptable regardless of how it performs in other tests.

It should be noted that since the desirability function provides the link between the test, which may be influenced by the method and testing conditions, and the predicted actual behavior, the desirability function requires subjective interpretation by the engineer or scientist conducting the study. However, it is through the desirability function that the interpretation of the experimental program is customized to the local performance requirements.

Overview of Methodology

The Methodology for designing concrete mixtures containing supplementary cementitious materials (SCMs), presented in *NCHRP Report 566*, is aimed at aiding the user select the optimum combination of locally available materials for maximum durability. This Methodology relies on established practices of statistical design and analysis of experiments. It is targeted for use in the development phase of concrete construction projects. This Methodology will help highway agency personnel and other engineers optimize and specify the material proportions and performance criteria for a specific project or set of conditions. The Methodology that was developed primarily considers the use of fly ash, silica fume, slag, and natural pozzolans both singularly and in combination. However, any combination of materials and performance criteria can be analyzed.

A basic understanding of concrete mixture proportioning and concrete technology is assumed of the user; however, background specifically related to durability issues and guidance for avoiding harmful material interactions is provided that may be referred to as needed. It is expected that all users, even experienced concrete practitioners, will find the Methodology valuable since the defined procedure provides an efficient method for optimizing concrete mixtures relative to locally applicable performance criteria with locally available materials. This is an objective that cannot be achieved through any means other than a large experimental investigation.

The Methodology consists of the following steps:

- **Step 1: Define Concrete Performance Requirements** - The service environment of the concrete is evaluated, and likely deterioration mechanisms are identified. The concrete properties required to resist deterioration are determined, and test methods to evaluate these properties are selected for inclusion in the testing program. A desirability function is defined for each response (measured property). Finally, SCM types and content ranges likely to produce desirable concrete performance for each property to be tested are identified.
- **Step 2: Select Durable Raw Materials** - The locally available raw materials under consideration for the project are evaluated. The various potential sources of each type of material are compared based on the information available in mill reports and elsewhere, and the specific materials types and sources most likely to produce durable concrete are selected as candidates for making the concrete mixtures. The potential for aggregate sources to participate in deleterious alkali-silica reactions is considered. A testing process, to be used where insufficient information is available, and mitigation strategies for ASR are recommended.
- **Step 3: Generate the Experimental Design Matrix** - Based on the scope of the testing program and the available resources, an orthogonal experimental design is selected. The size and shape of the design, i.e., the number and levels of factors to be tested, are controlled by the number of mixtures that can be tested within the allowable time and budget. The specific factors (such as material type, source, or content) and the corresponding levels (the specific types, sources or dosages) for testing are chosen from the candidate materials to fit within a predefined design matrix.
- **Step 4: Perform Testing** - The concrete mixtures listed in the experimental design matrix are produced and tested according to the program defined in Step 1.
- **Step 5: Analyze Test Results and Predict the Optimum Mixture Proportions** - The individual responses are converted to desirabilities for each mixture, and the Best Tested Concrete (BTC) is chosen as the mixture produced in the test program with the highest overall desirability. Empirical models relating response to factor levels are developed for each response, and an optimization routine is used to determine the combination of factors and levels that produce the highest predicted overall desirability. This combination is called the Best Predicted Concrete (BPC).
- **Step 6: Perform Confirmation Testing and Select the Best Concrete** - The BPC and BTC are batched and tested to confirm their performance. The test results are evaluated in terms of desirabilities, and the repeatability of the testing and accuracy of the modeling is assessed. Finally, the optimum performer, or Best Concrete (BC), is selected from these two candidates.

Implementation of Methodology

NCHRP Report 566 provides tools to aid in the application of each of the steps of the Methodology. These include flowcharts, worksheets for summarizing information, background discussions of the issues relevant to decisions that need to be made, tables of experimental matrices, and an explanation of the statistical analyses.

The decisions to be made in Step 1 and 2 have been laid out in two flowcharts. The product of the first flowchart (Figure S1.1: Selecting concrete service environment and properties) is a list of laboratory tests to be conducted (the responses) and the associated performance requirements for the concrete. These requirements are quantified in the form of desirability functions, and a discussion of how these functions work and how they are defined is provided. Guidance is given to support the flowchart regarding suitable ranges of various SCMs that have been shown in the literature to improve the responses. The information gathered from Figure S1.1 is collected by the user on a worksheet. This worksheet and others given in *NCHRP Report 566* are intended to provide a location for the user to record information relevant to the specific experiment being designed. The second flowchart (Figure S2.1: Selecting durable raw materials) outlines a process for evaluating the candidate raw materials and sources. Test data regarding these raw materials are collected, and combinations of materials that are likely to be durable are identified. The sources or types of raw materials will be the levels of “source or type factors” in the experimental design matrix. The quantities to which these raw materials will be varied are the levels of the “amount factors” in the experimental design matrix. The information gathered from Figure S2.1 is also collected in worksheets.

These worksheets are combined into the set of factors and levels in Step 3, where the experimental design to be used is selected from a table (Table 2) of orthogonal experimental designs defined by the number of mixtures to be tested and the number of two- and three-level factors to be investigated. This table shows that only certain sizes of experiments, namely those that permit a symmetric distribution of the number of test mixtures containing each level for each factor, are eligible for use. Figure I.2 shows schematically the relationship between the flowcharts and how they support the experimental design. This figure is intended to illustrate that, during this selection process, there will likely be compromises between the materials selected based on the performance objectives, the cost and scope of testing program, the selection of the experimental design matrix, and the number of materials that can be tested.

For each experiment, a numeric analysis (Step 5) will be performed. The analysis consists of two parts:

- The first part of the analysis is to compare the concrete mixtures that were tested to determine which one best matched the performance requirements. This is called the "Best Tested Concrete" (BTC). The identification of the BTC will involve tradeoffs between the different performance measures and uses the overall desirability function as a basis for comparison.
- The next part of the analysis is empirical modeling to determine the combination of the levels of the factors that will produce the "Best Predicted Concrete" (BPC), identified by the highest overall predicted desirability. This is estimated based on individual predictions for each of the responses (performance measures) for all possible combinations of the factors in the range tested. The empirical models can also be used to predict the response for any mixture (combination of factors) in each of the individual tests.

Table 2. Table S3.1 Number of mixtures required for an orthogonal design for various combinations of two- and three-level factors. The 9-mixture design selected for hypothetical case study is highlighted.

	# of 3-level factors							
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
# of 2-level factors **0**		**3**	**9**	**9**	**9**	**16**	**18**	**18**
1	**2**	**8**	**9**	**9**	**16**	**18**	**18**	**18**
2	**4**	**8**	**9**	**16**	**16**	**18**	**18**	**>18**
3	**4**	**8**	**16**	**16**	**16**	**18**	**>18**	**>18**
4	**8**	**8**	**16**	**16**	**18**	**>18**	**>18**	**>18**
5	**8**	**16**	**16**	**16**	**>18**	**>18**	**>18**	**>18**
6	**8**	**16**	**16**	**16**	**>18**	**>18**	**>18**	**>18**
7	**8**	**16**	**16**	**>18**	**>18**	**>18**	**>18**	**>18**
8	**12**	**16**	**16**	**>18**	**>18**	**>18**	**>18**	**>18**
9	**12**	**16**	**16**	**>18**	**>18**	**>18**	**>18**	**>18**
10	**12**	**16**	**>18**	**>18**	**>18**	**>18**	**>18**	**>18**
11	**12**	**16**	**>18**	**>18**	**>18**	**>18**	**>18**	**>18**
12	**16**	**16**	**>18**	**>18**	**>18**	**>18**	**>18**	**>18**
13	**16**	**>18**	**>18**	**>18**	**>18**	**>18**	**>18**	**>18**
14	**16**	**>18**	**>18**	**>18**	**>18**	**>18**	**>18**	**>18**
15	**16**	**>18**	**>18**	**>18**	**>18**	**>18**	**>18**	**>18**

Since the amount of data available to support the empirical modeling is limited with this experimental design approach and interactions are not estimated, the results of the modeling need to be confirmed by a second round of testing (Step 6). The BPC is not expected to be among the mixtures that were actually tested in the original matrix and thus, if it is to be used in construction with confidence, a confirmation batch of the BPC must be mixed and tested. Realistically, the amount of testing of the BPC that is conducted will be based on the amount of time available for Confirmation Testing and the predicted performance difference between the BPC and the BTC. At the end of the Confirmation Testing, the Best Concrete (BC), the mixture recommended for implementation, is chosen. The BC is expected to be the BPC. However, the BPC should be chosen only if the overall desirability based on the Confirmation Testing for that mixture is indeed higher than that for the BTC. Additional considerations may come into this selection, such as the actual difference in overall desirabilities between the BTC and BPC relative to the repeatability of the test methods, performance in areas determined to be critical to the application, and factors that may not have been included in the scope of the experiment, like cost or ease of production.

Hypothetical Case Study

To provide a basis for evaluating this Methodology, a case study, called the Hypothetical Case Study, was investigated. The service environment for this study was chosen as a bridge deck in a northern, Midwest environment subject to freezing and thawing and deicing salt exposure. Performance requirements were developed and locally available materials were obtained and used to perform an experimental study. This test program was conducted according to the process outlined in the Guidelines. The full, step-by-step details of this study are provided in Appendix A, but an overview of the process and the evaluation of accuracy of the analysis and modeling based on the actual results are presented here.

Step 1: Service Conditions

Based on a bridge deck application in a northern climate, the steps outlined by Figure S1.1 were used to characterize the universal design requirements and to evaluate issues relevant to a freezing climate subjected to chemical deicers, and where cracking was a concern. This environment was assumed to be neither coastal nor abrasive.

The required testing based on the service environment of the Hypothetical Case Study was summarized using Worksheet S1.1, which lists the properties of interest, the test methods to measure each property, and optimum target values. These target values were then used to develop a desirability function for each property. After each property of the concrete was considered, the recommended ranges of SCM contents expected to produce desirable performance were collected and summarized to form the basis for selecting the ranges for testing.

Step 2: Materials Selected

In Step 2, suitable raw materials were selected. The worksheets in Step 2 of the Guidelines were used to organize the available information regarding the locally available materials and facilitate decisions about the materials. For the Hypothetical Case Study, materials local to the Chicago area were used. Multiple sources of cement, fine and coarse aggregate, Class C fly ash, slag and admixtures were evaluated using this process, and those materials deemed most likely to produce durable concrete were chosen.

Step 3: Experimental Design Matrix

The review of the Hypothetical Case Study environment conducted in Step 1 suggested that a large test program was necessary to characterize each mixture's performance. As a result, it was determined that the experimental program was constrained by the available budget to a 9-mixture experiment. This number of experiments controlled the possible numbers of factors and levels as listed in Table S3.1 (Table 2).

Given this constraint, the next step was to select which factors and levels to include. The main focus chosen for the hypothetical experiment was to evaluate as wide a range of SCMs as possible. Therefore, to maximize the number of SCMs while limiting the size of the experimental design matrix to nine mixtures (based on three three-level factors and one two-level factor), the factors defined were: "First SCM Type," "First SCM Amount," "Amount of Silica Fume" and "w/cm."

The range of the investigation for each of the factors was chosen to span the region where the optimum level was expected. When the ranges recommended in Step 1 for silica fume were compiled for all the desired properties, one level resulted: 5%. The same was true for GGBFS (30%) and Class C Fly ash (25%). Since the objective of this research is to optimize SCMs, it was decided to center the test program on these recommended values, and levels for testing were chosen above and below these values.

Ordinarily, an Amount Factor such as "First SCM Amount" would have simple numerical values given as levels. However, since the appropriate ranges for types of SCMs may be dependent on that specific type, a Compound Factor was used. This Compound Factor, which links the definition of the Amount Factor to a Type Factor, allowed additional freedom in the definition of SCM contents. The levels of the First SCM Type factor were defined as slag, Class C fly ash, and Class F fly ash. Then, the levels of the First SCM Amount factor were defined generically as Low, Medium, and High, with different specific values of the SCM content associated with the generic definitions for the slag and for the fly ashes. Despite the generic definition, the "Amount of SCM1" is an Amount Factor, and the performance modeling is still capable of interpolating between the levels tested.

The factors and levels used for the Hypothetical Case Study are given in Table 3. The definitions of Low, Medium, and High are shown in Table 4.

Type, Source, and Amount Constants are those characteristics of the mixture design that will be consistent throughout the experiment. These included single sources for each raw material type, and defining a constant cementitious material content (658 lb/yd^3 [391 kg/m^3]) and coarse aggregate content (1696 lb/yd^3 [1007 kg/m^3]). The coarse aggregate content was selected based on the fineness modulus of the fine aggregate as recommended by ACI 211.1 (*2*). All SCM amounts were calculated as percentages by mass replacement of portland cement. Accordingly, changes in cementitious materials volumes were compensated by changes in fine aggregate content.

Two batches of a control mixture were also incorporated in this study. The control mixtures were made with no SCMs at a w/cm of 0.40. The mixture included 263 lb/yd^3 [156 kg/m^3] water, 658 lb/yd^3 [391 kg/m^3] cement, 1280 lb/yd^3 [760 kg/m^3] fine aggregate, and 1696 lb/yd^3

Table 3. Factors and levels for 9-mixture design used in Hypothetical Case Study

Factor No.	Factor Name	Level 1	Level 2	Level 3
Factor 1 (3 levels)	Type of SCM1	Fly ash (Class C)	Fly ash (Class F)	GGBFS
Factor 2 (3 levels)	Amount of SCM1	Low	Med	High
Factor 3 (3 levels)	Amount of silica fume (%)	0	5	8
Factor 4 (2 levels)	w/cm	0.45	0.37	-

Table 4. Definition of compound factor for Hypothetical Case Study

Factor 1, Factor 2 Combinations	Type of SCM	Amount of SCM
Type 1, Low level	Class C fly ash	15%
Type 1, Medium Level	Class C fly ash	25%
Type 1, High Level	Class C fly ash	40%
Type 2, Low level	Class F fly ash	15%
Type 2, Medium Level	Class F fly ash	25%
Type 2, High Level	Class F fly ash	40%
Type 3, Low level	slag	25%
Type 3, Medium Level	slag	35%
Type 3, High Level	slag	50%

[1007 kg/m^3] coarse aggregate. The intent of this mixture was to provide a comparison to assess relative performance of mixtures with SCMs. The replicate control mixture was added to provide an assessment of batch-to-batch variability for each test so that the significance of differences in test results could be evaluated.

As mentioned, the orthogonal design selected required that nine mixtures be evaluated to provide sufficient information to optimize these factors and levels. These mixes must be chosen according to the applicable table from the collected orthogonal experimental design matrices at the end of Step 3 of the Guidelines. The generic design matrix that applies for the nine-mixture experiment, three three-level factors and one two-level factor design is given in Table 5. Table 6 lists the specific design matrix after the factor levels were substituted into this generic matrix.

The actual mixtures and batch weights tested are listed in Table 7. The admixture dosage rates were determined based on trial batches.

Table 5. The levels for the 9-mixture design matrix with 3 three-level and 1 two-level factors. (The numbers in the columns refer to the levels indicated in Table 3.)

Mixture #	Factor 1 (3-Level)	Factor 2 (3-Level)	Factor 3 (3-Level)	Factor 4 (2-Level)
1	1	1	1	1
2	1	2	2	<u>**2**</u>
3	1	3	3	<u>**2**</u>
4	2	1	2	<u>**2**</u>
5	2	2	3	1
6	2	3	1	<u>**2**</u>
7	3	1	3	<u>**2**</u>
8	3	2	1	<u>**2**</u>
9	3	3	2	1

(If the font is underlined and bold, the level chosen for that Factor should be the one expected to produce the best result.)

Table 6. Experimental design matrix for Hypothetical Case Study

Mixture	First SCM Type	First SCM Amount	Amount of Silica Fume	w/cm
1	Fly Ash C	Low (15%)	0 %	0.45
2	Fly Ash C	Medium (25%)	5 %	0.37
3	Fly Ash C	High (40%)	8 %	0.37
4	Fly Ash F	Low (15%)	5 %	0.37
5	Fly Ash F	Medium (25%)	8 %	0.45
6	Fly Ash F	High (40%)	0 %	0.37
7	GGBFS	Low (25%)	8 %	0.37
8	GGBFS	Medium (35%)	0 %	0.37
9	GGBFS	High (50%)	5 %	0.45

Step 4: Test Program

The test program outlined in Step 1 (defined using Worksheet S1.1) was modified slightly in practice, and the actual program is summarized in Table 8. Appendix A gives the full details of the testing program.

Step 5: Best Tested Concrete, Best Predicted Concrete Analysis

After the tests were conducted, the responses were tabulated and converted into individual desirability values based on the desirability functions developed during the definition of the performance requirements. The results of this analysis were reviewed, and the responses to be included in the overall desirability calculations were re-evaluated. The initial assumptions for the desirability functions were also re-evaluated based on the test results. The purpose of the re-evaluation is to ensure that the combined desirability functions accurately interpret the performance of the mixtures and support model predictions that are realistic and practical. The results of the Hypothetical Case Study were interpreted relative to the objective of a durable bridge deck in a northern climate, and what follows is a description of how the particular test data were reconciled with this objective.

Analysis of Results and the BTC

Table 9 lists individual responses that were initially planned for use in Step 1 and tested in Step 4 as well as those that were actually used to calculate the overall desirability for the mixtures in Step 5. The following changes were made: The fresh concrete properties (slump, slump loss, plastic air content, and air content of hardened concrete) were eliminated from consideration in the calculation of the Overall Desirability. This was done since many of these properties can be adjusted by the concrete producer based on admixture dosage and were not uniquely determined by the factors defining the mixtures. No measure of the hardened air parameters was included since cyclic freezing resistance was tested directly.

Table 7. Mixtures as batched

	Mixture ID												
	C1	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**C2**	**BTC (8)**	**BPC**
w/cm	0.4	0.45	0.37	0.37	0.37	0.45	0.37	0.37	0.37	0.45	0.4	0.37	0.39
	Percent replacement of cement (by wt.)												
Fly Ash (Class C)		15	25	40									
Fly Ash (Class F)					15	25	40						
Slag								25	35	50		35	35
Silica Fume		0	5	8	5	8	0	8	0	5		0	8
	Theoretical weight per unit volume (lbs./cu. yd.)												
Water content	263	296	243	243	243	296	243	243	243	296	263	243	257
Cement	658	559	461	342	526	441	395	441	428	296	658	428	375
Fly Ash (Class C)	0	99	165	263	0	0	0	0	0	0	0	0	0
Fly Ash (Class F)	0	0	0	0	99	165	263	0	0	0	0	0	0
Slag	0	0	0	0	0	0	0	165	230	329	0	230	230
Silica Fume	0	0	33	53	33	53	0	53	0	33	0	0	53
Fine Aggregate	1280	1180	1300	1280	1294	1128	1261	1302	1316	1156	1280	1316	1262
Coarse Aggregate	1696	1696	1696	1696	1696	1696	1696	1696	1696	1696	1696	1696	1696
	Admixture dosage (fl. oz./cwt.)												
AEA	1.70	2.32	3.10	3.83	2.61	3.89	3.35	2.33	2.64	4.78	1.28	2.43	4.01
Superplasticizer	9.07	4.87	25.50	36.60	22.70	16.01	12.59	33.49	24.27	14.81	8.74	18.33	34.15
	Actual weight per unit volume as batched (lbs./cu. yd.)												
Water content	258	295	235	243	239	291	238	242	241	301	263	234	250
Cement	645	558	445	341	517	433	386	438	423	301	658	411	365
Fly Ash (Class C)	0	98	159	262	0	0	0	0	0	0	0	0	0
Fly Ash (Class F)	0	0	0	0	97	162	257	0	0	0	0	0	0
Slag	0	0	0	0	0	0	0	163	228	335	0	221	224
Silica Fume	0	0	32	52	32	52	0	52	0	33	0	0	51
Fine Aggregate	1255	1177	1256	1276	1271	1109	1233	1292	1303	1177	1280	1264	1227
Coarse Aggregate	1662	1693	1638	1690	1665	1667	1658	1684	1679	1727	1696	1629	1650

Table 8. Test methods used for the evaluation of mixture properties

Property	Test Methods
Total air content, plastic concrete	AASHTO T 152
Slump after High Range Water Reducer (HRWR) addition	AASHTO T 119
Slump, after 45 minutes	AASHTO T 119
Initial set time, minimum	AASHTO T 197
Finishability	Qualitative assessment
Cracking tendency (restrained shrinkage)	AASHTO PP 34-99
Thermal effects (heat of hydration)	Temperature rise in cylinder
Shrinkage (1, 3, 7, 14, 28, 56, 90 days after curing)	AASHTO T 160
Compressive strength (at 3, 7, 28, 56 days)	AASHTO T 22
Modulus of elasticity (at 7 and 28 days)	AASHTO T 22
Hardened air analysis	ASTM C 457
Freeze/thaw resistance	AASHTO T 161A
Electrical conductivity test	AASHTO T 277
Chloride penetration resistance (one 3-in. core from each slab, evaluated at 6 mos.)	Modified AASHTO T 259/T 260
Salt scaling resistance	ASTM C 672

Table 9. Responses used for calculation of overall desirabilities

Proposed Responses from Step 1	Selected Responses for Step 5 Design Matrix Analysis	Selected Responses for Step 6 Confirmation Analysis
1. Slump		
2. Slump Loss		
3. Plastic Air Content		
4. Air Content of Hardened Concrete		
5. Initial Set	1. Initial set	1. Initial set
6. Finishability	2. Finishability	
7. Cracking Tendency	3. Cracking Tendency	
8. Heat of Hydration - Temperature rise	4. Heat of Hydration - Temperature rise	2. Heat of Hydration - Temperature rise
9. Shrinkage	5. Shrinkage	3. Shrinkage
10. Specific Surface Area		
11. Compressive Strength, 7-Day	6. Compressive Strength, 7-day	4. Compressive Strength, 7-day
12. Compressive Strength, 28-Day		
13. Compressive Strength, 56-Day	7. Compressive Strength, 56-day	5. Compressive Strength, 56-day
14. Modulus of Elasticity	8. Modulus of Elasticity, 28-day	
15. Electrical Conductivity	9. Electrical Conductivity	6. Electrical Conductivity
16. Scaling (visual rating)		
17. Scaling (mass loss)	10. Scaling (mass loss)	7. Scaling (mass loss)
18. Freezing and Thawing Resistance (durability factor)	11. Freezing and Thawing Resistance (durability factor)	
19. Chloride Penetration Resistance (diffusion coefficient)	12. Chloride Penetration Resistance (diffusion coefficient)	8. Chloride Penetration Resistance (diffusion coefficient)

Another change that was made was the inclusion of 56-day strength in place of 28-day strength, based on the effect that one mixture that was slow to develop strength had on the analysis. This was rationalized since the age at which compressive strength is specified for a given project usually can be delayed if the rest of the performance justified such a change.

In the testing program, scaling resistance was evaluated in two ways: by visual rating and by mass loss. To limit the emphasis applied to scaling relative to the other performance measures, only the one measure deemed to be the best descriptor of scaling performance (mass loss) was included in the Overall Desirability Calculation.

Modifications to the desirability functions were made in some cases after the data were examined. For example, the desirability function for temperature rise due to heat of hydration was adjusted based on the test results. It was initially assumed, based on the insulation vessels, that the temperature rise would not be above 30°F (17ºC), and the desirability function was designed accordingly. However, the actual test results ranged from 30 to 50°F (17 to 29ºC). Therefore, the desirability function was adjusted to give credit to those mixtures that produced a lower temperature rise but not to overly punish the mixtures at the higher end of the scale.

The individual responses and overall desirabilities of all mixtures based on the test data are shown in Table 10. The Best Tested Concrete (BTC) is the mixture that had the highest overall desirability. Therefore, the BTC was Mixture #8.

Response Modeling and the BPC

By definition, the Best Predicted Concrete (BPC) is the mixture with the combination of factor levels that maximizes the overall desirability. This was identified based on empirical models for each of the responses. Linear models were fit to two-level factors while quadratic models were fit to three-level factors. The BPC was found by successively evaluating the calculated overall desirability based on the desirabilities for the individual responses predicted for many possible combinations of factor levels. The combinations of factor levels were produced by breaking the ranges for each factor specified in the experimental design matrix into small evenly spaced sets of levels. All combinations of these levels were evaluated. Of the more than 22,000 alternatives that were evaluated, the single combination that produced the highest overall desirability was selected as the BPC. In this way, the observed data, the desirability function, and the response models were used together to predict a BPC that is expected to perform better than the BTC.

The predicted overall desirabilities based on the response models for the BTC and BPC from the Step 4 test program is given in Table 11. Note that the predicted overall desirability for the BTC is slightly different from the actual overall desirability because the predicted value is calculated based on the models and not the actual test data. While small differences between the actual and predicted desirability of the BTC (and of all the other design matrix mixtures) is expected, large differences indicate that the models may not be predicting actual performance well and the test variability and data should be reviewed further. In determining the BPC, the models predict that for the materials tested, using the medium level of slag in the experimental design matrix is, in fact, optimum but that the amount of silica fume should be increased to 8% and that the w/cm should be increased by 0.02, from 0.37 to 0.39.

The prediction of the performance of the BTC and BPC mixtures in each of the individual responses is given in Table 12. Predicted responses are given for all properties tested in the initial test program, and predicted desirabilities are given for those responses used to determine

Table 10. Individual response desirabilities and overall desirabilities for design matrix testing

Mixture	C1	1	2	3	4	5	6	7	8	9	C2
Initial Set	1	1	1	0.8340	1	1	1	1	1	1	1
Finishability	0.9856	0.9725	0.8850	0.9425	0.9075	0.9688	0.9744	0.9500	0.9325	0.9600	0.9706
Cracking Tendency	0.9889	1	1	1	1	0.9833	0.9722	1	0.9556	1	0.9889
Heat of Hydration Temp. Rise	0.8917	0.9517	0.9550	0.9650	0.9617	0.9717	0.9800	0.9583	0.9567	0.9650	0.8800
Shrinkage	0.9105	0.7938	0.9585	0.9690	0.9650	0.9085	0.9580	0.9850	0.9795	0.9645	N/A
Compressive Strength - 7 Day	1	1	1	1	1	0.8608	0.6304	0.9040	0.9795	1	N/A
Compressive Strength - 56 Day	1	0.9711	1	1	1	0.9020	0.8655	0.9707	1	1	1
Modulus of Elasticity	1	1	1	1	1	1	1	1	1	1	N/A
Electrical Conductivity	0.5366	0.3806	0.9594	0.9658	0.9583	0.9544	0.7784	0.9801	0.9296	0.9653	0.4079
Scaling - Mass Loss	0.9849	0.9874	0.9304	0.7491	0.9838	0.9365	0.8889	0.9820	0.9740	0.7082	N/A
Freeze- Thaw Durability Factor	1	1	1	1	1	1	1	1	1	1	N/A
Chloride Diffusion Coefficient	0.1030	0.1245	0.6682	0.7199	0.6723	0.5029	0.1216	0.8561	0.8787	0.7062	N/A
Overall Desirability	0.7695	0.7532	0.9412	0.9231	0.9490	0.9029	0.7660	0.9645	0.9648	0.9323	0.8373
Desirability Rank	8	10	4	6	3	7	9	2	1	5	*

* Mixture Missing Data, was not considered for BTC.

Table 11. Selection of Best Tested (BTC) and Best Predicted Concrete (BPC) based on overall desirabilities

Mix	Type of SCM 1	Amount of SCM 1 (%)	Amount of silica fume (%)	w/cm	Actual Overall Desirability	Predicted Overall Desirability	Mixture No.
BTC	GGBFS	35	0	0.37	0.9648	0.9653	8
BPC	GGBFS	35	8	0.39	-	0.9744	-

Table 12. Predicted responses of Best Tested (BTC) and Best Predicted Concrete (BPC)

Property	Predicted Response		Predicted Desirability	
	BTC	BPC	BTC	BPC
Slump (in)	8.05	7.10		
Slump Loss (in)	1.89	2.49		
Plastic Air (%)	6.34	6.44		
Hardened Air (%)	6.09	6.70		
Initial Set (hr)	5.33	5.66	1.00	1.00
Finishability	11.83	11.41	0.95	0.94
Cracking Tendency (wks)	7.43	15.67	0.96	1.00
Heat of Hydration (°F)	44.63	43.83	0.96	0.96
Shrinkage (%)	-0.0445	-0.0434	0.98	0.98
Specific Surface Area (in^{-1})	417	424		
Compressive Strength - 7 Day (psi)	5366	5503	1.00	1.00
Compressive Strength - 28 Day (psi)	7193	7730		
Compressive Strength - 56 Day (psi)	7792	8383	1.00	1.00
Modulus of Elasticity (x 10^6 psi)	4.25	4.24	1.00	1.00
Electrical Conductivity (Coulombs)	1144	397	0.93	0.98
Scaling - Visual	0.00	0.01		
Scaling - Mass Loss (g/m^2)	93.4	183.0	0.97	0.95
Freeze-Thaw Durability Factor (%)	103.7	104.0	1.00	1.00
Chloride Diffusion (x 10^{-12} m^2/s)	1.95	1.38	0.85	0.90

the overall desirabilities. A review of this table, specifically where the individual desirabilities of the BPC are greater than those of the BTC, identifies the responses that were most significant in the selection of the BPC. Despite a slightly lower individual desirability for finishability and scaling-mass loss, the predicted individual desirabilities for the BPC for the chloride diffusion, cracking tendency, and electrical conductivity tests were higher. This led to the greater overall desirability and the selection of this mixture as the BPC.

Step 6: Confirmation Testing and Final Selection of Best Concrete

The BPC and BTC were tested according to a revised list of test methods outlined in Table 13. It is not essential that the confirmation testing be identical to the original test program. However, changes to the test program will affect the overall desirability. Changes limit direct comparison to the original test program and the assessment of repeatability. However, the primary goal is to compare the performance of the BTC and BPC, which can be done with a more limited test program. Table 9 lists the responses that were included in the calculation of the overall desirability for the Confirmation Testing. The test program varied from the program used in Step 5 in that it was limited only to those responses that showed significant performance differences and could be completed in the available timeframe. Therefore, the finishability, modulus of elasticity, and freezing and thawing tests were eliminated, since in these tests, the BTC and BPC mixtures were predicted to have a similar desirability value. The cracking tendency test was eliminated because that test could not be completed in the necessary time frame. One additional modification to the testing procedure was made because of time constraints; the method used to evaluate the chloride penetration resistance was changed to ASTM C 1556 with 56 days of exposure. However, since both of the chloride penetration test methods used measure similar performance and no other changes in the testing procedures were made, the initial and Confirmation test programs were considered essentially comparable. Therefore, the results from both rounds of testing could be fairly compared. The mixture proportions and batch weights of the Confirmation Testing program are given in Table 7.

The overall desirabilities of these mixtures were determined using the same individual desirability functions used to evaluate the design matrix mixtures. The measured overall desirabilities are compared with the predicted overall desirabilities in Table 14, which also includes the overall desirability of the original BTC batch calculated using the subset of responses included in the Confirmation Testing program. Note that the overall desirabilities based on the Confirmation Testing are slightly different than those calculated in Step 5 since the responses included in this calculation have been modified.

For the Hypothetical Case Study, the actual and predicted performances of the Confirmation BTC and BPC agreed very well, with less than 0.2% error in each of these predictions. In addition, the difference between the actual BPC and BTC performance was nearly nine times greater than the difference between the Original and Confirmation batch of the BTC. This provides confidence that the test program produced repeatable results and that the increase in desirability measured in the BPC is a significant and measurable improvement in the overall performance.

Table 13. Set of Confirmation tests for BPC and BTC

Property	Test Method
Compressive strength (at 3, 7, 28, 56 days)	AASHTO T 22
Electrical conductivity test (56 days)	AASHTO T 277
Shrinkage (1, 3, 7, 14, 28, 56, 90 days after curing)	AASHTO T 160
Thermal effects (heat of hydration)	Temperature Rise in Cylinder
Chloride diffusion (to 56 days)	ASTM C 1556
Scaling (mass loss)	ASTM C 672
Hardened air analysis (at greater than 7 days)	ASTM C 457

Table 14. Comparison of actual and predicted overall desirabilities from Confirmation Testing

Mixture	Actual Overall Desirability	Predicted Overall Desirability	% Difference
BTC Original Batch (Mixture #8)	0.9615	0.9601	0.1%
BTC Confirmation Batch	0.9601	0.9601	0.0%
BPC Confirmation Batch	0.9724	0.9700	0.2%

Table 15 and Table 16 present the actual and predicted individual responses and corresponding desirabilities for the Confirmation Testing for the BTC and BPC. These tables provide an opportunity to evaluate the accuracy of the predictions of the test responses and the corresponding desirabilities. The mixture responses that were least well-predicted, i.e., that showed the greatest percent difference, in terms of the test results for the BTC and BPC were the electrical conductivity and scaling-mass loss tests. However, the corresponding desirability values varied only slightly because the desirability functions placed only limited significance on these performance differences. In fact, only one desirability prediction was different by more than 5% and that was the 7-day strength prediction for the BTC which was off by 5.2%.

The Confirmation test results and the excellent agreement between the test responses and the model predictions used to select the BPC all contribute to the confidence in the accuracy of this statistical analysis. The result of this program justifies the selection of the BPC as the Best Concrete (BC), the mixture recommended for use. With this selection, the objective of this Methodology, which is the identification of an optimum mixture based on the available raw materials, was achieved.

Table 15. Comparison of individual responses and desirabilities for BTC

Property	Individual Responses				Individual Desirabilities		
	Original BTC Batch (Mixture #8)	**BTC Confirmation Test**	**BTC Prediction**	**BTC % Difference Response**	**BTC Confirmation Test**	**BTC Prediction**	**BTC % Difference Desirability**
Slump (in)	7.75	6.25	8.05				
Slump Loss (in)	1.75	2.25	1.89				
Plastic Air (%)	6.10	7.00	6.34				
Hardened Air (%)	5.70	7.50	6.09				
Initial Set (hr)	5.50	5.08	5.33	-4.8%	1.000	1.000	0.0%
Finishability	11.3	No test	11.8	-			
Cracking Tendency (wks)	7.0	No test	7.4	-			
Heat of Hydration Temp. Rise (ºF)	46	46	45	3.1%	0.957	0.959	-0.2%
Shrinkage (%) (negative)	-0.0441	-0.0452	-0.0445	1.7%	0.974	0.978	-0.4%
Specific Surface Area (in^{-1})	408	No test	417	-			
Compressive Strength - 7 Day (psi)	5705	6020	5367	12.2%	0.948	1.000	-5.2%
Compressive Strength - 28 Day (psi)	7888	7970	7194	10.8%			
Compressive Strength - 56 Day (psi)	8460	8520	7793	9.3%	0.997	1.000	-0.3%
Modulus of Elasticity ($x 10^6$ psi)	4.26	No test	4.25	-			
Electrical Conductivity (Coulombs)	1136	778	1143	-31.9%	0.961	0.929	3.5%
Scaling - Visual	0.0	0.0	0.1	-			
Scaling - Mass Loss (g/m^2)	86.7	25.0	93.4	-73.3%	0.993	0.972	2.1%
Freeze-Thaw Durability Factor (%)	103.8	No test	103.7	-			
Chloride Diffusion Coefficient ($x 10^{-12} m^2/s$)	1.62	1.88	1.95	-3.8%	0.859	0.853	0.7%

Table 16. Comparison of individual responses and desirabilities for BPC

Property	Individual Responses			Individual Desirabilities		
	BPC Confirmation Test	BPC Prediction	BPC% Difference Response	BPC Confirmation Test	BPC Prediction	BPC % Difference Desirability
Slump (in)	7.25	7.10				
Slump Loss (in)	3.00	2.49				
Plastic Air (%)	6.7	6.4				
Hardened Air (%)	6.3	6.7				
Initial Set (hr)	6.42	5.66	13.5%	1.000	1.000	0.0%
Finishability	No test	11.4	-			
Cracking Tendency (wks)	No test	15.7	-			
Heat of Hydration Temp. Rise (°F)	44	44	0.4%	0.960	0.960	0.0%
Shrinkage (%)	-0.0476	-0.0434	9.6%	0.962	0.983	-2.1%
Specific Surface Area (in^{-1})	No test	424	-			
Compressive Strength - 7 Day (psi)	5570	5504	1.2%	0.993	1.000	-0.7%
Compressive Strength - 28 Day (psi)	7710	7731	-			
Compressive Strength - 56 Day (psi)	8560	8383	2.1%	0.992	1.000	-0.8%
Modulus of Elasticity (x 10^6 psi)	No test	4.24	-			
Electrical Conductivity (Coulombs)	244	397	-38.5%	0.988	0.980	0.8%
Scaling - Visual	0.0	0.3				
Scaling - Mass Loss (g/m^2)	52.8	183.0	-71.2%	0.984	0.945	4.1%
Freeze-Thaw Durability Factor (%)	No test	104.0	-			
Chloride Diffusion Coefficient (x 10^{-12} m^2/s)	1.28	1.38	-6.8%	0.904	0.897	0.8%

INTERPRETATION, APPRAISAL AND APPLICATIONS

SEDOC Computational Tool

Statistical Experimental Design for Optimizing Concrete (SEDOC) is a pair of Microsoft® Excel workbooks and auxiliary "help files" that have been created to support the completion of Steps 1 through 6 in the Methodology as laid out in *NCHRP Report 566*. Each workbook (or individual Excel file) is made up of various worksheets that have been created to perform specific tasks in the Methodology. Electronic versions of much of *NCHRP Report 566* have been included as linked files, allowing the tool to be used as a stand-alone application.

The tool is divided in two parts: "SEDOC: Setup" and "SEDOC: Analysis." These two workbooks are used to complete Steps 1-3 and Steps 5-6, respectively. SEDOC: Setup provides guidance and information about appropriate test methods for different service environments and about potential raw materials, and electronic versions of the worksheets from the Guidelines for compiling data and making decisions. Ultimately, SEDOC: Setup leads to the selection of factors, levels and responses that will be part of the experiment. SEDOC: Analysis requires input of the selected factors and levels and provides the experimental design, i.e., the list of specific mixtures to be tested to support the statistical analysis. Based on the data generated by the experimental testing program (Step 4), this workbook performs the conversions to individual desirabilities, the calculation of the overall desirability, the selection of the Best Tested Concrete (BTC), and the modeling and prediction of the Best Predicted Concrete (BPC). There are many pre-formatted plots and tables included in the tool designed to help analyze and uncover trends within the data. Finally, SEDOC: Analysis includes a worksheet to analyze the Confirmation Test data and to provide a basis for making final recommendations for the Best Concrete mixture to be used in the application. A more complete description of the computational tool is given in the user's guide available on the TRB website (http://www.trb.org/TRBNet/ProjectDisplay.asp?ProjectID=474).

Overview of SEDOC: Setup Worksheets

SEDOC: Setup is an Excel workbook that includes the following functional worksheets:

- Task Center - This page is the focus point for the SEDOC: Setup workbook. The flowcharts in Step 1 (Performance Definition) and Step 2 (Materials Selection) have been converted to electronic form on this page. A list of test methods, selected based on service environment, is generated interactively. This worksheet also includes a place for the users to document each step in the Materials Selection and Experimental Design processes.
- Desirability Functions - Desirability functions for each of the common test methods are included on this page. Functions for additional responses not previously included in the tool may also be defined and included. (These functions will be later transferred to SEDOC: Analysis.)
- Guideline Worksheets - The worksheets from Step 2, designed to help collect data about the available raw materials, and from Step 3, intended to provide a location for narrowing down the choices of the factors and levels for the experimental testing program, are included in these Excel Worksheets.

Overview of SEDOC: Analysis Worksheets

SEDOC: Analysis includes the following functional worksheets:

- Experimental Design Worksheet - The mixtures for testing are selected based on the factors and levels input by the user.
- Compound Factor Settings Worksheet - If the user chooses to employ Compound Factors, such as the linked SCM Type and Amount Factors used in the hypothetical test matrix, the details are specified on this sheet.
- Response Selection Worksheet - The responses to be included in the analysis are selected on this worksheet. The user may "turn off" certain responses so that the best performers can be selected based on a subset of the test results, if desired. The sheet presents the individual desirabilities for each response for each mixture. It also calculates the overall desirability for each mixture.
- Data Entry Worksheet - This page is provided for the user to enter all the test data.
- Individual Response/Desirability Function Worksheets - Each performance test (response) has its own worksheet. The test data entered on the Data Entry Worksheet is copied from that worksheet and used to determine the desirability for each mixture on these worksheets. A default desirability function is already loaded on this page, but the user can modify these to match local service requirements. These sheets also contain scatter, trend, and factor effect plots so that the user can evaluate each individual response and compare the performance of the mixtures.
- Desirability Analysis Worksheet - The selection of the BTC concrete and BPC is performed on this page. The selection of the BTC is done automatically from the responses selected on the "Response Selection" sheet. The selection of the BPC is done through a Visual Basic macro. The user can input ranges and step sizes for interpolation between the settings of each factor level if desired.
- Confirmation Analysis Worksheet - This worksheet is used to input the data from the confirmation testing and compare the overall desirabilities of the BTC and BPC for making the final selection of the BC in Step 6.

This tool was developed so that users can immediately implement this Methodology. It is not a fully developed application but an experimental package that demonstrates the power of the Methodology and how the modeling and optimization may be performed. Currently, a limited number of the orthogonal designs shown in Table 2 are supported. Some recommendations for further development of this tool are given later in this document.

Methodology Application

Assuming proper placement and curing, the performance of concrete mixtures is governed by the constituent materials used in the production of the concrete and the relative dosages of these materials. This is especially true of concretes containing SCMs, like slag, fly ashes or silica fume, since these materials add a level of complexity to the mixture and increase the potential for interactions between materials. It has been demonstrated in numerous studies that various properties, especially those related to durability, can be improved greatly through the use of SCMs. However, such studies do not always provide consistent results when conducted with different material sources since SCMs are inherently variable, even within the same material type. This is because SCMs are largely by-products of other industries, and their quality and consistency are typically secondary concerns to their producers. Therefore, a universally applicable specification having an optimum amount of particular SCMs is not available, nor is it likely to ever be practical. Instead, the optimum proportions can only be determined by testing.

The design and execution of such a test program, especially if it involves the investigation of a number of performance characteristics, requires a significant level of knowledge about the raw materials, the available test methods, and perhaps most important, an understanding of how results from accelerated, laboratory testing translate into field performance. To maximize the usefulness of a test program, it is important to make rational choices based on the available information from the test methods that best predict actual field performance.

Even without the material variations inherent in SCMs, a universal specification is not possible on a nationwide or even region-wide basis, since the optimum concrete mixtures will vary for different performance requirements. The performance requirements differ based on a range of factors including the local environmental conditions, expected service and traffic loads, and design. Even constraining the scope of interest to maximizing durability of bridge decks, as was the case with this research project, does not reduce the significance of this difficulty. In defining performance requirements, the following challenges are present: The first question is how to evaluate what is truly optimum for a specific situation. Standards of desirable performance must be established with which to judge the properties of the concrete. Another concern, when multiple types of performance are to be evaluated, is how to choose among mixtures with contradictory trends among performance categories. For example, if a modification to a mixture improves one property that imparts durability to the concrete while worsening another, is the overall performance improved?

The Methodology developed in this project and presented in *NCHRP Report 566* provides a mechanism for dealing with each of these issues. In addition to providing an overall framework for tackling the problem of mixture optimization, the three most significant features of the Methodology are (1) the desirability function and overall desirability concepts, (2) the background guidance on setting up the testing program and evaluating raw materials, and (3) the empirical modeling. Each of these is discussed below.

Features of the Methodology

Desirability Concept

The first steps in the Methodology are to identify the relevant deterioration mechanisms, evaluate the ability of the available test methods to predict the performance of the concrete relative to those mechanisms, and finally, to define the desirability functions. The desirability functions allow fair and rational comparisons to be made about the overall desirability (quality) of particular mixtures. This approach gives a great deal of flexibility to the Methodology since the concept of the desirability function can be applied to any response, i.e., any type of performance or quality measure of the concrete mixture, from freezing and thawing resistance to cost.

The desirability approach is used within the Methodology to select the BTC from the tested mixtures and to identify the BPC as the single combination of levels that produced the highest overall desirability. The experimental design matrix consisting of a set number of mixtures tested as part of the Methodology is chosen to support modeling; however there is no requirement that a tested mixture be part of the matrix for the overall desirability to be evaluated. The desirability concept could be used to compare any mixtures subjected to the same testing program, i.e., any mixture that has an overall desirability calculated for the same list of responses. This may be used to compare concrete mixtures in use currently or in the future to those generated by this program.

As defined by the user, the desirability function reflects the importance of an individual response relative to the other responses used to calculate the overall desirability. It also determines the sensitivity with which variations in the response are interpreted. The interpretation of the results of any testing program containing a range of discrete tests is subjective, and the experience and beliefs of the people conducting the investigation play a significant role. The desirability concept provides a means for introducing a rational basis for decision making while at the same time allowing each user the freedom to focus on those issues they consider most important. For example, if two test methods are used to measure similar properties, the desirability function for these responses can be established to weight the method believed to most closely predict the in-place performance.

Modifications to the desirability functions can be used to bring a different perspective to the interpretation of what is considered the “best” concrete. If the desirability functions are changed, the data collected from one investigation could be used as a basis for modeling to find a new and different optimum concrete.

Guidance

While it is assumed that the user will have a general understanding of how to develop concrete mixture proportions based on a laboratory investigation, each step of the Methodology provides guidance relative to this objective. This is most obvious in Step 1, where the properties that produce durable concretes are discussed along with test methods to measure those properties, and in Step 2, where the importance of the properties of each of the raw materials is discussed relative to the long-term performance of concretes containing those materials. The guidance is intended to help efficiently initiate the mixture proportioning experiment for a user interested in learning more about the important considerations behind these decisions. References are also provided to other documents where further information is available regarding the relevant topics.

Modeling

In the Methodology, empirical models are created based on the design-matrix testing. These models are used to iteratively predict the performance of combinations of factor levels representing concrete mixtures throughout the test space. In this search, the concrete that produces the highest overall desirability is selected as the BC (Best Concrete). This model framework can also be useful in performing a range of other tasks because it supports comparisons between any mixtures within the test space.

This Methodology could be used to evaluate the consequences of switching sources of materials in mid-project, which has become an issue in the past few years due to the variable availability of raw materials, particularly cements. The effect of a simple change to the BC mixture, like swapping one source material for another, can be calculated easily. The optimization prediction and generation of a new BPC could also be repeated, with a newly unavailable source eliminated from consideration. The new BPC predicted in this way would be expected to vary more significantly in a situation where a cement or SCM is replaced. The consequences of choosing either the option of making a simple substitution or of re-optimizing the mixture can be quantified using the model predictions. The need for Confirmation Testing, which typically would be recommended if re-optimization is performed, could also be judged based on the differences in the overall desirability between the existing BC and the newly predicted BPC.

The two scenarios regarding material substitution discussed previously are only possible if the raw materials concerned were included in the design matrix. If this is not the case, a new material could be substituted in the design and tested to support subsequent modeling. This would only require a portion (one half if a two-level factor or one third if a three-level factor) of the test program to be repeated, given that the rest of the factors in the experimental design remained unchanged.

The models could also be used to evaluate the effect of production variability. For example, the differences in overall desirability when the content of a raw material is varied 1% from the optimum value can be predicted. In this way, the sensitivity and importance of batching accuracy for that particular mixture can be determined. This could help in the selection of a robust mixture, likely to produce consistent results.

Appropriate Uses

The mixture design methodology developed in this project was focused on maximizing the durability of bridge decks constructed with concretes containing SCMs. The local variations in the properties of these materials and in performance requirements dictate that experimental investigations are needed to identify the optimum mixture proportions. This can be achieved efficiently using statistically based experimental design concepts. The fractional orthogonal design and modeling approach adopted in the Methodology reported here is a main-effects method, meaning the models reflect the overall trends in the responses relative to the factors. The number of mixtures that are tested in a fractional orthogonal design is not sufficient to support the calculation of interaction terms in the empirical models. Interaction terms would model the effect of changing one factor relative to another and would produce more accurate estimates of performance but require that significantly more mixtures be tested. The cost of a sufficiently large investigation to support more accurate modeling was determined to be too great for concrete mixture development programs relative to the benefits. It is undeniable, however, that such interactions occur in concretes containing SCMs and, if it is felt that modeling these interactions is crucial, other experimental designs and modeling methods are available.

The experimental analysis process laid out in the Methodology is, nevertheless, a powerful one and can be used in a range of different applications. The challenge of selecting optimum SCM contents is also present in the development of high-strength concrete and mass concrete mixtures. Provided that test methods exist that accurately predict field performance of the concrete, desirability functions and modeling-friendly experimental programs can be defined to support optimization modeling based on those objectives.

Finally, this process is not limited to only concretes containing SCMs. Any mixture design problem can be investigated with this approach, provided that the performance can be measured accurately and consistently. This may include optimizing admixture contents in self-consolidating concretes, or simply selecting between available cements, aggregates and admixtures in more conventional concrete applications.

Implementation of Concrete Mixtures Designed for Durability

The recommended general process for the implementation of a concrete mixture where durability is a main objective for a given structure is summarized as follows: (1) targeted performance must be identified, in terms of general objectives and in terms of quantifiable measures; (2) the best available raw materials must be selected; (3) the best concrete mixture must be selected based on concretes produced with the specific raw materials and tested to evaluate performance; (4) trial batches of concrete must be produced with candidate ready-mix producers to demonstrate target performance is achievable in the field; and (5) construction practices and the concrete itself must be carefully monitored through trial placements and during construction by means of a comprehensive QA/QC program. This Methodology will help the user through the first three stages of the implementation process. Some additional challenges for implementing concrete mixtures designed for durability are discussed in this section.

The Methodology allows the user freedom to define the project objectives and determine what variables to compare and what tests to perform. However, if the correct objectives and tests are not selected, then the resultant concrete may not perform as desired. This problem is inherent in any laboratory test program that is expected to predict performance in the field, especially for durability.

If the test procedure is not accurate and reliable, incorrect comparisons and desirabilities may occur that are due solely to the inherent variability within a certain procedure, and results may not be representative of the actual effect of a changes in a test variable. To address this problem, the Methodology has a means to evaluate the repeatability of standard and non-standard tests. Duplicate control mixtures can also be used to assess test precision of the batching and testing processes. Careful consideration should be given to whether differences in test results are due to changes in factors or levels, or if the changes are just variations inherent within the test method. Tests that lack precision and accuracy should not be used to compare mixtures. The best test program may include non-standard or recently developed tests. Such tests should be included, provided that they reliably measure a type of performance not evaluated through other means.

Time and Cost Requirements

This Methodology can be most effective when adequate planning and time are available to complete the necessary design matrix and subsequent confirmation testing. Testing takes long periods of time when assessing concretes for durability, often over one year. Rapid, accelerated test methods are appealing in this setting but may not be adequate to accurately predict long-term performance. Therefore, planning and time is usually needed to develop the optimum mixture to meet the project goals.

Once the laboratory testing is completed, and the BTC and BPC have been identified, confirmation testing is strongly suggested to determine the best concrete from these two options. One possible way to expedite this process is for the Confirmation Testing to be performed on field trial batches generated by the producer. If Confirmation Testing is done in the laboratory, additional quality control testing on field-batched concrete is still recommended to ensure successful transfer of the results to the field. This field-trial testing should be done on samples cast from field-mixed concrete to confirm that the batch plant concrete is similar to the laboratory concrete and that local suppliers have the capability to produce this concrete.

Therefore, including field-batched concrete testing as part of the confirmation testing step of this Methodology may save time and expense on project-specific studies.

The Methodology can also be useful to a concrete supplier that might use it to develop standard commercial concrete mixtures. Since the need for such mixtures would be less time sensitive, and the sources of raw materials would be more consistent based on existing working relationships, a supplier could develop a large library of test results that could be used to generate multiple, optimum mixtures to fit specific design needs. For example, a 4000 psi (27.6 MPa) mixture, a 6000 psi (41.4 MPa) mixture, and a 8000 (55.2 MPa) psi mixture with varied durability properties could be identified using varied sets of desirability functions.

Cement and SCM sources often change during the year, and aggregate shipments also can be variable. It is a challenge to know when changes in raw materials have altered the desired performance of the concrete, and when additional testing is needed. If changes in raw materials are known to be a concern, the anticipated changes can be tested as a factor in the Methodology, such that the effect of the material variability can be measured against performance. Then limits can be set to ensure that the material variations do not adversely affect performance. Also, if long-term delays occur in a project, it is a good idea to retest some of the primary concrete properties as individual sources can change over time.

In addition to time, cost is often a concern during mixture development and testing. Cost typically will control the number of test mixtures that can be evaluated. The number of mixtures then controls the matrix and the levels and factors that are used. A larger number of factors and levels allow more possibilities to be considered and better optimization of the concrete, but the costs for a large testing program are not insignificant. Nevertheless, the potential long-term benefits of using improved concrete mixtures, such as reduced repair frequency, increased useful life, and minimized construction-related inconvenience to the traveling public have been demonstrated in the literature many times for many situations through life cycle cost analyses. A full commitment to the concrete implementation, including the mixture design and testing phase of this process, early in the test program is the best way to ensure that the in-place bridge deck or structure itself is optimized.

Specifications

State Departments of Transportation may have difficulty implementing a Best Concrete since, by definition, the BC is one mixture using one set of raw materials, and therefore it might be proprietary. If adequate time is available for bidders to test concrete, a performance specification may be practical. As typically used, performance specifications provide minimum values for certain durability-related tests, and potential bidders have to demonstrate that they can meet but not necessarily exceed the specified requirements. However, optimized performance could be encouraged by introducing pay incentives based on the desirability function framework. Pay could be directly proportional to overall desirability calculated based on desirability functions defined by the specifier. A potential flaw in this approach is the possibility that including only rapid (and potentially inadequate) quality control-oriented tests in this evaluation would allow concrete mixtures to be produced that perform well in those few tests but which would not actually be durable in the field. This use of desirability functions would only be effective if a complete set of responses that effectively predicted in-place performance were included in the overall desirability evaluation. It is also possible that a hybrid system could be used where improvements, measured in terms of desirability, beyond the performance minimums would merit additional compensation. This also allows the specifier to promote innovation by providing a motivation for the use of concretes that perform above and beyond minimum requirements. Some referee quality assurance testing would be needed if data are accepted from independent testing laboratories to ensure that the independent test results are consistent with the results from the mixture development work. (It should be noted that the example desirability functions provided in *NCHRP Report 566* were not developed to be used for the purpose of assigning pay factors. Significant additional consideration is needed before such a system could be introduced.)

Another option is to have concrete suppliers be pre-qualified based on testing of mixtures of trial batches developed with this Methodology. Mixtures could be screened, and those determined acceptable could be placed on an approved mixture list. When the project is bid, the contractor would provide concrete from the pre-approved mixtures and suppliers. Mixtures would still require some quality control testing immediately prior to use, especially if any raw material source changes had occurred.

Another way to specify the mixture is to list a Best Concrete and accept “or equals.” The immediate question is what is “or equal.” Changes in aggregate sources may not have a dramatic effect on the performance if they are similar aggregate types from similar pits. However, this is not necessarily true; depending on the performance criteria, a change in aggregate may have a dramatic effect on performance. Changes in cement source or SCM will likely change mixture performance and would not be considered “equal” unless it is demonstrated through testing. Changes in chemical admixture suppliers may not have a great effect on performance for most mixtures, if similar generic chemical types are substituted.

Production and Construction

The benefits of concrete mixture optimization and selection of excellent quality raw materials can be lost if production, transport, placing, and curing procedures are not performed well. Prior to starting any major project using a concrete mixture that the supplier or contractor is unfamiliar with, trial batches and placements should be performed. If a bridge deck is to be cast, it is beneficial to batch, transport, and place the trial concrete in a similar fashion as planned for the project. In a recent project, concrete was pumped to a slab-on-grade test section that was cast with congested reinforcing steel, tendons and anchorages to simulate the actual deck structure. Trials such as this allow problems with batching, scheduling, pumping, consolidation, finishing, and curing to be identified and corrected before the actual structure is built. In addition, an understanding of the influence of placement procedures on the concrete can be gained. For example, pumping can affect the air content and other plastic concrete properties, and it is important that the contractor is aware of the magnitude of this effect. The timing of finishing and curing operations for mixtures with SCMs, which may differ from conventional concretes, can also be estimated. This is especially important for concrete containing silica fume, which tends to experience less bleed water than other concretes and is more susceptible to plastic shrinkage cracking.

An in-depth quality control plan is needed to ensure that the Best Concrete mixture can be produced and installed in a consistent manner. The quality control program should include testing of raw materials (aggregates, cement, and SCMs), plastic concrete (slump, air content, temperature, unit weight) and hardened concrete (compressive strength, air void parameters, electrical conductivity). It has been successful on projects to require the contractor to perform quality control testing of the concrete, and have state-hired testing personnel perform quality assurance testing on split samples of approximately ten percent of the tests. This allows the contractor to set the pace of production and testing, while allowing state labs to check the accuracy of the concrete testing. Whenever a new concrete mixture is being evaluated, it may also be very beneficial to cast specimens from concrete sampled during construction for long-term durability testing to confirm that the project objectives are being met and to provide further confidence for using the concrete mixture in the future.

CONCLUSIONS AND SUGGESTED RESEARCH

Effectiveness of Approach

Optimizing concrete mixtures for durability is a challenge that must be dealt with on a local basis. The raw materials used in such concretes, particularly the SCMs, which are included because of the great potential for improved performance, are likely to vary significantly depending on their source and may not be universally available. The long-term deterioration mechanisms and the design requirements are different for different service environments, which are locally determined. SCMs add a significant level of complexity to such mixtures, especially if used as part of ternary or quaternary cementitious mixtures, and the exact mechanisms by which they influence the properties of the concrete are not well-enough understood to allow reliable mechanistic modeling. Because of these issues, there is no single set of guidelines for selecting mixture proportions. Instead, the optimum mixture proportions can only be determined for each situation separately, based on an experimental investigation. The Methodology developed in this research project provides a step-by-step process for conducting just such an investigation.

Evaluating the performance of concrete relative to the potential range of deterioration mechanisms, such as freezing and thawing, scaling, chloride induced corrosion, ASR, and drying shrinkage and thermal cracking requires a large program involving many separate tests. The concept of desirability and the desirability function has been introduced to provide a framework for evaluating the combined significance of all of these performance measures. The overall desirability permits the comparison of mixtures and the modeling that identifies the optimized mixture proportions. Because of the large scale of durability-related investigations, statistically based experimental design procedures have been adopted to efficiently investigate as many combinations of materials as possible with the minimum number of tests. The data generated by this test program are used to develop models that predict the performance of mixtures for any combination of the tested levels.

This Methodology is flexible and the user selects the responses to be included in the evaluation of the mixtures, designs the desirability functions for each response to reflect the importance and reliability of the test result, and chooses the factors to be evaluated. These factors can be Amount, Type, or Source factors. This flexibility makes it useful in a range of mixture proportioning applications.

The Hypothetical Case Study, based on a realistic set of mixture objectives and conducted with a set of locally available materials, showed that the approach laid out in *NCHRP Report 566* can be used to identify an optimum concrete mixture proportion. Predictions based on empirical modeling of each response were used to predict a BPC that was produced and tested. Excellent agreement was observed between the individual responses and the overall desirabilities of this concrete as predicted and actually tested. While this was only the first experiment conducted with this Methodology, the accuracy of the modeling demonstrated the far-ranging potential of this approach.

Suggested Research and Implementation

During this project, the experimental design approach outlined in the Methodology was successfully implemented for one situation, the Hypothetical Case Study. *NCHRP Report 566* was developed to be a stand-alone guide to allow this approach to be applied in a wide range of situations. However, implementation of the Methodology is a significant undertaking for even experienced users and additional work is warranted to facilitate this process. The following tasks are suggested to further develop the Methodology and to support its implementation:

- Methodology Validation and Development
- Software Development and Support
- Implementation Support

Each of these tasks is discussed individually below.

Methodology Validation and Development

To fully evaluate the effectiveness of the approach, additional validation testing in a range of applications is recommended. The Methodology has been designed to reflect the fact that the experimental constraints for each individual application will vary widely throughout the country. The effectiveness of this strategy should be proven through its implementation in other mixture optimization projects. The modeling accuracy should also be evaluated based on data collected from design matrices constructed with different numbers and categories of factors, and for different sets of raw materials. Finally, as is the case with the field implementation of any new technology, long-term monitoring of actual bridge decks constructed with mixtures developed using this Methodology is recommended. This performance should be compared with bridges produced with concrete mixtures selected by conventional means to evaluate whether the extra effort involved in the optimization process is, in fact, justified.

The process outlined in *NCHRP Report 566* requires significant input from the user in selecting and evaluating test methods and materials to include in the experimental program. The best future use of this Methodology will include consideration of new test methods and additional materials. Therefore, the continued development of this Methodology must be based on the knowledge and understanding of the engineers or scientists in a position to use it.

Software Development and Support

In this project, good progress was made towards providing a computational tool package that will support the Methodology, including significant efforts in terms of decision making, documentation, data analyses, and optimization modeling. This package, SEDOC, has been established within the framework of Microsoft® Excel. This approach was selected since Excel is widely available and provides calculation and plotting tools that are familiar to most users. However, the SEDOC: Analysis tool is based on the specific workbook developed to perform the analysis conducted for the Hypothetical Case Study while that analysis process was being developed. As a result, it does not contain all the functionality that could be included in a package designed from the ground up, and additional work to develop the SEDOC tool further would be worthwhile. In addition, to fully realize the potential of the Methodology, a distribution and support framework for the tool is needed.

The current user-interface is spreadsheet-based and requires the user to fill in appropriate cells, which can be confusing and difficult to locate for users unfamiliar with the Methodology or the software. The ease of use of the tool could be improved by incorporating dialogs that prompt the user to perform tasks in the correct sequence and query the user for information where needed.

The SEDOC package, in its present form, contains specific workbooks for a limited number of individual design matrices. While a user of this Methodology could develop spreadsheets for a specific unsupported matrix based on the information provided in *NCHRP Report 566*, the additional time required for that task would make the implementation of this Methodology a formidable task. The specific matrices that are currently supported were chosen to span the range of possibilities and include 9- and 18-mixture designs. Because the shape of the experiment in the current tool is limited to be one of those supported, additional development is needed to make SEDOC a viable tool for all practical experiment designs.

While the optimization routine implemented in the SEDOC package is a simple brute-force evaluation of all possible combinations, other optimization routines could be applied that would identify multiple mixtures worthy of consideration for selection as the BC. This would be of interest if multiple, local optima in the overall desirability response surface occur with significantly different combinations of materials but similar overall desirabilities. The selection of multiple, locally optimized mixtures would be based on thresholds for the overall desirability that would need to be defined by the user. Identifying a range of mixtures (if they exist) that provide similar performance, instead of a single optimized mixture, would provide additional flexibility to deal with specification and other construction-related issues.

A single program able to perform all the steps in the experimental setup and analysis process, able to deal with each of the potential orthogonal designs and incorporating the above modifications would be an improvement on the existing program. This could be achieved within Microsoft® Excel using Visual Basic routines or as an independent PC-based application created specifically to perform this task. The PC-based application will provide the most flexibility for the developers, allowing dynamic definition of the arrays depending on the design matrix selected for use, which would simplify the process of supporting multiple designs from a single interface. Dynamic array definition is also possible within Excel but was not incorporated in the SEDOC tool because of the substantial computer programming effort required, which was not a focus of this study. Developing an independent PC-based application has the disadvantage of requiring building many features from the ground up, including some that Excel already provides, like plotting and regression analysis.

An effort to develop a simpler and more robust software application would require at least the three following types of expertise: software development, statistical experimental design, and concrete mixture expertise. A team with a wide breadth of experience will be needed to complete this development. The first step in such a project will be establishing the scope of the application by balancing what is desirable for the experimental design and mixture development processes with what is feasible for the software development.

Implementation Support

The Methodology developed is a sequence of steps that requires users to evaluate their specific performance demands and materials and to design and conduct a unique experiment. This can be a difficult process to apply since each situation will be different, and the specific example provided in *NCHRP Report 566* shows only one of the many ways in which the process can be applied. Therefore, a support network to help potential users learn the Methodology and operate the computational tool should be established.

To help interested engineers and scientists implement this process, a short course (two to three days long) would be useful to teach potential users how to work through the Methodology. Each step of the process could be reviewed in detail, and specific questions relative to individual situations could be covered. On-going implementation support should include an internet-based bulletin board for specific questions on using the Methodology and a help contact for the SEDOC package, where questions related to performing the statistical-analysis could be answered.

The ultimate success of this research project will be based on the number of people and organizations that are able to make effective use of this process that was developed to select optimized mixture proportions for a local set of conditions and materials. That number will be maximized by ensuring that potentially interested parties are aware of and know how to use this Methodology.

REFERENCES

(1) Derringer, G. and Suich, R., "Simultaneous Optimization of Several Response Variables," *Journal of Quality Technology*, Vol. 12 (1980) pp. 214-219.

(2) ACI Committee 211, "Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete," ACI 211.1-91, American Concrete Institute, Farmington Hills, MI (1991).

APPENDIX: HYPOTHETICAL CASE STUDY

Introduction

Objective of Hypothetical Case Study

A methodology for designing hydraulic cement concrete mixtures incorporating supplementary cementitious materials that will result in enhanced durability of cast-in-place concrete bridge decks was developed using a statistically based experimental design approach under NCHRP Project 18-08A. This process is detailed in *NCHRP Report 566: Guidelines for Concrete Mixtures Containing Supplementary Cementitious Materials to Enhance Durability of Bridge Decks* and consists of the following six steps:

Step 1: Define Concrete Performance Requirements
Step 2: Select Durable Raw Materials
Step 3: Generate the Experimental Design Matrix
Step 4: Perform Testing
Step 5: Analyze Test Results and Predict the Optimum Mixture Proportions
Step 6: Perform Confirmation Testing and Select Best Concrete

To evaluate the effectiveness of this Methodology, a case study, called the Hypothetical Case Study, chosen as a bridge deck in a northern, Midwest environment subject to freezing and thawing and deicing salt exposure, was investigated. Hypothetical performance requirements were developed and materials locally available near Chicago, IL, were obtained and used to conduct an experimental study. This test program was conducted according to the process outlined in *NCHRP Report 566* and the accuracy of the statistical analysis and modeling was evaluated based on these results. The step-by-step details of this study are provided in this appendix, to serve both as an example of how the Methodology may be applied and to provide a basis for evaluating its effectiveness.

Organization of Document

To distinguish table and figure numbers in *NCHRP Report 566* from those in this document, *NCHRP Report 566* table and figure numbers are prefaced by an "S" followed by the Step number. For example, Table S1.1 is the first table in Step 1 of *NCHRP Report 566*. All figures and tables discussed in this appendix are all prefaced by the letter "A".

Step 1: Define Concrete Performance Requirements

Based on a bridge deck application in a northern climate, Figure S1.1 was used to characterize the design requirements and issues relevant to a freezing climate subjected to chemical deicers, where cracking was a concern. This environment was assumed to be neither coastal nor abrasive.

Worksheet S1.1, completed for the Hypothetical Case Study, is presented as Table A-1. This was filled out according to the guidance provided in Step 1 of *NCHRP Report 566*. The recommended testing program based on the service environment of the Hypothetical Case Study have been summarized on this worksheet, which list the properties of interest, the test methods to measure each property, and optimum target values that will be used to develop the desirability functions. Categories that were not applicable to the Hypothetical Case Study environment were struck out. The recommended ranges of SCM contents expected to produce desirable performance were collected for each property and the columns were summarized in the row at the bottom of the worksheet. This summary row will serve as a reference point for selecting the ranges for testing over which each material may be optimized.

Table A-1. Completed Worksheet S1.1 for the Hypothetical Case Study

Environment	Property/Test Method	Target Value for Test Method	Range of Class C Fly Ash	Range of Class F Fly Ash	Range of GGBFS	Range of silica fume	Range of other SCM	w/cm	Aggregate restrictions	Specified aggregate top size	Specified cement content	Other requirements
Universal performance requirements	Compressive strength: AASTHO T 22, ASTM C 143	4,500 - 8,000 psi	0-30	0-30	15-50	5-8		0.44-0.37				f'_c > 4500 psi
	Flexural strength: AASTHO T 177, T 97, or T 198, ASTM C 293, C 78, or C 496											
	Slump and Slump loss: AASHTO T 119, ASTM C 143	Max 8-in.; Max. 4-in. after 45 min.	10-30	10-40	15-40	5-8						slump > 3 in.
	Time of setting: AASHTO T 197, ASTM C 403	Min 3 hrs.	0-30	0-25	15-40	5-8						
	Finishability	Qualitative	0-25	0-25	10-30	0-8						
Freezing and thawing with chemical deicers	Chloride penetration: AASHTO T 259, ASTM C 1566	$D_a < 2x10^{-12}$ m^2/s	15-40	15-25	15-30	5-8		<0.40				slump > 3 in.
	Electrical Conductivity: AASHTO T 277, ASTM C 1202	<2000 at 56 days	15-40	15-25	15-30	5-8		<0.40				
	Scaling Resistance: ASTM C 672	0-1 at 50 cycles; <500 g/m^2	0-25	0-25	0-40	5-8		<0.45	Minimum amount of low density particles		>564 lb/yd^3	f'_c > 3500 psi
Freezing and thawing without chemical deicers	Air content, %: ASTM C 457	6 ± 1.5%	0-25	0-25	0-40	0-8						
	Spacing factor: ASTM C 457	Min 600 in^2/in^3	0-25	0-25	0-40	0-8						
	Freezing and Thawing Resistance: AASHTO T 161 A, ASTM C666 A	DF > 90% at 300 cycles	0-25	0-25	0-40	5-8		<0.45	Good quality		>564 lb/yd^3	f'_c > 4000 psi prior to testing
Coastal	Chloride penetration: AASHTO T 259, ASTM C 1566											
	Electrical Conductivity: AASHTO T 277, ASTM C 1202											
Abrasive	Abrasion: ASTM C944 or C 779 Procedure B											
Cracking resistance: ASR	Go to Raw Materials Flow Chart											
Cracking resistance: restrained shrinkage	Restrained Ring Cracking: AASHTO PP 34-99, ASTM C 1581	Longer time to cracking	10-25	10-25	15-35	0-5						
	Free drying Shrinkage: AASHTO T 150, ASTM C 157	<0.06% at 90 d	0-25	0-25	0-35	0-5						
Cracking resistance: thermal concerns	Heat of Hydration	Lowest temp. rise	0-25	25-35	30-60	0-8						
	Modulus of elasticity, ASTM C 469	3 to $5x10^6$ psi at 28 days	0-30	10-30	15-35	0-5						
Cracking resistance: plastic shrinkage	Plastic Shrinkage Cracking: ICC AC32 Annex A	Smaller cracking area	0-25	0-25	0-30	0-5						
Other design requirements												
SUMMARY			15-25	25	30	5		<0.40			>564 lb/yd^3	f'_c > 4500 psi

Step 2: Select Durable Raw Materials

The objective of Step 2 is the selection of suitable raw materials. The worksheets in Step 2 of *NCHRP Report 566* were used to organize the available information regarding the locally available materials and facilitate these decisions. Completed worksheets are presented in Table A-1 through Table A-10 based on the actual data available for the local materials, though aliases were substituted for the names of the specific suppliers. Per Step 2 procedures, Worksheet S2.1 was completed (Table A-2) listing the potential materials. The properties of the cement sources that were identified, namely "Cemsource 1" and "Cemsource 2", were listed in Worksheet S2.2 (Table A-3). The sources were then compared and a selection of that material type made. In this case, "Cemsource 2" was selected based on the comparatively lower alkali content and C_3S content compared to "Cemsource 1". This selection was denoted by a box drawn around the Source in Worksheet S2.1 (Table A-2). A similar process was performed for the fine aggregate using Worksheet S2.3 (Table A-4). "Fineagg manufacturer 2" was selected based on the higher fineness modulus and better soundness test results. This fine aggregate had larger amounts of potentially reactive particles, but both sources produced similar inconclusive results in ASTM C 1260 ASR testing. Since ASR may still be possible in this situation based on this data, the importance of the choice of a low-alkali cement is reinforced. This selection was recorded on Worksheet S2.1 (Table A-2). Completed versions of Worksheet S2.5 (Table A-6), Worksheet S2.6 (Table A-7), Worksheet S2.8 (Table A-8), Worksheet S2.9 (Table A-9), and Worksheet S2.10 (Table A-10) show how these worksheets can be used to select Class C fly ash sources, Class F fly ash sources, slag sources, silica fume sources and air-entraining agents and chemical admixtures, respectively.

Table A-2. Completed Worksheet S2.1, list of available raw materials

Raw Material	Source 1	Source 2	Source 3	Source 4
Cement	Cemsource 1	Cemsource 2		
Fine aggregate	Fineagg manufacturer 1	Fineagg manufacturer 2		
Coarse aggregate	Coarseagg manufacturer 1	Coarseagg manufacturer 2		
Class C fly ash	C-ashsource 1	C-ashsource 2		
Class F fly ash	F-ashsource 1			
Ground granulated blast furnace slag	Slagsource 1	Slagsource 2		
Silica fume	Silica fume source 1			
Other SCM				
Air entraining admixture	Air 1			
Chemical admixture	Super X	Super Y		
Chemical admixture				
Other:				

Selected for use

Table A-3. Completed Worksheet S2.2, Cement data

Test/Property	AASHTO Limit	Cement 1	Cement 2	Cement 3	Cement 4
Manufacturer		Cemsource 1	Cemsource 2		
Plant location		Anytown	Ourtown		
Mill report date		Apr 03	Aug 01		
AASHTO M 85 (ASTM C 150) Cements					
Type		I	I		
C_3S (%)[1]	≤ 58 for Type II	68	59		
C_2S (%)[2]		--	15		
C_3A (%)[3]	≤ 8 for Type II	8	9		
Total alkalis (Na_2O_{eq}) (%)[4]	≤ 0.60 for low alkali optional requirement	0.90	0.51		
SO_3 (%)	3.0 (unless C_3A> 8%, then 3.5 for Type I)[5]	2.4	2.4		
MgO (%)[6]	≤ 6.0	2.3	3.9		
Rapid stiffening (y/n)[7]		Workability restored upon remixing	48.5 mm penetration at 11 min.		
AASHTO M 240, ASTM C 595, or C 1157 Cements					
Type		N/a	N/a		
Portland cement, %		N/a	N/a		
Second constituent, %		N/a	N/a		
Third constituent, %		N/a	N/a		
Fourth constituent, %		N/a	N/a		

1 Relates to early age strength gain
2 Higher contents indicate slower early-age strength gain, but may have higher ultimate strength
3 C_3A reacts with sulfate to form ettringite; higher values indicate less resistance to external sulfate attack
4 This value is important if potentially reactive aggregates are being used in the mixture
5 These limits are for Type I and II cements; if SO_3 exceeds these limits, request ASTM C 1038 backup data. The expansion in water according to ASTM C 1038 should not exceed 0.020% at 14 days. Type III cement has different limits; see ASTM C 150 for details.
6 Excessive amounts of MgO (periclase) can result in unsoundness (deleterious expansion)
7 Prescreening cements by ASTM C 359 *Standard Test Method for Early Stiffening of Portland cement (Mortar Method)* may be desirable to test for flash or false set or high water demand. The needle penetration at 11 minutes or on remix should be greater than 35 mm

Table A-4. Completed Worksheet S2.3, Fine aggregate data

Test/Property	AASHTO M 6 Class A Limit	Local Requirements	Fine Agg. 1	Fine Agg. 2	Fine Agg. 3
Manufacturer			Fineagg manufacturer 1	Fineagg manufacturer 2	
Pit location			Anytown	Ourtown	
Date of last ASTM C 295 petrographic examination			2000	2000	
Primary Mineralogy			Limestone / quartz	Limestone / quartz	
Specific gravity (SSD)			2.650	2.671	
Absorption capacity (%)			0.7	1.1	
Clay lumps and friable particles	≤ 3.0% max	Details in Std. specs.	N/a	N/a	
Material finer than 75-µm (No. 200) sieve	≤ 2.0% max, concrete subject to abrasion	3% max.	N/a	N/a	
	≤ 3.0% max, all other concrete		N/a	N/a	
Coal and lignite, concrete where surface appearance is not important	≤ 0.25%, max		N/a	N/a	
Check meets standard gradation			√	√	
Fineness modulus	2.3-3.1		2.59	2.85	
Organic impurities	Lighter than color standard		N/a	N/a	
Soundness	Weighted average loss ≤10%*	Na_2SO_4: 10% max.	$MgSO_4$: 15%	$MgSO_4$: 9%	
Other deleterious substances	Local requirements		N/a	N/a	
Types and amounts (%) of particles deleteriously reactive with alkalis			1.3% potentially reactive chert	4% pot. react. chert, amounts of opal	
ASTM C 1260 Expansion	<0.10%†		0.17	0.16	
ASTM C 1293 Expansion	<0.04%†		N/a	N/a	

* When sodium sulfate is used; 15% when magnesium sulfate is used
† ASTM C 33 requirements

Table A-5. Completed Worksheet S2.4, Coarse aggregate data

Test/Property	AASHTO M 80 Class A Requirements†	Local Requirement IDOT Class A	Coarse Agg. 1	Coarse Agg. 2	Coarse Agg. 3
Manufacturer			Coarseagg manufacturer 1	Coarseagg manufacturer 2	
Pit location			Anytown	Ourtown	
Check meets standard gradation			√	√	
Date of last ASTM C 295 petrographic examination			2000	2000	
Primary Mineralogy			Limestone	Limestone	
Grading size number			CA11	CA7/11	
Specific gravity (SSD)			2.719	2.690	
Absorption capacity (%)			1.3	1.1	
Clay lumps and friable particles	≤ 2.0% max.	Details in specs	N/a	N/a	
Chert*	≤ 3.0% max.		Trace	N/a	
Sum of clay lumps, friable particles, and chert*	≤ 3.0% max.		N/a	N/a	
Material finer than 75-µm (No. 200) sieve	≤ 1.0% max.		N/a	N/a	
Coal and lignite	≤ 0.5% max.	0.25% max.	N/a	N/a	
Abrasion	≤ 50% max.	40% max	24	N/a	
Sodium sulfate soundness, 5 cycles	≤ 12% max. **	Na_2SO_4 15% max.	$MgSO_4$: 5.6	$MgSO_4$: 14.3	
Types and amounts (%) of particles deleteriously reactive with alkalis	--		Trace chert	0	
ASTM C 1260 Expansion	<0.10%‡		0.01	0.03	
ASTM C 1293 Expansion	<0.04%‡		0.01	0.01	

* Less than 2.40 specific gravity SSD
** 18% max. if magnesium sulfate is used.
† These are the most stringent AASHTO M 80 values.
‡ ASTM C 33 recommendations

Table A-6. Completed Worksheet S2.5, Class C fly ash data

Test/Property	AASHTO M 295 Requirement	Fly Ash 1	Fly Ash 2	Fly Ash 3	Fly Ash 4
Manufacturer		C-ashsource 1	C-ashsource 2		
Source/plant location		Anytown	Ourtown		
SiO_2+Al_2O_3+Fe_2O_3, %	≥ 50.0	59.9	59.2		
CaO, %		27.7	27.4		
SO_3, %	≤ 5.0	2.01	1.99		
Moisture content, %	≤ 3.0	0.06	0.06		
Loss on ignition, %	≤ 5.0	0.21	0.40		
Amt. retained when wet-sieved on 45 µm (No. 325) sieve, %	≤ 34	15.5	13.1		
Strength activity index, 7-day, % of control	≥ 75	103.4	104.8		
Strength activity index, 28-day, % of control	≥ 75	N/a	N/a		
Water requirement, % of control	≤ 105	91.7	92.6		
Soundness: autoclave expansion or contraction, %	≤ 0.8	0.11	0.11		
Density, variation from average, %	≤ 5	0	1.44		
Percent retained on 45-µm (No. 325) seive, percentage points from average	≤ 5 of variation	1.3	-0.7		
Available alkalis, %	≤ 1.5	1.05 (total 2.13)	(total 2.64)		

Table A-7. Completed Worksheet S2.6, Class F fly ash data

Test/Property	AASHTO M 295 Requirement	Fly Ash 1	Fly Ash 2	Fly Ash 3	Fly Ash 4
Manufacturer		F-ashsource 1			
Source/plant location		Anytown			
SiO_2+Al_2O_3+Fe_2O_3, %	≥ 70.0	90.5			
CaO, %		2.70			
SO_3, %	≤ 5.0	0.82			
Moisture content, %	≤ 3.0	0.14			
Loss on ignition, %	≤ 5.0	1.61			
Amt. retained when wet-sieved on 45 µm (No. 325) sieve, %	≤ 34	22.1			
Strength activity index, 7-day, % of control	≥ 75	79.1			
Strength activity index, 28-day, % of control	≥ 75	81.9			
Water requirement, % of control	≤ 105	97.5			
Soundness: autoclave expansion or contraction, %	≤ 0.8	-0.03			
Density, variation from average, %	≤ 5	N/a			
Percent retained on 45-µm (No. 325) seive, variation, percentage points from average	≤ 5	N/a			
Available alkalis, %	≤ 1.5	N/a			

Table A-8. Completed Worksheet S2.8, Ground granulated blast-furnace slag (GGBFS) data

Test/Property	AASHTO M 302 Value	GGBFS 1	GGBFS 2	GGBFS 3	GGBFS 4
Manufacturer		Slagsource 1	Slagsource 2		
Source/plant location		Anytown	Ourtown		
Grade		120	120		
Amt. retained when wet-sieved on 45 µm (No. 325) sieve, %	≤ 20	6.0	7.2		
Specific surface by air permeability (Method C 204)		536	349		
Air content of slag mortar, %	≤ 12	5.9	5.9		
7-day slag activity index, %*	Grade 100: ≥ 75 Grade 120: ≥ 95	N/a	N/a		
28-day slag activity index, %*	Grade 80: ≥ 75 Grade 100: ≥ 95 Grade 120: ≥ 115	133	125		
Sulfide sulfur (S), %	≤ 2.5	1.6	1.00		
Sulfate ion reported as SO_3, %	≤ 4.0	2.7	0.00		

*Any individual sample

Table A-9. Completed Worksheet S2.9, Silica fume data

Test/Property	AASHTO M 307 Value	Silica fume 1	Silica fume 2	Silica Fume 3	Silica fume 4
Manufacturer		Silicafume source 1			
Source/plant location		Anytown			
SiO_2, %	≥ 85.0	89.1			
Moisture content, %	≤ 3.0	n/a			
Loss on ignition, %	≤ 6.0	1.16			
Optional: moisture content of dry microsilica, %	≤ 3.0				
Optional: available alkalis as Na_2O, %	≤ 1.5				
Strength activity index: With portland cement at 7 and 28 days, min. percent of control	≥ 100				

Table A-10. Completed Worksheet S2.10, air entraining agent (AEA) and chemical admixture data

Test/Property	ASSHTO M 154* or M 194** Value	AEA 1	AEA 2	Chemical admixture 1	Chemical admixture 2	Chemical admixture 3
Brand Name	--	Air 1		Super X	Super Y	
Manufacturer	--	Admix Co 1		Admix Co 1	Admix Co 2	
Chemistry	--	Vinsol resin		Naphthalene sulfonate	Polycarboxy-late	
AEA:						
Initial time of setting, allowable deviation from control, not more than (hr:min)	1:15 earlier nor 1:15 later	Letter of compliance				
Final time of setting, allowable deviation from control, not more than (hr:min)	1:15 earlier nor 1:15 later	Letter of compliance				
Compressive strength, % of control at 3, 7 and 28 days	≥ 90					
Chemical admixtures:						
Type	--			F	F	
S setting time and other requirements	See Table 1 of ASTM C 494			Letter of compliance	Letter of compliance	

* Equivalent to ASTM C 260
**Equivalent to ASTM C 494

Step 3: Generate the Experimental Design Matrix

The completed Worksheet S3.1 (Table A-11) shows the final choices made in Step 1 and 2 from the recommendations developed in Worksheets S1.1 and S2.1. The completed Worksheet S1.1 (Table A-1) lists a large number of tests necessary to characterize each mixture's performance. As a result, the experimental program was constrained by the available budget to a 9-mixture experiment. This number of experiments controlled the possible number of Factors and Levels to be evaluated as listed in Table S3.1 of *NCHRP Report 566*.

Given this constraint, the next step was to select which factors and levels to include. To actively test the Methodology relative to its intended use, the focus of the hypothetical experiment was to evaluate as a wide a range of SCMs as possible. Therefore, to maximize the number of SCMs while limiting the size of the experimental test program to nine mixtures, a design matrix consisting of three three-level factors and one two-level factor was selected from Table S3.1 (Table A-13). The specific factors for testing were chosen as "First SCM Type," "First SCM Amount," "Amount of Silica Fume," and "w/cm."

The range (levels) of investigation for each of the factors was chosen to span the upper and lower bounds where the optimum level was expected. This was performed for the Hypothetical Case Study using Worksheet S1.1 (completed for Step 1 in Table A-1), which considered a wide range of exposure conditions. When the recommended ranges of silica fume were compiled for all the desired properties in the "Summary" row of this worksheet, one level resulted: 5%. The same was true for GGBFS (30%) and Class C Fly ash (25%). Since the objective of this research is to optimize SCMs, the test program was centered on the summary values shown in Table A-1. The levels for Amount of Silica Fume were chosen to be 0, 5, and 8% even though the summary row of Table A-1 (Worksheet S1.1) recommends a constant amount of 5%. Similarly, the summary of the level of w/cm from completed Worksheet S1.1 recommended that the w/cm be less than 0.40. However, it was decided to broaden this range to include w/cm's of 0.37 and 0.45.

Ordinarily, an Amount Factor such as "First SCM Amount" would have simple numerical values given as levels. However, since the appropriate ranges for types of SCMs are dependant on that type, a Compound Factor was used. This Compound Factor, which links the definition of the Amount Factor to a Type Factor, allowed additional freedom in the definition of SCM contents. The levels of the First SCM Type factor were defined as slag, Class C fly ash and Class F fly ash. Then, the first SCM amount factor were defined generically as Low, Medium and High, with different specific values of the SCM content associated with each slag or fly ash material. Despite the generic definition, the "Amount of SCM" is still an Amount Factor and the performance models are still capable of interpolating between the levels tested. The definitions of low, medium and high were determined with Worksheet S3.2, shown as Table A-12.

Type, Source and Amount Constants are those characteristics of the mixture design that will be consistent throughout the experiment. These include single sources for each raw material type, and defining a constant cementitious (658 lb/yd^3 [391 kg/m^3]) content and coarse aggregate (1696 lb/yd^3 [1007 kg/m^3]) content. All SCM amounts were calculated as percentages by weight replacement of portland cement. Accordingly, changes in cementitious volumes were compensated by changes in fine aggregate content.

Two control mixtures were also incorporated in this study. The control mixture was made with no SCMs at a w/cm of 0.40. The mixture includes 263 lb/yd^3 (156 kg/m^3) water, 658 lb/yd^3 (391 kg/m^3) cement, 1280 lb/yd^3 (760 kg/m^3) fine aggregate, and 1696 lb/yd^3 (1007 kg/m^3)

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Table A-11. Completed Worksheet S3.1, factors, levels, and constants to test for Hypothetical Case Study

Factor	Level 1	Level 2	Level 3	
First SCM Type	Class C fly ash	Class F fly ash	GGBFS	**Type Factors**
				Source Factors
First SCM Amount	Low	Medium	High	**Amount Factors**
Amount of Silica fume	0	5	8	
w/cm	0.45	0.37		

		Type Constants
Cement	Cemsource 2	**Source Constants**
Fine aggregate	Fineagg manufacturer 2	
Coarse aggregate	Coarseagg manufacturer 1	
Class C fly ash	C-ashsource 1	
Class F fly ash	F-ashsource 1	
GGBFS	Slagsource 2	
Silica fume	Silica fume source 1	
Air entraining agent	Air 1	
HRWR	Super X	
Cementitious Content	658 lb/yd^3	**Amount Constants**
Coarse aggregate amount	1696 lb/yd^3	
Air content	6.5 ± 1.5%	

Table A-12. Worksheet S3.2 completed for compound factor for Hypothetical Case Study

Factor 1, Factor 2	Type of SCM	Amount of SCM
Type 1, Low level	Class C fly ash	15%
Type 1, Medium Level	Class C fly ash	25%
Type 1, High Level	Class C fly ash	40%
Type 2, Low level	Class F fly ash	15%
Type 2, Medium Level	Class F fly ash	25%
Type 2, High Level	Class F fly ash	40%
Type 3, Low level	slag	25%
Type 3, Medium Level	slag	35%
Type 3, High Level	slag	50%

Table A-13. Table S3.1 Number of mixtures required for an orthogonal design for various combinations of two- and three-level factors. The design selected for Hypothetical Case Study is highlighted.

	# of 3-level factors							
# of 2-level factors	0	1	2	3	4	5	6	7
0		3	9	9	9	16	18	18
1	2	8	9	9	16	18	18	18
2	4	8	9	16	16	18	18	>18
3	4	8	16	16	16	18	>18	>18
4	8	8	16	16	18	>18	>18	>18
5	8	16	16	16	>18	>18	>18	>18
6	8	16	16	16	>18	>18	>18	>18
7	8	16	16	>18	>18	>18	>18	>18
8	12	16	16	>18	>18	>18	>18	>18
9	12	16	16	>18	>18	>18	>18	>18
10	12	16	>18	>18	>18	>18	>18	>18
11	12	16	>18	>18	>18	>18	>18	>18
12	16	16	>18	>18	>18	>18	>18	>18
13	16	>18	>18	>18	>18	>18	>18	>18
14	16	>18	>18	>18	>18	>18	>18	>18
15	16	>18	>18	>18	>18	>18	>18	>18

coarse aggregate. The intent of this mixture was to provide a comparison to assess relative performance of mixtures with SCMs. A replicate of the control mixture was also added to provide an assessment of batch-to-batch variability for each test so that the significance of differences in test results can be evaluated.

In summary, Table A-11 lists the factors and levels for the Hypothetical Case Study, and also defines the constant values selected for this experiment. Table A-12 defines the specific quantities for the generic descriptions “low,” “medium,” and “high” used in the Compound Factor.

As mentioned, the orthogonal design requires nine specific mixtures be evaluated to provide sufficient information to optimize these factors and levels. These mixtures must be chosen according to the applicable table from the collected orthogonal experimental design matrices at the end of Step 3 of *NCHRP Report 566*. The generic design matrix that applies for the nine-mixture, three three-level factor and one two-level factor design is given in Table A-14. Table A-15 lists the specific design matrix after the factor levels were substituted into this generic matrix. The mixtures and theoretical and actual batch weights per unit volume tested are listed in Table A-16. The actual batch weights per unit volume were calculated based on the unit weight measured for each batch according to ASTM C 138 Test Method for Unit Weight, Yield and Air Content (Gravimetric) of Concrete.

Table A-14. The levels for the 9-mixture design matrix with 3 three-level and 1 two-level factor (The numbers in the columns refer to the levels indicated in Table 3.)

Mixture #	Factor 1 (3-Level)	Factor 2 (3-Level)	Factor 3 (3-Level)	Factor 4 (2-Level)
1	1	1	1	1
2	1	2	2	**<u>2</u>**
3	1	3	3	**<u>2</u>**
4	2	1	2	**<u>2</u>**
5	2	2	3	1
6	2	3	1	**<u>2</u>**
7	3	1	3	**<u>2</u>**
8	3	2	1	**<u>2</u>**
9	3	3	2	1

(If the font is underlined and bold, the level chosen for that Factor should be the one expected to produce the best result.)

Table A-15. Experimental design matrix for Hypothetical Case Study

Mixture	First SCM Type	First SCM Amount	Amount of Silica Fume	w/cm
1	Fly Ash C	Low (15%)	0 %	0.45
2	Fly Ash C	Medium (25%)	5 %	0.37
3	Fly Ash C	High (40%)	8 %	0.37
4	Fly Ash F	Low (15%)	5 %	0.37
5	Fly Ash F	Medium (25%)	8 %	0.45
6	Fly Ash F	High (40%)	0 %	0.37
7	GGBFS	Low (25%)	8 %	0.37
8	GGBFS	Medium (35%)	0 %	0.37
9	GGBFS	High (50%)	5 %	0.45

Table A-16. Concrete test mixtures as batched

	Mixture ID												
	C1	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**C2**	**BTC (8)**	**BPC**
w/cm	0.4	0.45	0.37	0.37	0.37	0.45	0.37	0.37	0.37	0.45	0.4	0.37	0.39
	Percent replacement of cement (by wt.)												
Fly Ash (Class C)		15	25	40									
Fly Ash (Class F)					15	25	40						
Slag								25	35	50		35	35
Silica Fume		0	5	8	5	8	0	8	0	5		0	8
	Theoretical weight per unit volume (lbs./cu. yd.)												
Water content	263	296	243	243	243	296	243	243	243	296	263	243	257
Cement	658	559	461	342	526	441	395	441	428	296	658	428	375
Fly Ash (Class C)	0	99	165	263	0	0	0	0	0	0	0	0	0
Fly Ash (Class F)	0	0	0	0	99	165	263	0	0	0	0	0	0
Slag	0	0	0	0	0	0	0	165	230	329	0	230	230
Silica Fume	0	0	33	53	33	53	0	53	0	33	0	0	53
Fine Aggregate	1280	1180	1300	1280	1294	1128	1261	1302	1316	1156	1280	1316	1262
Coarse Aggregate	1696	1696	1696	1696	1696	1696	1696	1696	1696	1696	1696	1696	1696
	Admixture dosage (fl. oz./cwt.)												
AEA	1.70	2.32	3.10	3.83	2.61	3.89	3.35	2.33	2.64	4.78	1.28	2.43	4.01
Superplasticizer	9.07	4.87	25.50	36.60	22.70	16.01	12.59	33.49	24.27	14.81	8.74	18.33	34.15
	Actual weight per unit volume as batched (lbs./cu. yd.)												
Water content	258	295	235	243	239	291	238	242	241	301	263	234	250
Cement	645	558	445	341	517	433	386	438	423	301	658	411	365
Fly Ash (Class C)	0	98	159	262	0	0	0	0	0	0	0	0	0
Fly Ash (Class F)	0	0	0	0	97	162	257	0	0	0	0	0	0
Slag	0	0	0	0	0	0	0	163	228	335	0	221	224
Silica Fume	0	0	32	52	32	52	0	52	0	33	0	0	51
Fine Aggregate	1255	1177	1256	1276	1271	1109	1233	1292	1303	1177	1280	1264	1227
Coarse Aggregate	1662	1693	1638	1690	1665	1667	1658	1684	1679	1727	1696	1629	1650

Step 4: Perform Testing

The test program outlined in Step 1 (as shown in Worksheet S1.1, Table A-1) was modified slightly in practice and the actual program is given in Table A-17. The plastic shrinkage cracking test was eliminated because the costs involved were thought to outweigh the value of the information gained through the available test method. This was conducted on the mixtures listed in Table A-15. Since the experimental program required many samples, a volume of approximately seven cubic feet was required for each batch. Before the full size batches were produced, smaller trial batches were made for each mixture to determine the necessary chemical admixture dosage to achieve the desired plastic properties. The amount of admixtures varied for each mixture since both the w/cm and the amount and types of SCMs varied as shown in Table A-14. The concrete was mixed in a drum mixer and the order of addition of materials was as follows: The air-entraining admixture and the water were mixed together and all but approximately 20% of this solution was added to the mixer along with the coarse aggregate. The fine aggregate, cement, and SCMs were then added gradually to the mixer with half of the superplasticizer dosage over approximately three minutes. When these materials had been added to the mixer, the remaining mixer water and any final dose of superplasticizer was added. The batch time for the timed test methods was recorded as the time that all the materials were added to the mixer, and following that time a standard protocol of three minutes mixing, three minutes rest and two minutes mixing, as laid out in ASTM C 192 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory, was followed. Figure A-1 shows one of the full-scale concrete batches being produced.

Plastic Properties

The initial slump and the slump 45 minutes after all materials were added to the mixer were measured according to AASHTO T 119. The slump loss is the difference between these two measurements. The air content and initial set time was measured according to AASHTO T 152 and AASHTO T 197, respectively.

The assessment of finishability was performed in the following manner. A 1 x 2 x 0.5 ft (300 x 600 x 150 mm) form was filled with concrete and moved into a room with 43-52% relative humidity. Starting one hour after batching, the concrete was evaluated by three people who each screeded the slab and then graded how the concrete rated across four scales: stickiness vs. creaminess, segregation vs. homogeneity, harshness vs. smoothness, and prone to tearing vs. tear resistant. These were assigned point values from 1 to 5, respectively. The grades assigned for each category were averaged for all finishers, and then summed to produce an overall finishability rating. Figure A-2 shows the test being conducted and Figure A-3 shows the worksheet used to collect the data. The data for the plastic properties for all the concrete mixtures are summarized in Table A-18.

Table A-17. Program for testing of design matrix

Property	Target Values	Test Methods	Specimen Size and Number of Specimens	Curing
Total air content, plastic concrete	6.5 +/- 1.5%	AASHTO T 152	_	N/A
Max. slump after High Range Water Reducer (HRWR) addition	8 in.	AASHTO T 119	_	N/A
Slump, minimum after 45 minutes	4 in.	AASHTO T 119	_	N/A
Initial set time, minimum	3 hours	AASHTO T 197	_	N/A
Finishability	Comparative scale	Qualitative assessment	_	N/A
Cracking tendency (restrained shrinkage)	Longer time-to-cracking is preferred	AASHTO PP 34-99	Two 18-in. OD x 12-in. ID x 6-in.	Wet for 7 days
Thermal effects (heat of hydration)	Lowest change in temperature is preferred	Temperature rise in cylinder	One 6x12-in. cylinder	N/A
Shrinkage (1, 3, 7, 14, 28, 56, 90 days after curing)	< 0.06% at 90 days	AASHTO T 160	Three at each age; 3x3x11.25-in.	Wet for 7 days
Compressive strength (at 3, 7, 28, 56 days)	28-day specified* range: 4,500 - 8,000 psi	AASHTO T 22	Three at each age; 4x8-in.	Wet
Modulus of elasticity (at 7 and 28 days)	7-day target: $< 4 \times 10^6$ psi	AASHTO T 22	Three at each age; 4x8-in.	Wet
Hardened air analysis (greater than 7 days)	Total air content: 6.5 +/- 1.5%	ASTM C 457	One 4x8-in cylinder.	Wet for 7 days
	Max. air void spacing factor: 0.008 in			
Freeze/thaw resistance	DF>90% at 300 cycles	AASHTO T 161A	Three 3x4x16-in.	Wet for 14 days
Electrical conductivity	<2000 coulombs at 56 days	AASHTO T 277	Two slices at 4x8-in.	Wet for 56 days
Chloride penetration resistance (one 3-in. core from each slab, evaluated at 6 mos.)	$D_a < 2 \times 10^{-12}$ m^2/s at 6 months*	Modified AASHTO T 259/T 260	Three 12x12x3-in.	14 days moist, 28 days 50% RH
Salt scaling resistance	Visual rating of 0-1 at 50 cycles; Mass loss < 500 g/m^2 at 50 cycles	ASTM C 672	Three 12x12x3-in.	14 days moist, 14 days 50% RH

* Note that the average strength must be higher than the minimum specified to account for natural variability in the concrete performance.

Figure A-1. Batching of concrete

Figure A-2. Performing finishability test on concrete mixture

Finishing Data Worksheet 2002.2229 1D

Mix Number ____________________

Date __________________________

Concrete Temperature ______________

Air Temperature _________________

Relative Humidity _________________

1	2	3	4	5
Stickiness				Creaminess
1	2	3	4	5
Segregation				Homogeneity
1	2	3	4	5
Harshness				Smoothness
1	2	3	4	5
Prone to Tearing				Tear Resistant

Figure A-3. Finishability worksheet used to collect data

Table A-18. Plastic concrete results

Mixture	Description* (% by wt.) SCM/SF/(w/cm)	Cast date	Slump (in.)	Slump loss at 45 min. (in.)	Plastic Air (%)	Initial Set (hr:min)	Final Set (hr:min)	Finishability
C1	Control (w/c 0.40)	2/26/04	6.25	2.5	7.0	4:05	5:35	17.7
1	15C/0/0.45	3/9/04	8	2	6.0	6:25	8:45	15.6
2	25C/5/0.37	3/18/04	8	4.25	7.8	6:40	8:45	9.4
3	40C/8/0.37	3/18/04	6	3.25	6.2	9:20	13:00	11.7
4	15F/5/0.37	4/13/04	6	1.25	6.9	4:40	6:10	10.3
5	25F/8/0.45	4/13/04	6.75	0.75	7.4	5:55	8:10	15.0
6	40F/0/0.37	4/13/04	6.5	0.75	6.8	6:10	8:25	15.9
7	25S/8/0.37	3/23/04	6.75	3.5	6.2	4:40	6:30	12.0
8	35S/0/0.37	3/30/04	7.75	1.75	6.1	5:30	7:05	11.3
9	50S/5/0.45	3/23/04	6	1.5	4.7	5:40	7:00	13.6
C2	Control (w/c 0.40)	3/30/04	5.5	3.5	5.2	3:55	5:15	15.3
BTC	35S/0/0.37	1/14/05	6.25	2.25	7.0	5:05	6:55	
BPC	35S/8/0.39	1/14/05	7.25	3	6.7	6:25	9:05	

* C = Class C Fly Ash
F = Class F Fly Ash
S = Blast Furnace Slag
SF = Silica Fume

Measurement of Cracking Potential

Three tests were conducted to assess cracking potential. The first was cracking tendency, AASHTO PP34-99 (the restrained shrinkage test). Two rings were cast for each mixture, vibrated in the forms, and, wet cured for seven days. They were then stripped and moved to a 73°F (23ºC), 50% relative humidity room. The strain in the steel ring was measured with four strain gauges bonded to the interior steel surface. The rings were visually examined at regular interval for the presence of cracks and the strain gage output was logged throughout the test. The age of cracking was noted by a sudden change in strain. Steel rings of 3/4- and 1-in. (19- and 25-mm) thickness were used. All mixtures were tested with one ring of each thickness except for the first two mixtures batched, which were Mixture C1 (two 3/4-in. [19-mm] thick rings) and Mixture 1 (two 1-in. [25-mm] thick rings). Figure A-4 shows typical casting procedure for the rings and Figure A-5 shows the climate control room with the rings connected to the data logger. Figure A-6 shows the strain versus time for a specimen that cracked at just over 80 days of age.

The cracking tendency of these mixtures was low and the first observed crack in any of the mixtures occurred at an age of 43 days. As a result, the age to first crack was measured in terms of weeks rather than days. Many rings did not crack through 36 weeks of drying, but since a numerical result is required for calculating the desirability for this response based on the desirability function, the samples that did not crack were assigned a value of 36 weeks. In general, all mixtures were forgiving with respect to cracking tendency. This may be related to the limestone coarse aggregate, which has been seen to produce concretes that are less likely to crack than most in previous testing conducted by the researchers. The ages (in weeks, including curing) of the rings that cracked are listed in Table A-19.

Figure A-4. Rings being cast and vibrated for cracking tendency test

Figure A-5. Ring storage and data collection in 50% RH laboratory environment

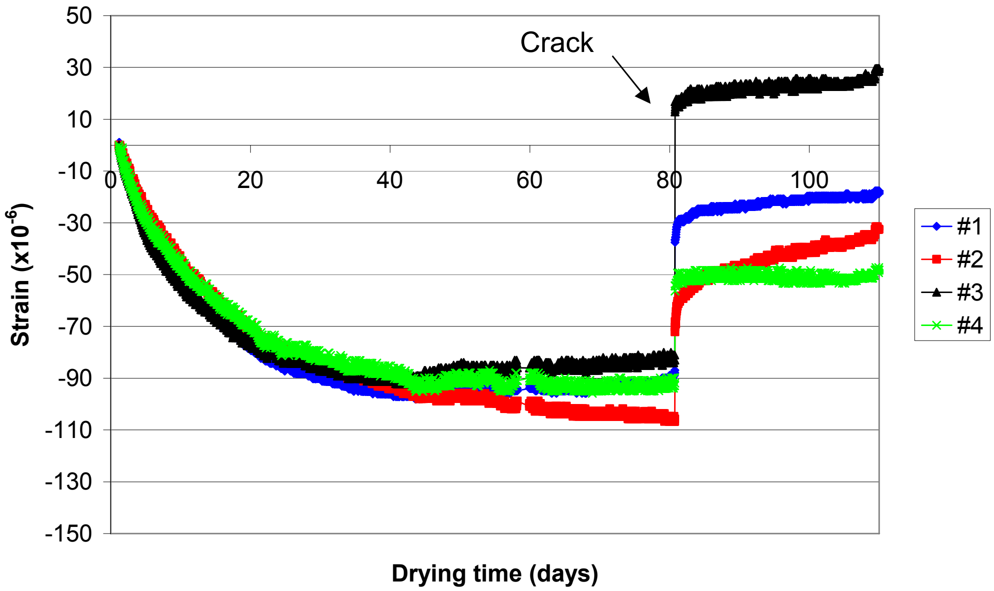

Figure A-6. Strain versus drying time for a typical cracking tendency test where cracking occurred

Table A-19. Cracking potential test results

Mixture	Description (% by wt.) SCM/SF/(w/cm)	Cracking Tendency* (Weeks)	Temperature Rise due to Hydration (ºF)	Shrinkage at 90 days (με)
C1	Control (w/c 0.40)	24	55	-0.0621
1	15C/0/0.45	36	49	-0.0684
2	25C/5/0.37	36	47	-0.0521
3	40C/8/0.37	36	41	-0.0474
4	15F/5/0.37	36	43	-0.0501
5	25F/8/0.45	23	37	-0.0633
6	40F/0/0.37	22	32	-0.0512
7	25S/8/0.37	36	45	-0.0442
8	35S/0/0.37	8	46	-0.0389
9	50S/5/0.45	36	41	-0.0457
C2	Control (w/c 0.40)	16	56	
BTC	35S/0/0.37		46	-0.0452
BPC	35S/8/0.39		44	-0.0476

*Average age to first crack calculated using 36 weeks for rings that did not crack.

A second test was developed to comparatively assess the heat of hydration of each concrete batch, with the idea that larger increases in temperature indicate that a concrete is more susceptible to thermal cracking. A 6 x 12-in. (150 x 300 mm) cylinder of concrete was cast, and a thermocouple was placed into the center of the cylinder as shown in Figure A-7. The cylinder was placed into a box of insulating foam and a cover of foam was placed over the sample as shown in Figure A-8. The thermocouple was attached to a data logger that recorded temperature over a period of more than 100 hrs. Figure A-9 shows the data from each concrete mixture. Table A-19 summarizes the increase in temperature each concrete mixture experienced due to hydration.

The final assessment of cracking potential was the free drying shrinkage test, AASHTO T 160. Three prisms, 3 x 3 x 11.25-in. (75 x 75 x 281 mm), were cast, cured for seven days, placed in a 73ºF (23ºC), 50% RH room, and their lengths were periodically measured. Figure A-10 shows the drying shrinkage behavior over time. The shrinkage at 91 days was used in calculations of the BTC and BPC. Table A-19 summarizes the shrinkage of each mixture at 91 days.

Measurement of Hardened Concrete Properties

An analysis of the air void system was performed on each concrete according to ASTM C 457. The total air content and air void spacing factors are presented in Table A-20.

The compressive strength was measured according to AASHTO T 22. Three cylinders were broken at each of the following ages: 3, 7, 28, and 56 days. The results are shown in Figure A-11 and Table A-20. The modulus of elasticity was also measured for each concrete at 7 and 28 days according to AASHTO T 22 on three cylinders. The average results are presented in Table A-20.

Figure A-7. A thermocouple was placed in the center of each concrete cylinder

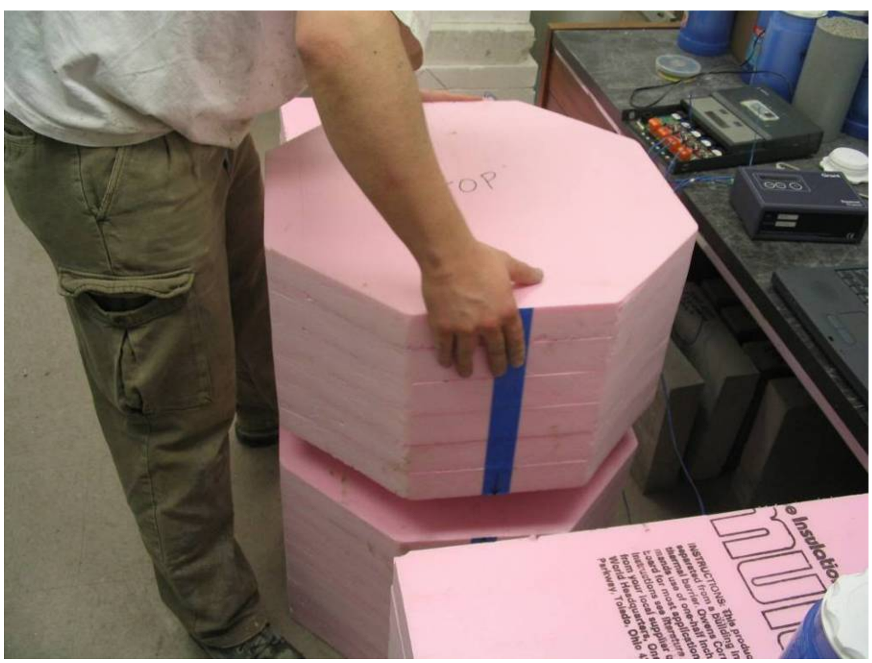

Figure A-8. An insulating foam cover was placed over the cylinder

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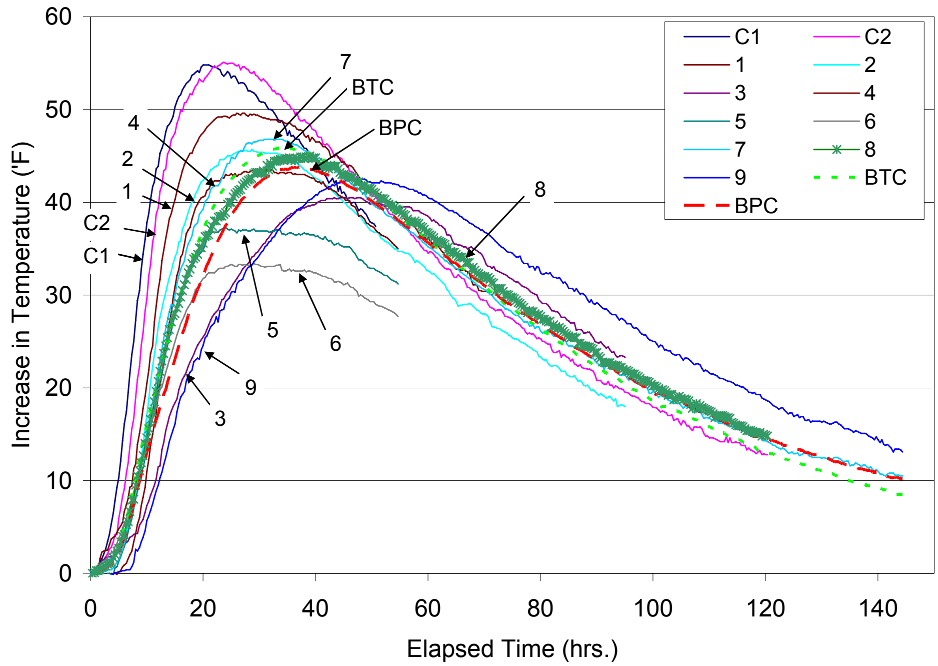


Figure A-9. Comparison of temperature rise for each concrete batch

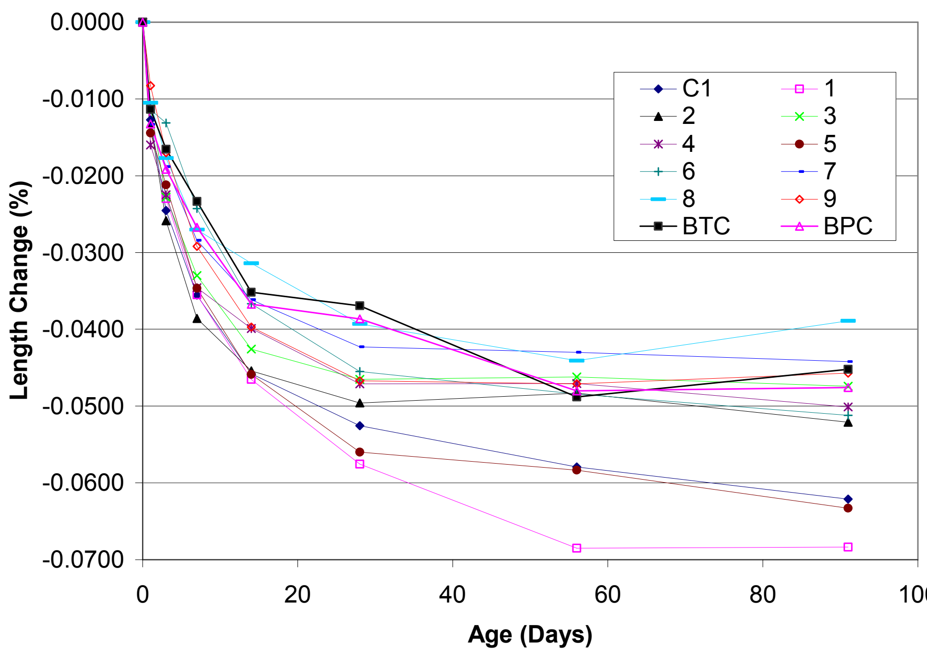


Figure A-10. Comparison of shrinkage curves for each concrete batch

Table A-20. Hardened concrete properties

Mix-ture	Description (% by wt.) SCM/SF/(w/cm)	Hardened Air (%)	Spacing Factor (in.)	Specific Surface (in^2/in^3)	Compressive Str.- 3-day (psi)	Compressive Str.- 7-day (psi)	Compressive Str.- 28-day (psi)	Compressive Str.- 56-day (psi)	Modulus E - 7-day ($x10^6$ psi)	Modulus E - 28-day ($x10^6$ psi)
C1	Control (w/c 0.40)	5.9	0.0069	668	4030	5000	5950	6190	3.48	4.06
1	15C/0/0.45	7.0	0.0058	657	2960	3780	4700	5280	3.32	3.52
2	25C/5/0.37	9.2	0.0052	463	3960*	4730	6300	6750	3.73	4.58
3	40C/8/0.37	7.2	0.0059	583	2790*	3530	6090	7080	3.36	4.80
4	15F/5/0.37	7.9	0.0068	424	3720	5010	6430	7230	3.63	4.37
5	25F/8/0.45	10.5	0.0045	563	1750	2730	4120	4770	3.17	3.67
6	40F/0/0.37	8.6	0.0054	594	1610	2290	3620	4490	3.10	3.43
7	25S/8/0.37	6.1	0.0090	418	4240	6460	7800	8720	4.40	4.49
8	35S/0/0.37	5.7	0.0108	408	3940	5710	7890	8460	4.26	4.82
9	50S/5/0.45	5.2	0.0070	646	2140	4380	6300	7000	3.65	4.36
C2	Control (w/c 0.40)	7.1	0.0078	437			6620	6490		4.37
BTC	35S/0/0.37	7.5	0.0090	381	4000	6020	7970	8520		
BPC	35S/8/0.39	6.3	0.0075	524	3250	5570	7710	8560		

*4-day tests

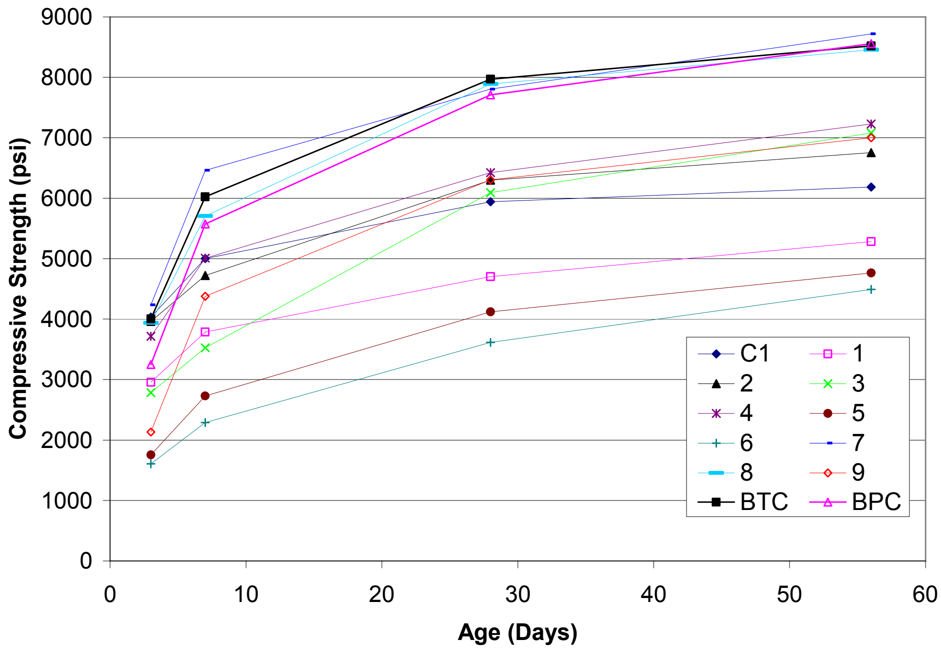
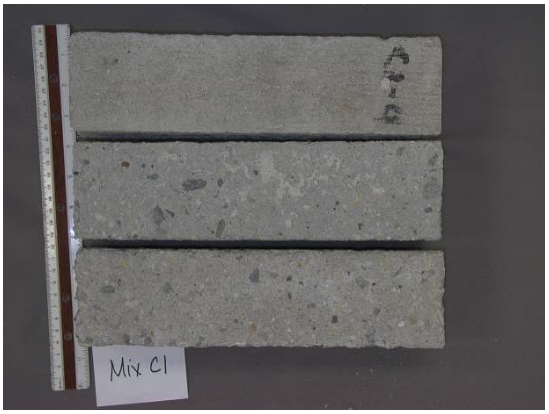


Figure A-11. Comparison of compressive strength curves for each concrete batch

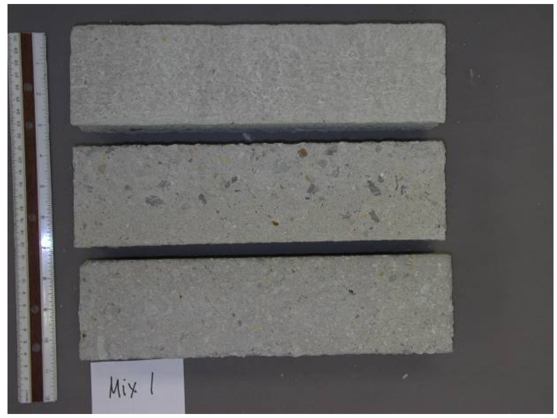
Assessment of Durability

Four separate properties were assessed to determine the durability of the concrete. The first was freezing and thawing resistance, which was performed according to AASHTO T 161 Method A. Three 3 x 4 x 16-in. (75 x 100 x 400 mm) prisms were cast and cured for 14 days prior to being subjected to rapid freezing and thawing. The durability factor, mass loss, and length change were measured periodically during the 300 cycle test. All the concrete performed well with durability factors exceeding 100% after 300 cycles. Some scaling of the surfaces occurred. Figure A-12 and Figure A-13 show photographs of the samples after exposure. The different faces (formed, finished) behaved differently as shown. Table A-21 summarizes the data.

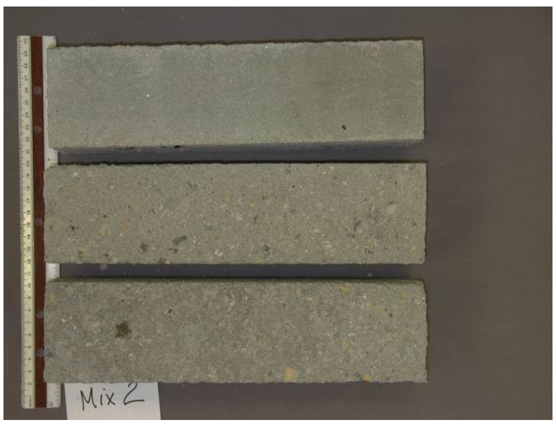
The salt scaling resistance was tested according to ASTM C 672. Three 12 x 12 x 6-in. (300 x 300 x 150 mm) slabs were cast for each mixture and finished with a wooden float. They were moist cured for 14 days and dried for 14 days at 50% RH. They were ponded with calcium chloride solution and cycled 50 times between freezing and thawing. Every five cycles the slabs were visually rated, the surfaces were rinsed, the scaled material collected, dried, and weighed and the number of popouts was recorded. The results are presented in Table A-21, which includes the average scaling visual rating, the average total mass loss, and the average number of small and large aggregate popouts noted. Figure A-14 shows the progression of mass loss with each five cycles. Figure A-15 and Figure A-16 are close-up photographs of the surfaces of one slab from each mixture.



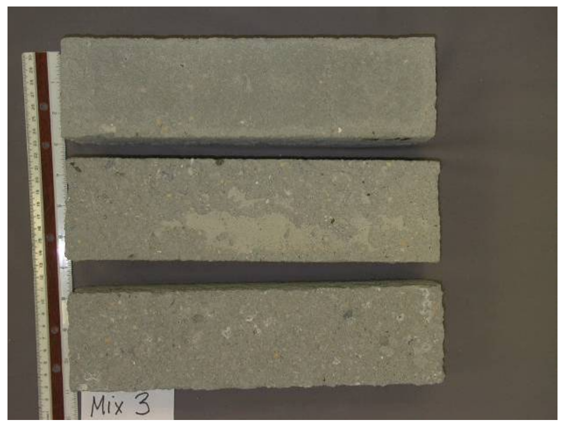
Mixture C1



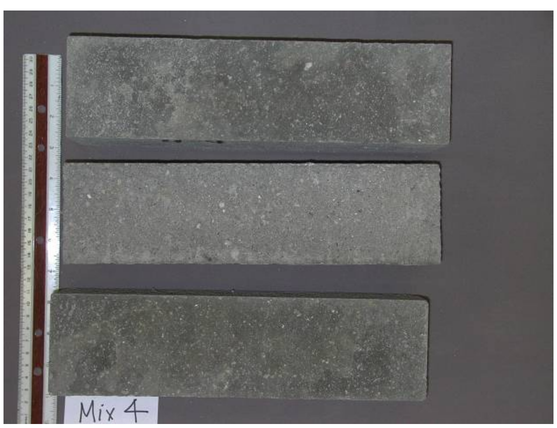
Mixture 1



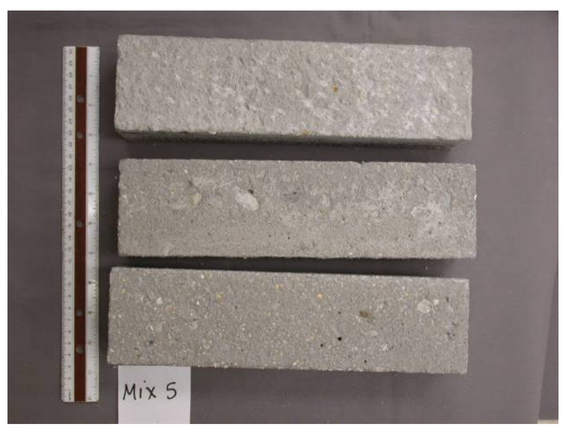
Mixture 2



Mixture 3

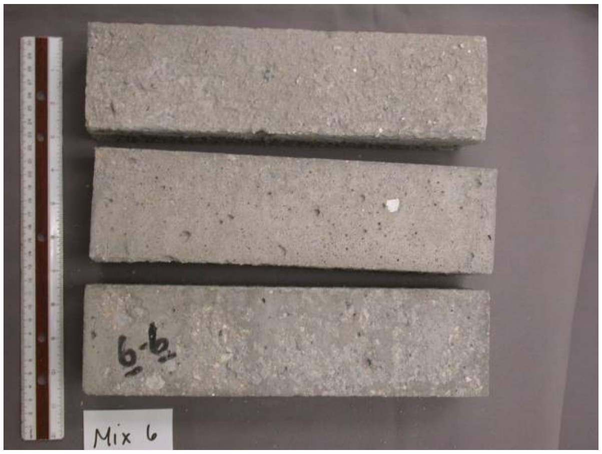


Mixture 4

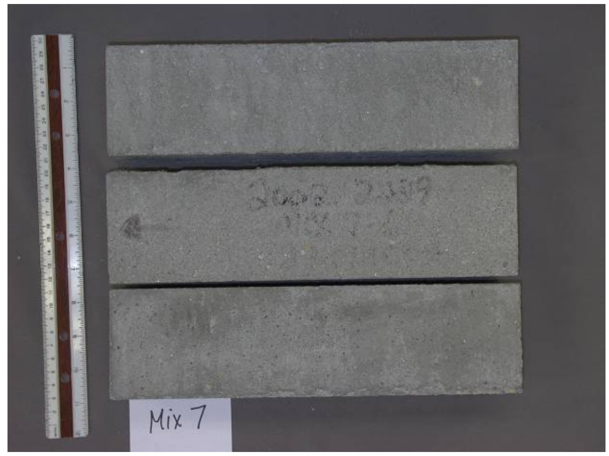


Mixture 5

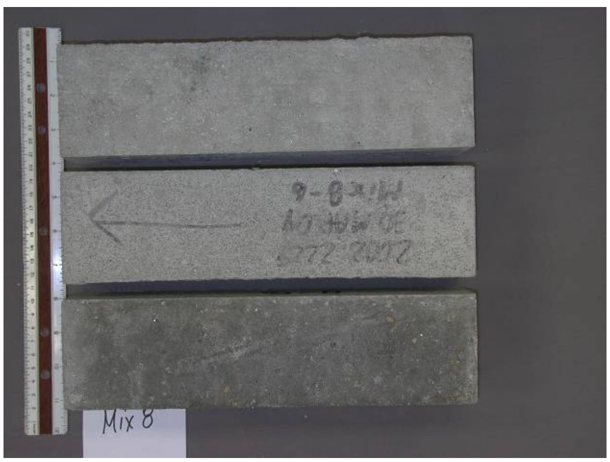
Figure A-12. Freeze/thaw specimens for Mixture C1 and Mixtures 1 to 5 after 300 cycles. The top prism shows a finished face, the center prism shows one of the side faces, and the bottom prism is a bottom face



Mixture 6



Mixture 7



Mixture 8

Mixture 9

Figure A-13. Freeze/thaw specimens for Mixtures 6 to 9 after 300 cycles. The top prism shows a finished face, the center prism shows one of the side faces, and the bottom prism is a bottom face

Table A-21. Durability assessment test results: freeze/thaw and salt scaling tests

Mixture	Description (% by wt.) SCM/SF/(w/cm)	Average scaling rating after 50 cycles	Average number of popouts (#small:#lg)	Salt scaling mass loss (g/m^2)	F/T: Ave. DF after 300 cyc. (%)	F/T: Ave. mass loss after 300 cyc. (%)	F/T: Ave. length change after 300 cyc. (%)
C1	Control (w/c 0.40)	0.0	8:3	50.42	100.1	-3.38	0.0033
1	15C/0/0.45	0.0	9:2	42.12	102.5	-2.01	0.0056
2	25C/5/0.37	1.0	-	273.56	100.5	-1.59	0.0192
3	40C/8/0.37	1.5	-	788.52	102.3	-2.16	0.0159
4	15F/5/0.37	0.3	12:-	75.42	102.1	-0.13	0.0194
5	25F/8/0.45	1.2	-	231.32	105.8	-0.91	0.0130
6	40F/0/0.37	2.2	-	531.58	106.3	-0.56	0.0024
7	25S/8/0.37	0.0	-	77.57	104.3	0.13	0.0094
8	35S/0/0.37	0.0	7:0.3	100.29	106.4	0.20	0.0169
9	50S/5/0.45	1.5	-	824.51	103.4	-0.11	0.0323
C2	Control (w/c 0.40)	--	--		--		
BTC	35S/0/0.37	0	-	24.99			
BPC	35S/8/0.39	0	-	52.78			

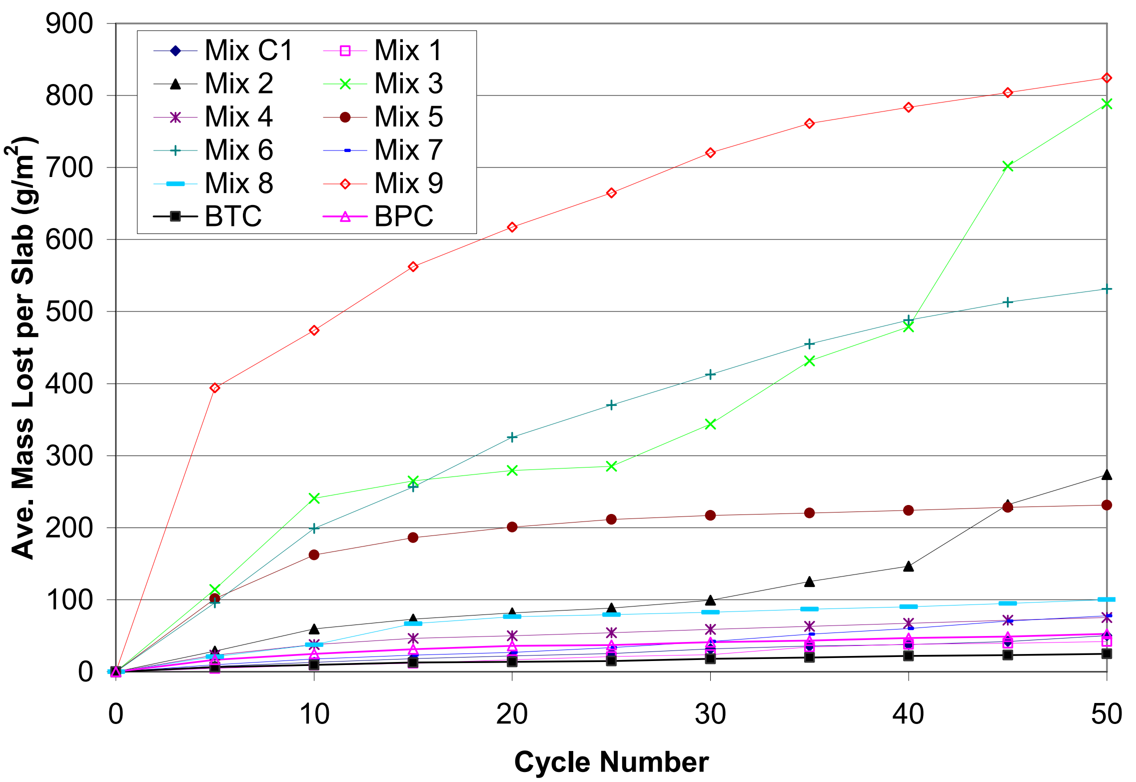
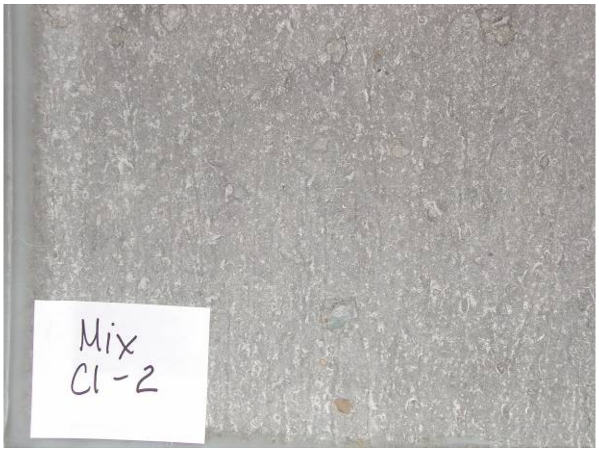
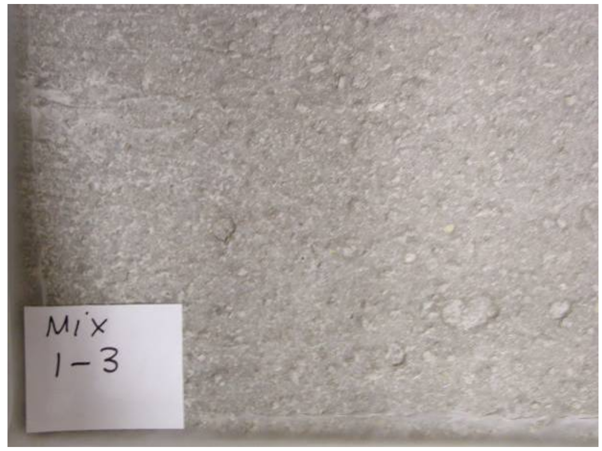


Figure A-14. Comparison of salt scaling mass loss for each concrete batch

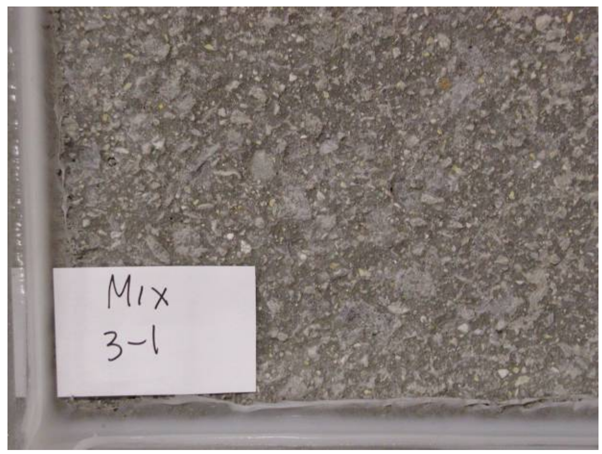


Mixture C1

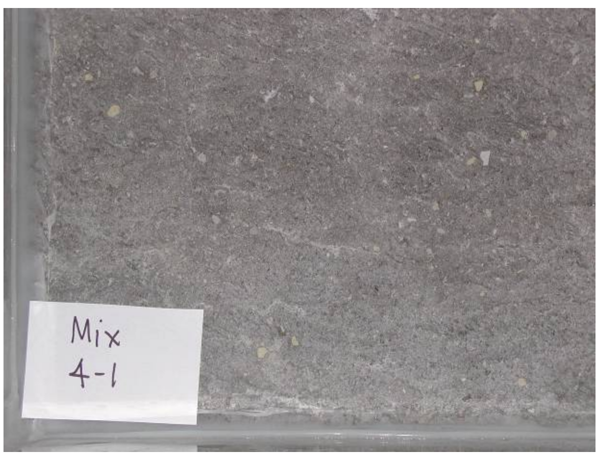


Mixture 1

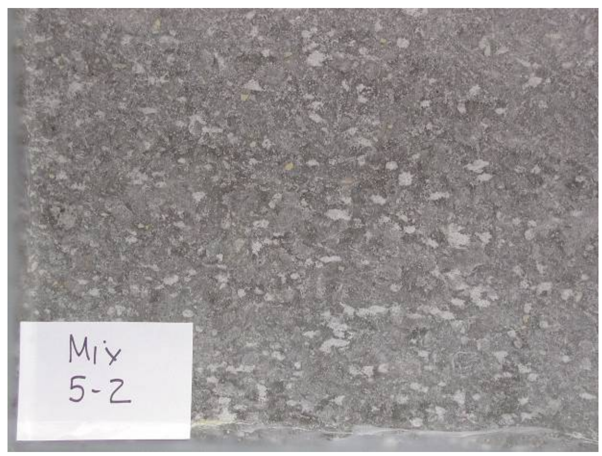
Mixture 2



Mixture 3

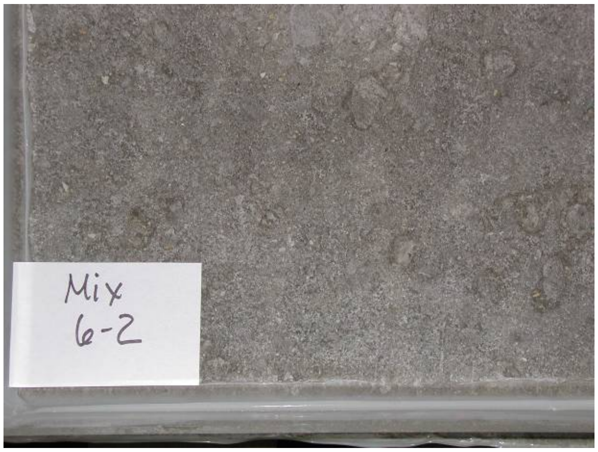


Mixture 4



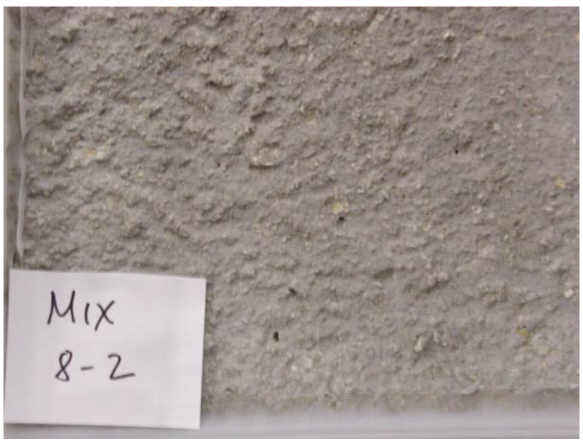
Mixture 5

Figure A-15. Salt scaling slabs for Mixture C1 and Mixtures 1 to 5 after 50 cycles

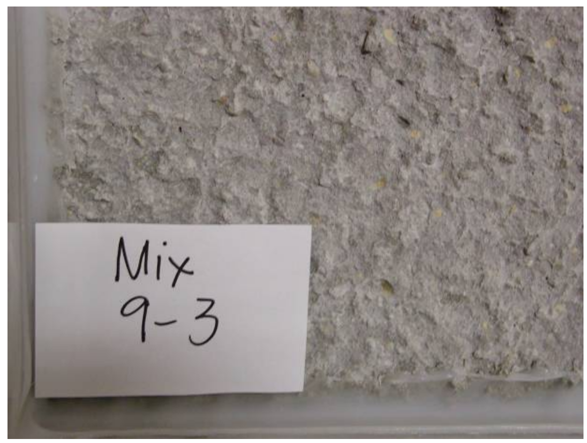


Mixture 6

Mixture 7



Mixture 8



Mixture 9

BTC

BPC

Figure A-16. Salt scaling slabs for Mixtures 6 to 9, BTC and BPC after 50 cycles

The resistance of the concrete to chloride permeability was estimated using AASHTO T 277 (the electrical conductivity test or RCP test). One top slice of two 4 x 8-in. (100 x 200 mm) cylinders were tested over six hours at an age of 56 days, and the charge passed in coulombs was recorded. The results were averaged and are given in Table A-22.

Table A-22. Durability assessment test results: chloride-related tests

Mixture	Description (% by wt.) SCM/SF/(w/cm)	Charge passed @ 56 days (Coulombs)	Surface Chloride (%)	Diffusion Coefficient ($x10^{-12}$ m^2/s)
C1	Control (w/c 0.40)	2878	1.03	7.879
1	15C/0/0.45	3398	1.26	7.022
2	25C/5/0.37	812	1.17	3.039
3	40C/8/0.37	684	1.14	2.743
4	15F/5/0.37	834	1.18	3.015
5	25F/8/0.45	912	1.35	3.983
6	40F/0/0.37	2072	1.18	7.134
7	25S/8/0.37	399	1.32	1.919
8	35S/0/0.37	1136	1.84	1.617
9	50S/5/0.45	694	1.40	2.822
C2	Control (w/c 0.40)	3307		
BTC	35S/0/0.37	778	1.28	1.879
BPC	35S/8/0.39	244	1.36	1.283

A second and more reliable method of assessing resistance to chloride penetration was by ponding or exposure to chloride solutions. For the original test matrix, this was conducted using a modified AASHTO T 259/T 260 test. Three 12 x 12 x 6-in. (300 x 300 x 150 mm) slabs were cast for each mixture and finished with a wooden float. They were moist cured for 14 days and dried for 28 days in a 50% R.H. room prior to ponding with a 15% NaCl solution for 6 months. The solution was topped off every week, and once a month the solution was replaced. At 6 months of age, one 3-in. core was removed from each slab, and five slices were cut from each core at specific depths. These slices were ground into powders, and the acid-soluble chloride was measured according to ASTM C 1152.

The apparent diffusion coefficient was determined using the well-known one-dimensional solution (Equation 1) of Fick's second law, which predicts diffusion rate in a uniform, homogeneous medium. The terms in Equation 1 are defined as follows: depth into a medium (x), chloride concentration at depth x (C_x), residual (background) chloride concentration within the concrete (C_o), surface chloride concentration (C_s), apparent chloride diffusion coefficient (D_a), and time in years (t). The *erf(x)* is the Gaussian error function. An iterative solution process was employed to yield the values for C_s and D_a that produces the profile giving the least sum of squares of error at each depth. The background chloride concentration, C_o, was assumed to be 0.08%, which is the chloride content measured in unexposed concrete and is due to chloride bound in the aggregate source. The exposure time, t, is the age of exposure, or 6 months.

$$\frac{C_x - C_o}{C_s - C_o} = 1 - erf\left(\frac{x}{2\sqrt{D_a \cdot t}}\right) \qquad (1)$$

Diffusion fits were generated for each of the three cores individually and the average apparent diffusion coefficient for each mixture was calculated from these values. A brief discussion of how this fitting is performed is provided in *NCHRP Report 566*. Examples of the chloride content data and the profile fits for this data based on the apparent diffusion coefficient are given in Figure A-17 for Mixture #8. The calculated surface chloride concentration and apparent diffusion coefficient from the chloride diffusion testing for all mixtures are presented in Table A-22.

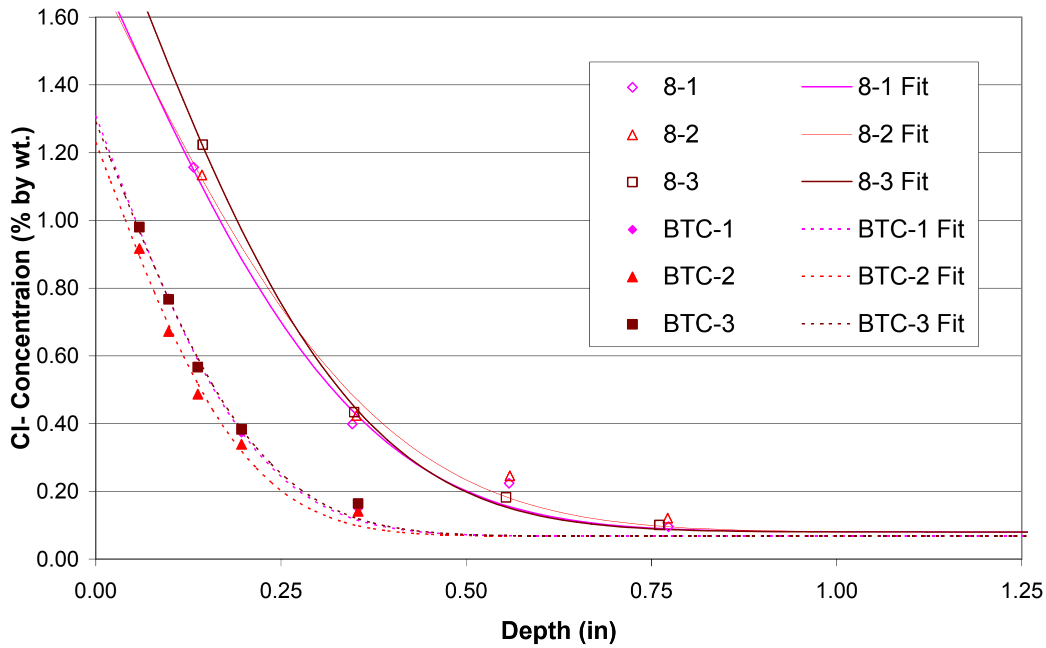


Figure A-17. Chloride profiles and fit based on calculated surface concentration and apparent diffusion coefficient for Mixture #8 and for BTC measured on samples conditioned according to AASHTO T 259 and ASTM C 1556, respectively

Step 5: Analyze Test Results and Predict the Optimum Mixture Proportions

After the tests were conducted in Step 4, the responses were tabulated and converted into individual desirability values based on the initially assumed desirability functions. The results of this analysis were reviewed and the responses to be included in the overall desirability calculations were re-evaluated. The initial assumptions for the desirability functions were also re-evaluated to ensure that they accurately interpreted the performance of the mixtures. This is an important step to make sure that the desirabilities properly reflect differences or similarities in performance.

Every experiment will have different considerations depending on the performance objectives and the results obtained. The results of the Hypothetical Case Study were interpreted relative to the objective of a durable bridge deck in a northern climate. What follows is a description of how the particular test data was reconciled with this objective.

Analysis of Results and the BTC

Table A-23 lists the individual responses that were initially planned in Step 1 and tested in Step 4 and those that were actually used to calculate the overall desirability for the mixtures in Step 5. Recall that the overall desirability is the geometric mean of individual response desirabilities. The plastic properties (slump, slump loss, plastic air content, and air content of hardened concrete) were eliminated from consideration in the calculation of the Overall Desirability. This was done since these properties can be adjusted by the concrete producer based on admixture dosage and were not uniquely determined by the mixture itself. Also, no measure of the hardened air parameters was included since cyclic freezing resistance was tested directly.

Another change that was made was the inclusion of 56-day strength in place of 28-day strength. This was necessary because Mixture #6, containing a high content of Class F fly ash, had 28-day strength of 3620 psi (25.0 MPa), which was well below the target minimum for the average compressive strength of 5000 psi (34.5 MPa) used to develop the desirability function. This resulted in a low individual desirability for this test (Figure A-18) that produced a low overall desirability for this mixture. This was dragging down all mixtures containing Class F fly ash, since the influence of a type factor is based on the average response for all mixtures containing that type. While our desirability function for the 28-day strength was reasonable for the targeted performance, a designer may be willing to wait for the concrete to reach a 56-day design strength, if that means that a more durable concrete with a lower diffusion coefficient and other more desirable responses can be achieved. Using the 56-day strength, which was 4490 psi (31.0 MPa) for the high-content Class F fly ash mixture (#6), instead of 28-day strength, gave a much more acceptable individual (Figure A-19) and overall desirability for that mixture.

Finally, scaling resistance was evaluated in two ways: visually and by mass loss. To limit the emphasis applied to scaling relative to the other performance measures, the measure deemed to be most definitive, mass loss, was included and the visually rating was not.

Modifications to the individual desirability functions were made in some cases after the data was examined. For example, the desirability function for temperature rise due to heat of hydration was adjusted based on the test results. It was initially assumed, based on the insulation

Table A-23. Responses used for calculation of overall desirabilities

Proposed Responses from Step 1	Selected Responses for Step 5 Design Matrix Analysis	Selected Responses for Step 6 Confirmation Analysis
1. Slump		
2. Slump Loss		
3. Plastic Air Content		
4. Air Content of Hardened Concrete		
5. Initial Set	1. Initial set	1. Initial set
6. Finishability	2. Finishability	
7. Cracking Tendency	3. Cracking Tendency	
8. Heat of Hydration - Temperature rise	4. Heat of Hydration - Temperature rise	2. Heat of Hydration - Temperature rise
9. Shrinkage	5. Shrinkage	3. Shrinkage
10. Specific Surface Area		
11. Compressive Strength, 7-Day	6. Compressive Strength, 7-day	4. Compressive Strength, 7-day
12. Compressive Strength, 28-Day		
13. Compressive Strength, 56-Day	7. Compressive Strength, 56-day	5. Compressive Strength, 56-day
14. Modulus of Elasticity	8. Modulus of Elasticity, 28-day	
15. Electrical Conductivity	9. Electrical Conductivity	6. Electrical Conductivity
16. Scaling (visual rating)		
17. Scaling (mass loss)	10. Scaling (mass loss)	7. Scaling (mass loss)
18. Freezing and Thawing Resistance (durability factor)	11. Freezing and Thawing Resistance (durability factor)	
19. Chloride Penetration Resistance (diffusion coefficient)	12. Chloride Penetration Resistance (diffusion coefficient)	8. Chloride Penetration Resistance (diffusion coefficient)

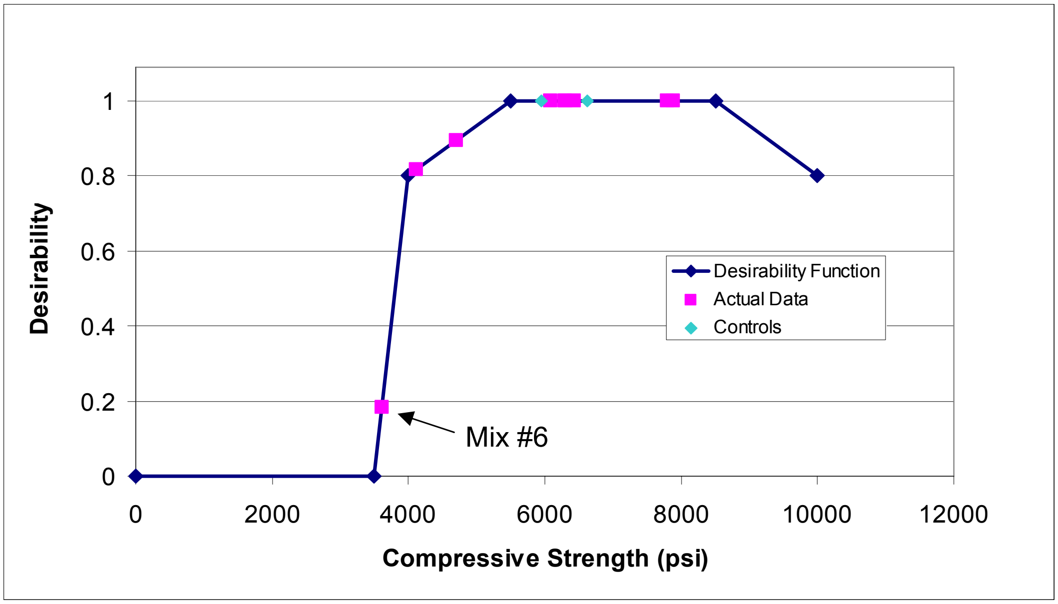


Figure A-18. Desirability function for 28-day compressive strength originally proposed. Note low desirability for Mixture #6

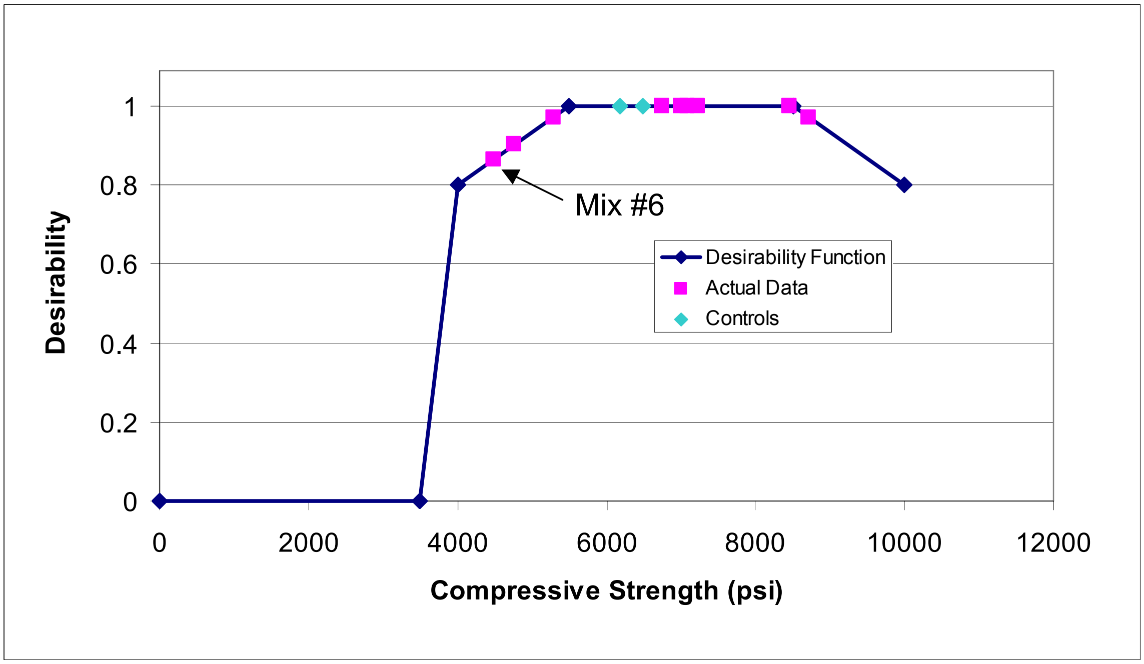


Figure A-19. Desirability function for 56-day compressive strength selected for Design Matrix testing

vessels, that the temperature rise would not be above 30°F (17ºC), and the desirability function was designed accordingly. However, the actual test results ranged from 30 to 50°F (17 to 29ºC). Therefore, the desirability function was adjusted to give some credit to those mixtures that produced a lower temperature rise but not to overly punish the mixtures at the higher end of the scale. Figure A-20 shows the original desirability function and the adjusted function with the test data. Such changes should be based on engineering judgment and may be necessary to provide a realistic prediction and appropriately reflect the importance of the test result.

The individual response and overall desirabilities of all mixtures based on the test data are shown in Table A-24. The Best Tested Concrete (BTC) is the mixture which had the highest overall desirability. Therefore, the BTC is Mixture #8.

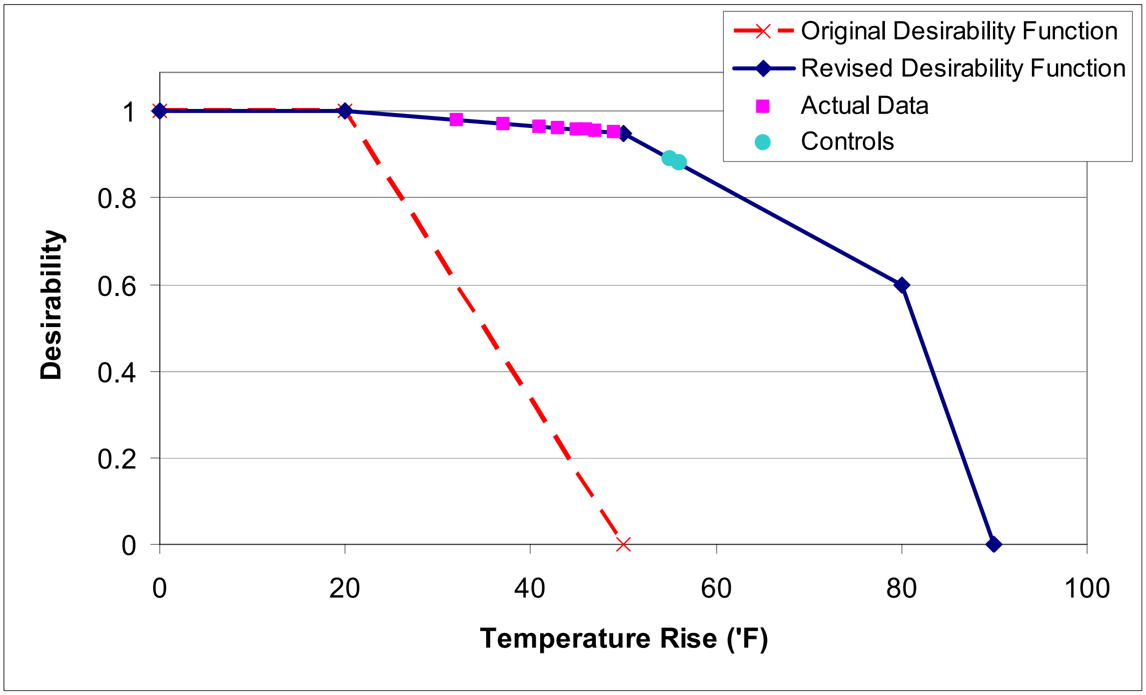


Figure A-20. Example of modification to temperature rise desirability function

Response Modeling and the BPC

By definition, the Best Predicted Concrete (BPC) is the combination of the factors that maximize the overall desirability. This was identified based on empirical models for each of the responses. Using the approach discussed in *NCHRP Report 566*, each response was modeled using Equation 2

$$y = e^{b_o + b_1x_1 + b_{11}x_1^2 + b_2x_2 + b_{22}x_2^2 + b_3x_3 + b_{33}x_3^2 + b_4x_4} \tag{2}$$

where e is the natural constant such that ln(e) =1, y represents the response, x_1 represents the Level of Factor 1, x_2 represents the Level of Factor 2 and so forth, and the parameters, b_0, b_1, and b_{11} are selected for each factor by standard linear regression analysis to allow the function to fit the data. Note that since there were only two levels for Factor 4 (w/cm) in the Hypothetical Case Study, the squared term for x_4 cannot be used. These model parameters were fit by first taking the natural log of the observed responses and then fitting the simple quadratic model to that transformed data using standard regression analysis:

$$\ln(y) = b_o + b_1x_1 + b_{11}x_1^2 + b_2x_2 + b_{22}x_2^2 + b_3x_3 + b_{33}x_3^2 + b_4x_4 \tag{3}$$

Once the values for the parameters, b_0, b_1, b_{11}, b_2, .., b_4 were chosen to make the function fit the natural log of the data, the response for any factor settings x_1, x_2, x_3, x_4, can be predicted using Equation 2.

Table A-24. Individual response desirabilities and overall desirabilities for design matrix testing

Property	Mixture										
	C1	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**C2**
Initial Set	1	1	1	0.8340	1	1	1	1	1	1	1
Finishability	0.9856	0.9725	0.8850	0.9425	0.9075	0.9688	0.9744	0.9500	0.9325	0.9600	0.9706
Cracking Tendency	0.9889	1	1	1	1	0.9833	0.9722	1	0.9556	1	0.9889
Heat of Hydration Temp. Rise	0.8917	0.9517	0.9550	0.9650	0.9617	0.9717	0.9800	0.9583	0.9567	0.9650	0.8800
Shrinkage	0.9105	0.7938	0.9585	0.9690	0.9650	0.9085	0.9580	0.9850	0.9795	0.9645	N/A
Compressive Strength - 7 Day	1	1	1	1	1	0.8608	0.6304	0.9040	0.9795	1	N/A
Compressive Strength - 56 Day	1	0.9711	1	1	1	0.9020	0.8655	0.9707	1	1	1
Modulus of Elasticity	1	1	1	1	1	1	1	1	1	1	N/A
Electrical Conductivity	0.5366	0.3806	0.9594	0.9658	0.9583	0.9544	0.7784	0.9801	0.9296	0.9653	0.4079
Scaling - Mass Loss	0.9849	0.9874	0.9304	0.7491	0.9838	0.9365	0.8889	0.9820	0.9740	0.7082	N/A
Freeze- Thaw Durability Factor	1	1	1	1	1	1	1	1	1	1	N/A
Chloride Diffusion Coefficient	0.1030	0.1245	0.6682	0.7199	0.6723	0.5029	0.1216	0.8561	0.8787	0.7062	N/A
Overall Desirability	0.7695	0.7532	0.9412	0.9231	0.9490	0.9029	0.7660	0.9645	0.9648	0.9323	0.8373
Desirability Rank	8	10	4	6	3	7	9	2	1	5	*

* Control Mixture 2 has missing data and was not considered for BTC.

The BPC was found by evaluating the overall desirability, calculated based on the desirabilities for the individual predicted responses, for many combinations of factor levels until the specific combination that produced the highest overall desirability was identified. These combinations were generated by increasing each factor successively by a small increment to fully describe the test range. In this way, the observed data, the desirability function, and the response models were used together to predict a BPC expected to perform better than the BTC. The predicted overall desirability based on the response models and the Mixture ID number from the Step 4 test program is given in Table A-25. The models predict that for the materials tested, using the same amount of slag tested as the medium level in the previous matrix is, in fact, optimum but that the amount of silica fume should be increased to 8% and that the w/cm should be increased by 0.02, from 0.37 to 0.39.

The prediction of the performance of the BTC and BPC in each of the individual test responses is given in Table A-26. Predicted responses are given for all properties tested and predicted desirabilities are given for those responses used to determine the overall desirabilities. A review of this table, specifically where the individual desirabilities of the BPC are greater than those of the BTC, identifies of the responses that were most significant in the selection of the BPC. Despite a slightly lower individual desirability for finishability and scaling-mass loss, the predicted individual desirabilities for the BPC for the chloride diffusion, electrical conductivity, and cracking tendency were all higher. This led to the greater overall desirability and the selection of this mixture as the BPC.

Table A-25. Selection of Best Tested (BTC) and Best Predicted Concrete (BPC) based on overall desirabilities

Mixture	Type of SCM1	Amount of SCM1 (%)	Amount of silica fume (%)	w/cm	Actual Overall Desirability	Predicted Overall Desirability	Mix No.
BTC	GGBFS	35	0	0.37	0.9648	0.9653	8
BPC	GGBFS	35	8	0.39	-	0.9744	-

Table A-26. Predicted responses of Best Tested (BTC) and Best Predicted Concrete (BPC)

Property	Predicted Response		Predicted Desirability	
	BTC	BPC	BTC	BPC
Slump (in)	8.05	7.10		
Slump Loss (in)	1.89	2.49		
Plastic Air (%)	6.34	6.44		
Hardened Air (%)	6.09	6.70		
Initial Set (hr)	5.33	5.66	1.00	1.00
Finishability	11.83	11.41	0.95	0.94
Cracking Tendency (wks)	7.43	15.67	0.96	1.00
Heat of Hydration (°F)	44.63	43.83	0.96	0.96
Shrinkage (%)	-0.0445	-0.0434	0.98	0.98
Specific Surface Area (in^{-1})	417	424		
Compressive Strength - 7 Day (psi)	5366	5503	1.00	1.00
Compressive Strength - 28 Day (psi)	7193	7730		
Compressive Strength - 56 Day (psi)	7792	8383	1.00	1.00
Modulus of Elasticity ($x10^6$ psi)	4.25	4.24	1.00	1.00
Electrical Conductivity (Coulombs)	1144	397	0.93	0.98
Scaling - Visual	0.00	0.01		
Scaling - Mass Loss (g/m^2)	93.4	183.0	0.97	0.95
Freeze- Thaw Durability Factor (%)	103.7	104.0	1.00	1.00
Chloride Diffusion (x 10^{-12} m^2/s)	1.95	1.38	0.85	0.90

Step 6: Perform Confirmation Testing and Select Best Concrete

In Step 6, the BPC and BTC were tested according to a revised list of test methods outlined in Table A-27. Table A-23 lists the responses that were included in the calculation of the overall desirability for the Confirmation Testing. The test program varied from the program used in Step 4 in that it was limited only to those responses that showed significant performance differences and that could be completed in the available timeframe. Therefore, the finishability, modulus of elasticity, and freezing and thawing tests were eliminated, since in all of these tests, the BTC and BPC mixtures were predicted to perform such that a similar desirability would be assigned for that response. The cracking tendency test was eliminated because this test could not be completed. One additional modification to the testing procedure was made because of time constraints; the method used to evaluate the chloride penetration was changed to ASTM C 1556 tested at 56 days. However, since both of the chloride penetration test methods used measure similar performance, and no other changes in the testing procedures were made, the initial and Confirmation Test programs were considered essentially comparable and the results from both rounds of testing fairly compared.

The mixture proportions and the results of the Confirmation Testing program are given in Table A-16 and in Table A-18 to Table A-22, respectively. The mixing procedures, test methods and all experimental details were consistent with the Step 4 testing program. As noted, the recently adopted ASTM C 1556 method was used to evaluate the chloride penetration resistance. In this test, 4 x 8-in. (100 x 200 mm) concrete cylinders are wet-cured for 28-days before they are cut to a length of approximately 3 in. (75 mm). All surfaces but the finished surface were sealed and the cylinders submerged in 15% NaCl solution for 56 days. At the end of the exposure time, five layers of the concrete surface were sampled at successive depths, all within 1/2 in. (13

Table A-27. Verification testing of BPC and BTC

Property	Test Method	Specimen Size and Number of Specimens	Curing
Compressive strength (at 3, 7, 28, 56 days)	AASHTO T 22	Three 4x8-in.	Moist
Electrical Conductivity test (56 days)	AASHTO T 277	Two 4x8-in.	Moist
Shrinkage (1, 3, 7, 14, 28, 56, 90 days after curing)	AASHTO T 160	Three 3x3x11.25-in.	7 days wet
Thermal effects (heat of hydration)	Temperature Rise in Cylinder	One 6x12-in. cylinder	N/A
Chloride diffusion (to 56 days)	ASTM C 1556	Two 4 x8 in. cylinders	28 days
Scaling (mass loss)	ASTM C 672	Three 3x12x12-in.	14 days wet + 14 days dry
Hardened air analysis (at greater than 7 days)	ASTM C 457	One 4x8-in. cylinder	Moist for 7 days

mm) of the surface, using a machinist's lathe and cutter as shown in Figure A-21. Examples of the chloride content data and the profile fits for the BTC from the Confirmation Testing based on the apparent diffusion coefficient are compared in Figure A-17 with that of Mixture #8 from the initial round of testing. The results of the chloride diffusion testing for all mixtures are presented in Table A-22. Note that the average apparent diffusion coefficients are very similar for Mixture #8 and the BTC, which were batched with identical mixture proportions, despite the different method used to determine the apparent diffusion coefficient.

The overall desirabilities of these mixtures were determined using the same individual desirability functions used to evaluate the Design Matrix Mixtures. The measured overall desirabilities are compared with the predicted overall desirabilities in Table A-28, which also includes the overall desirability from the original BTC batch calculated based on the Confirmation Testing program. Note that the overall desirabilities based on the Confirmation round of testing are slightly different than those calculated in Step 5, since the responses included in this calculation has been modified.

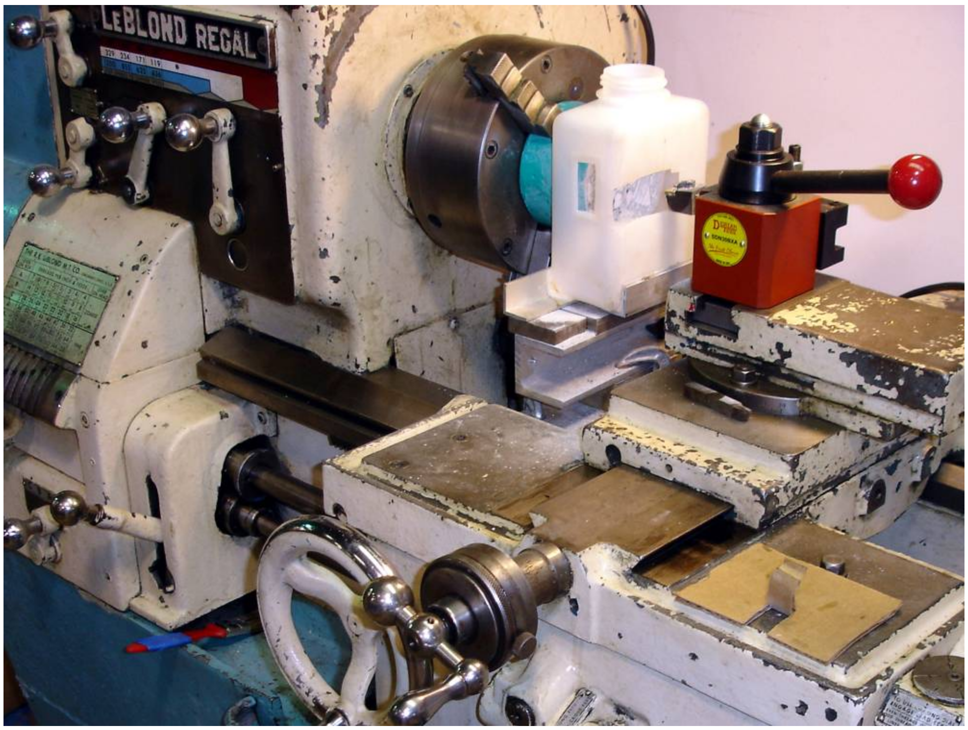


Figure A-21. Lathe used to mill surface of concrete cylinder

Table A-28. Comparison of actual and predicted overall desirabilities from Confirmation testing

Mixture	Actual Overall Desirability	Predicted Overall Desirability	% Difference
BTC Original Batch (Mixture #8)	0.9615	0.9601	0.1%
BTC Confirmation Batch	0.9601	0.9601	0.0%
BPC Confirmation Batch	0.9724	0.9700	0.2%

For the Hypothetical Case Study, the actual and predicted performances of the Confirmation BTC and BPC agreed very well. The difference between the actual BPC and BTC performance is nearly nine times greater than the difference between the Original and Confirmation Batch of the BTC. This provides confidence that the test program produced repeatable results and that the increase in desirability measured in the BPC is a significant and measurable improvement.

Table A-29 and Table A-30 present the actual and predicted individual responses and corresponding desirabilities for the Confirmation Testing for the BTC and BPC. These tables provide an opportunity to evaluate the accuracy of the predictions and the corresponding desirabilities for each response. The mixture responses that were least well-predicted, i.e., that showed the greatest percent difference, for the BTC and BPC were the electrical conductivity and scaling-mass loss tests. However, the corresponding desirability values varied only slightly since the desirability functions placed only limited significance on these differences. In fact, only one desirability prediction was different by more than 5% and that was the 7-day strength prediction for the BTC which was off by 5.2%.

The Confirmation test results and the good agreement between the test responses and the model predictions used to select the BPC contribute to the confidence in the accuracy of this statistical analysis. The result of this program justifies the selection of the BPC as the Best Concrete (BC), the mixture recommended for use. With this selection, the objective of this Methodology, which is the identification of an optimum mixture based on the available raw materials, has been achieved.

Table A-29. Comparison of individual responses and desirabilities for BTC

Property	Individual Responses				Individual Desirabilities			Included in Confirmation Test?
	Original BTC Batch (Mixture #8)	BTC Confirmation Test	BTC Prediction	BTC % Difference Response	BTC Confirmation Test	BTC Prediction	BTC % Difference Desirability	
Slump (in)	7.75	6.25	8.05	-22.4%				No
Slump Loss (in)	1.75	2.25	1.89	19.3%				No
Plastic Air (%)	6.10	7.00	6.34	10.4%				No
Hardened Air (%)	5.70	7.50	6.09	23.1%				No
Initial Set (hr)	5.50	5.08	5.33	-4.8%	1.000	1.000	0.0%	Yes
Finishability	11.3	No test	11.8	-				No
Cracking Tendency (wks)	7.0	No test	7.4	-				No
Heat of Hydration Temp. Rise ('F)	46	46	45	3.1%	0.957	0.959	-0.2%	Yes
Shrinkage (%) (negative)	-0.0441	-0.0452	-0.0445	1.7%	0.974	0.978	-0.4%	Yes
Specific Surface Area (in^{-1})	408	No test	417	-				No
Compressive Strength - 7 Day (psi)	5705	6020	5367	12.2%	0.948	1.000	-5.2%	Yes
Compressive Strength - 28 Day (psi)	7888	7970	7194	10.8%				No
Compressive Strength - 56 Day (psi)	8460	8520	7793	9.3%	0.997	1.000	-0.3%	Yes
Modulus of Elasticity (x 10^6 psi)	4.26	No test	4.25	-				No
Electrical Conductivity (Coulombs)	1136	778	1143	-31.9%	0.961	0.929	3.5%	Yes
Scaling - Visual	0.0	0.0	0.1	-				No
Scaling - Mass Loss (g/m^2)	86.7	25.0	93.4	-73.3%	0.993	0.972	2.1%	Yes
Freeze- Thaw Durability Factor (%)	103.8	No test	103.7	-				No
Chloride Diffusion Coefficient ($x10^{-12}$ m^2/s)	1.62	1.88	1.95	-3.8%	0.859	0.853	0.7%	Yes

Table A-30. Comparison of individual responses and desirabilities for BPC

Property	Individual Responses			Individual Desirabilities			Included in Confirmation Test?
	BPC Confirmation Test	BPC Prediction	BPC% Difference Response	BPC Confirmation Test	BPC Prediction	BPC % Difference Desirability	
Slump (in)	7.25	7.10	22.0%				No
Slump Loss (in)	3.00	2.49	20.4%				No
Plastic Air (%)	6.7	6.4	4.0%				No
Hardened Air (%)	6.3	6.7	-6.0%				No
Initial Set (hr)	6.42	5.66	13.5%	1.000	1.000	0.0%	Yes
Finishability	No test	11.4	-				No
Cracking Tendency (wks)	No test	15.7	-				No
Heat of Hydration Temp. Rise ('F)	44	44	0.4%	0.960	0.960	0.0%	Yes
Shrinkage (%)	-0.0476	-0.0434	9.6%	0.962	0.983	-2.1%	Yes
Specific Surface Area (in^{-1})	No test	424	-				No
Compressive Strength - 7 Day (psi)	5570	5504	1.2%	0.993	1.000	-0.7%	Yes
Compressive Strength - 28 Day (psi)	7710	7731	-				No
Compressive Strength - 56 Day (psi)	8560	8383	2.1%	0.992	1.000	-0.8%	Yes
Modulus of Elasticity (x 10^6 psi)	No test	4.24	-				No
Electrical Conductivity (Coulombs)	244	397	-38.5%	0.988	0.980	0.8%	Yes
Scaling - Visual	0.0	0.3					No
Scaling - Mass Loss (g/m^2)	52.8	183.0	-71.2%	0.984	0.945	4.1%	Yes
Freeze- Thaw Durability Factor (%)	No test	104.0	-				No
Chloride Diffusion Coefficient ($x10^{-12}$ m^2/s)	1.28	1.38	-6.8%	0.904	0.897	0.8%	Yes