OPTIMIZATION OF HIGH PERFORMANCE CONCRETE MIXTURES USING STATISTICAL EXPERIMENTAL DESIGN

John S. Lawler, PE, Wiss, Janney, Elstner Associates, Inc., Northbrook, IL
Paul D. Krauss, PE, Wiss, Janney, Elstner Associates, Inc., Northbrook, IL
Bruce E. Ankenman, Northwestern University, Evanston, IL

ABSTRACT

The use of supplementary cementitious materials (SCMs), such as fly ash, silica fume, blast furnace slag, and natural pozzolans, in concrete bridge decks is widespread, primarily with the objective of improving durability. However, clear conclusions concerning the optimum use of these materials for a specific situation or set of available materials is typically not available in the literature or elsewhere. Research performed under the National Cooperative Research Program (NCHRP) Project 18-08A developed a methodology for designing concrete mixtures containing SCMs to identify desired performance criteria and optimize material proportions to achieve project goals. This paper gives an overview of this methodology, which is available as published NCHRP guidelines. The methodology consists of the following procedures: First, the service environment and optimum concrete properties must be defined and desirability functions for these properties must be established. Desirability functions interpret each test result (response) relative to the significance of the test method and test result for the overall objective in an equivalent framework. With the help of background information provided in the guidelines, the user selects the available raw materials (cement, supplementary cementitious materials, and aggregates) most likely to produce durable concrete (or to meet other project goals). A matrix of concrete mixtures to be tested that supports a statistical analysis is then selected. After the test matrix is generated, testing is performed on the mixtures. Analyzing the test results statistically identifies the Best Tested Concrete (BTC) and Best Predicted Concrete (BPC) mix designs. The BPC is selected based on trends in the data and is anticipated to be a better concrete mixture than any of the concretes that were actually tested. The final step in the process is confirmatory testing of the BPC intended to verify that it is superior to the BTC.

Keywords: High performance concrete, Durability, Statistical experimental design, Mixture optimization

INTRODUCTION

Premature deterioration of our nation's concrete bridges has been a persistent and frustrating problem. There is a need to develop concrete mixtures that will better resist deterioration and provide longer service life. 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 improve performance 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, calcined clay, 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 has become 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. 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 associated high modulus of elasticity and low creep, which can result in 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 when 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 properties and quality of local raw 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. 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. 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. In addition, service environments and the associated deterioration mechanisms vary with geographical location such that a single concrete mixture will never be optimum for every location. Therefore, optimum concrete mix proportions are best determined by testing.

While efforts have been made to develop methods for optimizing concrete[1-3], the optimization of concrete mixtures has rarely been performed. Instead, designing mixtures to achieve minimum specification requirements is far more common. Specifying a mixture without real knowledge of the available materials is not an efficient way to produce durable concrete, and certainly does not ensure that the concrete produced is the best alternative for a given situation.

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.

METHODOLOGY

OVERVIEW

The objective of the research was to develop a methodology for designing portland cement concrete mixtures incorporating supplementary cementitious materials that will result in enhanced or optimized durability of concrete bridge decks or other structures. The process that was developed 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 (explained below), 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 detail in the NCHRP Report 566 - Guidelines for Concrete Mixtures Containing Supplementary Cementitious Materials to Enhance Durability of Bridge Decks[4], 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 flow charts 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. 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 anticipated 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 materials tests.

A range of statistically-based experimental approaches was evaluated. The fractional orthogonal design method was chosen for implementation in this Methodology. 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 (time and cost), and a discussion of the significant aspects of this selection is provided.

At the completion of concrete mixture testing in Step 4, statistical analysis of the data is conducted to identify the concrete mixture that performed best relative to the performance requirements that were developed by the user 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 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. Based on the analysis of the full testing program, the optimum mixture for the specific project and available concrete materials is generated.

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 in the Guidelines document. 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.

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 high strength concrete, optimizing admixture contents in self-consolidating concretes, or simply selecting between available cements, aggregates and admixtures in more conventional concrete applications.

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 as part of this research. This case study is summarized briefly below.

Finally, to aid potential users in the implementation of this Methodology, a computational 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 calculations.

BACKGROUND ON STATISTICAL DESIGN OF EXPERIMENTS

A designed experiment is conducted based on a test program laid out to produce results that answer a question or verify a hypothesis. Through the use of statistical design of experiments, it is possible to obtain useful information without testing every combination of variables at every level. The great advantage of using statistical experimental design is that the experiments conducted are more efficient, i.e., they allow predictions regarding large numbers of possible variations based on a limited number of tests. A brief discussion of the relevant terminology is needed as presented in Table 1.

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 raw material (e.g., cement, SCM, aggregate) 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. The goal is to define what materials or mix variables (factors) are to be tested and at what range of amounts (levels) of each material or type of material need to be evaluated.

The “**response**” is simply the test result. 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, air content, or apparent diffusion coefficient.

The "**experimental matrix**" is the matrix of combinations of factors and levels that is generated by the user with the aid of tables or software. 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 or grades 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. Every possible response is mapped by this function to a desirability value between 0 and 1. The specific desirability functions that are defined will vary with the intended application for the mixture. The relative importance (rating) of each test result (response) is also influenced by the desirability function. Designing a strict desirability function, which assigns high desirabilities only to mixtures exhibiting outstanding results and low desirabilities to mixtures with only satisfactory or worse results, places greater importance on that response. More forgiving desirability functions can be defined for less important responses.

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. The overall desirability is derived from the individual desirabilities for each response and so reflects the individual properties of the mixture and the importance of each of these properties to the overall concrete performance. To further emphasize properties judged to be of greater importance to a specific application, the relative importance of the results of each test can be weighted mathematically in the calculation of the overall desirability or the desirability function can be adjusted.

The concepts of desirability and overall desirability are discussed further in the section titled "Combining Test Results" below.

Methods of Designing Experiments

In this Methodology, a straightforward design method called fractional orthogonal design is used. Other experimental design methods are available, such as the one-factor-at-a-time method and central composite design; however, the first method is slow, while in most cases the number of mixtures required by the other methods is large. The biggest advantage of the fractional orthogonal approach is that it requires a relatively small number of mixtures be tested to efficiently cover a large test space or matrix. 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. Also, since the mixtures in a fractional orthogonal design are quite different from each other, there is an excellent 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.

Combining Test Results

In this Methodology, each test response is rated between 0 (unacceptable) and 1 (does not need to be improved) by a desirability function. The advantage of the desirability function is that all types of 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.[5]

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 then defined. Outside of this range, the individual desirability is 0 or totally unacceptable. The shape of the desirability function between the target and the boundaries of the allowable 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 1 demonstrates the shape of three possible desirability functions.

Mathematically, the overall desirability is defined 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 are between 0 and 1, the overall desirability also is a value between 0 and 1, where 0 is unacceptable and 1 is most desirable.

The geometric mean is used to calculate the overall desirability, because the effect of low individual desirabilities is accentuated compared with arithmetic mean-based approaches. The 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 for the responses 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.

IMPLEMENTATION OF METHODOLOGY

The Methodology is broken into six steps. In executing each step, the user performs the following tasks:

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. Special considerations for durability, such as the potential for aggregate sources to participate in deleterious alkali-silica reactions, are considered. If applicable, 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 matrix is selected. The size and shape of the design matrix, 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 experimental 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.

The Guidelines provide tools to aid in the application of each of the steps of the Methodology. These include flow charts, 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 flow charts. The product of the Step 1 flow chart is a list of laboratory tests to be conducted 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. The Step 2 flow chart 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 output from these decision processes 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. 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.

If the test procedure is not accurate and reliable, incorrect comparisons 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. Tests that lack precision and accuracy should not be used to compare mixtures. The best test program may include non-standard or user-developed tests. Such tests should be included, provided that they reliably measure a type of performance not evaluated through other means.

For each experiment performed in Step 4, a numeric analysis (Step 5) will be performed. The analysis consists of two parts: The first part is to compare the concrete mixtures that were tested to determine which mixture best matched the performance requirements. This mixture is called the "Best Tested Concrete" (BTC). The identification of the BTC 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.

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. At the end of the Confirmation Testing, the Best Concrete, the mixture recommended for implementation, is chosen. The Best Concrete 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 also come into the selection of the Best Concrete, such as cost, material availability, or other factors.

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 an Appendix of the NCHRP report documents, but an overview of the process and the evaluation of the analysis based on the actual results are presented here.

STEP 1: SERVICE CONDITIONS

Based on a bridge deck application in a northern climate, the universal design requirements were characterized and issues relevant to a deck in a freezing climate subjected to chemical de-icers and where cracking was a concern were evaluated. 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 in lists of 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 materials and 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 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. Since the objective of this research is to optimize SCMs, the test program was centered on values recommended in the Guidelines.

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]). 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.

Duplicate batches of a control mixture, which was not included in the statistical analysis, 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 [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 the selected factors and levels. The design matrix that applies for the nine-mixture experiment (a three three-level factors and one two-level factor design) is given in Table 5, which was developed after the factor levels were substituted into a generic matrix provided for this experimental design. The actual mixtures and batch weights tested are listed in Table 6. The admixture dosage rates were determined based on trial batches.

STEP 4: TEST PROGRAM

The test program outlined in Step 1 was modified slightly in practice, and the actual program is summarized in Table 7.

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 prior to testing. 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 themselves were also reviewed based on the test results. The purpose of the re-evaluation was to ensure that the combined desirability functions accurately interpret the performance of the mixtures and support model predictions that are realistic and practical. This reevaluation of the desirability functions based on the test data is an important step that provides a common-sense check based on the actual results (and should not be considered “cheating”).

Analysis of Results and the Best Tested Concrete (BTC)

The first column of Table 8 lists the individual responses that were planned for use in Step 1 and tested in Step 4. The second column lists those responses that were actually used to calculate the overall desirability for the mixtures in Step 5. A number responses were left out of the analysis to ensure that the information considered had a direct impact on the durability of the structure and that each property was given appropriate consideration. For example, 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.

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 insulated vessels used to hold the fresh concrete samples, that the temperature rise would not be above 30°F (17ºC), and the desirability function was designed accordingly. However, the actual temperature rise ranged from 30 to 50°F (17 to 29ºC). Therefore, the desirability function was adjusted to bracket the results obtained.

For the hypothetical case of a northern bridge deck, resistance to chloride ingress, as characterized by chloride diffusion and electrical conductivity testing, was deemed of greatest importance to produce a durable structure, and the desirability functions for these responses were defined so that only the mixtures with the best performance were awarded desirabilities near 1, while mixtures with poor results in these tests were given desirabilities near 0. Mixtures with lower shrinkage and lower heats of hydration were also rewarded with desirabilities near 1. Since the predefined minimum targets were met during strength and freezing and thawing durability testing, most mixtures were awarded a 1 for these responses, which did not factor strongly in the selection process.

The desirabilities for each individual response calculated from the test data and the associated overall desirabilities are shown in Table 9 for each mixture. This table also shows the rank of the mixtures based on the overall desirability. The Best Tested Concrete (BTC) is the mixture that had the highest overall desirability. Therefore, the BTC was Mixture #8.

Response Modeling and the Best Predicted Concrete (BPC)

By definition, the 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 the 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 by computation, 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 10. 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. 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.

A prediction of the performance of the BTC and BPC mixtures in each of the individual responses was made and a review of these values identified the responses that were most significant in the selection of the BPC. In this case study, the predicted individual desirabilities for the BPC for the chloride diffusion, cracking tendency, and electrical conductivity tests were most important in the selection of this mixture as the BPC. This is not unexpected, since the desirability functions were designed to give significant consideration to these properties, which are important to a bridge deck in a northern, Midwest environment.

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 the third column of Table 8. The primary goal of Step 6 is to compare the performance of the BTC and BPC. 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, some tests were eliminated, since in these tests, the BTC and BPC mixtures were predicted to have a similar desirability value. The mixture proportions and batch weights of the Confirmation Testing program are given in Table 6.

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 11, 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.

The Confirmation test results and excellent agreement between 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.

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 in plants of the candidate ready-mix concrete 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.

This Methodology can be most effective when adequate planning and time are available to complete the necessary design matrix and subsequent confirmation testing. Testing can take 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, commitment, planning and time is usually needed to develop the optimum mixture to meet the project goals. This commitment and planning can, however, produce great benefit by identifying highly durable concrete optimized specifically for a project or projects.

One possible way to expedite the Confirmation Testing of the BTC and BPC is to perform this testing 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.

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 clearly demonstrated using life cycle cost analyses.

To aid implementation, concrete suppliers can 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/supplier 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.

An in-depth quality control plan is suggested 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.

Although it is everyone’s ideal that pre-construction durability testing take as little time as possible, the reality is that accelerated testing for durability prediction requires a minimum of several months to obtain thorough, meaningful data. If the process of conducting a concrete test program can begin as early as possible in the design stages of construction, better specifications for concrete materials and mixtures can be provided, and a more durable structure will be produced.

CONCLUSIONS

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. 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 the Guidelines 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 effectiveness of the modeling demonstrated the far-ranging potential of this approach.

REFERENCES

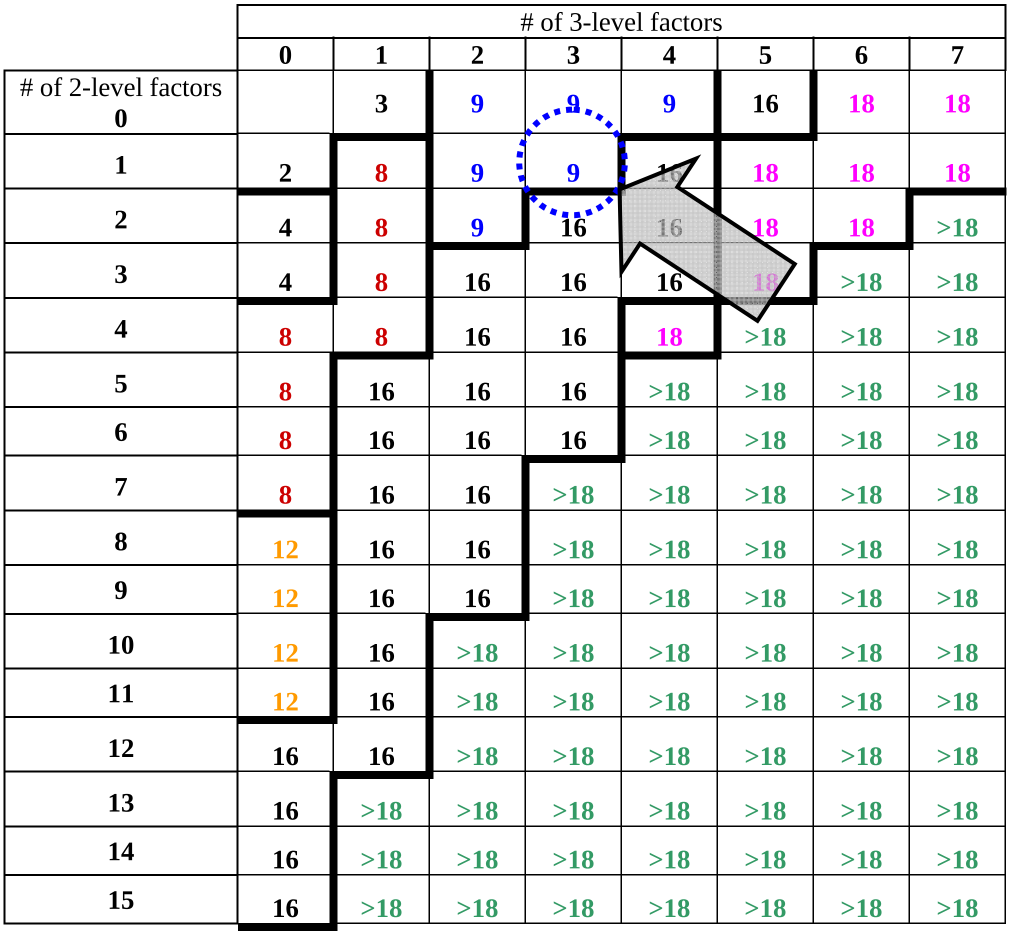
1. Simon, M. J., Lagergren, E. S., and Snyder, K. A., “Concrete Mixture Optimization using Statistical Mixture Design Methods,” PCI/FHWA International Symposium on High Performance Concrete, New Orleans, LA, 1997 pp. 230-244.
2. Simon, M., Snyder, K., and Frohnsdorff, G., “Advances in Concrete Mixture Optimisation,” Concrete Durability and Repair Conference, Dundee, Scotland, UK, 1999, pp. 21-32.
3. Ruiz, J.M., Rasmussen, R.O., and Simon, M., “Performance-Based Paving Concrete Mixture Design and Optimization:” ACI SP228-61, 2005, pp. 971-990.
4. Lawler, J.S., Krauss, P.D., Connolly, J.D., Tracy, S.L., Ankenman, B.E. *NCHRP Report 566 - Guidelines for Concrete Mixtures Containing Supplementary Cementitious Materials to Enhance Durability of Bridge Decks*, 2007 (in press.)
5. Derringer, G. and Suich, R., “Simultaneous Optimization of Several Response Variables,” *Journal of Quality Technology*, Vol. 12, 1980, pp. 214-219.

TABLES

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 selected Orthogonal Designs at end of Step 3 in the Guidelines.
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 the Guidelines.
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

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							
# 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

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%

Table 5. 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 6. 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 7. 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 8. 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)

Table 9. 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 Coef.	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.

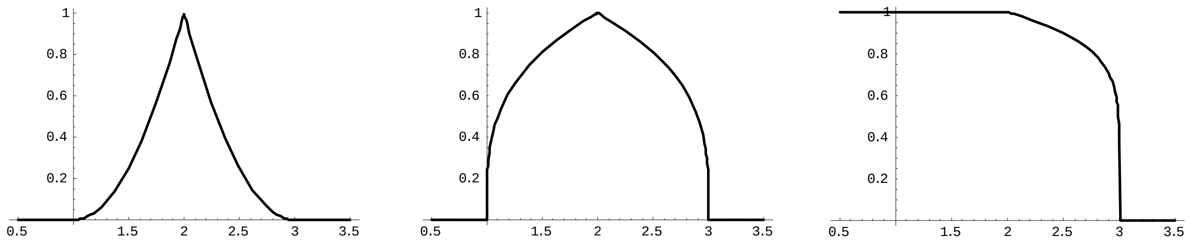
Table 10. Selection of Best Tested (BTC) and Best Predicted Concrete (BPC) based on overall desirabilities

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 11. 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%

FIGURES



(a) (b) (c)

Figure1. Individual desirability functions for (a) a response that must be close to a target value, (b) a response that must be in a range, but not necessarily close to the target value, and (c) a target that is considered perfect if it is below 2 and unacceptable if it is above 3.