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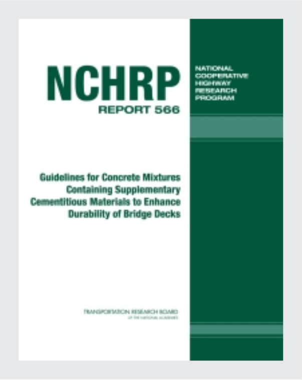

Guidelines for Concrete Mixtures Containing Supplementary Cementitious Materials to Enhance Durability of Bridge Decks

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 566

Guidelines for Concrete Mixtures Containing Supplementary Cementitious Materials to Enhance Durability of Bridge Decks

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Bridges, Other Structures, and Hydraulics and Hydrology • Materials and Construction

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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John S. Lawler, Associate III, assumed the role of principal investigator for this project at approximately the halfway point after the initial principal investigator, Sharon L. Tracy, joined United States Gypsum Corp. Bruce E. Ankenman, Associate Professor of Industrial Engineering and Management Sciences at Northwestern University, contributed his expertise in statistical experimental design and is a coauthor of this report. The other contributing authors from WJE are James D. Connolly and Paul D. Krauss. The hard work of Todd Nelson, Leo Zegler, Ryan Keesbury, John Drakeford, Matt Kern, Joe Zacharowski, and the rest of the staff of WJE is also gratefully acknowledged.

FOREWORD

By Amir N. Hanna
Staff Officer
Transportation Research Board

This report presents guidelines to facilitate highway agencies' use of supplementary cementitious materials to enhance durability of concrete used in highway construction, especially bridge decks. Encompassed in these guidelines is a methodology for selecting optimum concrete mixture proportions. The methodology focuses on durability aspects of concrete and the performance requirements for specific environmental conditions and is presented in a text format and as a computational tool, in the form of a Visual Basic–driven Microsoft® Excel spreadsheet. Background information, a user's guide, and a hypothetical case study are also available. These guidelines should be of interest to state engineers and others involved in the design and construction of concrete bridge decks and other structures incorporating supplementary cementitious materials.

The use of supplementary cementitious materials, such as fly ash, silica fume, slag, and natural pozzolans, in concrete construction has become a widely used practice that is accepted by many state highway agencies, primarily because of the favorable effects on durability. A great deal of research has been performed on properties of concrete containing one or more supplementary cementitious materials; however, research has not provided clear conclusions on the optimum use of these materials to reduce permeability and cracking and thus enhance durability and long-term performance. Without such information, selection of optimum types and proportions of supplementary cementitious materials cannot be ensured, which can lead to the use of materials and mixtures that result in undesirable performance and often the need for premature and costly maintenance or repair. Thus, research was needed to develop an appropriate methodology for designing concrete mixtures containing supplementary cementitious materials for use in bridge deck construction.

Under NCHRP Project 18-8A, "Supplementary Cementitious Materials to Enhance Durability of Concrete Bridge Decks," Wiss, Janney, Elstner Associates, Inc., of Northbrook, Illinois, worked with the objective of developing 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. This research considered the use of fly ash, silica fume, slag, and natural pozzolans both singularly and in combination.

To accomplish this objective, the researchers developed a statistically based experimental methodology that can be used to identify the optimum concrete mixture proportions for a specific set of conditions. The methodology incorporates the following six steps:

1. Defining concrete performance requirements
2. Selecting durable raw materials

3. Generating an experiment design matrix
4. Performing a test program
5. Analyzing test results and predicting optimum mixture performance
6. Conducting confirmation testing and selecting best performing concrete mixture

To facilitate use, the researchers presented the methodology as a computational tool, dubbed SEDOC (Statistical Experimental Design for Optimization of Concrete), in the form of a Visual Basic–driven Microsoft® Excel spreadsheet; prepared a user's guide; and illustrated use of the methodology in a hypothetical case study. The researchers also provided background information on the work performed in this project in a supplementary report.

The guidelines presented herein provide a systematic approach for conducting an experimental study to select the optimum combination of available materials and is targeted for use in the development phase of a concrete construction project where durability is the main consideration; it is recommended for consideration and adoption by AASHTO.

The research agency's report containing background information on the methodology developed in this project and the hypothetical case study are not published herein. These documents are available on the TRB website as *NCHRP Web-Only Document 110* (http://www.trb.org/news/blurb_detail.asp?id=7715). Also, SEDOC, the computational tool for the concrete mixture optimization methodology, and the user's guide are available on the TRB website (http://www.trb.org/news/blurb_detail.asp?id=7714).

CONTENTS

Introduction to Methodology

Background

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 this deterioration is primarily dependent on the permeability of the concrete to moisture and aggressive substances and on cracking of the concrete.

Because nearly all concrete deterioration processes are driven in some manner by the ingress of water and waterborne agents, such as chloride and sulfate ions, one way to minimize problems is to make the concrete less permeable by, for example, densifying the cementitious paste. This densification is achieved by using lower water–cementitious materials ratio (w/cm) and supplementary cementitious materials (SCMs), such as silica fume, fly ash, ground granulated blast furnace slag, or metakaolin. However, if the concrete cracks, aggressive agents may reach the interior of the concrete and the reinforcing steel regardless of concrete impermeability.

Excessive cracking can result from freezing and thawing action, alkali-silica reaction (ASR), corrosion of reinforcement, plastic shrinkage, restrained shrinkage, or thermal stress. Early-age cracking became relatively common with the use of 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 shrinkage, and plastic shrinkage cracking. However, researchers and practitioners have developed materials, mixtures, and construction practices to combat these problems. It is now better understood that high strengths are not necessarily required for durable concrete. In fact, high strengths may be detrimental because of the associated high modulus of elasticity, which could result in the development of restraint-induced stress sufficient to produce cracks. Instead, the mixture can be optimized to minimize permeability and shrinkage/thermal cracking while enabling ease of placement, consolidation, and finishing, thus, minimizing construction-related problems and maximizing durability.

A "one size fits all" approach to concrete mixtures does not achieve the goal of maximizing long-term durability because the quality of local materials used to produce the concrete strongly influence mixture properties and performance. Large variability within, and interactions between, concrete raw materials may influence the short-term properties and long-term durability of the concrete. Therefore, concrete mixtures cannot be truly optimized without testing local materials. This situation implies that even specifying a mixture, without real knowledge of the currently available materials, does not ensure that the concrete produced is the best alternative for a given situation. Concrete mixtures are commonly designed to achieve minimum specification requirements; optimization is rarely performed.

Because accelerated testing for durability prediction requires a minimum of several months to obtain meaningful data, the process of conducting a concrete test program should begin as early as possible in the design stages of construction. This early start will help develop better specifications for concrete materials and mixtures and build a more durable structure.

Problem Statement and Scope of Research

A great deal of research has been performed on properties of concrete containing one or more supplementary cementitious materials. However, this research, conducted on specific SCM sources, has not provided clear conclusions concerning the optimum use of these materials. NCHRP Project 18-08A was conducted to develop a statistically based experimental methodology for determining the best possible mixture proportions of high-performance concretes.

The methodology for designing concrete mixtures containing supplementary cementitious materials presented in these Guidelines is aimed at aiding the user in conducting an experimental study to select the optimum combination of locally available materials. It is intended for use in the development phase of concrete construction projects where durability is a main objective.

The objective of this research was to develop 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. The methodology that was developed mainly considers the use of fly ash, silica fume, slag, and natural pozzolans, both singularly and in combination; but it applies to any combination of materials and performance criteria.

This methodology relies on established practices of statistical design and analysis of experiments. It provides a framework for comparing varied types of performance simultaneously and obtains useful information while testing a small number of the possible combinations of variables that describe the full test range.

This methodology includes a process for determining concrete performance requirements in durability tests based on a selected service environment, as well as a process for selecting durable raw materials. Guidance for SCM types, combinations, and ranges of use for bridge deck applications is provided. Also, a process for selecting mixture variables to put into an orthogonal experimental design matrix is described. Although the user is expected to have a basic understanding of concrete mixture and concrete technology, background specifically related to durability issues and guidance for avoiding harmful material interactions is provided for reference. The methodology is particularly valuable because it defines a procedure for optimizing concrete mixtures relative to locally applicable performance criteria with locally available materials.

Products of Research

NCHRP Project 18-08A, "Supplementary Cementitious Materials to Enhance Durability of Concrete Bridge Decks," produced the following:

- *NCHRP Report 566: Guidelines for Concrete Mixtures Containing Supplementary Cementitious Materials to Enhance Durability of Bridge Decks*
- *NCHRP Web-Only Document 110: Supplementary Cementitious Materials to Enhance Durability of Concrete Bridge Decks*, the project report that includes a hypothetical case study
- A Microsoft® Excel–based computational tool for the concrete mixture optimization methodology and a user's guide

These Guidelines present the information required to work through the process of developing an optimized concrete mixture using locally available materials. It provides a framework and guidance for making the decisions involved in this process and explains how to perform the experiment design and statistical analysis. *NCHRP Web-Only Document 110* (available on the TRB website: http://www.trb.org/news/blurb_detail.asp?id=7715) provides a condensed description of the methodology and the process by which it was developed. It also discusses the scope and capabilities of the methodology and how and where it may be best applied. The appendix of *NCHRP Web-Only Document 110* presents the details of the test program conducted in parallel with the development of the methodology, including a description of the materials examined, the tests performed, and the results obtained. The tool, Statistical Experimental Design for Optimization of Concrete (SEDOC), was developed to guide the user and to execute the statistical analysis and modeling. The computational tool and the user's guide are available on the TRB website (http://www.trb.org/news/blurb_detail.asp?id=7714).

Relationship of the Methodology to the Implementation of Concrete Mixtures Designed for Durability

The recommended process for the implementation of concrete mixtures designed for durability for a given structure is summarized as follows:

1. Identify targeted performance in terms of general objectives and in terms of quantifiable measures
2. Select the best available raw materials
3. Select the best concrete mixture based on concretes produced with the specific raw materials and tested to evaluate performance
4. Produce trial batches of concrete with the selected raw materials by candidate ready-mixed concrete producers to demonstrate that target performance can be achieved in the field
5. Conduct a comprehensive quality assurance/quality control program and monitor construction practices and the concrete itself through trial placements and during construction

The methodology developed in this project will aid the user through the first three stages of the implementation process.

The methodology consists of the following steps:

1. **Define concrete performance requirements.** The future service environment of the concrete is assessed and used to define the desired concrete performance. Tests to evaluate these properties are selected and a "desirability function"

is created for each test response. The type of SCMs and general ranges of SCM content that are expected to produce this performance are also identified.

2. **Select durable raw materials.** The raw materials that are under consideration for the project are evaluated in this step. Worksheets are used to compile and then compare the different properties of the candidate raw materials. The materials most likely to produce durable concrete are selected based on this information.
3. **Generate the experimental design matrix.** An orthogonal experimental design is selected for the investigation that is compatible with the identified types and ranges of materials and the scope of the test program. Based on the design, the experimental matrix (the specific mixtures to be tested) is chosen.
4. **Perform testing.** In this step, concrete mixtures are batched according to the experimental matrix and tests are conducted as defined in Step 1.
5. **Statistically analyze the results with the desirability functions and generate the optimal mixture(s).** The test results are compared within the framework provided by the desirability functions. The Best Tested Concrete (BTC) is selected based on the overall desirabilities calculated for each mixture. The performance is modeled for each factor and these models are used to identify the Best Predicted Concrete (BPC).
6. **Confirm the optimum mixtures by testing.** The BPC and BTC are batched and tested to confirm their durability and to select the optimum performer, or Best Concrete (BC).

Introduction to Supplementary Cementitious Materials

Four types of SCM are commonly used in concrete bridge deck construction: ground granulated blast furnace slag (GGBFS), fly ash, natural pozzolans, and silica fume.

GGBFS or slag, a by-product of iron ore processing, is specified in AASHTO M 302 (ASTM C 989), Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars.

Fly ash, a by-product of coal-burning electric power plants, is specified in AASHTO M 295, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete, and ASTM C 618, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. Fly ash is divided into two classes by this specification based largely on the total combined percentage of silicon dioxide, aluminum oxide, and iron oxide. Fly ashes with this combined percentage greater than 70% are Class F, while those with this combined percentage less than 70% and greater than 50% are Class C. Class F fly ashes usually contain low amounts of calcium oxide (CaO) (less than 10%) while Class C ashes may have more CaO content (between 10% and 30%). The class is largely determined by the type of coal burned during the generation of the fly ash.

Natural pozzolans are also governed by AASHTO M 295 (ASTM C 618). Some of the more common materials that fall into this category are metakaolin and calcined clay. These materials are not by-products but are processed from naturally occurring raw materials.

Silica fume, a by-product of silicon alloy production, is governed by ASTM C 1240, Standard Specification for Silica Fume Used in Cementitious Mixtures. Silica fume is probably the SCM most associated with concrete designed for durability because of its extremely fine particle size that densifies the microstructure and thus influences strength, permeability, and other properties.

SCMs are hydraulic or pozzolanic (or combinations thereof) materials that are combined with portland cement and contribute to the properties of the concrete. The term “hydraulic” means that the material will set and harden by reacting chemically with water. “Pozzolanic” materials, when finely divided and in the presence of water and portland cement, react chemically with the calcium hydroxide released during the hydration of the cement to form hydration products (e.g., calcium silicate hydrate). GGBFS and Class C fly ash fall in the hydraulic category. AASHTO M 295 Class F fly ash and Class N natural pozzolans and silica fume fall in the pozzolanic category (*1*). These materials are discussed in much greater detail in Step 2 of this methodology.

Statistical Design of Experiments

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

Terminology

Table I.1 summarizes the terminology associated with the statistical experimental design that can be applied to the design of concrete mixtures. The three most common terms are “factor,” “level,” and “response.”

Table I.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).
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 the "Selected Orthogonal Design Matrices" section in Step 3.
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
Overall desirability	Combined desirability for a single mixture based on all the individual desirabilities. This combination is calculated as the geometric mean of the individual desirability functions for each response.	Overall desirability = 0.984 for Mixture #1

The term "factor" refers to the independent variable, or *x*-variable, to be varied in the experiment. There are several 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," which will 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." It is the *y*-variable, or test result when a mixture is tested for a certain characteristic using a specific test method, such as strength or elastic modulus (i.e., "response" equals 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 software. It includes the specified number of "mixtures" to be evaluated and how the levels of each of the factors should be set for each mixture.

The "desirability function" refers to a plot or equation that rates a given output from a test on a scale from 0 to 1, where 0 is an unacceptable result and 1 is a result that needs no improvement. For example, for a test of compressive strength at 7 days, an outcome of 1200 psi (8.3 MPa) for a certain mixture might be considered unacceptable and that mixture would be assigned a desirability for strength of 0. If a different

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mixture tested at 5000 psi (34.5 MPa) or higher after 7 days, it might be considered highly desirable and that mixture would be given a desirability for 7-day strength of 1. Mixtures with results in between 1200 and 5000 psi (8.3 and 34.5 MPa) could be assigned a desirability between 0 and 1 according to the desirability function. The desirability function for a response covers every possible outcome of the test to a number between 0 and 1. Through the desirability function, the user is able to define and set the relative importance of each test result (response). The desirability function will be discussed in more detail later in this Introduction and in Step 5.

The overall performance or "overall desirability" of a mixture is the combined desirability of each test response and allows a direct comparison of one mixture with another to decide which mixture is best overall. This comparison is possible because the overall desirability is derived from the individual desirabilities for each response and thus reflects the individual properties of the mixture and importance of that property in the overall concrete performance. Overall desirability is calculated from the geometric mean of the values of the desirability functions for each response.

Methods of Designing Experiments

Through the use of statistical design of experiments, useful information can be obtained regarding a range of mixtures in question 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 type 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 generally requires the testing of a relatively small number of mixtures 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 of the discrete combinations of factor levels instead of all 3^4 (i.e., 81) possible discrete combinations. This method also allows consideration of non-quantitative factors (such as source of material), which are often variables. Also, this method does not limit the number of responses or the form of the desirability functions.

Using the tests results based on only the selected combinations, the orthogonal design method can provide a prediction of the best level for each of the factors in the experiment. If the optimal level for any factor (e.g., SCM content) substantially changes for different levels of other factors, the predicted optimum level of that factor may be poorly estimated, but it will not affect the evaluation of the concretes that are actually batched and tested. Because the mixtures in an orthogonal design are quite different from each other, the chance of finding a good mixture is increased even in the cases where the optimum level for some factors is difficult to predict. The confirmation testing strategy, where the BPC and BTC are tested, addresses this issue. The alternative is to test substantially more mixtures as in the mixture or central composite design approaches (at least 24 of the 81 possibilities would need to be tested for these methods).

Desirability Functions and Combining Test Results

If only one test were to be performed, the performance of the mixtures could be compared based only on the measured value of that test for each concrete mixture. However, because 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 combination is achieved by describing a desirability function (*2*) that provides 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 would be required. 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.

Mathematically, the overall desirability function is the geometric mean of the desirability functions for each of the tests. For example, if the desirability functions for three different tests are represented by d_1, d_2, and d_3, the overall desirability, D, will be defined as $\sqrt[3]{d_1 \times d_2 \times d_3}$. In general, for n desirabilities, the overall desirability is the nth root of the product of the desirability functions. Because 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.

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. 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

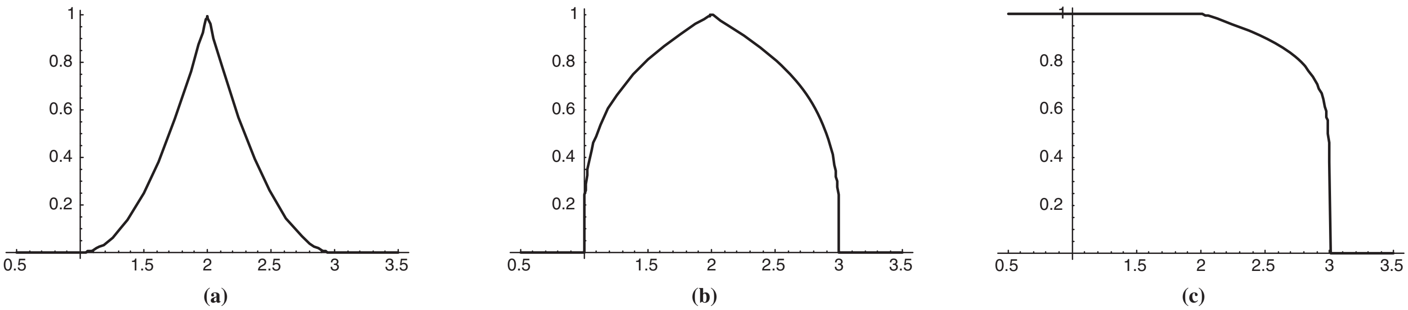

Figure I.1. Individual desirability functions for (a) a response that must be close to a target value, (b) a response that must be in a range, but not necessarily close to the target value, and (c) a target that is considered perfect if it is below 2 and unacceptable if it is above 3.

desirability functions. Because a mixture that receives a desirability of 0 on a single test will have an overall desirability of 0, the performance range assigned to 0 by the function will make that mixture unacceptable regardless of performance in all other categories.

Because the desirability function provides the link between the test that may be influenced by the method and testing conditions and predicted actual behavior, the accuracy of the desirability function requires subjective interpretation by the engineer or scientist conducting the study. After the desirability function has been applied to the test responses and a maximum overall desirability has been selected, users must apply their expertise in concrete technology to carefully study the predicted responses for each test to ensure that the tradeoffs made in maximizing the desirability function did not lead to an unexpected (i.e., contrary to well-established principles) result.

Examples of desirability functions for a number of properties (response types) are given in the guidance provided in support of Steps 1 and 2. The desirability functions to be used must be chosen carefully because they are a critical part of the analysis and modeling process. The functions must be adjusted based on what tests are conducted and the understanding of how each response (test result) affects the overall performance. Functions may be set to avoid problems or define performance not directly measured by the experimental program. For example, the desirability function for air content might be adjusted depending on whether cyclic freezing testing is performed. Sometimes functions will be established for two or more responses in the experimental program to define a certain type of performance and thus the importance or weight of this issue will be indirectly increased. Therefore, all functions should be carefully reviewed to ensure that the proper weight is established for each parameter. The desirability functions provided here are examples that may not be consistent with the development objectives of the concrete mixture for the specific structure or structures being considered. Therefore, the individual mixture requirements should be assessed and appropriate desirability functions should be developed. The example functions were developed for use in an experimental setting and have not been designed or tested for establishing degree of compliance or project pay factors.

Analyzing the Orthogonal Design Experiment

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

- The concrete mixtures that were tested will be compared to determine which one best matched the performance requirements for the project in question. The best match is the 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.
- Statistical modeling will be employed to predict the combination of the levels of the factors that will produce the BPC according to the same desirability functions. This modeling will be accomplished based on individual predictions for each of the responses (performance measures) for all possible combinations of the factors in the range tested. The statistical models will also provide a prediction of results for the BPC on each of the individual tests, such as strength and elastic modulus.

Because the experimental design approach involves a relatively small number of tested concretes compared with the number of factors and test combinations, the results of the statistical model need to be confirmed by a second round of testing (Step 6). Typically, the BPC will not be among the mixtures that were actually tested in the original matrix; thus, if it is to be used in an application with confidence, a confirmation batch of the BPC must be mixed and tested. Realistically, the recommended level of testing of the BPC will be based on the amount of time available for confirmation

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testing and the predicted performance difference between the BPC and the BTC.

Application of Methodology

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 are provided in these Guidelines to aid the user in the application of each of these steps.

The Process

The initial decisions to be made for designing concrete mixes are laid out in Steps 1 and 2. The end products of Step 1 are the laboratory tests to be conducted (the responses) and the associated performance requirements for the concrete to be designed. Guidance is given regarding suitable ranges of various SCMs that have been shown to improve the responses. The information gathered from Step 1 is collected in a worksheet. This worksheet and others given in these Guidelines are intended to provide a location for the user to record information relevant to the specific experiment being conducted. Because these worksheets will be marked up as decisions are made, it is recommended that the user photocopy the pages or print the worksheets (from SEDOC) in case the methodology is to be used more than once.

The end products of Step 2 are the potential raw materials' sources, test data regarding these raw materials, and combinations that are likely to be durable. 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 full set of (source, type, or amount) factors are the independent variables in the study. The information gathered from Step 2 is collected in several worksheets.

The information on these worksheets are combined into the set of factors and levels used in Step 3. Step 3 guides the user in the selection of the experimental matrix from a table 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 (note that only certain combinations of specifically sized factors, varied in specific ways, will produce the symmetrically distributed experiment necessary for the statistical analysis.) Figure I.2 schematically illustrates the relationship between the first two steps and how they provide information for the experiment design process. This figure illustrates that, during this selection process, there will likely be interaction among the materials selected based on the performance objectives, the cost and scope of the testing program, the selection of the experimental design matrix, and the number of materials that can be tested.

User Aids

Examples

As part of the research conducted to develop this methodology, the process of identifying an optimum concrete mixture was evaluated using real materials and test results and a hypothetical set of performance requirements. The complete details of this hypothetical case study can be found in the appendix of *NCHRP Web-Only Document 110* (http://www.trb.org/news/blurb_detail.asp?id=7715); select examples from that investigation are presented throughout these Guidelines to demonstrate how each step may be completed.

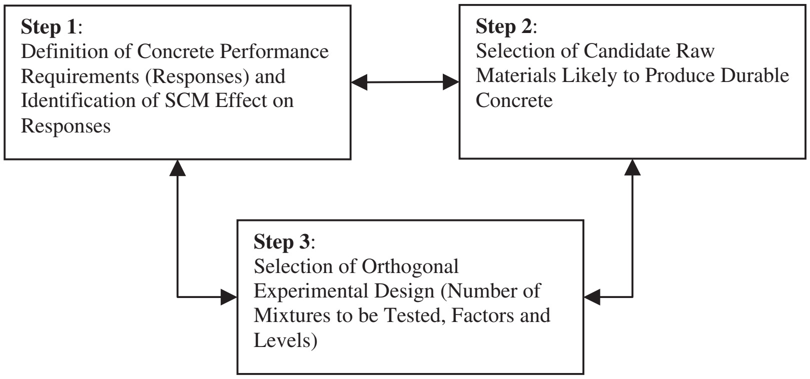

Figure I.2. Relationship between flowcharts and experimental design of concrete mixtures.

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Computational Tool

In parallel with these Guidelines, SEDOC—a computational tool consisting of Microsoft® Excel–based worksheets—was developed to automate several of these tasks. SEDOC is described in detail in the user's guide available on the TRB website (http://www.trb.org/news/blurb_detail.asp?id=7715). The first workbook, titled "SEDOC: Setup," is based on the flowcharts developed for Steps 1 and 2 of this study to aid in the development of the experimental matrix. The second workbook, titled "SEDOC: Analysis," helps to perform the statistical modeling and analysis that leads to the prediction of the optimum concrete.

Glossary

A glossary of terms is included after the six steps of the methodology. This glossary contains definitions for some of the statistical jargon used to discuss the application of this methodology.

STEP 1

Define Concrete Performance Requirements

Introduction

The first task in determining the optimum concrete mixture for a particular application is to define what properties of the concrete are significant. This procedure requires differentiating between what properties are not relevant, what properties must meet but not necessarily exceed a minimum level of performance, and what properties are to be maximized (e.g., durability) or minimized (e.g., shrinkage). The definition of the properties (the performance under a given set of conditions) must be in both general terms (e.g., the concrete must be resistant to freezing and thawing) and in specific terms (e.g., the concrete must be capable of withstanding 500 cycles of cyclic freezing and thawing as defined by ASTM C 666, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, Procedure A, with a durability factor of no less than 85% at the end of testing).

The general definition requires local knowledge of the service environment to which the structure will be exposed and the potential mechanisms that may lead to deterioration of the structure. The specific definition includes both a test method and desired test responses. Because the test methods used to evaluate durability are accelerated tests, developed to predict field performance over a time scale greater than actually tested, determining the appropriate desired response requires a good understanding of what is actually tested and the accuracy of the simulation to real performance for a given method.

While specification of minimum performance requirements will not be unfamiliar to most engineers, this methodology requires taking the definition of desirable performance one step further. To provide a basis for comparing the concrete mixtures to be evaluated, the minimum acceptable and desired responses are interpreted in terms of a single desirability function that summarizes the desirability of the performance over the full range of possible test outcomes.

The objectives of Step 1 of the methodology are the generation of the following:

- A list of general performance objectives for the concrete mixture based on the service environment and design objectives
- The selection of test methods that will provide a basis for evaluating the concrete mixtures
- The definition of desirability functions to be used to numerically compare the measured responses and generate an overall desirability for each mixture.

Performance Definition Process

To aid in the achievement of the objectives of Step 1, users can consider a series of questions regarding the service environment of the bridge deck that is to be constructed with the goal of defining the performance characteristics required for the concrete in their specific application. This process is formalized as the flowchart in Figure S1.1. Each potential service environment relates to a concrete property, a test method, and a target test response for that property. For each entry in Figure S1.1, there is a corresponding narrative description in this section of the Guidelines giving background to the entry, recommended performance requirements for each test, a general discussion of the likely influence of SCMs on the concrete with respect to each property, and some general recommendations for other mixture proportion variables, such as w/cm. The identification number given in square brackets (e.g., [D1]) in each decision box of the flowchart refers to the code placed after the heading of the subsection that discusses the background relevant to that entry.

Worksheet S1.1 is provided to aid users in summarizing the information required for the experimental design process including (1) concrete properties selected as important in the chosen service environments; (2) target values for specific test methods related to those properties; (3) guidance for

SCM types, ranges for use, and effect on each property; and (4) other relevant mixture issues. Typical SCM ranges for use for each property are summarized in Table S1.1.

The first step in using Figure S1.1 is to define the concrete parameters that are universal performance requirements for bridge decks. These parameters usually include concrete strength, workability, and finishability—properties typically required for the concrete irrespective of the particular service environment.

To help define service environments and concrete characteristics, answers to six questions about categories of service environment/concerns are needed to determine if the bridge will be built in (1) a freezing and thawing environment, (2) a location where chemical deicers are used, (3) a coastal environment, (4) an abrasive environment, (5) an area of concern for alkali-silica reactivity (where, if so, the user is forwarded to Step 2), and (6) an area of concern for cracking. If the answer to any of these questions is "yes," the concrete properties that are required for durability in that environment and the tests to be used to assess the concrete's performance relative to that type of environment are described for consideration. The user should progress through the service environment categories, considering each individually and recognizing that more than one service environment category probably exists for most bridge decks.

The background information associated with each decision box in Figure S1.1, found in the subsection titled "Guidance on Concrete Design Requirements and Appropriate Test Methods," provides guidance on the test method selection and target values for the test results. The user should summarize the target values relevant to the structure to be built in the first column of Worksheet S1.1 to provide a basis for developing desirability functions. The desirability functions are an important part of the analysis to be performed in Step 4. Example desirability functions are provided in the "Guidance" subsection. These functions should be reviewed and adjusted as needed to match the target values identified for the specific project in question.

The background information also discusses the influence of SCMs on each property. Table S1.1 summarizes typical usage of SCMs to produce desirable performance for each property. Also, background information and suggestions are provided in Table S1.1 regarding each SCM and its influence on the properties considered. The recommendations relevant to the experiment being conducted should be recorded in Worksheet S1.1, which lists each property and provides columns for recording recommended ranges for each mixture parameter, such as the contents of the SCMs.

A few other requirements for properties are included in Tables S1.2 through S1.7. This information should be considered and also included in the relevant rows and columns of Worksheet S1.1.

Any tests not deemed relevant can be crossed out of Worksheet S1.1, leaving the tests that must be performed on each mixture in the developed experimental design matrix (as described in Step 3). After completion of Worksheet S1.1 (except for the row on ASR if applicable), the user can then proceed to Step 2. If ASR is not to be considered, the user can proceed by summarizing the values of each of the columns, which list the mixture parameters recommended to achieve the desired performance. The objective is to provide a basis for determining the ranges over which the experiment will be conducted by identifying the ranges of SCM contents and other mixture parameters consistent with most, if not all, of the recommendations. If many properties are being evaluated, it is possible that a small or even non-existent range remains after all the recommendations have been considered; the user is then free to broaden the range for testing as necessary.

Because the Guidelines consider each property separately, recommendations for improving one property may conflict with the recommendations for improving another. These conflicts may be reconciled either by including both recommendations in the scope of the experiment so that the experimental process will identify the best balance or by choosing to follow one of the recommendations and maximize performance in terms of the property known to be the most important at the expense of the other.

While a set of performance measures is discussed in the Guidelines based on meeting the demands of the specific service environment categories, the experimental analysis procedure is flexible and capable of differentiating and modeling any characteristic of the concrete if that characteristic can be evaluated with a desirability function. For example, the cost of the concrete mixture could be included as a response in the analysis process and a desirability function defined so that less expensive mixtures are more desirable. However, cost was not included as a response in the default experimental program or the hypothetical case study because the in-place cost is difficult to predict and is often a secondary concern compared to durability-related performance.

Example from Hypothetical Case Study

The hypothetical case study (Appendix A of *NCHRP Web-Only Document 110*) was based on a bridge deck application in a northern climate. For this hypothetical environment, the steps outlined by Figure S1.1 were used to characterize the universal design requirements and evaluate 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.

Table S1.8 presents an example of Worksheet S1.1 completed for the hypothetical case study according to the guidance provided in this chapter. The recommended testing program based on the service environment of the hypothetical case study is summarized on this worksheet, which lists 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 will serve as a reference point for selecting the ranges for testing over which each material may be optimized.

Guidance on Concrete Design Requirements and Appropriate Test Methods

The following subsections discuss concrete performance requirements that are mentioned in Figure S1.1.

Universal Performance Requirements

Nearly all concrete construction projects involve performance requirements that characterize the strength of the material and evaluate the influence of the concrete on the ease of construction.

Compressive Strength [D1]

Compressive strength is almost always specified by the designers of the bridge. It is measured by AASHTO T 22 (ASTM C 39), Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. In this method, a compressive axial load is applied at a specified rate to molded concrete cylinders. The peak load applied divided by the cross-sectional area gives the compressive strength.

Desirability Function for Compressive Strength. The desired compressive strength will depend on the design specifications for the structure, which will vary depending on the project. The compressive strength must meet the minimum design criteria. However, it is often disadvantageous for the compressive strength to be much higher than required because the accompanying higher elastic modulus may render the concrete more susceptible to cracking and higher strength is usually associated with increased cost. Considering a maximum strength when defining the compressive strength desirability function to minimize cracking potential is particularly important if appropriate limits are not set for the elastic modulus or cracking tendency. The cracking tendency can be measured with ASTM C 1581, Standard Test Method for Determining Age of Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete Under Restrained Shrinkage (also known as the restrained ring shrinkage test).

Figure S1.2 gives a suggested 7-day desirability function for a concrete expected to meet a specified 28-day strength of 5000 psi (34.5 MPa). The strength of the mixture is considered to need no improvement if the strength is between 3500 and 5500 psi (24.1 and 37.9 MPa) and is therefore assigned a desirability of 1 over that range. This function penalizes mixtures if the strength is greater than 5500 psi (37.9 MPa) at this age. Penalizing mixtures with high early strengths is a strategy for minimizing cracking because the stresses that cause most early thermal and drying shrinkage–related deck cracking are related to the stiffness (elastic modulus) of the concrete at these early ages. A reduction in the desirability of mixtures with high early strength is especially important for bridge deck designs that have high restraint conditions if other tests to evaluate early-age cracking, such as elastic modulus or cracking tendency, are not included in the experimental program. Avoiding very high-strength mixtures also will make the concrete more economical, a factor not directly considered in this example.

Figure S1.3 shows an example where the target average 28-day compressive strength is at least 5500 psi (37.9 MPa) and desirability of 1 would be assigned to the mixture for this response if the strength is between 5500 and 8500 psi (37.9 and 58.6 MPa). This target average may be selected for a specified design strength of 5000 psi (34.5 MPa), because it will ensure that even with some variation, the design strength will be exceeded. Because mixtures with high strengths at later ages will also likely have high early strengths, which may be related to early cracking, a penalty was assigned to high-strength mixtures. Figure S1.4 gives a similar desirability function for 56-day strength. Evaluating the concrete performance at this later age, if consistent with construction schedules, may be more appropriate than 28 days because of the decreased rate of hydration and strength gain typical with many SCM-based mixtures.

Effects of SCMs on Compressive Strength

Fly Ash. The interactions between cement and fly ash are complex, and their effect on compressive strength is not always predictable. Typically, mixtures with Class F fly ashes develop strength more slowly than comparable mixtures containing only portland cement. Although 28-day strengths may be lower for concrete containing fly ash, particularly Class F fly ash, fly ash continues to hydrate over time, and the long-term strength of concrete with fly ash typically exceeds that of a comparable portland cement concrete. Silica fume can be used in combination with fly ash to increase the rate of strength gain at early ages.

Class C (high calcium) fly ashes show a higher rate of reaction at early ages than Class F fly ashes and typically do not result in a significant difference in compressive strength from pure portland cement concrete at replacements up to 30%. Therefore, they can be proportioned on a one-to-one replacement basis for portland cement without a negative effect on early-age strength (*3*) and they can achieve 28-day strengths that are comparable to portland cement concrete. At later ages (beyond 28 days), some Class C fly ashes may not show the strength gain expected from Class F fly ashes (*4*).

GGBFS. Fernandez and Malhotra (*5*) found that lower strengths were obtained through 91 days when GGBFS was used, with a possible lesser effect at lower (25% vs. 50%) dosages. However, slag is categorized in AASHTO M 302 (ASTM C 989) by grades, which is a measure of the reactivity, defined as the percentage of strength achieved in mortar cubes made with 50-50 portland cement–slag combinations versus only portland cement. American Concrete Institute (ACI) Committee 233 (*6*) reports that Grade 120 slag can have reduced strength at early ages (1 to 3 days) and increased strength at 7 days and beyond. A Grade 100 slag will typically have lower strength until 21 days, and equal or greater strength thereafter. A trend in recent years has been to grind slag to sufficiently high fineness that little reduction in the rate of hydration occurs when compared with cement. Cement manufacturers sometimes blend portland cement and slag or fly ash at low levels while conforming to ASTM C 150 cement requirements.

Silica Fume. The effect of silica fume is most pronounced on strength between 3 and 28 days, after which its influence on strength is minimal. At conventional dosage rates, silica fume–containing concrete always has higher strength than ordinary portland cement concrete at a comparable w/cm (*7*).

Class N Pozzolans (Metakaolin). Concrete with an addition of 7% of metakaolin was found to have higher early-age strengths than portland cement concrete and concrete with 7% silica fume addition. At 28 days, metakaolin-containing concrete was found to be 10% stronger than portland cement concrete and 5% to 10% weaker than an equivalent mixture with silica fume. In one study, between 90 and 365 days, metakaolin-containing concrete gained strength, whereas the strength of silica fume–containing concrete decreased slightly (*8*). Ding and Li (*9*) found compressive strength of concrete with 5% to 15% replacement of metakaolin at 3 to 65 days increased from 4% to 53% over plain portland cement concrete. Calcined clay additions were found to exhibit slower early-age strength gain but higher 28-day strength than portland cement concrete (*10*).

Tensile/Flexural Strength [D2]

The tensile strength of concrete is theoretically defined as the peak tensile load divided by the cross-sectional area. However, because of the difficulty in applying direct tension, it is almost never tested in this way. Instead, the tensile performance is approximated using splitting tension or flexural testing. Flexural strength is the peak tensile stress developed in a beam assuming elastic beam theory. Flexural strength is usually specified for highway or airfield pavements and occasionally for bridge decks.

Test Methods. Three types of tests are related to tensile strength of the concrete: (1) direct tension, (2) flexure, and (3) splitting tension. Only flexure and splitting tension will be discussed here.

Flexural strength is measured by two methods. The most common method is AASHTO T 97 (ASTM C 78), Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). In this method, a concrete beam, 6×6×21 in. (150×150×535 mm) in size, is supported at the ends and loaded at the third points until failure. The modulus of rupture is calculated as the stress at the extreme fiber. The second method is AASHTO T 177 (ASTM C 293), Test Methods for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading), which loads the beam at its center point. This method is rarely used because its results are more variable (*11*). Because the specimens are quite large and heavy for both tests, neither test method for flexural strength is convenient. The test results may be influenced by the concrete moisture content at the time of testing. Also, the modulus-of-rupture calculations are based on elastic beam theory, which is not completely accurate for these conditions and overestimates the tensile strength of concrete. Neville (*11*) cites a reference by Raphael (*12*) that states the "correct" tensile strength is three-quarters of the calculated modulus of rupture.

Tensile strength can be measured indirectly using the splitting tensile test, AASHTO T 198 (ASTM C 496), Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. In this test, a concrete cylinder or core is compressed parallel to its axis, resulting in a splitting failure. The tensile strength is calculated from the peak compressive load. Neville (*11*) reports that the results are believed to be closer to the actual tensile strength of concrete than those measured in flexural strength testing. Also, the tensile splitting test is less variable and easier to conduct. However, if splitting tensile strength results are to be used to show compliance with flexural strength specifications, a correlation should be established for the mixture in question.

Desirability Function for Tensile/Flexural Strength. For 5000 psi (34.5 MPa) compressive strength concrete, the tensile strength measured with a splitting tensile test is approximately 500 psi (3.5 MPa), while for 6000 psi (41.4 MPa) concrete, the tensile strength is close to 600 psi (4.1 MPa) (*11*). The expected corresponding moduli of rupture for mixtures with these compressive strengths are 530 and 580 psi (3.7 and 4.0 MPa), respectively. An example of a desirability function for modulus of rupture is shown in Figure S1.5 based on a specified minimum modulus of rupture of 530 psi (3.7 MPa) and an assumed target average modulus of rupture of 580 psi (4.0 MPa) or greater.

Effect of SCMs on Tensile/Flexural Strength. Because tensile and flexural strength are typically linked to compressive strength, the effects of SCMs on these properties are generally similar.

Fly Ash. If fly ash is substituted on a one-to-one basis by weight or volume for portland cement, flexural strengths are usually lower until about 3 months of age but may be higher beyond this age (*13*).

GGBFS. GGBFS typically increases modulus of rupture because of increased denseness of paste and improved bond between aggregates and paste (*6*).

Silica Fume. Silica fume can result in higher flexural strength, compared with plain portland cement concrete (*7*) likely due to the increase in interfacial bond between paste and aggregates.

Class N Pozzolans (Metakaolin). Taylor and Burg (*8*) report little difference in splitting tensile strength results between portland cement, metakaolin-containing, and silica fume–containing concrete. However, Caldarone et al. (*14*) report 28% to 36% increases in flexural strength over portland cement concrete at 7 to 90 days when 10% metakaolin was added.

Workability and Finishability [D3]

"Workability" is a qualitative or subjective term that has been defined by various sources, according to Neville (*11*), as (1) "the amount of useful internal work necessary to produce full compaction," (2) "property determining the effort required to manipulate a freshly mixed quantity of concrete with minimal loss of homogeneity," and (3) "that property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished."

No test measures workability directly, but there are tests that measure properties related to workability. Some of these include the slump test (AASHTO T 119/ASTM C 143), Test Method for Slump of Hydraulic-Cement Concrete, which measures the tendency of the concrete to flow under its own weight and is often used as a measure of consistency; a slump loss test, which is simply the difference in two measurements of slump taken over an interval of time; and time of setting as measured by AASHTO T 197 (ASTM C 403), Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance, which measures the setting time of a mortar sieved from concrete. No direct measurement of finishability exists, but a relative, qualitative assessment (non-standard test) can be useful in comparing concrete mixtures.

Slump. During the slump test, concrete is placed in three layers into a conical mold held against a flat surface. Each concrete layer is rodded before the introduction of the next layer. The concrete is struck off, and the cone is slowly lifted, allowing the concrete to drop or slump when unsupported. The decrease in height is measured and is called the slump.

When slump is too low, workability and the ability to consolidate the concrete are likely to be poor. When slump is too high, segregation of the paste from the aggregate is possible. Too high of a slump can also indicate that the w/cm is too high, or if superplasticizer is used, that the dosage is high.

Desirability Functions for Slump. The target value for slump at placement varies depending on the placing requirements and procedures and on mixture proportions of the concrete, especially the presence of chemical admixtures, such as superplasticizer or high-range water reducers (HRWRs). For cast-in-place bridge decks, the target value for slump is typically 5 in. (125 mm) at placement. If HRWRs are used, the slump at the start of placement can be as high as 8 in. (200 mm) without problems; however, if an appropriate amount of the HRWR is not used, an 8-in. (200-mm) slump will likely be achieved through the use of excess water, resulting in low strength or segregation.

A desirability function for slump, based on concrete containing HRWR, is given in Figure S1.6. This function suggests any slump in the range of 4 to 8 in. (100 to 200 mm) is acceptable, but slumps higher or lower than this range are penalized severely to ensure that concrete is workable enough to allow easy consolidation but prevent segregation.

HRWRs are typically used for water reduction and higher workability. The admixture coats the surfaces of the cementitious particles and, by electrostatic repulsion and hindrance, helps the particles stay dispersed in water. Decreasing the need for additional water for flow and workability generally increases the quality of the concrete. The permeability of the concrete is decreased and strength is increased because the pore space occupied by water is decreased. When silica fume is used, HRWRs are needed to decrease water demand and increase silica fume dispersion. If the slump is outside the desired range, the mixture can be modified to achieve the desired slump by increasing or decreasing the amount of HRWR, usually without adverse effects. Slump could be highly weighted (important) in a test program if the methodology is used for evaluating the effect of admixtures on slump and other plastic properties.

Effect of SCMs on Workability and Slump

Fly Ash. Because fly ash particles are spherical in shape, they have generally been shown to permit a reduction in water content for a given workability (*4*). Also, when fly ash is substituted for cement by weight, the volume of the paste relative to total concrete volume is increased because the density of fly ash is less than that of cement and results in an increase in plasticity and cohesiveness (*4*). Other studies summarized in Malhotra and Ramezanianpour (*3*) indicate that fly ash particles that are less than 45 µm can reduce water requirements. In general, fly ash substitutions increase slump; however, there are data to the contrary as well. Apparently, fly ashes with higher carbon contents and coarser particle sizes can increase water and air-entraining agent requirements. Because fly ash behavior in concrete is complex, the effect of the particular fly ash can be determined only by testing the specific concrete mixture.

GGBFS. Several studies cited in ACI Committee 233 (*6*) indicate slump increases with increasing GGBFS content.

Silica Fume. ACI Committee 234 (*7*) summarized the effect of silica fume on water demand and workability and suggests that the water demand of the concrete increases when silica fume content increases. An HRWR is generally used to optimize the properties of silica fume concrete. Silica fume–containing concrete exhibits increased cohesiveness and decreased tendency to segregate compared with ordinary portland cement concrete. ACI Committee 234 (*7*) recommends an initial slump of silica fume concretes 2 in. (50 mm) above that required for ordinary portland cement concretes to maintain the same apparent workability.

Class N Pozzolans (Metakaolin). Less HRWR is required to achieve a similar workability for metakaolin-containing concrete than for silica fume–containing concrete at equivalent dosages (*8, 9*). Caldarone et al. (*14*) quantified the decrease in HRWR required for equivalent slump as 25% to 35%.

Slump Loss. Concrete loses slump over time because of many factors including absorption of mix water by aggregates, loss of water by evaporation, initial chemical reactions of the cementitious materials, and interactions with chemical admixtures and temperature. SCMs can influence the rate of slump loss. An additional measurement of the slump after a designated amount of time is of value, as it gives an indication of slump at the time of placement, for example, after the concrete has been batched and transported to the job site.

Desirability Function for Slump Loss. Slump loss is measured as a difference in slump between an initial test and after a specified time chosen to represent job conditions. The target value for slump 45 minutes after cement and water are mixed might be 4 in. (100 mm). While a high slump after 45 minutes is generally desirable, it may also indicate the concrete will experience high setting times. If setting time tests are not conducted as part of the experimental program, decreasing the upper limit of acceptable slump at 45 minutes should be considered.

The desirability function for slump loss is shown in Figure S1.7. This function can be interpreted to suggest that a lower slump loss is always best, such that slump losses less than 2 in. (50 mm) lead to a slightly reduced desirability. Slump losses more than 2 in. (50 mm) are penalized more severely and mixtures with a slump loss more than 6 in. (150 mm) would be considered unacceptable for a bridge deck application.

Effect of SCMs on Slump Loss. Slump loss is typically governed by temperature effects, cement chemistry, and the water-reducing admixtures.

Fly Ash. A study by Ravina (*15*) indicates that at least some Class F fly ashes reduce slump loss. Slump retention is greater when the cement replacement percentage is increased (up to 40%). This phenomenon may reflect a decreased reliance on HRWR admixtures in fly ash mixtures. Some Class C fly ashes react quickly with water and may have a negative effect on slump retention (*16*).

GGBFS. There is little information on the effect of GGBFS on slump loss (*6*). Some studies reported a reduction in slump loss, whereas other studies showed no difference in slump loss with GGBFS.

Silica Fume. Experience suggests silica fume does not usually affect slump loss (*7*). However, silica fume is usually used with chemical admixtures, resulting in changes in slump loss characteristics.

Class N Pozzolans (Metakaolin). Taylor and Burg (*8*) found slightly higher slump losses associated with concrete containing metakaolin or silica fume compared with plain portland cement concrete.

Time of Setting. Time of setting is measured by AASHTO T 197 (ASTM C 403), Standard Method of Test for Time of Setting of Concrete Mixtures by Penetration Resistance. In this method, the mortar fraction is sieved from the concrete test sample, and penetration resistance is measured as a function of time. As defined by the test method, initial setting is attained when the penetration resistance reaches

500 psi (3.5 MPa), and final setting is attained at 4000 psi (27.6 MPa).

Desirability Function for Time of Setting. The time of setting indicates the working time of the concrete. Because time of setting is affected by temperature, it may be desirable to evaluate the time of setting at different temperatures.

An example of a desirability function for time of initial setting, developed for cast-in-place bridge decks, is shown in Figure S1.8. According to this function, concrete that reaches initial setting in less than 2 hours (regardless of other performance) is not acceptable and a time of initial setting between 3 and 8 hours cannot be improved. The desirability then decreases for mixtures with increasing times of initial setting up to 24 hours because finishing operations will be affected and the risk of plastic and settlement cracking will increase.

Effect of SCMs on Time of Setting

Fly Ash. In general, both Class F and Class C fly ashes have been found to extend the time of setting of concrete (*4*). Detwiler et al. (*17*) state that fly ash can retard setting time by approximately 20 minutes per 10% addition of fly ash.

GGBFS. In general, GGBFS increases the setting time of portland cement concrete mixtures. The amount of GGBFS, w/cm, and concrete temperature all influence the setting time. Typical extensions of setting time are reported to be 0.5 to 1 hour at 73°F, with little change at temperatures above 85°F (*6*). At colder temperatures, the increase in setting time may be significant. Hooton (*18*) found that with GGBFS replacement levels of 50%, setting time can be extended 1 to 2 hours at low temperatures (less than 15°C). This extension would require delayed finishing and extended curing periods. Fernandez and Malhotra (*5*) found that, at a w/cm of 0.55, final setting was more affected than initial setting when GGBFS was used in the mixture. Detwiler et al. (*17*) state that delays of 10 to 20 minutes per 10% addition of GGBFS-blended cement can be expected.

Silica Fume. ACI Committee 234 (*7*) indicates that use of silica fume by itself should not affect setting time. However, setting time may be affected if chemical admixtures are used in conjunction with silica fume.

Class N Pozzolans (Metakaolin). Caldarone et al. (*14*) found the initial time of setting of metakaolin-containing concrete was slightly less than portland cement concrete and comparable to concrete with an equivalent dosage of silica fume. However, Taylor and Burg (*8*) report comparable time of setting for all mixtures.

Finishability. "Finishability" is a qualitative term that describes the ease of being able to screed and finish concrete. Concrete bridge decks are typically screeded to the desired thickness and finished with an Astroturf or burlap drag. Areas near edges where the mechanical screeds cannot reach are usually floated by hand.

Finishability can include characteristics such as (1) stickiness, whereby the concrete sticks to finishing tools (usually because of the presence of silica fume), or creaminess, whereby the concrete flows well and finishes easily; (2) segregation, whereby the mortar fraction separates from the aggregates; (3) harshness, whereby there is not enough paste or the aggregate is poorly shaped or graded; and (4) proneness to tearing, whereby the surface of the concrete tears when manipulated.

There is no standard test method to assess finishability. During the hypothetical case study, a non-standard qualitative assessment was performed in which a concrete sample was screeded, floated, and broomed by three experienced personnel. A numerical rating of 1 to 5 was then assigned to the concrete by each of the three individuals with respect to the stickiness, segregation, harshness, and tear resistance of the concrete. The average ratings in each category were added together for a total score. Lower scores indicate worse performance and higher scores indicate better performance. This test was conducted with consistent concrete temperature, air temperature, and relative humidity, and each mixture was evaluated by the same personnel.

Desirability Function for Finishability. The example shown in Figure S1.9 is based on the finishability test method defined above. Four categories were assessed, so the finishability scores ranged from 4 to 20. Because this test is qualitative in nature and somewhat subjective, the desirability function was designed to range from 0.5 to 1, and a relatively generous gradient was chosen so that, while higher finishability ratings receive a higher desirability, all mixtures with a finishability rating of 12 or higher are assigned a desirability greater than 0.95. Mixtures with a finishability rating of 12 or less were considered to be less desirable; therefore, the negative slope of the function increases below this value. This test was not deemed definitive enough to eliminate any mixture from consideration, and therefore the lowest desirability assigned is 0.5 and not 0.

If another method for testing finishability is used, a new desirability function will be needed. Obviously, the rating depends on the number of finishing characteristics that are chosen for rating. For example, if three categories are chosen, the rating scale could range from 3 to 15.

Effect of SCMs on Finishability

Fly Ash. Several issues are relevant to finishing concrete containing fly ash. Because some fly ash–containing concretes can take longer to set, such concrete should be finished at a later time to avoid trapping bleed water under the top surface and causing a plane of weakness (*4*). Also, very light fly ash particles can float to the surface and cause an unacceptable appearance. Typically this occurrence is not a problem on bridge decks that are not hard-trowel finished. Also, stickiness may result if the fly ash contains too much fine material.

GGBFS. The influence of GGBFS on finishability is unclear. Hooton (*18*) states that the finer particle size of GGBFS makes concrete more cohesive and easier to place, finish, and compact. Balogh (*19*) reports that improved pumping and placing properties are because the smooth and dense surfaces of slag particles result in a more fluid paste with more workability. Concrete containing slag has also been described as chalky.

Silica Fume. Silica fume, particularly at dosages in the range of 10% to 20%, has been shown to greatly decrease bleed water and increase the stickiness of the concrete (*7*).

Class N Pozzolans. Ding and Li (*9*) suggest that metakaolin-containing concrete may have better finishing characteristics than silica fume–containing concrete because of its lower requirement for HRWR. Caldarone et al. (*14*) describe metakaolin-containing concrete as less sticky than silica fume–containing concrete. The time of finishing of metakaolin-containing concrete may "require more care," because of the very small amount of bleeding (*8*). Barger et al. (*10*) suggest the mass replacements of lower density (than portland cement) calcined clay increases paste volume and results in better flow characteristics and workability. Metakaolin mixtures are typically creamier than similar silica fume mixtures.

Freezing and Thawing Climates [F1]

Freezing and thawing environments adversely influence the durability of concrete bridge decks. Freezing water within critically saturated concrete generates internal pressures that may produce damage in either paste or aggregate phases within the concrete. For the paste, resistance to the damaging mechanisms resulting from freezing water is achieved through the use of air-entraining admixtures that stabilize and help distribute air bubbles within the concrete. Because the air void system is critical to performance, it is often independently characterized microscopically. Direct testing of the freezing and thawing response of the concrete is often also conducted to confirm the effectiveness of the air void system. The resistance of aggregate to freezing and thawing damage depends on the aggregate's resistance to saturation by moisture and subsequent expansion, which is a function of pore structure and aggregate strength. This resistance is typically evaluated directly in concrete specimens exposed to freezing.

In addition to providing a quality air void system, the general recommendations listed in Table S1.2 can be taken to maximize the freezing and thawing resistance of concrete (*24*). The importance of designing a concrete mixture to be resistant to freezing and thawing depends on the environmental conditions to which the concrete will be exposed. For this program, moderate exposure is defined as 3 to 50 freezing and thawing cycles per year, and severe exposure is defined as more than 50 cycles per year (*20*). Local weather would dictate the emphasis placed on this property of the concrete.

Air Void System Parameters [F2]

Air voids in concrete are typically classified as either entrapped or entrained air. Entrapped air occurs unintentionally in concrete as a by-product of the mixing and placing processes. Entrained air, on the other hand, is intentionally introduced in the concrete to provide resistance to freezing and thawing and to salt scaling. Entrained air is achieved through the use of chemical admixtures that stabilize air bubbles introduced into the concrete during mixing. The air-entraining admixtures (AEA) are electrically charged and thus produce very small, spherical bubbles that are prevented from coalescing and breaking. These bubbles are small, with the majority of the bubbles between 0.0004 and 0.0039 in. (10 and 100 μm) in diameter, and have a reduced likelihood of rising to the concrete surface. By comparison, entrapped air voids are larger and are typically larger than 0.0394 in. (1 mm) in diameter (*21*).

Entrained air increases concrete resistance to freezing and thawing damage by providing local release for the hydraulic and osmotic pressure produced when water within the concrete expands before and during freezing (water expands about 9% just before freezing). Water moves through the concrete into these voids, and the air voids must be closely spaced so that the pressure can be released before freezing occurs. The critical distance that water can be expected to move without causing freezing damage in typical paste is approximately 0.010 in. (0.254 mm) (*22*). Therefore, the effectiveness of the entrained air at providing freezing and thawing resistance to the concrete is governed by the volume and spacing of the air bubbles within the concrete.

While air is entrained in concrete primarily to resist damage by freezing and thawing, it also has beneficial ramifications for water demand, bleeding reduction, increased slump and workability, and some resistance to internally driven expansion mechanisms such as ASR. Entrained air has negative ramifications for strength (compressive strength is typically reduced 2% to 6% for each percentage of air) and elastic modulus (*21*).

Test Methods. The quantity of air voids can be measured when the concrete is plastic, while the characteristics of the air void system are assessed after the concrete has hardened. The two primary methods for determining the plastic air content of concrete are AASHTO T 152 (ASTM C 231), Standard Method for Test of Air Content of Freshly Mixed Concrete by the Pressure Method, and AASHTO T 196 (ASTM C 173), Standard Method for Test of Air Content of Freshly Mixed Concrete by the Volumetric Method. Method T 152 is based on the principle that the volume of air is inversely related to pressure. A known pressure is applied to concrete, and the amount of volume reduction is measured and used to determine the air content. Method T 196 is typically used with lightweight aggregate where the pressure method does not apply. A known volume of consolidated concrete and water is agitated, and the final combined volume is used to determine the air content.

The method for characterizing the air voids in hardened concrete is ASTM C 457, Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete. In this method, a sample of concrete is cut and prepared to expose a smooth plane of concrete for examination under a microscope. The specimen is moved in a predefined pattern, either along parallel lines or to points in a grid under the microscope, and the operator identifies the air voids, paste, and aggregate constituents that are observed. Based on limited observations, two parameters are determined statistically to characterize the full air void system. One parameter is the specific surface area that is defined as the ratio of the surface area of the air voids to the total volume of air within the sample. This parameter does not describe the size distribution of all the air voids, which can range from 0.0004 to 1 in. (10 to 25,400 μm), but is analogous to an average for all the air voids. The other parameter is the spacing factor, which is an index related to the maximum distance from a point in the cement paste to the nearest air void. This parameter is calculated based on the observations made on the sample surface and assumptions about the relative geometry of the air voids (*23*).

Desirability Functions for Air Content. The air content of the concrete should be balanced such that sufficient air is present to provide freezing and thawing resistance without unduly reducing concrete strength. Because the air voids provide relief for freezing water primarily from the cement paste, the amount of air needed in the concrete to provide freezing damage protection will be higher in mixtures containing a larger volume of paste. The suggested desirability function is based on ACI recommendations for 0.75 to 1 in. (19 to 25 mm) maximum nominal aggregate size (*24*). The recommendations for air parameters in hardened concrete are based on correlations with laboratory and field performance (*23*).

To limit the total number of desirability functions (and the weight or importance of the air void system measurement on the total response), it is recommended that only one function be included to characterize the air void parameters. The spacing factor is commonly believed to be the most important value in determining freezing and thawing performance because there is a critical distance that water can move as it freezes without causing damage. The spacing factor is analogous to the average distance between any point in the concrete and the nearest entrained air bubble. Therefore, concretes with spacing factors greater than the critical distance are susceptible to freezing and thawing deterioration. Spacing factor, however, depends on the total air content and is largely determined by the amount of air-entraining admixture added to the mixture, which is adjusted to accommodate the influence of SCMs or other changes in the mixture on the air void system. Specific surface, on the other hand, is normalized to the total volume of air observed in the mixture and, therefore, it may be more indicative of influences of the mixture components on the ability of the mixture to entrain air. It is generally true that spacing factors less than 0.008 in. and specific surfaces of greater than 600 in.^{2}/in.^{3} will provide good freezing and thawing resistance. Strength also may play a role in freezing and thawing resistance. Desirability functions for air content in plastic and hardened concrete subject to severe exposures are shown in Figure S1.10. These functions are designed such that mixtures with air contents between 5.5% and 10% in severe exposures and between 4.5% and 10% in moderate exposures can not be improved with respect to this response. Air contents below these ranges may result in inadequate freezing and thawing protection, while air contents above this range may have a significant detrimental effect on strength or surface quality and, therefore, are assigned lower desirabilities.

When the w/cm is less than 0.38 and HRWR is used, slightly higher spacing factors will not negatively impact freeze/thaw durability. Desirability functions for spacing factor for concretes with and without HRWR are shown in Figure S1.11. These functions suggest that it is very important to have a spacing factor less than 0.010 and 0.008 in. for mixtures with and without HRWR, respectively. After a steep decline that gives some credit to mixtures with spacing factors only slightly higher than these thresholds, mixtures with larger spacing factors are considered unusable. Because there is no advantage to having entrained air bubbles closer together than the threshold value, all mixtures above the threshold are assigned the same desirability value of 1.

A desirability function for specific surface area is given in Figure S1.12. This function assigns higher desirability to concrete mixtures with increasing specific surface area, up to 800 in.^{2}/in^3. The slope of the increase in desirability with specific surface area is lower as the specific surface area increases because the benefits of those increases become less significant.

Effect of SCMs on Air Content. The composition of the SCMs may have a significant influence on the effectiveness of air-entraining admixtures and the stability of the air voids in the plastic concrete. Therefore, trial batches are essential for selecting mixtures with acceptable air void systems. In general, materials with smaller particle sizes tend to increase the amount of AEA required for a given air content.

Fly Ash. It is difficult to generalize the effect of fly ash on air entrainment. However, air content for a given dosage of air-entraining agent typically decreases with an increase of the loss on ignition of the fly ash, which is a measure of its carbon content (*4*).

GGBFS. Slag, if finely ground, may reduce air content for a given dosage of air-entraining agent (*21*).

Silica Fume. Silica fume can be expected to reduce air content for a given dosage of air-entraining agent (*7*).

Class N Pozzolans (Metakaolin). Taylor and Burg (*8*) report that more AEA was required with a 7% addition of metakaolin than for plain portland cement concrete.

Resistance to Freezing and Thawing [F3]

While freezing of moisture in the cementitious paste leads to deterioration, another potential source of freezing damage is moisture within the aggregates. Aggregates absorb water, and, when contained in freezing concrete, some aggregates are prone to internal cracking and expansion that damages surrounding paste. This damage may take the form of popouts, which are small areas spalled out of the concrete when the aggregates are near the concrete surface, or overall expansion if the aggregates are deeper within the concrete. Evaluation of the influence of aggregate on freezing and thawing resistance is typically performed directly on concrete exposed to freezing and thawing conditions. More details on the selection of aggregates are included in Step 2.

Test Methods. The total effect of all the factors on the concrete freezing and thawing resistance may be evaluated by directly simulating cyclic freezing in laboratory conditions using one of two methods. The first and most common method is AASHTO T 161 (ASTM C 666), Standard Method for Test of Resistance of Concrete to Rapid Freezing and Thawing, in which concrete specimens are subjected to cyclic freezing using a controlled test chamber. The second method, ASTM C 671, Test Method for Critical Dilation of Concrete Specimens Subjected to Freezing, determines the magnitude of the critical dilation of a continuously wet concrete specimen sample during a single freezing event. When the focus of interest is specifically the aggregates, this method may be used as laid out in ASTM C 682, Practice for Evaluation of Coarse Aggregate in Air-Entrained Concrete by Critical Dilation Procedures. (Both ASTM C 671 and C 682 were withdrawn in 2003.)

AASHTO T 161 is the most common method. In this test, concrete specimens between 3 and 5 in. (75 and 125 mm) high and wide and 11 to 16 in. (279 to 406 mm) long are subjected to 300 cycles between 40°F and 0°F (4°C and −18°C), each of which takes between 2 and 5 hours (testing can also be extended to 500 or more cycles if a more rigorous test is desired). AASHTO T 161 includes two procedures: Procedure A, where freezing and thawing take place with the specimens submerged in water, and Procedure B, where the freezing is achieved in air, and the thawing occurs in water.

The deterioration of the concrete during the cycling is measured at least every 36 cycles on thawed specimens according to ASTM C 215, Standard Test Method for Fundamental Transverse, Longitudinal and Torsional Resonant Frequencies of Concrete Specimens. The fundamental transverse frequency is used to calculate the relative dynamic modulus of elasticity of the specimen, P_c, after c cycles, which is given by

$$P_c = \frac{n_1^2}{n^2} \times 100$$

where n = frequency at 0 cycles and n_1 = frequency after c cycles. Internal damage occurring in the specimen will reduce the dynamic modulus. The durability factor at the end of the test is equal to P_c unless the test was stopped prematurely.

Two additional characterizations of the specimens also are made to provide more information about the effect of the freezing and thawing cycles on the concrete. Tracking the weight loss during the test provides information about the surface damage such as would be caused by surface popouts that may occur without reducing the relative dynamic modulus. In addition, measuring the length of the specimens gives an indication of the influence of freezing aggregates and internal microcracking (*21*). For highly durable mixtures containing quality air void systems, 500 cycles or more may be necessary to differentiate concretes of varying composition.

Some criticisms of the AASHTO T 161 test include (1) the rate at which freezing occurs is more severe than typical environmental conditions, (2) the rigidity of the container in which the specimens are held during freezing may increase or relieve pressure resulting from freezing depending on its stiffness, and (3) the concretes exhibiting intermediate performance show greater variability than those performing well or poorly (*25*). However, despite the theoretical considerations, this accelerated test gives a direct measure of the performance of concrete under freezing conditions and is useful for making relative comparisons between concrete mixtures.

Desirability Functions for Freezing and Thawing Resistance. A durability factor of 100% corresponds to no decrease in relative dynamic modulus, suggesting no damage has occurred; performance that is as close to this level as possible is desired. This performance level is reflected in the sets of example desirability functions that are given for the durability factor after 300 and 500 cycles in Figures S1.13 and S1.14 for severe and moderate environments, respectively. For severe environments (Figure S1.13), a durability factor of 100% is assigned a value of 1, with a gentle decrease in desirability to 0.9 for lower durability factors of 90% after 300 cycles and 80% after 500 cycles. Below these values the desirability decreases more steeply with decreasing durability factor. For durability factors lower than 50% after 300 cycles and 40% after 500 cycles, the performance is considered unacceptable and assigned a desirability of 0. A similar but somewhat more forgiving shape of the desirability function is assumed for moderate environments (Figure S1.14) because of the less severe exposure environment.

Also, the AASHTO T 161 method provides for only 14 days of moist curing before cycling is initiated. Therefore, concretes containing SCMs may compare unfavorably to those containing portland cement only because the strength gain of the SCM mixtures is likely to occur more slowly. As a result, at least 28 days of curing prior to testing is recommended.

Effect of SCMs on Freezing and Thawing Resistance. The ability of concrete to resist freezing and thawing is largely governed by the amount and quality of the air void system within the concrete and by the aggregate behavior during freezing. For comparable air void systems, age, paste maturity, moisture content, and aggregate soundness, concretes containing SCMs will perform similarly to those without SCMs (*4, 6, 7, 8, 10*). However, SCMs can adversely affect the air void parameters; therefore, testing of SCM mixtures is suggested.

Scaling Resistance [S1]

The use of chemical deicers on bridges and pavements increases the occurrence of scaling due to freezing and thawing. The primary mechanism causing scaling is physical (*24*); it involves osmotic and hydraulic pressures in the paste portion of the concrete. Osmotic pressure develops in the surface region of the concrete as water moves to the concrete surface layers to equalize the concentration gradient of salt. When freezing takes place at the surface, hydraulic pressure is also generated. There is also the possibility that in some areas deicing agents increase the number of freeze-thaw cycles (*11*). The deterioration mechanism is strongly dependent on the saturation of the concrete, the type of deicer, and the concentration gradient of the deicer (*24, 26*). Other mixture considerations for salt scaling resistance are listed in Table S1.4.

Test Method. ASTM C 672, Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals, was first introduced in 1971 (*26*). The method consists of fabricating concrete of a desired proportion into specimens of at least 72 in.^{2} (465 cm^2) in area and 3 in. (75 mm) deep. The concrete must be finished with three passes of a wood strike-off board, with a final surface treatment of a medium-stiff brush or other finish if desired. The specimens are removed from molds at 20 to 24 hours, cured in moist storage for 14 days, and then stored in air at 45% to 55% relative humidity for an additional 14 days. The method states that if concretes of differing rates of strength gain are compared, the specimens should be maintained in moist storage until a desired strength level is obtained. Dikes are adhered to the surfaces of the specimens during the drying time.

After completion of the moist and air curing, the surfaces of the specimens are covered with approximately 0.25 in. (6 mm) of 4% calcium chloride solution. Other deicer solutions may be used to simulate actual exposure conditions. The specimens are then placed in a freezing environment for 16 to 18 hours, followed by conditioning in laboratory air (73.5 ± 3.5°F [23.0°C ± 2.0°C], 45% to 55% RH) for 6 to 8 hours. Cycling continues generally for 50 cycles, but may continue beyond if differences between comparative tests have not developed. The solution is flushed every five cycles, a visual examination made, and the number of popouts may be quantified to assess the aggregate performance. The method relies on a visual examination of the test specimens after the procedure is completed.

Performance may also be evaluated by quantifying the removed debris when flushing the slabs (*28*). In this method, detached particles and debris are collected when the surface is rinsed with fresh saline solution. The particles are washed in water, sieved using an 80 μm sieve, dried at 60°C (140°F) until a constant mass is obtained, and weighed. The mass is expressed in g/m^2 (oz/ft^2) of surface. The limit on mass loss after 56 cycles is cited as 500 g/m^2 (1.6 oz/ft^2) and 1000 g/m^2 (3.3 oz/ft^2) in Quebec and Sweden, respectively (*28*).

Desirability Functions for Visual Inspection. ASTM C 672 describes a visual rating system of scaling that ranges from 0 to 5, 0 being best and 5 being worst. Table S1.3 describes the meaning of these ratings.

Previous work included scaling resistance as one of the criteria for defining high-performance concrete (HPC) based on long-term performance (*20*). This evaluation recommended that the grade or performance required be tied to the volume of deicing salt application (in tons/lane-mile/year) used (use of more salt requires better performance), although a realistic value for applied salt is not always easily obtained. Because records of amount of salt applied over a given area are often not available, use may be categorized according to potential concern of deicer salt scaling: a large concern, a moderate concern, or no concern. For severe and moderate deicer salt scaling environments, visual ratings of 0 to 1 and 2 to 3 at 50 cycles, respectively, are recommended. However, this test does not need to be run if deicer salt scaling is of no concern. Example desirability functions for the two conditions where testing is warranted are given in Figure S1.15. For severe exposure, lower ratings are assigned higher desirabilities, with average scaling ratings of 1 and 2.5 assigned desirability values of 0.9 and 0.4, respectively. For moderate exposure, the desirability function allows higher ratings; an average scaling rating of 1 or less is assigned a desirability of 1, and an average rating of 3 is assigned a desirability of 0.4. For both exposures, a scaling rating of 5 means that the entire mixture is unacceptable and thus a desirability of 0 is given.

Desirability Function for Mass Loss. Some researchers use a mass loss measurement to quantify the material that has scaled off a specimen (*28*). This method generates non-subjective metrics of the concrete performance that are not based on, at least, a half number scale; it, therefore, can differentiate between mixtures that display good performance and would ordinarily receive the same visual rating. One problem with mass loss testing is that in addition to collecting scaled material, aggregates also can be collected that have failed because of other mechanisms such as popouts and popoffs. Popouts include mechanisms whereby porous, substandard aggregates absorb water and fail when exposed to freezing and thawing cycles. They are discerned by a conical failure near the surface of the concrete, with part of the aggregate that has failed left at the bottom of the cone. Popoffs are related to non-substandard aggregates (*29*). In this case, a thin mortar layer above a near-surface coarse aggregate pops off. These failures are described as "a very shallow truncated cone centered over or near the offending coarse aggregate particle." Although all these failures are related, there are some differences as to the causes of the loss of surface material.

If a mass loss value is desired, the following desirability functions apply to the environmental cases described above. The Quebec specification limits on mass loss are described in Saric-Coric and Aïtcin (*28*). Example desirability functions are shown in Figure S1.16. For both severe and moderate exposures, a lower mass loss is rated higher. A change in the function was defined at a mass loss of 500 g/m^2 below which the desirability decreases at a greater rate with increasing mass loss than above this value. These functions do not assign great importance to variations in response over this range and assign no desirability lower than 0.5 for mass losses less than 1200 g/m^2. If higher mass loss results are found during testing, the function should be extended so lower desirabilities are assigned.

Effect of SCMs on Scaling Resistance. SCMs are generally known to decrease scaling resistance of concrete (*30*). SCMs usually hydrate more slowly than portland cement, resulting in a lower early-age strength (less than 28 days) and a higher initial permeability; these trends are often reversed at later ages. However, in comparative early-age tests between concrete containing various combinations of SCMs, a minimum strength, instead of moist curing for 14 days, could be specified. Conflicting information exists in the literature as to the impact of additional curing time on scaling resistance. For example, Talbot et al. (*30*) states that the negative influence of the SCMs on scaling resistance was not noticeably reduced when the curing time for mixtures containing fly ash and slag was increased from 14 to 28 days. However, Saric-Coric and Aïtcin (*28*) report that increasing moist curing time from 13 to 27 days allowed slag-blended cements (up to 80% slag) to fully mature and pass the Quebec Ministry of Transportation limits on mass loss during ASTM C 672 testing. The method of curing used when comparing mixtures including SCMs should be selected carefully.

Fly Ash. ACI Committee 232 (*4*) recommends that concrete exposed to deicing salts be air entrained and allowed to reach a specified strength prior to exposure to the salts; no guidance is given as to the minimum strength. However, a minimum strength of 3500 psi (24 MPa) is given for freezing and thawing resistance. A mention is made that concrete containing 40% fly ash may be more susceptible to scaling. Talbot et al. (*30*) show that Class C fly ashes tested at 20% replacement increase the mass lost on a trowelled surface by approximately two times or more (from 1 kg/m^2 to 1.8–2.8 kg/m^2 with various Class C fly ashes at a w/cm of 0.4). Afrani and Rogers (*31*) state that, for the Ontario Ministry of Transportation, the maximum amount of fly ash that can be substituted for portland cement is 10% when the concrete is exposed to freezing and thawing and deicers are used. Additionally, if fly ash and GGBFS are used together, the fly ash content is also limited to 10%, and the total fly ash plus GGBFS content is limited to 25%. ACI Committee 318 (*32*) limits fly ash and natural pozzolans to 25% by mass for concrete exposed to deicing chemicals.

GGBFS. ACI Committee 233 (*6*) states that some laboratory tests indicate less resistance to deicer salt scaling when GGBFS is used; although, little difference is observed in service. More scaling is found when concrete has higher w/cm and higher percentages of GGBFS. No quantities are mentioned. Experience cited in Saric-Coric and Aïtcin (*28*) indicates that GGBFS quantities greater than 20% reduced scaling resistance. Hooton (*18*) states that the Ontario Ministry of Transportation limits GGBFS quantities to 25% based on poor results in ASTM C 672 but suggests that up to 35% will not impact salt scaling performance whereas 50% might be a concern. ACI Committee 318 (*32*) limits GGBFS to 50% by mass when concrete is exposed to deicing chemicals.

Silica Fume. ACI Committee 234 (*7*) states that with proper air-entrainment, silica fume should have no detrimental effect on scaling resistance. However, a study by Pigeon et al. (*33*) showed reduced resistance to salt scaling when silica fume replacement exceeded 5%, while another study by Sørensen (*34*) showed similar results when the silica fume content exceeded 10%. ACI Committee 318 (*32*) limits silica fume to 10% when concrete is exposed to deicing chemicals.

Class N Pozzolans. Barger et al. (*10*) found good scaling resistance (visual ratings 0 to 1) for concrete containing 18% to 20% calcined clay by replacement.

Combinations of SCMs. ACI Committee 318 (*32*) limits the total of fly ash or other pozzolans, GGBFS, and silica fume to 50% by mass of concrete exposed to deicing chemicals, with the fly ash or other pozzolans limited to 25% and silica fume limited to 10% of the total cementitious materials. If fly ash or other pozzolans are used with silica fume, the total is limited to 35% by mass, with the fly ash or other pozzolans limited to 25% and the silica fume limited to 10%.

Corrosion Concerns for Concrete [CL1]

The most frequent cause of deterioration in concrete bridge decks in northern climates is corrosion of the reinforcing steel. The products of the corrosion process occupy a larger volume than the original steel and thus generate internal forces that lead to cracking and spalling. In freshly placed concrete, reinforcing steel is protected from corrosion by the formation of a passive oxide layer on the surface of the steel. This oxide layer is stabilized by the highly alkaline environment produced by the combination of portland cement and the mixture water. However, the oxide layer can eventually break down through the process of carbonation, the penetration of carbon dioxide into the concrete which causes a reduction in the pH, or by the presence of chloride ions. This latter mechanism, which typically occurs when the concentration of chloride at the steel surface is approximately 0.2% by mass of cement, is especially significant for bridge decks because chloride-based deicing salts are often used to improve vehicle traction during winter.

Chloride Penetration Resistance [CL2]

Chloride ions permeate through concrete to the reinforcing steel initially by capillary action, especially if the concrete is dry, and then by other mechanisms, the most significant of which is diffusion. The rate of permeation is largely determined by the pore structure of the concrete matrix, which can be modified significantly through the use of SCMs. Concrete with low permeability is more resistant to corrosion-related damage and to other deterioration mechanisms that require the ingress of water or aggressive water-borne agents into the concrete such as ASR, sulfate attack, and freezing and thawing distress. While water permeability, which directly influences these deterioration mechanisms, can be measured, testing for chloride penetration is the most common test for corrosion-related concerns.

Test Methods. Resistance to chloride ion penetration can be measured directly using AASHTO T 259, Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration, or ASTM C 1556, Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion, and ASTM C 1543, Standard Test Method for Determining the Penetration of Chloride Ion into Concrete by Ponding. It can also be assessed indirectly by accelerated testing conducted according to AASHTO T 277 (ASTM C 1202), Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, also known as the rapid chloride permeability (RCP) test or the electrical conductivity test; this test is referred to as the electrical conductivity test in these Guidelines.

Diffusion Testing. In the procedure laid out by AASHTO T 259, four concrete slabs not less than 3 in. (75 mm) thick are cast, moist cured for 14 days, and dried for 14 more days in a 50% RH environment. At that time, the concrete surface may be abraded to simulate the wearing effects of vehicle traffic. Dams that will hold a sodium chloride solution on top of the slabs are then attached to all but one control slab. The slabs are then subjected to an additional 14 days of drying, after which a ponding solution of 3% sodium chloride is applied to a depth of 0.5 in. (13 mm) and allowed to permeate the concrete for 90 days. ASTM C 1543 suggests a very similar exposure routine except that the specimens are to be cured as laid out by ASTM C 672.

For AASHTO T 259, two samples are taken from the slabs at 0.0625 to 0.5000 in. (1.6 to 13.0 mm) and 0.5 to 1.0 in. (13 to 25 mm) from the surface. For ASTM C 1543, samples are taken at four depths between 10 and 65 mm. These samples can be either cores, which are ground, or powder obtained after drilling with a rotary hammer-drill. The water or acid-soluble chloride content of the samples is measured according to AASHTO T 260, Standard Method of Test for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials, or ASTM C 1152, Test Method for Acid-Soluble Chloride in Mortar and Concrete. Testing for acid-soluble chloride gives a measure closer to the total chloride content in the sample and includes the chloride that is chemically combined. Measurements of water-soluble chloride approximate the amount of chloride that has permeated the concrete without including chemically bound, currently unavailable chloride. Either of these methods may be used for comparing relative mixture performance because the chloride content in the control slab is used as the baseline to estimate how much chloride penetrated the test slabs.

Many variations of chloride ponding tests can be found in the literature. Comparisons between studies are difficult because not only is the permeability affected by the concrete microstructure, but also the test results are strongly influenced by the moisture content of the concrete when exposure is initiated, the temperature of the concrete, the extent of hydration of the cement, the curing regimen, and the surface preparation. When conducting tests to judge relative performance, it is important to keep these factors constant.

Some of the limitations of the standard AASHTO T 259 test include the 14-day wet curing regime, which may not permit the complete hydration of the SCMs which typically occurs more slowly than the hydration of portland cement. Also, the wet curing regimen has been viewed by Sherman et al. (*35*) as unrealistically long in comparison with standard practice of 7 days of curing. Because of the low permeability of high-performance concrete, a 90-day test duration using 3% sodium chloride solution may not be sufficient to differentiate between proposed mixtures. Therefore, using 15% sodium chloride solution and longer ponding times, such as 6 months or 1 year, may be necessary. Precise sampling is best achieved with cores where the depth of penetration can be more accurately measured and there is less likelihood of contamination than when drilling powder samples from the test slabs.

ASTM C 1556 addresses some of these issues. In this test, finished cylinders that had been cured 28 days are saturated in lime solution and submerged in 16.5% sodium chloride solution for at least 45 days. After the exposure period, near surface samples are taken using a machine lathe or end mill. Because of the precision of these instruments, concrete samples can be taken at 1 mm intervals, and for low permeability concretes, as many as eight samples may be taken within the first 12 mm.

Common practice during chloride ponding testing is to estimate the chloride concentration profiles and determine the "effective" diffusion coefficient as defined by Fick's second law of diffusion (*36*), using the procedure provided in ASTM C 1556. The diffusion coefficient is "effective" because other mechanisms besides diffusion also play a role in the transport of chloride through the concrete and are lumped into this single coefficient. AASHTO T 259 provides for determining the chloride concentration at only two sample depths, which is not sufficient to accurately determine diffusion coefficients. When the diffusion coefficient is to be determined, the chloride concentrations of six or more thin concrete slices at various depths anticipated to span the range of chloride content within the samples should be measured. The diffusion coefficient is calculated using an iterative least squares fitting procedure or other methods (*37*).

Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. In the AASHTO T 277 test (referred to here as the electrical conductivity test), 2-in. (50-mm) thick concrete specimens are cut from nominally 4-in. (100-mm) diameter cylinders or cores, saturated with water, and placed between solutions of 3% sodium chloride and 0.3 *N* sodium hydroxide. A 60 V DC potential is applied across each specimen, and the total electrical charge passing through the specimen in 6 hours is measured.

The relative simplicity and short duration of this electrical conductivity test has resulted in its widespread adoption for measuring chloride permeability in lieu of diffusion testing. This test is also commonly used for quality control where durability is a primary objective. Many researchers and engineers have viewed the use of the electrical conductance value as an oversimplified approximation of permeability and inappropriate for certain materials, particularly when SCMs are used. This view is held especially for mixtures containing silica fume. Electrical conductivity depends on conductivity of pore fluid and the nature of the porosity in the paste. Despite the apparent relationship between permeability and the charge passed presented in tabular form in AASHTO T 277, correlations between the two test methods should be established for the specific material combinations before concretes containing different cementitious materials are compared (*38*). Also, the measured charge passed overestimates the actual chloride permeability because it includes the movement of hydroxyl, chloride ions, and other ions (*39*). SCMs may react with hydroxides preventing their movement and making concretes containing these materials appear to have a lower permeability than is actually the case. The electrical conductivity test also has a higher variability than the diffusion tests.

All of the chloride penetration tests discussed here are strongly influenced by the age and curing conditions of the specimen. The microstructure of the concrete continues to develop over time and significant reductions in penetration can be observed when testing is initiated at later ages, especially for concretes containing SCMs. Electrical conductivity test results for concretes containing SCMs obtained after 56 or 90 days of wet curing may be expected to be significantly lower than those measured after only 28 days. Therefore, during concrete mixture selection, testing both at 28 days and at 56 and/or 90 days of age is recommended.

Desirability Functions for Chloride Penetration and Electrical Conductivity. To minimize the rate of penetration of harmful water-borne agents into the concrete, the permeability should be minimized. ASTM C 1556 or the long-term AASHTO T 259 test method more realistically simulate the penetration mechanisms of chlorides in concrete that occur in bridge decks. A desirability function for the apparent chloride ion diffusion coefficient test is shown in Figure S1.17. This function rewards lower apparent chloride diffusion coefficients, only assigning a desirability of 1 for a coefficient of 0. Because this response is likely to be important when this test is included in the test program, a steep slope of the function is assumed: a coefficient of 2×10^{-12} m^2/s is assigned a desirability of 0.85 and a coefficient of 6×10^{-12} m^2/s is assigned a desirability of 0.15. Because of this slope, the response will strongly influence the overall desirability and optimization analysis.

Electrical conductivity test results are a less precise predictor of actual concrete performance and generally more prone to variability. A sample desirability function for the electrical conductivity test is shown in Figure S1.18. This function rewards lower amounts of passed charge by assigning a desirability of 1 for 0 Coulombs passed and increasingly lower desirabilities for higher amounts of passed charge up to 5000 Coulombs passed. This function provides less steep slope than that for the desirability function for chloride diffusion coefficient because a concrete mixture that may have a passed charge as high as 2000 Coulombs could be highly resistant to chloride penetration as measured using the more accurate ponding- or exposure-based test methods. Therefore, a passed charge of 2000 Coulombs or less is assigned a moderately high desirability of 0.8 or higher.

Effect of SCMs on Chloride Penetration Resistance. The chloride penetration resistance of uncracked concrete is determined at the microstructural level by the porosity and extent of interconnected voids in the bulk cementitious paste and in the interfacial zone between paste and aggregates. Lower water–cementitious materials ratios result in increases in the density of the paste microstructure (reduced porosity) and reduced permeability. SCMs also densify the paste microstructure by virtue of their size distributions, which typically are smaller than portland cement, and enable the SCMs to fill the spaces between the cement particles. Blends of two or more SCMs may be more effective at minimizing penetration than use of just one, because the particle size distributions of the various materials may complement each other. In addition, SCMs may react with calcium hydroxide to form additional hydration products that also help fill pore space in the concrete.

Fly Ash. Class F and Class C fly ashes are typically used at rates of 15% to 25% and 15% to 40% by mass of total cementitious materials, respectively (*21*), although some researchers recommend 25% to 35% replacement (*40*). Because the reactivity of fly ashes is variable, testing is essential to determine the optimum content required for minimizing penetration. Some concretes containing fly ash, especially as replacement of cement, can have low chloride penetration resistance. Some fly ash increases penetration resistance by refining the pore structure as a result of its reaction with calcium hydroxide (*4*). This reaction occurs slowly and thus requires adequate moisture and prolonged curing before exposure.

GGBFS. GGBFS has been shown to be effective at reducing the permeability of concretes both when used alone and when used in combination with other SCMs (*6*). Recommended quantities for bridge deck concretes range from 15% to 30% by mass of total cementitious materials.

Silica Fume. Silica fume is finer than the other typical SCMs, and it is therefore most effective in reducing concrete permeability because it fills voids in the pore structure and along the interfacial transition zone. For projects where minimizing chloride penetration is essential, silica fume (or metakaolin) should be included. Silica fume additions of more than 5% by weight have been shown to significantly reduce electrical conductivity and additions as high as 7.5% to 10% have been specified where corrosion resistance is considered essential (*7*). However, high dosages (greater than 7%) of silica fume can make the concrete more susceptible to early cracking and can defeat the low permeability within the paste if special precautions are not taken to prevent early cracking.

Class N Pozzolans. The small size of the metakaolin particles has been shown to significantly reduce chloride permeability at contents of 8% to 12% by weight of cementitious materials when tested using both the electrical conductivity and diffusion approaches (*41*). Metakaolin is marketed as an alternative to silica fume and reportedly achieves similar reductions in permeability (*9*). Detwiler et al. (*17*) report an apparent diffusion coefficient of 1.7 to 1.9×10^{-12} m^2/s for concrete containing 20% to 30% calcined clay, respectively, compared to 5.4×10^{-12} m^2/s for a Type I portland cement concrete made with a water-cement ratio (w/c) of 0.4.

Other Mixture Considerations for Minimizing Chloride Penetration. HRWR admixtures have been shown to reduce the chloride penetration of concretes containing SCMs (*42*) presumably because the combination of HRWRs and SCMs improves dispersion synergistically and reduces water demand for a given workability thereby minimizing penetration. For this reason, especially when silica fume is used, HRWR admixture should be used.

The general recommendations listed in Table S1.5 can be followed to minimize chloride penetration of concrete.

Coastal Environments [CO1]

Concerns about durability in coastal environments also include airborne-chloride exposure that can lead to corrosion problems in a manner similar to exposure to chloride from deicing salts as discussed previously in "Chloride Penetration Resistance." Direct contact with sea water in tidal zones is the most aggressive exposure; airborne-chloride exposure is less severe than tidal or deicer exposure.

Two methods are suggested to decrease the potential of corrosion due to airborne sources of chloride. In one method, the depth of cover is increased in a manner related to the distance from the coast. Tanaka et al. (*43*) describe a study performed in Japan in which the level of airborne chloride was measured in different regions of the country and at different distances from the coastline and provide a method for determining a recommended minimum depth of cover based on the location of the structure and the design life.

The other method involves restricting the upper limit of the w/cm to decrease concrete permeability. SCMs can be used to decrease the permeability of the concrete and decrease the diffusion coefficient. Table S1.6 lists mixture considerations for chloride penetration resistance in coastal environments. Concrete exposed to airborne chloride only is considered to be subject to moderate exposure while concrete in sea water or within 4 m of sea water is considered to be subject to severe exposure.

Abrasive Environments [AB1]

Abrasion on highway bridges causes deterioration of the concrete surface through two mechanisms: (1) wearing, as foreign particles such as sand or other grit are ground across the surface by vehicular traffic, and (2) impact of steel chains or studs attached to the tires of automobiles and trucks to provide additional traction during winter. The latter mechanism is the more severe. Chains are required in a limited number of areas, mostly where mountainous roads demand better traction. Because the surface of the concrete is also affected by many other deterioration mechanisms, such as salt scaling, abrasion resistance may strongly influence the lifespan of the bridge deck. The duration of winter season and the frequency of traffic with chains or studded tires indicate the relevance of this property to the overall durability of the bridge deck. Table S1.7 lists the mixture considerations other than SCM contents that are relevant to abrasion resistance.

Abrasion Resistance [AB2]

The ability of concrete to resist abrasion is governed by aggregate properties, concrete strength, and surface treatment (*44*). Because aggregate is generally the hardest component of concrete, it is usually the determining factor in abrasion performance. Aggregates with greater density and hardness have been shown to produce concretes that wear more slowly than aggregates made of softer materials. The shape of the aggregates is also a factor; more angular aggregates produce a better bond with the cementitious paste and a more uniform traffic-bearing surface.

Concrete strength has also been linked to abrasion resistance, probably because strength is related to paste density and hardness (e.g., concretes with low w/cm containing silica fume have high strengths and high abrasion resistance). Properties that reduce concrete density such as entrained air have been shown to adversely affect abrasion resistance. When soft aggregates are used, steps to increase strength can be taken.

The third factor in determining abrasion resistance is surface treatment, i.e., finishing and curing. A smoother finish provides a more uniform load-carrying surface that will distribute abrasion-causing wear and impact. However, the smoother surface will reduce skid resistance. Curing procedures influence the strength of the surface because the amount of hydration at the surface depends on the presence of moisture.

Test Methods [AB3]. While several methods exist to assess abrasion resistance, two test methods best simulate the loading that would be experienced by bridge deck concrete: ASTM C 779, Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces Procedure B, and ASTM C 944, Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method. Both methods provide for abrading the concrete surface with dressing wheels (steel wheels with sharp points) that roll over the concrete surface under a specified load in a manner that is intended to simulate chain impact. The ASTM C 779 method requires a more elaborate setup and a machine specifically designed for this test. The ASTM C 944 test uses a modified drill press and is easier to run. However, it typically results in poorer reproducibility than the ASTM C 779 method, which uses three instead of just one dressing wheel assembly. The ASTM C 944 method measures abrasion in terms of the depth of wear or the mass loss from a concrete specimen after it has been abraded using the dressing wheel head under 22 lbs (10 kg) of load for three 2-minute periods, between which the specimen is cleaned. The abrasion is conducted on three separate areas on the concrete, and the average depth of wear or mass loss is reported.

Desirability Function for Abrasion Resistance. In spite of its poor reproducibility, the ASTM C 944 test method has value in distinguishing relative abrasion performance. Therefore, after the testing is completed, the desirability function for this property may have to be modified to bracket the actual test results. However, Figures S1.19 and S1.20 give examples of desirability functions for mass loss and depth of wear as a starting point. Either mass loss or depth of wear can be used to assess performance for either test method. Both of the functions for abrasion resistance are based on thresholds (mass loss of 2 g after 6 minutes and depth of wear of less than 0.5 mm after 6 minutes) below which the performance is considered as good as necessary and assigned a desirability of 1. Above these thresholds, the desirability function decreases with increasing wear.

Effect of SCMs on Abrasion Resistance. The aggregate has the largest influence on abrasion resistance, but mixture modifications that will increase concrete strength will generally increase abrasion resistance.

Fly Ash. Replacement of cement with fly ash has little influence on abrasion resistance (*45*).

GGBFS. A study conducted to assess the influence of slag on abrasion showed that slag increased the loss due to abrasion when used at more than 25% (*5*). Therefore, if abrasion resistance is a prime objective, the recommendation is to limit the content of slag to 25% replacement.

Silica Fume. Silica fume is known to increase the strength of concrete and can be used to increase abrasion resistance (*46*). To have a significant effect on abrasion resistance, the recommended dose for silica fume content would be greater than 5% addition.

Alkali-Silica Reactivity Potential [ASR1]

ASR is a concern in some areas of the United States. Problems occur when aggregates of certain compositions react with the hydroxides of cement pastes. This reaction is manifested by the formation of gel and subsequent cracking of concrete. This form of cracking is inherently a materials issue; it will be dealt with in Step 2, which describes the selection of durable raw materials.

Cracking Resistance [CR1]

Concrete cracking is a nationwide problem on bridge decks. Cracking can occur while the concrete is still plastic and after the concrete is hard. Krauss and Rogalla (*47*) reported on extensive work performed to identify causes of early-age cracking. The cracking usually occurs within the first 6 to 12 months after construction. The cracks often can become quite large (0.010 to 0.015 in. [0.25 to 0.38 mm] wide). Identifying the causes and preventing cracking in these structures is difficult and complex.

Concrete develops cracks when local tensile stresses exceed the local tensile strength of the concrete. Tensile stresses in bridge decks are caused by temperature changes in the bridge, concrete shrinkage, and sometimes bending from dead or live loads. A combination of shrinkage and thermal stresses causes most early-age cracks.

Shrinkage and thermal stresses develop in all composite decks, because the girders and decking restrain the natural thermal and shrinkage movement of the concrete. When the deck and girders consist of different materials (steel and concrete, or different concretes) with different thermal expansion rates, even a constant temperature change will cause stresses because the different materials expand differently and cannot expand freely where they are attached. Temperatures are rarely uniform or linearly distributed, and shrinkage is also not linearly distributed. Nonlinear shrinkage and temperature changes cause internal stresses, even without external restraint. Because considerable friction exists between the concrete and its supporting girders or a composite metal deck, these elements restrain concrete movement. To a lesser extent, embedded reinforcement in the deck also restrains the deck against shrinkage and against thermal movements.

A decision should be made on whether deck cracking is a concern. Many aspects of high performance concrete and modern cement characteristics increase the potential for deck cracking (*47*). Historically, conventional concrete mixtures cast on typical bridge supports have experienced cracking. Therefore, cracking resistance is an important consideration unless the deck is prestressed, will not experience shrinkage, or will receive a membrane, or somehow it is known that cracking will occur.

If cracking is not considered an important concern or if there is no time to evaluate this characteristic, general design and construction procedures are provided to assist engineers with design and construction decisions.

Causes of Cracking

Deck cracking in hardened concrete (not plastic cracking) is usually either restrained concrete shrinkage cracking and/or thermal cracking due to temperature differentials within the concrete or relative to the supporting structure. Neither of these factors is usually measured directly. However, several tests are available to help compare different mixtures to estimate if one mixture is more prone to cracking than another mixture.

Many concrete properties affect its cracking tendency. Such properties include heat of hydration, coefficient of thermal expansion, tensile strength, paste-aggregate bond strength, drying shrinkage, modulus of elasticity, and creep. The time dependency of each of these properties is important. The following tests are used to evaluate some of these individual properties:

- Drying Shrinkage: AASHTO T 160, ASTM C 157
- Tensile Strength: AASHTO T 198
- Flexural Strength: AASHTO T 97, AASHTO T 177
- Modulus of Elasticity: ASTM C 469
- Creep: ASTM C 512
- Heat of Hydration: CRD-C38
- Coefficient of Thermal Expansion: CRD-C39 or AASHTO TP 60

Restrained Shrinkage [CR2]

Restrained shrinkage cracking is evaluated using AASHTO PP 34-99, Standard Practice for Estimating the Cracking Tendency of Concrete, or ASTM C 1581, Standard Test Method for Determining Age of Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete Under Restrained Shrinkage. Although free shrinkage—as measured in AASHTO T 160 (see next subsection)—provides some indication of the driving force behind drying shrinkage cracking, the test for it does not offer sufficient information alone to predict cracking behavior of concrete structures because almost all structures are restrained in some fashion, and stiffness and creep of the concrete interact with shrinkage to determine whether cracking will occur. The restrained ring test was found to correlate better to deck cracking than standard shrinkage tests because most of the important time-dependent factors are part of the test (drying shrinkage, rate of tensile strength gain, elastic modulus, creep, etc.) Only a limited amount of work has been done in evaluation of SCMs and restrained shrinkage. For evaluation of SCM mixtures, only restrained ring and drying shrinkage testing is proposed. However, for projects with strict cracking concerns, tests for determining tensile strength gain, elastic modulus, and creep at early ages may provide useful data.

Drying Shrinkage [CR3]

Drying shrinkage is typically measured using AASHTO T 160, Standard Test Method for Length Change of Hardened Hydraulic Cement, Mortar, and Concrete. Specimens (3×3×11.25 in. [75×7×281 mm] for maximum aggregate size less than 1 in. [25 mm]) of concrete or mortar are cast and moist cured in lime water for 28 days. They are then dried at 73.4 ± 3.0°F (23.0 ± 1.7°C) and 50% RH, and the drying shrinkage is measured. The test may be modified to closer simulate field curing conditions (e.g., 7- or 14-day curing may be more representative of the age when drying of the in-place bulk concrete begins).

Desirability Function for Drying Shrinkage. Usually minimization of concrete shrinkage due to drying is desired because the lower shrinkage results in lower stress and thus less potential for cracking. Figure S1.21 shows a sample desirability function for drying shrinkage. Free drying shrinkage of the concrete mixture is only one of the factors that determine whether shrinkage-related cracking will occur. A measurement of drying shrinkage provides some indication of whether cracking is likely but does not measure the cracking tendency directly. Therefore, this desirability function was defined to avoid rating any mixture with a very low desirability. It assigns a desirability of 1 to mixtures with shrinkage strains at 90 days below a magnitude of –0.04%; the desirability decreases gently with increasing (more negative) shrinkage strain between –0.04% and –0.06%, and then decreases more rapidly with greater shrinkage increases.

Effect of SCMs on Drying Shrinkage. In general, use of SCMs in concrete mixtures increases the potential for shrinkage because a higher paste volume results when SCMs are used as replacement of cement. However, Klieger and Perenchio (*48*) found that Class F fly ash had little or no effect on drying shrinkage, but Brooks and Neville (*49*) found that fly ash can increase shrinkage by as much as 20%. Most of the research on silica fume and GGBFS shows an increase in shrinkage with the replacement of cement. Some of the increased shrinkage associated with the use of SCMs can be mitigated by proper curing procedures. The fine pore structure in SCM concretes is also thought to contribute to the increase in drying shrinkage. Testing is recommended because many chemical admixtures used in concrete mixtures can increase shrinkage.

Cracking Tendency [CR4]

Cracking tendency is most directly measured using AASHTO PP 34-99, Standard Practice for Estimating the Cracking Tendency of Concrete, or ASTM C 1581, Standard Test Method for Determining Age of Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete Under Restrained Shrinkage. These methods call for concrete to be cast around steel rings and subjected to a drying environment (50% RH). Strain gauges measure the stress in the steel, and the time when a sudden drop in stress is observed is recorded as the time to first cracking. The procedure is intended for use in determining the effects of variations in the properties of concrete on the time to cracking of the concrete when restrained. The procedure provides comparative data and is not intended to determine the time of initial cracking of concrete cast in a specific type of structure. Cracking in service is influenced by many factors including degree of restraint, hydration effects, and environmental conditions. The method is useful to determine the relative likelihood of early concrete cracking and to aid in selection of concrete mixtures that are less likely to crack. The test method may also be modified to evaluate other factors that may affect cracking such as curing time, method, or temperatures. The rate of stress increase can also be compared to evaluate concrete mixtures that do not crack; the mixture exhibiting the lowest strain rate would be preferred.

Desirability Function for Restrained Shrinkage. Mixtures that do not crack or crack at later ages during cracking tendency testing are preferred. The standard test methods call for only 24 hours of wet curing while bridge decks are generally cured for 7 days. Depending on the likely curing regimen for the actual bridge deck, this period may be varied and the desirability function must be adjusted accordingly. Figure S1.22 shows an example of a desirability function for time to first crack after 7 days of curing. This function rewards longer times to cracking; if the concrete mixture can last up to 6 weeks before cracking, it is rated a 0.95 or higher. Mixtures cracking at less than 6 weeks receive lower desirabilities with a desirability of 0 assigned to mixtures that crack before 1 week. Twenty-four hours of curing appears to be the more rigorous test and thus the desirability function would have to be shifted to assign higher desirabilities at lower ages of cracking if such curing regimen was applied.

Effect of SCMs on Cracking Resistance

Fly Ash and GGBFS. The effect of SCMs on the cracking resistance of concrete under restrained shrinkage is not well known. Slowing the early-age (less than 7-day) hydration of the concrete may help reduce the risk of cracking by slowing the rate at which the modulus of elasticity increases and by increasing early-age creep. Fly ash and slag typically reduce the early-age strength of concretes when used as a replacement of cement. Replacement of cement with Class F fly ash is typically more effective at slowing strength gain than replacement with Class C fly ash or GGBFS. Generally, the addition of fly ash or GGBFS to the concrete does not affect the cracking tendency of the concrete greatly if the total cementitious volume is not changed. Cracking (drying shrinkage) may be reduced if the improved workability of the mixture containing the SCM contributes to reduced water demand and reduced paste volume.

Silica Fume. Silica fume has been shown to increase the cracking tendency of concretes in the restrained shrinkage test. Li et al. (*50*) found that silica fume replacement of cement not only increases the cracking tendency but also increases the crack width in the restrained shrinkage test.

Class N Pozzolans (Metakaolin). Ding and Li (*9*) report that metakaolin shrinks less than portland cement concrete and less than silica fume–containing concrete at equivalent dosages. For metakaolin they also found that the rate of shrinkage was higher than for plain portland cement concrete up to 5 days and lower after that. With respect to restrained shrinkage, crack widths of metakaolin-containing concrete were less than those for portland cement concrete but were initiated at earlier ages. Taylor and Burg (*8*) report similar shrinkage for metakaolin- and silica fume–containing concretes.

Thermal Concerns for Cracking Resistance [CR5]

Heat evolution is usually considered only for more massive concrete applications. However, thermal gradients can cause large early-age stresses in concrete bridge decks and result in cracking. Concretes containing large quantities of cement with rapid hydration characteristics are more prone to thermal cracking and, therefore, large thermal gradients within the deck should be avoided. Modifying construction practices is one approach to minimize the likelihood of cracking. However, testing concrete mixtures to identify mixtures with low rate of heat evolution, low total heat of hydration, and low coefficient of thermal expansion and thus to reduce the risk of thermal cracking is another approach.

If a review of the bridge structural analysis and proposed mixture indicates only small or moderate risk for cracking, consideration should be given to curing practices that minimize thermal gradients in the concrete (see "Special Construction Practices [CR10]"*)*. An effective means to reduce thermal cracking may involve temperature monitoring and appropriate adjustment of curing procedures.

If the deck is thick or integral with piers or beams such that high concrete hydration temperatures may occur, or if the concrete has large amounts of rapid hardening cementitious materials, it may be prudent to test concrete mixtures and select SCM mixtures that reduce the heat of hydration. This property can be used to model the three-dimensional temperature gradients within the structure. Aggregates also can be selected to minimize the coefficient of thermal expansion of the concrete.

Heat of Hydration [CR6]

The heat of hydration and the rate of the heat evolution are not normally measured for bridge deck concrete. However, the rate of heat evolution may influence the development of thermal cracks because the rapid heat evolution can result in high temperatures during initial hardening and develop more severe thermal gradients when the concrete cools rapidly. The heat of hydration, or total energy released during the hydration process, is a major concern for mass concrete placements. However, for bridge decks, the rate of heat evolution is more important than the heat of hydration because peak temperature differentials in decks typically occur within a few days of construction and are determined by the interaction between hydration-related heat evolution and cooling.

Another temperature-related concern for concrete is the phenomenon of delayed ettringite formation (DEF), in which the formation of early-age ettringite is suppressed by high curing temperatures but ettringite reforms under moist conditions at some time later in the concrete's life, causing deleterious expansion and cracking. For precast concrete, the Canadian Standards Association (*51*) currently recommends that ordinary portland cement concrete in a moist environment should not reach a concrete temperature above 140°F (60°C) during curing. This concrete temperature curing limit is also applicable to concrete where no heat is applied. Use of SCMs may reduce the risk of DEF.

Test Methods. There are no direct test methods for measuring the heat of hydration of concrete. The U.S. Army Corps of Engineers published a method in 1973, CRD-C38, which measures the temperature increase of freshly mixed concrete over time in adiabatic conditions (i.e., in a controlled environment where no heat is allowed to enter or escape the sample). This test is difficult to perform and few laboratories are equipped to perform it. Instead, it is more practical to evaluate the relative performance of mixtures by monitoring temperature rise in an insulated container. Some heat loss is inevitable with this type of testing configuration and this loss may approximate the cooling experienced by freshly placed concrete decks with peak temperatures typically occurring within 8 to 24 hours. Concrete mixtures that have a higher rate of heat evolution will produce a higher peak temperature. Therefore, performance of mixtures relative to thermal stresses in concrete bridge decks can be evaluated based on the peak temperature in the insulated container. The peak temperature in this type of testing is different from the likely significantly higher peak temperature that might be achieved in adiabatic conditions. It is also possible to track temperature evolution over time and calculate the maximum rate of temperature increase, which may be used as an evaluation criterion. The insulated containers and ambient conditions during this testing must be similar to provide a basis for relative performance.

For the case study conducted as part of the development of this methodology, 6×12-in. (150×300-mm) diameter cylinders were cast for each mixture and cured inside blocks of insulating foam. The cylinders were cured inside containers that meet ASTM C 684, Standard Test Method for Making, Accelerated Curing, and Testing Concrete Compression Test Specimens, Procedure C. These containers were kept in a controlled environmental chamber held at a temperature of 73°F (23°C) before and during hydration. Before batching, all the raw materials were stored in a climate-controlled room and stabilized at room temperature. The temperature of the cylinders was monitored with thermocouples that were embedded in the center of the concrete, and the temperature rise resulting from the heat evolution during hydration for each mixture was recorded.

Desirability Function for Temperature Rise. Because the test for temperature rise is not standardized, each laboratory will have to develop a specific method of test and interpretation of the results. A sample desirability function for heat of hydration (temperature rise) is shown in Figure S1.23. This function stipulates that a lower temperature rise is preferred. However, because temperature rise, like free drying shrinkage, is only one of the many factors that determine whether a bridge deck cracks, this function was defined to downgrade mixtures only slightly for adequate performance or better. It assigns a desirability of 1 to temperature rises of 20°F (11°C) or less and slightly lower desirabilities to temperature rises of up to 50°F (28°C). If the temperature rise is more than 80°F (44°C) above the initial 73°F (23°C), the maximum allowable temperature of 150°F (66°C) chosen for this example based on potential susceptibility to DEF will be exceeded and thus the mixture would be considered unacceptable. This function should, however, be adjusted based on the specific application and the test procedure used.

Effect of SCMs on Heat of Hydration. The heat of hydration is influenced by the amount and type of cement, the type and amount of SCMs used, and curing conditions. Modern portland cements tend to have high tricalcium silicate (C_3S) contents, and high fineness that result in more rapid heat generation during hydration compared with cements used in past decades. Therefore, the heat of hydration may be a more important parameter than it has historically been.

Fly Ash and GGBFS. Replacement of cement with fly ash and GGBFS will reduce the rate of heat evolution in concrete structures. The greater the replacement, the lower the early heat of hydration. The hydration processes of fly ash and to some extent GGBFS are slow because of their reaction with the calcium hydroxide products of the cement hydration process. In the case of fly ash, the pozzolanic reaction may not actively occur until a week after mixing. Use of Class F fly ashes to replace cement is typically most effective at reducing the rate of hydration. Some Class C fly ashes may actually increase the rate of heat production. Cement replacement of up to 75% with GGBFS or 40% with Class F ash is sometimes used for mass concrete applications.

Silica Fume. Researchers do not agree on the effect of silica fume on the development of heat of hydration. Kadri and Duval (*52*) found that, at early ages, silica fume accelerates the hydration process, and that at 10% cement replacement, the cumulative heat of hydration is greater than portland cement concrete. However, Alshamsi (*53*) found that a 10% cement replacement of silica fume decreases the heat of hydration.

This decrease may result from the reduction in hydroxide ions available to react with the other SCMs. Low dosages of silica fume (i.e., 3% to 5%) are sometimes used to achieve cohesiveness while minimizing heat generation.

Coefficient of Thermal Expansion [CR7]

The coefficient of thermal expansion of the concrete is important with respect to early-age cracking because it describes the free strain in the material for a given temperature change. Coefficient of thermal expansion is measured using the U.S. Army Corps of Engineers test CRD-C39, Test Method for Coefficient of Linear Thermal Expansion of Concrete, or AASHTO TP 60, Standard Test Method for Coefficient of Thermal Expansion of Hydraulic Cement Concrete. The coefficient of thermal expansion is mainly a function of the aggregate; the effect of SCMs on this value is expected to be very small. Therefore, testing for this coefficient is not suggested as part of the screening for SCM mixtures.

Modulus of Elasticity [CR7]

The modulus of elasticity (*E*) is the ratio of stress to strain in the linear portion of the stress-strain curve before the onset of significant microcracking; it can range from 2 to 6 × 10^6 psi (13.8 to 41.4 GPa). The modulus of elasticity is determined according to ASTM C 469, Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression. The deformation of the concrete under compression loading is measured with strain gauges adhered to the concrete specimens or using deflection gauges mounted in a frame known as a compressometer. The *E* value relates the stress in the material for a given strain; high values of *E* may indicate susceptibility to cracking resulting from external strains such as drying shrinkage or thermal deformation since, for a given strain, greater stress is developed. The modulus of elasticity is a function of w/cm, volume of paste, and the aggregate modulus of elasticity and is typically related to strength.

Desirability Function for Modulus of Elasticity. The modulus of elasticity may be specified by the designer. Low elastic modulus values are undesirable because they may result in large deformations; however, too high a value may increase the potential for cracking due to restraint. A sample desirability function for elastic modulus at an early age (7 days) is shown in Figure S1.24. This function suggests that the ideal range for elastic modulus is between 3 and 5 × 10^6 psi (20.7 to 34.5 GPa) at 7 days. Mixtures with elastic moduli greater than 1 × 10^6 psi (6.9 GPa) outside this range are considered unacceptable and assigned a desirability of 0, while those with elastic moduli less than 1 × 10^6 psi (6.9 GPa) outside this range are given an intermediate desirability.

Effect of SCMs on Modulus of Elasticity

Fly Ash. The modulus of elasticity of Class F fly ash–containing concrete is somewhat lower at early ages and a little higher at later ages than ordinary portland cement concrete (*4*).

GGBFS. Fernandez and Malhotra (*5*) found that the elastic moduli were comparable between mixtures containing GGBFS and ordinary portland cement.

Silica Fume. ACI Committee 234 (*7*) reports that the modulus of elasticity of concrete containing silica fume is similar to that of ordinary portland cement concrete of similar strength.

Class N Pozzolans (Metakaolin). Taylor and Burg (*8*) report a slightly higher modulus of elasticity for metakaolin-containing concrete than for silica fume–containing concrete. Caldarone et al. (*14*) found modulus of elasticity to be 15% to 18% higher with metakaolin at 5% to 10% addition than portland cement concrete.

Plastic Shrinkage [CR8]

Plastic shrinkage cracks occur after the concrete has been placed but before the concrete has set. They usually appear on exposed horizontal surfaces and can occur anytime when the ambient conditions (temperature, humidity, wind velocity) are conducive to rapid evaporation. Plastic shrinkage cracking generally occurs when the rate of evaporation exceeds the rate of bleeding of the concrete. The width of cracks at the surface may be as much as 0.25 in. (6.3 mm); however, the cracks are usually no more than 2 or 3 ft (0.6 or 0.9 m) long and are rarely more than 2 to 3 in. (50 to 75 mm) deep. Such cracks are seldom significant structurally, and once the crack forms, the stresses rapidly dissipate. Plastic shrinkage cracks occur very early after casting and are not associated with long-term aging. However, these early-age cracks can allow the penetration of deicer salts, water, and gases into the concrete, which may adversely influence the durability of the structure.

The likelihood of plastic shrinkage cracking may be reduced by reducing the evaporation rate or increasing the bleeding capacity of the concrete. The former can be accomplished to various degrees by sunscreens, windbreaks, fog mist, or monomolecular curing films. Increasing the bleeding capacity of the concrete is usually not practical and may cause settlement cracking; however, use of a water-reducing admixture containing hydroxylated carboxylic acid may increase the bleeding rate.

The most effective means of avoiding the loss of bleed water (reducing evaporation) is by using impermeable curing covers such as polyethylene sheeting. During placing and finishing operations, the use of a fog mist applied just above the concrete surface from the upwind side of the work is also very effective. Use of a commercial grade fog nozzle is required to provide broad coverage and produce a fine mist that does not damage the concrete by depositing drops of water on the surface. Dry cotton blankets can be applied to the plastic concrete and wetted immediately after concrete finishing (even before the concrete can support the weight of workers). The wetted blankets can then be covered with soaker hoses and plastic sheeting. This method provides immediate curing and should eliminate most plastic cracking problems.

Plastic shrinkage cracks sometimes form in winter conditions when concrete is cast outside in heated forms and covered with a tarpaulin. The forms and the warm concrete heat the air between the concrete and the tarpaulin, greatly increasing the air's capacity to hold moisture. This warm, moist air leaks out and is replaced by cold, dry air that quickly warms up and absorbs moisture from the concrete, possibly leading to plastic shrinkage cracking.

Test Methods for Plastic Shrinkage Cracking [CR9]. Testing of concrete for plastic cracking is uncommon. One test method has been developed for evaluating the effect of fibers on plastic shrinkage cracking. This method is described in ICC Evaluation Service (ICC-ES) report "Acceptance Criteria for Concrete with Synthetic Fibers" (ICC AC32 Annex A). While testing for plastic cracking is not normally suggested as part of mixture development programs, if problems occur, comparative testing may be helpful in identifying better performing mixtures; a desirability function curve can be proposed.

Effect of SCMs on Plastic Shrinkage Cracking. Plastic shrinkage cracking has become a significant problem in recent years because of the wide usage of silica fume, latex modifiers, superplasticizers (HRWRs), and air-entraining admixtures. HRWRs greatly reduce the water content and therefore the bleeding capacity of concrete. As a result, the rate of evaporation can more easily exceed the rate of bleeding. Silica fume intensifies the problem because HRWRs must be used to compensate for the extreme fineness of the silica fume material. The HRWR reduces the amount of bleed water available while the high fineness of the silica fume reduces the rate at which the water can move through the concrete. Air entrainment also reduces the bleeding rate.

Special Construction Practices [CR10]

Krauss and Rogalla (*47*) identify practices that will reduce the tendency for deck cracking: (1) reduce concrete restraint (structural design), (2) reduce rapid heat of hydration (mixture), (3) reduce the rate of concrete cooling (construction procedures), (4) reduce the concrete coefficient of thermal expansion (aggregate selection), (5) reduce drying shrinkage (materials), (6) reduce the rate of drying (construction practice), (7) increase concrete creep (mixture), and (8) reduce the concrete modulus (materials).

Krauss and Rogalla provide additional information concerning early-age deck cracking (*47*). Also, the software package HIPERPAV (HIgh PERformance PAVing) that was recently developed through the FHWA (*54*) identifies the risk of early-age problems based on portland cement concrete pavement design, concrete mixtures, construction methods, and environmental conditions.

Although the concrete mixture proportions and specific construction practices can affect cracking, key elements of the design also can greatly influence cracking. Design factors such as the geometry of the deck and the size, spacing, and type of supporting girders can have a major effect on the amount of cracking. In some cases, these design features can lead to cracking despite the construction practices. Restrained ring tests can be used to measure the cracking tendency of concrete mixtures, evaluate proposed mixtures, and select mixtures having a low cracking tendency. Instrumenting concrete placements to monitor concrete strains and concrete temperatures (at the top and middle of the slab) can also help in identifying causes of and reducing cracking in future applications.

Restraint can cause large shrinkage and thermal stresses, but creep (stress-relaxation) serves to offset this stress development. This relationship is illustrated in the following simplified one-dimensional example. If the concrete has a free shrinkage of 500 microstrain ($\mu\varepsilon$), but it is restrained and allowed to shorten only 250 $\mu\varepsilon$, the restraint is 50%. Concrete with a modulus of elasticity of 4×10^6 psi (28 GPa) might have an effective modulus of only 2×10^6 psi (14 GPa), because of creep. The resultant tensile stress would be the product of the strain (500 $\mu\varepsilon$) times the restraint (50%) times the effective modulus of elasticity [2×10^6 psi (14 GPa)] for a resultant tensile stress of 500 psi (3.4 MPa). If the tensile strength of the concrete is greater than 500 psi (3.4 MPa), cracking will not occur. However, additional tensile stresses that may result from thermal gradients or loading could crack such a concrete. Therefore, the effects of shrinkage and temperature changes, effective concrete modulus, restraint conditions, tensile strength, and loading conditions must be considered during the process to reduce deck cracking.

Concrete Mixture Influences on Cracking. The mixture and raw materials of concrete significantly affect cracking. Generally, high-strength concrete is more prone to cracking. These concretes are stiffer (higher elastic modulus) and develop higher stresses for a given temperature change or amount of shrinkage, and, most important, these concretes creep (relax) little to relieve these stresses. However, these concretes also develop greater tensile strengths, and the interaction between these properties is complex. Typically, high-early-strength concretes are particularly prone to cracking because little shrinkage has dissipated before the concrete has developed a high modulus and low creep properties. Also, because high-strength concretes typically contain more cement, they may shrink more and develop higher temperatures during early hydration.

The risk of cracking may be reduced by selecting a concrete mixture that does not excessively exceed the required compressive strength yet is still durable in service.

Cement content, fineness, and chemical composition also affect the rate of hydration, early strength gain, and the heat generated initially by the concrete. Modern cements are more apt to cause cracking because they are finer and have higher sulfate and alkali contents.

In general, concretes with higher aggregate contents and lower cement paste contents are less likely to develop cracks. Because the hydrated cement paste is the component of the concrete that shrinks, reducing cement paste volume reduces shrinkage. Leaner mixtures are also thermally less expansive and develop smaller thermal stresses. The concrete mixture should contain the largest possible aggregate size consistent with placement and consolidation requirements. Larger aggregates permit a leaner mixture, help maintain workability, and reduce thermal and shrinkage stresses. The maximum aggregate size should be either one-third the deck thickness or three-fourths the minimum clear spacing between reinforcing bars, whichever is smaller.

Concrete Placement. Mixtures having a high cracking tendency may be selected based on good performance in other tests. If this is the case, measures should be taken to reduce the risk of cracking during construction. The first large stresses in a new concrete slab usually develop during the first 12 to 24 hours, when the concrete temperatures change rapidly during early hydration. Reducing the concrete temperatures during this process will reduce early stresses. Concrete temperatures can be reduced by placing concrete during cooler periods (such as during the evening or at night), placing cool concrete, misting the concrete during placement, wet curing, and shading the deck.

Plastic shrinkage cracking can occur when SCMs are used and the concrete has little bleed water. When wind speeds are higher than 5 mph (light breeze) during placement, moisture evaporation rates from the concrete should be measured and special precautions to reduce drying should be taken if evaporation rates are high. For normal concreting, an evaporation rate of 0.2 pounds per square foot (psf) per hour (1.0 kg/m^2 per hour) is considered excessive, while, for modern concretes with high cement contents, silica fume, HRWRs, or other ingredients that reduce bleed water, an evaporation rate of 0.1 to 0.15 psf per hour (0.5 to 0.75 kg/m^2 per hour) is considered excessive.

In summary, the ideal concrete mixture should incorporate the largest practical aggregate size, lowest paste volume consistent with other performance requirements, and minimum strength required to meet project requirements; gain strength slowly; and contain the highest w/cm that will provide the required strength and durability. A cement with a low rate of heat evolution and the use of SCMs should be considered to achieve a concrete that gains strength slowly but steadily.

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Worksheet for Step 1

Worksheet S1.1. Desired concrete performance and associated considerations for mixture proportioning.

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: AASHTO T 22, ASTM C 39											
	Flexural strength: AASHTO 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											
	Time of setting: AASHTO T 197, ASTM C 403											
	Finishability											
Freezing and thawing with chemical deicers	Chloride penetration: AASHTO T 259, ASTM C 1566											
	Electrical conductivity: AASHTO T 277, ASTM C 1202											
	Scaling Resistance: ASTM C 672											
Freezing and thawing without chemical deicers	Air content, %: ASTM C 457											
	Spacing factor: ASTM C 457											
	Freezing and thawing resistance: AASHTO T 161 A, ASTM C 666 A											
Coastal	Chloride penetration: AASHTO T 259, ASTM C 1566											
	Electrical conductivity: AASHTO T 277, ASTM C 1202											
Abrasive	Abrasion: ASTM C 944 or C 779 Procedure B											
Cracking resistance: ASR	Go to Raw Materials Flowchart											
Cracking resistance: restrained shrinkage	Restrained ring cracking: AASHTO PP 34-99, ASTM C 1581											
	Free drying shrinkage: AASHTO T 160, ASTM C 157											
Cracking resistance: thermal concerns	Heat of hydration											
	Modulus of elasticity, ASTM C 469											
Cracking resistance: plastic shrinkage	Plastic shrinkage cracking: ICC AC32 Annex A											
Other design requirements												
SUMMARY												

Figures for Step 1

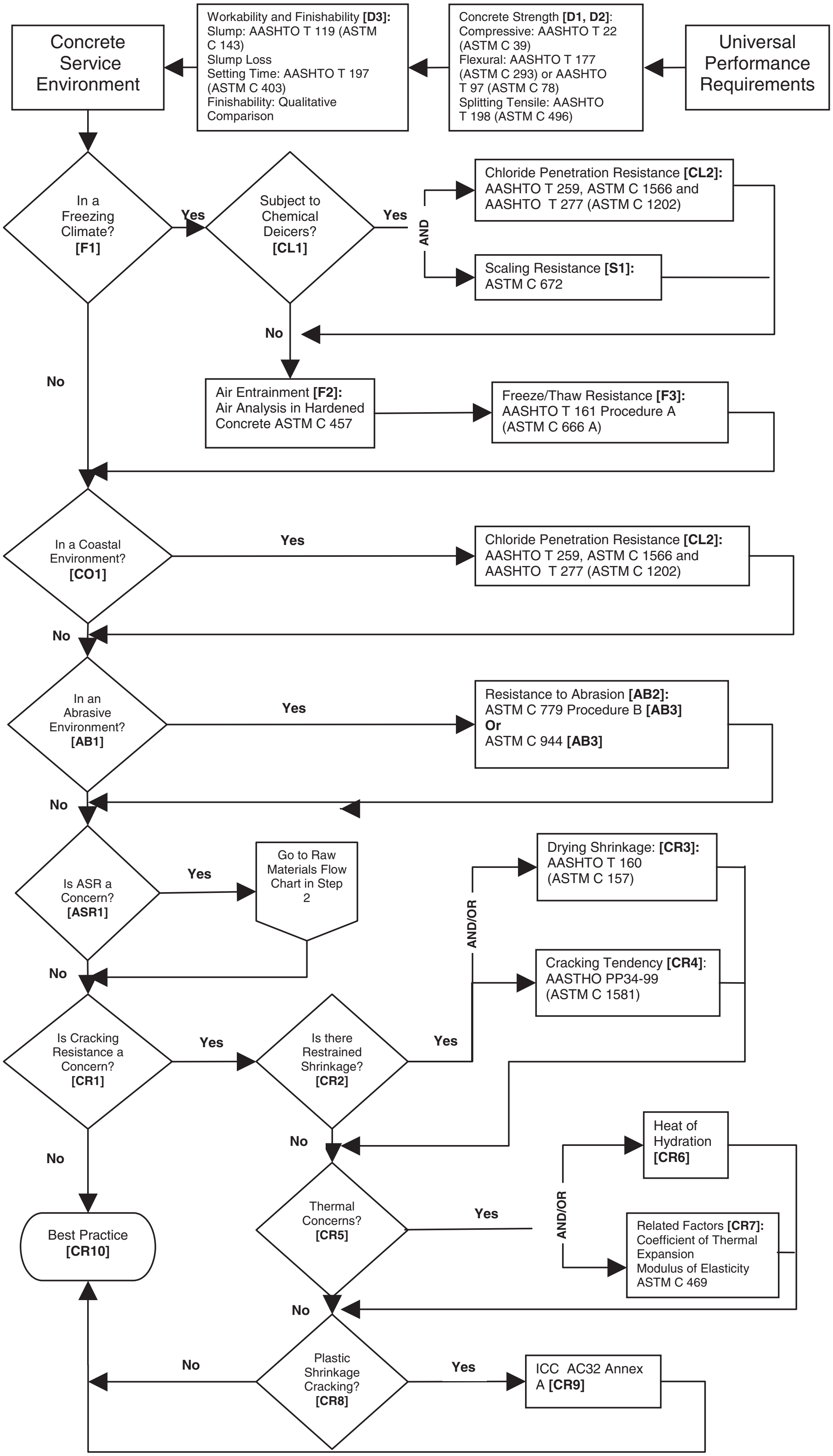

Figure S1.1. Selecting concrete service environment and properties.

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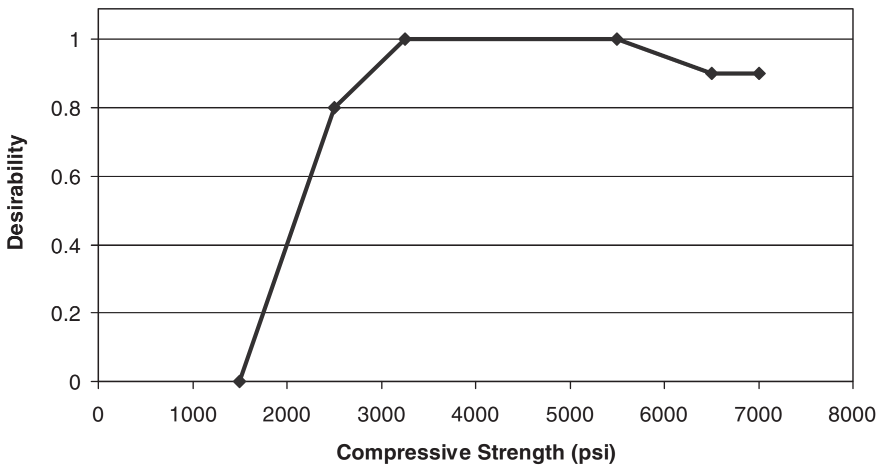

Figure S1.2. Desirability function for average compressive strength at 7 days.

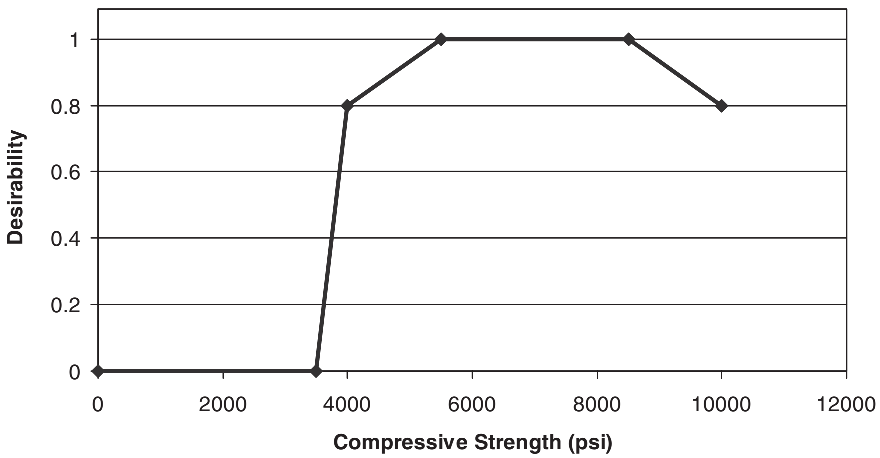

Figure S1.3. Desirability function for average compressive strength at 28 days.

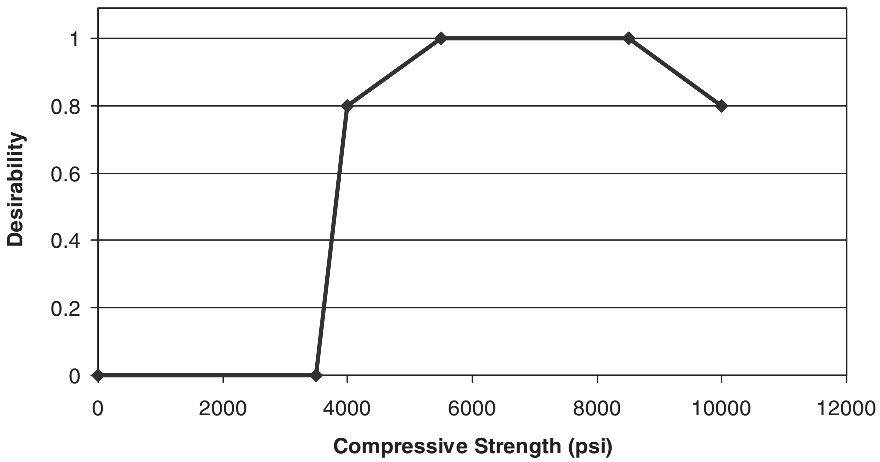

Figure S1.4. Desirability function for average compressive strength at 56 days.

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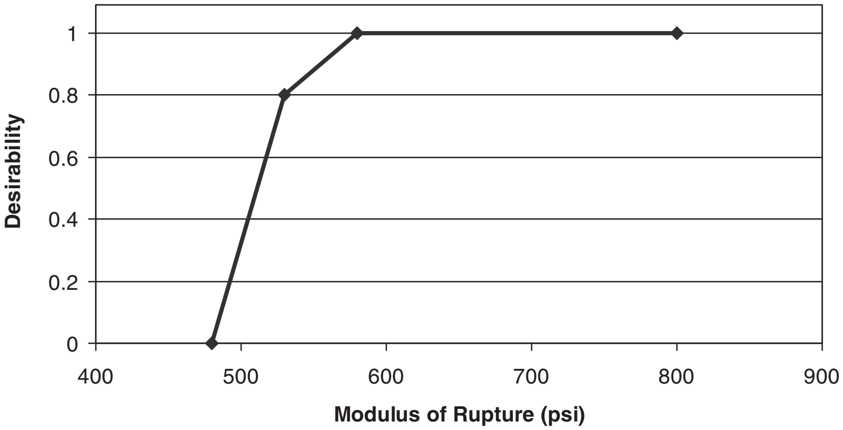

Figure S1.5. Desirability function for modulus of rupture (flexural strength).

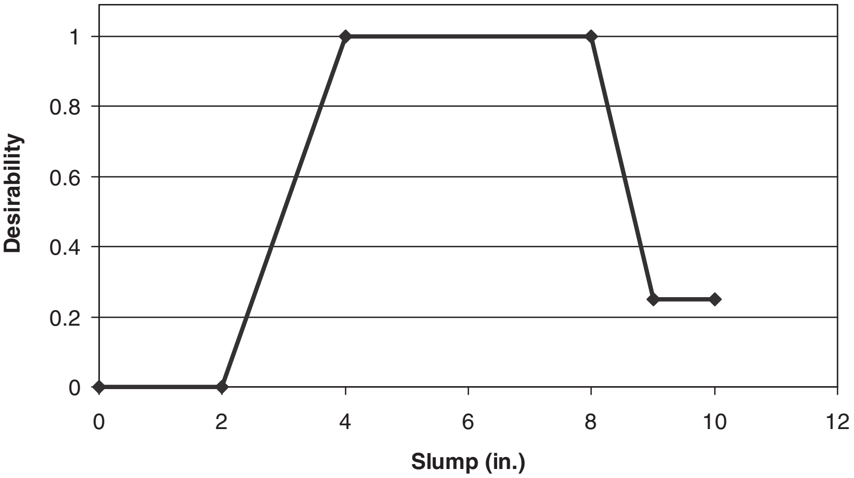

Figure S1.6. Desirability function for slump (HRWR is used).

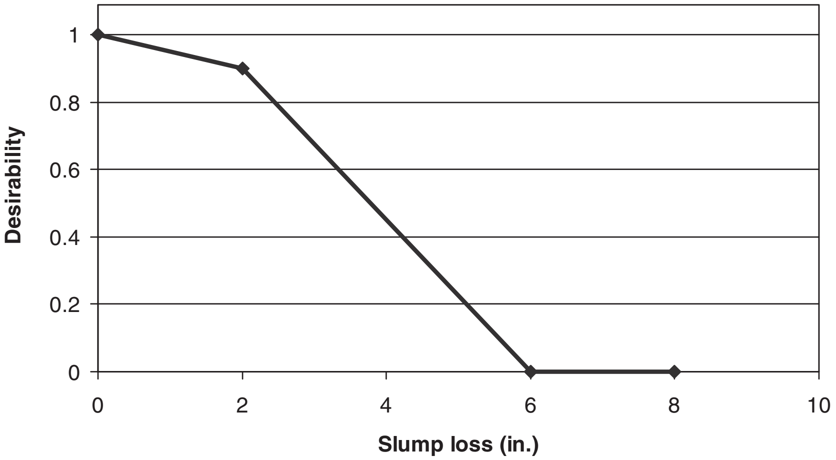

Figure S1.7. Desirability function for slump loss.

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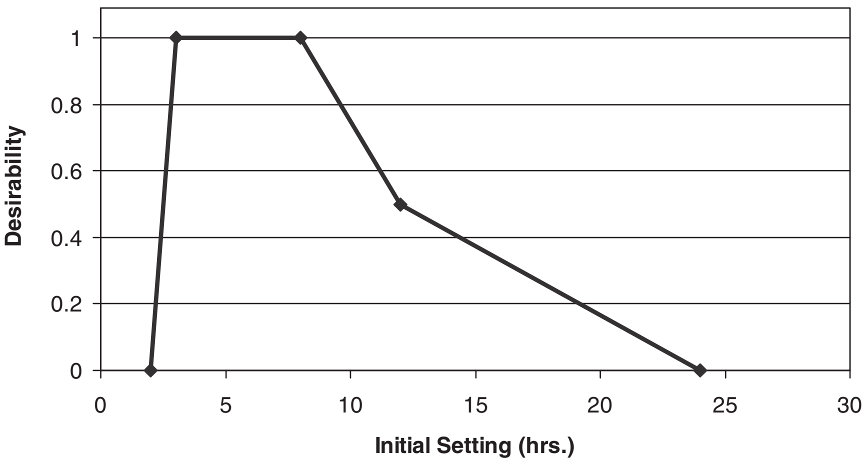

Figure S1.8. Desirability function for time of initial setting.

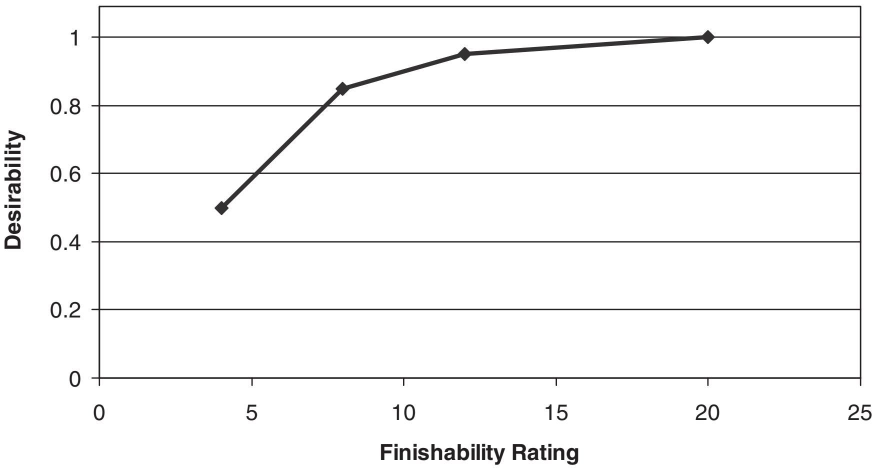

Figure S1.9. Desirability function for finishability.

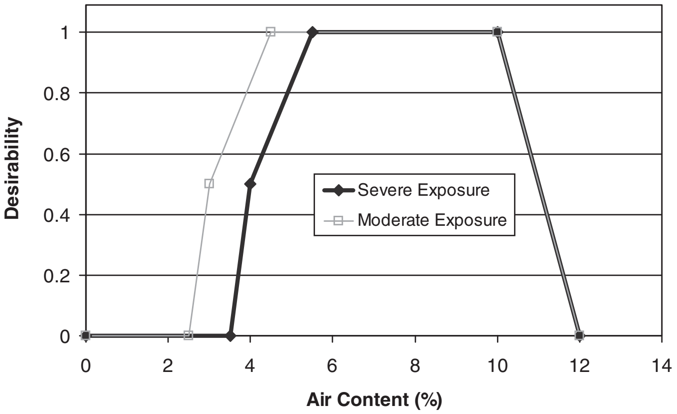

Figure S1.10. Desirability functions for air content.

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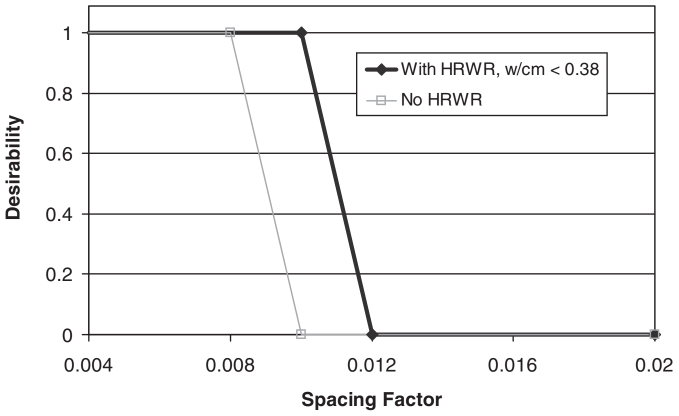

Figure S1.11. Desirability functions for spacing factor with and without HRWR.

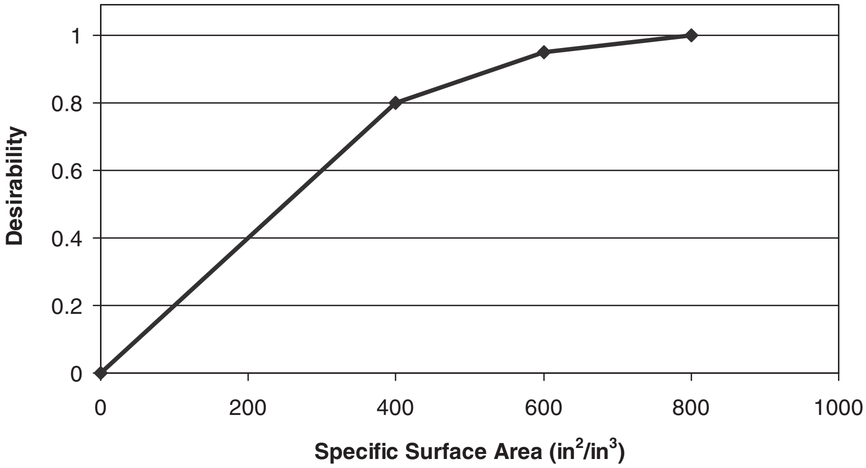

Figure S1.12. Desirability function for specific surface area.

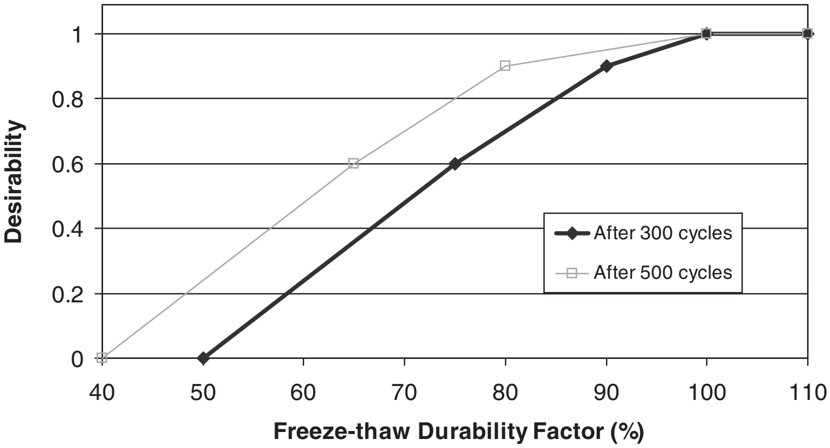

Figure S1.13. Desirability functions for durability factor in a severe environment after 300 cycles and after 500 cycles.

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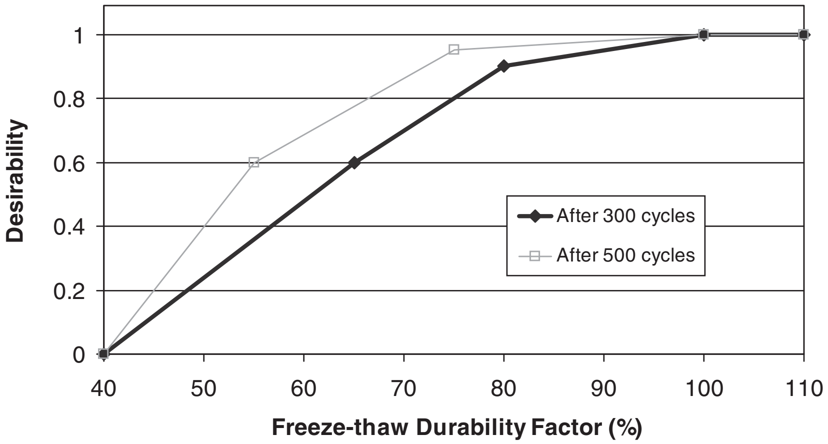

Figure S1.14. Desirability function for durability factor in moderate environment after 300 and 500 cycles.

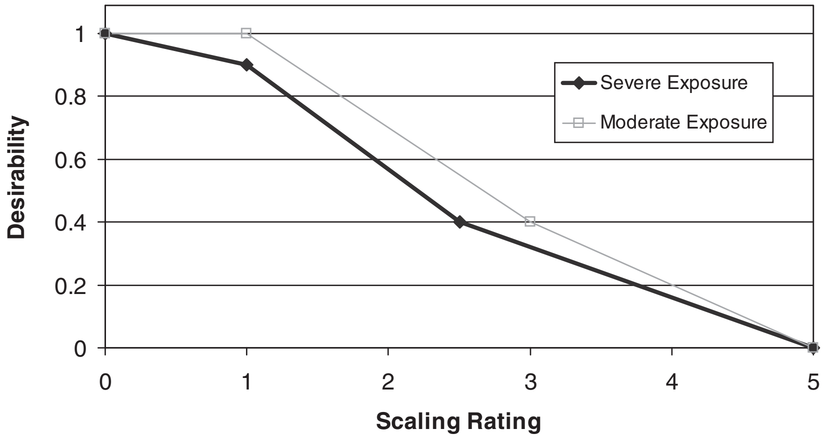

Figure S1.15. Desirability function for visual rating of scaling for severe exposure.

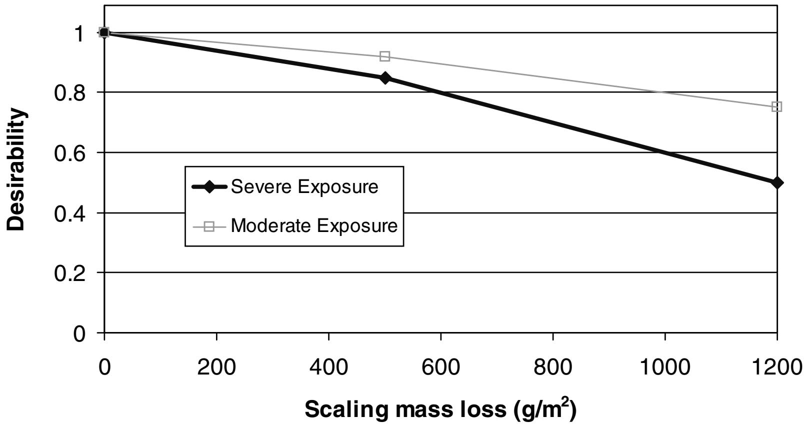

Figure S1.16. Desirability function for mass loss for scaling for severe exposure.

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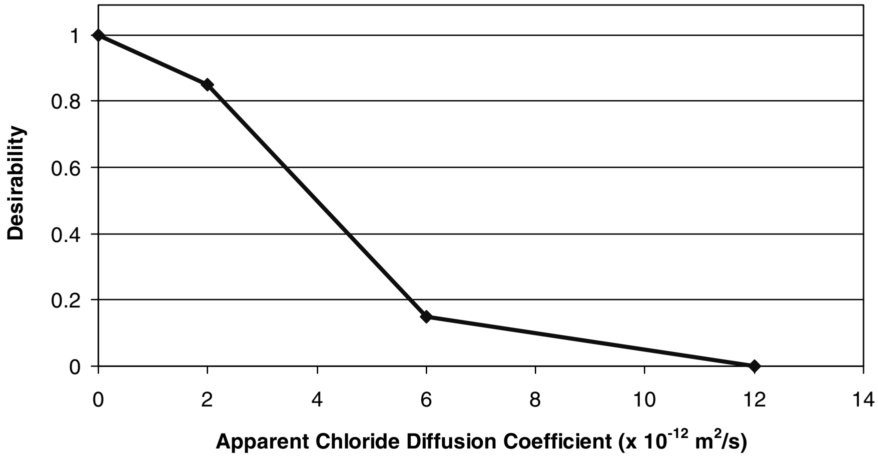

Figure S1.17. Desirability function for chloride ion penetration test.

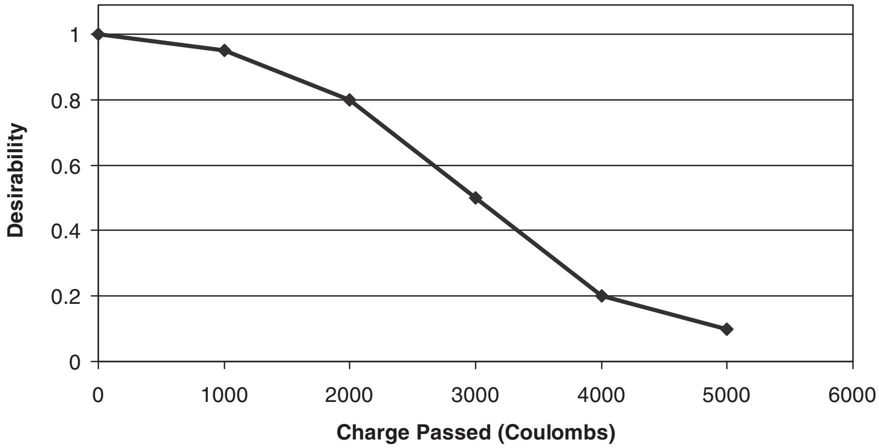

Figure S1.18. Desirability function for electrical conductivity test.

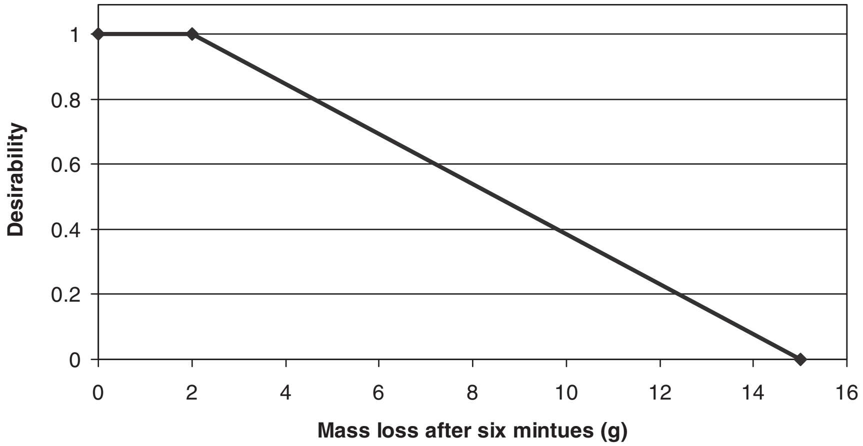

Figure S1.19. Desirability function for mass loss after abrasion (ASTM C 944).

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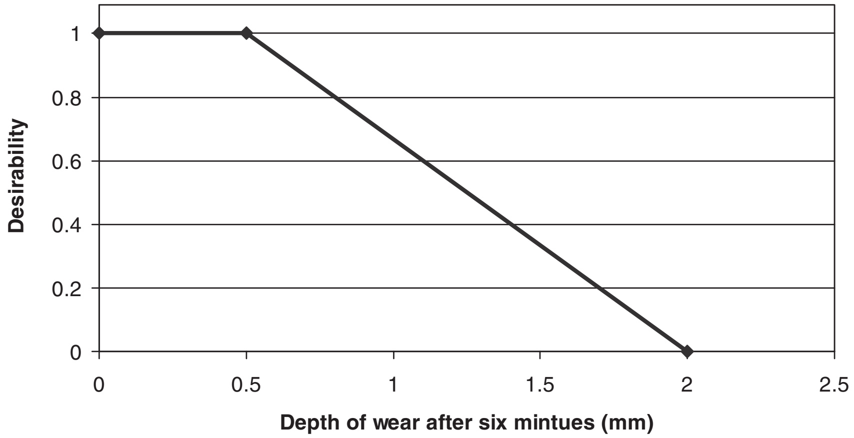

Figure S1.20. Desirability function for depth of wear after abrasion (ASTM C 944).

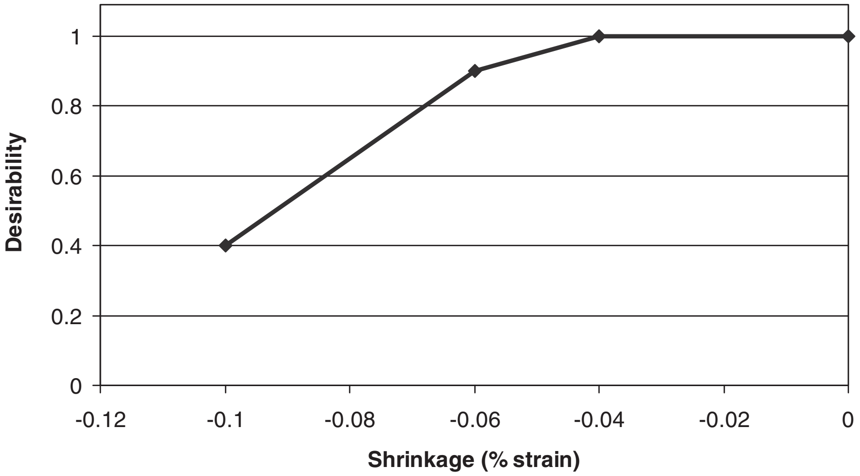

Figure S1.21. Desirability function for drying shrinkage after 90 days.

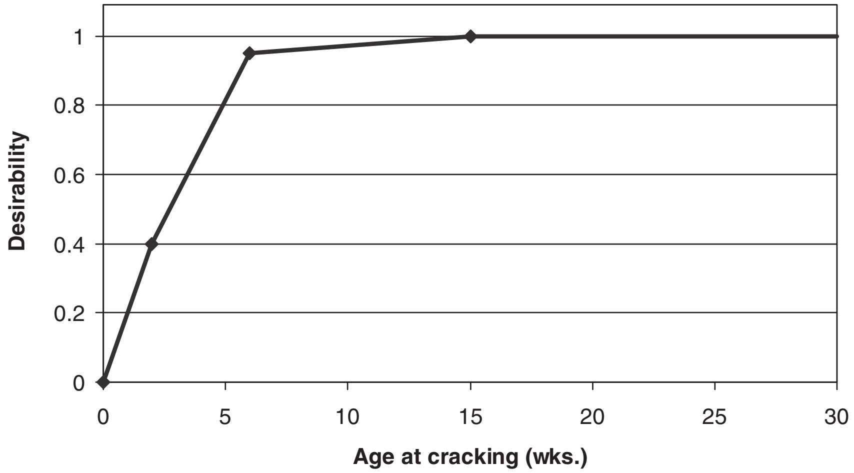

Figure S1.22. Desirability function for time to first crack in restrained-ring shrinkage cracking test.

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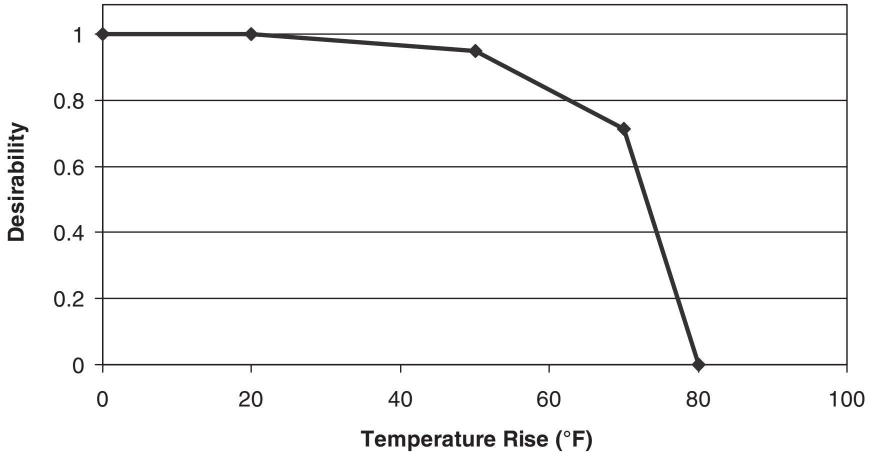

Figure S1.23. Desirability function for temperature rise due to heat of hydration.

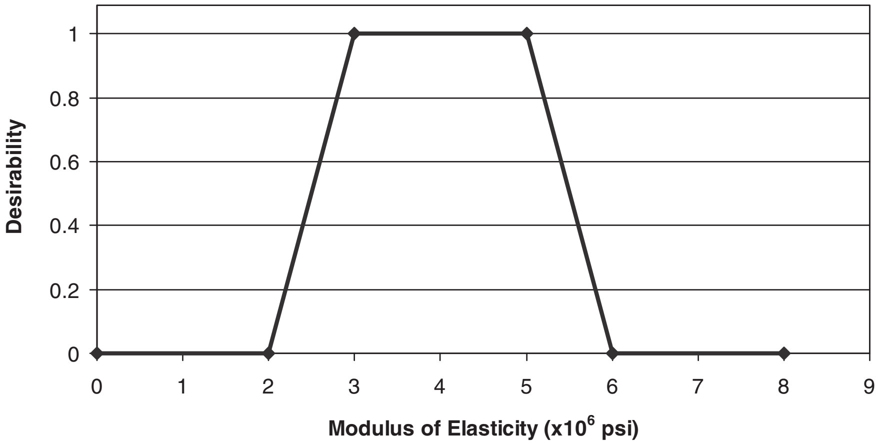

Figure S1.24. Desirability function for modulus of elasticity at 7 days.

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Tables for Step 1

Table S1.1. Summary of typical SCM ranges of use for each concrete property.

Environment	Property/Test Method	Range of Class C Fly Ash (%)	Range of Class F Fly Ash (%)	Range of GGBFS (%)	Range of Silica Fume (%)	Range of Metakaolin (%)
Universal performance requirements	Compressive strength: AASHTO T 22, ASTM C 39	0-30	0-30	15-50	5-8	5-15
	Flexural strength: AASHTO T 177, T 97, or T 198, ASTM C 293, C 78, or C 496	0-30	0-30	15-50	5-8	5-15
	Slump and slump loss: AASHTO T 119, ASTM C 143	10-30	10-40	15-40	5-8	5-10
	Time of setting: AASHTO T 197, ASTM C 403	0-30	0-25	15-40	5-8	5-15
	Finishability	0-25	0-25	10-30	0-8	5-15
Freezing and thawing with chemical deicers	Chloride penetration: AASHTO T 259, ASTM C 1566	15-40	15-25	15-30	5-8	8-12
	Electrical conductivity: AASHTO T 277, ASTM C 1202	15-40	15-25	15-30	5-8	8-12
	Scaling resistance: ASTM C 672	0-25	0-25	0-40	5-8	0-10
Freezing and thawing without chemical deicers	Air content, %: ASTM C 457	0-25	0-25	0-40	0-8	0-10
	Spacing factor: ASTM C 457	0-25	0-25	0-40	0-8	0-10
	Freezing and thawing resistance: AASHTO T 161 A, ASTM C 666 A	0-25	0-25	0-40	5-8	5-10
Coastal	Chloride penetration: AASHTO T 259, ASTM C 1566	15-40	15-25	15-30	5-8	8-12
	Electrical conductivity: AASHTO T 277, ASTM C 1202	15-40	15-25	15-30	5-8	8-12
Abrasive	Abrasion: ASTM C 944 or C 779 Procedure B	0-25	0-25	0-25	5-8	Unknown
Cracking resistance: ASR	Go to Raw Materials Flowchart	Not recommended	>25*	>40*	5-8**	10-15
Cracking resistance: restrained shrinkage	Restrained ring cracking: AASHTO PP 34-99, ASTM C 1581	10-25	10-25	15-35	0-5	0-10
	Free drying shrinkage: AASHTO T 160, ASTM C 157	0-25	0-25	0-35	0-5	0-10
Cracking resistance: thermal concerns	Heat of hydration	0-25	25-40	30-75	0-8	Unknown
	Modulus of elasticity, ASTM C 469	0-30	10-30	15-35	0-5	0-5
Cracking resistance: plastic shrinkage	Plastic shrinkage cracking: ICC AC32 Annex A	0-25	0-25	0-25	0-5	Unknown

*If ASR is an issue, the minimum quantity of SCM for ASR shall prevail over quantities for other properties

**Combinations of silica fume and other SCMs have been found to be effective for controlling ASR

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Table S1.2. Mixture considerations for freezing and thawing resistance.

Property	Recommendation
Aggregate	Good quality
w/cm	< 0.45
Minimum cement content	564 lbs/yd^3 (335 kg/m^3)
Compressive strength when exposed to freezing	Minimum 2,500 psi (17 MPa), minimum 4000 psi (28 MPa) if critically saturated
Curing	Minimum 7 days controlled wet curing
Air entrainment	See Kosmatka et al. (*21*), Tables 9-5 and 9-15

Table S1.3. ASTM C 672 surface rating conditions.

Rating	Condition of Surface
0	No scaling
1	Very slight scaling (3 mm [1/8 in.] depth max., no coarse aggregate visible)
2	Slight to moderate scaling
3	Moderate scaling (some coarse aggregate visible)
4	Moderate to severe scaling
5	Severe scaling (coarse aggregate visible over entire surface)

Table S1.4. Other mixture considerations for salt scaling resistance.

Property	Recommendation
Aggregates	Minimal popouts (low % of porous particles)
Minimum cement content	564 lb/yd^3 (335 kg/m^3)
Air void system	Adequate or better
w/cm	< 0.45
Finishing	No hard trowel
Minimum compressive strength	3500 psi (24 MPa)

Table S1.5. Other mixture considerations for reducing chloride penetration.

Property	Recommendation
w/cm	< 0.40
Slump	> 3 in. (75 mm)

Table S1.6. Mixture considerations for reducing chloride penetration in coastal environments.

Property	Recommendation
Cover, minimum	2 in. (50 mm)
w/cm	0.37-0.40

Table S1.7. Other mixture considerations for abrasion resistance.

Property	Recommendation
Aggregates	Hard
Compressive strength, 56 days	Maximize
w/cm	Low

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Table S1.8. 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: AASHTO T 22, ASTM C 39	4,500 - 8,000 psi	0-30	0-30	15-50	5-8		0.44-0.37				f'_c > 4500 psi
	Flexural strength: AASHTO 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 C 666 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 C 944 or C 779 Procedure B											
Cracking resistance: ASR	Go to Raw Materials Flowchart											
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 160, 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

Introduction

The raw materials for use in concrete must be selected based on availability and potential for durability. There are certain deterioration mechanisms that are directly related to the raw materials, such as ASR of the aggregate or unsoundness in the cement. Careful review of the raw materials at this early stage of the mixture development is an important part of optimizing the concrete performance, so that the likelihood of these mechanisms affecting the bridge deck durability is minimized.

The raw materials for bridge deck concrete include cement, coarse aggregate, fine aggregate, supplementary cementitious materials, and chemical admixtures. Choices regarding potential raw materials may be based on information already available from the suppliers in mill reports, test reports, or other formats. However, additional testing may be necessary to provide reasonable confidence in the quality of the raw materials required.

The objectives of Step 2 of the methodology are (1) the generation of a list of locally available materials consistent with the performance objectives of the project and (2) the identification of those materials that will be considered for selection as variables in the test matrix.

Raw Materials Selection Process

Figure S2.1 provides a procedure to organize and evaluate the information about raw materials that potentially may be used in designing the concrete mixture. As with Figure S1.1, additional background information for each of the decisions or tasks to be performed in this flowchart was collected (and is presented in "Guidance on Raw Materials Selection"). The code shown in brackets, e.g., [C], for each topic in the flowchart refers to the subsection discussing that topic.

The first box in Figure S2.1 directs the user to list all available raw materials on Worksheet S2.1 before their evaluation and selection. Listing these materials will help the user to review all possibilities, so that a wide range of materials can be considered. As the user moves through the remainder of the flowchart, the most durable sources identified based on the guidance or the user's own experience should be selected from each category and circled on Worksheet S2.1. Likewise, if a material was determined to be undesirable it should be excluded and have an "X" marked through it on Worksheet S2.1. When making these choices for each type of material, the user may want to include sources with a range of properties so that the effect of the properties in that range can be assessed.

Next, the user is directed to list all cement sources on Worksheet S2.2. Current mill certificates of potential sources of cement should be gathered and reviewed. Testing may be performed on the cements for properties that are not routinely published on the mill certificates such as early stiffening. For cements that are not pure portland cement (such as blended cements), the user is directed to obtain the composition of the cement (i.e., the percentage of portland cement, and the type and percentage of integral SCM components) from the manufacturer.

Worksheets S2.3 and S2.4 are provided to help organize test information regarding the aggregates; both fine and coarse aggregates should be verified to meet AASHTO M 6, Standard Specification for Fine Aggregate for Portland Cement Concrete and AASHTO M 80, Standard Specification for Coarse Aggregate for Portland Cement Concrete (or ASTM C 33, Standard Specification for Concrete Aggregates), respectively. As a part of these specifications, the mineralogical composition of the aggregates should be determined, if not already available, by performing a petrographic analysis of the aggregate according to ASTM C 295, Standard Guide for Petrographic Examination of Aggregates for Concrete. From this analysis, the quantities of all the constituents in the aggregate, including the potentially alkali-silica reactive material, are tabulated. If the amount of material that is potentially deleteriously reactive with alkalis indicates a potential for harmful expansion, further work, such as an assessment of the service record of the aggregate (discussed in "Guidance on Raw Materials Selection" of this chapter), is required. If records are not available, then ASTM C 1260, Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method), must be performed to assess ASR potential. Depending on the results, either the mixture must be adjusted according to the ASR mitigation guidelines in this chapter and tested according to either ASTM C 1567, Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method), or a modified 2-year version of ASTM C 1293, Test Method for Determination of Length Change of Concrete Due to Alkali Silica Reaction, or the aggregates can be tested without mitigation in a 1-year ASTM C 1293 test. Figure S2.1 together with the background in the following section provides recommendations on the assessment of the aggregates and the potential use of SCMs or low alkali cement for ASR mitigation.

The SCMs should also be screened; the compositions of each type of material should be reviewed from current certificates of analysis; and the data compiled in Worksheets S2.5 through S2.9.

Lastly, the chemical admixtures should be reviewed for compliance with the respective AASHTO or ASTM specifications. Letters of compliance should be requested from the admixture producers. Other additional testing on the admixtures is usually limited; however, the effect of chemical admixtures on setting time and other properties of concrete can be important and should be compiled. Worksheet S2.10 has been provided to help with this process.

After all the information regarding the raw materials has been reviewed, Worksheet S2.1 will have some sources circled and some sources with an "X" marked through them to reflect which are viewed as likely and unlikely choices, respectively. Suggested ranges of SCMs to be tested for ASR mitigation should be placed on Worksheet S1.1 and compared with the ranges suggested for optimizing the other concrete properties. When ASR is a concern, the minimum levels of SCMs given in the ASR Mitigation Guidelines override the minimum values for all other properties when summarizing each SCM column. The sources and ranges of SCMs for experimental testing will be selected from Worksheets S1.1 and S2.1 in Step 3. Therefore, while working through Step 2, some thought should be given to which sources would be of interest for inclusion in the experimental program.

Guidance on Raw Materials Selection

The following subsections contain background discussions regarding concrete performance requirements, which accompany Figure S2.1.

Cement [C]

Three categories of specifications govern cement types: (1) AASHTO M 85 (ASTM C 150), Standard Specification for Portland Cement; (2) AASHTO M 240 (ASTM C 595), Standard Specification for Blended Hydraulic Cements; and (3) ASTM C 1157, Standard Performance Specification for Hydraulic Cement. There are slight differences between the AASHTO and ASTM specification requirements. Each category will be described separately.

AASHTO M 85 (ASTM C 150) Portland Cement

Worksheet S2.2 can be used to organize the information about various cement sources that may be available for a project. Selected relevant data from AASHTO M 85 (ASTM C 150) specifications have been listed, with notes regarding their importance. The specifications have more requirements than those listed in Worksheet S2.2, and the user should refer to the specifications if needed. Further background information regarding basic information about portland cement is presented in the following subsection.

Chemistry. The main components of portland cement are calcium silicates (i.e., C_2S and C_3S, where C and S represent CaO and SiO_2, respectively), calcium aluminates (i.e., C_3A and C_4AF, where A and F stand for Al_2O_3 and Fe_2O_3, respectively), and calcium sulfate (i.e., $C\bar{S}$, where $\bar{S}$ stands for SO_3) (*11*). Calcium sulfate (mostly gypsum, calcium sulfate dihydrate) is included to control the setting of C_3A, which may cause rapid stiffening (flash setting) of the concrete if not adequately controlled.

Types. Cement is classified by AASHTO M 85 (ASTM C 150) into five types: Type I for normal usage, Type II for moderate sulfate resistance and moderate heat of hydration, Type III for high early strength, Type IV for low heat of hydration, and Type V for high sulfate resistance. Types I, II, and possibly III are used in bridge deck construction. These types of cement are produced by controlling the chemical composition and fineness of the cement. The properties of the cement and its chemistry are regularly tested by the manufacturer and reported on a mill report, which also certifies the cement's conformance to the applicable ASTM or AASHTO standards.

Rate of Hydration. The rate of hydration of cement—and thus the rate at which the concrete produced with the cement sets, generates heat, and gains strength—is governed by cement chemistry and fineness. C_2S, C_3S, and C_3A make up the bulk of cement, and the relative portions of these compounds influence reaction rates and setting: C_3A reacts very quickly with gypsum in a reaction that generates heat and some stiffening. Then the reactions that are responsible for strength begin, and the compounds that participate in this, in order from fastest to slowest, are C_3S, C_3A (influenced by the gypsum), and C_2S (*21, 11*). The more C_3S and C_3A present, the more quickly hydration can be expected to occur. Cements with finer size distributions can also be expected to hydrate more quickly because of the greater surface area exposed to water during mixing.

Cement fineness, the surface area for a given mass, is estimated using AASHTO T 153 (ASTM C 204), Test Method for Fineness of Hydraulic Cement by Air Permeability Apparatus, which measures the Blaine fineness, and AASHTO T 98 (ASTM C 115), Test Method for Fineness of Portland Cement by the Turbidimeter, which measures Wagner fineness. Limits for cement properties obtained using these methods are provided in AASHTO M 85, although Blaine fineness is easiest to measure and most commonly reported. Typical Blaine finenesses range from 350 to 425 m^2/kg for Type I or II cement and 550 m^2/kg for Type III. Fineness measurements give an indication of the relative size of the average cement particle but do not describe the size distribution that may significantly influence the reactivity of the cement and the rheology of the concrete (*55*).

The setting time of cement is measured using AASHTO T 131 (ASTM C 191), Test Method for Time of Setting of Hydraulic Cement by Vicat Needle, and AASHTO T 154 (ASTM C 266), Test Method for Time of Setting of Hydraulic Cement Paste by Gillmore Needles. In the Vicat test, initial and final setting is defined by the time required for a 1-mm diameter needle to penetrate a paste specimen of given consistency to a maximum depth of 15 mm. For the Gillmore test, initial and final set is defined as when needles under 0.25- and 1-lb weights, respectively, can be supported by paste without producing indentations. ASTM C 150 specifies that initial and final setting time for all types of cement be greater than 60 and less than 600 minutes, respectively, when using the Gillmore apparatus and greater than 45 and less than 375 minutes, respectively, when using the Vicat apparatus. Although both tests are used, the correlation between setting time of paste measured using either method and of concrete determined using AASHTO T 197 (ASTM C 403), Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance, is not always consistent, perhaps because of the arbitrary definitions used for initial and final setting (*55*).

As stated, calcium sulfate is used to control the reaction of the C_3A in the cement. The content and form of the calcium sulfate must be balanced with the reactivity of the C_3A, which is influenced by the fineness and other properties of the cement. When not properly balanced, false set (when too much calcium sulfate reacts initially) or flash set (when not enough calcium sulfate reacts with the C_3A) may occur. Stiffening due to false set can be reversed by additional mixing while flash set is irreversible. This balance and the likelihood of early stiffening can be evaluated by testing according to ASTM C 359, Standard Test Method for Early Stiffening of Hydraulic Cement (Mortar Method).

Durability Aspects. The chemistry of the cement also has implications for the long-term durability of the concrete. Certain reactions—such as that of free lime (CaO) and periclase (MgO) which form calcium and magnesium hydroxide, respectively—may occur after the cement has set, resulting in expansive products that may cause concrete cracking. AASHTO M 85 places limits on the amount of MgO that may be present in the cement. In addition, AASHTO T 107 (ASTM C 151), Standard Test Method for Autoclave Expansion of Portland Cement, tests the propensity of the cement for developing expansion; AASHTO M 85 limits acceptable expansion to less than 0.8%.

Sulfate (SO_3) may contribute to a reaction that produces expansive ettringite (DEF or internal sulfate attack); limits for this compound that vary depending on the type of the cement and the amount of C_3A present are defined in AASHTO M 85. While DEF is not fully understood, if temperatures above 150°F (65°C) are developed during initial curing, ettringite that forms from C_3A and sulfate compounds immediately after water and cement are combined may break down. The components that make up ettringite remain in the hardened concrete and reform ettringite over time in the presence of moisture (*21*). Currently, only long-term (2-year or longer) test procedures on heat-cured samples are available to evaluate the risk of DEF. Keeping bridge deck concrete below 150°F (65°C) during the first 4 days of age is recommended in lieu of testing. Internal sulfate attack occurs when there is sufficient sulfate to cause such reaction without heat curing. If internal sulfate attack is a possible deterioration mechanism, the cement can be evaluated according to ASTM C 1038, Standard Test Method for Expansion of Hydraulic Cement Mortar Bars Stored in Water. This method measures the expansion of 1×1×11.25-in. (25×25×286-mm) mortar bars stored in lime-saturated water for 14 days.

The amount of alkali present in the cement is also listed on the mill report in terms of equivalent or total alkali, which represents the contribution of both Na_2O and K_2O. Specific limits on the equivalent alkali (0.6%) are given only if the cement is to be labeled low alkali. The amount of alkali present is significant because a harmful reaction, ASR, occurs between alkali in cement and reactive silica that may be present in the aggregate. The product of this reaction is a gel that expands when wet and can cause damage to the concrete over time. The ASR requires both cement of sufficient alkalinity and aggregate that is reactive, and it can be avoided if either of these conditions is not met. The significance of cement alkalinity should be assessed based on testing of the candidate aggregates, which is a time-consuming process. A procedure for aggregate evaluation is outlined in "Aggregates [A1]." The amount of alkali present in the cement can also affect the reaction rates of the phases of the cement.

AASHTO M 240 (ASTM C 595) Blended Hydraulic Cements

AASHTO M 240 (ASTM C 595) covers the requirements for blended cements. These cements are composed of portland cements pre-blended with GGBFS and/or pozzolans. There are six classes of blended cements:

- Type IS, portland blast furnace slag cement. GGBFS constitutes 25% to 70% by mass of the blended cement.
- Type IP, portland-pozzolan cement. This blend consists of either portland or portland blast furnace slag cement and fine pozzolan. The pozzolan constitutes 15% to 40% by mass of the blended cement.
- Type P, a portland-pozzolan cement. This blend is for use when higher strengths at early ages are not required.
- Type I (PM), pozzolan-modified portland cement. This blend consists of either portland or portland blast furnace slag cement and fine pozzolan. The pozzolan constitutes less than 15% by mass of the blended cement.
- Type I (SM), slag-modified portland cement. GGBFS constitutes less than 25% by mass of a mixture of GGBFS with portland cement.
- Type S, slag cement. GGBFS constitutes at least 70% by mass of a mixture of GGBFS with portland cement.

AASHTO M 240 should be consulted as to the various chemical and physical requirements of blended cements. It is important to obtain from the manufacturer information on both the blend used in the cement (actual quantities of portland cement and types and quantities of SCMs) and, if possible, the chemical and physical composition of the portland cement itself. This information is needed when setting up the test matrix so that duplicate additions of an SCM do not occur inadvertently.

ASTM C 1157 Hydraulic Cement

ASTM C 1157 is a performance specification, and there are no chemical requirements for cements that are manufactured according to this specification (they can include SCMs). The types of cements include the following:

- Type GU for general use
- Type HE for high early strength
- Type MS for moderate sulfate resistance
- Type HS for high sulfate resistance
- Type MH for moderate heat of hydration
- Type LH for low heat of hydration
- Option R for low reactivity with alkali-reactive aggregates

ASTM C 1157 should be consulted for the various physical requirements of these types of hydraulic cements. It is important to obtain from the manufacturer information on both the blend used in the cement (actual quantities of portland cement and types and quantities of SCMs) and, if possible, the chemical and physical composition of the portland cement itself and of the blend.

Supplementary Cementitious Materials

Class C fly ash, Class F fly ash, GGBFS, silica fume, and Class N natural pozzolans are the most common types of SCM used in bridge deck concrete; each is discussed in this section.

Fly Ash [FA]

Fly ash is the finely divided residue created from the combustion of ground or powdered coal in coal-fired electric power–generating plants. When coal is ignited to 2700°F (1500°C), any non-combustible materials melt and form droplets. These droplets are rapidly cooled and then collected from the flue gases. The cooled droplets maintain their spherical shape and can be solid or hollow ranging in size from less than 1 μm to greater than 100 μm with a median size of 5 to 20 μm. The composition of the fly ash depends on the coal source (*4, 21*). AASHTO M 295, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, and ASTM C 618, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, separate fly ash into two classes, Class C and Class F.

Class C Fly Ash

Composition. Class C fly ash originates from subbituminous and some lignite coals. It is generally composed of 50% to 90% calcium aluminosilicate glass manifested as solid and hollow spheres. The crystalline phases include relatively chemically inactive phases such as quartz, mullite, ferrite spinel, and hematite. Some of the more chemically active phases include calcium sulfate, alkali sulfate, C_2S, C_3A, and others. The SiO_2, Al_2O_3, and Fe_2O_3 contents of Class C fly ash are higher than those of Type I portland cement; the CaO content is lower. The CaO content of Class C fly ash is higher than Class F fly ash (typically 10% to 30% versus 0.7% to 7.5%). The carbon contents of Class C fly ash are generally less than 2% and the Blaine fineness is typically about 300 to

450 m^2/kg (comparable to Type I portland cement); its relative density is around 2.5 to 2.7.

Hydration. Class C fly ashes are considered hydraulic materials because they will harden on their own. They also undergo some pozzolanic reactions with the calcium hydroxide product of portland cement hydration. As for portland cement, calcium silicate hydrate is the main hydration product of Class C fly ash. When Class C fly ash is combined with portland cement, the hydration of the fly ash is assisted by the heat and hydroxyl ions generated by the hydrating portland cement, which facilitates the breakdown of the glassy structure of the fly ash. The glassy structure reacts with calcium hydroxide forming calcium silicate hydrate C-S-H.

Specifications. The specifications that govern Class C fly ash are AASHTO M 295 and ASTM C 618. The minimum amount of $SiO_2 + Al_2O_3 + Fe_2O_3$ in Class C fly ash is 50%. There are also chemical requirements for maximum sulfur trioxide, maximum moisture content, and maximum loss on ignition. Mandatory physical requirements include a limit on the amount of material retained when wet sieved on a 45-µm (No. 325) sieve, 7- and 28-day minimum percentage of control strength (strength activity index), maximum water requirement as a percentage of control, maximum autoclave expansion or contraction (soundness), and uniformity. AASHTO M 295 (but not the most recent version of ASTM C 618) gives an optional chemical requirement for the amount of available alkalis that should be specified if the aggregate is potentially reactive. ASTM C 618 suggests that a mortar-bar expansion test be conducted to assess reactivity instead and provides criteria for evaluating the results. There are some optional physical requirements, including a maximum increase in drying shrinkage, maximum difference of AEA required to produce a given air content in a single batch compared to 10 preceding batches, and effectiveness in contributing to sulfate resistance.

Class F Fly Ash

Composition. Class F fly ash originates primarily from burning anthracite and bituminous coals. Like Class C fly ash, it is generally composed of 50% to 90% aluminosilicate glass manifested as solid and hollow spheres. The crystalline phases include relatively chemically inactive phases such as quartz, mullite, ferrite spinel, and hematite. The SiO_2, Al_2O_3, and Fe_2O_3 contents of Class F fly ash are higher than those of Type I portland cement; the CaO content is lower. The CaO content of Class F fly ash is lower than Class C fly ash (0.7% to 7.5% versus 10% to 30%). The carbon contents of Class F fly ash are generally less than 5%, although sometimes it may be as high as 10% and may adversely affect air entrainment. The Blaine fineness of Class F fly ash is on the order of 300 to 450 m^2/kg (comparable to Type I portland cement); its relative density is around 2.3 to 2.4.

Hydration. Class F fly ashes are considered pozzolanic materials that react with the calcium hydroxide from the hydrating portland cement to form additional C-S-H. When Class F fly ash is combined with portland cement, the hydration of the fly ash is assisted by the heat and hydroxyl ions generated by the hydrating portland cement, which facilitates the breakdown of the glassy fly ash structure, allowing the fly ash to react. Class F fly ash hydration products are believed to be more fluid than those of portland cement, thereby filling pores and making the paste more dense and less permeable.

Specifications. The specifications that govern Class F fly ash are AASHTO M 295 and ASTM C 618. The minimum amount of $SiO_2 + Al_2O_3 + Fe_2O_3$ for Class C fly ash is 70%. There are also chemical requirements for maximum sulfur trioxide, maximum moisture content, and maximum loss on ignition. Mandatory physical requirements include a limit on the amount of material retained when wet sieved on a 45-µm (No. 325) sieve, 7- and 28-day minimum percentage of control strength (strength activity index), maximum water requirement as a percentage of control, maximum autoclave expansion or contraction (soundness), and uniformity. As for Class F fly ash, there is an optional chemical requirement on the amount of available alkalis in AASHTO M 295 and a maximum limit on mortar-bar expansion given in ASTM C 618 intended to assess the effectiveness at controlling ASR. There are some optional physical requirements, including a maximum increase in drying shrinkage, maximum difference of AEA required from a control, and effectiveness in contributing to sulfate resistance.

Ground Granulated Blast Furnace Slag [S]

GGBFS, also called slag cement or just slag, is an industrial by-product of the iron-making process in a blast furnace. It occurs when the iron oxides (such as iron ore) are heated to around 2700°F (1500°C). In this process the liquid, metallic iron is separated from the molten slag oxides that float on its surface. The slag is rapidly quenched in water, thereby forming a glassy material. This material is dried and then ground finer than Type I portland cement so that it has a surface area between 400 and 600 m^2/kg as measured by AASHTO T 153 (ASTM C 204); the particles have an angular shape. Because GGBFS is produced simultaneously with a manufactured product, its variability within a source is minimal; however, different plants produce different products, such that the variability between sources can be higher (particularly when comparing GGBFS sources outside North America).

Composition. GGBFS is composed primarily (90% to 95%) of glassy calcium silicates and calcium aluminosilicates. The composition of the calcium silicates is in the same region of the CaO-SiO_2 phase diagram as C_2S. The SiO_2, Al_2O_3, and MgO contents of GGBFS are higher than those of typical Type I cement; Fe_2O_3 and CaO contents are lower. Sulfide sulfur is also a component of GGBFS. The relative density of GGBFS is 2.94.

Hydration. Many GGBFSs will hydrate by themselves, albeit slowly. Some require activators such as alkalis or lime. The principal reaction product of GGBFS is essentially the same as that of portland cement, which is calcium silicate hydrate (*6*). When GGBFS is combined with portland cement, the hydroxyl ions released during portland cement hydration break down the glassy structure of the GGBFS and allow its hydration. GGBFS hydrates are more fluid than those of portland cement, which reduces pore sizes and increases the denseness of the paste.

Specifications. The specification that governs GGBFS is AASHTO M 302 (ASTM C 989), Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars. In this specification, three grades of slag (80, 100, and 120) are defined based on their performance in slag activity tests. These tests compare the compressive strength of 50% slag/portland cement blended mortars to 100% portland cement mortars (specific requirements are stipulated for total alkali content and 28-day compressive strength of the portland cement). The grades refer to the percentage of strength of the slag blended mortars to the reference mortar at 28 days. Grades 100 and 120 are by far the most commonly used for bridge deck concrete.

Other physical requirements in the specification include a limit on the amount of material retained on a 45-µm sieve when wet screened, specific surface by air permeability, and air content of slag mortar. There are chemical requirements for the maximum amount of sulfide sulfur as well as sulfate ion reported as SO_3.

While not specified for slag, the potential for possible future deleterious reactions can be evaluated by testing the slag in combination with the cement at a similar mixture ratio as that expected to be used (as is specified with fly ash) for soundness (autoclave expansion). This test would be conducted in accordance with ASTM C 151, Test Method for Autoclave Expansion of Portland Cement. An appropriate criterion for soundness is that the percentage of change in length should not be more than 0.8%.

Silica Fume [SF]

Silica fume is an industrial by-product, which results from the production of silicon-metal or ferrosilicon alloys at 3632°F (2000°C). It is the material that is condensed from the flue gases of electric arc furnaces that are used to reduce high-purity quartz with coal or coke and wood chips (*7*).

Composition. Silica fume consists of at least 85% silicon dioxide, in an amorphous (non-crystalline) form. Because silica fume is derived from flue gases (similarly to fly ash), the particles are spherical; however, they are extremely small with an average diameter of 0.1 µm or 1/100th of a cement particle. The relative density is 2.2. Silica fume is supplied in a condensed powder form or as slurry in water. Special handling and mixing procedures are needed to assure uniform distribution and to minimize nodules or lumps of silica fume and settling.

Hydration. Silica fume is very reactive because of its small particle size and, when mixed with portland cement, reacts with calcium hydroxide to form C-S-H. It increases the density of the paste because of particle packing as well as its reaction products. It may increase the bond between the paste and aggregate, as well as the density of the interfacial transition zone. The C-S-H based on silica fume has been reported to have a lower calcium/silicon ratio than that made from portland cement alone, which allows it to incorporate ion substitutions into its structure such as alkalis.

Specifications. The specifications that govern silica fume in concrete are AASHTO M 307 and ASTM C 1240, Standard Specification for Silica Fume Used in Cementitious Mixtures. The chemical requirements of this specification restrict the minimum SiO_2 content (85%), the maximum moisture content (3.0%), and the maximum loss on ignition (6.0%). The physical requirements are for oversize particles retained on a 45-µm (No. 325) sieve, accelerated pozzolanic strength activity index (minimum percentage of control is 105% at 7 days), and a minimum specific surface (15 m^2/g). There are optional physical requirements regarding uniformity of the quantity of air-entraining admixture required to produce an air content of 18%, reactivity with cement alkalis, and sulfate resistance.

Natural Pozzolans (Class N)

Types. Diatomaceous earth, high-reactivity metakaolin, and calcined clay are a few of the types of SCMs that are categorized as natural pozzolans.

Diatomaceous Earth. Diatomaceous earth consists of deposits of microscopic algae skeletons, which are composed of silica and have open frameworks. These skeletons are found mostly in western states and are relatively uncommon.

High-Reactivity Metakaolin. High-reactivity metakaolin is formed by heating kaolinite clay ($Al_2O_3{\cdot}2SiO_2{\cdot}2H_2O$) to between 1100°F to 1650°F (600°C and 900°C) such that the chemically combined water is driven off, resulting in an amorphous structure of metastable aluminosilicate ($Al_2O_3 \cdot 2SiO_2$). It is not a by-product material; the source is natural. Metakaolin reacts with calcium hydroxide to form calcium silicate and calcium aluminate hydrates (*14*). Its relative density is 2.5; the average particle size ranges from 0.5 to 20 µm (*4*).

Calcined Clay. The origin of calcined clay is kaolinite mixtures, e.g., 85% kaolinite, 10% quartz, and 5% other clays (*10*). The mixtures are heated to 550–750°C to release chemically bound water, resulting in an amorphous aluminosilicate phase. The composition is 54% SiO_2, 38% Al_2O_3, and 2% Fe_2O_3. The particles are not as fine as metakaolin and can be used with silica fume to reduce permeability. When hydrated, C-S-H is formed as well as ettringite and possibly stratlingite (C_2ASH_8).

Specifications. The specifications that govern Class N pozzolans are AASHTO M 295 and ASTM C 618. The minimum amount of $SiO_2 + Al_2O_3 + Fe_2O_3$ for Class N pozzolan is 70%. There are also chemical requirements for maximum sulfur trioxide, maximum moisture content, and maximum loss on ignition. There is an optional available alkali limit. Mandatory physical requirements include maximum percentage of material retained when wet sieved on a 45-µm (No. 325) sieve, 7- and 28-day minimum percentage of control strength (strength activity index), maximum water requirement as a percentage of control, maximum autoclave expansion or contraction (soundness), and uniformity. There are some optional physical requirements, including a maximum increase in drying shrinkage, maximum difference of AEA required from a control, effectiveness in controlling ASR, and effectiveness in contributing to sulfate resistance.

Aggregates [A1]

AASHTO M 6/80 (ASTM C 33)

AASHTO M 6, Standard Specification for Fine Aggregate for Portland Cement Concrete; AASHTO M 80, Standard Specification for Coarse Aggregate for Portland Cement Concrete; or ASTM C 33, Standard Specification for Concrete Aggregates, defines the requirements for grading and quality of normal weight aggregates. Worksheets S2.3 and S2.4 are provided to help organize test data of the fine and coarse aggregates.

Grading. The grading requirements for coarse aggregate are given in Table 2 of AASHTO M 80. Typically, the largest size aggregate considered appropriate for the application should be used to reduce the concrete paste volume and lower shrinkage and cost. Grading is a measure of the particle size distribution of an aggregate as determined by a sieve analysis. The grading and grading limits are expressed as the percentage of material passing each sieve. Grading of the aggregate affects aggregate and cement proportions and water requirements. It can also affect the workability of the concrete. In general, aggregates with a smooth grading curve will produce the best results.

For highway construction, AASHTO M 43 (ASTM D 448), Standard Classification for Sizes of Aggregate for Road and Bridge Construction, lists the same 13 sieve size numbers as in AASHTO M 80 plus an additional six more coarse aggregate sizes. Fine aggregate has only one range of particle sizes given in AASHTO M 6 (ASTM C 33) as shown in Table S2.1. In leaner mixtures or mixtures with small-size coarse aggregate, the grading that is close to the maximum recommended percentage passing each sieve is most desirable for workability.

AASHTO allows the amounts passing the No. 50 (300 µm) and No. 100 (150 µm) sieves to be reduced to 5% and 0%, respectively, if

- The concrete is air entrained and contains at least 400 lbs of cement per cubic yard (237 kg/m^3), or
- The concrete contains more than 500 lbs of cement per cubic yard (297 kg/m^3), or
- An approved SCM is used to supply this deficiency in the material passing these two sieves.

Other requirements for the fine aggregate are

- Less than or equal to 45% must be retained between any two consecutive sieves and
- The fineness modulus (FM) as calculated by adding the cumulative percentage retained on each designated sieve and dividing by 100 must be between 2.3 and 3.1. The higher the FM, the coarser the aggregate. The FM of the fine aggregate is used to estimate the proportions of the coarse and fine aggregate in the mixture.

AASHTO M 80 (ASTM C 33) allows a wide range in grading. Generally, the amount of cement and water required in a mixture decreases as the maximum size of the coarse aggregate increases because of the decrease in the total aggregate surface area.

The maximum size of the aggregate is the size of the smallest sieve that all of the aggregate will pass through. The nominal maximum size of the aggregate is the size of the smallest sieve through which the major portion of the aggregate will pass. The nominal maximum size sieve may retain 5% to 15% of the aggregate (depending on the size number). For example, the maximum size of a No. 67 aggregate is 1 in. (25 mm) and the nominal maximum size is 0.75 in. (19 mm), because 90% to 100% of this aggregate must pass the 0.75 in. (19 mm) sieve, and 100% must pass the 1 in. sieve.

The maximum size of the aggregate should not exceed

- One-fifth of the narrowest dimension of a concrete member,
- Three-quarters of the spacing between reinforcing bars and three-quarters of the spacing between the reinforcement and forms, and
- One-third the depth of a slab.

Combined Aggregate Grading. An assessment of the combined grading of the coarse and fine aggregate can provide a better indication of the aggregate performance in the concrete. For example, inadequate quantities of mid-size aggregate particles (e.g., 0.375 in. [9 mm]) can result in concrete with poor workability (including poor pumpability), higher water demand, and consequently higher shrinkage characteristics.

A smooth distribution of aggregate sizes, as illustrated in Figure 5-10 of Kosmatka et al. (*21*), represents an optimum type of gradation. Shilstone (*56*) provides suggested options for optimizing grading of aggregate and describes the benefits of a combined aggregate analysis.

Particle Surface Texture. Smooth, rounded aggregate particles are harder to bond to than rough, angular particles. Bond of the cement paste to the aggregate particles is a particularly important consideration for concrete with relatively high flexural strength.

Some SCMs, such as metakaolin and silica fume, improve the transition zone and the bond between cement paste and certain aggregates. Improvement of the transition can help to reduce the permeability of some concretes.

Particle Shape. Because flat and elongated particles require an increase in mixing water that can result in lower strength if the w/c is not adjusted by increasing the cement content, such particles should be limited to 15% by weight of total aggregate. The determination of flat and elongated particles is given in ASTM D 4791, Standard Test Method for Flat Particles, Elongated Particles, and Flat and Elongated Particles in Coarse Aggregate, and a method for providing an index of aggregate particle shape and texture is given in ASTM D 3398, Standard Test Method for Index of Aggregate Particle Shape and Texture.

Soundness. The durability of an aggregate can be assessed by the soundness test. In this test, the aggregate is soaked in 10% sodium sulfate solution or 15% magnesium sulfate solution and then dried. This process is repeated for five cycles to create a salt crystallization (salt hydration) pressure that simulates pressures generated by water freezing in the pores of the aggregate. Although this test has been found to be appropriate for stratified rocks with porous layers or weak bedding planes, it also has been known to give erroneous results for some aggregates. The aggregate can be accepted if it has given satisfactory service when exposed to weathering similar to that to be encountered, or if it gives satisfactory performance when tested in concrete with ASTM C 666, Standard Test Method of Resistance of Concrete to Rapid Freezing and Thawing.

Deleterious Substances

Coarse Aggregate. Deleterious substances described in AASHTO M 80 (ASTM C 33) include clay lumps and friable particles, chert (with a relative density of less than 2.40), material finer than the 75-µm (No. 200) sieve, and coal and lignite. Maximum allowable amounts of these substances are presented in Table 3 of the standard. The allowable amounts of deleterious materials for bridge deck concrete vary depending on the weathering region (exposure) of the structure as shown in Table S2.2.

Fine Aggregate. Table S2.3 lists the recommended limits for deleterious substances in fine aggregate.

AASHTO M 6 and M 80 (ASTM C 33) have limits on deleteriously reactive materials, which will be discussed in the following section on ASR.

Alkali Silica Reactivity [ASR]

According to AASHTO M 80 (ASTM C 33), the aggregate shall not contain any materials that are deleteriously reactive with the alkalis in cement in an amount sufficient to cause excessive expansion of the concrete. Use of the potentially reactive aggregate is not prohibited when used with a cement containing less than 0.60% alkalis, calculated as sodium oxide equivalent ($Na_2O + 0.658\ K_2O$) or with the addition of a material that has been shown to prevent harmful expansion due to the alkali-aggregate reaction. However, many reactive aggregates may react at later ages when used with low-alkali cement.

Laboratory tests for determining whether an aggregate is potentially reactive include ASTM C 295, Standard Guide for Petrographic Examination of Aggregates for Concrete; ASTM C 1260, Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method); ASTM C 1293, Test Method for Determination of Length Change of Concrete Due to Alkali Silica Reaction; ASTM C 289, Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method); ASTM C 227, Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method); ASTM C 441, Test Method for Effectiveness of Mineral Admixtures or Ground Blast Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction; and ASTM C 1567, Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations on Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method).

ASTM C 295 [A2]. ASTM C 295 should be used to determine the type(s) and amount(s) of reactive components. Fine and coarse aggregate containing more than the quantities of the constituents listed in Table S2.4 are considered potentially reactive (*57*).

Materials known to be deleteriously alkali-carbonate reactive include calcareous rocks that contain substantial amounts of relatively large crystals of dolomite scattered in a finer grained matrix of calcite and clay. The acid-insoluble residue of these rocks typically contains a significant amount of clay. Alkali-carbonate test procedures will be discussed in the following section.

Service Record Evaluation [A3]. Before any laboratory tests beyond the petrographic analysis are performed, the historical performance of the aggregate should be reviewed. Valid, comparable concrete service record data, if available, can take precedence over laboratory test results. However, several significant criteria must be met for a truly valid comparable service record, including a satisfactory performance record for at least 10 to 20 years, although longer periods of documented service are often required. For a valid comparison, the composition of the historical concrete mixtures must be similar to the composition of the proposed concrete mixtures with respect to the following:

- Alkali contents of the cements
- Cement content of the concrete
- Water-cement ratio
- Presence and amount of SCMs
- Geological composition of aggregate (preferably as determined by petrographic reports of both historical and current aggregate)

If the similarity of composition cannot be documented to this extent, the service record should not be used as a basis for accepting the aggregate.

Laboratory Testing. If the designer chooses to forgo prescreening, the chosen ASR test performance can be evaluated as part of the full experimental design process. In this case, the chosen mitigation tests must be included as the responses in the experimental design. ASTM C 1260 and ASTM C 1293 are standardized tests, and certain variables such as cement content and w/cm are fixed. Because the results of these standardized tests are independent of cement content and w/cm, keeping these values constant as required will not cause any problems in the analysis of the entire test program defined in the experimental design. Therefore, cement content and w/cm can still be chosen as variables in the experimental design and varied in all tests except those related to ASR.

ASTM C 1260 [A4]. ASTM C 1260 is an accelerated screening test for aggregate that develop deleterious expansions slowly over a long period of time. This test is generally considered overly conservative and some aggregates that perform well in the field have been shown to fail this test. However, such an innocuous result gives good confidence that the aggregate is acceptable for use. Generally accepted expansion limits for this test are as listed in Table S2.5. Figure S2.2 shows a desirability function for ASTM C 1260 generated from the ASTM criteria. This function eliminates mixtures with aggregates that expand beyond the recommended limits and only gives full credit (desirability equal to 1) if the expansion is well below the limits.

Aggregates with expansion greater than 0.10% should be either

- Tested using ASTM C 1293,
- Evaluated based on historical performance (see subsection “Service Record Evaluation”), or
- Reevaluated with mitigating SCMs using ASTM C 1567, Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method).

ASTM C 1293 [A5]. ASTM C 1293 uses an elevated alkali content and the exposure condition of ASTM C 227 (storage over water in a closed container maintained at 100.4 ± 3.6°F [38.0 ± 2°C]). Aggregates with expansions equal to or greater than 0.04% at 1 year are considered potentially deleteriously reactive. ASTM C 1293 is considered to be the most reliable test method for assessing ASR of an aggregate. Its main disadvantage is the length of time (1 year) needed for the testing. Figure S2.3 shows a desirability function for ASTM C 1293 generated from the ASTM criteria. This function eliminates mixtures with aggregates that expand beyond the recommended limits and only gives full credit (desirability equal to 1) if the expansion is well below the limits.

According to the Appendix of ASTM C 33, “When interpreting expansion of laboratory specimens, consideration should be given not only to expansion values at specific ages, but also to the shape of the expansion curve, which may indicate whether the expansion is leveling off or continuing at a constant or accelerating rate.” This statement applies when using ASTM C 1260, ASTM C 1293, or any of the other methods discussed here.

Other Laboratory Testing for ASR

ASTM C 289 (Chemical Method). ASTM C 289 is a relatively rapid screening test (48 hours) that measures quantities of dissolved silica and reduction in alkalinity; it provides helpful information except for some slowly reactive rocks, such as some granite gneiss and quartzite. In addition, “[r]esults may not be correct for aggregates containing carbonates or magnesium silicates, such as antigorite (serpentine), or constituents with late-slow reactivity.” This test is somewhat unreliable and should not be used as the sole determination of aggregate reactivity. If the results indicate deleterious or potentially deleterious reactivity, the aggregate should be tested by using ASTM C 227, ASTM C 1260, or ASTM C 1293.

ASTM C 227 (Mortar-Bar Method for Cement Aggregate Combinations). Expansions measured in this test are generally considered excessive if they exceed 0.10% at 6 months—a not conservative limit for some slowly reactive aggregates. Thus, this method is not suitable for slowly reactive aggregates typically containing strained or microgranulated quartz. Aggregates that may be slowly reactive should be evaluated using ASTM C 1260 or ASTM C 1293.

ASTM C 441. ASTM C 441, Standard Test Method for Effectiveness of Mineral Admixtures or Ground Blast Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction, measures the effectiveness of a mineral admixture or SCM for mitigating excessive expansion due to a potentially reactive aggregate. This test method uses mortar bars as in ASTM C 227. ASTM C 618 provides additional criteria for its use with pozzolans. ASTM C 989, Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars, Appendix X3, describes the use of ASTM C 441 for GGBFS including guidance on interpretation of the results.

Determining the Risk of ASR. A risk-evaluation process for making decisions regarding potentially reactive aggregates has been proposed by Fournier et al. (*58*). This process is based on the assessment of the following factors:

- The degree of reactivity of the particular aggregate
- The size of the concrete element and the environmental conditions it will face
- The expected service life of the structure

For the proposed process, the level of risk for concrete exposed to humid air is rated on a scale of 1 to 4 as shown in Table S2.6.

Reactivity Level. The degree of reactivity of the aggregate is based on ASTM C 1293 and C 1260 testing data as shown in Table S2.7.

Level of Prevention. Based on the risk level and the intended service life, a Level of Prevention was proposed as shown in Table S2.8.

Preventative Measures. Depending on the level of prevention needed, the preventative measures listed in Table S2.9 are recommended. Essentially, these recommendations limit the alkali contributed by the cement, require use of SCMs to control expansion, or both.

Recommended Levels of SCMs for Mitigation. Fournier et al. (*58*) suggest types and quantities of SCMs for ASR mitigation based on experience and previous laboratory investigations. These guidelines consider the level of prevention needed and the composition of the SCM. They suggest that laboratory studies can be used to evaluate the effectiveness of SCMs that do not meet recommended compositional requirements or to evaluate the effectiveness of lower concentrations of the SCMs. Examples of some of their recommendations are listed in Table S2.10.

Summary of ASR Mitigation Guidelines [A6]. If an aggregate is judged to be potentially deleteriously reactive by ASTM C 1260 or C 1293 or by historical performance, the following measures can be taken to mitigate this reaction (these guidelines should be incorporated with the other durability guidelines listed in Worksheet S1.1):

- Use a low-alkali cement (<0.60% Na_2O_{eq}) and/or limit the total alkalinity of the concrete to 1.8 to 3.0 kg/m^3 (3.0 to 5.0 lb/yd^3) based on the risk level and desired service life as previously described.
- Use a blended cement (ASTM C 595 with Table 2 optional mortar expansion requirement) known and tested to mitigate ASR.
- Use a cement meeting performance specification ASTM C 1157 with Option R.
- Use a pozzolanic material shown to be effective in controlling ASR (a minimum of 25% to 30% [by weight of cement] Class F fly ash has been shown to be effective for mitigating ASR).
- Test and use 5% to 8% silica fume by weight of cement (combinations of SCMs must be used if these levels are not effective).
- Test a GGBFS shown to be effective for preventing excessive expansion per ASTM C 989, Appendix X3. ASTM C 989 states a minimum of 40% GGBFS alone "will generally prevent excessive expansion with cements having alkali contents up to 1.0%. . . ."
- Test combinations of SCMs per footnote "c" in Table S2.10.
- Test 10% to 15% replacement of cement by metakaolin (*59*).

The type(s) and quantities of the above SCMs or combinations of SCMs should be tested to evaluate their ability to adequately mitigate deleterious expansion using either test method ASTM C 1567, described in the following section, or ASTM C 1293 with mitigating measures included and performed for 2 years. To be considered effective in the 2-year ASTM C 1293 test, the expansion should be less than 0.04%.

ASTM C 1567 [A7]. ASTM C 1567, Standard Test Method for Determining the Potential Alkali Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method), is based on ASTM C 1260, but allows the addition of SCMs to be tested in an accelerated manner. According to the Appendix of this method, "[c]ombinations of cement, pozzolan or ground granulated blast-furnace slag, and aggregate that expand less than 0.10% at

16 days after casting are likely to produce acceptable expansions when tested in concrete (that is, Test Method C 1293) and to have a low risk of deleterious expansion when used in concrete under field conditions." Furthermore, "[c]ombinations of cement, pozzolan or ground granulated blast-furnace slag, and aggregate that expand more than 0.10% at 16 days after casting are indicative of potentially deleterious expansion. However, the potential for deleterious reaction should be confirmed by testing the same combination of materials in concrete (that is, Test Method C 1293). The expansion may be reduced by retesting the material combination using the pozzolan or ground granulated blast-furnace slag at a higher replacement level."

Alkali-Carbonate Rock Reaction

Alkali-carbonate rock reaction is a mechanism where the alkali from the cement reacts with carbonate forms of aggregate. ASTM C 586, Standard Test Method for Potential Alkali Reactivity of Carbonate Rocks as Concrete Aggregates (Rock-Cylinder Method), is a preliminary screening test to indicate the potential for deleterious expansion of carbonate rocks. Such rock is relatively infrequent. Another test, ASTM C 1105, Standard Test Method for Length Change of Concrete Due to Alkali-Carbonate Rock Reaction, is used to evaluate specific combinations of materials. A cement aggregate combination might be classified as potentially reactive if the average expansion of six specimens is greater than 0.015% at 3 months, 0.025% at 6 months, or 0.300% at 1 year.

ASTM C 1293 (CSA A23.2-26A) is the most suitable test for identifying potentially reactive alkali-carbonate rock aggregate when an unknown cement is to be used. Concrete expansion exceeding 0.04% at 1 year is considered as potentially alkali-carbonate reactive.

Pozzolans generally have not been found to control alkali-carbonate reaction. Mitigation measures include the following:

- Selective quarrying
- Diluting the reactive rock to less than 20% of the aggregate in the concrete
- Using smaller maximum size of the aggregate
- Using very low alkali cement. An alkali limit of 0.60% Na_2O_{eq} may not be adequate to prevent excessive expansion

Air-Entraining Admixtures [AEA]

Air-entraining admixtures are chemicals that, upon being mixed in concrete, stabilize air bubbles into the paste fraction of the concrete. The purpose of air entrainment is for freezing and thawing durability (see Step 1), although entrained air also can improve workability and reduce segregation. The materials typically used for this purpose are Vinsol (wood) resins or combinations of materials such as sulfonated hydrocarbons, wood rosins, and tall oil fatty acid soaps.

The specification governing air-entraining admixture materials is AASHTO M 154 (ASTM C 260), Standard Specification for Air-Entraining Admixtures for Concrete. The physical requirements for the concrete containing the air-entraining admixture include deviation from initial and final setting time of not more than 1 hour 15 minutes (1:15) earlier nor 1:15 later than the control concrete. The compressive strength is required to be at least 90% of the control at 3, 7, and 28 days. The purchaser may also require that the flexural strength at 3, 7, and 28 days be a minimum of 90% of the control. The minimum relative durability factor as measured according to ASTM C 666 cyclic freezing tests is required to be 80%. The bleeding as a fraction of the net amount of mixing water has a limit of 2% over the control.

Chemical Admixtures [CH]

The specification for chemical admixtures is AASHTO M 194 (ASTM C 494), Standard Specification for Chemical Admixtures for Concrete. There are seven types of chemical admixtures:

- Type A, water-reducing
- Type B, retarding
- Type C, accelerating
- Type D, water-reducing and retarding
- Type E, water-reducing and accelerating
- Type F, water-reducing, high range
- Type G, water-reducing, high range, and retarding

For each type of admixture, there are requirements regarding the performance of the concrete in which they are added. These requirements include a maximum deviation of the initial and final times of setting from the control; a minimum percentage of compressive strength of the control at 1, 3, 7, and 28 days, 6 months, and 1 year; a minimum percentage of flexural strength of control at 3, 7, and 28 days; a maximum shrinkage in terms of percentage of control or increase over control; and a minimum relative durability factor. However, admixtures meeting ASTM M 194 can cause unanticipated changes to setting times and shrinkage.

A certificate of compliance to AASHTO M 194 (ASTM C 494) can be requested from the manufacturer. The behavior of the chemical admixture in a specific cementitious blend, or with other chemical admixtures, and at varying dosages can be complicated and is best tested in trial batches. It is recommended that the manufacturer provide data on admixture compatibility with SCMs and other admixtures and review the admixture's effect on strength, setting, and shrinkage.

Example from Hypothetical Case Study

To demonstrate how the worksheets in this step may be used, examples of several completed worksheets are presented in Tables S2.11 through S2.15. According to the procedure outlined in the previous section, Table S2.11 lists all the potential materials considered. Then the properties of the cement sources that were identified, namely "Cemsource 1" and "Cemsource 2," are listed in Table S2.12 (completed Worksheet S2.2). Once all the data were collected for the cements, the sources were compared, and a selection of that material type was made. In this case, "Cemsource 2" was selected because of the comparatively lower alkali content; this selection was denoted by a box drawn around the Source in Table S2.11. A similar process was followed for the fine aggregate using Worksheet S2.3 (see Table S2.13) and "Fineagg manufacturer 2" was selected because of the higher fineness modulus and the better soundness test results; this selection was recorded in Table S2.11. Completed versions of Worksheet S2.5 (Table S2.14) and Worksheet S2.10 (Table S2.15) can be used to perform the same functions for Class C fly ash sources and air-entraining and chemical admixtures. If the user would be interested in testing which Class C fly ash would give the best performance (i.e., using a Class C fly ash as a type factor in the experiment), two Class C fly ash sources could be selected by having boxes drawn around them in Worksheet S2.1 (Table S2.11).

Worksheets for Step 2

Worksheet S2.1. List of available raw materials.

Raw Material	Source 1	Source 2	Source 3	Source 4
Cement				
Fine aggregate				
Coarse aggregate				
Class C fly ash				
Class F fly ash				
Ground granulated blast furnace slag				
Silica fume				
Other SCM				
Air-entraining admixture				
Chemical admixture				
Chemical admixture				
Other:				

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Worksheet S2.2. Cement data.

Test/Property	AASHTO Limit	Cement 1	Cement 2	Cement 3	Cement 4
Manufacturer					
Plant location					
Mill report date					
AASHTO M 85 (ASTM C 150) Cements					
Type					
C_3S (%)[1]	≤ 58 for Type II				
C_2S (%)[2]					
C_3A (%)[3]	≤ 8 for Type II				
Total alkalis (Na_2O_{eq}) (%)[4]	≤ 0.60 for low alkali optional requirement				
SO_3 (%)	3.0 (unless $C_3A > 8\%$, then 3.5 for Type I)[5]				
MgO (%)[6]	≤ 6.0				
Rapid stiffening (y/n)[7]					
AASHTO M 240, ASTM C 595, or C 1157 Cements					
Type					
Portland cement, %					
Second constituent, %					
Third constituent, %					
Fourth constituent, %					

[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.

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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					
Pit location					
Date of last ASTM C 295 petrographic examination					
Primary Mineralogy					
Specific gravity (SSD)					
Absorption capacity (%)					
Clay lumps and friable particles	≤ 3.0% max				
Material finer than 75-µm (No. 200) sieve	≤ 2.0% max, concrete subject to abrasion				
	≤ 3.0% max, all other concrete				
Coal and lignite, concrete where surface appearance is not important	≤ 0.25%, max				
Check meets standard gradation					
Fineness modulus	2.3-3.1				
Organic impurities	Lighter than color standard				
Soundness	Weighted average loss ≤10%*				
Other deleterious substances	Local requirements				
Types and amounts (%) of particles deleteriously reactive with alkalis					
ASTM C 1260 Expansion	<0.10%†				
ASTM C 1293 Expansion	<0.04%†				

* When sodium sulfate is used; 15% when magnesium sulfate is used

† ASTM C 33 requirements

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Worksheet S2.4. Coarse aggregate data.

Test/Property	AASHTO M 80 Class A Requirements[†]	Local Requirements	Coarse Agg. 1	Coarse Agg. 2	Coarse Agg. 3
Manufacturer					
Pit location					
Check meets standard gradation					
Date of last ASTM C 295 petrographic examination					
Primary Mineralogy					
Grading size number					
Specific gravity (SSD)					
Absorption capacity (%)					
Clay lumps and friable particles	≤ 2.0% max.				
Chert*	≤ 3.0% max.				
Sum of clay lumps, friable particles, and chert*	≤ 3.0% max.				
Material finer than 75-µm (No. 200) sieve	≤ 1.0% max.				
Coal and lignite	≤ 0.5% max.				
Abrasion	≤ 50% max.				
Sodium sulfate soundness, 5 cycles	≤ 12% max. **				
Types and amounts (%) of particles deleteriously reactive with alkalis	--				
ASTM C 1260 Expansion	<0.10%[‡]				
ASTM C 1293 Expansion	<0.04%[‡]				

* Less than 2.40 relative density SSD

** 18% max. if magnesium sulfate is used.

[†] These are the most stringent AASHTO M 80 values.

[‡] ASTM C 33 recommendations

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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					
Source/plant location					
SiO_2+Al_2O_3+Fe_2O_3, %	$\geq$ 50.0				
CaO, %					
SO_3, %	$\leq$ 5.0				
Moisture content, %	$\leq$ 3.0				
Loss on ignition, %	$\leq$ 5.0				
Amt. retained when wet-sieved on 45 µm (No. 325) sieve, %	$\leq$ 34				
Strength activity index, 7-day, % of control	$\geq$ 75				
Strength activity index, 28-day, % of control	$\geq$ 75				
Water requirement, % of control	$\leq$ 105				
Soundness: autoclave expansion or contraction, %	$\leq$ 0.8				
Density, variation from average, %	$\leq$ 5				
Percent retained on 45-µm (No. 325) sieve, percentage points from average	$\leq$ 5 of variation				
Available alkalis, %	$\leq$ 1.5				

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					
Source/plant location					
$SiO_2+Al_2O_3+Fe_2O_3$, %	≥ 70.0				
CaO, %					
SO_3, %	≤ 5.0				
Moisture content, %	≤ 3.0				
Loss on ignition, %	≤ 5.0				
Amt. retained when wet-sieved on 45 µm (No. 325) sieve, %	≤ 34				
Strength activity index, 7-day, % of control	≥ 75				
Strength activity index, 28-day, % of control	≥ 75				
Water requirement, % of control	≤ 105				
Soundness: autoclave expansion or contraction, %	≤ 0.8				
Density, variation from average, %	≤ 5				
Percent retained on 45-µm (No. 325) sieve, variation, percentage points from average	≤ 5				
Available alkalis, %	≤ 1.5				

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Worksheet S2.7. Class N natural pozzolan data.

Test/Property	AASHTO M 295 Requirement	Natural Pozzolan 1	Natural Pozzolan 2	Natural Pozzolan 3	Natural Pozzolan 4
Manufacturer					
Source/plant location					
$SiO_2+Al_2O_3+Fe_2O_3$, %	≥ 70				
CaO, %					
SO_3, %	≤ 4.0				
Moisture content, %	≤ 3.0				
Loss on ignition, %	≤ 5.0				
Amt. retained when wet-sieved on 45 µm (No. 325) sieve, %	≤ 34				
Strength activity index, 7-day, % of control	≥ 75				
Strength activity index, 28-day, % of control	≥ 75				
Water requirement, % of control	≤ 115				
Soundness: autoclave expansion or contraction, %	≤ 0.8				
Density, variation from average, %	≤ 5				
Percent retained on 45-µm (No. 325) sieve, percentage points from average	≤ 5				
Available alkalis, %	≤ 1.5				

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					
Source/plant location					
Grade					
Amt. retained when wet-sieved on 45-µm (No. 325) sieve, %	≤ 20				
Specific surface by air permeability (Method C 204)					
Air content of slag mortar, %	≤ 12				
7-day slag activity index, %*	Grade 100: ≥ 75				
	Grade 120: ≥ 95				
28-day slag activity index, %*	Grade 80: ≥ 75				
	Grade 100: ≥ 95				
	Grade 120: ≥ 115				
Sulfide sulfur (S), %	≤ 2.5				
Sulfate ion reported as SO_3, %	≤ 4.0				

*Any individual sample

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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					
Source/plant location					
SiO_2, %	≥ 85.0				
Moisture content, %	≤ 3.0				
Loss on ignition, %	≤ 6.0				
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				

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Worksheet S2.10. Air-entraining agent (AEA) and chemical admixture data.

Test/Property	**AASHTO M 154* or M 194** Value**	**AEA 1**	**AEA 2**	**Chemical Admixture 1**	**Chemical Admixture 2**	**Chemical Admixture 3**
Brand Name	--					
Manufacturer	--					
Chemistry	--					
AEA:						
Initial time of setting, allowable deviation from control, not more than (hr:min)	1:15 earlier nor 1:15 later					
Final time of setting, allowable deviation from control, not more than (hr:min)	1:15 earlier nor 1:15 later					
Compressive strength, % of control at 3, 7 and 28 days	≥ 90					
Chemical admixtures:						
Type	--					
Setting time and other requirements	See Table 1 of ASTM C 494					

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

Figures for Step 2

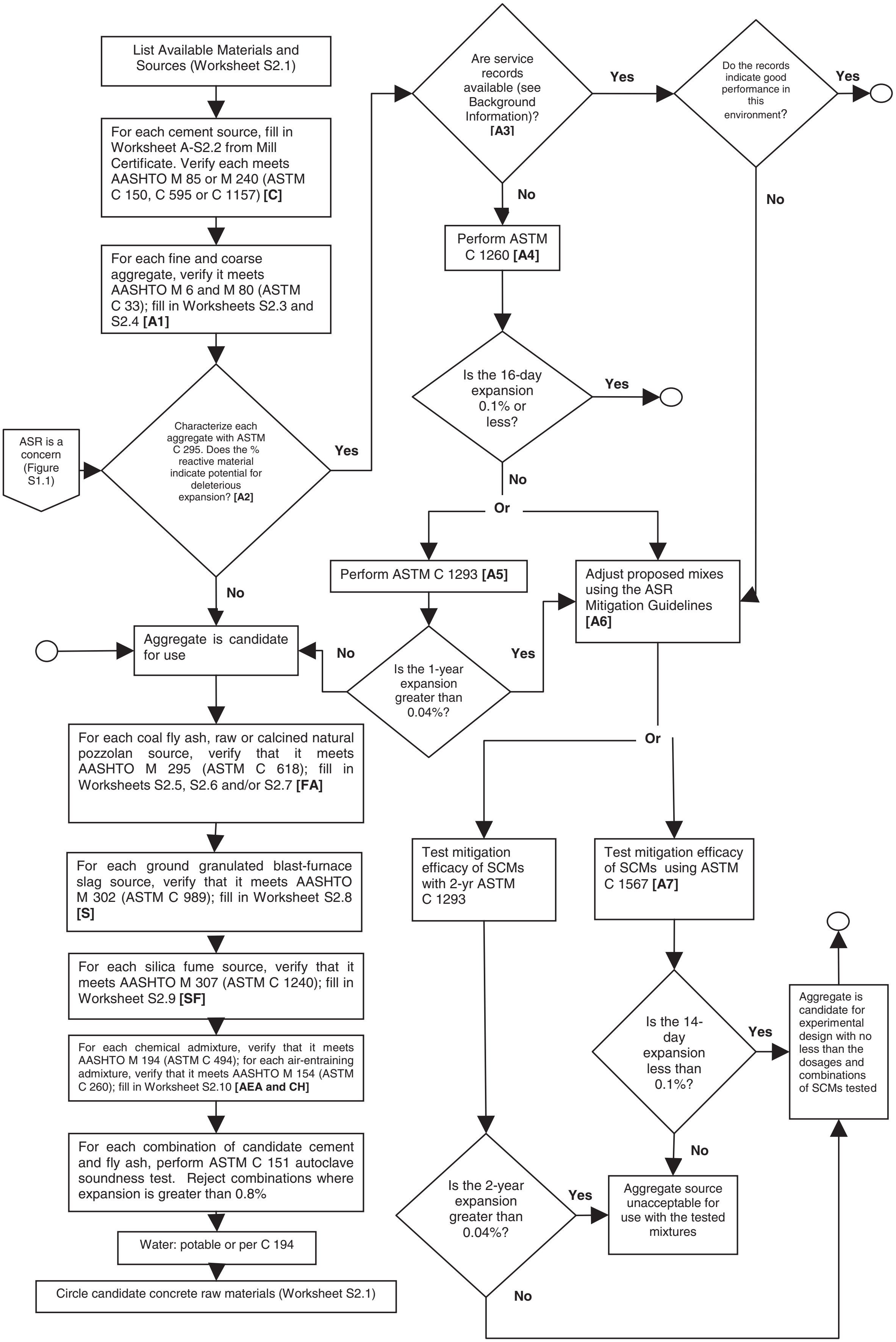

Figure S2.1. Selecting durable raw materials.

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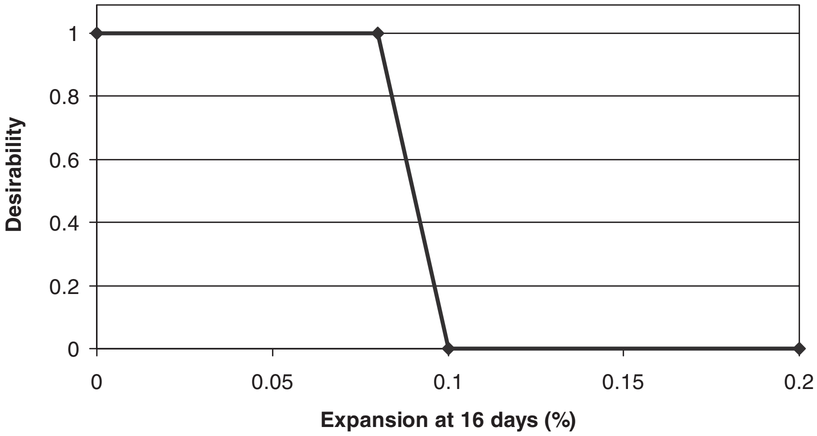

Figure S2.2. Desirability function for ASTM C 1260.

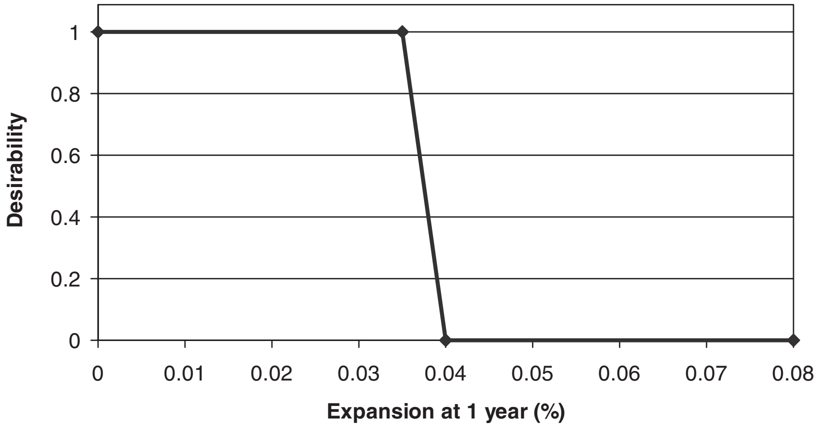

Figure S2.3. Desirability function for ASTM C 1293.

Tables for Step 2

Table S2.1. Grading limits for fine aggregate (AASHTO M 6/ASTM C 33).

Sieve Size	% passing by mass
9.5 mm (3/8 in.)	100
4.75 mm (No. 4)	95 to 100
2.36 mm (No. 8)	80 to 100
1.18 mm (No. 16)	50 to 85
0.6 mm (No. 30)	25 to 60
0.3 mm (No. 50)	5 to 30 (AASHTO 10 to 30)
0.15 mm (No. 100)	0 to 10 (AASHTO 2 to 10)

Table S2.2. Recommended limits (ASTM C 33 and AASHTO M 80) for deleterious substances in coarse aggregates.

Weathering Region*	Maximum allowable, %							
	(1) Clay Lumps and Friable Particles		(2) Chert < 2.4 Specific Gravity		Sum of (1) and (2)		Material finer than 200 mesh sieve	Coal and lignite
	C 33	M 80	C 33	M 80	C 33	M 80	C 33 and M 80	C 33 and M 80
Severe	3.0	2.0	5.0	3.0	5.0	3.0	1.0	0.5
Moderate	5.0	3.0	5.0	3.0	7.0	5.0	1.0	0.5
Negligible	5.0	5.0	**	5.0	**	7.0	1.0	0.5

* The locations of the weathering regions are given in Figure 1 of ASTM C 33.
** No specifications given.

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Table S2.3. Recommended limits (ASTM C 33 and AASHTO M 6 Class A) for deleterious substances in fine aggregates.

Deleterious Substances	Max % by mass	
	ASTM C 33	AASHTO M 6 Class A
Clay lumps and friable particles	3.0	3.00
-200 mesh fraction (for concrete subject to abrasion)	3.0*	2.00
-200 mesh fraction (for all other concrete)	5.0*	3.00
Coal and lignite	1.0	0.25
Other deleterious substances (such as shale, alkali, mica, coated grains, and soft and flaky particles)	—	Specifier shall insert appropriate limits

*For manufactured sand, if -200 mesh (< 74 µm) fraction is free of clay or shale, these limits can be increased to 5% and 7%, respectively—not a category in ASTM C 33.

Table S2.4. Quantities of constituents considered potentially reactive in aggregates.

Constituent	Amount
Optically strained, microfractured, or microcrystalline quartz	5.0%
Chert or chalcedony	3.0%
Tridymite or cristobalite	1.0%
Opal	0.5%
Natural volcanic glass in volcanic rocks	3.0%

Source: Portland Cement Association (*57*)

Table S2.5. ASTM C 1260 limits on expansion.

Expansion at 14 days*	Typical Field Behavior
<0.10%	Innocuous
>0.20%	Potentially deleterious
0.10% to 0.20%	Includes both innocuous and deleterious behavior

* Some aggregates such as granites, gneiss, metabasalts (greenstones) grandodiorites of Grenville age and some horizons of the Potsdam sandstone (upper New York and southwest Quebec) have reacted deleteriously in field concrete, but exhibit less than 0.10% expansion at 14 days.

Table S2.6. Risk levels for concrete exposed to humid air.

Aggregate	Risk Level
Non-reactive	1
Moderately reactive	3
Highly reactive	4

Source: Fournier et al. (*58*)

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Table S2.7. Degree of reactivity of aggregates.

Reactivity Level	ASTM C 1293 % Expansion at 1 year*	ASTM C 1260 % Expansion at 14 days**
Non-reactive	<0.04	<0.15 (0.10 for limestone and certain other aggregates)
Moderately reactive	0.04 to 0.12	—
Highly reactive	>0.12	>0.15 (0.10 for limestone)

* Based on a combination of fine and coarse aggregate intended for use in concrete. If combination result is not available, the result for the most expansive of the aggregates shall be used.

** When ASTM C 1260 and ASTM C 1293 data conflict, the results of the ASTM C 1293 tests should be considered definitive.

Source: Fournier et al. (*58*)

Table S2.8. Level of prevention.

ASR Risk Level	Level of Prevention*		
	< 5 Years of Service Life (Temporary Element)	5 to 50 Years of Service Life	> 50 Years of Service Life
3	V	X	Y
4	W	Y	Z

*V, W, X, Y, Z represent preventative measures described in Table S2.9.

Source: Fournier et al. (*58*)

Table S2.9. Preventative measures.

Prevention Level	Measures to Prevent Deleterious ASR*		
	Limit Alkali Contributed by Portland Cement to (kg of Na_2O_{eq}/m^3 of concrete)**	And/Or	SCM Mitigation
V	—	—	—
W	<3.0	Or	Sufficient SCM to control expansion
X	<2.4	Or	Sufficient SCM to control expansion
Y	<1.8	Or	Sufficient SCM to control expansion
Z	<1.8	**And**	Sufficient SCM to control expansion

* The first option for conditions W through Z is to reject the proposed aggregate. For condition V, accept for use without any preventative measure.

** $lb/yd^3 = 1.686 \times kg/m^3$, % Na2Oeq ≈ $0.043 \times kg/m^3$ for normal weight concrete

Source: Fournier et al. (*58*)

Table S2.10. Recommended levels of SCMs.

Type of SCM	Total Alkali Content of SCM (% Na_2O_{eq})	Composition Requirement	Cement Replacement Level (% mass)[a, c]		
			Prevention Level W	Prevention Level X	Prevention Level Y & Z
Fly Ash (Class F)	<3.0	<8% CaO	15	20	25
	3.0 to 4.5	<8% CaO	20	25	30
GGBFS	<1.0	—	25	35[d]	50[d]
Silica Fume	<1.0	SiO_2 >85%	2.0 × alkali content[b]	2.5 × alkali content[b]	3.0 × alkali content[b, e]

[a] The maximum alkali content of the cement used in combination with the SCMs should be <1.0% Na_2O_{eq}.

[b] Based on the alkali content of the concrete (expressed as kg/m^3 Na_2O_{eq}), except where silica fume is the only SCM when the minimum silica fume content shall be 7.0%.

[c] When two or more SCMs are used together, the sum of the parts of each SCM shall be 1. For example, if silica fume and GGBFS are used together, the silica fume may be reduced to one-third of the recommended amount provided that the GGBFS is at least two-thirds of the minimum GGBFS level recommended.

[d] In some regions, this level of GGBFS is not allowed in deck concrete because of concerns about deicer salt scaling.

[e] Concrete with silica fume additions greater than 5% by weight of cement can be very sensitive to early shrinkage cracking.

Source: Fournier et al. (*58*)

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Table S2.11. Completed Worksheet S2.1, example 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

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Table S2.12. Completed Worksheet S2.2, example of 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]		Remixes out - 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.

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Table S2.13. Completed Worksheet S2.3, example of 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.

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Table S2.14. Completed Worksheet S2.5, example of Class C fly ash data.

Test/Property	AASHTO M 295 Requirements	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) sieve, percentage points from average	≤ 5 of variation	1.3	-0.7		
Available alkalis, %	≤ 1.5	1.05 (total 2.13)	(total 2.64)		

Table S2.15. Completed Worksheet S2.10, example of air entraining agent (AEA) and chemical admixture data.

Test/Property	AASHTO 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	Polycarboxylate	
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	
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

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STEP 3

Generate the Experimental Design Matrix

Introduction

The application of statistically based experimental design enables investigating a test space containing a large number of possible combinations of factors with a relatively small number of tests. The goal of this methodology is to conduct an experiment to determine the combination of the available and appropriate raw materials that will best produce the desired performance in a concrete mixture. The method requires mixing and testing several different concrete mixtures.

In this step, the experimental matrix (i.e., the specific factors to be investigated and the selected subset of the possible combinations for actual testing) will be chosen and tradeoffs will be made between desired and practical properties. The user should understand this step completely before trying to apply this portion of the methodology. Many approaches to the design and analysis of such experiments are possible; the "Orthogonal Design Method" is recommended. The method requires a minimum number of mixtures (usually 8 to 18) for a reasonably comprehensive investigation, while still allowing statistical modeling to predict the performance of mixtures that were not actually tested.

Several methods for designing experiments to select concrete mixtures together with their strengths and weaknesses (especially compared with the Orthogonal Design Method) follow:

- **Expert Opinion Method.** In this method, experts look at the available materials and the potential levels of the factors and identify a number of different concrete mixtures that are likely to perform well based on the experts' experience and knowledge. Samples of these mixtures are then cast and evaluated, and the concrete that performs the best is chosen. This method can produce many potentially very different types of mixtures, allowing for several chances of choosing a good mixture. Also, the number of mixtures is easily selected without constraints. However, if none of the chosen mixtures turn out to be acceptable, predicting how to adjust the mixtures to achieve better performance is difficult. Also, investigating a limited number of mixes may not produce the optimum mixture.
- **One-Factor-at-a-Time Method.** In this method, experts select a single mixture, called the "control mixture," that is most likely to perform well. One factor is then varied from its level in the control mixture, and a new mixture (with only that factor changed) is cast and tested. The number of mixtures needed can be easily calculated because one additional mixture is needed for each two-level factor, and two additional mixtures are needed for each three-level factor being considered. Some prediction of the performance of future mixtures can be made because each factor's effect can be estimated using the mixtures with that varied factor. However, because only two mixtures (or three mixtures in the case of a three-level factor) are used to estimate the factor effects, the estimates and prediction are likely to be quite poor. Also, because only one factor is varied at a time, the mixtures that are actually cast and tested are quite similar to each other and thus have a relatively high chance of all producing poor results if the control mixture is ill-chosen. In addition, for durability-based investigations that involve long-term testing, subsequent mixtures are not selected until testing is completed on the previous mixture, making this method probably the least-suited for development of mixtures where durability is a main objective.
- **Orthogonal Design Method.** This method will be applied in this research and is recommended for most situations where there are a moderate number of factors to be studied, the number of mixtures is limited (typically 8 to 16 mixtures for three to seven factors), and reasonably good prediction of the performance of future mixtures is needed. In this method, a statistically designed experiment matrix that contains a list of mixtures to be tested is chosen. The recommended design will be an orthogonal, main effects design (for brevity, called orthogonal designs). Orthogonal

designs are created so that each factor level is balanced with every other factor level such that an independent estimate of each factor effect is possible. The method allows for relatively simple statistical analysis and reasonably good estimates of the factor effects because all mixtures are used in the estimation of each factor effect. Also, because all factors are varied simultaneously, mixtures are likely to be quite different from each other, thus increasing the chance of finding a good mixture. The factor effects are estimated with much more precision than in the one-factor-at-a-time method, and thus it is much more likely to be able to predict a new (untested) mixture that has good or better performance than the tested mixtures.

- **A Response Surface Method.** This method is an in-depth study that requires more mixtures (17 to 31 mixtures for three to five factors) than the other methods. This method is appropriate if the goal is to truly optimize the mixture (with less regard for high testing cost and time requirements). This method is most likely to find the truly optimal mixture, but it requires a very large number of mixtures in most practical cases, making it less attractive to many practitioners. In addition, this method requires a high level of statistical sophistication to apply.

In Step 1 (through the use of Figure S1.1 and Worksheet S1.1), the user will have identified the service environment, the appropriate concrete performance and testing requirements, and reviewed the guidance on the influence of SCMs on these properties. In Step 2, the user will have summarized the durable sources of raw materials in Worksheet S2.1 and excluded some of these sources. (Excluded sources should have an "X" marked through them on Worksheet S2.1.) The information in Worksheets S1.1 and S2.1 will now be combined into Worksheet S3.1, which summarizes the potential factors and levels that could be tested in the orthogonal design experiment. Finally, the potential choices in Worksheet S3.1 will be narrowed down to a final selection of factors and levels to actually be tested, based on available time and resources.

Generation of the Experimental Matrix

The following steps should be followed to fill out Worksheet S3.1 with the potential factors and levels (this list will be trimmed later based on the practical constraints of the investigation):

1. Type Factors (information from Worksheet S2.1)
   a. Any time that different types of materials are to be substituted for each other in different mixtures, a type factor should be created that describes the general category of the materials being substituted. For example, if different types of SCM (like slag or fly ash) are to replace each other in different mixtures, then a type factor called "Type of SCM" should be created. The levels of the type factor are the material names to be used as the SCM (if there is more than one SCM used in any mixture, the SCMs could be designated as the first SCM, the second SCM, etc.). The example presented in this step demonstrates the use of type factors for two SCMs.
   b. If there are two material sources to be chosen as a type factor, their names should be filled in as Levels 1 and 2 of that type factor on Worksheet S3.1, and Level 3 is left blank. If there are three material sources, they become the Levels 1 through 3 for that type factor.
   c. After filling out the row for the new type factor, the user places an asterisk beside the type that is most likely to perform very well in this application (if known). If there is high confidence that one of the types is best, then the user places a double asterisk next to that type. The asterisks will be useful later because some design matrices use certain levels more often than others. In these cases, levels that are expected to perform very well will be tested more often.
2. Source Factors (information from Worksheet S2.1)
   a. Any row in Worksheet S2.1 that has more than one source should be copied into the "Source Factors" section of Worksheet S3.1 (sources excluded by an "X" should be ignored). The name of the factor should consist of the material name and "Source." For example, if Class C fly ash has two sources, then a new source factor named "Class C fly ash Source" is to be created in Worksheet S3.1.
   b. If there are two sources to be investigated as a source factor, their names should be filled in as Levels 1 and 2 of that source factor, and Level 3 is left blank. If there are three sources, they become the Levels 1 through 3 for that source factor.
   c. After filling out the row for the new source factor, the user places an asterisk beside the source that is most likely to perform very well in this application (if known). If there is high confidence that one of the sources is best, then the user places a double asterisk next to that source.
   d. The previous steps are repeated for all rows in Worksheet 2.1 that have more than one source listed.
3. Amount Factors (information from Worksheet S1.1)
   a. Any column in Worksheet S1.1 that has a range of possible amounts in the summary should become a row in the "Amount Factors" section of Worksheet S3.1.
   b. The column heading and "Amount" (such as "Class F fly ash Amount") become the new amount factor name.

   c. Note: If two levels are examined in an amount factor, a trend can be established to describe the influence of the factor. However, testing three levels provides the ability to determine an optimum (pessimum) level for that factor. For this reason, it is most advantageous if SCMs are tested at three levels.
   d. The user observes the range of amounts listed for the new amount factor in Worksheet S1.1. If the best performance is clearly expected at one or the other end of the range, then this factor should be assigned two levels. Typically, Level 1 will be the bottom of this range, and Level 2 will be the top of the range; however, any two values in the range can be selected.
   e. If the best performance of a particular factor is likely to be at an amount somewhere inside the range listed in Worksheet S1.1, then that factor should be a three level factor. Level 1 will be the bottom of this range, Level 2 will be the middle of the range, and Level 3 will be the top of the range. However, for practical considerations, the number of three-level factors should be kept to a minimum, because three-level factors will increase the required testing.
   f. After filling out the row for the new amount factor, the user places an asterisk beside the level that is most likely to perform well in this application (if known). If there is high confidence that one of the levels is best, then the user places a double asterisk next to that amount.
   g. The previous steps are repeated for all columns in Worksheet S1.1 that have a range listed in the summary box.
4. Compound Factor (information from Worksheet S1.1)
   a. A compound factor is actually two factors: a type factor and an amount factor that work together to define different amounts for different materials. This is possible because, for the purposes of the experiment, the amount factor is defined generically. However, the generic definition is different for each level of the associated type factor. For example, suppose that Factor 1 is a type factor for SCM, and its levels are fly ash or slag. Factor 2 then is selected as an amount factor whose levels are low and high. The amounts specified for low and high for each type of SCM can be different. 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 Factor 2 change (from 15% and 40% to 25% and 50%) depending on the level of Factor 1 (either fly ash or slag).

      The reason for using a compound factor is that it allows more than one type of SCM to be used interchangeably while still testing at appropriate levels for that specific SCM. Without a compound factor, it would only be possible to set a type factor as multiple types of SCM and an amount factor at certain levels, but then those levels would apply to all of the SCM types. Relying on this non-compound factor is potentially problematic because, for example, slag is typically used at higher contents than fly ashes. While this greater flexibility may be of value in some situations, using compound factors adds to the complexity of the data analysis. In addition, the modeling is performed on each factor individually, and so the responses from all mixtures with the same generic amount definition will be averaged together even if the specific definitions are quite different. The modeling can still be performed on the amount factor component of the compound factor to allow interpolation; however, the levels must be scaled over an artificial range so the analysis can be performed over the same ranges. (More discussion on the analysis is given in Step 5.)
   b. For compound factors, the type factor and the amount factor will be named as before; however, the amounts to be used for each type must be separately specified. Worksheet S3.2 should be used to create a compound factor from a type factor and an amount factor. Examples are provided in the “Example from Hypothetical Case Study” section of this chapter.
5. Type Constants (information from Worksheet S2.1)
   a. Type constants are those types of materials that are not to be investigated but are part of the mixture. These types of materials are not varied but are constant throughout the test.
   b. Type constants are recorded at one level only. For example, if only Type I cement is to be used, the type constant would be “type of cement,” and the only level to be recorded in Worksheet S3.1 would be Type I. The previous steps are repeated for all rows in Worksheet S2.1 that have a single type listed.
6. Source Constants (information from Worksheet S2.1)
   a. Source constants are materials that are not to be investigated but are part of the mixture. These materials are not varied but are constant throughout the test.
   b. Any row in Worksheet S2.1 that has only one source should be copied into the “Source Constants” section of Worksheet S3.1 (sources excluded by an “X” should be ignored). The name of the constant should consist of the material name and “Source.” For example, if Class C fly ash has only one source, then a new source constant named “Class C fly ash Source” should be created in Worksheet S3.1.
   c. The single source should be copied into a “Source Constant” row. This single source will be used for all mixtures that include this material. These steps should be repeated for all rows in Worksheet S2.1 that have a single source listed.

7. Amount Constants (information from Worksheet S1.1)
    a. Amount constants are those types of materials that are not to be investigated but are part of the mixture. These types are not varied but are constant throughout the test.
    b. Any column in Worksheet S1.1 that has a single (nonzero) value in the summary box at the bottom of the column should become a row in the "Amount Constants" section of Worksheet S3.1.
    c. The column heading and "Amount" (such as "Class F fly ash Amount") will become the new amount constant name.
    d. The value in the summary box in Worksheet S1.1 should be entered in the "Amount Constant" row. This value will be the amount of this material in all mixtures tested. If there is a zero in the summary box in Worksheet S1.1, then this material will be left out of all mixtures that are to be tested. Repeat for all columns in Worksheet S1.1 that have a single value listed in the summary box.

Considerations in Selecting the Number of Mixtures

Worksheet S3.1 should now summarize the potential factors and levels that could be tested in the statistically designed experiment. Worksheet S3.1 is then used to determine how many factors and levels can actually be tested when the number of test mixtures is limited because of time or budget constraints.

Because the testing of any given concrete involves many tests and a great deal of time, the number of different concrete mixtures to be tested must be chosen carefully to reduce cost while still obtaining valid conclusions regarding the effect of each factor. Performing more testing will almost always provide more information; however, use of a statistical design will help determine the minimum amount of testing necessary to produce the information needed for determining the best mixture possible. The tradeoffs between the size of the experiment and the number of factors and levels that can be studied is discussed in this section.

In addition to cost consideration, the number of concrete mixtures that can be examined relates to the shape of the experimental matrix because, for a specific number of factors and mixtures to be tested, only certain matrices qualify as orthogonal designs. Table S3.1 lists the minimum number of mixtures that are needed for an orthogonal design matrix with various combinations of two-level and three-level factors, including 4-, 8-, 9-, 12-, 16- and 18-mixture designs. For example, for a combination of three three-level factors and six two-level factors, 16 mixtures are needed for an orthogonal design. However, this number must be reduced if testing 16 mixtures is beyond the project budget.

When reconciling the number of potential factors on Worksheet S3.1 with the amount of testing required, the user must consider the factors perceived to be the most important, the combinations that are likely to give the best performance, and the materials that are expected to provide a sufficiently wide scope of the experiment and maximize the chances of finding an optimum mixture. The two main options for reducing the number of mixtures are as follows:

1. **Reduce a three-level factor to a two-level factor.** An experiment with two three-level factors and three two-level factors will require a 16-mixture experiment. However, as shown in Table S3.1, an 8-mixture orthogonal design will accommodate one three-level factor and four two-level factors, which is close to the original experiment. The best way to convert a three-level factor to a two-level factor is to choose the two levels that are most likely to provide good performance. This approach restricts the range of the factor around the most promising area and often provides a good tradeoff against testing a large number of mixtures. In Worksheet S3.1, any three-level factor that has a level marked with two asterisks is a good candidate for being reduced to two levels. When a three-level factor is to be reduced to a two-level factor, the user will eliminate one of the levels in Worksheet S3.1 by drawing "X" through that level or changing the levels as desired.
2. **Hold some factors constant.** To reduce testing further, the user may consider eliminating some factors. Eliminating a factor is achieved by holding this factor constant in all tested mixtures at the level that the user feels is best (this level could be, but need not be, zero). The factors marked with double asterisks in Worksheet S3.1 would be good candidates for being held constant. In the example discussed previously, if one of the two-level factors is held constant, a 9-mixture orthogonal array is available for two three-level factors and two two-level factors. In this case, an "X" should be drawn through all the levels for that factor except one on Worksheet S3.1.

Another means for reducing the cost of the program while maintaining the same number of possible mixtures is to reduce the number of responses to be evaluated. Although Step 1 was designed to identify those tests that are relevant to the service environment, it is possible that some tests could be eliminated if the performance could be evaluated based on some other means. For example, freezing and thawing resistance could be assumed based on the presence of an adequate air void system in the hardened concrete. Because this is an assumption, the user may want to return to this test after the Best Concrete has been selected or perhaps during the confirmation testing to be conducted in Step 6. Also, the electrical conductivity (AASHTO T 277/ASTM C 1202) test, which actually measures conductivity not permeability, is often used to evaluate chloride penetration resistance instead of the longer-term diffusion testing as a means for reducing cost and time. However, this approach is not recommended because the correlation between the two tests is mixture dependent, and the diffusion test provides a better representation of chloride ion penetration conditions occurring in the field.

Selection of the Design Matrix

The next step is to set up a design matrix with the selected factors and levels. It is an iterative process that involves selecting the factors, their levels, and the number of mixtures and usually requires some discussion and tradeoffs. Ultimately, the many possible alternatives must be reduced to a specific set of factors that will be included at a specific set of levels. When this decision is reached, Worksheet S3.1 should be fully updated by drawing an "X" through all levels of factors that are not to be used in the mixtures. Table S3.1 then can be used to determine the number of mixtures that must be made. The section titled "Selected Orthogonal Design Matrices" presents generic orthogonal design matrices for every combination of two-level and three-level factors that can be accommodated in 4-, 8-, 9-, 12-, 16-, and 18-mixture orthogonal designs. These tables show the combinations of levels for the factors that should be tested in each of the mixtures to be produced. The levels are referred to generically as 1, 2, or 3, so that the specific levels can be substituted in these tables.

The following example explains how the shape of the design matrix is chosen and how the mixtures to be tested are defined. Suppose that two three-level factors and three two-level factors are considered for the experiment. Table S3.1 shows that 16 mixtures are needed for an orthogonal design with these factors. If this number of mixtures was determined to be too many, one of the three-level factors could be reduced to a two-level factor and thus an 8-mixture matrix will accommodate the one three-level factor and four two-level factors. Table S3.2 (reproduced from "Selected Orthogonal Design Matrices") shows the generic 8-mixture matrix defined to accommodate this experiment. The selected levels of each factor are referred to as Levels 1, 2, and 3 for the three-level factor and Levels 1 and 2 for the two-level factors. The specific levels are then substituted into Table S3.2 for the level number under the factor to which they correspond; the table then defines the mixtures to be tested. This process is described in "Example from Hypothetical Case Study" using actual factor and level names.

The tables of design matrices are applicable to a range of two-level factors; the two-level factor columns should be disregarded if they are not needed. For example, the matrix in Table S3.2 would also be used if there were one three-level factor and only three two-level factors, but the last column would simply be ignored. Note that the SEDOC tool discussed in Step 5 supports only selected design matrices and does not permit dropping factors.

After the generic design matrix is selected, a few more steps must be completed to customize the design matrix for use in a particular application:

1. Map the factors and their remaining levels in Worksheet S3.1 to specific columns of the generic design matrix. Sometimes a factor column in the design matrix has one level that appears more often than the others. That level should be shown in bold and underlined. For example, Level 2 is used four times in the first column of Table S3.2, and Levels 1 and 3 are only used twice each. The user should recognize this and use it to include more desirable levels in more of the mixtures. If there is a factor column that has Level 2 twice as often as Level 1, a factor that has a double asterisk on one of its levels should be chosen for that column if possible. The level with the double asterisk (or at least a level with a single asterisk) should be mapped to Level 2.
2. Sometimes orthogonal designs suggest concrete mixtures that are recognized by an experienced user as having some highly undesirable characteristics (such as very low workability). Therefore, the user should carefully check the overall reasonableness of the mixtures being proposed by the matrix after choosing a matrix and mapping the factor and levels onto it. If some mixtures appear to be undesirable there are several possible corrections:
    a. Adjust the mapping of the levels or factors to avoid the undesirable mixture.
    b. Reevaluate the factors, levels, and matrix selection until all mixtures seem viable and likely to be suitable concrete for the intended application. This step attempts to bring some of the strengths of the Expert Opinion Method into the Orthogonal Design Method.

Experimental Details

Mixture Proportioning and SCM Level Definition

The amount of a particular SCM in a mixture is described as the percentage replacement of cement or as an addition, and the percentage is calculated in terms of mass or in terms of volume. It is probably most common to consider a percentage replacement by weight and follow the guidelines of ACI Committee 211 (*59*) for developing the mixture proportions using the method of absolute volume mixture design. In this method, air content is chosen to meet a certain type of exposure condition, the water content is selected to produce the desired slump, and the w/cm is chosen based on a target strength or durability requirements. In combination, the water content and w/cm determine the cementitious materials content. The coarse aggregate content is chosen based on the fineness modulus of the fine aggregate and the size of the coarse aggregates. Then, the balance of material required to produce a unit volume of concrete—after considering the volume of the predefined contents of cementitious materials, water, air and coarse aggregate—is made up with fine aggregate.

Because many properties of the concrete ingredients, such as the aggregate shape and gradation, are not explicitly included in this process, trial mixtures are batched in the laboratory to verify that the mixture is workable and appropriate for field use and to adjust the mixture proportions if necessary. In the setting of this methodology, only the factors included in the design matrix are varied during the Step 4 test program to eliminate complicating influences on performance.

The dosage rates of admixtures are typically reported as volume per weight of cement, such as ounces per 100 lbs of cement (oz/cwt) or milliliters per 100 kg of cement. The addition of other cementitious materials raises the question of whether they should be included in the dosage calculation (i.e., oz/cwt of total cementitious material). For example, superplasticizers are thought to act primarily on the surface of cement grains while AEAs, in general, act in the paste and water/air interfaces, suggesting not including them in the former case but including them in the latter. Nevertheless, admixture dosage should be reported in a consistent manner.

The number of potential factors to be held constant for an experiment targeted at studying the effect of SCM contents is large; recommendations for factors such as w/cm and cement content can be found in the literature (*56, 60*).

Control Mixtures

A control mixture made with no SCMs but with similar other mixture characteristics may be included in the study. This mixture would provide a comparison to assess relative performance of mixtures with SCMs to conventional concrete or to a mixture currently in use.

Repeat Testing

A replicate of the control mixture or another mixture may be added to provide an assessment of batch-to-batch variability. Such a replicate will give the user a basis for evaluating whether the differences in measured responses on the concrete mixtures result are due to differences in the concrete or to test variations.

Example from Hypothetical Case Study

This example shows how the design matrix is selected based on recommendations from Steps 1 and 2 summarized in Worksheets S1.1 and S2.1. The completed Worksheet S1.1 (Table S1.8) suggests that a large test program was necessary to characterize each mixture's performance but it was constrained (by the available budget) to a 9-mixture experiment. This number of mixtures controls the possible number of factors and levels to be evaluated as listed in Table S3.1.

The next step is to select the factors and levels to include. 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 (Table S3.3). The factors and levels to be varied in the design matrix for the hypothetical case study were selected using the top half of Worksheet S3.1, completed as Table S3.4. While not apparent based on this table, several sets of factors and levels were proposed for testing, before the final selection shown was made. The specific factors for testing were chosen as "First SCM Type," "First SCM Amount," "Amount of Silica Fume," and "w/cm."

Once the factors were selected, the range of investigation for each of the factors was chosen to span the upper and lower bounds where the optimum level is expected. For the example Worksheet S1.1 completed for Step 1 (Table S1.8), 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 F fly ash (25%). Because the objective of this research is to study SCMs, the test program was centered on the summary values shown in Table S1.8. For example, the levels for amount of silica fume were chosen to be 0%, 5%, and 8% (although the summary row of Table S1.8 recommends only 5%). Similarly, w/cm's of 0.37 and 0.45 were included (although the summary of the level of w/cm from Table S1.8 recommended that the w/cm be less than 0.40).

Ordinarily, an amount factor such as "First SCM Amount" would have simple numerical values given as levels. However, because the appropriate ranges for types of SCMs are dependent on that type, a compound factor was used. This factor links the definition of the amount factor to a type factor and allows flexibility 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 was 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 an amount factor and the performance models are capable of interpolating between the levels tested.

The definitions of low, medium, and high were determined with Worksheet S3.2, which is completed in Table S3.5. (An example of a compound factor based on two type levels and two amount levels is given in Table S3.6.)

After the factors and levels to be varied are chosen, the type, source and amount constants must be defined for the experiment. These characteristics of the mixture proportions will remain consistent throughout the experiment. For example, this step may include defining a constant cementitious content (658 lb/yd^3 [391 kg/m^3]) and a constant coarse aggregate amount (1696 lb/yd^3 [1007 kg/m^3]).

In summary, the top half of Table S3.4 lists the factors and levels for the hypothetical case study, while the bottom half of this table defines the constant values selected for this experiment. Table S3.5 defines the specific quantities for the general descriptions "low," "medium," and "high" used in the compound factor.

The orthogonal design in this example 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 "Selected Orthogonal Design Matrices." The generic design matrix that applies for the 9-mixture (three three-level factor and one two-level factor) design is given in Table S3.7. The factors chosen in the top half of Table S3.4 were numbered Factor 1 to Factor 4 and the levels for each were also numbered Level 1 to Level 3. Table S3.8 lists the specific design matrix after the factor levels were substituted into the generic matrix according to this numbering. The batch weights for the mixtures to be tested corresponding to the selected levels and based on the source and amount constants are listed in Table S3.9. All SCM amounts were calculated as percentages by weight replacement of portland cement and changes in cementitious volumes were compensated by changes in fine aggregate content.

Worksheets for Step 3

Worksheet S3.1. Factors and levels to test.

Factor	Level 1	Level 2	Level 3	
				Type Factors
				Source Factors
				Amount Factors
				Type Constants
				Source Constants
				Amount Constants

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Worksheet S3.2. Compound factor table.

Factor 1, Factor 2	Type	Amount
Type 1, Low Level		
Type 1, Medium Level		
Type 1, High Level		
Type 2, Low Level		
Type 2, Medium Level		
Type 2, High Level		
Type 3, Low Level		
Type 3, Medium Level		
Type 3, High Level		

Tables for Step 3

Table S3.1. Number of mixtures required for an orthogonal design for various combinations of two- and three-level factors.

Number of 2-Level Factors	Number of 3-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

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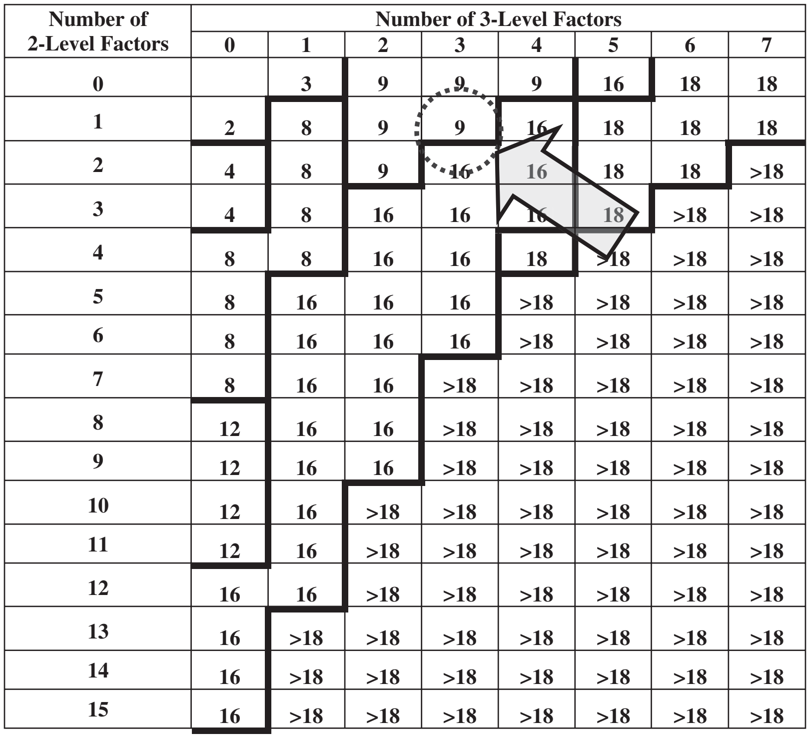
Table S3.2. An 8-mixture design matrix for one three-level and four two-level factors.

Mixture	Factor 1 (3-Level)	Factor 2 (2-Level)	Factor 3 (2-Level)	Factor 4 (2-Level)	Factor 5 (2-Level)
1	1	1	1	2	2
2	**2**	1	2	1	2
3	**2**	1	2	2	1
4	3	1	1	1	1
5	1	2	2	1	1
6	**2**	2	1	2	1
7	**2**	2	1	1	2
8	3	2	2	2	2

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

Table S3.3. Selection of the 9-mixture design selected for the hypothetical case study.



Number of 2-Level Factors	Number of 3-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

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Table S3.4. 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 S3.5. An example of Worksheet S3.2 filled out for a compound factor of three type levels and three amount levels.

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 S3.6. An example of Worksheet S3.2 filled out for a compound factor of two type levels and two amount levels.

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

Note: Type 3 and medium are ignored because each factor only has two levels.

Table S3.7. The levels for the 9-mixture design matrix with three three-level factors and one two-level factor.

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	**2**
3	1	3	3	**2**
4	2	1	2	**2**
5	2	2	3	1
6	2	3	1	**2**
7	3	1	3	**2**
8	3	2	1	**2**
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.

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Table S3.8. 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 S3.9. Trial mixture designs.

Material	Batch Weights (lb/yd^3)								
	Mixture 1	Mixture 2	Mixture 3	Mixture 4	Mixture 5	Mixture 6	Mixture 7	Mixture 8	Mixture 9
Water	296	243	243	243	296	243	243	243	296
Cement	559	461	342	526	441	395	441	428	296
Class C Fly Ash	99	165	263	0	0	0	0	0	0
Class F Fly Ash	0	0	0	99	165	263	0	0	0
GGBFS	0	0	0	0	0	0	165	230	329
Silica Fume	0	33	53	33	53	0	53	0	33
Fine Aggregate	1180	1300	1280	1294	1128	1261	1302	1316	1156
Coarse Aggregate	1696	1696	1696	1696	1696	1696	1696	1696	1696

Selected Orthogonal Design Matrices

A 4-mixture design matrix for two to three two-level factors.

Mixture	Factor 1 (2-Level)	Factor 2 (2-Level)	Factor 3 (2-Level)
1	1	1	1
2	2	1	2
3	1	2	2
4	2	2	1

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

An 8-mixture design matrix for four to seven two-level factors.

Mixture	Factor 1 (2-Level)	Factor 2 (2-Level)	Factor 3 (2-Level)	Factor 4 (2-Level)	Factor 5 (2-Level)	Factor 6 (2-Level)	Factor 7 (2-Level)
1	1	1	1	2	2	2	1
2	2	1	1	1	1	2	2
3	1	2	1	1	2	1	2
4	2	2	1	2	1	1	1
5	1	1	2	2	1	1	2
6	2	1	2	1	2	1	1
7	1	2	2	1	1	2	1
8	2	2	2	2	2	2	2

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

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An 8-mixture design matrix for one three-level factor and one to four two-level factors.

Mixture	Factor 1 (3-Level)	Factor 2 (2-Level)	Factor 3 (2-Level)	Factor 4 (2-Level)	Factor 5 (2-Level)
1	1	1	1	2	2
2	**2**	1	2	1	2
3	**2**	1	2	2	1
4	3	1	1	1	1
5	1	2	2	1	1
6	**2**	2	1	2	1
7	**2**	2	1	1	2
8	3	2	2	2	2

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

A 9-mixture design matrix for two three-level and up to two two-level factors.

Mixture	Factor 1 (3-Level)	Factor 2 (3-Level)	Factor 3 (2-Level)	Factor 4 (2-Level)
1	1	1	1	1
2	1	2	**2**	**2**
3	1	3	**2**	**2**
4	2	1	**2**	**2**
5	2	2	**2**	1
6	2	3	1	**2**
7	3	1	**2**	**2**
8	3	2	1	**2**
9	3	3	**2**	1

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

A 9-mixture design matrix for three three-level factors and one two-level factor.

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	**2**
3	1	3	3	**2**
4	2	1	2	**2**
5	2	2	3	1
6	2	3	1	**2**
7	3	1	3	**2**
8	3	2	1	**2**
9	3	3	2	1

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

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A 9-Mixture Design Matrix for four three-level factors.

Mixture	Factor 1 (3-Level)	Factor 2 (3-Level)	Factor 3 (3-Level)	Factor 4 (3-Level)
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

A 12-mixture design matrix for 8 to 11 two-level factors.

Mixture	Factor 1 (2-Level)	Factor 2 (2-Level)	Factor 3 (2-Level)	Factor 4 (2-Level)	Factor 5 (2-Level)	Factor 6 (2-Level)	Factor 7 (2-Level)	Factor 8 (2-Level)	Factor 9 (2-Level)	Factor 10 (2-Level)	Factor 11 (2-Level)
1	2	2	2	2	2	2	2	2	2	2	2
2	1	2	1	2	2	2	1	1	1	2	1
3	1	1	2	1	2	2	2	1	1	1	2
4	2	1	1	2	1	2	2	2	1	1	1
5	1	2	1	1	2	1	2	2	2	1	1
6	1	1	2	1	1	2	1	2	2	2	1
7	1	1	1	2	1	1	2	1	2	2	2
8	2	1	1	1	2	1	1	2	1	2	2
9	2	2	1	1	1	2	1	1	2	1	2
10	2	2	2	1	1	1	2	1	1	2	1
11	1	2	2	2	1	1	1	2	1	1	2
12	2	1	2	2	2	1	1	1	2	1	1

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

A 16-mixture design matrix for 12 to15 two-level factors.

Mixture	Factor 1 (2-Level)	Factor 2 (2-Level)	Factor 3 (2-Level)	Factor 4 (2-Level)	Factor 5 (2-Level)	Factor 6 (2-Level)	Factor 7 (2-Level)	Factor 8 (2-Level)	Factor 9 (2-Level)	Factor 10 (2-Level)	Factor 11 (2-Level)	Factor 12 (2-Level)	Factor 13 (2-Level)	Factor 14 (2-Level)	Factor 15 (2-Level)
1	1	1	1	1	1	1	2	2	2	1	2	1	2	2	1
2	2	1	2	1	1	2	2	2	1	1	1	2	1	2	2
3	1	2	2	1	1	1	1	2	2	2	1	2	2	1	2
4	2	2	1	1	1	2	1	2	1	2	2	1	1	1	1
5	1	1	1	2	1	2	1	1	1	2	1	2	2	2	1
6	2	1	2	2	1	1	1	1	2	2	2	1	1	2	2
7	1	2	2	2	1	2	2	1	1	1	2	1	2	1	2
8	2	2	1	2	1	1	2	1	2	1	1	2	1	1	1
9	1	1	1	1	2	2	2	1	2	2	1	1	1	1	2
10	2	1	2	1	2	1	2	1	1	2	2	2	2	1	1
11	1	2	2	1	2	2	1	1	2	1	2	2	1	2	1
12	2	2	1	1	2	1	1	1	1	1	1	1	2	2	2
13	1	1	1	2	2	1	1	2	1	1	2	2	1	1	2
14	2	1	2	2	2	2	1	2	2	1	1	1	2	1	1
15	1	2	2	2	2	1	2	2	1	2	1	1	1	2	1
16	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

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A 16-mixture design matrix for 1 three-level factor and 5 to 12 two-level factors.

Mixture	Factor 1 (3-Level)	Factor 2 (2-Level)	Factor 3 (2-Level)	Factor 4 (2-Level)	Factor 5 (2-Level)	Factor 6 (2-Level)	Factor 7 (2-Level)	Factor 8 (2-Level)	Factor 9 (2-Level)	Factor 10 (2-Level)	Factor 11 (2-Level)	Factor 12 (2-Level)	Factor 13 (2-Level)
1	1	1	1	1	2	2	2	1	2	1	2	2	1
2	**2**	1	1	2	2	2	1	1	1	2	1	2	2
3	**2**	1	1	1	1	2	2	2	1	2	2	1	2
4	3	1	1	2	1	2	1	2	2	1	1	1	1
5	1	2	1	2	1	1	1	2	1	2	2	2	1
6	**2**	2	1	1	1	1	2	2	2	1	1	2	2
7	**2**	2	1	2	2	1	1	1	2	1	2	1	2
8	3	2	1	1	2	1	2	1	1	2	1	1	1
9	1	1	2	2	2	1	2	2	1	1	1	1	2
10	**2**	1	2	1	2	1	1	2	2	2	2	1	1
11	**2**	1	2	2	1	1	2	1	2	2	1	2	1
12	3	1	2	1	1	1	1	1	1	1	2	2	2
13	1	2	2	1	1	2	1	1	2	2	1	1	2
14	**2**	2	2	2	1	2	2	1	1	1	2	1	1
15	**2**	2	2	1	2	2	1	2	1	1	1	2	1
16	3	2	2	2	2	2	2	2	2	2	2	2	2

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

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A 16-mixture design matrix for two three-level factors and three to nine two-level factors.

Mixture	Factor 1 (3-Level)	Factor 2 (3-Level)	Factor 3 (2-Level)	Factor 4 (2-Level)	Factor 5 (2-Level)	Factor 6 (2-Level)	Factor 7 (2-Level)	Factor 8 (2-Level)	Factor 9 (2-Level)	Factor 10 (2-Level)	Factor 11 (2-Level)
1	1	1	2	2	1	1	2	2	1	2	1
2	**2**	1	1	2	1	2	1	2	2	1	2
3	**2**	1	2	1	2	1	2	1	2	1	2
4	3	1	1	1	2	2	1	1	1	2	1
5	1	**2**	2	1	2	2	1	2	1	1	2
6	**2**	**2**	1	1	2	1	2	2	2	2	1
7	**2**	**2**	2	2	1	2	1	1	2	2	1
8	3	**2**	1	2	1	1	2	1	1	1	2
9	1	**2**	1	2	2	2	2	1	2	1	1
10	**2**	**2**	2	2	2	1	1	1	1	2	2
11	**2**	**2**	1	1	1	2	2	2	1	2	2
12	3	**2**	2	1	1	1	1	2	2	1	1
13	1	3	1	1	1	1	1	1	2	2	2
14	**2**	3	2	1	1	2	2	1	1	1	1
15	**2**	3	1	2	2	1	1	2	1	1	1
16	3	3	2	2	2	2	2	2	2	2	2

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

A 16-mixture design matrix for three three-level factors and two to six two-level factors.

Mixture	Factor 1 (3-Level)	Factor 2 (3-Level)	Factor 3 (3-Level)	Factor 4 (2-Level)	Factor 5 (2-Level)	Factor 6 (2-Level)	Factor 7 (2-Level)	Factor 8 (2-Level)	Factor 9 (2-Level)
1	1	1	3	2	2	1	1	1	1
2	**2**	1	**2**	1	2	2	2	2	1
3	**2**	1	**2**	2	1	2	2	1	2
4	3	1	1	1	1	1	1	2	2
5	1	**2**	**2**	1	2	2	1	2	2
6	**2**	**2**	1	2	2	1	2	1	2
7	**2**	**2**	3	1	1	1	2	2	1
8	3	**2**	**2**	2	1	2	1	1	1
9	1	**2**	**2**	2	1	1	2	2	2
10	**2**	**2**	3	1	1	2	1	1	2
11	**2**	**2**	1	2	2	2	1	2	1
12	3	**2**	**2**	1	2	1	2	1	1
13	1	3	1	1	1	2	2	1	1
14	**2**	3	**2**	2	1	1	1	2	1
15	**2**	3	**2**	1	2	1	1	1	2
16	3	3	3	2	2	2	2	2	2

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

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A 16-mixture design matrix for four three-level factors and one to three two-level factors.

Mixture	Factor 1 (3-Level)	Factor 2 (3-Level)	Factor 3 (3-Level)	Factor 4 (3-Level)	Factor 5 (2-Level)	Factor 6 (2-Level)	Factor 7 (2-Level)
1	1	1	3	**2**	1	2	1
2	**2**	1	**2**	3	2	1	1
3	**2**	1	**2**	**2**	2	2	2
4	3	1	1	1	1	1	2
5	1	**2**	**2**	3	1	1	2
6	**2**	**2**	1	**2**	2	2	2
7	**2**	**2**	3	1	2	1	1
8	3	**2**	**2**	**2**	1	2	1
9	1	**2**	**2**	1	2	2	2
10	**2**	**2**	3	**2**	1	1	2
11	**2**	**2**	1	3	1	2	1
12	3	**2**	**2**	**2**	2	1	1
13	1	3	1	**2**	2	1	1
14	**2**	3	**2**	1	1	2	1
15	**2**	3	**2**	**2**	1	1	2
16	3	3	3	3	2	2	2

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

A 16-mixture design matrix for five three-level factors.

Mixture	Factor 1 (3-Level)	Factor 2 (3-Level)	Factor 3 (3-Level)	Factor 4 (3-Level)	Factor 5 (3-Level)
1	1	1	3	**2**	**2**
2	**2**	1	**2**	3	**2**
3	**2**	1	**2**	**2**	3
4	3	1	1	1	1
5	1	**2**	**2**	3	1
6	**2**	**2**	1	**2**	3
7	**2**	**2**	3	1	**2**
8	3	**2**	**2**	**2**	**2**
9	1	**2**	**2**	1	3
10	**2**	**2**	3	**2**	1
11	**2**	**2**	1	3	**2**
12	3	**2**	**2**	**2**	**2**
13	1	3	1	**2**	**2**
14	**2**	3	**2**	1	**2**
15	**2**	3	**2**	**2**	1
16	3	3	3	3	3

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

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An 18-mixture design matrix for four three-level factors and four two-level factors.

Mixture	Factor 1 (3-Level)	Factor 2 (3-Level)	Factor 3 (3-Level)	Factor 4 (3-Level)	Factor 5 (2-Level)	Factor 6 (2-Level)	Factor 7 (2-Level)	Factor 8 (2-Level)
1	1	1	1	1	1	1	1	1
2	1	2	3	3	1	**2**	**2**	1
3	1	3	2	3	**2**	1	**2**	1
4	1	2	2	1	**2**	**2**	1	2
5	1	3	1	2	**2**	**2**	**2**	2
6	1	1	3	2	**2**	**2**	**2**	2
7	2	2	2	2	**2**	**2**	1	1
8	2	3	1	1	**2**	**2**	**2**	1
9	2	1	3	1	**2**	**2**	**2**	1
10	2	3	3	2	1	1	1	2
11	2	1	2	3	1	**2**	**2**	2
12	2	2	1	3	**2**	1	**2**	2
13	3	3	3	3	**2**	**2**	1	1
14	3	1	2	2	**2**	1	**2**	1
15	3	2	1	2	1	**2**	**2**	1
16	3	1	1	3	**2**	**2**	1	2
17	3	2	3	1	**2**	1	**2**	2
18	3	3	2	1	1	**2**	**2**	2

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

An 18-mixture design matrix for five three-level factors and one to three two-level factors.

Mixture	Factor 1 (3-Level)	Factor 2 (3-Level)	Factor 3 (3-Level)	Factor 4 (3-Level)	Factor 5 (3-Level)	Factor 6 (2-Level)	Factor 7 (2-Level)	Factor 8 (2-Level)
1	1	1	1	1	1	1	1	1
2	1	2	3	3	1	**2**	**2**	1
3	1	3	2	3	2	1	**2**	1
4	1	2	2	1	3	**2**	1	2
5	1	3	1	2	3	**2**	**2**	2
6	1	1	3	2	2	**2**	**2**	2
7	2	2	2	2	2	**2**	1	1
8	2	3	1	1	2	**2**	**2**	1
9	2	1	3	1	3	**2**	**2**	1
10	2	3	3	2	1	1	1	2
11	2	1	2	3	1	**2**	**2**	2
12	2	2	1	3	3	1	**2**	2
13	3	3	3	3	3	**2**	1	1
14	3	1	2	2	3	1	**2**	1
15	3	2	1	2	1	**2**	**2**	1
16	3	1	1	3	2	**2**	1	2
17	3	2	3	1	2	1	**2**	2
18	3	3	2	1	1	**2**	**2**	2

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

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An 18-mixture design matrix for six three-level factors and one to two two-level factors.

Mixture	Factor 1 (3-Level)	Factor 2 (3-Level)	Factor 3 (3-Level)	Factor 4 (3-Level)	Factor 5 (3-Level)	Factor 6 (3-Level)	Factor 7 (2-Level)	Factor 8 (2-Level)
1	1	1	1	1	1	1	1	1
2	1	2	3	3	1	2	**2**	1
3	1	3	2	3	2	1	**2**	1
4	1	2	2	1	3	3	1	2
5	1	3	1	2	3	2	**2**	2
6	1	1	3	2	2	3	**2**	2
7	2	2	2	2	2	2	1	1
8	2	3	1	1	2	3	**2**	1
9	2	1	3	1	3	2	**2**	1
10	2	3	3	2	1	1	1	2
11	2	1	2	3	1	3	**2**	2
12	2	2	1	3	3	1	**2**	2
13	3	3	3	3	3	3	1	1
14	3	1	2	2	3	1	**2**	1
15	3	2	1	2	1	3	**2**	1
16	3	1	1	3	2	2	1	2
17	3	2	3	1	2	1	**2**	2
18	3	3	2	1	1	2	**2**	2

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

An 18-mixture design matrix for seven three-level factors and one two-level factor.

Mixture	Factor 1 (3-Level)	Factor 2 (3-Level)	Factor 3 (3-Level)	Factor 4 (3-Level)	Factor 5 (3-Level)	Factor 6 (3-Level)	Factor 7 (3-Level)	Factor 8 (2-Level)
1	1	1	1	1	1	1	1	1
2	1	2	3	3	1	2	2	1
3	1	3	2	3	2	1	3	1
4	1	2	2	1	3	3	1	2
5	1	3	1	2	3	2	2	2
6	1	1	3	2	2	3	3	2
7	2	2	2	2	2	2	1	1
8	2	3	1	1	2	3	2	1
9	2	1	3	1	3	2	3	1
10	2	3	3	2	1	1	1	2
11	2	1	2	3	1	3	2	2
12	2	2	1	3	3	1	3	2
13	3	3	3	3	3	3	1	1
14	3	1	2	2	3	1	2	1
15	3	2	1	2	1	3	3	1
16	3	1	1	3	2	2	1	2
17	3	2	3	1	2	1	2	2
18	3	3	2	1	1	2	3	2

If not all factors are needed, unused columns can simply be ignored. If the font is underlined and bold, the level chosen for that factor should be the one expected to produce the best result.

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STEP 4

Perform Testing

Introduction

In Step 1, the performance requirements are selected, and a battery of tests to evaluate that performance is identified. In Step 2, locally available raw materials that are expected to produce durable concretes are selected, and in Step 3 specific combinations of those materials are selected to form a statistically based experimental design. The objective of Step 4 is the generation of performance data for the selected combinations of materials as laid out in the experimental design matrix. Thus, in Step 4, the actual concrete is made and evaluated.

Test Program Considerations

The quality of the predictions made by the methodology is related to the quality of the data collected. Therefore, the tests must be conducted so that they are consistent from mixture to mixture and in such a way that the test conditions permit prediction of actual in-place exposure performance as closely as possible. Also, the laboratory personnel conducting the testing are expected to be familiar with the test methods and to follow these methods closely.

Although users of this methodology are expected to be experienced in trial batching concrete mixtures, the following suggestions are presented for emphasis:

- **Keep constant all properties that are not tested directly.** Certain properties of the concrete influence other performance. While those properties may be included in the analysis, if feasible, they should be held as constant as possible. For example, the air content of the concrete has a significant influence on the strength, elastic modulus, and freezing and thawing resistance, and the slump may have an effect on the permeability. Both of these properties likely affect the finishability and can be controlled by admixture dosage. A target value with a tight range of acceptability on these values should be selected during trial batching to allow direct comparisons of performance or durability properties.
- **Use trial batches to determine admixture contents.** Trial batches can be used to determine the admixture dosages required to keep non-investigated properties of the concrete that may influence performance in other tests within a small range. Because the response of concretes containing SCMs to chemical admixtures varies, multiple trial batches will be required to achieve the desired range of fresh properties of each of the concrete mixtures.
- **Ensure consistency of materials.** Consistency of cementitious materials may vary over the length of time required to batch the various mixtures and perform this test program. Therefore, sufficient materials to complete the work should be collected at the beginning of the test program. Also, because the water content of the concrete can have a profound effect on the concrete performance, the moisture content of the aggregates should be determined throughout the test program and compensated for during batching. In addition, consistency should be maintained in terms of test personnel if possible, particularly for those methods where some subjective evaluation is necessary (i.e., scaling testing) or where slight changes in the method may influence the results.
- **Follow a consistent mixing process that simulates actual batching procedures.** ASTM C 192, Standard Practice for Making and Curing Concrete Tests Specimens in the Laboratory, provides a basis for producing the specimens for testing. The order of admixture addition should be the same as anticipated for actual production. The objective of the test program must be considered. For example, for testing heat of hydration, preconditioning of materials at similar temperatures is essential to obtain meaningful data.

Example from Hypothetical Case Study

The test program outlined in Step 1 (listed in the completed Worksheet S1.1 [Table S1.8]) was conducted on the mixtures selected in Step 3 and listed in Table S3.8 for the hypothetical case study.

STEP 5

Analyze Test Results and Predict the Optimum Mixture Proportions

Introduction

After all the data from the individual tests conducted as part of Step 4 have been collected, the tested mixtures are compared in this step using the framework of desirability functions developed in Step 1. In addition, for each individual test method, the response versus the factors tested is modeled. These models are used to predict the performance of potential concrete mixtures that were not tested but are within the range of the levels analyzed.

The goal of the modeling is to use the trends in the data to identify mixtures that have not yet been tested but may give improved performance. When a limited amount of data is available for each factor level, as is the case in the type of experiments outlined in this methodology, using a complicated model is not warranted. A simple model that compares the average performance of each response at each factor level would be adequate for predicting a set of "best" factor levels.

A model that matches the characteristics of the data should be chosen. For example, a model for predicting the strength of the concrete should never predict negative values. In addition, the data collected should be chosen carefully to meet the model requirements. For example, because the models use the average response at each factor level, the same amount of comparable data should be collected for each of the levels of a factor. This parity is needed because the orthogonal experimental designs require that each level of each factor is used the same number of times in combination with each level of the other factors.

Finally, before the model is used to predict the response of mixtures that have not been tested, the accuracy of its predictions should be evaluated for the mixtures for which results are available. The coefficient of determination (R^2) in standard regression analysis is a measure of how well the model fits the collected data; a similar concept will be used to assess the fit of our models.

The objective of this step is to analyze the test results to find the Best Tested Concrete (BTC) and the Best Predicted Concrete (BPC). The BTC is the concrete mixture that best meets the performance criteria as described by the desirability functions. The BPC is a concrete mixture that may not be in the design matrix (and thus has not been tested) but is likely to perform better than the BTC according to the statistical model. The Best Concrete (BC)—the concrete mixture that is recommended for the application—will be either the BTC or the BPC; it will be selected after the confirmation testing that is done in Step 6.

Analysis Process

The analysis depends heavily on the desirability functions that were introduced earlier. For each test performed on the concrete, there must be a desirability function that rates any feasible test result from that test on a scale from 0 to 1, where 0 means that the test result is unacceptable, and 1 means that there is no room for improvement. The analysis process is summarized as follows:

1. Review data to check for errors and to check for expected trends.
2. Review or create a desirability function for each test performed. These desirability functions must match the needs of the application for which this mixture is being developed.
3. Convert each test result from each concrete into an individual desirability using the desirability function for that test.
4. Calculate the overall desirability for each concrete mixture in the design matrix. The overall desirability is the geometric mean of the individual desirabilities for that concrete mixture. (This is discussed in the next section.)
5. Select the BTC as the concrete in the test matrix that has the highest overall desirability.

6. Create a regression model for each test response so that results can be predicted for concrete mixtures with factor settings that do not appear in the matrix.
7. Select the BPC as the mixture that has the highest predicted overall desirability from all the potential concrete mixtures in the test space. A proposed optimization process is given below:
    a. Select a factor setting for each factor to produce a combination of factor levels that does not necessarily appear in the design matrix. (The settings should probably be within the range tested during Step 4 of the methodology. Using the models to extrapolate beyond the tested range is computationally possible but should only be used if supported by additional testing.)
    b. Use the regression model for each response to predict the test results for that mixture.
    c. Convert each of these predicted test results into predicted individual desirabilities using the desirability functions.
    d. Calculate the predicted overall desirability for this hypothetical mixture as the geometric mean of the predicted individual desirabilities.
    e. Repeat Steps 7a through 7d on a large grid of potential concrete mixtures, and choose the one that has the highest overall desirability.
8. Perform the confirmation testing and final selection in Step 6.

The implementation of the design matrix and the analysis of the resulting data can be done in commercial statistical packages such as Minitab® or Design Expert®. However, a substantial amount of data manipulation and modeling will be required to use these packages. Otherwise, users may use SEDOC—the customized Microsoft® Excel–based tool and the user's guide available on the TRB website (http://www.trb.org/news/blurb_detail.asp?id=7714).

Data Plots and Verification

An important part of any data analysis is to plot the data to verify their reasonableness and that they are correctly entered into the software that will be used for the analysis. Before making any calculations, the user should at least observe simple scatter or trend plots of each response versus each factor. This check will likely uncover any gross typographical errors (like typing in 1000 instead of 100) and will also allow the knowledgeable practitioner to see if data show expected trends. For example, increasing the w/cm is well known to decrease the strength of the concrete mixture. If a plot does not indicate that the data follow this trend, then an investigation should be done to determine if errors occurred.

An example of a scatter plot that follows an expected trend is given in Figure S5.1. The trend simply connects the average strength of the mixtures with a w/cm of 0.37 with the average strength of the mixtures with a w/cm of 0.45. This plot shows that Mixture #6 has a fairly low strength despite having a low w/cm. Some quick checks would be appropriate to make sure that the data for Mixture #6 were correctly entered. Once the user is satisfied that the data are correctly observed and entered into the analysis tool, computational and statistical analysis can begin.

Desirability Functions and Individual Desirabilities

The desirability function for a particular performance test rates any feasible test result on a scale from 0 to 1. Step 1 provides example desirability functions for most common concrete performance tests that can be used to calculate an individual desirability for any concrete mixture. The example desirability function for 56-day strength, Figure S5.2, shows that the individual desirability for Mixture #6 in the hypothetical case study that has a 56-day strength of about 4500 psi (31.0 MPa) is 0.87.

The desirability function shown in Figure S5.2 indicates that a 56-day strength between 3500 and 4000 psi (24.1 and 27.6 MPa) is marginal, a 56-day strength between 4000 and 5500 psi (27.6 and 37.9 MPa) is generally acceptable, and a 56-day strength between 5500 and 8500 psi (37.9 and 58.6 MPa) is considered to be perfect (with no room for improvement and no preference for a strength greater than 8500 psi [58.6 MPa]). This function has been designed to give a lower desirability to concrete that is too strong because of its potential for early-age cracking.

A desirability function has to be created for every property that is to be evaluated in the design matrix. The suggested default desirability functions are piecewise linear functions, i.e., the function consists of line segments connecting various vertices (corner points). However, users can define the functions in different forms. The SEDOC tool has a separate worksheet for each performance test and contains the corner points for the sample desirability functions. The location of the corner points is easily changed by typing over the old corner points or eliminating unwanted corner points. For example, if there was an advantage in being as close to 8500 psi (58.6 MPa) as possible, the fourth corner point might be changed to 5500 psi (37.9 MPa) and 0.8 desirability (from 5500 psi [37.9 MPa] and 1.0 desirability), yielding the desirability function shown in Figure S5.3 that gives a desirability equal to 1 only at 8500 psi (58.6 MPa).

After the appropriateness of all the desirability functions for each of the performance tests is determined (based on an evaluation of the test and performance requirements), every test response from each mixture is converted into an individual desirability. Each concrete mixture in the test matrix will have a calculated individual desirability for each performance test. Once again, it would be desirable to examine the individual desirabilities to make sure that they appear to be reasonable. Comparing the range of calculated individual desirability values and the range of measured test responses can help in evaluating the appropriateness of the desirability function and in making adjustments to the desirability function to better fit the data response range or importance.

Overall Desirability

The overall desirability for each mixture is the geometric mean of the individual desirabilities for that mixture for each of the tests. For example, if only three performance tests were run on each mixture and the individual desirability values for the three different tests on Mixture #1 are represented by d_1, d_2, and d_3, the overall desirability, D, for Mixture #1 is given by $D = \sqrt[3]{d_1 \times d_2 \times d_3}$. In general for n desirabilities, the overall desirability is the nth root of the product of the individual desirabilities. Because the desirabilities range between 0 and 1, the overall desirability also ranges between 0 and 1, where 0 is unacceptable, and 1 is desirable. Therefore, if a single response results in a desirability of 0, the overall desirability will also be 0. If this situation occurs and it does not seem appropriate, the individual desirability function must be adjusted. In addition, for a fair comparison of overall desirability for each mixture, all mixtures must have an individual desirability calculated for each response included.

Best Tested Concrete

The first part of the analysis is to compare the concrete mixtures in the design matrix to identify the mixture providing the best performance characteristics, the BTC. Selection of the BTC will be guided by comparison of overall desirabilities but ultimately should be confirmed by review of the actual test results and verification that this mixture is best suited to the application. The SEDOC tool automatically calculates the individual desirabilities from the raw test data and then combines them into an overall desirability for each mixture. The following cases explain how the BTC is selected:

- If there is one mixture that clearly stands out as having the best overall desirability with a relatively high overall desirability value (close to 1), this mixture will probably be considered the BTC. Nevertheless, the user should review the individual desirabilities and test results for each of the tests to confirm that the performance of this mixture is good in all tests. If it is confirmed, then this mixture should be called the BTC.
- If there are several mixtures with high overall desirabilities, the user should investigate the individual desirabilities and test results for each of these mixtures. The user may also reevaluate the desirability functions based on more information or consideration of the importance of the various test results. The mixture that is considered to best match the performance characteristics at minimum cost should be selected as the BTC.
- If none of the mixtures has a high overall desirability, the desirability functions must be reevaluated. The user should investigate the individual test results of the mixtures with the highest desirability and reassess the weaknesses of the mixture and whether these weaknesses make the mixture unsuited for the application. Also, the desirability functions may be modified, and the BTC should be chosen based on the judgment of the user with consideration to the test results.
- For all mixtures that have an overall desirability of 0, the user should investigate the individual desirabilities and determine which of the test results has failed. Before declaring the BTC, the user should reevaluate the desirability functions that produced the zero desirability value and confirm that the zero-desirability mixtures are unacceptable.

Best Predicted Concrete

Modeling

The next part of the analysis involves a statistical modeling to help predict a combination of the levels of the factors and materials that will produce an untested mixture that will perform better than the BTC, to be designated the BPC. The BPC will be determined through statistical prediction using the desirability functions (including any modifications that were made during the determination of the BTC).

The purpose of the BPC analysis is to use trends in the data to predict better concrete mixtures than any of the concretes that were tested in the design matrix. For example, suppose that the four factors given in Table S5.1 are being tested; the relationships observed between the four factors and the response, 56-day strength, are those shown in Figure S5.4; and the objective is to maximize strength. Figure S5.4(a) shows that slag (GGBFS) produces higher strength than the other two supplementary materials that could be used as SCM1; the next plot suggests that the low level of slag is best; Figure S5.4(c) does not show a preferred level of silica fume but it indicates that 5% is slightly better than 8%; and Figure S5.4(d) shows that decreasing the w/cm is best. However, because all combinations of the factors were not tested, none of the concretes that were actually tested in the experimental design matrix have a low level of slag, a w/cm of 0.37, and 5% silica fume; the goal of the BPC analysis is to consider such situations and suggest a different, potentially better, concrete mixture.

To capture the trend and curvature in Figure S5.4(a), a simple quadratic equation of the form $y = b_0 + b_1x_1 + b_{11}x_1^2$, where y represents the response (e.g., 56-day strength) and x_1 represents the setting of the Factor 1, could be used. Because this is a type factor to be used in the equation, the levels for type of SCM1 are coded into the numerical levels: –1 for Class C fly ash, 0 for Class F fly ash, and 1 for slag. The parameters b_0, b_1, and b_{11} are determined by standard linear regression analysis to obtain the function that best fits the data. By including the other factors in a similar form, the following becomes the response equation:

$$y = b_0 + b_1x_1 + b_{11}x_1^2 + b_2x_2 + b_{22}x_2^2 + b_3x_3 + b_{33}x_3^2 + b_4x_4 \qquad (1)$$

where x_2 represents the setting of the Factor 2 and so forth. Because there are only two levels for Factor 4, the squared term for x_4 cannot be used.

Most responses in concrete testing (e.g., strength, scaling mass loss, chloride diffusion coefficient, and modulus of elasticity) can take on only positive values. However, the model in Equation 1 can predict negative values for y, indicating inappropriateness for most of the responses. To correct this deficiency, the following model is employed:

$$y = e^{b_0 + b_1x_1 + b_{11}x_1^2 + b_2x_2 + b_{22}x_2^2 + b_3x_3 + b_{33}x_3^2 + b_4x_4} \qquad (2)$$

where e is the natural constant such that $\ln(e) = 1$. Because e is a positive constant, this model will yield only positive values for y. A simple way to fit the model in Equation 2 is to take the natural log of the observed responses and fit the simple quadratic model to that transformed data using standard regression analysis:

$$\ln(y) = b_0 + b_1x_1 + b_{11}x_1^2 + b_2x_2 + b_{22}x_2^2 + b_3x_3 + b_{33}x_3^2 + b_4x_4 \quad (3)$$

Once the values for the parameters b_0, b_1, b_{11}, b_2, …, b_4 are determined 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.

For ordinary amount factors, the levels can simply be input into Equation 2. For type factors and the amount factor component of compound factors, the levels must be coded to allow numerical evaluation of the model coefficients. For type factors, levels are coded as –1, 0, and 1 for three-level type factors and as 0 and 1 for two-level type factors. When modeling is performed, these factors are only evaluated at the whole number points: –1, 0, and 1 (or 0 and 1). A similar coding approach can be applied for the generically defined amounts in compound factors. However, unlike the procedure used for type factors, the amount factor component of the compound factor can be varied continuously over the range –1 to 1 (or 0 to 1). The coded value is then converted back to a specific amount of the associated type factor based on how the generic ranges for that type were defined.

To maximize overall performance, many responses need to be optimized with the understanding that the best settings to optimize one response will not be the best for other responses. This case can be illustrated by the plots in Figure S5.5 representing the relationships between the same factors used in the previous example and the response, specific surface area (which is also to be maximized). Based on the data for this response, better performance is obtained with high amounts of Class C fly ash, no silica fume, and w/cm of 0.45—different levels from those required for optimizing strength. The desirability calculations will help to trade off between maximizing strength and maximizing specific surface area, but first the trends for specific surface area must be fitted (in the same way as was done for 56-day strength) to obtain a set of parameter values b_0, b_1, b_{11}, b_2, …, b_4 for predicting the effect of the mixture on specific surface area.

If many responses are to be considered, this fitting process must be repeated for all the responses; then, for any settings of the factors x_1, x_2, x_3, x_4, each response can be predicted using Equation 2 and the respective values of b_0, b_1, b_{11}, b_2, …, b_4 for each response. For any predicted value of the response, the desirability of that response can be determined based on the respective desirability function (desirability functions for 56-day strength and for specific surface area are shown in Figure S5.2 and S5.6, respectively).

To generate the BPC, the factor settings x_1, x_2, x_3, x_4 that maximize the overall desirability (defined as the geometric mean or the n^{th} root of the product of n values) of the individual response desirabilities must be identified. Table S5.2 shows the calculations for the simple example of two responses (strength and specific surface area) for all possible combinations of the levels shown in Table S5.1. For these two responses, the factor settings that predict the highest overall desirability are fly ash (Class C) at the high level with 5% silica fume and a w/cm of 0.45. The predicted value of 56-day strength for this mixture is 5515 psi, which gives an individual desirability of 1.000. The predicted value of specific surface area is 757 in.^{2}/in.^{3}, which has an individual desirability of 0.989. The overall desirability is calculated as the square root of the product of 1.000 and 0.989, which is 0.995.

When there are more than two responses, the process is simply expanded to include a prediction and desirability for each response. For factors such as the amount of SCM1, the amount of silica fume, and the w/cm, a finer grid that interpolates between the specified levels of the factors can also be used to find a BPC; such a process involves more calculations and effort to do the optimization.

Once a combination of factor settings that produces the highest predicted overall desirability has been identified, the user should review the predicted individual desirabilities and the predicted test results for the new mixture to verify that it will in fact improve the performance.

In this process, the observed data, the desirability functions, and modeling are used together to predict a BPC that may perform better than the BTC. However, because of the many approximations and assumptions in the modeling and prediction, confirmation testing (Step 6) must be conducted to compare the BTC and the BPC and confirm their performance before the BC is selected.

Note on Extrapolation

It is mathematically possible to choose factor levels that are outside of the range used in the experiment and predict the test result, the individual desirability, and the overall desirability. However, such predictions should be viewed with extreme caution. It is very likely that the regression model will not define the true performance of mixtures that are substantially different from the ones that were used in the design matrix because the regression model is based only on data from the mixtures in the design matrix. Thus, performance predictions will likely be more accurate when the factor levels selected for extrapolation are close to the tested range. Predicting new, high-performing concrete mixtures outside the experimental range would require substantial confirmation testing. If extrapolation is performed and a promising mixture is identified, the extrapolated mixture may be produced and tested in addition to the BTC and BPC during the confirmation testing conducted in Step 6 but should not be considered as replacement for either of these mixtures.

Repeatability and Scaled Factor Effects

A question that is intrinsic to any statistical model is whether the effects of the factors that are used in the model are due to random variability or are due to actual trends in the data. Statistically significant coefficients in the model can be identified by specific statistical tests, which require some estimate of the variability of the random error of the experiment (the repeatability). Multiple batches of some concrete mixtures must be tested to get an estimate of repeatability. A formal test of statistical significance is impractical because of the very limited amount of data in the experiments. However, three methods may be used to estimate repeatability for each performance test and to estimate the effect of each factor.

- Use the standard deviation or coefficient of variation that is published by ASTM and obtained from repeated measurements of the same concrete mixture by various laboratories that have followed the ASTM standard being used. This standard deviation/coefficient of variation is usually based on repeated testing of a single batch.
- Use the standard deviation of repeated measurements on the same concrete from the testing laboratory's own records for the test procedure being used.
- Make and test multiple batches of the control or other mixture concrete and use the standard deviation of the test results from these replicates to estimate repeatability. This estimate also includes any variation resulting in the batching process.

Published ASTM data account for multiple laboratories and often have a large number of replicates; however, these data are sometimes not available or may not be a good representation of the repeatability in the laboratory where testing is being conducted because of the batch-to-batch variations. The testing laboratory's historical data are probably best if good records of the same test being run on multiple batches of the same concrete are available. However, these data often do not exist. Making and testing multiple batches as part of this test has the advantage that the same procedures can be used for both the controls and the mixtures in the design matrix and thus the repeatability measured will be similar to the repeatability for the rest of the experiment. However, making and testing a large number of control batches is expensive, and using a small number of control batches will yield a poor estimate of repeatability. In some cases, the best choice may be to defer to the ASTM-published data.

A very simple test is used for assessing the factor effects with respect to variability and with respect to each other. The regression analysis is used to estimate the amount of variability that is explained by each factor and then the ratio of the variability estimate to the variance (the square of the standard deviation) of repeatability. This ratio is the standard "partial F-ratio" for each factor in a standard regression analysis or ANOVA (analysis of variance), where the mean square error is the square of the standard deviation selected to represent repeatability (*61*), and is referred to as the "scaled factor effect." Because the accuracy of the repeatability estimate is unknown, no attempt will be made to perform a precise statistical test of significance on this ratio as is done in most regression analyses. However, the user may observe the scale of the factor effects: first, checking to see if the scaled factor effects are less than or much greater than 1 and then comparing the scaled factor effects of the different factors to see the relative size of the factor effects with respect to each other. If this ratio is less than one, then the factor effect is smaller than the repeatability; and it should not be considered to be an actual trend in the data. If the ratio is much larger than one, for example, greater than 10, then the factor probably is statistically significant.

For example, the factor effects chart for the scaled factor effect on electrical conductivity (Figure S5.7) shows that the amount of silica fume and the w/cm probably have a real effect on the conductivity and that the type and amount of SCM1 may have an effect, but there is no clear trend. Because none of the ratios are below 1, all of these factor effects could be real trends in the data. Because of the uncertainty of this test, no attempt is made to reduce the regression models by removing terms.

Statistical Experimental Design for Optimizing Concrete Computational Tool

To help the user implement the analysis process, SEDOC, a Microsoft® Excel–based computational tool, is provided with these Guidelines. While the tool supports all the steps in the methodology except for the actual mixture proportioning and batching, it is most useful during Steps 5 and 6. It is designed to perform conversions to individual desirabilities based on data generated by the experimental testing program, as well as the calculation of the overall desirability, the selection of the BTC, and the modeling and prediction of the BPC. The tool includes many pre-formatted plots and tables designed to help the user analyze and discover trends within the data. SEDOC and the user's guide are available on the TRB website (http://www.trb.org/news/blurb_detail.asp?id=7714).

Example from Hypothetical Case Study

The following discussion is based on the test results collected as part of the hypothetical case study presented in Appendix A of *NCHRP Web-Only Document 110* (http://www.trb.org/news/blurb_detail.asp?id=7715). While every experiment will have different considerations depending on the performance objectives and the results obtained, this example will show how a given set of results can be interpreted relative to the hypothetical objective of a durable bridge deck in a northern climate.

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 reevaluated. The initial assumptions for the desirability functions were also reevaluated to ensure that they accurately interpreted the performance of the mixtures (i.e., properly reflected differences or similarities in performance).

Table S5.3 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. One of the primary changes made was the elimination of fresh properties (i.e., slump, slump loss, plastic air content, and air content of hardened concrete) because these properties can be adjusted by the concrete producer based on admixture dosage and were not uniquely determined by the factors investigated in this experiment. 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 change was necessary because the mixture containing a high content of Class F fly ash had a 28-day strength of 3620 psi (25.0 MPa), which was well below the minimum of 5000 psi (34.5 MPa) used to develop the desirability function. This change penalizes all mixtures containing Class F fly ash because the influence of a type factor is based on the average response for all mixtures containing that type. While the desirability function for 28-day strength was reasonable, a designer may be willing to wait for the concrete to reach design strength at 56 days, if that means that a more durable concrete with a lower diffusion coefficient and other more desirable responses may be achieved. Using the 56-day strength, which was 4490 psi (31.0 MPa) for the high-content Class F fly ash mixture, gave a much more acceptable overall desirability for that mixture.

Finally, scaling resistance was evaluated visually and by mass loss. To limit the weight applied to scaling relative to the other performance measures, mass loss (the most definitive measure) was included, and the visual rating was not.

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 much above 30°F (17°C), and the desirability function was designed accordingly. However, the test results ranged from 30°F to 50°F (17°C to 29°C). Therefore, the desirability function was adjusted to give some credit to those mixtures that produced a lower temperature rise without overly punishing the mixtures at the higher end of the scale; Figure S5.8 shows the original and adjusted desirability functions.

To generate the BPC, the factors that maximize the overall desirability must be identified by evaluating the overall desirability for many possible combinations of factor levels and finding the combination that produced the highest overall desirability. For amount factors such as the amount of SCM1, the amount of silica fume, and the w/cm, the responses were evaluated at several, evenly spaced sets of levels between the level ranges specified in the test experimental matrix to find the BPC. For the type factor type of SCM1, the responses were evaluated for each discrete type. In this way, the observed data, the desirability function, and the response models were used together to predict a BPC that would perform better than the BTC. The BTC and BPC that were selected based on the test program results are given in Table S5.4. The predicted overall desirability and the mixture number from the Step 4 test program are also shown. 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 predictions of the performance of the BTC and BPC are given in Table S5.5. These predictions were taken from SEDOC output used to perform this analysis. 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 the responses that were most significant in the selection of the BPC. Despite a slightly lower individual desirability for finishability and mass loss, the predicted individual desirabilities for the BPC for the chloride diffusion, electrical conductivity, and cracking tendency were all higher; these individual desirabilities contributed to the greater overall desirability and the selection of this mixture as the BPC.

Figures for Step 5

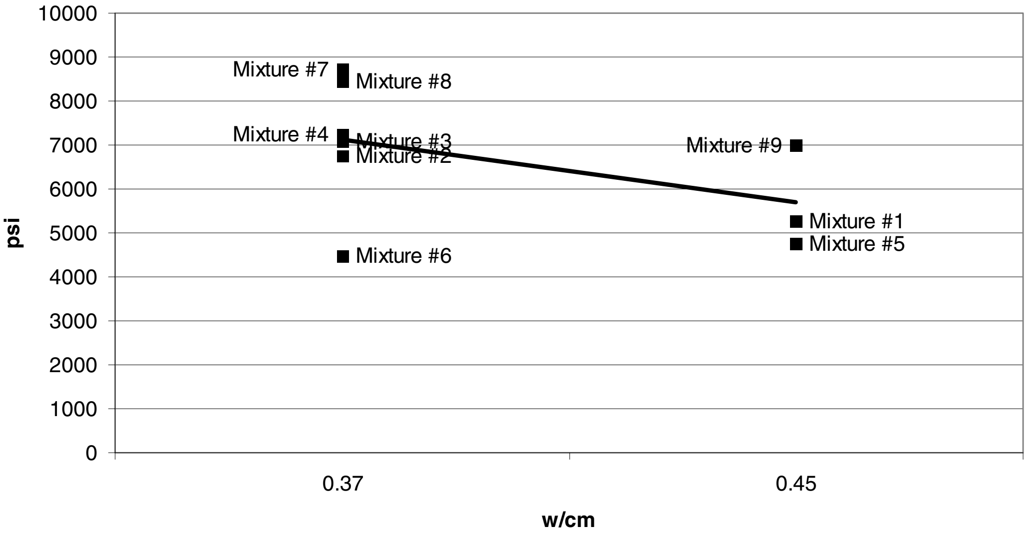

Figure S5.1. Scatter plot of 56-day strength vs. w/cm with trend line.

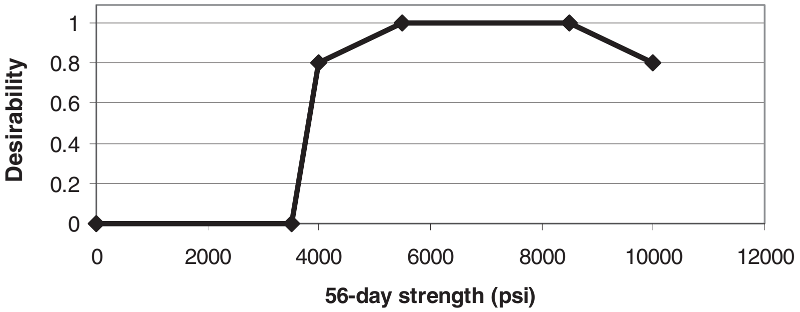

Figure S5.2. Desirability function for 56-day strength.

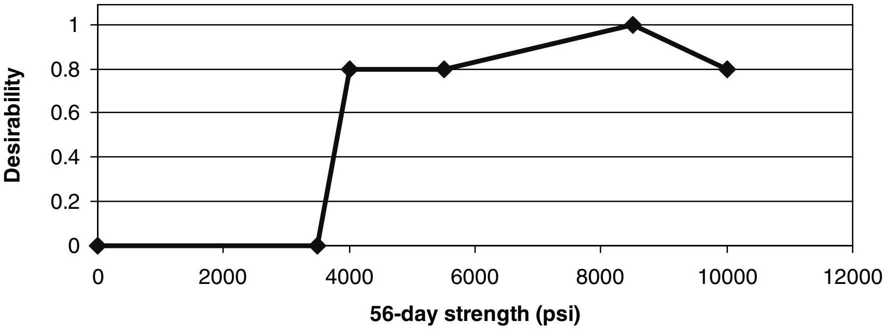

Figure S5.3. Modified desirability function for 56-day strength.

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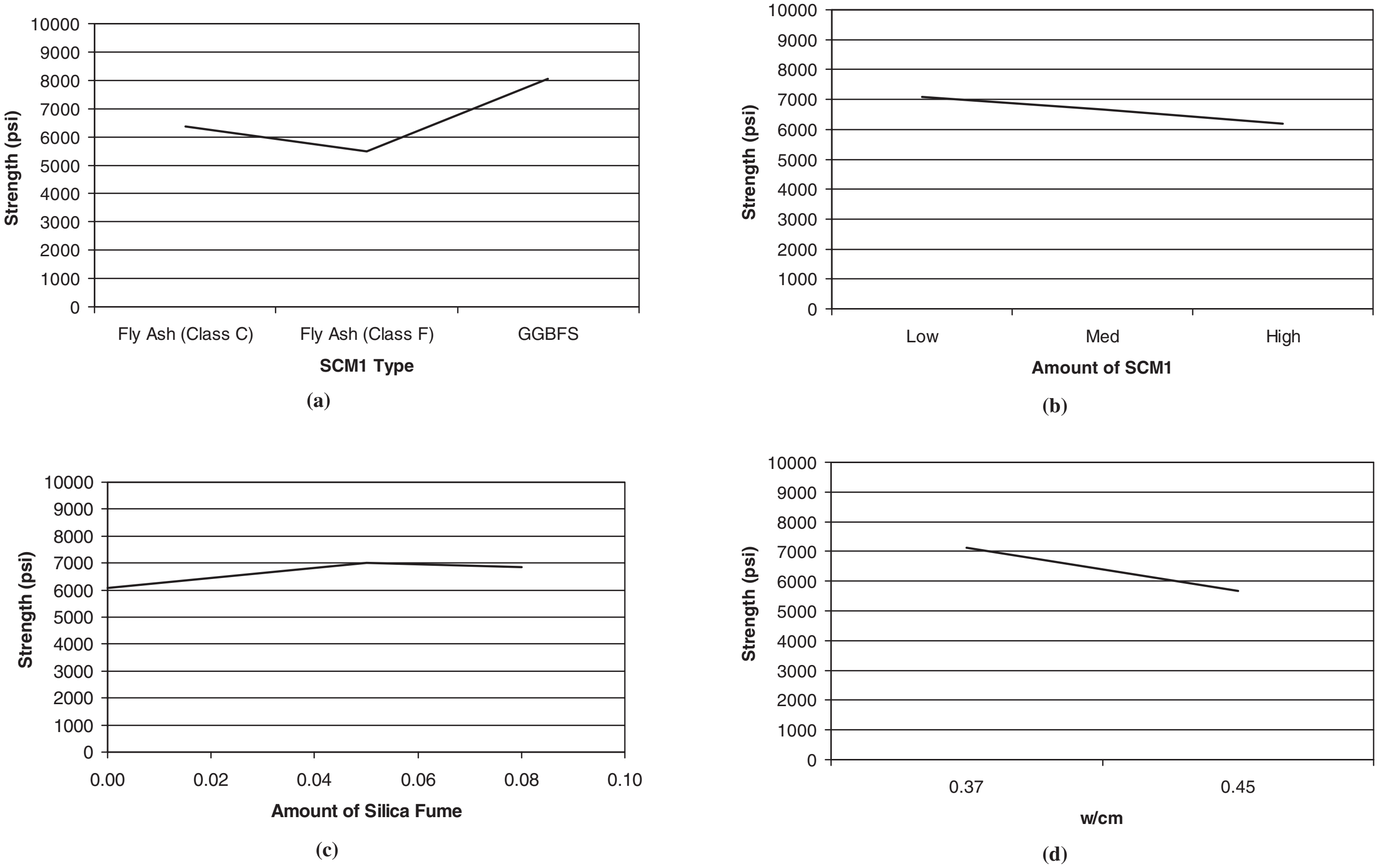

(a)

(b)

(c)

(d)

Figure S5.4. Relationships between 56-day strength and factors.

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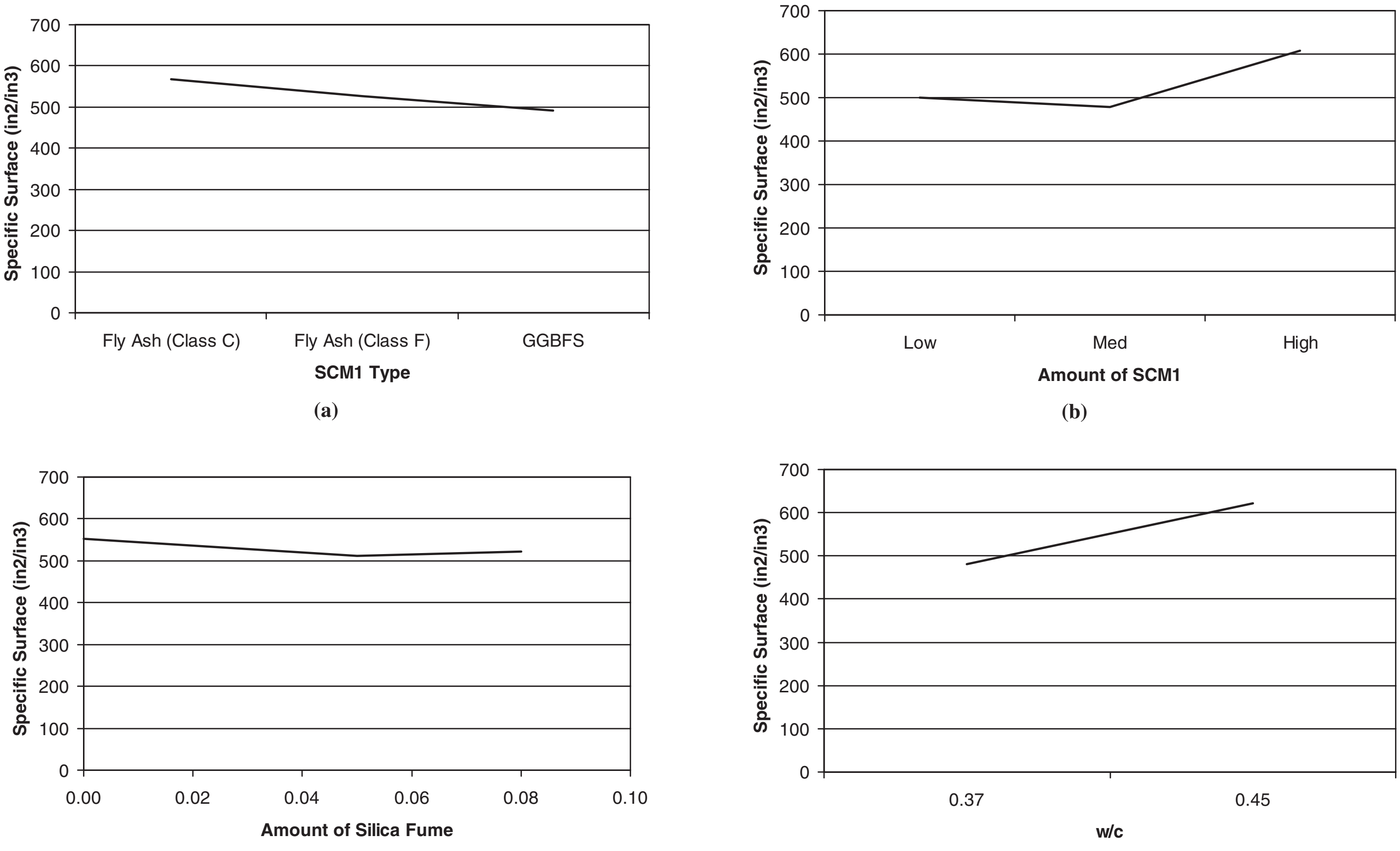

(a)

(b)

(c)

(d)

Figure S5.5. Relationships between specific surface area and factors.

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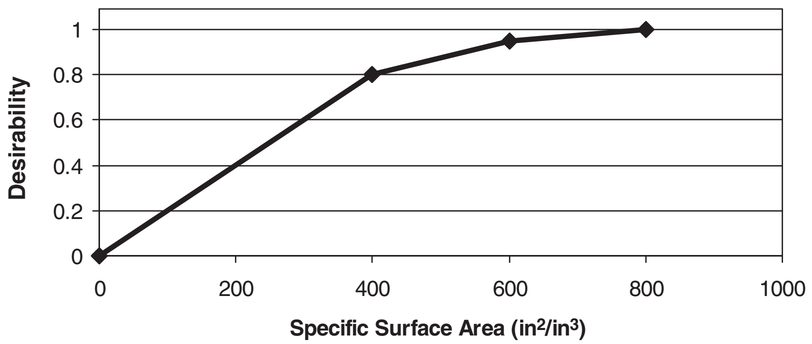

Figure S5.6. Desirability function for specific surface area.

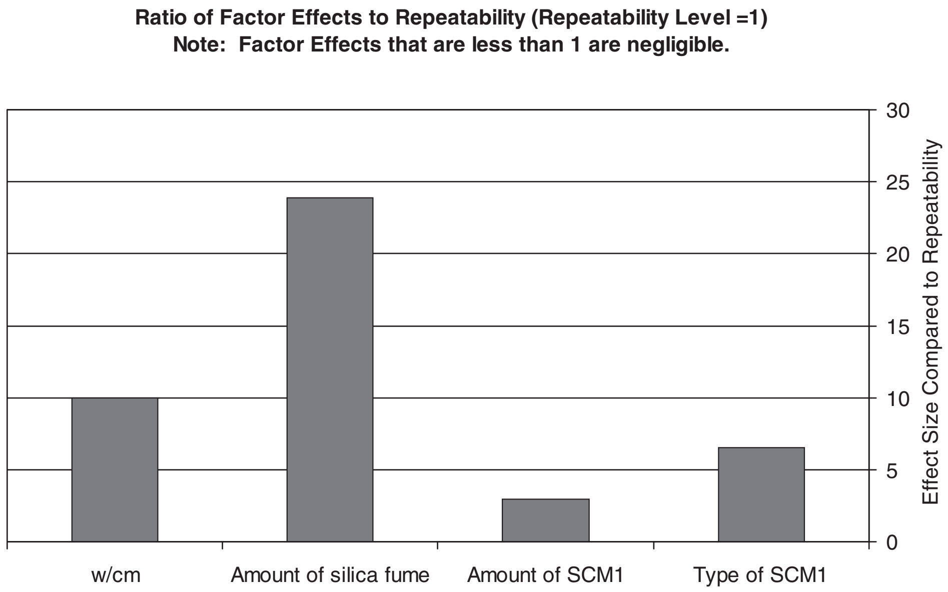

Figure S5.7. Ratio of factor effects to repeatability for electrical conductivity test.

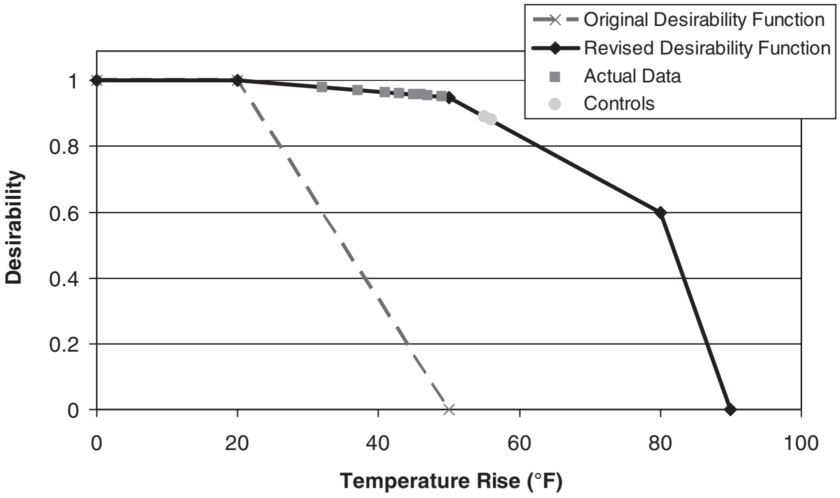

Figure S5.8. Example of modification to temperature rise desirability function.

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Tables for Step 5

Table S5.1. Factors and levels for 9-mixture design.

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	Medium	High
Factor 3 (3 levels)	Amount of silica fume (%)	0	5	8
Factor 4 (2 levels)	w/cm	0.37	0.45	

Table S5.2. Predicted responses and associated individual and overall desirabilities at each level combination (examples).

Factor 1	Factor 2	Factor 3	Factor 4	Predicted 56-Day Strength	Predicted Specific Surface Area	56-Day Strength Desirability	Specific Surface Area Desirability	Overall Desirability
Fly ash (Class C)	Low	0%	0.37	5843	504	1.000	0.878	0.937
Fly ash (Class C)	Low	0%	0.45	4703	657	0.971	0.964	0.968
Fly ash (Class C)	Low	5%	0.37	7239	467	1.000	0.850	0.922
Fly ash (Class C)	Low	5%	0.45	5827	609	1.000	0.952	0.976
Fly ash (Class C)	Low	8%	0.37	6630	479	1.000	0.859	0.927
Fly ash (Class C)	Low	8%	0.45	5336	625	1.000	0.956	0.978
Fly ash (Class C)	Med	0%	0.37	5574	489	1.000	0.867	0.931
Fly ash (Class C)	Med	0%	0.45	4486	637	0.925	0.959	0.942
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Fly ash (Class C)	**High**	**5%**	**0.45**	**5515**	**757**	**1.000**	**0.989**	**0.995**
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
GGBFS	High	5%	0.37	8701	495	0.973	0.871	0.848
GGBFS	High	5%	0.45	7000	646	1.000	0.962	0.962
GGBFS	High	8%	0.37	8277	508	1.000	0.881	0.881
GGBFS	High	8%	0.45	6659	663	1.000	0.966	0.966

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Table S5.3. Responses for overall desirability calculation.

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 S5.4. Overall desirabilities of Best Tested and Best Predicted Concretes.

Mixture	Type of SCM1	Amount of SCM1 (%)	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	–

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Table S5.5. Predicted responses of Best Tested and Best Predicted Concretes.

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 (h)	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 at 7 Days (psi)	5366	5503	1.00	1.00
Compressive Strength at 28 Days (psi)	7193	7730		
Compressive Strength at 56 Days (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 Coefficient (x 10^{-12} m^2/s)	1.95	1.38	0.85	0.90

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STEP 6

Perform Confirmation Testing and Select Best Concrete

Introduction

In Step 5, the BTC and the BPC were identified. The BTC is the produced concrete that performed better than the other produced concretes tested. The BPC is a concrete identified based on numerical modeling as having performance that exceeds that of the BTC. In Step 6, additional testing and subsequent analysis will be performed to confirm that the BTC and BPC actually perform as suggested by the modeling performed in Step 5.

The objective of this step is to select the BC. The Step 6 testing and analysis are intended to provide confirmation that the performance of this mixture is better than the BTC as predicted so that this selection can be made with a high level of confidence.

In some cases, time or budget constraints will not allow for additional testing. In these cases, the BTC should almost certainly be selected as the BC and recommended for use. Because no testing has been done on the BPC, it is highly risky to select the BPC as the BC without actually mixing a batch of the BPC and subjecting it to the most critical performance tests for the application. The user will have to consider experience or well-documented research in making this decision.

Confirmation Testing

The following questions need to be answered regarding confirmation testing:

- What concrete mixtures should be mixed and tested?
- What performance tests should be run?
- How should the test data be analyzed?
- Did the data and models in Step 5 accurately predict the performance of the BTC and BPC?
- What concrete mixture should be selected as the BC and recommended for the application?

Mixtures and Tests

If possible, batches of both the BTC and the BPC should be mixed and should be tested using all the performance tests that were used in the analysis in Step 5. However, in some cases, conducting all performance tests for both the BPC and the BTC will not be feasible. In these cases, the first consideration should be whether the BPC appears to provide a substantial improvement over the BTC (e.g., as indicated from the predicted overall desirability for the BPC and the BTC). However, a more detailed examination/comparison of the predicted test results for the two concrete mixtures should be done to determine if the BPC should be pursued. If the predicted performance of the BPC is not significantly better than the performance of the BTC, then there is little reason to test the BPC. The confirmation test budget could be used to run more testing on the BTC to confirm that the high performance observed in the earlier tests can be repeated.

If the predicted performance of the BPC is substantially higher than the BTC for at least some important performance tests, as many performance tests as practical should be run on new batches of the BTC and the BPC. If not all tests can be performed, the number of performance tests should be reduced:

- Any performance test that is absolutely critical to the application should not be eliminated from the confirmation testing. Performance tests that are very expensive or take an extremely long time are probably the most likely tests to be eliminated. However, because the BPC has never been tested, eliminating a test that is critical to the application will result in a deficient evaluation of the BPC, making it unsuited for selection as the BC.
- A side-by-side comparison of the predicted performance of the BPC and the BTC should be observed. In many tests, the predicted performance of the BPC may not differ significantly from that of the BTC. This difference should be

evaluated in terms of the individual desirability and not the actual response value, because the individual desirability will influence overall desirability. Performance tests that produced little difference are not likely to yield much new information in the confirmation testing and thus should be the first to be eliminated if budget and time constraints require it. If all mixtures performed well in freezing and thawing resistance tests as a result of good air void systems such that the predicted desirabilities are all essentially 1, then repeating this test is not likely to contribute much information and the test may be eliminated. However, the air content of the hardened concrete could still be measured as an indication of good cyclic freezing resistance.

Based on the above guidelines and the judgment of the users, the concrete mixtures (BTC and/or the BPC) and a set of tests can now be selected for determining the overall desirability from the confirmation testing.

Data Analysis: Model Checking

Once the confirmation testing is completed, the data should be compared with the results of the main test program. These data may be added to the plots already created.

Although not as important as determining the BC, checking the accuracy of the model prediction from Step 5 is a useful step for gaining confidence in the use of the regression models. The accuracy of the model prediction can be evaluated for all the performance tests that were repeated in the confirmation testing. If only a subset of the performance tests is run in the confirmation testing, a predicted overall desirability for the BTC and the BPC for only those tests should be calculated from the regression models used in Step 5 (this predicted overall desirability will be somewhat different from the one used to select the BTC and the BPC).

Next, an overall desirability from the actual confirmation test results needs to be calculated for both the BTC and the BPC. Comparing the predicted overall desirability and the actual overall desirability is a useful first step, but the user should also compare the individual predictions of each test result with the actual results obtained in the confirmation testing. In some cases, calculating a percentage difference is useful, but judgment is needed to determine what constitutes poor prediction accuracy. If the models predict well, then more confidence can be placed in the prediction and trends observed in the previous step. It also builds confidence in the predicted values for the BPC for any tests that were not performed in the confirmation testing. If there are major problems with the prediction accuracy, then all decisions should be based only on actual data, which in most cases would favor the BTC that has been batched and tested more often than the BPC.

Final Selection of the BC

It is expected that the concrete mixture that has the highest overall desirability will be chosen as the BC, although additional considerations may affect this selection. The most important consideration is that the results for each of the important performance tests should indicate that the concrete mixture will perform well on those performance characteristics that are critical to the application. If there is little difference between the overall desirabilities of the BTC and the BPC, then individual response performance and desirabilities should be examined, and the mixture that performs best in the tests that are most significant for the application should be chosen. The cost, availability of materials, and ease of production may also be considered. If the differences are not sufficient to justify the production of the mixture with the higher desirability, then that mixture should not be chosen. Finally, the accuracy of the test program conclusions should be considered. If the overall desirabilities of the BTC batches in the original test program and the confirmation tests are different by a greater amount than the BTC and BPC, the difference is likely within the range of repeatability of the experiment. Then, the primary consideration should be individual test performance with secondary consideration placed on cost and other factors.

Example from Hypothetical Case Study

The BPC and BTC identified in the hypothetical case study were tested according to the revised list of test methods. Table S5.3 lists the responses that were included in the calculation of the overall desirability for the confirmation testing. The confirmation test program was limited to those responses that showed significant performance differences for BTC and BPC and that could be completed in the available timeframe. Therefore, the finishability, modulus of elasticity, and freezing and thawing tests were eliminated because the BTC and BPC mixtures were predicted to perform such that a similar desirability would be assigned to that response. The cracking tendency test was eliminated because the test could not be completed in the allotted time. The method used to evaluate the chloride penetration was changed to ASTM C 1556 tested at 56 days because of time constraints. However, because both of the chloride penetration test methods used measure similar performance, the initial and confirmation test programs were considered essentially comparable.

The overall desirabilities of these mixtures were determined using the individual desirability functions and the results obtained during the confirmation testing. These overall desirabilities are compared with the predicted overall desirabilities in Table S6.1, which also includes the overall desirability from the original BTC batch calculated using only the tests in the confirmation testing program. Slight differences between the overall desirabilities based on the confirmation round of testing and those calculated based on the Step 4 round of testing are due to the different set of responses used in the confirmation analyses (see Table S5.3).

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 much greater than the difference between the performance of the original and confirmation batches of the BTC. This result indicates that the test program produced repeatable results and that the increase in desirability measured in the BPC is a significant and measurable improvement.

Tables S6.2 and S6.3 present the actual and predicted individual responses and corresponding desirabilities for the confirmation testing for the BTC and BPC that could be used to evaluate the accuracy of the predictions in terms of the test responses and the corresponding desirabilities, one response at a time. The mixture responses that were least well-predicted (i.e., mixtures that showed the greatest percentage difference) in terms of the test result for the BTC and BPC were the electrical conductivity and mass-loss scaling tests. However, the corresponding desirability values varied only slightly because the desirability functions placed only limited significance on these differences. In fact, only one desirability prediction was different by more than 5%: the 7-day strength prediction for the BTC differed by 5.2%.

The confirmation test results evaluated in terms of the overall desirability and the good agreement between the test responses and the model predictions used to select the BPC confirm the accuracy of the statistical analysis. This result justifies the selection of the BPC as the recommended BC mixture—the optimum mixture based on the available raw materials.

Tables for Step 6

Table S6.1. 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 S6.2. Comparison of individual responses and desirabilities for Best Tested Concrete.

Property	Individual Responses				Individual Desirabilities			Included in Confirmation Test Analysis
	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 (h)	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 Temperature Rise (°F)	46	46	45	3.1%	0.957	0.959	-0.2%	Yes
Shrinkage (%)	-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 at 7 Days (psi)	5705	6020	5367	12.2%	0.948	1.000	-5.2%	Yes
Compressive Strength at 28 Days (psi)	7888	7970	7194	10.8%	1.000	1.000	0.0%	Yes
Compressive Strength at 56 Days (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 (x 10^{-12} m^2/s)	1.62	1.88	1.95	-3.8%	0.859	0.853	0.7%	Yes

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Table S6.3. Comparison of individual responses and desirabilities for Best Predicted Concrete.

Property	Individual Responses			Individual Desirabilities			Included in Confirmation Test Analysis
	BPC Confirmation Test	BPC Prediction	BPC% Difference Response	BPC Confirmation Test	BPC Prediction	BPC % Difference Desirability	
Slump (in.)	7.25	7.10	2.2%	–	–	–	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 (h)	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 at 7 Days (psi)	5570	5504	1.2%	0.993	1.000	-0.7%	Yes
Compressive Strength at 28 Days (psi)	7710	7731	-0.3%	1.000	1.000	0.0%	Yes
Compressive Strength at 56 Days (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 (x 10^{-12} m^2/s)	1.28	1.38	-6.8%	0.904	0.897	0.8%	Yes

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Glossary of Statistical Experimental Design–Related Terms

The following are definitions of the terms used in the statistical experimental design.

Amount Constant: An unchanging amount of material to be used in all mixtures to be tested.
Amount Factor: A variable (factor) that varies the amount of raw material for the mixture.
ANOVA Analysis: Analysis of Variance, a statistical method used to compare relative statistical significance of the effects of a factor by comparing the ratio of the variation explained by each factor to the variance of the random error.
Bar Chart: A graph used to show relationships and trends by comparing the height of two or more bars. (In this document, the charts are used to compare the relative scale of the factor effects.)
Best Concrete (BC): The concrete mixture that is to be recommended for the application after collection and analysis of the data. The final decision is made by comparing the experiment's Best Tested Concrete (BTC) with the Best Predicted Concrete (BPC) in the confirmation testing step.
Best Predicted Concrete (BPC): A concrete mixture that is predicted to have the best performance through statistical modeling of the data from the design matrix.
Best Tested Concrete (BTC): The concrete mixture from the design matrix that has the best tested performance as determined by the overall desirability.
Compound Factor: A pair of variables (factors) that act together to define the type and amount of a certain material so that the amount of each material can be customized for each type.
Confirmation Testing: A second round of testing to confirm the performance of the BTC and BPC.
Constant: A single level that is necessary for defining the experiment but which is not varied.
Corner Points: Vertices of a piecewise linear function. In this document, they are the points at which a desirability function changes slope.
Design Matrix: The table (matrix) of combinations of factors and levels that defines which concrete mixtures to mix and test.
Desirability Function: A function that converts any test result into a value between 0 and 1, where 0 means the result is unacceptable, and 1 means the result needs no improvement. Intermediate values show the level of acceptability (desirability) of the result.
Expert Opinion Method: An experimental methodology that begins by using the experts' prediction of best performance. Samples of these mixtures are cast and tested in various tests, and the concrete that performs the best is chosen for the application. This method is probably the most typical used for identifying a concrete mixture for an application.
Extrapolate: Using test results to predict performance for mixtures that have factor levels that are outside the range of factor levels tested. This procedure is not recommended.
Factor: The independent variables, or *x*-variables, that are intentionally varied in an experiment.
Factor level: A level associated with a specific factor.
F-ratio: A ratio used in ANOVA analysis. The F-ratio for a certain factor is the amount of variation explained by that factor divided by the variance of random error. A large (substantially larger than 1) F-ratio indicates a large statistical significance of the effects of the factor.
Geometric Mean: The *n*th root of the product of *n* values. For example, the geometric mean of the numbers 4, 5, 6, 7, and 8 is the fifth root of $4 \times 5 \times 6 \times 7 \times 8$, which is $\sqrt[5]{6720} = 5.83$.
Individual Desirability: A mathematical value assigned to an individual test result to determine acceptability of that result. The scale ranges from 0 to 1, with 0 being unacceptable and 1 being a result that needs no improvement. Individual desirabilities for each test performed are used to calculate a geometric mean to determine an overall desirability for the concrete mixture.
Interpolate: Using test results to predict performance for mixtures that have factor levels that are within the range of factor levels tested.
Level: The setting of a factor. For example, if the factor is amount of silica fume, the level (or setting) might be 5%.
Linear Function: A mathematical formula that represents the line that best fits data.
Mean Square Error: The average variance due to random error.
Mixture: A combination of factor levels that define the concrete to be tested. It is assumed that the mixture is batched according to the factor levels and cast into proper specimens for testing.
One Factor-at-a-Time Method: An experimental methodology that begins by having experts select a single mixture, called the "control mixture," that is considered to be most likely to perform well. Each factor that is chosen for the study is varied from its level in the control mixture, and a new mixture is cast and tested with only that factor changed.
Orthogonal Design Method: An experimental methodology where an orthogonal design matrix is chosen that contains a list of mixtures to be tested. Orthogonal designs are created so that each factor level is balanced with every other factor level such that an independent estimate of each factor effect is possible. This is the method used in this report.
Quadratic Model: A mathematical function that includes second order (squared) terms to model curvature.

Random Error or Random Variability: Variability due to uncontrollable changes in materials, mixing and measurement procedures. (Also called random variability or repeatability.)

Regression Analysis: A statistical method of fitting lines and curves to data to create a prediction model.

Repeatability: Variation due to repeated mixing and testing of the same concrete mixture. Same as Random Error.

Response Surface Approach: An experimental methodology that requires a large enough design matrix to estimate both curvature and two-factor interactions between factors. This approach is more thorough than the Orthogonal Design Approach but often requires more testing than is feasible (typically 17 to 32 mixtures for three to five factors).

Response: The measured value from a performance test. This value is the dependent, or *y*-variable, used in an experiment. Same as "test result."

Scatter Plot: A graph of two columns of numbers used to show relationships and trends by plotting the response as a function of the factor level. (See Trend.)

Setting: The level of a factor. For example, if the factor is amount of silica fume, the level (or setting) might be 5%.

Source Constant: An unchanging source of material used in all mixtures to be tested.

Source Factors: Variables (factors) that vary the source of raw material for the mixtures.

Standard Deviation: A mathematical measure of variability of data. For example, the standard deviation of the numbers 3, 4, 5, 6, 7, and 8 is 1.87.

Statistical Experimental Design for Optimization of Concrete (SEDOC): Microsoft Excel®–based tool developed with this methodology to support this orthogonal design experiment. Functionality includes guidance in the design of the experiment, calculation of individual and overall desirabilities, modeling of individual responses, selection of BTC and BPC, and evaluation of prediction accuracy.

Type Constant: An unchanging type of material used in all mixtures to be tested.

Trend: The general pattern of the data. Trends on scatter plots are found by connecting the average of *y*-values at each level of the factor (*x*-values).

Type Factors: Variables (factors) that change the type of material used to accomplish the particular function.

Vertices: A point where a function abruptly changes slope. In this document, they are the points at which a desirability function changes slope. Same as corner points.

References

1. Portland Cement Association, "Supplementary Cementing Materials for Use in Concrete," CD format (2002).
2. Derringer, G., and Suich, R., "Simultaneous Optimization of Several Response Variables," *Journal of Quality Technology*, Vol. 12 (1980) pp. 214–219.
3. Malhotra, V.M., and Ramezanianpour, A.A., *Fly Ash in Concrete*, 2nd Edition. CANMET (1994) 307 pp.
4. ACI Committee 232, "232.2R-96: Use of Fly Ash in Concrete," *Manual of Concrete Practice*, American Concrete Institute, Farmington Hills, MI (1996).
5. Fernandez, L., and Malhotra, V.M., "Mechanical Properties, Abrasion Resistance, and Chloride Permeability of Concrete Incorporating Granulated Blast-Furnace Slag," *Cement, Concrete, and Aggregates,* Vol. 12, No. 2 (1990) pp. 87–100.
6. ACI Committee 233, "233R-95: Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete," *Manual of Concrete Practice*, American Concrete Institute, Farmington Hills, MI (1995).
7. ACI Committee 234, "234R-96: Guide for the Use of Silica Fume in Concrete," *Manual of Concrete Practice,* American Concrete Institute, Farmington Hills, MI (1996).
8. Taylor, P.C., and Burg, R.G., "Low-Cost, Durable Concrete," *The Concrete Producer* (April 1999) pp. 33–34.
9. Ding, J.-T., and Li, Z., "Effects of Metakaolin and Silica Fume on Properties of Concrete," *ACI Materials Journal,* Vol. 99, No. 4 (July–Aug. 2002) pp. 393–398.
10. Barger, G.S., Lukkarila, M.R., Martin, D.L., Lane, S.B., Hansen, E.R., Ross, M.W., and Thompson, J.L., "Evaluation of a Blended Cement and a Mineral Admixture Containing Calcined Clay Natural Pozzolan for High-Performance Concrete," *Sixth International Purdue Conference on Concrete Pavement Design and Materials for High Performance*, West Lafayette, IN, Proceedings Vol. 1, (November 18–21, 1997).
11. Neville, A.M., *Properties of Concrete*, 4th Edition. John Wiley & Sons, Inc. (1996) 844 pp.
12. Raphael, J.M. "Tensile Strength of Concrete," *ACI Materials Journal*, 81-17, (March–April 1984), pp. 158–165.
13. "Fly Ash in Concrete Part II—How It is Used: Proportioning and Testing," *Concrete Construction* (May 1982) available at www.worldofconcrete.com.
14. Caldarone, M.A., Gruber, K.A., and Burg, R.G., "High-Reactivity Metakaolin: A New Generation Mineral Admixture," *Concrete International* (November 1994) pp. 37–40.
15. Ravina, D., "Slump Loss of Fly Ash Concrete," *Concrete International*, Vol. 6, No. 4 (1984) pp. 35–39.
16. "ACI Education Bulletin E3-01, Cementitious Materials for Concrete," American Concrete Institute, Farmington Hills, MI (2001).
17. Detwiler, R.J., Bhatty, J.I., Barger, G., and Hansen, E. R., "Durability of Concrete Containing Calcined Clay," *Concrete International* (April 2001) pp. 43–47.
18. Hooton, R.D., "Canadian Use of Ground Granulated Blast-Furnace Slag as a Supplementary Cementing Material for Enhanced Performance of Concrete," *Canadian Journal of Civil Engineering,* Vol. 27, No. 4 (2000) pp. 754–760.
19. Balogh, A., "Using Slag to Enhance Concrete Performance," *Concrete Construction* (March 1994) pp. 235–240.
20. Goodspeed, C., Vanikar, S., and Cook, R., "High-Performance Concrete (HPC) Defined for Highway Structures," *Concrete International*, Vol. 18, No. 2 (1996) pp. 62–67.
21. Kosmatka, S.H., Kerkhoff, B., and Panarese, W.C., *Design and Control of Concrete Mixtures,* 14th Edition. Portland Cement Association (2002) 372 pp.
22. Powers, T.C., "Void Spacing as a Basis for Producing Air-Entrained Concrete," *Journal of American Concrete Institute*, Vol. 25, No. 9 (1954) pp. 741–760.
23. Hover, K.C., "Air Content and Unit Weight of Hardened Concrete." *Significance of Tests and Properties of Concrete and Concrete-Making Materials,* 4th Edition, P. Klieger and J.F. Lamond, editors, STP:169c, ASTM, Fredericksburg, VA (1994) pp. 296–314.
24. ACI Committee 201, "201.2R-01: Guide to Durable Concrete," *Manual of Concrete Practice,* American Concrete Institute, Farmington Hills, MI (2001).
25. Newlon, H., Jr., and Mitchell, T.M., "Freezing and Thawing." *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, 4th Edition, P. Klieger and J.F. Lamond, editors, STP:169c, ASTM, Fredericksburg, VA (1994) pp. 153–163.
26. Browne, F.P., and Cady, P.D., "Deicer Scaling Mechanisms in Concrete," *Durability of Concrete*, ACI SP 47-6, American Concrete Institute, Detroit, MI (1975) pp. 101–120.
27. Newlon, H., Jr., "Resistance to Weathering," *Significance of Tests and Properties of Concrete and Concrete-Making Materials,* STP:169B, ASTM, Baltimore, MD (1978) pp. 351–368.
28. Saric-Coric, M., and Aïtcin, P.-C., "Is ASTM C 672 Curing Procedure Still Appropriate to Test the Scaling Resistance of Blended Cements?" *Cement, Concrete, and Aggregates,* Vol. 24 (2002) pp. 92–96.
29. Lankard, D., "Scaling Revisited," *Concrete International* (May 2001) pp. 43–49.
30. Talbot, C., Pigeon, M., and Marchand, J., "SP192-39: Influence of Fly Ash and Slag on Deicer Salt Scaling Resistance of Concrete,"

Fifth ACI/CANMET International Conference on the Durability of Concrete, American Concrete Institute, Farmington Hills, MI (2000) pp. 645–657.

31. Afrani, I., and Rogers, C., "The Effects of Different Cementing Materials and Curing on Concrete Scaling," *Cement, Concrete, and Aggregates*, Vol. 16, No. 2 (1994) pp. 132–139.
32. ACI Committee 318, "318-02: Building Code Requirements for Structural Concrete," American Concrete Institute, Farmington Hills, MI (2002) p. 43.
33. Pigeon, M., Perraton, D., and Pleau, R., "SP-100: Scaling Tests of Silica Fume Concrete and the Critical Spacing Factor Concept," *Concrete Durability*, American Concrete Institute, Farmington Hills, MI (1987) pp. 1155–1182.
34. Sørensen, E.V., "Freezing and Thawing Resistance of Condensed Silica Fume (Microsilica) Concrete Exposed to Deicing Chemicals," *Fly Ash, Silica Fume, Slag, and Other Mineral By-Products in Concrete*, Proceedings of the First CANMET/ACI International Conference, SP-79, V.M. Malhotra, editor, American Concrete Institute, Farmington Hills, MI (1983) pp. 709–718.
35. Sherman, M.R., McDonald, D.B., and Pfeifer, D.W., "Durability Aspects of Precast Prestressed Concrete—Part 2: Chloride Permeability Study," *PCI Journal*, Vol. 41, No. 4 (July–August 1996) pp. 75–95.
36. Berke, N.S., and Hicks, M.C., "Predicting Chloride Profiles in Concrete," *Corrosion*, Vol. 50, No. 3 (March 1994) pp. 234–239.
37. Suryavanashi, A.K., Swamy, R.N., and Cardew, G.E., "Estimation of Diffusion Coefficients for Chloride Ion Penetration into Structural Concrete," *ACI Materials Journal*, Vol. 99, No. 5 (September–October 2002) pp. 441–449.
38. Pfeifer, D.W., McDonald, D.B., and Krauss, P.D., "The Rapid Chloride Permeability Test and Its Correlation to the 90-day Chloride Ponding Test," *PCI Journal,* Vol. 39, No. 1 (January–February 1994) pp. 38–47.
39. Andrade, C., "Calculation of Chloride Diffusion Coefficients in Concrete from Ionic Migration Measurements,*" Cement and Concrete Research,* Vol. 23 (1993) pp. 724–742.
40. Lafave, J.M., Pfeifer, D.W., Sund, D.J., Lovett, D., and Civjan, S.A., "Using Mineral and Chemical Durability-Enhancing Admixtures in Concrete," *Concrete International,* Vol. 24, No. 8 (August 2002) pp. 71–78.
41. Gruber, K.A., Ramlochan, T., Boddy, A., Hooton, R.D., and Thomas, M.D.A., "Increasing Concrete Durability with High-Reactivity Metakaolin," *Cement and Concrete Composites*, Vol. 23 (2001) pp. 479–484.
42. Scanlon, J.M., and Sherman, M.R., "Fly Ash Concrete: An Evaluation of Chloride Penetration Testing Methods," *Concrete International*, Vol. 18, No. 6 (June 1996) pp. 57–62.
43. Tanaka, Y., Kawano, H., Watanabe, H., and Nakajo, T., "Study on Required Cover Depth of Concrete Highway Bridges in Coastal Environments," *17th U.S.–Japan Bridge Engineering Workshop* (2001).
44. Liu, T.C., "Abrasion Resistance," *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, 4th Edition, P. Klieger and J.F. Lamond, editors, STP:169c, ASTM, Fredericksburg, VA (1994) pp. 182–191.
45. Gebler, S.H., and Klieger, P. "Effect of Fly Ash on Some Physical Properties of Concrete," *Research and Development Bulletin RD089*, Portland Cement Association (1986).
46. Laplante, P.C., Aïtcin, P.C., and Vezina, D., "Abrasion Resistance of Concrete," *Journal of Materials in Civil Engineering,* Vol. 3, No. 1 (February 1991) pp. 19–28.
47. Krauss, P.D., and Rogalla, E.A., *NCHRP Report 380: Transverse Cracking in Newly Constructed Bridge Decks*, Transportation Research Board, National Research Council, Washington, DC (1996) 126 pp.
48. Klieger, P., and Perenchio, W., "Laboratory Studies of Blended Cement: Portland-Pozzolan Cements," *Research and Development Bulletin RD013*, Portland Cement Association, Skokie, IL (1972).
49. Brooks, J., and Neville, A., "Creep and Shrinkage of Concrete as Affected by Admixtures and Cement Replacement Materials." *Creep and Shrinkage of Concrete Effect of Materials and Environment*, SP135, Detroit, MI (1992) pp. 19–36.
50. Li, Z., Qi, M., Li, Z., and Ma, B., "Crack Width of High-Performance Concrete Due to Restrained Shrinkage." *Journal of Materials in Civil Engineering*, Vol. 11, No. 3 (August 1999) pp. 214–223.
51. Canadian Standards Association, "A23.4-00, Precast Concrete—Materials and Construction/Qualification Code for Architectural and Structural Precast Concrete Products" (2002).
52. Kadri, E., and Duval, R., "Effect of Silica Fume on the Heat of Hydration of High-Performance Concrete," *Seventh CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete,* SP199, American Concrete Institute, Detroit, MI (1999).
53. Alshamsi, A., "Microsilica and Ground Granulated Blast Furnace Slag Effects on Hydration Temperature." *Cement and Concrete Research*, Vol. 27, No. 12 (September 1997) pp. 1851–1859.
54. McCullough, B.F., and Rasmussen, R.O., Fast-Track Paving: Concrete Temperature Control and Traffic Opening Criteria for Bonded Concrete Overlays Volume II: HIPERPAV User's Manual, Federal Highway Administration Report FHWA-RD-98-168, Washington (1999).
55. Struble, L., and Hawkins, P., "Hydraulic Cements—Physical Properties," *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, 4th Edition, P. Klieger and J.F. Lamond, editors, STP:169c, ASTM, Fredericksburg, VA (1994) pp. 449–461.
56. Shilstone, J.M., Sr., "Concrete Mixture Optimization," *Concrete International* (June 1990) pp. 33–39.
57. Portland Cement Association, "Guide Specification for Concrete Subject to Alkali-Silica Reactions," PCA R&D Serial No. 2001, Skokie, IL (1998) 8 pp.
58. Fournier, B., Bérubé, M.-A., and Rogers, C., "Proposed Guidelines for the Prevention of Alkali-Silica Reaction in New Concrete Structures," *Transportation Research Record: Journal of the Transportation Research Board No. 1668* (1999) pp. 48–53.
59. ACI Committee 211, "211.1-91: Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete," *Manual of Concrete Practice*, American Concrete Institute, Farmington Hills, MI (1995).
60. Mehta, P.K., and Aïtcin, P.C., "Principles Underlying Production of High-Performance Concrete," *Cement, Concrete and Aggregates*, CCAGDP, Vol. 12, No. 2 (1990) pp. 70–78.
61. Montgomery, D.C., and Runger, G.C., *Applied Statistics and Probability for Engineers*, 3rd Edition. John Wiley & Sons, Inc. (2003).

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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