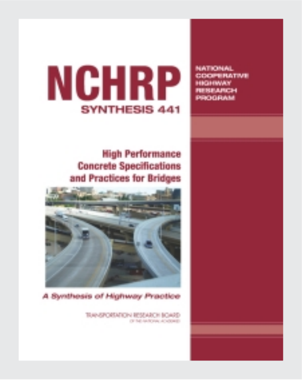

High Performance Concrete Specifications and Practices for Bridges

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 441

High Performance Concrete Specifications and Practices for Bridges

A Synthesis of Highway Practice

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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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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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Cover Figure: High performance concrete was used for the deck and substructure of the Lake Champlain Bridge in New York State. (Tony Straseske, Wisconsin Department of Transportation. *Courtesy:* New York State Department of Transportation.)

FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice.*

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Jo Allen Gause
Senior Program Officer
Transportation
Research Board

This synthesis documents the types of specifications and practices used by state transportation agencies to produce high performance concrete for bridges. The report also identifies specifications and practices reported as having improved concrete performance and those that have been less successful.

Information used in this study was acquired through a review of the literature, a survey of state departments of transportation (DOTs), and follow-up interviews with selected state DOTs.

Henry G. Russell, Henry G. Russell, Inc., Glenview, Illinois, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable with the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

HIGH PERFORMANCE CONCRETE SPECIFICATIONS AND PRACTICES FOR BRIDGES

SUMMARY

Specifications for concrete to be used in bridge structures have traditionally been prescriptive in nature, meaning that the constituent materials of the concrete and their relative proportions are stated like a recipe for a cake. In the 1990s, FHWA began to introduce the concept of performance specifications, which designate required results rather than means. FHWA suggested eight performance characteristics that could be quantified using standard tests, four related to concrete durability and four related to concrete strength for structural design. The durability characteristics were intended to increase the service life of the concrete, in particular, bridge decks, which have always been the Achilles heel of bridges. The structural design characteristics related to the applications of high-strength concrete, which allows the use of longer span lengths; wider girder spacings and fewer girders; shallower girders; or a combination of these, resulting in more economical structures. This material was called high performance concrete (HPC). State transportation agencies adopted these characteristics for concrete in bridges to varying degrees.

State documents for bridges generally include standard specifications, supplemental specifications, and special provisions. The standard specifications document is used for all projects. It may be updated periodically through the use of supplemental specifications or through the issuance of a revised document. Special provisions are issued to define the requirements for specific projects. This last type was used by those states that initially moved forward with the HPC concept. Since then, some states have begun to require HPC in their standard specifications, while others have changed their prescriptive specifications as a result of experience with HPC (although the concrete may not be called HPC).

The primary objectives of this synthesis are to document the types of specifications and practices used by state agencies to produce HPC, and to identify specifications and practices reported as having improved concrete performance and those that have not. Information for the synthesis was gathered from a survey sent to the departments of transportation (DOTs) of all U.S. states and Washington, D.C. The survey achieved an 82% response rate (42 responses). Six agencies were contacted after the survey for additional details about their specifications and practices. Information was also obtained from specifications for bridges published by AASHTO and state DOTs and from a literature review. The synthesis is intended to help bridge owners and designers determine the appropriate specifications for HPC in bridges.

Information collected for this synthesis indicates that specifications for concrete to be used in bridges remain largely prescriptive. The use of performance specifications is generally limited to special provisions for individual projects. Nevertheless, numerous changes have been made to the specifications, and states report that the performance of HPC is better than that of conventional concrete. However, despite the use of HPC, states still express concern about the amount of cracking in concrete bridge decks.

All states now permit the use of supplementary cementitious materials in the form of fly ash, silica fume, or slag cement in the concrete. These materials reduce the permeability of concrete, which makes the concrete more resistant to the penetration of water and deicing salts, and thus reduces the likelihood of bridge girder and deck deterioration from freeze-thaw damage and reinforcement corrosion.

States' prescriptive specifications limit the total amount of cementitious materials (cement plus supplemental cementitious materials) that may be used in the concrete, along with the percentages of supplementary cementitious materials that may be included. These specifications also address fine aggregate, coarse aggregate, chemical admixtures, air entraining admixtures, and other additives.

The survey of the state DOTs provided information about practices that were successful and unsuccessful in reducing bridge deck cracking. The successful practices generally related to reducing drying shrinkage of the concrete mix—for example, limiting the amounts of cementitious materials and water in the concrete and using the largest practical size of aggregate—in combination with construction practices to minimize deck cracking. These included avoiding high compressive strength concrete; applying wet curing immediately after finishing the concrete surface and continuing wet curing for at least seven days; and applying a curing compound after the wet curing to slow the moisture loss from the concrete. Overall, no single best practice that can be used to enhance concrete bridge deck performance was identified.

Several practices were identified by individual respondents as having no effect in improving concrete bridge deck performance in their state. These included specifying maximum slump; using prescriptive mix designs; specifying maximum and minimum concrete temperatures; using curing membranes and evaporation retardants; and omitting the casting of a trial or test slab before casting the deck.

Specifications for precast, prestressed concrete are less prescriptive than for cast-in-place concrete, with greater reliance placed on the supplier to develop the mix proportions. Compressive strength is the dominant property specified for precast, prestressed concrete. Precast, prestressed concrete beams appear to be performing satisfactorily using the existing specifications, with only a few performance issues reported in the survey.

In response to the survey, seven states suggested topics for future research, all but one of which were related to cracking in concrete bridge decks. The scope of these included identifying causes of cracking, evaluating the effect of different constituent materials, and identifying cost-effective methods of sealing cracks. The one exception asked for more effective means to ensure that concrete meets the performance criteria for the intended application.

CHAPTER ONE

INTRODUCTION

BACKGROUND

In 1993, FHWA initiated a national program to implement the use of high performance concrete (HPC) in bridges (Rabbat and Vanikar 1999). As part of this initiative, FHWA developed quantifiable definitions for eight concrete performance characteristics—four relating to durability and four relating to structural design (Goodspeed et al. 1996). Details about these characteristics are provided in chapter two.

The program included the construction of 19 demonstration bridges by state departments of transportation (DOTs) and dissemination of the technology and results at showcase workshops. Information about each bridge was compiled into a single compact disc (Russell et al. 2006a), which included a description of the bridge, benefits and costs of HPC, structural design details, specified properties, concrete mix proportions, measured concrete properties, research data, sources for the data, and the HPC specifications. After the bridges had been in service for several years, the bridge decks were inspected and their performance evaluated relative to the previously compiled data (Mokarem et al. 2009). The inspection indicated that cracking in the reinforced concrete bridge decks ranged from none to more than expected. Other observations also suggest that the use of HPC has resulted in more cracking of concrete bridge decks (Russell 2004).

A survey of highway agencies in 2003/2004 by FHWA showed that almost every agency had either incorporated HPC into their standard specifications, or had tried it at least during the previous 10 years (Triandafilou 2009). However, results were inconclusive as to the extent of HPC usage by each agency. A follow-up survey in 2006/2007 solicited information as to the number of bridges constructed with an HPC element (Triandafilou 2009). The results of the survey indicated a wide range of usage between agencies. The survey also revealed that agencies use three different methods to specify HPC. Twenty-two agencies reported using special provisions for individual projects, 22 reported using a combination of special provisions and general specifications, and eight used only general specifications. Also, HPC specifications were usually prescriptive or used a combination of performance and prescriptive provisions. Little use was being made of end-result performance specifications.

As a result of these activities, the use of HPC has increased but its success has been variable. At the same time, highway agencies have developed a wide range of specifications for HPC.

HIGH PERFORMANCE CONCRETE DEFINITIONS

Ever since the term “high performance concrete” was introduced into bridge industry terminology, numerous definitions have been created and published (Russell 2011).

Strategic Highway Research Program Definition

The first definition was developed as part of the first Strategic Highway Research Program (SHRP). It defined HPC by the following three requirements (Zia et al. 1991):

1. Maximum water-cementitious materials (w/cm) ratio of 0.35,
2. Minimum durability factor of 80% as determined by ASTM C666 Method A, and
3. Minimum compressive strength of
   a. 3.0 ksi within 4 hours after placement,
   b. 5.0 ksi within 24 hours, or
   c. 10.0 ksi within 28 days.

Federal Highway Administration Definition

In 1996, Goodspeed et al. published a definition for HPC that FHWA adopted for bridges. The definition consisted of four strength-related performance characteristics (compressive strength, modulus of elasticity, drying shrinkage, and creep) and four durability-related performance characteristics (freeze-thaw resistance, scaling resistance, abrasion resistance, and chloride penetration). For each characteristic, a standard test method was listed and various performance grades established. Consequently, the selection of performance characteristics and performance grades became a decision to be made by the owner for the intended application. For example, a precast, prestressed concrete bridge beam could be required to have a high concrete compressive strength and normal chloride permeability, whereas a bridge deck could have a low chloride permeability and normal concrete compressive strength. Both concretes would be HPC but with different requirements. More details of the FHWA definition are given in chapter two.

The intent of the FHWA definition was to stimulate the use of higher quality concrete in highway structures. Based on lessons learned from the implementation of HPC in bridges, the characteristics of alkali-silica reactivity (ASR), sulfate resistance, and workability were added to the previous eight performance characteristics (Russell and Ozyildirim 2006). The last characteristic became important with the introduction of self-consolidating concrete.

American Concrete Institute Definition

Although not intended specifically for bridges, the American Concrete Institute (ACI) defines HPC as "concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents, and normal mixing, placing, and curing practices" (ACI 2010). ACI has a separate definition for high strength concrete; that is, concrete that has a specified compressive strength for design of 8000 psi or greater (ACI Committee 363 2010).

American Association of State Highway and Transportation Officials Bridge Specifications

AASHTO LRFD (Load and Resistance Factor Design) Bridge Construction Specifications (AASHTO 2010a) includes two classes of HPC designated as P(HPC) and A(HPC). Class P(HPC) is intended for use in prestressed concrete members with a specified concrete compressive strength greater than 6.0 ksi. Class A(HPC) is intended for use in cast-in-place (CIP) construction with a specified concrete compressive strength less than or equal to 6.0 ksi and where performance criteria in addition to concrete compressive strength are specified. The Commentary to the AASHTO LRFD Bridge Design Specifications (AASHTO 2010b) includes a Class P(HPC) concrete intended for use when concrete compressive strengths in excess of 4.0 ksi are required.

OBJECTIVES AND SCOPE

The two primary objectives of this synthesis are as follows:

1. Document the specifications and practices for HPC used by state agencies, and
2. Identify specifications and practices reported as having improved bridge performance and those that have been less successful.

This synthesis is intended to help bridge owners, designers, contractors, and material suppliers determine the appropriate specification requirements for the use of HPC in bridges by providing information about current practices.

For purposes of this synthesis, HPC includes FHWA's 11 performance characteristics of permeability, freeze-thaw resistance, deicer scaling, abrasion resistance, workability, resistance to ASR, sulfate resistance, compressive strength, modulus of elasticity, creep, and drying shrinkage. It does not include ultra-high performance concrete (UHPC). UHPC is generally defined as a cementitious-based composite material with fiber reinforcement and having a compressive strength greater than 20 ksi and enhanced durability by means of a discontinuous pore structure (Graybeal 2011).

The synthesis does not include information on bonded overlays, internally cured concrete, lightweight concrete, self-consolidating concrete, and substructure concrete unless such information was supplied in response to the survey.

The synthesis describes the evolution of HPC for bridges in the United States. It then reports on current specifications for CIP and precast, prestressed concrete with primary emphasis on CIP bridge decks; precast, prestressed concrete beams; and precast, prestressed concrete deck panels.

Information gathered for this synthesis includes the following:

- State DOTs' approaches for incorporating HPC in their specifications and implementation in construction practices;
- State specifications and practices addressing materials, construction, testing, acceptance criteria, and performance of HPC;
- Testing requirements for the acceptance of a new HPC mixture's performance (e.g., structural or durability);
- Specification types used by states (e.g., prescriptive, performance, or hybrid);
- Practices for evaluating short- and long-term HPC performance of in-service structures; and
- Specifications and practices reported as successful or unsuccessful.

RESEARCH METHODOLOGY

Information for this synthesis was obtained from a review of published literature, review of state agencies' specifications, and a survey of highway agencies through the AASHTO Highway Subcommittee on Bridges and Structures. The purpose of the survey was to obtain information about actual state practices, both successful and unsuccessful, that could not be learned from reviewing the specifications. Specifications include a range of options, some of which might not be used in practice.

Forty-two agencies (an 82% response rate) returned the survey. Following completion of the survey, six states were selected for a more in-depth report on their specifications and practices.

TERMINOLOGY

Many state specifications originated when cement was the only cementitious material used, most cement was shipped in bags, and water quantity was measured in gallons. Consequently, many specifications still refer to cement content rather than cementitious materials content, bags of cement rather than lb/yd^3, and gallons/bag rather than w/cm ratio (ACI 2010). This synthesis uses the current terminology. For purposes of the survey and reviewing the state specifications for this synthesis, it has been assumed that "cement" when used in specifications refers to cementitious materials content unless stated otherwise. Also, a bag of cement is assumed to weigh 94 lb and a gallon of water to weigh 8.33 lb. In some specifications, fly ash, silica fume, and slag cement are referred to as mineral admixtures. In this synthesis, they are called "supplementary cementitious materials" (SCMs). Specifications also refer to ground granulated blast-furnace slag. The terminology "slag cement" is generally used in this synthesis.

The terms water curing, wet curing, and moist curing are used in specifications to describe the means by which the surface of the concrete is kept continuously wet for a specified time period. This synthesis uses the terminology "wet curing."

The terminology "rapid chloride permeability" as used in this synthesis refers to measurements made using the AASHTO Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration (AASHTO T 277 or ASTM C1202). In this test method, concrete with a permeability less than or equal to 2000 coulombs and greater than 1000 coulombs is defined as having low chloride ion penetrability and is frequently called low permeability concrete. However, other test methods exist that can be used to measure permeability.

REPORT ORGANIZATION

The text of the synthesis is organized as follows:

- Chapter two addresses the evolution of HPC for bridges beginning with the first strategic Highway Research Program in the 1980s. It describes the various initiatives undertaken by FHWA and AASHTO to promote the use of HPC with the state agencies.
- Chapter three addresses how states are currently incorporating HPC in their specifications and in their construction of CIP concrete with emphasis on bridge decks. This includes information about materials, construction, testing, acceptance criteria, and short- and long-term performance of in-service structures. Most of the information for chapter three came from the survey of state DOTs and review of state bridge specifications.
- Chapter four addresses how states are currently incorporating HPC in their specifications and in their construction practices for precast concrete with emphasis on precast, prestressed concrete beams and deck panels. This includes information about materials, construction, testing, acceptance criteria, and short- and long-term performance of in-service structures. Most of the information for chapter four came from the survey of state DOTs and review of state bridge specifications.
- Chapter five provides a more in-depth discussion of the development and usage of HPC in the states of Kansas, Louisiana, New York, Virginia, Washington, and Wisconsin.
- Chapter six summarizes the current status of specifications with regard to HPC and the practices and details that have proven to enhance the performance of concrete bridges. Practices that have not been successful are also identified, and some knowledge gaps that could be filled by research are listed.
- Appendices provide the survey questionnaire (Appendix A), a summary of the responses to the questionnaire (Appendix B), and a listing of websites for state specifications (Appendix C).

CHAPTER TWO

EVOLUTION OF HIGH PERFORMANCE CONCRETE FOR BRIDGES

The concept of HPC was first introduced in the 1980s and was often associated with high strength concrete for columns of high-rise buildings with measured compressive strengths as high as 19.0 ksi. During the same period, high strength concrete was used in limited bridge applications in the United States such as the East Huntington Bridge across the Ohio River (8.0 ksi design strength) and Tower Road Bridge in Washington State (9.0 ksi design strength) (ACI Committee 363 2010).

In the mid- to late 1980s, greater interest developed in the potential use of HPC in bridges to extend the service life of concrete bridge decks and the capacities of prestressed concrete beams. The interest at the national level began with the first Strategic Highway Research Program (SHRP).

STRATEGIC HIGHWAY RESEARCH PROGRAM

SHRP was a five-year national research program initiated in 1987 to develop and evaluate techniques and technologies to combat the deteriorating conditions of the nation's highways. One of the four program areas of SHRP was Concrete and Structures, which included project C-205 titled "Mechanical Behavior of High Performance Concrete." The SHRP project included both bridge and pavement applications.

For purposes of the SHRP project, HPC was initially defined by the following three requirements (Zia et al. 1991):

1. Maximum w/cm ratio of 0.35,
2. Minimum durability factor of 80% as determined by ASTM C666 Method A (AASHTO T 161, Method A), and
3. Minimum compressive strength of
    a. 3.0 ksi within 4 hours after placement,
    b. 5.0 ksi within 24 hours, or
    c. 10.0 ksi within 28 days.

This definition incorporated criteria related to both durability and strength. A subsequent report cautions against confusing high performance concrete with high strength concrete, as there are many factors that may be more important than strength in a given application (Zia et al. 1997). By completion of the project, the criteria for HPC had been refined to those shown in Table 1.

SHRP's research on the mechanical behavior of HPC had three general objectives:

1. Obtain information needed to fill gaps in existing knowledge;
2. Develop new, significantly improved engineering criteria for the mechanical properties and behavior of HPC; and
3. Provide recommendations and guidelines for using HPC in highway applications according to the intended use, required properties, environment, and service.

Both plain and fiber-reinforced concretes were included in the study.

The first task of the project was a literature search and review to define the existing knowledge about the mechanical properties of HPC. An annotated bibliography containing 830 references published between 1974 and 1989 was compiled and published (Leming et al. 1990). About 150 references from the bibliography were selected for critical review leading to a state-of-the-art report (Zia et al. 1991).

Subsequent tasks addressed the properties for the various types of concrete listed in Table 1. The results were published in six related reports:

Volume 1 Summary Report (Zia et al. 1993a)
Volume 2 Production of High Performance Concrete (Zia et al. 1993b)
Volume 3 Very Early Strength (VES) Concrete (Zia et al. 1993c)
Volume 4 High Early Strength (HES) Concrete (Zia et al. 1993d)
Volume 5 Very High Strength (VHS) Concrete (Zia et al. 1993e)
Volume 6 High Early Strength Fiber-Reinforced Concrete (HESFRC) (Naaman et al. 1993).

The project involved extensive testing of concrete mixes to develop information about compressive strength, flexural tensile strength, splitting tensile strength, drying shrinkage, creep, freeze-thaw resistance, rapid chloride permeability, AC impedance, concrete to concrete bonding, and concrete to steel bonding. The research involved laboratory experiments as well as field studies.

TABLE 1
CRITERIA FOR HIGH PERFORMANCE CONCRETE

Category of HPC	Minimum Compressive Strength	Maximum Water/ Cement Ratio	Minimum Frost Durability Factor
Very Early Strength (VES)			
Option A	2.0 ksi in 6 hours	0.40	80%
Option B	2.5 ksi in 4 hours	0.29	80%
High Early Strength (HES)	5.0 ksi in 24 hours	0.35	80%
Very High Strength (VHS)	10.0 ksi in 28 days	0.35	80%

Based on Zia et al. (1993a).

The research determined that the specifications at that time had been formulated primarily from the knowledge of conventional materials. As such, some requirements may not be applicable to HPC and would serve as barriers to the acceptance of HPC for highway applications (Zia et al. 1993a). Although no barriers were identified in the codes and specifications of AASHTO, ASTM, and ACI, several barriers were identified in the specifications of state highway agencies. The authors of the six reports encouraged state agencies to update their specifications to accommodate the latest information on concrete technology.

In 1996, the same authors of the SHRP state-of-the-art report published two sequel reports, which covered the period from 1989 to 1994 (Zia et al. 1996, 1997). The authors reported a phenomenal growth in the amount of research and applications of HPC in this five-year period, with increasing emphasis being placed on concrete durability rather than strength.

FEDERAL HIGHWAY ADMINISTRATION DEMONSTRATION PROJECTS

In 1993, the FHWA initiated a national program to implement the use of HPC in bridges. The program included the construction of demonstration bridges by state DOTs in each of the FHWA regions and dissemination of the technology and results at showcase workshops. Eighteen bridges in 13 states were included in the national program. In addition to the joint state-FHWA HPC initiative, other states have implemented the use of HPC in various bridge elements (Russell et al. 2006a).

The bridges are located in different climatic regions of the United States and use different types of superstructures as listed in Table 2. The bridges demonstrate practical applications of HPCs.

In addition, construction of these bridges provided opportunities to learn more about the placement and actual behavior of HPC in bridges. Consequently, many of the bridges were instrumented to monitor their short- and long-term performance. Also, concrete material properties were measured for most of the bridges.

All bridges used precast, prestressed concrete beams with specified concrete compressive strengths ranging from 5.5 to 8.8 ksi at strand release and 8.0 to 14.0 ksi for design as listed in Table 2. Rapid chloride permeability was specified for the beams of 11 bridges with values ranging from 1000 to 3000 coulombs at 56 days or 1000 to 2500 coulombs at 28 days using accelerated curing.

All bridges except the one in Ohio used a CIP deck with thicknesses ranging from 7.0 to 9.0 in. The Ohio bridge used a 3-inch-thick asphalt overlay on top of adjacent box beams. Specified concrete compressive strengths for the deck concretes ranged from 4.0 to 8.0 ksi with most values being in the 4.0 to 6.0 ksi range as shown in Table 3. Rapid chloride permeability was specified for nine bridge decks with values ranging from 1000 to 2000 coulombs at 56 days or 1500 to 2500 coulombs at 28 days using accelerated curing.

The concrete mixes for the precast, prestressed concrete beams and CIP concrete decks contained various combinations of cement and fly ash; cement, fly ash, and silica fume; and cement and silica fume. Only one bridge included slag cement, which was used in combination with cement and silica fume for the precast, prestressed concrete beams and in combination with cement only for the CIP concrete deck (Russell et al. 2006a).

As part of the initiative to implement the use of HPC in bridges, FHWA introduced eight performance characteristics, shown in Table 4, to encompass both durability and structural design. The four characteristics for durability were freeze-thaw resistance, scaling resistance, abrasion resistance, and chloride ion penetration. The four structural design characteristics were compressive strength, modulus of elasticity, drying shrinkage, and creep.

For each characteristic, an ASTM or AASHTO standard test method was selected. When the test methods offered alternative procedures, such as specimen size, the alternative to be used was specified. A range of two to four performance grades was also selected for each characteristic. With this approach, it was

TABLE 2
HPC DEMONSTRATION BRIDGES AND SUPERSTRUCTURE TYPES

State	Bridge Name	Superstructure Type	Specified Concrete Design Strength for Beams, ksi	Open to Traffic (year)
Alabama	Highway 199	BT-54	10.0 at 28 days	2000
Colorado	Yale Avenue	Box Beam	10.0 at 56 days	1998
Georgia	SR-920	AASHTO Type II, IV	10.0 at 56 days	2002
Louisiana	Charenton Canal Bridge	AASHTO Type III	10.0 at 56 days	1999
Nebraska	120th Street	NU1100	12.0 at 56 days	1996
New Hampshire	Route 104, Bristol	AASHTO Type III	8.0 at 28 days	1996
New Hampshire	Route 3A, Bristol	NE 1000	8.0 at 28 days	1999
New Mexico	Rio Puerco	BT1600	10.0 at 56 days	2000
North Carolina	US-401	AASHTO Type IV, III	10.0 at 28 days	2000/2002
Ohio	U.S. Route 22 near Cambridge	Box Beam B42-48	10.0 at 56 days	1998
South Dakota	I-29 Northbound	AASHTO Type II	9.9 at 28 days	1999
South Dakota	I-29 Southbound	AASHTO Type II	9.9 at 28 days	2000
Tennessee	Porter Road	BT-72	10.0 at 28 days	2000
Tennessee	Hickman Road	BT-72	10.0 at 28 days	2000
Texas	Louetta Road	Texas U 54	13.1 at 56 days[1]	1998
Texas	San Angelo	AASHTO Type IV	14.0 at 56 days[1]	1998
Virginia	Route 40, Brookneal	AASHTO Type IV	8.0 at 28 days	1996
Virginia	Virginia Avenue, Richlands	AASHTO Type III	10.0 at 28 days	1997
Washington	State Route 18	Washington W 74G	10.0 at 56 days	1998

Based on Russell et al. (2006a).

[1] For the Texas bridges, different concrete strengths were specified for different girder span lengths. Listed strengths are the largest values.

not necessary to specify every characteristic or to specify the same grade for different characteristics. The intent was to select the characteristics and grades to match the intended application and its environment. Each state selected the characteristics for its demonstration bridges. Estimates of relationships between each performance grade and severity of field conditions were provided to assist designers in selecting the grade of HPC for a particular project (Goodspeed et al. 1996).

Following completion of the demonstration projects, information about each bridge was collected and compiled into a single source compact disc. Details about the characteristics specified and measured on each demonstration project are given in Russell et al. (2006a). An analysis of the specifications used for the demonstration bridges indicated that the primary characteristic specified for durability was rapid chloride permeability with values ranging from 1000 to 3000 coulombs. Approximately three-quarters of the specified values were between 800 and 2000 coulombs. Freeze-thaw resistance was specified for one bridge, whereas scaling resistance and abrasion resistance were not specified for any bridges.

For strength characteristics, compressive strength was the only characteristic specified for the girders and decks of all bridges. For the majority of the bridges, the specified compressive strength for the girder concrete was 10.0 ksi. This corresponds with the upper limit in the AASHTO LRFD Specifications (AASHTO 2010b). The majority of measured compressive strengths were in the range of 10 to 14 ksi.

For the deck concrete, the majority of the specified strengths ranged from 4 to 6 ksi. This is to be expected because there is no reason to specify higher strengths for the concrete deck in most slab and girder bridges. Durability properties are more important for bridge decks and a high strength concrete does not guarantee a durable concrete (Russell et al. 2006a).

TABLE 3
HPC DEMONSTRATION BRIDGES AND SPECIFIED DECK CONCRETE PROPERTIES

State	Bridge Name	Specified Properties for Deck Concrete	
		Compressive Strength, ksi	Permeability, coulombs
Alabama	Highway 199	6.0 @ 28 days	—
Colorado	Yale Avenue	5.1 @ 28 days	—
Georgia	SR-920	7.3 @ 56 days	2000 @ 56 days
Louisiana	Charenton Canal Bridge	4.2 @ 28 days	2000 @ 56 days
Nebraska	120th Street	8.0 @ 56 days	1800 @ 56 days
New Hampshire	Route 104, Bristol	6.0 @ 28 days	1000 @ 56 days
New Hampshire	Route 3A, Bristol	6.0 @ 28 days	1000 @ 56 days
New Mexico	Rio Puerco	6.0 @ 28 days	—
North Carolina	US-401	6.0 @ 28 days	—
South Dakota	I-29 Northbound	4.5 @ 28 days	—
South Dakota	I-29 Southbound	4.5 @ 28 days	—
Tennessee	Porter Road	5.0 @ 28 days	1500 @ 28 days[1]
Tennessee	Hickman Road	5.0 @ 28 days	1500 @ 28 days[1]
Texas	Louetta Road	4.0 and 8.0 @ 28 days	—
Texas	San Angelo	6.0 and 4.0 @ 28 days	—
Virginia	Route 40, Brookneal	4.0 @ 28 days	2500 @ 28 days[1]
Virginia	Virginia Avenue, Richlands	5.0 @ 28 days	2500 @ 28 days[1]
Washington	State Route 18	4.0 @ 28 days	—

Based on Russell et al. (2006a).
[1] Includes curing for 21 days at 100°F.
— = not specified.

Based on a review of the FHWA characteristics, grades, and test methods, Russell et al. (2006a) proposed the following revisions:

- Each characteristic should have three grades.
- Grades should always be considered minimum performance levels.
- The addition of alkali-silica reactivity, sulfate resistance, and flowability to the eight previous characteristics.
- Modifications to some of the test procedures.
- Requirement to specify a characteristic only when it is necessary for the intended application.

The 11 characteristics and the three grades of performance are shown in Table 5.

After the demonstration bridges described above had been in service for five to 10 years, the decks were inspected and their performance evaluated using relevant information pertaining to the construction of each bridge deck (Mokarem et al. 2009). The construction data included concrete mix design, construction practices during and after concrete placement, average daily traffic on the bridge, and maintenance performed.

The deck inspections included a detailed visual inspection of the top surface, as well as the preparation of detailed crack maps. Concrete cores were acquired from selected locations for petrographic analysis.

The field surveys found that the HPC was generally performing well with no indication of any significant deterioration resulting from material properties. There were no indications of alkali-silica reaction, sulfate attack, or other deleterious reactions. There was also no significant spalling or delamination observed on the bridge decks. There was some spalling along the edges of some cracks, but this was not considered significant.

When the structural system of the bridge included continuity over the supports, negative moment transverse cracks

TABLE 4
GRADES OF EIGHT PERFORMANCE CHARACTERISTICS FOR HIGH PERFORMANCE STRUCTURAL CONCRETE

Performance Characteristic	Standard Test Method	FHWA HPC Performance Grade			
		1	2	3	4
Freeze-thaw Durability (x = relative dynamic modulus of elasticity after 300 cycles)	AASHTO T 161 (ASTM C666) Proc. A	$60\% \leq x < 80\%$	$80\% \leq x$		
Scaling Resistance (x = visual rating of the surface after 50 cycles)	ASTM C672	$x = 4,5$	$x = 2,3$	$x = 0,1$	
Abrasion Resistance (x = avgerage depth of wear in mm)	ASTM C944	$2.0 > x \geq 1.0$	$1.0 > x \geq 0.5$	$0.5 > x$	
Chloride Penetration (x = coulombs)	AASHTO T 277 (ASTM C1202)	$3000 \geq x > 2000$	$2000 \geq x > 800$	$800 \geq x$	
Strength (x = compressive strength)	AASHTO T 22 (ASTM C39)	$6 \leq x < 8$ ksi	$8 \leq x < 10$ ksi	$10 \leq x < 14$ ksi	$x \geq 14$ ksi
Elasticity (x = modulus of elasticity)	ASTM C469	$4 \leq x < 6 \times 10^6$ psi	$6 \leq x < 7.5 \times 10^6$ psi	$x \geq 7.5 \times 10^6$ psi	
Drying Shrinkage (x = microstrain)	ASTM C157	$800 > x \geq 600$	$600 > x \geq 400$	$400 > x$	
Creep (x = microstrain/pressure unit)	ASTM C512	$0.52 \geq x > 0.41$/psi	$0.41 \geq x > 0.31$/psi	$0.31 \geq x > 0.21$/psi	$0.21/\text{psi} \geq x$

Adapted from Russell et al. (2006a).

TABLE 5
REVISED GRADES OF PERFORMANCE CHARACTERISTICS FOR HIGH PERFORMANCE STRUCTURAL CONCRETE

Performance Characteristic	Standard Test Method	FHWA HPC Performance Grade		
		1	2	3
Freeze-thaw Durability (F/T = relative dynamic modulus of elasticity after 300 cycles)	AASHTO T 161 (ASTM C666) Proc. A	$70\% \leq F/T < 80\%$	$80\% \leq F/T < 90\%$	$90\% \leq F/T$
Scaling Resistance (SR = visual rating of the surface after 50 cycles)	ASTM C672	$3.0 \geq SR > 2.0$	$2.0 \geq SR > 1.0$	$1.0 \geq SR \geq 0.0$
Abrasion Resistance (AR = average depth of wear in mm)	ASTM C944	$2.0 > AR \geq 1.0$	$1.0 > AR \geq 0.5$	$0.5 > AR$
Chloride Penetration (CP = coulombs)	AASHTO T 277 (ASTM C1202)	$2500 \geq CP > 1500$	$1500 \geq CP > 500$	$500 \geq CP$
Alkali-silica Reactivity (ASR = expansion at 56 d) (%)	ASTM C441	$0.20 \geq ASR > 0.15$	$0.15 \geq ASR > 0.10$	$0.10 \geq ASR$
Sulfate Resistance (SR = expansion) (%)	ASTM C1012	$SR \leq 0.10$ at 6 months	$SR \leq 0.10$ at 12 months	$SR \leq 0.10$ at 18 months
Flowability (SL = slump, $S F$ = slump flow)	AASHTO T 119 (ASTM C143) and proposed slump flow test	$SL > 7\text{-}1/2$ in. and $SF < 20$ in.	$20 \leq SF \leq 24$ in.	24 in. $< SF$
Strength (f'_c = compressive strength)	AASHTO T 22 (ASTM C39)	$8 \leq f'_c < 10$ ksi	$10 \leq f'_c < 14$ ksi	14 ksi $\leq f'_c$
Elasticity (E_c=modulus of elasticity)	ASTM C469	$5 \leq E_c < 6 \times 10^6$ psi	$6 \leq E_c < 7 \times 10^6$ psi	7×10^6 psi $\leq E_c$
Drying Shrinkage (S = microstrain)	AASHTO T 160 (ASTM C157)	$800 > S \geq 600$	$600 > S \geq 400$	$400 > S$
Creep (C = microstrain/pressure unit)	ASTM C512	$0.52 \geq C > 0.38$/psi	$0.38 \geq C > 0.21$/psi	$0.21/\text{psi} \geq C$

Adapted from Russell et al. (2006a).

occurred. The bridge geometry influenced the amount of concrete cracking. For example, bridges with skewed supports exhibited more cracking than rectangular bridges because of the torsional stresses.

Using crack survey data from each bridge, the length of the transverse, diagonal, and longitudinal cracks on each deck were calculated. For all bridge decks, the average crack lengths were 0.073 ft/ft^2 transversely; 0.008 ft/ft^2 diagonally; 0.042 ft/ft^2 longitudinally; and 0.123 ft/ft^2 totally. However, the total crack lengths on each bridge ranged from 0.003 to 0.741 ft/ft^2. In comparison, Browning and Darwin (2007) reported crack lengths ranging from 0.0 to 0.31 ft/ft^2 for bridge decks in Kansas. The results also indicated that in some cases, the use of HPC reduced bridge deck cracking, whereas in other cases the crack lengths were greater.

By comparing the crack lengths with the corresponding concrete mix proportions, Mokarem et al. (2009) concluded that a high performance concrete mix with a w/cm between 0.35 and 0.40 and a cementitious materials content between 600 and 700 lb/yd^3, used with construction practices such as seven-day wet curing, should result in shorter crack lengths.

RESEARCH PROJECTS

Each demonstration project included a research component. On some projects, the research focused on concrete material properties. Measurements were made on different projects to determine compressive strength, modulus of elasticity, tensile strength, creep, drying shrinkage, chloride permeability, freeze-thaw resistance, deicer scaling resistance, and abrasion resistance. Concrete temperatures were measured during curing to determine the heat of hydration of the prestressed concrete beams. The use of match-cured cylinders for measurements of concrete compressive strengths compared with the use of conventionally cured cylinders was also investigated. On other projects, the research was used to determine prestress losses, temperature gradients in the deck and girders resulting from daily and seasonal temperature changes, strand transfer length, long-term camber, and load distribution. Information from the showcase bridges was collected by the FHWA and compiled onto a compact disc for easy retrieval and viewing (Russell et al. 2006a).

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS LEAD STATES TEAM FOR HIGH PERFORMANCE CONCRETE IMPLEMENTATION

To implement the results of the SHRP program, AASHTO created a task force consisting of multiple teams (Moore 1999). The AASHTO Lead States Team for HPC implementation consisted of representatives of industry, FHWA, and states. Its mission was to promote the implementation of HPC technology for use in pavements and bridges and to share knowledge, benefits, and challenges with the states and their customers. The team began its work in 1996.

When the HPC lead states team's mission ended in 2000, a majority of states were using conventional strength HPC for bridge decks, almost half were using high strength HPC for bridge beams, and others were using HPC for superstructures and substructures (Moore and Ralls 2000). The team's outreach initiatives included HPC bridge showcases, international symposia, conference and meeting presentations, articles in various publications, and establishment of points of contact in each state to champion HPC technology.

FEDERAL HIGHWAY ADMINISTRATION HIGH PERFORMANCE CONCRETE TECHNOLOGY DELIVERY TEAM

The FHWA HPC Technology Delivery Team (TDT) was established in 1997 through funding in the Intermodal Surface Transportation Efficiency Act (ISTEA). The TDT helped 13 states build HPC bridges and host or participate in technology transfer forums such as showcases and workshops. Working with the AASHTO Lead States Team, the TDT influenced many additional DOTs to try HPC in their highway structures. When the ISTEA funding ended in 1997, about 25 states had used HPC (Halkyard 2002).

The mission of the TDT was renewed in 2002 with a focus on field delivery of HPC technology. A new community of practice website for HPC was developed, allowing users to post questions, participate in discussions, and review work in progress. This website is archived at https://www.transportationresearch.gov/dot/fhwa/hpc/Lists/aReferences/AllItems.aspx [August 11, 2012]. One publication by the TDT is the High Performance Concrete Structural Designers Guide, a source of information to structural designers for the design and construction of highway bridges and related structures using HPC. The guide includes all aspects of developing and producing HPC with desirable and beneficial characteristics (Triandafilou et al. 2005).

The TDT also conducted surveys of state highway agencies in 2003–2004 and 2006–2007 to determine the usage of HPC in bridges. Figures 1 and 2 summarize the results of the two surveys. These two figures indicate that every state except two has used HPC in bridge decks or beams. In the 2006–2007 survey, Montana and Mississippi reported that they had not used HPC in beams and bridge decks. However, both states reported using HPC in overlays and Mississippi reported using HPC in substructures. Therefore, every state has used HPC in at least one bridge component.

In the 2003–04 survey, 37 respondents reported using of HPC for its low permeability, 30 for its high strength, and 26 for both performance characteristics (Triandafilou 2004). Asked why HPC was being used, respondents ranked deck cracking at less than five years as the most common reason,

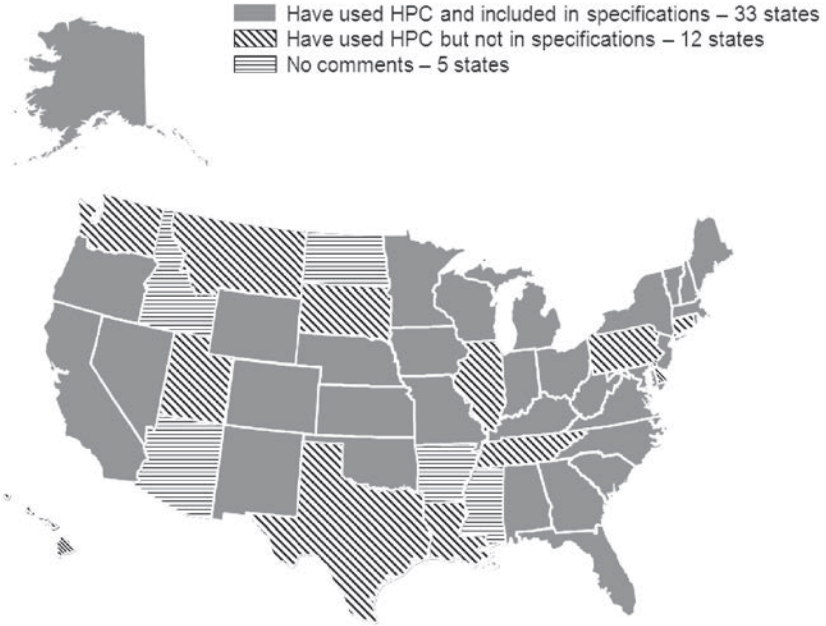

FIGURE 1 States' use of HPC in 2003–2004 survey.

followed by corrosion of reinforcing steel, cracking of girders and substructure elements, and freeze-thaw damage. The survey indicated that, over the past 10 years, 77% of the respondents had made changes in their bridge deck curing requirements, 72% had made changes in their specified concrete strengths, and 64% had made changes in testing and acceptance requirements.

The 2006–07 survey asked about the usage since 2003 of HPC for deck overlays, deck slabs, superstructures, and substructures (Triandafilou 2009). Sixty-four percent of the states reported using HPC in deck overlays, 81% in decks, 62% in superstructures, and 55% in substructures. Only three states reported not using HPC in any of those four components.

Rapid chloride permeability values in the range of 1001 to 2000 coulombs were most commonly specified. Compressive strength of 4.0 to 5.0 ksi was most commonly specified for bridge decks and substructures, with 3.0 to 4.0 ksi being the next most common range. For superstructures, the compressive strength range of 8.0 to 10.0 ksi was the most frequently specified, followed by the 4.0 to 5.0 ksi range.

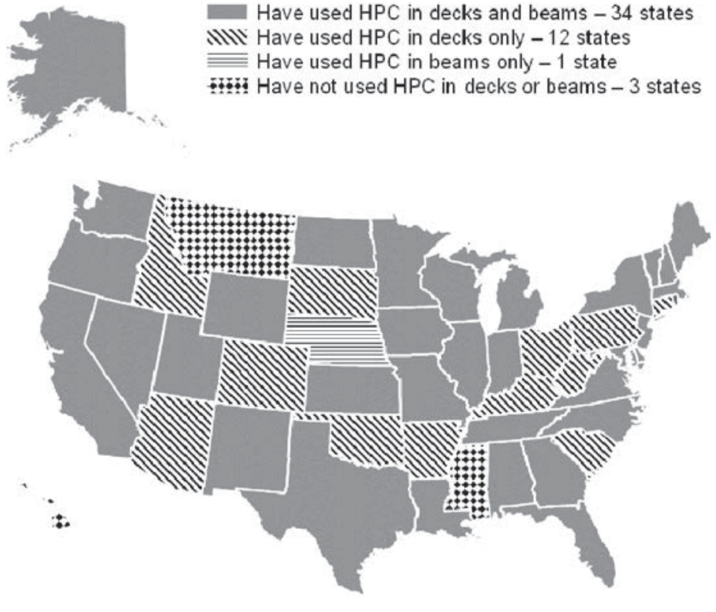

FIGURE 2 States' use of HPC in 2006–2007 survey.

The most common procedure of specifying HPC was either by special provisions for a particular project (22 agencies) or a combination of special provisions and general specifications (22 agencies). Only eight agencies used only general specifications. Only one agency, Virginia, had made substantial progress with end-result, performance-based specifications.

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS SPECIFICATIONS

The current AASHTO specifications related to the design and construction of the bridges with HPC include the *AASHTO LRFD Bridge Design Specifications,* the *AASHTO LRFD Bridge Construction Specifications,* and the *AASHTO Standard Specifications for Transportation Materials and Methods of Sample and Testing.* A review of these documents was made as part of the FHWA project: Compilation and Evaluation of Results from High Performance Concrete Bridge Projects (Russell et al. 2006a). Where sufficient information existed, proposed revisions were developed to facilitate the implementation of HPC (Russell et al. 2006b). The proposed revisions included 17 articles of the LRFD design specifications, 16 articles of the LRFD construction specifications, 15 material specifications, and 14 test methods. In addition, two new material specifications were proposed. Most of the proposed revisions resulted in changes to the specifications and test methods to remove the barriers to the use of HPC. As a result, the *AASHTO LRFD Bridge Design Specifications* and the *AASHTO LRFD Bridge Construction Specifications* specifically address the use of HPC as described in the next two sections.

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS LOAD RESISTANCE FACTOR DESIGN (LRFD) BRIDGE DESIGN SPECIFICATIONS

The Commentary in Article C5.4.2.1—Compressive Strength includes a table of concrete mix characteristics by class (AASHTO 2010b). Class P and Class P(HPC) concretes are intended to be used when compressive strengths in excess of 4.0 ksi are required. A maximum w/cm ratio of 0.49 is specified along with a minimum cementitious content of 564 lb/yd^3. For Class P concrete used in or over salt water, the w/cm ratio shall not exceed 0.45. Class P(HPC) concrete is permitted to have a total cementitious materials content up to 1,000 lb/yd^3 compared to 800 lb/yd^3 for other classes of concrete.

When the *LRFD Bridge Design Specifications* was first developed, its applicability was limited to a maximum design compressive strength of 10.0 ksi for normal weight concrete unless physical tests are made to establish the relationships between concrete strength and other properties. The current specifications allow higher strengths to be used when allowed by specific articles. This has permitted changes to be made as the results of ongoing research on higher strength concrete become available.

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS LOAD RESISTANCE FACTOR DESIGN (LRFD) BRIDGE CONSTRUCTION SPECIFICATIONS

Article 8.2.2 of the *AASHTO LRFD Bridge Construction Specifications* defines two classes of HPC (AASHTO 2010a). Class P(HPC) is intended for use in prestressed concrete members with a specified concrete strength greater than 6.0 ksi. Class A(HPC) is intended for use in CIP construction where performance criteria and concrete compressive strength are specified, or where the concrete is exposed to salt or brackish water or sulfates in soils or water.

Minimum cementitious materials content is not included for either class because this should be selected by the producer based on the specified performance criteria. However, a maximum cementitious materials content of 1,000 lb/yd^3 is specified. Maximum w/cm ratios of 0.40 and 0.45 for Class P(HPC) and Class A(HPC), respectively, have been included. For Class P(HPC) concrete, a coarse aggregate maximum size of 0.75 in. is specified, since it is difficult to achieve the higher concrete compressive strengths with larger size aggregates. For Class A(HPC) concrete, the maximum aggregate size is selected by the producer based on the specified performance criteria.

Air content for Class P(HPC) and A(HPC) concretes is to be determined from trial tests, but a minimum of 2% is recommended in the specifications. For both classes of concrete, trial batches using all the intended constituent materials are required prior to concrete placement to ensure that the specified properties can be achieved and the cementitious materials and admixtures are compatible.

For Class P(HPC) and Class A(HPC) concretes, the specifications permit any combination of cement and SCMs as long as the properties of the freshly mixed and hardened concrete comply with the specified values.

For acceptance of Class P(HPC) and Class A(HPC) concretes, the specifications state that any concrete represented by a test that indicates a strength less than the specified strength will be rejected and shall be removed and replaced with acceptable concrete. It also states that the concrete age when the specified strength is to be achieved must be shown on the contract documents, because 56 days or longer may be more appropriate for HPC.

For precast concrete with specified concrete compressive strength greater than 6.0 ksi, the specifications require the use of match curing for the test cylinders. The procedures for match curing are described in AASHTO PP-54 (2006). For Class A(HPC) concrete, wet curing is required to commence immediately after finishing operations are complete on any portion of the placement. For bridge decks, the specification requires water curing for a minimum period of seven days irrespective of concrete strength. These curing procedures are required because HPC tends to have very little bleed water.

CURRENT DEFINITIONS OF HIGH PERFORMANCE CONCRETE

As part of the survey for this synthesis, agencies were asked if they had a definition, formal or informal, for high performance concrete. Twenty agencies supplied a definition. Just under half related to one or more performance characteristic such as permeability; a similar number related to a prescriptive approach such as minimum amount of SCMs. The remaining definitions were more general, such as concrete with a life cycle of 75 years or more based on durability. The individual responses are provided in the answer to Question 1 in Appendix B.

From the responses to this one question, it is clear that transportation agencies define or perceive HPC in many different ways. Nevertheless, many responses to other questions indicated that agencies are looking for improved performance through the use of lower permeability concrete and reduced deck cracking. The lower permeability is being achieved through the use of SCMs (fly ash, silica fume, slag cement, or a combination). This follows the trend that was started during the demonstration projects where permeability was the most common durability characteristic that was specified. (Russell et al. 2006a.)

SPECIFICATION TYPES

In general, specifications can be classified as prescriptive, performance or performance-based, or a combination. A prescriptive specification for concrete is one in which the recipe to produce the concrete is detailed, listing the ingredients and their relative proportions and generally stated in lb/yd^3 of concrete. The specific ingredients are generally required to satisfy AASHTO or ASTM material standards, although generic names may be used if a material standard does not exist.

A performance or performance-based specification is one in which the requirements are stated in terms of the desired end results rather than specific composition (ACI 2010). Performance specifications are sometimes called end result specifications. The most obvious example of a performance specification is concrete compressive strength. In reality, most concrete specifications are a combination of prescriptive and performance requirements, such as a specified minimum cementitious materials content in combination with a specified minimum concrete compressive strength.

The use of performance specifications involves a shift in roles, responsibilities, and risks between owners, designers, and contractors (Chrzanowski 2011). The owner or design engineer becomes responsible for defining the quality characteristics and acceptance criteria of the concrete for the intended application. This requires being specific about sampling frequency, test methods, acceptance criteria, and pay factors for acceptable and inferior quality concrete.

A performance specification provides the concrete supplier with the freedom to design mixes without any restrictions in proportioning except for using constituent materials complying with the specifications (Ozyildirim 2011). However, the concrete supplier may not have the ability or interest in developing the mix proportions. In addition, the cost of the concrete may increase because the risk of not meeting the specification requirements is transferred to the contractor and concrete supplier.

With prescriptive specifications, the owner assumes the primary share of the risk (Taylor 2004). The use of a performance specification, however, does not preclude the use of some prescriptive requirements if this approach is more practical (Carino 2011).

Agency specifications consist of several documents. The primary document is often called the "Standard Specifications" and is applicable to all projects. This document is usually updated every few years. Some agencies issue "Supplemental Specifications" to augment the standard specifications. These are issued more frequently than the standard specifications. The third document is called "Special Provisions,' which is implemented on a project-by-project basis. The special provisions generally modify the standard specifications.

In the survey for this synthesis, agencies were asked whether they used standard specifications or special provisions to specify HPC. The results are shown in Figure 3. The most frequent response was special provisions for specific projects. The agencies were also asked if their standard specifications and special provisions for HPC were prescriptive, performance based, or a combination. As illustrated in Figure 4, the most frequent response from agencies for which the question was applicable was a combination. Only three states reported using only performance requirements for HPC in their standard specifications and special provisions. New Hampshire and New Mexico use performance requirements in their standard specifications and Maine and New Mexico in their special provisions.

LESSONS LEARNED FROM PREVIOUS APPLICATIONS

In the survey for this synthesis, agencies were asked how the HPC was performing in comparison with conventional concrete in an effort to determine if the use of HPC was beneficial. The results are shown in Figure 5 for CIP concrete, precast concrete girders, and precast concrete deck panels. It can be noted that only a limited number of agencies have experience with precast concrete deck panels.

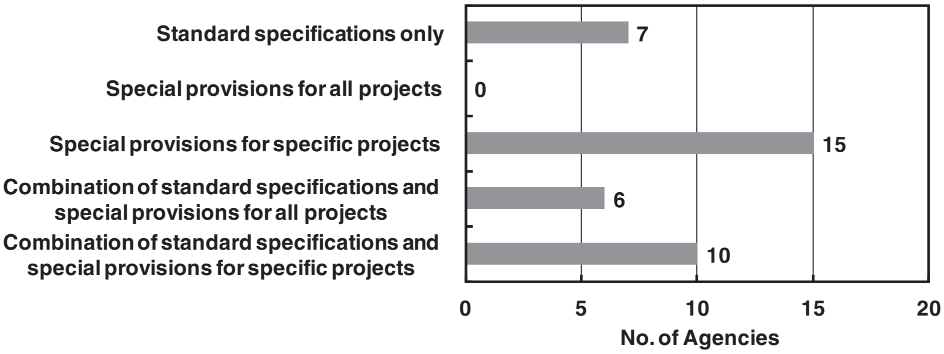

FIGURE 3 Number of agencies using standard specifications or special provisions for HPC.

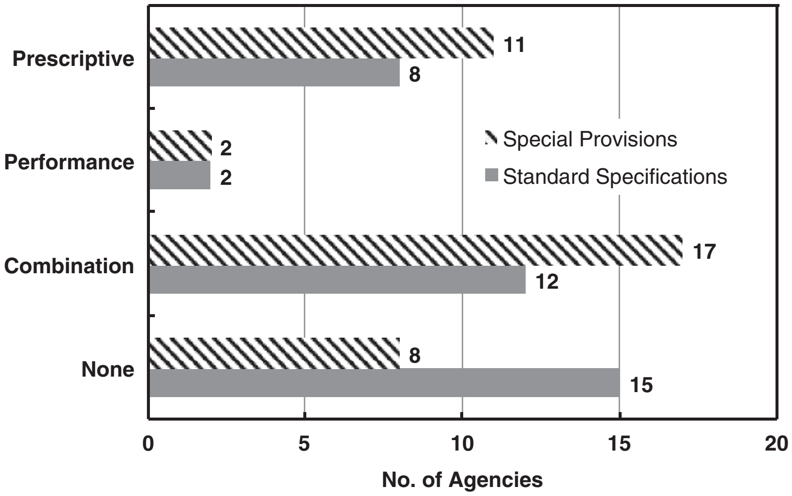

FIGURE 4 Number of agencies using prescriptive or performance criteria for HPC.

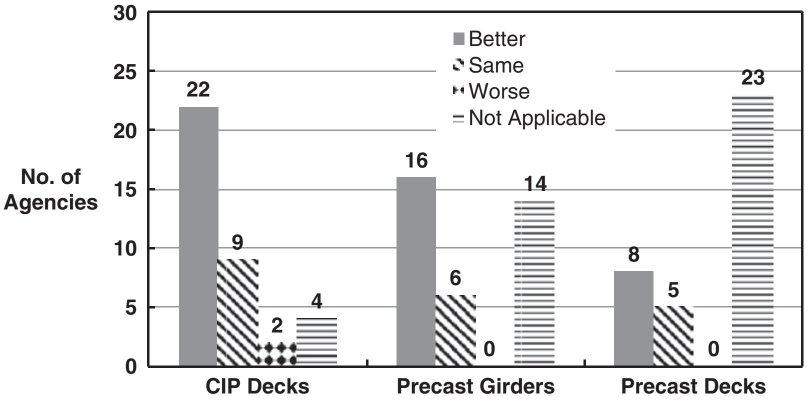

FIGURE 5 Relative performance of HPC versus conventional concrete.

Overall, 67% of the agencies that reported on performance stated that the CIP HPC was performing better that the conventional CIP concrete. Only two agencies reported worse performance. For precast concrete girders and deck panels, all respondents indicated the same or better performance with HPC.

Agencies also identified performance issues in using HPC in CIP concrete decks, precast concrete beams, and precast concrete deck panels. For CIP concrete decks, 23 states pointed to specific issues; the dominant one being drying shrinkage cracking. It appears that the use of HPC has resulted in better performance, as shown in Figure 5, but has not eliminated concerns about deck cracking. Other issues mentioned for CIP concrete were workability, regional availability of aggregates, ASR, corrosion, mix proportions, heat of hydration, effect of fly ash on air entrainment, and autogenous shrinkage. For precast concrete, seven states reported performance issues related to corrosion, ASR, shrinkage, slump consistency, consolidation, and cracking.

On the positive side, agencies reported many changes in specifications and practices that have resulted in improved concrete performance. These included the following:

- Developing special provisions for specific projects,
- Using performance-based specifications for bridge decks,
- Implementing a specification addressing ASR,
- Using high-strength concrete in precast girders to improve durability,
- Providing multiple options for concrete constituent materials,
- Specifying the amount of drying shrinkage,
- Specifying permeability limits,
- Starting wet curing immediately after concrete placement,
- Specifying and ensuring a longer wet curing period,
- Testing for more concrete properties than previously,
- Specifying limits on rate of strength gain,
- Using lower cement contents,
- Increasing the use of SCMs (fly ash, silica fume, and slag cement),
- Optimizing aggregate gradation,
- Using a corrosion inhibitor,
- Using self-consolidating concrete (SCC),
- Placing concrete at nighttime,
- Controlling evaporation rates, and
- Strictly enforcing air content requirements.

Increasing the use of SCMs, specifying and ensuring a longer wet curing period, and specifying permeability were listed more frequently than other factors.

Agencies were also asked to identify the specifications and practices that were unsuccessful. The following were listed:

- High early strength concretes were more prone to deck cracking.
- High concrete strengths have led to increased cracking in bridge decks.
- The use of silica fume resulted in workability issues and cracking in new decks.
- The use of shrinkage-reducing admixtures was successful in the laboratory, but the specified air content could not be maintained in the field.
- The use of shrinkage-reducing admixtures has helped reduce cracking but not to a satisfactory degree.
- Increasing the cement content to obtain lower permeability resulted in more cracks in the deck.
- Use of an evaporation retarder between final pass of the screed and start of wet curing resulted in excessive cracking in decks.
- Use of fly ash in bridge decks has resulted in increased cracking.
- Limited success was achieved with Class F fly ash content greater than 30%.
- The use of 14-day wet cure for decks still results in deck cracking.

The responses did not show any general consensus. The one practice that was not successful for three states was the use of silica fume.

A comparison of the successful and unsuccessful practices listed above indicates that different states have had conflicting experiences with the same practices. The use of lower cement content in combination with the use of SCMs has resulted in lower permeability concrete but may result in increased deck cracking. Specifying a maximum value for permeability can be beneficial in reducing chloride penetration, but a low value can lead to increased deck cracking. The use of fly ash has been beneficial in some states but detrimental in others.

One observation that emerges from the answers to these questions is the need to reduce concrete bridge deck cracking while providing a concrete with low permeability. According to *NCHRP Synthesis 333* (Russell 2004), the use of concretes with lower w/cm ratios and SCMs has resulted in concretes with higher concrete compressive strengths, higher tensile strength, higher moduli of elasticity, and lower creep. Although the tensile strength is higher, the higher moduli of elasticity and lower creep have led to an increase in the amount of cracking. This provides the chlorides with an easier path to the reinforcement, thus eliminating the benefits of the low permeability concrete between the cracks.

SUMMARY OF THE EVOLUTION OF HIGH PERFORMANCE CONCRETE FOR BRIDGES

The first activities towards the use of HPC for bridges began in 1987 with the SHRP project titled "Mechanical Behavior of High Performance Concrete." This was followed by demonstration projects in 13 states, the formation of an AASHTO Lead States Team for HPC Implementation, and an FHWA HPC Technology Delivery Team. At the same time, revisions were made to the *AASHTO LRFD Bridge Design Specifications* and the *AASHTO LRFD Bridge Construction Specifications* to remove barriers to the use of HPC. As a result, state DOTs began to move away from the use of prescriptive specifications to the greater use of performance specifications and the use of HPC in bridges.

Overall, the use of HPC in bridge decks, precast girders, and precast decks has resulted in better or the same performance compared with conventional concrete. In the survey for this synthesis, state agencies identified many changes in specifications and practices that led to the improvement in performance. States also identified unsuccessful practices. The major issue with the performance of concrete bridges is the need to reduce deck cracking while providing a concrete with low permeability. Relatively few issues were identified regarding the use of HPC in precast girders or deck panels.

CHAPTER THREE

CURRENT SPECIFICATIONS AND PRACTICES FOR CAST-IN-PLACE CONCRETE

This chapter addresses the specifications and practices for the use of CIP HPC primarily in bridge decks. The information was obtained from a review of the state specifications and information obtained from the survey. A list of the websites for the state standard specifications is provided in Appendix C. The standard specifications of nearly every state include a table that provides the basic requirements for several different classes or grades of concrete intended for different applications. The table generally includes information on cementitious materials content, w/cm ratio or water content, air content, slump, and compressive strength. Some tables include complete mix proportions. Numerous footnotes or related text provide further information about the type and quantities of materials, substitutions, and exceptions. This chapter and chapter four include information from these tables and the related text.

As part of the survey for this synthesis, agencies were asked if they had used HPC for CIP bridge decks. Thirty-one agencies responded that they had and eight agencies responded that they had not. Reasons for not using HPC included:

- Agency used HPC for deck overlays only.
- Agency had tried it in comparison with conventional concrete on one project and observed no noticeable difference.
- The improved curing process improved the durability of decks, but the additional expense of HPC was not justified.
- Standard concrete with epoxy-coated reinforcement was performing well.
- Cost-benefit ratio was not favorable.
- Agency does not call it HPC but uses a prescriptive approach.
- HPC was not needed.

SPECIFIED PROPERTIES

The standard specifications of all states have some prescriptive requirements for the concrete. These include values for the amounts of cementitious materials, w/cm ratio, slump, and air content. The amounts of cementitious materials are discussed in the next section. At least 45 states specify an upper limit or an exact value for the w/cm ratio. About 75% of the states specify a maximum w/cm ratio between 0.40 and 0.45 for concrete to be used in bridge decks. Rather than specifying a w/cm ratio, at least two states specify an upper limit for the total water content. The total water content includes any water in the SCMs and admixtures and any water beyond the saturated surface dry condition of the fine and coarse aggregates. At least 44 states specify a minimum cementitious materials content.

Specified slump varies from a low of zero to a high of 8 in. The tolerances of most slump values are either ±1 in. or ±1½ in. Most slumps are specified to be applicable before the addition of any water-reducing admixtures. Some states provide a wide range for slump and require the contractor to select a target value to which a tolerance is then applied.

Specified air contents also vary considerably from a low of zero to a high of 8%. The lower values are specified by states with less likelihood of freezing. Most specified air contents have a tolerance of ± 1½%.

Agencies were asked which characteristics were specified in their performance specifications for CIP concrete and which characteristics were considered in developing their prescriptive specifications. The results are shown in Figure 6. The four dominant characteristics in both types of specifications were compressive strength, permeability, workability, and ASR resistance. The selection of compressive strength and permeability by many agencies is consistent with the high usage in the demonstration projects. At that time, workability and ASR resistance were not included as characteristics.

Other characteristics that agencies listed were restrained shrinkage cracking, surface resistivity, air content, w/c ratio, strength gain, corrosion resistance, and reduced maximum cementitious materials content. Some of these properties are not related to HPC characteristics.

The review of the state standard specifications revealed that several states include a high performance class of concrete or require an HPC performance characteristic for some of their other classes of concrete. The specifications for those concretes require the use of one or more SCMs, with at least 16 states specifying a maximum permeability. The specified permeabilities in terms of charge passed per AASHTO T 277 range from 750 to 4000 coulombs, with most values in the 1000 to 2000 coulomb range.

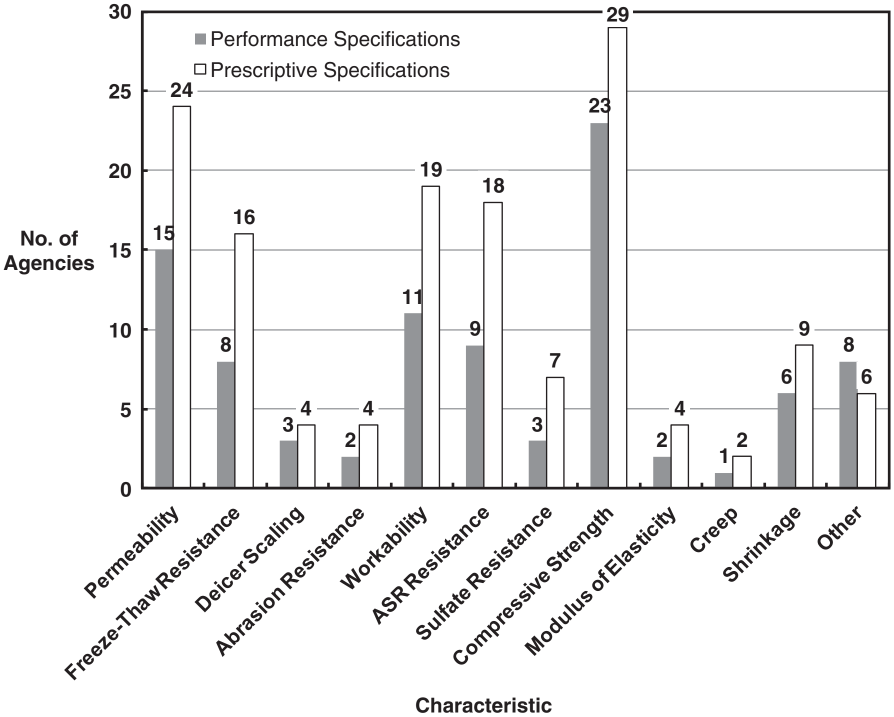

FIGURE 6 Characteristics included in performance specifications and considered in prescriptive specifications for CIP concrete decks.

CONCRETE CONSTITUENT MATERIALS

Most state bridge standards define that concrete shall consist of hydraulic cement or portland cement, SCMs, fine aggregate, coarse aggregate, water, chemical admixtures, and air-entraining admixtures. Other state specifications do not include a precise definition, although all the concrete constituent materials are included in the specifications.

Cementitious Materials

At least 39 state specifications limit the types of cement that may be used in bridges or define specific chemical requirements for the cement. Some specifications restrict the use of some types of cement to specific components, such as the use of Type III cement in only precast concrete members. At least 44 states specify a minimum cementitious materials content, which generally ranges from 560 to 750 lb/yd^3. Some specifications also include an upper limit, which is generally in the 700 to 800 lb/yd^3 range.

All states permit the use of fly ash. Two states specify only Class C fly ash, 10 states specify only Class F fly ash, and 38 states specify both classes. At least 12 states specifically state that Class N pozzolan may be used. At least 47 state specifications have an upper limit on the amount of fly ash that may be included. The upper limit is usually in the range of 15% to 30% of the total cementitious materials content with some as low as 10% or as high as 35%. Some states require the use of a higher percentage of pozzolans such as fly ash to control ASR.

In contrast to the optional use of SCMs by most states, the California specifications require the use of minimum amounts of SCMs. The minimum quantity of SCMs varies depending on the exposure condition and aggregate reactivity.

Silica fume is specifically permitted by at least 36 states, while others do not address its use. Where permitted, its use is generally restricted to an upper limit that ranges between 7% and 10% of the total cementitious materials content. Some specifications also include a lower limit of 5% or 7% when silica fume is used.

The use of slag cement is permitted by at least 39 state standard specifications. The upper limit for the maximum amount is usually in the range of 30% to 50% of the total cementitious materials content.

To obtain information about the actual practices, agencies were asked to identify the percentage of bridges that use different SCMs in bridge deck concrete. The responses are shown in Table 6.

From these data, it appears that Class F fly ash is the most frequently used SCM in HPC bridge decks, followed by silica fume and slag cement, which are used in about equal amounts. The least used SCM is the Class N pozzolan.

TABLE 6
NUMBER OF AGENCIES REPORTING THE OF USE OF SCMS IN HPC BRIDGE DECKS

Supplementary Cementitious Material	Extent of Use as a Percentage of All Bridge Decks			
	None	1 to 33	34 to 67	68 to 100
Fly Ash Class C	17	8	3	5
Fly Ash Class F	2	17	5	11
Pozzolan Class N	27	3	0	1
Silica Fume	11	16	1	7
Slag Cement	10	12	6	7

Aggregates

Aggregates for concrete used in bridge decks may be normal weight aggregates conforming to AASHTO Specifications M 6 and M 80, lightweight aggregates conforming to AASHTO M 195, or a combination of them. The coarse aggregate size is generally selected to be the largest size practical under job conditions (Kosmatka and Wilson 2011). AASHTO Specifications M 6 and M 43 contain grading requirements for the fine and coarse normal weight aggregates. In addition, a few states specify a combined grading. A standard specification for combined aggregates for hydraulic cement concrete is included in Section 8 of the *AASHTO LRFD Bridge Construction Specifications* (2010a). A combined grading can be used to improve the workability of concrete at given water and paste contents, minimize water and paste contents for a given workability, or improve workability and hardened properties of the concrete (Russell et al. 2006a). The possibility of including a small quantity of lightweight fine aggregate in concrete has received attention recently as a means to provide internal curing (ESCSI 2012). However, this approach was not identified in any standard specifications.

Admixtures

Chemical admixtures are generally required to conform to AASHTO M 194 or ASTM C494. This specification lists seven types of admixtures (A through G) although not all seven are permitted by every state. Other admixtures included in state specifications are air entraining and corrosion inhibiting admixtures.

Agencies were also asked about the percentage of total bridge decks using chemical admixtures conforming to AASHTO M 194, corrosion inhibitors, shrinkage reducing admixtures, and expansive components. The number of respondents for each percentage range is shown in Table 7.

TABLE 7
NUMBER OF AGENCIES REPORTING THE USE OF ADMIXTURES IN HPC BRIDGE DECKS

Admixture	Extent of Use as a Percentage of All Bridge Decks			
	None	1 to 33	34 to 67	68 to 100
AASHTO M 194 Type A—Water-reducing admixtures	4	4	5	22
AASHTO M 194 Type B—Retarding admixtures	9	11	7	7
AASHTO M 194 Type C—Accelerating admixtures	23	8	2	2
AASHTO M 194 Type D—Water-reducing and retarding admixtures	11	11	5	6
AASHTO M 194 Type E—Water-reducing and accelerating admixtures	23	8	1	0
AASHTO M 194 Type F—High range water-reducing admixtures	10	8	7	10
AASHTO M 194 Type G—High range water-reducing and retarding admixtures	16	11	2	3
Corrosion Inhibitors	20	9	0	4
Shrinkage Reducing Admixtures	25	5	0	1
Expansive Components	27	4	0	0

The data indicate that agencies use a variety of the chemical admixtures specified in AASHTO M 194 with Type A—water-reducing and Type F—high range water-reducing being the more frequently used types and Type E—water reducing and accelerating the least common. Corrosion inhibitors, shrinkage reducing admixtures, and expansive components are used by a few agencies. The review of the state specifications indicated that at least 16 states permit the use of a corrosion inhibitor, usually calcium nitrite.

CONSTRUCTION PRACTICES

All state standard specifications address construction practices, although the amount of detail and the requirements vary considerably. Topics addressed in the specifications include concrete production, transportation, placement, finishing, curing, and quality control. For concrete bridge decks, curing practice is an important topic.

With HPCs, the application of wet curing immediately after concrete finishing is extremely important because these concretes have less bleed water and greater likelihood of plastic shrinkage cracking (Khaleghi and Weigel 2001; Praul 2001; Schell and Konecny 2001). Whiting and Detwiler (1998) emphasized the importance of curing silica fume concrete. The lack of bleed water means that water lost from the surface as a result of evaporation cannot be readily replaced. States now specify that wet curing begin within a certain distance or a short time after final finishing. For example, the Kansas LC-HPC specifications require that wet burlap be applied within 10 minutes after strike-off, as shown in Figure 7. In a 2003 survey of agencies in the United States and Canada, 82% of the respondents reported that they specify that curing must begin immediately after finishing any portion of the deck (Russell 2004). At least two states require that a curing compound be applied at the end of the wet curing period. This allows the concrete to dry out more slowly and leads to slower development of tensile stresses from drying shrinkage.

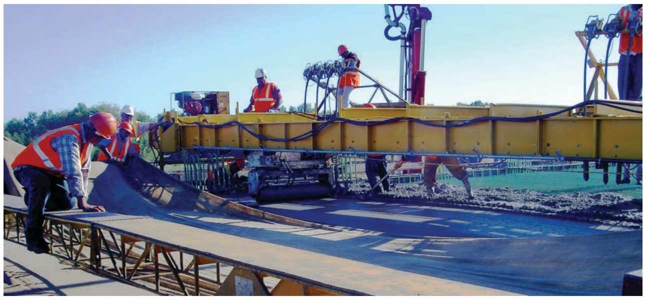

FIGURE 7 Application of wet burlap within 10 minutes after strike off [Photo courtesy of the University of Kansas, Transportation Research Institute].

FIGURE 8 Wet curing of a concrete bridge deck under polyethylene sheeting [Photo courtesy of Oregon Department of Transportation].

Based on the results from the survey for this synthesis, all responding agencies wet-cure concrete bridge decks, as illustrated in Figure 8. The duration of wet curing, however, ranges from three to 14 days, as shown in Figure 9.

In a survey for *NCHRP Synthesis 333* published in 2004, agencies in the United States and Canada indicated a range of

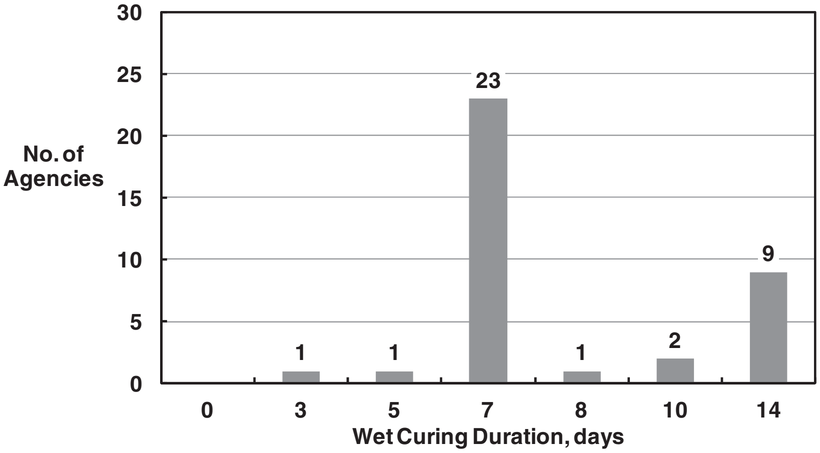

FIGURE 9 Duration of wet curing for concrete bridge decks.

curing periods from three to 14 days, with the most frequent value being seven days (Russell 2004). However, between 2004 and the current survey, the percentage of agencies specifying seven days or fewer has decreased from 87% to 67%, while the percentage specifying 14 days has increased from 11% to 24%. In the current survey, only two states reported fewer than seven days wet-curing.

Some states require a trial deck placement before construction of the actual bridge deck. One state reported that eliminating the requirement for a trial placement was not beneficial.

TESTING AND ACCEPTANCE PRACTICES

Responses to the survey for this synthesis revealed that all agencies have practices or tests for the acceptance of new HPC mixtures used for concrete bridge decks. The amount of testing, however, varies considerably. All responding states require a trial batch or batches with the measurement of one or more of the following properties:

- Abrasion resistance
- Air content
- ASR on the aggregate
- Compressive strength
- Creep
- Freeze-thaw resistance
- Heat of hydration
- Hydraulic cement content
- Modulus of elasticity
- Mortar bar expansion
- Permeability
- Rate of strength gain
- Scaling
- Drying shrinkage
- Concrete temperature
- Unit weight
- Workability (slump).

Two states mentioned that they require a trial placement similar to that required for the LC-HPC concrete in Kansas. Two states mentioned that they require trial batches from each plant that supplies concrete to the project. From the responses, it appears that most states are willing to accept a new HPC mix for bridge decks based on laboratory trial mixes only.

PERFORMANCE OF IN-SERVICE STRUCTURES

In the responses to the survey for this synthesis, five agencies stated that they routinely conduct tests of the hardened CIP concrete to check end product performance. The listed tests were permeability, surface resistivity, and chloride penetration resistance.

Twelve agencies responded that they sometimes do tests for permeability, chloride ion content, in-place strengths, in-place air content, surface resistivity, petrographic analysis, and chloride penetration resistance. Twenty agencies responded that they never do tests of the hardened CIP concrete to check in-service performance. Most tests of the in-place concrete are only performed when sub-standard concrete is suspected.

Regarding the current practices to evaluate short- and long-term performance of HPC in bridge decks, all the responding states rely on the quality control tests during construction and the biannual bridge inspections. One state responded that the only formal evaluation occurs if the deck is part of a research project. In summary, very little is done to determine the properties of the in-place concrete.

BRIDGE DECK CRACKING

As part of the survey for this synthesis, agencies were asked to identify the strategies that they are currently using to minimize cracking in CIP concrete bridge decks. Their responses are provided in Table 8.

Strategies that were mentioned included immediate wet curing, only allowing Type A or Type A/F admixtures, requiring 20% pozzolans, requiring 55% coarse aggregate as a percentage of the total aggregate, specifying a minimum w/cm ratio, permitting slump adjustments only with the addition of admixtures, requiring the contractor to have a weather station on site, nighttime concrete placements, use of internal curing, use of polypropylene fibers, and limiting hand finishing.

The use of wet curing applied in a timely manner and maintained for at least seven days was listed most often as the most effective strategy in minimizing deck cracking. Other strategies mentioned by more than one respondent were reduction in cement or paste content, limit on maximum concrete temperature, control of water content, and evaporation rate control. The use of fogging equipment to control evaporation rate is illustrated in Figure 10.

A number of less effective strategies to minimize deck cracking were identified by the responding agencies. These strategies included specifying a maximum slump; using prescriptive mix designs; specifying maximum and minimum concrete temperatures; using curing membranes and evaporation retardants; having high cement contents, high compressive strength requirements, and low w/cm ratios; and not requiring a trial slab placement before casting the deck.

Cracking in concrete bridge decks was discussed in *NCHRP Synthesis Report 333* (Russell 2004) because of the increased amount of cracking that had been observed in concrete bridge decks. At that time (2003), agencies were also asked about strategies used to minimize cracking in bridge decks; percent-

TABLE 8
STRATEGIES USED TO MINIMIZE CRACKING IN CIP BRIDGE DECKS

Strategy to Minimize Bridge Deck Cracking	2012 Survey Responses		2003 Survey Responses
	No.	%[1]	%
Specify maximum w/cm ratio	34	94	—
Specify minimum concrete compressive strength	33	94	—
Specify maximum concrete temperature at placement	32	94	80
Specify maximum slump	30	86	98
Specify minimum concrete temperature at placement	30	83	—
Required fogging when evaporation rates are high	27	77	67
Specify minimum cementitious materials content	26	76	—
Specify maximum cementitious materials content	19	54	33
Require use of the ACI surface evaporation nomograph	18	55	—
Specify maximum water content	14	42	—
Require windbreaks during concrete placement	13	38	22
Specify maximum concrete temperature during curing	9	30	—
Require evaporation retardants	9	28	29
Specify a ratio between 7- and 28-day compressive strengths	5	16	—
Specify a maximum concrete compressive strength	4	13	4

[1] Percentages appear inconsistent because not every respondent answered every option.
— = not included in the survey.

age responses are shown in Table 8. In comparison with the current survey, the biggest differences are that agencies currently specify a maximum cementitious materials content and fewer agencies are specifying wind breaks during concrete placement. Otherwise, the strategies appear to be similar in percentage usage.

FIGURE 10 Fogging equipment is used to control evaporation rates [Photo courtesy of the University of Kansas Transportation Research Institute].

SUMMARY OF CURRENT SPECIFICATIONS AND PRACTICES FOR CAST-IN-PLACE CONCRETE BRIDGE DECKS

State specifications, in general, are prescriptive except for the specification of concrete compressive strength. Other primary characteristics that are considered in the development of prescriptive and performance specifications are permeability, workability, and ASR resistance.

Most state specifications permit the use of SCMs with Class F fly ash being the most frequently used material. Silica fume and slag cement are used to a lesser extent and Class C fly ash and Class N pozzolan are the least used. All states permit the use of chemical admixtures with AASHTO M 194 Type A water-reducing admixture being the most frequently used.

The quantities of cementitious materials are generally in the following ranges:

- Minimum cementitious materials content of 560 to 750 lb/yd^3,
- Maximum cementitious materials content of 700 to 800 lb/yd^3,

- Maximum fly ash content of 15% to 30% of the total cementitious materials content,
- Maximum silica fume content of 7% to 10% of the total cementitious materials content,
- Minimum silica fume content of 5% to 7% of the total cementitious materials content, when used, and
- Maximum slag cement content of 30% to 50% of the total cementitious materials content.

Specified maximum w/cm ratios generally range from 0.40 to 0.50 for bridge decks. Aggregate specifications are generally the same for HPC and conventional concrete. Some state specifications include a combined grading for coarse and fine aggregates, which can improve the properties of HPC.

All state specifications address construction practices. Most states now require seven or 14 days wet curing of CIP concrete bridge decks. All states require trial batches of concrete prior to acceptance of a new HPC mix for bridge decks. The type of test data to be supplied with the trial batch information varies. Most states accept a new HPC mix for bridge decks based on laboratory trial mixes only.

Five agencies reported that they routinely conduct tests of the hardened concrete to check the end product performance, measuring permeability, surface resistivity, and chloride penetration resistance. The other agencies only do tests when substandard concrete is suspected.

Many states have implemented strategies to reduce bridge deck cracking. The primary ones are specifying a maximum w/cm ratio, minimum concrete strength, maximum concrete temperature at placement, maximum slump, minimum concrete temperature at placement, fogging when evaporation rates are high, and minimum cementitious materials content. The most effective strategy was the use of wet curing applied in a timely manner and maintained for at least seven days. Other effective strategies included reducing cement or paste content, limiting maximum concrete temperature, controlling water content, and controlling evaporation rate.

CHAPTER FOUR

CURRENT SPECIFICATIONS AND PRACTICES FOR PRECAST, PRESTRESSED CONCRETE GIRDERS AND DECK PANELS

This chapter addresses the specifications and practices for the use of HPC in precast, prestressed concrete for bridge girders and deck panels. The information was obtained from the synthesis survey and from a review of the state specifications, some of which include the information in the same sections that deal with CIP concrete and others of which address precast, prestressed concrete in a separate section.

The state standard specifications for concrete to be used in precast, prestressed concrete members are less prescriptive than for CIP concrete. More reliance appears to be placed on the capability of the precaster to develop the concrete mix proportions and to produce an acceptable finished product, allowing the specifications for precast products to be more performance-based.

As part of the survey, agencies were asked if they had implemented HPC in precast, prestressed concrete components. Twenty-one agencies responded that they had and 16 agencies responded that they had not. Several agencies stated that they had not seen any need for or advantage to using HPC because precast, prestressed girders have performed adequately.

SPECIFIED PROPERTIES

The primary performance criteria for precast, prestressed concrete beams and deck panels are concrete compressive strength at transfer of the prestressing force and at a later age. The age at which the prestressing transfer occurs is determined by the precaster's production schedule and can be as short as 12 hours for a daily production cycle or as long as three days over a weekend. The later age for the design strength is usually specified at 28 days, although 56 days is sometimes used for higher strength concretes.

In addition to specifying compressive strength, some states have developed permeability specifications. The factors that contribute to high-strength concrete also help produce a low permeability concrete. It is, therefore, much easier to achieve lower permeabilities with precast, prestressed concrete because of the higher quantity of cementitious materials used in the product, the greater use of SCMs, the lower w/cm ratio, and the use of heat curing (PCI 2011).

The specified maximum w/cm ratios for precast, prestressed concrete vary from 0.38 to 0.44. No minimum is stated. Other specified properties such as slump and air content are similar to corresponding values for CIP deck concrete. Some states, however, do not consistently specify an air content for the higher strength concretes used in precast concrete beams.

Agencies were asked which characteristics were specified in their performance specifications and which were considered in developing their prescriptive specifications. The results are shown in Figures 11 and 12 for beams and deck panels, respectively.

For precast, prestressed concrete beams, the characteristic most frequently specified for the performance specifications and considered for prescriptive specifications was concrete compressive strength. Workability, permeability, freeze-thaw resistance, and ASR resistance were the next most frequently reported characteristics, but more commonly listed in the development of prescriptive specifications than in performance specifications.

For precast, prestressed concrete deck panels, it was difficult to identify a clear pattern from the survey results for both the performance and prescriptive specifications. This may be the result of fewer states using precast concrete deck panels and a lack of experience in their use. The use of precast deck panels is shown in Figure 13.

CONCRETE CONSTITUENT MATERIALS

The concrete constituent materials specified for use in precast, prestressed concrete members are similar to those specified for CIP concrete and described in chapter three. Most specifications explicitly allow the use of Type III cement and silica fume. Both of these materials facilitate the development of high early strengths required for prestress transfer. Silica fume is also beneficial in reducing concrete permeability.

Concrete for use in precast, prestressed concrete members is generally specified to have a minimum cementitious materials content that ranges from 560 to 750 lb/yd^3 of concrete. The specified maximum cementitious materials content ranges from 750 to 925 lb/yd^3. However, exceptions may be made to achieve higher strength concretes. The specified percentage limits for cementitious materials contents for precast concrete are similar to those for CIP concrete.

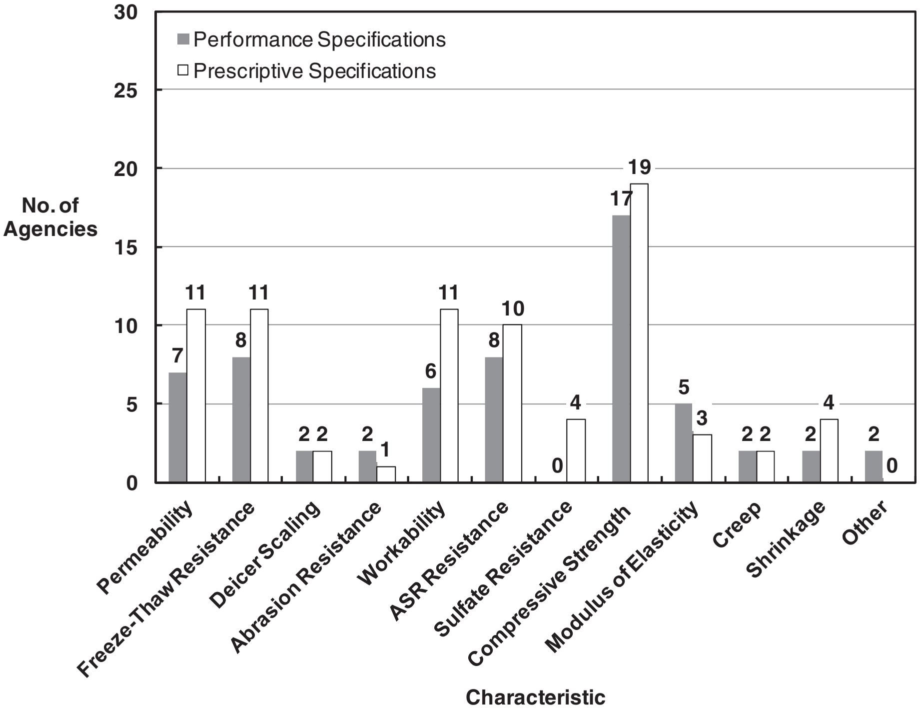

FIGURE 11 Characteristics included in performance specifications and considered in prescriptive specifications for precast, prestressed concrete beams.

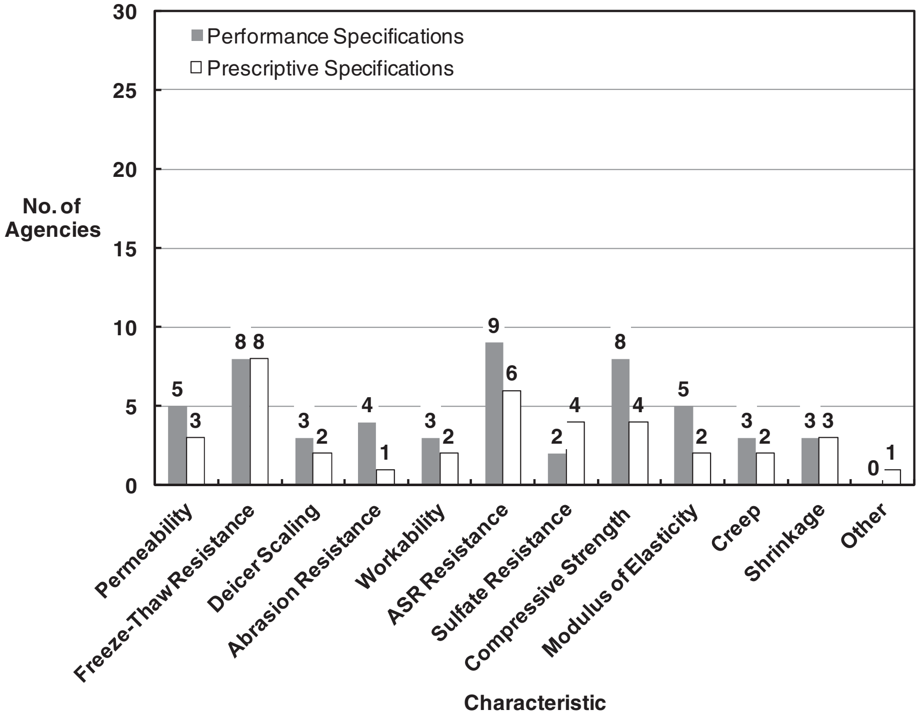

FIGURE 12 Characteristics included in performance specifications and considered in prescriptive specifications for precast, prestressed concrete panels.

FIGURE 13 Precast concrete deck panels [Photo courtesy of NYSDOT].

To obtain information about the actual practices, agencies were asked to identify the percentage usage of SCMs in precast, prestressed concrete beams and deck panels. The number of responses for each percentage range is summarized in Tables 9 and 10 for beams and deck panels, respectively. Both tables show similar trends, with Class F fly ash and silica fume being used most frequently in beams and panels. The frequent use of Class F fly ash is similar to that for CIP concrete decks.

Agencies were also asked about the percentage usage of chemical admixtures conforming to AASHTO M 194, corrosion inhibitors, shrinkage reducing admixtures, and expansive components in precast, prestressed concrete beams and deck panels. The number of respondents for each percentage range is shown in Tables 11 and 12 for beams and deck panels, respectively.

The survey results for both beams and deck panels show similar patterns. Agencies use a variety of chemical admixtures specified in AASHTO M 194, with Types A and F being used the most. This is similar to those used for CIP bridge decks. Corrosion inhibitors, shrinkage reducing admixtures, and expansive components are used in a relatively small number of applications.

CONSTRUCTION PRACTICES

Agencies responding to the survey for this synthesis indicated that precast, prestressed concrete components may be heat cured with either steam or radiant heat until the specified strength for release of strands is achieved; or wet cured for a minimum period of three, four, seven, or 14 days. Some

TABLE 9
NUMBER OF AGENCIES REPORTING THE USE OF SCMS IN PRECAST, PRESTRESSED CONCRETE BEAMS

Supplementary Cementitious Material	Extent of Use as a Percentage of All Bridges			
	None	1 to 33	34 to 67	68 to 100
Fly Ash Class C	24	2	1	3
Fly Ash Class F	10	11	2	6
Pozzolan Class N	23	4	0	1
Silica Fume	14	10	2	2
Slag Cement	16	5	3	3

TABLE 10
NUMBER OF AGENCIES REPORTING THE USE OF SCMS IN PRECAST, PRESTRESSED CONCRETE DECK PANELS

Supplementary Cementitious Material	Extent of Use as a Percentage of All Bridges			
	None	1 to 33	34 to 67	68 to 100
Fly Ash Class C	22	2	1	1
Fly Ash Class F	12	6	3	4
Pozzolan Class N	22	3	0	0
Silica Fume	16	6	1	1
Slag Cement	18	3	3	1

TABLE 11
NUMBER OF AGENCIES REPORTING THE USE OF ADMIXTURES IN PRECAST, PRESTRESSED CONCRETE BEAMS

Admixture	Extent of Use as a Percentage of All Bridges			
	None	1 to 33	34 to 67	68 to 100
AASHTO M 194 Type A—Water-reducing admixtures	8	6	5	8
AASHTO M 194 Type B—Retarding admixtures	14	5	5	1
AASHTO M 194 Type C—Accelerating admixtures	18	3	4	0
AASHTO M 194 Type D—Water-reducing and retarding admixtures	12	7	4	2
AASHTO M 194 Type E—Water-reducing and accelerating admixtures	18	4	2	1
AASHTO M 194 Type F—High range water-reducing admixtures	3	3	7	15
AASHTO M 194 Type G—High range water-reducing and retarding admixtures	14	5	3	4
Corrosion Inhibitors	14	7	2	4
Shrinkage Reducing Admixtures	20	4	0	1
Expansive Components	24	0	0	0

specifications limit the maximum temperature to 160° F for either the enclosure or the concrete during heat curing.

TESTING AND ACCEPTANCE PRACTICES

Many agencies reported that the only requirement for acceptance of new HPC mixtures for precast, prestressed concrete components is compressive strength. Other agencies reported requiring test results for slump, air content, temperature, permeability, or ASR of the aggregates. Some agencies require the same information for precast, prestressed concrete as for CIP concrete. Some states require or permit the use of match curing of cylinders for the measurement of compressive strength at the time of prestress transfer.

PERFORMANCE OF IN-SERVICE STRUCTURES

Four agencies reported that they routinely conduct tests of the hardened precast, prestressed concrete to check end product performance. The listed tests were surface resistivity, modulus of elasticity, and permeability.

Seven agencies reported that they sometimes perform tests for in-place strength, surface resistivity, and permeability. Sixteen agencies reported that they never do in-place tests of the hardened concrete to check end product performance. It appears that most tests of the hardened precast, prestressed concrete are only performed when sub-standard concrete is suspected. Instead, agencies evaluate short- and long-term performance of HPC in precast, prestressed components based

TABLE 12
NUMBER OF AGENCIES REPORTING THE USE OF ADMIXTURES IN PRECAST, PRESTRESSED CONCRETE DECK PANELS

Admixture	Extent of Use as a Percentage of All Bridges			
	None	1 to 33	34 to 67	68 to 100
AASHTO M 194 Type A—Water-reducing admixtures	9	5	4	6
AASHTO M 194 Type B—Retarding admixtures	14	5	4	0
AASHTO M 194 Type C—Accelerating admixtures	15	3	4	0
AASHTO M 194 Type D—Water-reducing and retarding admixtures	13	6	4	0
AASHTO M 194 Type E—Water-reducing and accelerating admixtures	15	4	2	1
AASHTO M 194 Type F—High range water-reducing admixtures	9	2	4	8
AASHTO M 194 Type G—High range water-reducing and retarding admixtures	16	4	1	2
Corrosion Inhibitors 1	4	4	2	3
Shrinkage Reducing Admixtures	19	3	0	0
Expansive Components	20	0	0	0

on information from the biannual bridge inspections. One state responded that the only formal evaluation occurs in connection with research projects.

SUMMARY OF CURRENT SPECIFICATIONS AND PRACTICES FOR PRECAST, PRESTRESSED CONCRETE GIRDERS AND DECK PANELS

All state specifications permit the use of SCMs, with Class F fly ash and silica fume being the most frequently used materials. Slag cement is used slightly more frequently than Class C fly ash and Class N pozzolan. All states permit the use of chemical admixtures with AASHTO M 194 Type A water-reducing admixture and Type F—high range water-reducing admixture being the most frequently used. The quantities of SCMs are similar to those listed for CIP concrete at the end of chapter three. Specified maximum w/cm ratios generally range from 0.38 to 0.44, which are slightly lower than for CIP concrete.

Mix proportions for precast, prestressed concrete are selected to provide a high early strength for release of the prestressing strand as well as a minimum 28- or 56-day compressive strength. More reliance appears to be placed on the capabilities of the precaster to develop the mix proportions rather than prescribing detailed requirements.

CHAPTER FIVE

CASE EXAMPLES OF HIGH PERFORMANCE CONCRETE APPLICATIONS IN BRIDGES

Following completion of the survey, the states of Kansas, Louisiana, New York, Virginia, Washington, and Wisconsin were asked to provide more details about their implementation of HPC and levels of performance. These states were selected based on the extent that they have implemented HPC in CIP or precast construction, and to represent different regions of the United States. Information for these case examples was obtained from the survey responses, follow-up contact by phone and e-mail, and a literature review.

KANSAS DEPARTMENT OF TRANSPORTATION

In 2003, the Kansas Department of Transportation (KDOT) became the lead state of a pooled fund study with 18 other states and FHWA. The goal of the study was to construct at least 40 low-cracking, high performance concrete (LC-HPC) bridge decks (Browning and Darwin 2007; Browning et al. 2009). The specifications for LC-HPC included the following requirements:

- Cementitious materials content of 500 to 540 lb/yd^3,
- Maximum w/cm of 0.42 (later revised to 0.43 to 0.45),
- Air content of 7.0% to 9.0% (later revised to 6.5% to 9.5%),
- Compressive strength at 28 days of 3.5 to 5.5 ksi,
- Paste content (total volume of water and cement) less than 25%,
- Slump of 1.5 to 3.0 in.,
- Concrete placement temperature of 55°F to 70°F,
- Combined aggregate gradation optimized for uniform size distribution,
- Wet curing with one layer of burlap starting within 10 minutes of concrete strike off followed by a second layer of burlap within five minutes,
- Fourteen days of wet curing followed by application of a curing compound,
- A qualification slab with dimensions equal to the bridge width, full depth, and 33 ft long to be cast before bridge deck placement to demonstrate the contractor's capabilities,
- Use of only Type I/II cement,
- Maximum aggregate absorption of 0.7%.

Two of the primary lessons learned were that these concrete specifications can be implemented at a reasonable cost and that the low-paste concrete mix is workable, placeable, and finishable in the field (Browning et al. 2009). Concrete strengths were about 4.0 ksi. The establishment of a good working relationship among owners, inspectors, contractors, and concrete suppliers was of prime importance for the successful construction of an LC-HPC bridge deck. All participants must clearly communicate their expectations and needs to successfully meet the specifications (Browning et al. 2009). Bridge decks constructed with LC-HPC had less than 10% of the cracking found in traditional bridge decks.

A second phase of the project is underway to include the use of SCMs, internal curing agents, and shrinkage reducing admixtures.

In the survey for this synthesis, KDOT reported that the use of HPC has resulted in better performance compared with conventional concrete because of maximum allowable permeability, SCMs, optimized aggregate gradations, and a 14-day wet cure. It was noted that the binary mixes (cement plus an SCM) were not as effective as ternary mixes (cement plus two SCMs) in reducing permeability. The predominant admixtures used were Type A—water-reducing admixture and Type F—high range water-reducing admixture.

LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

In 1988, a bridge project in Louisiana was used as an experiment to determine if a concrete compressive strength of 8.0 ksi could be obtained on a real project (Bruce et al. 1998). The specifications required a cement content of 800 lb/yd^3. However, 2,370 linear ft of girder or 68% of the total length did not achieve the specified strength.

In 1992, an experimental 24-in. square pile was cast using a concrete containing 750 lb/yd^3 of cement and 95 lb/yd^3 of silica fume. Average concrete compressive strengths were 8.5 and 10.5 ksi at 18 hours and 28 days, respectively. In 1993, AASHTO Type IV girders with concrete compressive strengths of 8.4 and 11.2 ksi at 18 hours and 14 days, respectively, were produced for a bridge in Shreveport.

The Charenton Canal Bridge, completed in 1999 and shown in Figure 14, was Louisiana's first HPC bridge (Bruce et al. 2001). High-strength concrete with a specified compressive strength of 10.0 ksi was used in the prestressed concrete piles and girders. HPC for durability was used in the CIP bent caps

FIGURE 14 High performance concrete was used in all components of the Charenton Canal Bridge in Louisiana [Photo courtesy of Louisiana Department of Transportation, Bridge and Structural Design Section].

and bridge deck. The CIP concrete was required to have a minimum compressive strength of 4.2 ksi at 28 days, a maximum permeability per AASHTO T 277 of 2000 coulombs, a minimum cement content of 658 lb/yd^3, and a maximum w/cm of 0.40. An inspection of the bridge deck four years later revealed only transverse cracks in the negative moment region over the intermediate piers (Mokarem et al. 2009).

In the survey for this synthesis, the Louisiana Department of Transportation and Development (LaDOTD) reported that HPC has better performance than conventional concrete for CIP decks, precast girders, and precast deck panels. The improved concrete performance resulted from the use of chemical admixtures, fly ash, slag cement, and silica fume. For bridge decks, Class C fly ash and slag cement were reported to be the most frequently used SCM. Water-reducing admixture Type A was the most frequently used chemical admixture. For precast girders and slabs, Class C fly ash was also reported to be the most frequently used SCM and water-reducing admixture Types A and F were the most frequently used chemical admixtures.

The LaDOTD Standard Specifications has classes of concrete with specified compressive strengths of 5.0, 6.0, and 7.5 ksi for precast girders. For bridge decks, a minimum cementitious materials content of 560 lb/yd^3 and a maximum w/cm ratio of 0.44 are specified, and the use of both Class F and C fly ashes, silica fume, and slag cement is permitted.

NEW YORK STATE DEPARTMENT OF TRANSPORTATION

The New York State Department of Transportation (NYSDOT) development of HPC began in 1994 in an effort to produce more durable and longer lasting bridge decks (Streeter 1999). The newly developed Class HP concrete was achieved by using pozzolans to reduce the cement content, lowering the water-cementitious materials ratio, and using normal range water-reducing admixtures. A comparison of the Class HP concrete mix criteria with NYSDOT's Class E and H concretes is shown in Table 13 (Owens and Alampalli 1999). Placement of Class HP concrete on a NYSDOT bridge deck is shown in Figure 15.

TABLE 13
MIX CRITERIA FOR NYSDOT CLASS E, H, AND HP CONCRETES

Property	Concrete Class		
	E	H	HP
Cement Content, lb/yd^3	647	674	506
Fly Ash Content, lb/yd^3	0	0	135
Silica Fume Content, lb/yd^3	0	0	42
w/cm Ratio	0.44	0.44	0.40
Sand, % of Total Aggregate	35.8	40.0	40.0
Air Content, %	6.5		
Slump Range, in.	3–4		

Based on Owens and Alampalli (1999).

In addition to modifying the mix proportions, greater attention was paid to construction details. Training sessions were held to highlight the procedures to be followed. The addition of silica fume and water-reducing admixtures was tightly controlled. Concrete placement was limited to 5 to 8 ft ahead of the finishing machine. Wet curing was applied immediately after texturing the surface and initially continued for seven days. This was increased to 14 days in November 1999.

Performance of Class HP concrete was reported to be good (Streeter 1999). The average compressive strength was 5.4 ksi or about 20% higher than for conventional concrete. Permeabilities in the field averaged 1600 coulombs at 28 days, which was about 30% to 50% of the values for conventional concrete. Cracking was reduced and those cracks that did form were finer. Between 1995 and 1998, 84 bridges had been constructed using Class HP concrete (Alampalli and Owens 2000) and a study was undertaken in 1998 to inspect and

FIGURE 15 Placement of Class HP concrete [Photo courtesy of NYSDOT].

quantify the enhanced performance of Class HP concrete in those projects indicated that:

- 49% had no cracks.
- 48% had transverse cracks.
- 44% had longitudinal cracks.
- 40% of the decks had both transverse and longitudinal cracks.

Of the decks with cracks, more than half began cracking within 14 days of concrete placement.

Class HP bridge decks were observed to crack with less frequency and exhibited narrower and shorter cracks than their non-HPC counterparts. The average measured length of the transverse cracks was 0.021 ft/ft^2 compared with lengths of 0.0 to 0.31 ft/ft^2 reported by Browning and Darwin (2007) for conventional concrete bridges. Eighty percent of the Class HP decks were reported to perform as well as or better than Class E and H decks. Based on a statistical analysis, cracking densities were found to be independent of superstructure type, superstructure material, span length, or support conditions.

NYSDOT's first use of high-strength HPC for bridge beams began with the completion of three bridges in 2001 (Royce 2002 and 2006). Initial experience showed that concrete with a compressive strength of 10 ksi allowed the design of bridge beams for significantly longer span lengths compared with lower strength concretes. Based on the success of the initial applications in 2001 through 2003, NYSDOT specified the following seven performance criteria for high-strength HPC for precast, prestressed concrete beams beginning in 2004:

- Compressive strength at 56 days by AASHTO T 22: > 10.15 ksi,
- Modulus of elasticity by ASTM C469 at the concrete age when the compressive strength is achieved: ≥ 4350 ksi,
- Drying shrinkage after 56 days of drying by AASHTO T 160: < 600 millionths,
- Specific creep after 56 days of loading by ASTM C512: ≤ 41 millionths/psi,
- Freeze-thaw relative dynamic modulus after 300 cycles by AASHTO T 161 Procedure A: ≥ 80%,
- Scaling resistance by ASTM C672 visual rating: ≤ 3, and
- Chloride penetration by AASHTO T 259 (modified) increase in chloride ion content by weight: < 0.025% at 1 in. depth.

In addition, certain prescriptive requirements were established for the mixes:

1. Minimum entrained air content of 3%,
2. Minimum silica fume content of 5% by weight of the cementitious materials,
3. Maximum w/cm ratio of 0.40, and
4. Calcium nitrite corrosion inhibitor at a dosage rate of 646 fl oz/yd^3.

According to Royce (2006), these criteria resulted in a chloride penetration resistance many times higher than for conventional concrete used for bridge beams prior to 2004. The calcium nitrite corrosion inhibitor elevates the corrosion initiation threshold so it takes longer for active corrosion to begin. NYSDOT stated that it is confident that the combination of high strength HPC and corrosion inhibitor will provide a service life of 75 to 100 years.

In the survey for this synthesis, NYSDOT reported that the use of HPC has resulted in better performance compared with conventional concrete for both CIP and precast concrete decks. The survey did not solicit a response for the use in girders. The improved performance is attributed to the prescriptive mix requirements developed in the 1990s, which provided a lower permeability in the field. At the same time, extending the length of wet curing to 14 days and enhancing placement and consolidation practices were beneficial. Transverse cracks are still observed on many decks although the cracks are fewer and narrower. Autogenous shrinkage has been a concern that has led to consideration of the use of internal curing.

NYSDOT reported that silica fume is used in more than two-thirds of its bridge decks. Class F fly ash and slag cement are used on one-third to two-thirds of the decks. The predominant chemical admixtures are Type A—water-reducing admixture, Type B—retarding admixture, and Type D—water-reducing and retarding admixture. Each admixture is used in over two-thirds of the CIP bridge decks. The NYSDOT Standard Specifications requires that the cementitious materials used in Class HP concrete contain 20% pozzolan and 6% silica fume and that a water-reducing admixture and/or a water-reducing and retarding admixture be used.

Whereas NYSDOT's approach to HPC in bridge decks is prescriptive, its approach for precast concrete is mainly based on performance of the proposed mix. The predominant SCM used in precast, prestressed concrete beams and panels is silica fume. The predominant chemical admixtures are Type A—water-reducing admixture and Type F—high range water-reducing admixture. Corrosion inhibitors are also used.

The NYSDOT Standard Specifications includes the performance criteria listed above for precast, prestressed concrete beams. In addition, the concrete is required to contain a minimum of 5% silica fume. This is one of the few specifications that include numerous performance requirements in the standard specifications rather than in special provisions.

Approval of an HPC mix in the NYSDOT specifications is a two-step process. In the first step, the contractor is required to submit information about the constituent materials, proposed concrete mix proportions, production procedures, and testing procedures. After approval, the contractor is required to perform tests and to submit test results showing that the proposed mix proportions satisfy all the performance requirements.

Once approved, the mix may be used on multiple projects without further testing for each project.

VIRGINIA DEPARTMENT OF TRANSPORTATION

Standards for HPC use in Virginia have evolved through extensive laboratory research and field testing (Napier 2005). In 1988, the Virginia Department of Transportation (VDOT) added requirements for limiting surface evaporation rates for concrete bridge decks. In 1994, a trial provision requiring seven days of wet curing for low permeability concrete was introduced, which later became a standard requirement. In addition, VDOT requires the use of curing compound following the seven-day wet curing period. Also in 1994, VDOT introduced a permeability provision for HPC with maximum values of 1500 coulombs for precast, prestressed concrete, 2500 coulombs for deck concrete, and 3500 coulombs for the substructure concrete. These values were selected on the basis that they could be achieved consistently. VDOT also used an accelerated method of curing for the test specimens consisting of one week at 73°F followed by three weeks at 100°F, with permeability testing at 28 days. This curing regime gave similar results at 28 days to those obtained at six months using standard curing (Ozyildirim 1998). This method has been adopted by several other states and is used for all HPC projects in Virginia.

In 1992, VDOT began using corrosion inhibitors at low dosage rates in low permeability concrete containing pozzolans or slag cement used in a marine environment (Napier 2005). According to the survey for this synthesis, VDOT no longer uses corrosion inhibitors in CIP bridge decks and uses them in less than one-third of precast girders and deck panels. The VDOT standard specifications now requires the use of 3.5 gallons/yd^3 of calcium nitrite in prestressed concrete piles, beams, and slabs unless at least 40% of the cementitious material is slag cement or at least 7% is silica fume. Concrete for structures over tidal waters, beams and slabs within 15 ft of high tide, and exposed piles are also required to contain calcium nitrite. The dosage rate is 2.2 gallons/yd^3.

Also, in 1992, VDOT began requiring either cement with an alkali content of less than 0.40% or the use of pozzolans or slag cement with cement having an alkali content up to 1% to address the potential for ASR (Napier 2005).

In 2008, VDOT started requiring low permeability for all concrete and implemented lower permeability requirements for all elements of bridges over tidal waterways. The specified maximum permeability values are 1500 coulombs for prestressed concrete and overlays and 2000 coulombs for general concrete. Permeabilities are measured at a concrete age of 28 days following accelerated curing.

In the survey for this synthesis, VDOT reported that its special provisions for HPC combine performance and prescriptive requirements. Both types of specifications address strength, permeability, and workability. In addition, ASR is considered for the prescriptive specifications.

To minimize deck cracking, VDOT specifies minimum and maximum concrete temperatures at time of deck placement of 40°F and 85°F, respectively; maximum w/cm ratio of 0.45; maximum slump of 4 in.; and use of wind breakers and fogging when evaporation rates are determined to be high according to the ACI surface evaporation nomograph (ACI Committee 305, 1999). Class F fly ash and slag cement are each used in one- to two-thirds of its bridge decks.

WASHINGTON STATE DEPARTMENT OF TRANSPORTATION

Washington State Department of Transportation (WSDOT) has used HPC in both CIP concrete bridge decks and precast, prestressed concrete girders. The focus for bridge decks has been improved durability through the use of fly ash (Khaleghi and Weigel 2001). Air entrainment is required for all WSDOT concrete decks to provide freeze-thaw resistance. Initially, contractors expressed concerns about the addition of fly ash and the requirement for 14 days' wet curing. These concerns diminished rapidly because the fly ash improved workability and the wet curing was not the problem originally envisioned.

The use of high-strength HPC began with a showcase project in 1997 (Russell et al. 2006a). Specified concrete compressive strengths for the girders were either 7.4 or 5.0 ksi at strand release and either 9.5 ksi at 28 days or 10.0 ksi at 56 days. Subsequent experience gained through design and fabrication of HPC girders showed that specifying a release strength of 7.5 ksi and a design strength of 8.5 ksi at 28 days resulted in optimum design economy (Weigel 2000). In 2004, Weigel reported that WSDOT had been using HPC in all its precast, prestressed concrete bridge girders since 1998—an average of 20 bridges per year. According to WSDOT's response in the survey, the use of HPC has resulted in better performance of precast, prestressed concrete girders.

In the survey for this synthesis, WSDOT reported that the performance of HPC in CIP bridge decks was worse than that of conventional concrete, based on an observed increase in the amount of cracking, which appeared to be associated with the required use of fly ash. The cracking, however, may be caused by the use of girders with wide top flanges. These girders provide more restraint to the differential shrinkage between the deck concrete and the girders. WSDOT reported that none of the strategies that it has tried was effective in minimizing cracking. The use of evaporation retardants was found to be the least effective. WSDOT is evaluating the use of lower cementitious materials contents as a means of reducing the deck concrete drying shrinkage.

The WSDOT Standard Specifications for bridge deck concrete specifies a minimum cementitious materials content of 660 lb/yd^3, with a fly ash content between 10% and 20% or a slag cement content between 10% and 30%. If both fly ash and slag cement are included, the maximum allowable content is increased to 40%. The use of a water-reducing admixture and a retarding admixture is required. The use of a high range water-reducing admixture is permitted.

WISCONSIN DEPARTMENT OF TRANSPORTATION

In the mid to late 1990s, the Wisconsin Department of Transportation (WisDOT) introduced a Quality Management Program (QMP) (Parry 2011). The principal motivation for these changes was to improve the quality and durability of concrete and to decrease bridge deck cracking. The QMP incorporated the following specification changes:

- Introduced percentage within limits requirements for compressive strength with incentive/disincentive payments,
- Reduced the minimum cementitious materials content from 610 to 565 lb/yd^3,
- Increased maximum nominal size of coarse aggregate from ¾ to 1½ in., and
- Required seven-day continuous wet cure with burlap cover.

In 1998–99, WisDOT initiated a pilot program that equated HPC with high-strength concrete and low w/cm ratio, using the following requirements:

- Minimum compressive strength of 5.0 ksi at 28 days,
- High range water-reducing admixture required, and
- Maximum w/cm ratio of 0.40.

This approach resulted in a large amount of deck cracking on several structures and the specification was removed from several scheduled projects.

The second generation of HPC specifications for bridge decks was used first on the Marquette Interchange in Milwaukee, constructed between 2004 and 2008, and shown in Figure 16. The specifications included the following:

- Mandatory use of SCMs,
- Cementitious materials content between 565 and 660 lb/yd^3,
- Minimum compressive strength of 5.0 ksi at 28 days,
- Maximum rapid chloride permeability of 2000 coulombs using 28-day standard curing,
- Wet burlap placement within 10 minutes of surface finishing,
- Continuous wet cure for 10 days, and
- Silane sealer applied to the deck after cutting longitudinal grooves in the hardened concrete.

FIGURE 16 The Marquette Interchange in Milwaukee, Wisconsin, used the second generation of HPC specifications [Photo courtesy of Tony Straseske, Wisconsin Department of Transportation].

After construction of the Marquette Interchange, it was decided to require a minimum compressive strength of 4.0 ksi for future HPC bridge decks. Contractors reported it was difficult to satisfy the 28-day rapid chloride permeability requirement using fly ash as the preferred SCM. The accelerated curing method developed by the Virginia Transportation Research Council was adopted (Ozyildirim 1998). These changes were incorporated into the third generation of HPC specifications, along with the following:

- Maximum cementitious materials content of 610 lb/yd^3,
- Maximum rapid chloride permeability of 1500 coulombs at 28 days, and
- Continuous wet cure for 14 days.

The WisDOT use of HPC has been limited to bridge decks. In the survey for this synthesis, the agency reported that the use of HPC has resulted in better performance compared with conventional concrete. The primary practices leading to the improved performance have been a 14-day wet cure, reduced cementitious materials content, and a reduced w/cm ratio. The survey results show limited use of Class C fly ash and slag cement and no use of Class F fly ash, Class N pozzolan, silica fume, and chemical admixtures.

The WisDOT Standard Specifications includes cementitious materials contents of 565 and 610 lb/yd^3 for bridge deck concrete Grades A and D, respectively. The water content for these concrete grades is equivalent to a w/cm ratio of 0.40. In Grade A concrete, fly ash and slag cement are permitted at 30% of the cementitious materials content. For QMP concrete, Class C fly ash or Grade 100 or 120 slag cement is required. For binary mixes, fly ash is required at 15% to 30% or slag at 20% to 30% of the total cementitious materials content. For ternary mixes, fly ash and slag cement are required in combination at 15% to 30% of the total cementitious materials content. The target w/cm ratio is required to be not greater than 0.45.

CHAPTER SIX

CONCLUSIONS

CONCLUSIONS

In 1993, the FHWA initiated a national program to implement the use of high performance concrete (HPC) in bridges by encouraging the use of performance or performance-based specifications. States adopted this concept to varying degrees. Some states modified their specifications to include aspects of HPC without specifically calling the concrete HPC. At the same time, the state agencies have developed a wide range of specifications for HPC. Consequently, the use of HPC has increased but the results have been variable.

All state specifications for concrete to be used in bridge structures follow the traditional approach of being prescriptive in nature. The use of performance specifications as proposed by the FHWA implementation program is largely limited to special provisions for specific projects. In general, the performance specifications only address strength and permeability. Nevertheless, numerous changes have been made to the specifications to enhance the performance of concrete particularly when used in bridge decks even though the concrete may not be called HPC.

All state specifications now specifically permit the use of one or more secondary cementitious materials (SCMs)—fly ash, silica fume, and slag cement—along with the use of hydraulic cements. The specifications, however, limit the quantities of these materials that may be used for both cast-in-place (CIP) and precast concrete. The following limitations were identified during a review of state specifications.

- Minimum cementitious materials content of 560 to 750 lb/yd^3,
- Maximum cementitious materials content of 700 to 800 lb/yd^3 for cast-in-place (CIP) concrete and 750 to 925 lb/yd^3 for precast concrete,
- Maximum fly ash content of 15% to 30% of the total cementitious materials content,
- Maximum silica fume content of 7% to 10% of the total cementitious materials content,
- Minimum silica fume content of 5% to 7% of the total cementitious materials content, if used, and
- Maximum slag cement content of 30% to 50% of the total cementitious materials content.

Specified maximum w/cm ratios range from 0.40 to 0.50 for CIP concrete and 0.38 to 0.44 for precast concrete. The use of SCMs reduces the permeability of concrete, which slows the rate of penetration of water and chlorides into the concrete. Many states report that the use of HPC has improved concrete performance, but they still express concern about deck cracking.

The following practices were identified as factors in reducing cracking of CIP concrete bridge decks:

- Decreasing the amount of water and cementitious materials in the concrete mix while achieving the specified properties,
- Using the largest practical maximum size aggregate to reduce water content,
- Avoiding concrete compressive strengths higher than normally required,
- Applying wet curing immediately after finishing the surface and curing for at least seven days, preferably longer, and
- Applying a curing compound after the wet curing period to slow down the drying shrinkage and enhance the other concrete properties.

The following practices were identified as less effective in minimizing deck cracking:

- Using lower w/cm ratios,
- Having high cement contents,
- Using high compressive strength concrete,
- Specifying maximum slump,
- Using prescriptive mix designs,
- Specifying maximum and minimum concrete temperatures,
- Using curing membranes and evaporation retardants, and
- Not requiring a test slab before casting the deck.

Specifications for precast concrete are more performance-oriented than those for CIP concrete, with compressive strength being the property specified most frequently. Specifications for precast concrete place more reliance on the capability of the producer to develop mix proportions that will meet the specifications instead of providing detailed prescriptive requirements. Precast, prestressed concrete beams appear to be performing satisfactorily using the existing specifications with only a few performance issues reported in the survey.

From the survey of state agencies, numerous changes in specifications and practices were identified that have improved performance. These include the following:

- Developing special provisions for specific projects,
- Using a performance-based specification for bridge decks,
- Implementing a specification addressing alkali-silica reaction (ASR),
- Using high-strength concrete in precast girders to improve durability,
- Providing multiple options for concrete constituent materials,
- Specifying the amount of drying shrinkage,
- Specifying permeability limits,
- Starting wet curing immediately after concrete placement,
- Specifying and ensuring a longer wet curing period than used previously,
- Testing for more concrete properties than previously,
- Specifying limits on rate of strength gain,
- Using lower cement contents,
- Using SCMs (fly ash, silica fume, and slag cement) in more applications,
- Optimizing aggregate gradation,
- Using a corrosion inhibitor,
- Using self-consolidating concrete (SCC),
- Placing concrete at night,
- Controlling evaporation rates, and
- Strictly enforcing air content requirements.

The following practices were identified as contributing to adverse performance:

- High early-strength mixes used to allow early opening to traffic were more prone to cracking.
- High concrete strengths have led to cracking in bridge decks.
- The use of silica fume reduced workability and led to cracking in new decks.
- The use of shrinkage reducing admixtures meant that specified air content could not be maintained in the field.
- The use of shrinkage reducing admixtures has helped reduce cracking but not to a satisfactory degree.
- Increasing the cement content to obtain lower permeability resulted in more cracks in the deck.
- Use of an evaporation retardant resulted in excessive cracking in decks.
- The use of fly ash in bridge decks has resulted in increased cracking.
- The use of Class F fly ash content greater than 30% only produced limited success.
- Concrete with a rapid strength gain resulted in more deck cracking.
- The use of 14-day wet curing for decks did not eliminate deck cracking.

These two lists indicate that different states have had conflicting experiences with some of the same practices. Overall, the information collected for this synthesis indicates that there is no single practice that can be used to enhance concrete bridge deck performance.

SUGGESTIONS FOR FUTURE RESEARCH

Responses to the survey for this synthesis provided the following suggestions for future research and development programs:

- Identify causes of cracks in concrete bridge decks.
- Study several types of structures to see if they can be improved to reduce deck cracking.
- Define how to achieve a low permeability concrete deck without shrinkage cracks and determine if expansive additives or polypropylene fibers would be effective.
- Develop effective means, using non-destructive or other tests, to ensure that concrete meets the required performance criteria for the intended environment. Tests that can be performed on fresh concrete would be particularly useful.
- Identify the most cost-effective methods of sealing cracks in decks to reduce future maintenance.
- Evaluate the effect of concrete compressive strength, modulus of elasticity, drying shrinkage, and creep on cracking.
- Investigate the use of internal curing to reduce deck cracking.

GLOSSARY

Abrasion resistance—ability of a surface to resist being worn away by rubbing and friction.

Alkali-silica reaction (ASR)—the reaction between the alkalies (sodium and potassium) in portland cement and certain siliceous rocks or minerals, such as opaline chert, strained quartz, and acidic volcanic glass, present in some aggregates; the products of the reaction may cause abnormal expansion and cracking of concrete in service.

Autogenous shrinkage—change in volume produced by continued hydration of cement, exclusive of effects of applied load and change in either thermal condition or moisture content.

Binary concrete mix—concrete containing two cementitious materials.

Chloride penetration—extent to which chlorides penetrate concrete.

Compressive strength—the measured maximum resistance of a concrete specimen to axial compressive loading; expressed as force per unit cross sectional area.

Corrosion resistance—resistance of metal to destruction by chemical, electrochemical, or electrolytic reaction within its environment.

Creep—time-dependent deformation due to sustained load.

Drying shrinkage—shrinkage resulting from loss of moisture.

Flowability—ability of fresh concrete to flow into place.

Freeze-thaw resistance—ability of concrete to withstand cycles of freezing and thawing.

Heat curing—a system in which temperature is maintained in freshly placed concrete by supplying heat generated by steam or electrical heaters.

Internal curing—a process by which hydration of cement and pozzolanic reactions continue because of an internal water source in addition to the mixing water.

Match curing—a system in which concrete specimens are cured at the same temperature as that measured in a concrete member.

Modulus of elasticity—the ratio of normal stress to corresponding strain for tensile or compressive stress below the proportional limit of the material.

Performance specification—a specification in which the requirements are stated in terms of results with criteria for verifying compliance rather than specific composition, design, or procedure.

Permeability—property of allowing passage of fluids.

Plastic shrinkage—shrinkage that takes place before cement paste, mortar, grout, or concrete sets.

Prescriptive specification—a specification that defines the means and methods of construction including composition of the concrete mix.

Rapid chloride permeability—an electrical indication of concrete's ability to resist chloride ion penetration.

Scaling resistance—ability of a hardened concrete surface to resist disintegration and flaking, frequently caused by freeze-thaw cycles and application of deicing chemicals.

Sulfate resistance—ability of concrete to withstand sulfate attack.

Surface resistivity—measurement of resistance between two locations on the same concrete surface.

Ternary concrete mix—concrete containing three cementitious materials.

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APPENDIX A

Survey Questionnaire

The following survey for this synthesis was mailed in January 2012 to 50 U.S. state highway agencies and the District of Columbia to collect information about their specifications and practices for high performance concrete. Forty-two responses were received.

Synthesis Survey
Topic 43-02
High Performance Concrete Specifications and Practices for Bridges

1. INTRODUCTION

KEY DEFINITION:

For the purpose of this survey, high performance concrete (HPC) does not include ultra-high performance concrete—a cementitious-based composite material with fiber reinforcement and having a compressive strength greater than 20 ksi.

Please enter the date (MM/DD/YYYY). ________________________________

Please enter your contact information.
First Name ____
Last Name ____
Title ____
Agency/Organization _______________________________
Street Address _____________________________________
Suite ____
City ____
State ____
Zip Code ___________________________________
Country ____
E-mail Address _____________________________________
Phone Number ______________________________________
Fax Number ____
Mobile Phone ______________________________________
URL ____

2. GENERAL

1. Does your agency have a definition (formal or otherwise) for high performance concrete (HPC)?

( ) Yes
( ) No

If yes, please provide the definition.

2. How does your agency specify HPC? Select only one.

( ) Standard specifications only
( ) Special provisions for all projects
( ) Special provisions for specific projects
( ) Combination of standard specifications and special provisions for all projects
( ) Combination of standard specifications and special provisions for specific projects

3. Are your agency's standard specifications for HPC prescriptive, performance-based, or a combination?

( ) Not applicable
( ) Prescriptive
( ) Performance
( ) Combination

4. Are your agency's special provisions for HPC prescriptive, performance-based, or a combination?

○ Not applicable
○ Prescriptive
○ Performance
○ Combination

5. In general, how is your agency's HPC performing compared to conventional concrete?

	Worse	Same	Better	Not Applicable
Cast-in-place concrete				
Precast concrete decks				
Precast concrete girders				

6. What performance issues with HPC has your agency identified?

	Issue
Cast-in-place concrete	
Precast concrete decks	
Precast concrete girders	

7. What specifications and practices has your agency used that resulted in improved concrete performance?

8. What specifications and practices has your agency used that were unsuccessful?

What is the basis for this assessment?

9. What lessons has your agency learned about the implementation of HPC? Specific case studies would be useful for the synthesis. Please list any reports or attach files in Question 35.

3. CAST-IN-PLACE CONCRETE

10. Has your agency implemented high performance concrete in cast-in-place bridge decks?

○ Yes. Go to next question.
○ No.

If no, why not?

After completing this question, go to Section 4.

11. In your agency's performance specifications, which of the following characteristics are currently specified for cast-in-place concrete bridge decks? Check all that apply.

☐ Not applicable
☐ Permeability
☐ Freeze-thaw resistance
☐ Deicer scaling
☐ Abrasion resistance
☐ Workability
☐ ASR resistance
☐ Sulfate resistance
☐ Compressive strength
☐ Modulus of elasticity
☐ Creep
☐ Shrinkage
☐ Other

If other, please list.

12. In your agency's prescriptive specifications, which of the following characteristics are currently considered in developing the specifications for cast-in-place concrete bridge decks? Check all that apply.

[ ] Not applicable
[ ] Permeability
[ ] Freeze-thaw resistance
[ ] Deicer scaling
[ ] Abrasion resistance
[ ] Workability
[ ] ASR resistance
[ ] Sulfate resistance
[ ] Compressive strength
[ ] Modulus of elasticity
[ ] Creep
[ ] Shrinkage
[ ] Other

If other, please list.

13. What strategies does your agency currently use to minimize cracking in cast-in-place concrete bridge decks?

	Yes	No
None		
Specify minimum cementitious materials content		
Specify maximum cementitious materials content		
Specify minimum concrete compressive strength		
Specify maximum concrete compressive strength		
Specify a ratio between 7- and 28-day compressive strength		
Specify minimum concrete temperature at placement		
Specify maximum concrete temperature at placement		
Specify maximum concrete temperature during curing		
Specify maximum water-cementitious materials ratio		
Specify maximum slump		
Specify maximum water content		
Require use of the ACI surface evaporation nomograph		
Require wind breaks during concrete placement		
Require evaporation retardants		
Require fogging during placement when evaporation rates are high		
Other		

If other, please list.

What strategies to minimize cracking in cast-in-place concrete bridge decks have been most effective?

What strategies to minimize cracking in cast-in-place concrete bridge decks have been least effective?

14. What is the frequency of use of the following supplementary cementitious materials in your agency's cast-in-place concrete bridge decks?

	None	1 to 33%	34 to 67%	68 to 100%
Fly ash Class C				
Fly ash Class F				
Pozzolan Class N				
Silica fume				
Ground-granulated blast-furnace slag				
Other				

If other, please list.

15. What is the frequency of use of the following admixtures for cast-in-place concrete bridge decks?

	None	1 to 33%	34 to 67%	68 to 100%
AASHTO M 194 Type A—Water-reducing admixtures				
AASHTO M 194 Type B—Retarding admixtures				
AASHTO M 194 Type C—Accelerating admixtures				
AASHTO M 194 Type D—Water-reducing and retarding admixtures				
AASHTO M 194 Type E—Water-reducing and accelerating admixtures				
AASHTO M 194 Type F—High range water-reducing admixtures				
AASHTO M 194 Type G—High range water-reducing and retarding admixtures				
Corrosion inhibitors				
Shrinkage reducing admixtures				
Expansive components				

16. What length of wet curing does your agency currently specify for cast-in-place concrete bridge decks?

	None	3 days	7 days	14 days	Other
Check only one					

If none, what method is used? If other, state how long.

17. What practices or tests, if any, does your agency currently use for acceptance of a new HPC mixture for concrete bridge decks?

18. Does your agency conduct tests of the hardened cast-in-place concrete to check end-product performance other than compressive strength?

( ) Routinely
( ) Sometimes
( ) Never

If routinely or sometimes, what tests are performed?

19. What are your agency's current practices to evaluate short- and long-term performance of HPC in bridge decks?

4. PRECAST, PRESTRESSED CONCRETE

20. Has your agency implemented high performance concrete in precast, prestressed concrete components?

( ) Yes. Go to next question.
( ) No.

If no, why not?

After completing this question, go to Section 5.

21. In your agency's <u>performance</u> specifications, which of the following characteristics are currently specified for precast, prestressed concrete beams and deck panels? Check all that apply.

	Precast Beams	Precast Panels
Not applicable		
Permeability		
Freeze-thaw resistance		
Deicer scaling		
Abrasion resistance		
Workability		
ASR resistance		
Sulfate resistance		

Compressive strength > 6.0 ksi		
Modulus of elasticity		
Creep		
Shrinkage		
Other		

If other, please list.

22. In your agency's <u>prescriptive</u> specifications, which of the following characteristics are currently considered in developing the specifications for precast, prestressed concrete beams and deck panels? Check all that apply.

	Precast Beams	Precast Panels
Not applicable		
Permeability		
Freeze-thaw resistance		
Deicer scaling		
Abrasion resistance		
Workability		
ASR resistance		
Sulfate resistance		
Compressive strength > 6.0 ksi		
Modulus of elasticity		
Creep		
Shrinkage		
Other		

If other, please list.

23. What is the frequency of use of the following supplementary cementitious materials in your agency's precast, prestressed concrete beams?

	None	1 to 33%	34 to 67%	68 to 100%
Fly ash Class C				
Fly ash Class F				
Pozzolan Class N				
Silica fume				
Ground-granulated blast-furnace slag				
Other				

If other, please list.

24. What is the frequency of use of the following supplementary cementitious materials in your agency's precast, prestressed concrete deck panels?

	None	1 to 33%	34 to 67%	68 to 100%
Fly ash Class C				
Fly ash Class F				
Pozzolan Class N				
Silica fume				
Ground-granulated blast-furnace slag				
Other				

If other, please list.

25. What is the frequency of use of the following admixtures for precast, prestressed concrete bridge beams?

	None	1 to 33%	34 to 67%	68 to 100%
AASHTO M 194 Type A—Water-reducing admixtures				
AASHTO M 194 Type B—Retarding admixtures				
AASHTO M 194 Type C—Accelerating admixtures				
AASHTO M 194 Type D—Water-reducing and retarding admixtures				
AASHTO M 194 Type E—Water-reducing and accelerating admixtures				
AASHTO M 194 Type F—High range water-reducing admixtures				
AASHTO M 194 Type G—High range water-reducing and retarding admixtures				
Corrosion inhibitors				
Shrinkage reducing admixtures				
Expansive components				

26. What is the frequency of use of the following admixtures for precast, prestressed concrete deck panels?

	None	1 to 33%	34 to 67%	68 to 100%
AASHTO M 194 Type A—Water-reducing admixtures				
AASHTO M 194 Type B—Retarding admixtures				
AASHTO M 194 Type C—Accelerating admixtures				
AASHTO M 194 Type D—Water-reducing and retarding admixtures				
AASHTO M 194 Type E—Water-reducing and accelerating admixtures				
AASHTO M 194 Type F—High range water-reducing admixtures				
AASHTO M 194 Type G—High range water-reducing and retarding admixtures				
Corrosion inhibitors				
Shrinkage reducing admixtures				
Expansive components				

27. What curing, if any, of precast, prestressed components is currently specified after they are removed from the casting bed?

28. What practices or tests, if any, does your agency currently use for acceptance of a new HPC mixture for precast, prestressed concrete components?

29. Does your agency conduct tests of the hardened precast, prestressed concrete to check end-product performance other than compressive strength?

( ) Routinely
( ) Sometimes
( ) Never

If routinely or sometimes, what tests are performed?

30. What are your agency's current practices to evaluate short- and long-term performance of HPC in precast, prestressed components?

5. RESEARCH

31. Please list any research in progress by your agency related to HPC.

32. Please list any recommendations for future research needs related to HPC.

33. Please list any agency research reports that document the performance of HPC in bridges and are available to be referenced in this synthesis. Please provide links or upload files in Question 35.

34. Are you willing to answer follow-up questions for this synthesis?

( ) Yes
( ) No

If no, is there an alternative contact?
( ) Yes
( ) No

If yes, please provide contact information.

6. UPLOAD FILES

35. This question may be used to upload up to five relevant files (up to 10 megabytes per file). Additional files may be e-mailed to Henry Russell at henry@hgrconcrete.com.

7. REVIEW

You may now review your answers and download a pdf version at the bottom of the page.

8. THANK YOU!

Thank you for taking our survey. Your response is very important to us. If you have any questions or comments, please feel free to contact Henry Russell at:

- E-mail: henry@hgrconcrete.com
- Phone: 847-998-9137
- Mailing Address: 720 Coronet Road, Glenview, IL 60025

APPENDIX B

Summary of Responses to Survey Questionnaire

This appendix contains a summary of the responses to the questionnaire. Only those agencies that submitted comments to the questions are listed.

1. INTRODUCTION

Responses to the survey were received from the following U.S. highway agencies:

Alabama
Alaska
Arizona
California
Colorado
District of Columbia
Florida
Georgia
Hawaii
Idaho
Illinois
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Missouri
Montana
Nebraska
Nevada
New Hampshire
New Jersey
New Mexico
New York
North Carolina
Ohio
Oklahoma
Oregon
Pennsylvania
South Carolina
South Dakota
Tennessee
Texas
Utah
Virginia
Washington
Wisconsin
Wyoming

2. GENERAL

1. Does your agency have a definition (formal or otherwise) for high performance concrete (HPC)?

Yes:	18 agencies
No:	21 agencies

If yes, please provide the definition.

Agency	Definition
Alaska	Concrete with engineered properties (strength, permeability, and wear resistance) that exceed those of conventional concrete
Arizona	See Jaber 2007.
Illinois	Illinois DOT uses special mix designs for various applications. We are getting away from the term high performance concrete because it has a very broad definition which makes the connotation ambiguous.
Kansas	High Performance Low Cracking Concrete is a specified concrete. However the general definition/description is durable, placeable, low permeability concrete using supplemental cementitious materials with reduced cement and water and optimized gradations.
Maryland	Concrete that has a life cycle of 75 years or better based on durability without a need for major repair. HPC is based on less permeable mixes, not high strength.
Massachusetts	Please refer to subsection M4.06.1 of Supplemental Specifications to the 1988 Standard Specifications for Highways and Bridges 2010.

Michigan	Concrete that will perform better for a given application than a "standard" mix design would have.
Nebraska	We try to follow AASHTO definition.
Nevada	Typically used for bridge decks, approach slabs, and bridge rail. Our specifications require a "Contractor Quality Control Plan." This addresses concrete production, QC testing, transport, a contingency plan for equipment failure and weather, placement, and curing. The mix design consists of a three-bin aggregate blend, cement, and 20% minimum pozzolan. Chloride permeability testing, AASHTO T 303 testing for ASR potential, and testing for all of the specific criteria established for a particular structure together with 10-day wet curing
New Hampshire	HPC consists of four strength-related performance characteristics (compressive strength, modulus of elasticity, shrinkage, and creep) and four durability-related performance characteristics (freeze-thaw resistance, scaling resistance, abrasion resistance, and chloride penetration).
New Jersey	From NJDOT Design Manual (20-1): Concrete that meets specific performance criteria
New Mexico	We have several "High Performance Concrete" applications. Basically, a "High Performance Concrete" mix is one that has been optimized for the performance properties required for the specific application. Our most common "High Performance Concrete" application is a "High Performance Deck" application for bridge decks and approach slabs.
New York	There is no specific definition for HPC although we have a mixture design defined as "HP" that is prescriptive in nature and incorporates the inclusion of 26% pozzolans to reduce thermal concerns to reduce cracking potential and to lower permeability.
North Carolina	Prescriptive mix design that produces concrete with low chloride permeability
Ohio	Our HPC mixes were designed to provide low permeability (typically 400 to 700 coulombs on the rapid chloride permeability testing). A consequence of this was high strength (typically 7,000 to 9,000 psi), but the bridge design are still based on 4,500 psi.
Oregon	Concrete designed for enhanced durability and performance characteristics. This definition is from section 02001.01 in the 2008 Oregon Standard Specifications for Construction. According to Section 02001.30 in these same specifications, high performance concrete mix designs must contain cementitious material with 66% portland cement, 30% fly ash, and 4% silica fume. Alternate mixes are permitted when a trial batch demonstrates the mix design provides a maximum of 1,000 coulombs at 90 days when tested according to AASHTO T 277.
South Carolina	Class E/6500 psi
Texas	Concrete that contains a minimum amount of SCM's replacing a portion of the cement or concrete that meets a specified permeability requirement
Virginia	Informal definition: Concrete that has high workability (SCC), high strength (exceeding 6 ksi), and low permeability (< 2,500 coulombs for decks)

2. How does your agency specify HPC? Select only one.

Standard specifications only:
    7 agencies
Special provisions for all projects:
    No agencies
Special provisions for specific projects:
    15 agencies
Combination of standard specifications and special provisions for all projects:
    6 agencies
Combination of standard specifications and special provisions for specific projects:
    10 agencies

3. Are your agency's standard specifications for HPC prescriptive, performance-based, or a combination?

Not applicable:	15 agencies
Prescriptive:	8 agencies
Performance:	2 agencies
Combination:	12 agencies

4. Are your agency's special provisions for HPC prescriptive, performance-based, or a combination?

Not applicable:	8 agencies
Prescriptive:	11 agencies
Performance:	2 agencies
Combination:	17 agencies

5. In general, how is your agency's HPC performing compared to conventional concrete?

Bridge Element	**Number of Agencies**			
	Worse	**Same**	**Better**	**Not Applicable**
Cast-in-place concrete	2	9	22	4
Precast concrete girders	0	6	16	14
Precast concrete deck panels	0	5	8	23

6. What performance issues with HPC has your agency identified?

Agency	**Cast-in-Place Concrete**	**Precast Concrete Girders**	**Precast Concrete Decks**
Alaska	Mix design issues and decreased workability	—	—
Arizona	Supply, regional availability of aggregates, construction QA	—	—
California	Corrosion, ASR, shrinkage	Corrosion, ASR, shrinkage	—
Colorado	Shrinkage cracking	—	—
District of Columbia	Cracking in bridge decks	—	—
Florida	Some cracking if curing is not started at the appropriate time	If curing is not initiated at the appropriate time, cracks develop.	—
Idaho	Cracking	—	—
Illinois	Concrete may be too strong for bridge decks, which may be causing cracks.	—	—
Iowa	Shrinkage cracks	—	—
Kansas	Requires attention to details, in particular cement content, gradations, and curing requirements	—	—
Maine	Cracking and workability issues	—	—
Minnesota	Transverse deck cracking	—	—
Nebraska	—	Slump consistency	—
Nevada	Minor cracking still apparent	Occasional voids still occur	—

New Jersey	Deck cracking	—	—
New Mexico	ASR, shrinkage, heat of hydration, cracking	ASR, shrinkage, heat of hydration, cracking, creep	ASR, shrinkage, heat of hydration, cracking, creep
New York	We still see some cracking but believe it is related to the numerous variables of deck construction—not always specific to HPC although there are still concerns w/autogenous shrinkage.	—	No concerns with the panels themselves and HPC use
Ohio	Cracking	—	—
Oklahoma	—	Buggy textured surface susceptible to minor cracking	—
Oregon	Shrinkage cracking has increased. We are working to reduce/mitigate cracking using various methods.	Although our girders typically use high-strength concrete, they generally do not require silica fume and we therefore would not classify the mix as high performance.	—
South Carolina	Shrinkage cracks	—	—
South Dakota	There have been some instances of increased cracking.	—	—
Texas	Some issues during construction related to fly ash affecting air entrainment.	—	—
Virginia	SCC can segregate and lose air, HPC can provide high strengths (unintentionally) that can make concrete more prone to cracking.	SCC can segregate and lose air.	—
Washington	Deck cracking	—	—

7. What specifications and practices has your agency used that resulted in improved concrete performance?

Agency	**Specifications and Practices**
Alabama	The Special Provision written for our only (known) HPC bridge project in 1999–2000 resulted in very good quality concrete, which appears to have performed significantly better than conventional concrete.
Alaska	Precast girders (high strength concrete typically $f'_c > 10$ ksi) appear to be very durable. We typically use the same concrete in decked girders resulting in very good deck performance.
Arizona	Special provision for a specific project. See Jaber 2007.
California	Limiting shrinkage in decks, limiting shrinkage in special structures, enhancing corrosion
Colorado	Lower cement contents, increased fly ash content, required wet curing for 7 days, using 56 days for strength acceptance
District of Columbia	Coulomb values for low permeability concrete and use of 50% slag cement

Florida	Our latest revision to Section 346 requires the use of fly ash or slag cement in all concrete. Where high strength and durability are required for a particular environmental classification, silica fume, metakaolin, or ultra fine fly ash may be required as well.
Iowa	Enhanced curing requirements such as longer wet cure and evaporation rate control and lower permeability through the use of mineral admixtures
Kansas	Maximum allowable permeability, use of SCMs, optimized aggregate gradations, and 14-day wet cure
Louisiana	Admixtures and cementitious substitutions: Fly ash/slag cement/silica fume
Maine	Implemented an ASR specification, implemented the Quality Level Analysis Specification for structural concrete
Maryland	Addition of fibers and corrosion inhibitors, reduction of the design compressive strength, and strict adherence to curing specifications
Massachusetts	Air entrainment of 6.5 ± 1.5%, target slump of 4 in., w/c ratio limited to 0.4 maximum, an addition of calcium nitrite corrosion inhibitors, use of fly ash and slag cement
Michigan	Implementation of supplemental cementitious materials, optimized aggregate gradations, 7-day wet cure, night placements
Minnesota	Performance based specification for concrete bridge decks
Nebraska	Use of fly ash or Class N pozzolan to mitigate ASR, used SCC concrete on precast concrete girders
Nevada	10-day wet cure and 3-bin coarse aggregate gradation
New Hampshire	NHDOT uses the term QC/QA concrete in our specifications, which is our version of HPC. The utilization ASR testing of aggregates, permeability requirements, and strict conformance to air requirements for all our mixes has shown to produce improved concrete.
New Mexico	We require that a mix be tested in the laboratory for performance properties before being allowed for use on actual projects. Properties tested for include air content, durability, permeability, shrinkage, and optimization of aggregate structure. We also require that batch weights and plastic properties be properly documented before allowing the fresh concrete to actually be placed.
New York	CIP HPC was established in 1996. We developed a prescriptive mixture requirement that shows the potential for reduced cracking and typically a 50% reduction in permeability in the field. At the same time we went to a 14-day wet curing process to further hydrate the HPC. Placement/vibration requirements were also enhanced at that time.
North Carolina	The substitution of silica fume and corrosion inhibitors for a portion of the portland cement
Ohio	The standard specification calls for No. 8 coarse aggregate, 660 lb of total cementitious materials (cement, slag cement or fly ash, and silica fume) and 0.40 w/c ratio. Due to cracking experienced with this mix, some districts have adopted revised design by plan notes that require a combination of No. 57 and No. 8 aggregates, 600 lb of total cementitious materials and 0.43 w/c ratio. One district has excluded the use of coarse aggregate with absorptions less than 1.0% in their bridge decks. They have experienced fewer problems with cracking from these mixes. Presumably from a combination of better grading, less shrinkage from cement, less autogenous shrinkage, and some internal curing from the higher absorption aggregates. These were all introduced at the same time, so how much improvement is attributed to what change has not been determined.
Oklahoma	Use of SCC
Oregon	We have changed curing requirements to require covering the concrete within 20 ft and 20 minutes of the last pass of the screed. We occasionally use polypropylene fibers to reduce cracking. This has generally been successful, but at a cost premium. We are doing research on precast deck panels which we anticipate will eliminate cracking and improve abrasion resistance. We are doing research on shrinkage reducing admixtures and lightweight fine aggregate to reduce shrinkage and potentially reduce curing time.

Pennsylvania	Some key aspects to improved performance are: 1. Limiting rate of strength gain, keeping 28-day/7-day strength to 1.20 maximum 2. Reducing the amount of cementitious material and paste content during mix design approval 3. Improved curing practices consistent with ACI, including mandatory 14-day wet cure 4. Evaporation rate controls per ACI-305R-99, Fig 2.1.5 5. Preclude pumping of concrete
South Carolina	Using supplementary cementitious materials such as fly ash and silica fume, and using a corrosion inhibitor
South Dakota	The addition of fly ash has been an improvement.
Tennessee	Maximum limit on chloride ion penetrability as per AASHTO of 1500 coulombs
Texas	Give multiple options to provide HPC
Utah	We developed a specification for self-consolidating concrete.
Virginia	Require SCM for ASR resistance, permeability testing with accelerated curing
Wisconsin	14-day wet cure, reduced cement content, reduced w/c ratio

8. What specifications and practices has your agency used that were unsuccessful?

   What is the basis for this assessment?

Agency	**Unsuccessful Specifications and Practices**	**Basis**
Alaska	Although the permeability is improved, the workability of concrete deck overlays with HPC is decreased.	HPC in deck overlays often has a cracked appearance during construction.
Florida	Our Section 353 is used for slab replacement concrete. This concrete is prone to cracking since the concrete must develop high early strength (2,200 psi in 6 hours or less). This is not really considered HPC but it is required to perform under some extenuating circumstances.	The mix for the slab replacement concrete has a high cementitious content to ensure the required strength at opening to traffic. These mixes are very susceptible to early age cracking due to excessive stresses in the concrete at opening to traffic. Normally we get the required strength based on cylinder breaks or maturity but cracking still occurs.
Illinois	Concrete may be too strong for bridge decks, which may be causing cracks.	Field observations
Maine	Surface tolerance and finish	An acceptable finish can be subjective at times.
Massachusetts	Silica fume alone	Workability issues from field, cracking reported in new decks
Michigan	Shrinkage reducing admixture	Laboratory mixes were successful, but during field trials we could not maintain the specified entrained air content. Construction was halted and conventional concrete was used to complete the project.
Minnesota	Have had limited success with high fly ash (> 30% Type F) bridge deck mixes.	Field surveys
Nevada	We have implemented shrinkage reducing admixture into deck concrete that is placed on steel girders in order to reduce cracking. This has helped, but not to a satisfactory degree.	Observation

New Hampshire	We originally had no lower limit on our permeability specification and the contractors were getting numbers below 800 coulombs by adding cement to get the bonus. We adjusted the specification and increased the lower limit.	The added cement to lower the permeability number was creating more cracks and a brittle deck. It also created work issues.
New Jersey	14-day wet cure of decks, some deck cracking	—
New Mexico	Since the actual air content is so important to know, we used to require that the air content be measured for compliance of the theoretical maximum unit weight, and corroborated with the pressure pot. However, we had great difficulty in getting our inspectors to do both tests, and they were recording pressure pot results without actually performing the test. We have now eliminated the pressure pot tests and use only the air determined from the theoretical maximum unit weight.	Experience
New York	Nothing specific that has resulted in any design changes or specification revisions	We continue to see transverse cracking on many decks although the cracks are fewer and finer. Autogenous shrinkage has been a concern that has led to the consideration of internal curing with HPC.
Ohio	The standard HPC specification can obviously be improved upon.	The designs by plan note are performing better as far as cracking is concerned. They are not getting as high strength as the standard, but still well above the design strength.
Oklahoma	Use of silica fume	Visual
Oregon	Initial use of high performance concrete with an evaporation reducer placed immediately following the last pass of the screed was not successful. Excessive cracking using this procedure resulted in the 20 feet and 20 minute requirement mentioned above.	—
Pennsylvania	1. Supplied concrete that had a rapid strength gain, focusing too much on maintaining the construction schedule 2. Potentially by not enforcing the maximum slump limits when pumping concrete	Assessment is primarily based on feedback from field personnel, and the concrete deck performance outcome as to deck cracking.
South Dakota	The use of silica fume was not successful for us.	The concrete with silica fume was difficult to work with (decreased workability) and resulted in increased cracking.
Texas	Requiring air entrainment in all concrete combined with HPC. Have since been more selective on where air entrainment is required	Problems in the field. We ended up with concrete with excessive amounts of air in the hardened concrete as a result of contractor overdosing and testing equipment unable to adequately measure air content correctly in fresh concrete.
Washington	HPC specifications requiring fly ash for bridge decks	Increased cracking

9. What lessons has your agency learned about the implementation of HPC? Specific case studies would be useful for the synthesis. Please list any reports or attach files in Question 35.

Agency	Response
Alabama	One requirement in our Special Provision for this project was that the contractor would be required to perform a test pour of the HPC. We did not specify the conditions under which the test pour should be performed. As a result, the test pour was performed during the summer in extremely hot temperatures, while the actual girder pours were made in winter months when the temperature was much cooler. The concrete struggled to meet the strength requirement during the production pours, as evident by the fact that 8 out of 18 pours failed to meet the 28-day strength requirement at the time. See attached Research Project reports from Auburn University, done in conjunction with ALDOT (Stallings and Eskildsen 2001 and Stallings and Porter 2002).
Alaska	Cast-in-place HPC may need to focus more on workability—not just the engineering properties.
Arizona	See Jaber 2007.
Florida	We know from data collected during the last 30 years that Class F fly ash is a necessity to ensure durable concrete. We have combined the use of the fly ash with low w/c ratios (0.38 to 0.41) and have developed a defense mechanism that has protected our structures from chlorides and sulfates. We have a few structures that are in need of some rehabilitation, but for the most part our structures are in exceptional condition.
Georgia	We have learned that we can use HPC for our prestressed concrete beams and piling.
Idaho	Location can have a significant impact. Less sophisticated suppliers, geometry of the deck, etc., can be major influences.
Kansas	Potential issues with low cement content and angular aggregates. University of Kansas, LC-HPC Study. Binary mixes are not as effective for reduction of permeability as ternary mixes. US-59 project, the report is being prepared at this time.
Louisiana	See LTRC Reports on HPC (2008) and long-term monitoring of the HPC Charenton Canal Bridge (Bruce et al. 2009).
Maryland	Placement techniques had to be slightly modified to account for the consistency of the mix that required the use of fibers.
Michigan	Prices for HPC will not necessarily be much in excess of the cost of a conventional concrete. A variety of plants have been able to successfully batch our HPC.
Minnesota	Work closely with industry, may require many field trials
Nebraska	Require higher degree of QC and timing when the ingredients go into the mixer
Nevada	The prewetted or very moist burlap covers must be placed within 20 to 30 minutes after final finish with high pressure fogging between the hand finishers and the burlap crew. The burlap must remain soaked until the hoses and covers are placed.
New Hampshire	Again, we use QC/QA specifications that were developed with a committee made up of DOT, concrete suppliers, and contractors. This aided in the implementation process because all had a say in the development.
New Mexico	HPC can be very effective, but it must be completely and thoroughly thought out, and implemented at the project level. Laboratory tests need to stay in the laboratory and field tests need to be used to corroborate the consistency of the mix that was measured in the laboratory.
New York	After a few years of use, the effectiveness of HPC to reduce cracking was questioned. A research study was progressed—Technical Report 03-01 (Graves 2003).
Oklahoma	We have been successful in making high strength concrete.
Oregon	Continuous fogging and curing in place as soon as practical is essential.
Pennsylvania	See attached files (Taylor et al. 2010 and PACA undated).

South Carolina	HPC mix was hard to handle in the field. The mix was very rich and sticky and needed experienced contractors.
South Dakota	Inclusion of fly ash in the mix decreased permeability and increased workability with little or no other effect to the concrete
Tennessee	Research shows our standard mix meets most HPC criteria.
Texas	With time, HPC became the normal concrete in most urban locations. However, we still have rural areas of the state where we cannot get SCM's and concrete producers don't care to provide us concrete containing them. It turns out you cannot force the issue.
Virginia	HPC requires attention to mixture proportioning and construction practices. End result specifications are effective in achieving quality product.
Washington	Move to performance specifications for bridge decks

3. CAST-IN-PLACE CONCRETE

10. Has your agency implemented high performance concrete in cast-in-place bridge decks?

Yes:	31 agencies
No:	8 agencies

If no, why not?

Agency	**Reason**
Alaska	Have used HPC for deck overlays with some mixed results and we don't do many cast-in-place decks.
California	We do not call it HPC. We address it prescriptively.
Georgia	It is not needed for Georgia DOT bridge decks.
Idaho	We did one project with a cast-in-place high performance concrete deck (half a bridge was regular concrete and the other half high performance concrete). There was no noticeable difference between the two decks. It should be noted the geometry of the deck almost assured cracking.
Nebraska	Only on deck overlays, where we use silica fume
Oklahoma	It appears that the improved curing process has improved the durability of our decks. The additional expense for the HPC decks does not appear to be justified at this time.
Utah	Material availability. Understanding of cost/benefit. Awareness. Resources required to control quality
Wyoming	Our standard concrete, epoxy-coated reinforcement, and 8 in. thick decks are performing well.

After completing this question, go to Section 4.

11. In your agency's performance specifications, which of the following characteristics are currently specified for cast-in-place concrete bridge decks? Check all that apply.

Not applicable:	11 agencies
Permeability:	15 agencies
Freeze-thaw resistance:	8 agencies
Deicer scaling:	3 agencies
Abrasion resistance:	2 agencies
Workability:	11 agencies
ASR resistance:	9 agencies
Sulfate resistance:	3 agencies

Compressive strength: 23 agencies
Modulus of elasticity: 2 agencies
Creep: 1 agency
Shrinkage: 6 agencies
Other: 8 agencies

Other characteristics included restrained shrinkage cracking, surface resistivity, air content, corrosion resistance, w/c ratio, and strength gain such that the 7-day compressive strength can be no greater than 80% of the 28-day strength, and the 56-day compressive strength must be at least 108% of the 28-day compressive strength.

12. In your agency's prescriptive specifications, which of the following characteristics are currently considered in developing the specifications for cast-in-place concrete bridge decks? Check all that apply.

Not applicable: 3 agencies
Permeability: 24 agencies
Freeze-thaw resistance: 16 agencies
Deicer scaling: 4 agencies
Abrasion resistance: 4 agencies
Workability: 19 agencies
ASR resistance: 18 agencies
Sulfate resistance: 7 agencies
Compressive strength: 29 agencies
Modulus of elasticity: 4 agencies
Creep: 2 agencies
Shrinkage: 9 agencies
Other: 6 agencies

Other characteristics included surface resistivity such as 29 kohm-cm at 28 days, corrosion resistance, air content, admixtures, reduced "overdesign" strength, reduced maximum cementitious content, 14-day wet cure, and restrained shrinkage cracking.

13. What strategies does your agency currently use to minimize cracking in cast-in-place concrete bridge decks?

Strategy to Minimize Bridge Deck Cracking	**No. of Agencies**	
	Yes	**No**
None	0	11
Specify minimum cementitious materials content	26	8
Specify maximum cementitious materials content	19	16
Specify minimum concrete compressive strength	33	2
Specify maximum concrete compressive strength	4	27
Specify a ratio between 7- and 28-day compressive strength	5	27
Specify minimum concrete temperature at placement	30	6
Specify maximum concrete temperature at placement	32	2
Specify maximum concrete temperature during curing	9	21
Specify maximum water-cementitious materials ratio	34	2
Specify maximum slump	30	5
Specify maximum water content	14	19
Require use of the ACI surface evaporation nomograph	18	15
Require wind breaks during concrete placement	13	21
Require evaporation retardants	9	23

Require fogging during placement when evaporation rates are high	27	8
Other	12	5

If other, please list.

Agency	**Other Strategies**
Alabama	Note: wind breaks are only required when evaporation rate is too high.
Arizona	Fast track finishing technique, minimum surface manipulation, concrete surface protection, immediate wet curing after surface cover is applied
Colorado	Only allow Type A & dual rated A/F admixtures, require a minimum 20% pozzolan, require the use of 55% size 57, 6 or 67 coarse aggregate as a percentage of total aggregate, minimum w/cm ratio, all mix water must be added at batching, and no slump adjustments with water, but with admixtures
Florida	We require the contractor to have a portable weather station on site when concrete is being placed. This tells the inspector and the contractor when wind speeds have been exceeded and protection needs to be in place. It also informs the contractor when the temperature is too high and that he needs to fog the concrete or protect the concrete from rapid moisture loss by one of the approved methods.
Iowa	Require evaporation retardants—allow as needed, but not for finishing. Other—Wet burlap cure within 10 minutes of final finishing. Continuously wet for 7 days and maintain greater than or equal to 50 F for 7 days.
Louisiana	For mass concrete, specify maximum concrete temperature during curing.
Maryland	Require wet curing
Michigan	Use of evaporation nomograph, nighttime concrete placements, 7-day wet cure
Nevada	Wet burlap placement within 30 minutes
New Hampshire	The contractor has to submit a plan before a deck placement. Evaporation and curing must be addressed in the plan.
New Mexico	Windbreaks and evaporation retarders are allowed if evaporation potential is too high.
New York	Being prescriptive, the specification does not address some of the expected benefits or controls that went into the specification development for HPC. The specification does restrict w/c ratio, cementitious content, and environmental controls. Newer special specifications are looking to address some of the other concerns like rate of strength gain and ratio of 7 to 28 day strengths as well as mix temperature. Additionally, use of internal curing is being experimented with.
Ohio	7-day wet cure followed by curing compound
Oregon	In some cases, we may specify polypropylene fibers in the mix.
South Dakota	Require 20% fly ash in the cementitious materials and a minimum 7-day wet cure
Texas	Wet curing
Virginia	Specify minimum cementitious materials content—in ERS minimum cementitious content is not required.
Wisconsin	Limit hand finishing, 14-day wet cure, place wet burlap within 10 minutes of finishing

What strategies to minimize cracking in cast-in-place concrete bridge decks have been most effective?

Agency	**Most Effective Strategies to Minimize Concrete Deck Cracking**
Alabama	Use of nomographs, wind breaks, and fogging
Arizona	Good curing plan and good protection plan as in other above
California	Curing
Colorado	Wet curing
District of Columbia	Reduction of total cement
Florida	Effective and adequate curing in a timely manner is the best means of minimizing cracking.
Georgia	Proper curing and controlling the concrete temperature
Hawaii	Use of shrinkage-reducing admixture
Iowa	Early wet cure, reduction in portland cement content, evaporation rate control, limit on maximum concrete temperature at time of placement
Kansas	Fogging, 14-day wet cure, SCMs, reduced cement and water content
Louisiana	Prompt and proper construction methods
Maine	Extra steel in areas subject to movement, minimize delays in applying wet curing
Maryland	Wet curing and fibers
Massachusetts	Wet curing
Michigan	Nighttime concrete placements, 7-day wet cure
Minnesota	University of Kansas mix designs, limited cement content, shrinkage testing, performance-based specifications based on meetings with industry
Nebraska	Increased the curing from 5 days to 7 days
Nevada	Wet curing
New Hampshire	Placing wet burlap on the deck as soon as possible after placement and keeping it wet for 7 days
New Mexico	Mix modifications to minimize characteristic shrinkage potential, controlling batch weights and water, proper curing
New York	Maintaining reasonable w/c and water content controls appear to impact performance. Internal curing is showing promise but still too early to know for certain.
North Carolina	The limit on maximum temperature and prescriptive requirements for the curing of the deck
Ohio	Wet curing, using mix designs with well-graded aggregates has also helped.
Oregon	Reducing time between concrete placement and application of wet cure
Pennsylvania	No pumping, reduced paste content, 14-day wet cure, slow strength gain via 28-day/7-day ratio
South Carolina	Require wind breaks during concrete placement, require fogging during placement when evaporation rates are high
Texas	Temperature controls

Utah	Proper curing and placing sequence
Wisconsin	Limiting cement content, wet cure

What strategies to minimize cracking in cast-in-place concrete bridge decks have been least effective?

Agency	**Least Effective Strategies to Minimize Concrete Deck Cracking**
Alabama	Maximum slump
Colorado	Prescriptive mix designs
Florida	Normally the contractor wants to wait until he gets the entire deck concrete placed before he starts to cure the concrete. This is usually too late to prevent crack initiation. With that, we have a requirement for the curing to start as soon as the initial sheen is gone from the concrete. As soon as the bleed water is gone from the concrete surface the contractor is required to implement one of the approved methods of curing.
Kansas	Maximum and minimum temperature control
Louisiana	Improper construction methods
Massachusetts	Curing membranes
Minnesota	High cement contents, high compressive strength requirements
Nevada	Evaporative retarders and curing compound
New Hampshire	Monitoring evaporation before and during placement. This is a required procedure by contractors and must be addressed in their plan.
New York	Controlling construction practices has been difficult as the focus is often on getting the work done—not necessarily getting the work done correctly. That is not a specification issue but one of enforcement that needs to be corrected.
Pennsylvania	Poor QC, not requiring a test slab to ensure workability
Texas	Maximum w/c ratio and minimum compressive strength
Virginia	Rich mixtures and low water-cementitious materials ratio
Washington	Evaporation retardants

14. What is the frequency of use of the following supplementary cementitious materials in your agency's cast-in-place concrete bridge decks?

Supplementary Cementitious Material	**Extent of Use as a Percentage of All Bridge Decks**			
	None	**1 to 33**	**34 to 67**	**68 to 100**
Fly ash Class C	17	8	3	5
Fly ash Class F	2	17	5	11
Pozzolan Class N	27	3	0	1
Silica fume	11	16	1	7

Ground-granulated blast-furnace slag	10	12	6	7
Other	9	0	0	0

No other supplementary cementitious materials were listed.

15. What is the frequency of use of the following admixtures for cast-in-place concrete bridge decks?

Admixture	**Extent of Use as a Percentage of All Bridge Decks**			
	None	**1 to 33**	**34 to 67**	**68 to 100**
AASHTO M 194 Type A— Water-reducing admixtures	4	4	5	22
AASHTO M 194 Type B—Retarding admixtures	9	11	7	7
AASHTO M 194 Type C—Accelerating admixtures	23	8	2	2
AASHTO M 194 Type D—Water-reducing and retarding admixtures	11	11	5	6
AASHTO M 194 Type E—Water-reducing and accelerating admixtures	23	8	1	0
AASHTO M 194 Type F—High range water-reducing admixtures	10	8	7	10
AASHTO M 194 Type G—High range water-reducing and retarding admixtures	16	11	2	3
Corrosion inhibitors	20	9	0	4
Shrinkage reducing admixtures	25	5	0	1
Expansive components	27	4	0	0

16. What length of wet curing does your agency currently specify for cast-in-place concrete bridge decks?

	None	3 days	7 days	14 days	Other
Check only one	0	1	23	9	4

Other lengths of wet curing were 5, 8, and 10 days.

17. What practices or tests, if any, does your agency currently use for acceptance of a new HPC mixture for concrete bridge decks?

Agency	**Practices or Tests Used for Acceptance of New HPC Mixtures for Concrete Bridge Decks**
Alabama	AASHTO T 22, ACI 211.4R, AASHTO T 119, AASHTO T 152, AASHTO T 309, 3-point curve of w/c ratios vs. compressive strength, AASHTO T 27
Arizona	Trial batches and pre-qualification of HPC mixes according to Special Provision for accepting HPC deck
Colorado	Each project must construct a test deck the width of the largest pour and a minimum of 30 ft long and at least the depth of the deck. It shall have the same reinforcement as the deck. This is to demonstrate that the concrete will consolidate properly and allow the contractor's crew to practice placing, finishing, and curing the HPC.
District of Columbia	Slump, air content, unit weight of plastic concrete, permeability, and compressive strength
Florida	Mixes are trial batched for initial approval. They are required to meet the minimum compressive strength and in most cases the concrete is trial batched under hot weather concrete conditions. It must maintain the allowable slump called for by the class of mix at greater than 90 degrees for 90 minutes. If the slump falls below the minimum for the class or application, the mix is rejected.

Illinois	Slump, air content, and strength
Iowa	Trial batch strength and permeability
Kansas	Approval of the mix by testing permeability using permeable voids or rapid chloride permeability and ACI statistical strength analysis
Louisiana	Trial batch
Maine	Permeability trial batch for new concrete plants or new mix from existing plants
Maryland	Trial batch
Massachusetts	Trial batch testing (temperature, air, slump) 28-day compressive strength
Michigan	Must meet specification requirements for material content/proportioning, coarseness and workability factors, and compressive strength
Minnesota	Laboratory testing of those properties indicated in Question No. 11 and a full-scale field test placement
Nevada	ASTM C1202 Rapid Chloride Permeability, AASHTO T 303 Mortar Bar Expansion, Modulus of Elasticity, California Method for Creep when required, and shrinkage by the California Method
New Hampshire	Test results for air, strength, permeability, ASR on the aggregates, w/c ratio must be submitted with the mix.
New Jersey	Verification testing on new mix design
New Mexico	Comprehensive tests performed at an approved testing laboratory for compressive strength, hardened air content, ASR mitigation, maximum shrinkage potential, permeability, durability, and rate of strength gain
New York	An in-house evaluation where we are concerned with shrinkage cracking, scaling and freeze-thaw durability, and reduced permeability
North Carolina	The mix design is reviewed for compliance with the project specifications and special provisions. The Materials & Testing Laboratory performs standard tests.
Ohio	Slump and air content in the field. HPC strength is tested, but not necessarily as an acceptance tool.
Oregon	Compressive strength per AASHTO T 23, temperature, air content, slump, water-cementitious materials ratio, density, and yield
Pennsylvania	Permeability, compressive strength, air content, heat of hydration, chloride ion, scaling, ASR, freeze-thaw durability, abrasion resistivity, and shrinkage
South Carolina	Compressive strength
South Dakota	Slump, air, 28-day strength, and water/cement ratio
Tennessee	AASHTO T 277
Utah	Trial batch is submitted to the materials laboratory for evaluation. It must meet or exceed parameters of conventional concrete.
Virginia	Trial batch
Wisconsin	A laboratory trial mix must be produced as well as a trial mix from each plant used to supply the project. All mixes must be tested at a department qualified laboratory, with the following tests: AASHTO T 119 for slump, AASHTO T 121 for density, AASHTO T 152 for air content, AASHTO T 22 for compressive strength, AASHTO T 277 for rapid chloride permeability, and AASHTO T 309 for temperature, and water-cement ratio.

18. Does your agency conduct tests of the hardened cast-in-place concrete to check end-product performance other than compressive strength?

Routinely:	5 agencies
Sometimes:	12 agencies
Never:	20 agencies

If routinely or sometimes, what tests are performed?

Agency	**Tests Performed to Check End Product Performance**
Arizona	Rapid chloride permeability, chloride ion content in bridge deck profile
Florida	When there is a issue with low strength, we require the contractor to remove cores. We'll use two cores to verify the strength then one or two cores to verify resistivity of the concrete. In some cases if the strength is very low and there is a question as to whether the concrete will stay in place, we may test the concrete for chlorides as well as surface resistivity to ensure that we have a durable concrete in place.
Iowa	Permeability (rarely)
Kansas	If there is a reason to question the quality of the in place concrete cores may be taken for hardened air content and permeability.
Louisiana	Permeability—surface resistivity
Maine	For permeability if acceptance tests are disputed
Massachusetts	Soundness and cores
Minnesota	Hardened air content, permeability
Nevada	Permeability
New York	When we originally developed HPC we did perform field testing for strength, permeability, absorption, unit weight, and freeze-thaw from field samples. We observed consistent performance and thus stopped any testing after 2 years.
North Carolina	Chloride permeability
Ohio	Initially we had rapid chloride permeability tests (AASHTO T 277), drying shrinkage (ASTM C157),and heat of hydration testing performed to evaluate the designs. That was discontinued after a short time.
Pennsylvania	Document amount of deck cracking by observation
South Dakota	Petrographic analysis of cores
Texas	Only if there are problems
Virginia	Permeability
Wisconsin	Chloride penetration resistance—AASHTO T 259, T 277

19. What are your agency's current practices to evaluate short- and long-term performance of HPC in bridge decks?

Agency	**Current Practice to Evaluate Performance of HPC in Bridge Decks**
Alabama	Testing slump, air, and compressive strength of the concrete at the first load delivered, then once every 50 yd^3
Alaska	Monitor deck condition as part of bridge inspection program

Arizona	Monitoring HPC report, see Jaber 2007.
California	Monitor Maintenance Reports
Colorado	None, other than the required routine bridge deck inspections
District of Columbia	None at this time except rapid chloride permeability and compressive strength
Florida	Our bridge inspectors assess our non-movable bridges every 2 years and the movable ones every year. They have been trained to look for areas of corrosion or severe cracking and spalling. When this is reported to the Corrosion Section Field Operations, they investigate the structure in more detail. They may take resistance measurements, or remove cores to verify chloride content and take chloride profiles.
Illinois	Field observations
Kansas	Air content of concrete sampled at placement, permeability of concrete sampled at placement, and strength of concrete sampled at placement
Louisiana	Visual inspection
Maryland	Visual inspections every 2 years, major waterway bridges are visually inspected yearly.
Michigan	Periodic site visits to evaluate deck condition, including cracking, scaling, overall condition
Minnesota	In-service bridge inspections, occasional special inspections
Nevada	The Structural Division inspects bridges every 2 years
New Mexico	Monitoring through a pavement management program
North Carolina	The deck and all other components of the bridge are inspected every 2 years.
Oregon	Visual inspection following construction and during required two-year routine inspections
Pennsylvania	Implemented a deck performance database to track amount of deck cracking and actual deck rating over time
South Dakota	The only formal evaluation are [of] those decks involved in research projects.
Texas	Decks are walked to check for cracking but not much else.
Virginia	Visual inspection and sometimes coring and testing

4. PRECAST, PRESTRESSED CONCRETE

20. Has your agency implemented high performance concrete in precast, prestressed concrete components?

Yes:	21 agencies
No:	16 agencies

Agency	**Reasons for Not Using HPC in Precast, Prestressed Concrete**
Arizona	Unfamiliar with practice
California	We do not call it HPC—we require SCMs (in some cases).
Colorado	We allow the suppliers to use whatever concrete they see fit. We do not approve their concrete mixtures. Some use SCC.

Idaho	Haven't seen the advantage in doing so
Illinois	Illinois DOT has not seen a compelling reason to have low permeability concrete beams.
Kansas	Due to the low water-cement ratios and controlled environment of the precast plants we have not been as involved. KDOT does however allow the use of the same SCMs and require permeability testing of the precast concrete. Aggregates are KDOT approved materials to prevent ASR and freeze-thaw damage.
Maryland	Our definition of HPC based on a lower compressive strength does not lend itself to precast/prestressed elements.
Ohio	There are permeability requirements for prestressed concrete, but that's not necessarily high performance. For precast and prestressed concrete, the producers use their own designs.
Oregon	We have used high performance concrete in selected applications, but not for typical applications. We have had excellent long-term performance with precast concrete girders without using a high performance concrete. We typically get 10,000 + psi concrete strength with existing mix designs. Our precasters are comfortable achieving these strengths, but are not confident they can achieve significantly higher strengths with the aggregates they have available.
Pennsylvania	Precast components use high-early strength concrete due to plant production schedules.
Tennessee	No specific definition of HPC
Utah	Supplier ability, awareness, etc.
Wisconsin	Have not had a need

After completing this question, go to Section 5.

21. In your agency's <u>performance</u> specifications, which of the following characteristics are currently specified for precast, prestressed concrete beams and deck panels? Check all that apply.

Characteristic	**Precast Beams**	**Precast Panels**
Not applicable	10	14
Permeability	7	5
Freeze-thaw resistance	8	8
Deicer scaling	2	3
Abrasion resistance	2	4
Workability	6	3
ASR resistance	8	9
Sulfate resistance	0	2
Compressive strength > 6.0 ksi	17	8
Modulus of elasticity	5	5
Creep	2	3
Shrinkage	2	3
Other	0	0

22. In your agency's prescriptive specifications, which of the following characteristics are currently considered in developing the specifications for precast, prestressed concrete beams and deck panels? Check all that apply.

Characteristic	Precast Beams	Precast Panels
Not applicable	7	13
Permeability	11	3
Freeze-thaw resistance	11	8
Deicer scaling	2	2
Abrasion resistance	1	1
Workability	11	2
ASR resistance	10	6
Sulfate resistance	4	4
Compressive strength > 6.0 ksi	19	4
Modulus of elasticity	3	2
Creep	2	2
Shrinkage	4	3
Other	2	1

The one other characteristic was flexural strength.

23. What is the frequency of use of the following supplementary cementitious materials in your agency's precast, prestressed concrete beams?

Supplementary Cementitious Material	Extent of Use as a Percentage of All Bridges			
	None	1 to 33	34 to 67	68 to 100
Fly ash Class C	24	2	1	3
Fly ash Class F	10	11	2	6
Pozzolan Class N	23	4	0	1
Silica fume	14	10	2	2
Ground-granulated blast-furnace slag	16	5	3	3
Other	13	0	0	1

The other material was Type IP cement.

24. What is the frequency of use of the following supplementary cementitious materials in your agency's precast, prestressed concrete deck panels?

Supplementary Cementitious Material	Extent of Use as a Percentage of All Bridges			
	None	1 to 33	34 to 67	68 to 100
Fly ash Class C	22	2	1	1
Fly ash Class F	12	6	3	4
Pozzolan Class N	22	3	0	0
Silica fume	16	6	1	1

Ground-granulated blast-furnace slag	18	3	3	1
Other	14	0	0	0

25. What is the frequency of use of the following admixtures for precast, prestressed concrete bridge beams?

Admixture	**Extent of Use as a Percentage of All Bridges**			
	None	**1 to 33**	**34 to 67**	**68 to 100**
AASHTO M 194 Type A—Water-reducing admixtures	8	6	5	8
AASHTO M 194 Type B—Retarding admixtures	14	5	5	1
AASHTO M 194 Type C—Accelerating admixtures	18	3	4	0
AASHTO M 194 Type D—Water-reducing and retarding admixtures	12	7	4	2
AASHTO M 194 Type E—Water-reducing and accelerating admixtures	18	4	2	1
AASHTO M 194 Type F—High range water-reducing admixtures	3	3	7	15
AASHTO M 194 Type G—High range water-reducing and retarding admixtures	14	5	3	4
Corrosion inhibitors	14	7	2	4
Shrinkage reducing admixtures	20	4	0	1
Expansive components	24	0	0	0

26. What is the frequency of use of the following admixtures for precast, prestressed concrete deck panels?

Admixture	**Extent of Use as a Percentage of All Bridge Decks**			
	None	**1 to 33**	**34 to 67**	**68 to 100**
AASHTO M 194 Type A—Water-reducing admixtures	9	5	4	6
AASHTO M 194 Type B—Retarding admixtures	14	5	4	0
AASHTO M 194 Type C—Accelerating admixtures	15	3	4	0
AASHTO M 194 Type D—Water-reducing and retarding admixtures	13	6	4	0
AASHTO M 194 Type E—Water-reducing and accelerating admixtures	15	4	2	1
AASHTO M 194 Type F—High range water-reducing admixtures	9	2	4	8
AASHTO M 194 Type G—High range water-reducing and retarding admixtures	16	4	1	2
Corrosion inhibitors	14	4	2	3
Shrinkage reducing admixtures	19	3	0	0
Expansive components	20	0	0	0

27. What curing, if any, of precast, prestressed components is currently specified after they are removed from the casting bed?

Agency	**Curing Method**
Alabama	Either wet cure for a minimum of 3 days, or steam cure for minimum of 24 hrs. This is all prior to detensioning.
Alaska	Although several methods are permitted, most all girders are steam cured.
Florida	The curing for these elements is 72 hours of wet curing. If the forms are released or removed, the curing process must be continued to meet the full duration of the 72 h.
Hawaii	Wet curing or water curing
Maine	Wet cured until design strength is achieved
Massachusetts	Steam/wet cure until 4000 psi is achieved
Michigan	Temperature range of 70°F to 160°F. Only apply steam or radiant heat after initial set. Maximum ambient and concrete temperatures are specified, as well as maximum cooling rate.
Minnesota	None, we only require curing until 45% of design strength and detensioning strength is always higher than that.
Nevada	Steam curing and curing compound method, radiant heat curing has been included on recent projects.
New Hampshire	Curing is allowed to be stopped when the member reaches release strength.
New Mexico	They are checked for minimum strength for release and transportation purposes.
New York	Unless steam curing is complete, all elements must be cured for 7 days. If removed from forms wet burlap/plastic covers used as we further require application of penetrating sealers and curing compounds would have to be removed.
Oregon	Members are cured using low-pressure steam or radiant heat inside an enclosure.
South Dakota	Low pressure steam, radiant heat, or as specified for CIP structural concrete
Texas	4 days wet cure required for piling and top surfaces of direct traffic beams (i.e., box and slab beams)
Utah	Panels are wet cured for 14 days. Nothing for beams after they are removed from the bed.
Virginia	Steam curing or wet curing
Washington	Both steam and radiant curing methods are used.

28. What practices or tests, if any, does your agency currently use for acceptance of a new HPC mixture for precast, prestressed concrete components?

Agency	**Practices or Tests Used for Acceptance of New HPC Mixtures for Precast, Prestressed Concrete Components**
Alabama	Same as for cast-in-place
Alaska	Strength tests
Colorado	Just strength

Florida	All of our mixes are trial batched and verified by the district inspectors. This may change as the department looks at ways to economize their processes. There is a major push for performance specifications in an effort to minimize department interaction with the contractor. The thinking is that we tell the contractor what we want for a finished product, he delivers it, and we verify it. If it meets the requirements of the plans, he gets paid; if it does not, we go to resolution.
Georgia	Strength data, permeability data, concrete test data (slump, air entrainment, temperature, etc.)
Hawaii	Same tests as non-HPC mixtures
Iowa	Strength and permeability
Louisiana	Trial batch
Maine	Mix design review
Massachusetts	Air, slump, temperature, finish/color, compressive strength
Michigan	Compressive strength
Minnesota	Compressive strength
Nebraska	Trial batches
Nevada	Same as deck concrete
New Hampshire	Test results for strength, permeability, air, and slump/spread on the mix, and ASR on the aggregates/mix
New Jersey	Verification testing of new mix design
New Mexico	Same as cast-in-place concrete except we do not require a controlled strength gain curve due to nature of precasting operations.
New York	Mixture prequalification is required. Other testing during production is done for acceptance. See specification 718-06 at https://www.dot.ny.gov/main/business-center/engineering/specifications/english-spec-repository/section700.pdf
North Carolina	The mix design is reviewed for compliance with the project specifications and special provisions. The Materials & Tests Laboratory performs standard tests.
Oklahoma	Compressive strength and visual inspection
Oregon	Use of HPC in prestressed concrete components is rare. When used, testing is similar to non-HPC mixes.
South Dakota	Slump, air, strength, and water/cement ratio
Utah	Trial batch is submitted to the materials lab for evaluation. It must meet or exceed parameters of conventional concrete.
Virginia	Trial mixture

29. Does your agency conduct tests of the hardened precast, prestressed concrete to check end-product performance other than compressive strength?

Routinely:	4 agencies
Sometimes:	7 agencies
Never:	16 agencies

If routinely or sometimes, what tests are performed?

Agency	Tests Performed
Florida	If there is a question as to the strength of the concrete, cores may be removed to verify in-place strength, or surface resistivity may be performed to validate durability.
Georgia	Permeability is checked.
Iowa	Permeability
Louisiana	Surface resistivity
Maine	Verification of permeability if applicable (very rare)
Nebraska	Modulus of elasticity
New Hampshire	Permeability
New Mexico	Plastic properties and compressive strength tests
New York	Acceptance testing performed per the PCCM found at https://www.dot.ny.gov/divisions/engineering/structures/manuals/pccm
North Carolina	Permeability
Virginia	Permeability

30. What are your agency's current practices to evaluate short- and long-term performance of HPC in precast, prestressed components?

Agency	Current Practices to Evaluate Performance of HPC in Precast, Prestressed Concrete Components
Alabama	Same as for cast-in-place.
Alaska	Examine condition of the girders as part of the bridge inspection program
Florida	Our bridges are inspected every 2 years, and any defect concerning a question of the durability of the concrete will be evaluated further by a representative of the Corrosion Section, or by the Structural Materials Section. If repairs are required then one of our consultants would be brought in to perform the work.
Minnesota	In-service inspections
Nebraska	Monitor fresh concrete characteristics, and testing at release, 7, 28, and 56 days
New Mexico	Pavement management program
North Carolina	The precast, prestressed girders and all other components of the bridge are inspected every 2 years.
Oklahoma	Visual inspection (NBIS)
Oregon	Routine bridge inspections every 2 years according to federal standards
South Dakota	Only those components involved in research projects are formally evaluated.
Texas	Visual
Virginia	Visual inspection

5. RESEARCH

31. Please list any research in progress by your agency related to HPC.

Agency	Research in Progress
Arizona	HPC project study and monitoring the bridge HPC deck
Florida	We are investigating the use of a field device that can perform several NDT evaluations in one pass. We have a prototype that can be attached to the side of a prestressed girder. The scanning device initiates at a starting point and evaluates the concrete at any interval not to exceed 5 square feet. For instance, we could evaluate every square inch of a 5 foot square area without any outside influence using pulse velocity, acoustic emission (echo impact), and radar at the same time in one pass.
Illinois	Illinois DOT is currently working on a report to assess the performance of HPC bridge decks constructed between 2000 and 2003.
Iowa	Shrinkage
Kansas	High Performance Low Cracking Concrete, University of Kansas. Effects of Temperature and Curing on Concrete with SCMs, KDOT.
Louisiana	LTRC: 03-7ST, 10-3TIRE, 09-4C, 09-6C, 09-5C, 10-1C.
Michigan	Precast bridge systems: http://rip.trb.org/browse/dproject.asp?n=27330 Causes and Solution Strategies for Deck Cracking: http://rip.trb.org/browse/dproject.asp?n=27311 Effects of Debonded Strands in Prestressed Beams: http://rip.trb.org/browse/dproject.asp?n=27303 Rapid Deck Replacement, Precast Panels: http://rip.trb.org/browse/dproject.asp?n=27302 University of Kansas Pooled Fund Project for Construction of Crack-Free Bridge Decks, Including Development of LC-HPC (Low Cracking High Performance Concrete).
Minnesota	Bridge deck cracking surveys, participating in University of Kansas study, trial projects with HPC for deck placements and precast substructures. Will build our first full-depth precast deck panels this summer
Nevada	We are looking at air entrainment of in-place concrete relative to sampling at the mixer versus sampling at the end of the pump truck hose.
New Hampshire	Our research program includes a project to establish upper limits for supplementary cementitious materials (fly ash and slag cement) for durable concrete. However, the project has not begun.
New York	Internal curing of HPC experimentation progressing to see if there is a reduction in deck cracking
Oregon	Shrinkage Limits and Testing Protocols for High Performance Concrete at Oregon State University. Self-Curing Concrete at National Chiag-Tung University, Taiwan. Internal Curing of Concrete Bridge Decks (using lightweight fine aggregate) at Oregon State University. Abrasion-Resistant Concrete Mix Designs for Bridge Decks at Oregon State University
Pennsylvania	On-going "Bridge Deck Cracking Prevention and Remediation" research project, to document deck cracking rates and to develop "best practices" regarding engineering design, mix design, and construction methods, to produce the highest quality bridge decks
South Dakota	SD2005-11 Evaluation of Crack Free Bridge Decks and TPF5(051) Construction of Crack Free Bridge Decks
Tennessee	Tennessee Tech: Low Permeability Mix Development and Low Heat of Hydration. UT: Surface Resistivity Correlation to Rapid Chloride Ion Permeability
Texas	Project Title: "Investigation of Alternative Supplementary Cementing Materials (SCMs)"—University of Texas Austin - 0-6717 Note: TxDOT has funded many research projects related to HPC. These report can be found at: http://library.ctr.utexas.edu/dbtw-wpd/textbase/websearchcat.htm.
Virginia	SCC in substructure repairs, lightweight SCC
Washington	Shrinkage test with WSU. Concrete mix test with UW. Concrete mix test for floating bridges with WSU

32. Please list any recommendations for future research needs related to HPC.

Agency	Recommendations for Future Research
District of Columbia	Causes of bridge deck cracks
Florida	Effective means to evaluate concrete in all applications so that we can move towards performance specifications. To me this is the one facet of the performance specification puzzle that has not been completed. If we had reliable NDT tests that could tell us that we had the compressive strength that we need for design and the durability to meet the environmental needs, this could be a major shift of our philosophy towards acceptance of concrete.
Louisiana	LTRC: 03-7ST (Bruce et al. 2009)
Michigan	Development of a durability test or tests. An accelerated method to determine if proposed developments will provide the extended service lives that our bridges must meet. Tests that can be performed on plastic concrete would be particularly useful.
New Mexico	The concept of HPC needs to be extended to PCCP. We are currently implementing very similar performance requirements for PCCP to improve performance of our concrete pavements.
Pennsylvania	Several types of structures and conditions could be studied to see how they can be improved to reduce deck cracking, such as integral abutments due to the longitudinal restraint. Are expansive additives or polypropylene fibers effective in reducing deck cracking and improving deck performance. Also, when decks crack, what are the most cost-effective means of sealing cracks to reduce future maintenance.
South Carolina	Permeability and shrinkage cracks
Virginia	Emphasize durability, avoid high strength in decks, consider shrinkage, elastic modulus, and creep for reduced cracking

33. Please list any agency research reports that document the performance of HPC in bridges and are available to be referenced in this synthesis. Please provide links or upload files in Question 35.

Agency	Research Reports about Performance of HPC in Bridges
Alabama	ALDOT Research Project No. 930-373 (Stallings and Eskildsen 2001 and Stallings and Porter 2002)
Colorado	http://www.coloradodot.info/programs/research/pdfs/2003/newdeckcracking.pdf/view http://www.coloradodot.info/programs/research/pdfs/2001/bridgedeckmix.pdf/view http://www.coloradodot.info/programs/research/pdfs/2010/classhconcrete/view
Michigan	Research reports available at http://www.michigan.gov/mdot/0,1607,7-151-9622_11045_24249---,00.html#BRIDGES_STRUCTURES
North Carolina	Behavior of a New High Performance Concrete Bridge on US 401 Over Neuse River in Wake County (Project ID 2002-17) and Kowalsky et al. 2002 and 2003
Pennsylvania	See PACA undated
South Dakota	SD2002-02 Improved Concrete Mix Designs for Bridge Deck Overlays, SD2000-06 Optimized Fly Ash Content in PCC for Structures. SD1998-06 Evaluation of High Performance Concrete in Two Bridge Decks and Prestressed Girders (Ramakrishnan and Sigl 2001)
Virginia	VDOT's Research Center (VCTIR) has publications that deal with HPC: http://vtrc.virginiadot.org/Allpubs.aspx.
Washington	Through WSDOT Research Office—Please contact Kim Willoughby at willowk@wsdot.wa.gov.

APPENDIX C

Websites for State Standard Specifications [Effective May 26, 2012]

State	State Specification Website
Alabama	http://www.dot.state.al.us/conweb/specifications.htm
Alaska	http://www.dot.state.ak.us/stwddes/dcsspecs/resources.shtml
Arizona	http://www.azdot.gov/Highways/ConstGrp/contractors/PDF/2008StandardSpecifications.pdf
Arkansas	http://www.arkansashighways.com/standard_spec_2003.aspx
California	http://www.dot.ca.gov/hq/esc/oe/specifications/std_specs/
Colorado	http://www.coloradodot.info/business/designsupport/construction-specifications/2011-Specs/2011-specs-book/2011-Specs-Book.pdf/view
Connecticut	http://www.ct.gov/dot/cwp/view.asp?a=1385&q=464504
Delaware	http://www.deldot.gov/information/pubs_forms/manuals/standard_specifications/index.shtml
Florida	http://www.dot.state.fl.us/specificationsoffice
Georgia	http://dot.state.ga.us/doingbusiness/thesource/pages/specifications.aspx
Hawaii	http://hawaii.gov/dot/highways/specifications2005/specifications/spectble.htm
Idaho	http://itd.idaho.gov/manuals/ManualsOnline.htm
Illinois	http://dot.state.il.us/desenv/hwyspecs.html
Indiana	http://www.ai.org/dot/div/contracts/standards/book/index.html
Iowa	http://www.dot.state.ia.us/specifications/index.htm
Kansas	http://www.ksdot.org/burConsMain/specprov/specifications.asp
Kentucky	http://transportation.ky.gov/construction/pages/kentucky-standard-specifications.aspx
Louisiana	http://www.dotd.la.gov/highways/specifications/home.aspx
Maine	http://www.state.me.us/mdot/contractor-consultant-information/ss_standard_specification_2002.php
Maryland	http://www.sha.maryland.gov/Index.aspx?PageId=44
Massachusetts	http://www.massdot.state.ma.us/highway/DoingBusinessWithUs/ManualsPublicationsForms.aspx
Michigan	http://mdotwas1.mdot.state.mi.us/public/specbook/
Minnesota	http://www.dot.state.mn.us/pre-letting/spec/index.html
Mississippi	http://www.gomdot.com/Divisions/Highways/Resources.aspx?Div=Construction
Missouri	http://www.modot.mo.gov/business/standards_and_specs/highwayspecs.htm
Montana	http://www.mdt.mt.gov/business/contracting/standard_specs.shtml
Nebraska	http://www.nebraskatransportation.org/ref-man/
Nevada	http://www.nevadadot.com/uploadedFiles/NDOT/About_NDOT/NDOT_Divisions/Engineering/Specifications/2001StandardSpecifications.pdf
New Hampshire	www.nh.gov/dot/org/projectdevelopment/highwaydesign/specifications/index.htm
New Jersey	http://www.state.nj.us/transportation/eng/specs/index.shtml
New Mexico	http://dot.state.nm.us/Standards.html
New York	https://www.dot.ny.gov/main/business-center/engineering/specifications/2008-standard-specs-us
North Carolina	http://www.ncdot.org/doh/preconstruct/ps/specifications/
North Dakota	http://www.dot.nd.gov/dotnet/supplspecs/StandardSpecs.aspx
Ohio	http://www.dot.state.oh.us/Divisions/ConstructionMgt/OnlineDocs/Pages/2005CMS.aspx
Oklahoma	http://www.okladot.state.ok.us/cnstrctengr.htm
Oregon	http://www.oregon.gov/ODOT/HWY/SPECS/standard_specifications.shtml
Pennsylvania	ftp://ftp.dot.state.pa.us/public/bureaus/design/pub408/pub%20408-2011.pdf
Rhode Island	http://www.dot.state.ri.us/publications/
South Carolina	http://www.dot.state.sc.us/doing/const_man.shtml
South Dakota	http://sddot.com/business/contractors/Specs/default.aspx
Tennessee	http://www.tdot.state.tn.us/construction/specs.htm
Texas	http://www.dot.state.tx.us/business/specifications.htm
Utah	http://www.udot.utah.gov/main/f?p=100:pg:0:::1:T,V:3696,
Vermont	http://www.aot.state.vt.us/conadmin/2011StandardSpecs.htm
Virginia	http://www.virginiadot.org/business/const/spec-default.asp
Washington	http://www.wsdot.wa.gov/biz/construction/MoreBooks.cfm
West Virginia	http://www.transportation.wv.gov/highways/contractadmin/specifications/Pages/default.aspx
Wisconsin	http://roadwaystandards.dot.wi.gov/standards/stndspec/index.htm
Wyoming	http://www.dot.state.wy.us/wydot/engineering_technical_programs/manuals_publications/2010_Standard_Specifications

Abbreviations used without definitions in TRB publications:

A4A	Airlines for America
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	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
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
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
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
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