TRC0002

Use of High Performance Concrete on Highway Bridge Decks

Valerie Farris, Brett Creswell, and Micah Hale

Final Report

2005

Use of High Performance Concrete in Highway Bridge Decks

By

Valerie Farris, Brett Creswell, and Micah Hale

Final Report for TRC0002

TABLE OF CONTENTS

CHAPTER

CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

High Performance Concrete (HPC) is an engineered material that is specially formulated to meet the construction, strength, and durability requirements of each individual construction project. The application of HPC to bridge decks is of particular interest to the Arkansas Highway and Transportation Department (AHTD). However, the lack of a performance-based specification for structural concrete represents a barrier to AHTD's implementation of HPC. It is therefore proposed that research be conducted in order to provide AHTD with a state of the art report on the use of HPC in bridge decks. If possible, a performance-based specification for structural concrete may also be provided.

1.2 BACKGROUND

In 1989 the Strategic Highway Research Program (SHRP) brought attention to the concept of HPC by funding a four-year study of this construction material. The primary objective of this research was to evaluate the structural and economic benefits from using HPC in highway structures. This study ultimately focused on the development of three classes of HPC and their use in the construction and repair of highway pavements and bridge decks. AHTD was a major contributor to the success of this research program.

Since the conclusion of the SHRP project in 1993 the AHTD has, on more than five occasions, specified an HPC mixture for use in the repair of a highway pavement section. These applications represent the extent of AHTD's use of HPC to date.

In 1996, the Federal Highway Administration (FHWA), through the implementation arm of SHRP, started a program to promote the use of HPC in bridge structures. The goal of the High Performance Concrete Bridge Showcase has been to educate the bridge engineering community regarding the benefits of HPC as well as highlight its successful application. Subsequent to a mini showcase held in Arkansas, the AHTD began to consider the use of HPC in its bridges. With the majority of bridge superstructures in Arkansas being constructed of steel, the most promising use for HPC is in a bridge deck. When compared to a conventional concrete deck, an HPC deck has the potential for greater durability, to be stronger, to require fewer repairs, and to be more cost effective over the life of the structure. However, there are potential barriers to the implementation of HPC.

The performance of a concrete mixture is largely dependent on the characteristics of its constituents. This issue becomes magnified when talking about an HPC mixture. Research conducted by the University of Arkansas has shown that HPC mixtures can be produced using the locally available materials in Arkansas. Thus, the ability to produce an HPC mixture should not be a barrier to AHTD's use of this material.

For an HPC mixture to be effective it must be proportioned to satisfy appropriate and quantifiable performance criteria. In its current form, AHTD's specification for structural concrete is prescriptive in nature. The only performance criteria mentioned in the specification include slump, air content, and compressive strength. Further, the specification limits the use of some admixtures commonly found in HPC. Therefore, both the lack of a performance-based specification and the restricted use of some constituent materials represent barriers to HPC's use in Arkansas.

1.3 SCOPE

In order to devise a new specification it will be necessary to collect and analyze a variety of data from existing and newly constructed bridge decks. Acquisition of the necessary data will be accomplished through a literature review and through a state DOT survey. The primary deliverable from this research will be a state of the art report on the use of HPC in bridge decks.

The ultimate goal of this research is to provide AHTD with a state of the art report on use of HPC bridge decks and possibly a performance based specification. This can be achieved if the specification for deck class concrete not only permits but also promotes the use of HPC. Such a specification must,

- include a list of performance characteristics, for the fresh and hardened concrete, that are pertinent to the environment and traffic conditions in Arkansas
- define reasonable, and attainable, levels of performance for any one characteristic
- permit the use of a wide range of admixtures
- identify any special proportioning, production, placing, and curing requirements
- provide requirements for evaluating the in-place performance of an HPC deck

The current AHTD specification for structural concrete is prescriptive in nature. The specification lists the constituents that can and can not be added to a mixture, how much can or must be added, and places limits on the characteristics of some ingredients. It also contains information on production, placement, curing, testing, and payment issues. Slump, air content, and compressive strength are the only performance criteria that are defined and require that require field measurement. Air content and slump are each defined by a single range in value. Compressive strength is defined by a single minimum value. Air entrainers, set retarders, and fly ash are the only admixtures permitted for use without special permission. Therefore, in its current form, the specification for structural concrete contains a number of barriers that inhibit the use of high performance concrete in highway bridge decks. Thus, before the use of HPC can be fully implemented, it will be necessary to revise the current AHTD specification. The new specification must contain information of the type outlined in the bulleted list above.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The definition of HPC concrete (HPC) as given by the American Concrete Institute (ACI) is concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely when using conventional constituents and normal mixing, placing and curing practices. (1)

HPC can be designed to give high strength, exceptional durability, or both. HPC concrete has been used in bridge deck applications for over a decade due to advantages given by the high durability of this material in extending the life of a structure. HPC concrete with high durability is usually prized for such characteristics as high freeze-thaw resistance, high abrasion and scaling resistance, and low permeability to chloride ions and other damaging chemicals. In the last ten years, HPC concrete has been specified for bridge projects in forty-five out of fifty states in America (2) and in many countries throughout Europe and Asia. A number of HPC concrete bridge projects are currently designed for 75- to 100- year instead of the typical 50-year service life of conventional concrete structures. (3)

HPC concrete can be produced using locally available materials with adaptations regarding the allowed types and amounts of chemical admixtures and supplementary cementitious materials. Often supplementary cementitious materials such as fly ash, silica fume, or ground granulated blast furnace slag are used in combination with portland cement to capitalize on specified strength and durability characteristics.

HPC concrete can be adapted to many applications with minor revisions to address concerns with finishibility and placement. HPC also requires more intense preplanning and stricter quality control especially concerning curing than conventional concrete, but the benefits of HPC have been found to outweigh these modifications.

2.2 HPC CONCRETE MATERIALS SELECTION

HPC concrete is not fundamentally different from conventional concrete in terms of materials and cost. The major components of both types of concrete consist of portland cement, coarse and fine aggregates, and water. The main difference between the two is the amounts and types of admixtures allowed.

The cost of high performance concrete is growing closer to that of conventional concrete as it becomes more prominent in structure design. In the Louetta Road overpass in Texas the cost per square foot of deck for conventional concrete ranged from $21-27 while the cost of high performance concrete ranged from $23-25 per square foot. However, depending upon the strengths required high performance concrete could cost up to fifty to seventy percent more than conventional concrete. (4)

The use of supplementary cementitious materials such as fly ash, silica fume, or ground granulated blast furnace slag in HPC mixtures is routine. The most common of these is silica fume, but fly ash and ground granulated blast furnace slag have both become more wide spread in HPC in recent years. (5) HPC concrete uses these materials to partially replace portland cement in order to increase strength, decrease permeability, and reduce heat of hydration and decrease thermal strains.

HPC concrete in general requires a low water to cementitious materials (w/cm) ratio when compared to conventional concrete. In a study by the Strategic Highway Research Program (SHRP), one of the definitions given for HPC concrete is concrete with a maximum w/cm ratio of 0.35. (1) However, in many bridge deck applications for HPC this ratio can be as high as 0.40.

A lower w/cm ratio requires the use of water reducers to produce concrete that is workable enough for placement demands. High and normal range water reducers are used separately or in combination, sometimes including a set retarder depending upon conditions. Another chemical admixture commonly employed in HPC is an air-entraining agent to reduce freeze-thaw damage. In cases where extreme exposure to harsh conditions is present, a corrosion reducer may be used. The amounts of chemical admixtures used in HPC are a departure from conventional concrete design.

2.2.1 Cement

Portland cement is the primary binder for HPC concrete as well conventional concrete. The type of portland cement used can vary depending upon the requirements for the project. In most cases the United States preferred to use unblended portland cement for HPC concrete applications, while Canada largely used cement preblended with silica fume. (5)

Research from Rutgers University suggests that reducing the amount of cement in concrete can reduce transverse cracking in bridge decks. The research also advised the use of Type II portland cement for bridge deck construction. (6) Type II cement is known for its low alkali levels and moderate heat of hydration making it useful for preventing alkali-silica reaction and controlling thermal stresses. Type II cement is specified for highly aggressive environments by the Florida Department of Transportation. (7)

In the U.S. HPC bridge decks commonly use Type I or II cement or a Type I/II mixture. In a few cases where high early strength was required, Type III was specified. The preferred cement used in Canada was Type 10 or Type 10E-SF, which is preblended with silica fume and can be produced in a low alkali variation for aggressive environments in which alkali-silica reactions are a concern. The cement type for a HPC concrete project should be chosen with desired characteristics of the application in mind.

2.2.2 Supplementary Cementitious Materials

Supplementary cementitious materials are binders that can be used to replace a portion of the portland cement in concrete acting as fine fillers and pozzolans. A pozzolan is a finely-divided material that reacts with calcium hydroxide and alkalis to form compounds possessing cementitious properties. (8) These materials include silica fume, fly ash, ground granulated blast furnace slag (GGBFS), metakaolin, and rice husk ash. The most common for use in HPC concrete are silica fume, fly ash, and GGBFS.

When used either separately or in combination, these materials can help to lower the heat of hydration, decrease permeability, increase early age strength, increase late age strength, and reduce costs. (9) Often ternary or quaternary mixes utilizing two or more of these materials are employed. Two concerns when using supplementary cementitious materials are the possibility of increased shrinkage and cracking risks and tighter curing restrictions due to decreased bleedwater and other conditions. Mixtures including supplementary cementitious materials should be test batched prior to placement to insure proper interaction of constituents.

2.2.2.1 Silica Fume

Silica fume, or microsilica, is a byproduct of the silicon industry created by the filtering and condensation of escaping furnace gases. (9) It is available in dry densified powder or slurry forms. (10) In the U.S. silica fume is typically added during mixing, while in Canada it is preferred to purchase cement already blended with silica fume. Silica fume can enhance mechanical and durability properties of concrete, especially strength and permeability.

Silica fume is an extremely fine material that greatly decreases permeability by creating a very dense structure. The permeability measured by the rapid chloride ion permeability test (ASTM C 1202) is normally in the low to very low categories for concrete containing silica fume. (10) Silica fume also increases workability due to its high particle fineness and increases early and late strengths with its dense concrete structure. However, silica fume can produce micro- and macro-cracking due to self-dessication. (11) Self-dessication is a condition in which concrete dries itself from the inside out due to water absorption from hydration. The specific surface area of silica fume is high thus requiring a higher water absorption quantity than cement. This increased water demand calls for the use of high range water reducers in order to maintain the low w/cm. (5) Silica fume can produce concrete that can be sticky and difficult to finish but this problem can be alleviated by keeping a low evaporation environment through fogging or night placement. In some cases where these precautions were not taken, a "skin" formed on the concrete surface preventing proper finishing and curing. (12)

When silica fume is used the mixing process must be carefully monitored because of the possibility of microsilica "balling." This condition is caused when silica fume is exposed to high pH level water and consolidates. This risk may increase with use of the slurry form of silica fume but is not commonly a problem with the powder version when added to cement before mixing. (13) For ready-mix concrete, care should be taken that a proper number of revolutions is performed before trucks leave the plant and concrete should be examined prior to placement. (14)

The optimal replacement range of silica fume is five to ten percent of total cementitious materials. (9) This level of silica fume counterbalances the strength and permeability advantages with the possibility of increased cracking and finishing problems. When using silica fume special care must be taken during curing to prevent drying shrinkage due to low levels of bleedwater and a quick drying surface. However, if the correct curing procedures are followed silica fume concrete can produce durable crack-free concrete. (15)

2.2.2.2 Fly Ash

Fly ash is a waste product produced by the burning of coal typically in power plants. There are two classes of fly ash, Class C and Class F. Class C fly ash comes from lignite or sub-bituminous coal from the eastern portions of the U.S. while Class F is produced from anthracite or bituminous coal found in the western states. (16) Class F has pozzolanic properties, typically it can be used to replace between fifteen to twenty percent of total cement content. Class C fly ash has both pozzolanic and cementitious properties, it can replace between fifteen and forty percent of total cement. (9)

Fly ash hydrates more slowly and at lower temperatures than portland cement and when used in replacement of cement increases later age strength and reduces thermal strains. (5) Fly ash also reduces the permeability of HPC concrete by creating a denser substructure. The workability of concrete including fly ash is slightly higher than that of concrete containing cement alone thus decreasing the required amount of high range water reducers.

Research has cautioned that high carbon contents in fly ash may interfere with air entrainment under certain circumstances, primarily high volume use. (11) Fly ash may be preferred over silica fume use in bridge decks due to fly ash's decreased probability of shrinkage and drying cracks and easier placement and finishing requirements. (17) The optimum range of use for fly ash is twenty to thirty percent of total cementitious material. When used in conjunction with five percent silica fume the optimal range is ten to fifteen percent. Research has shown that a trinary or even quaternary use of supplementary cementitious materials can have the greatest benefits due to the combination of each materials' effects. (18)

2.2.2.3 Ground Granulated Blast Furnace Slag

Ground granulated blast furnace slag is produced when blast furnace slag is rapidly cooled and then ground to a cement-like fineness. GGBFS is composed primarily of silicates and aluminosilicates of calcium. (5) GGBFS comes in three grades according to ASTM C 989: Grade 80, 100, and 120. The higher the grade level the higher the potential compressive strength. (19)

Ground granulated blast furnace slag reduces concrete permeability and increases resistance to chloride ion penetration through the pozzolanic reaction. In addition, the low calcium hydroxide content of GGBFS reduces the risk of sulfate attack. The workability of concrete also increases due to the dense, smooth surface of slag particles which absorb little water and increase particle distribution and fluidity. (5)

Something to consider when using ground granulated blast furnace slag is that it can increase vulnerability to salt scaling under some conditions. (11) Also, concrete using GGBFS can have reduced early age strengths but its late age strengths will surpass those of conventional concrete.

Ground granulated blast furnace slag has pozzolanic properties and can replace up to eighty percent of portland cement, though in most cases a lower level from twenty to thirty percent is used. (9) Research has implied that mixtures containing up to fifty percent slag performed better than similar fly ash counterparts. (20) Overall, the use of GGBFS offers many environmental, economical, and mechanical advantages.

2.2.2.4 Other Supplementary Cementitious Materials

In recent years a number of supplementary cementitious materials have been studied for application in concrete. Metakaolin is a white pozzolan created by heating kaolin clay to temperatures of 600-800˚C. (21) The use of metakaolin is being researched as not many properties of its effect on concrete are known. However, it is believed that concrete containing metakaolin has reduced permeability when compared to similar mixtures without metakaolin. Rice husk ash, produced when rice husk is burned for fuel, has very good pozzalanic properties. It can replace up to fifty percent of portland cement in mixtures and is still undergoing research to examine all of its effects on concrete properties. (22)

2.2.3 Water to Cementitious Materials Ratio

The term-- water to cementitious materials ratio (w/cm)-- has been chosen by the industry for use in HPC to better reflect the use of supplementary cementitious materials in addition to portland cement. A SHRP study defines HPC as concrete having a 0.35 or less w/cm ratio (1) but in many bridge deck applications a 0.40 ratio is desirable.

The w/cm ratio affects many properties of fresh and hardened concrete such as slump, permeability, freeze/thaw resistance, and compressive strength. For HPC concrete used in bridge structures, lower w/cm ratios are preferred in order to maximize durability characteristics. A lower w/cm ratio also increases the compressive strength of concrete. (23)

The w/cm ratio most directly controls the shrinkage of placed concrete. Although autogenous shrinkage, shrinkage due to self-dessication, decreases with increasing w/cm ratio, the durability becomes increasingly poor offsetting this relatively minor effect. Plastic shrinkage, due to surface evaporation, increases with increasing w/cm ratio, thus it is important to maintain a low w/cm ratio in order to decrease risks of cracking. (23) Self-desiccation is a condition under which concrete dries from the inside out when the internal water level is not high enough to fully hydrate cement grains. This condition is more probable with lower w/cm ratios but can be alleviated with the proper curing. (5) When using a low w/cm ratio it should be remembered that concrete with low w/cms can be more cohesive in nature than conventional concrete and may require a set retarder, especially if the travel time between the plant and jobsite is extended. (24)

Consensus has not been reached on a maximum w/cm ratio, but it is generally accepted that 0.40 to 0.45 is the maximum for HPC applications. Theoretically, HPC concrete with a ratio of 0.36 and an external source of water would not autogenously shrink at all. It has been suggested that the target value should be 0.37 for bridge decks to efficiently increase the durability and still produce concrete that can be easily placed and cured with reduced risks of plastic shrinkage. (15) However, it has also been recorded in Virginia that bridge deck concrete with a w/cm ratio of 0.45 would meet permeability and strength requirements and be less prone to cracking. The w/cm ratio is very important to the characteristics of an HPC mix and should be selected with care.

2.2.4 Chemical Admixtures

Chemical admixtures are a vital part of HPC concrete since it typically has a very low w/cm ratio, requires low permeability, and should resist freeze-thaw damage. Water reducers and superplasticizers are invaluable in providing the desired slump to high cement and low water volume concrete. Air entraining agents help reduce the risk of freeze-thaw damage in concrete. Set retarders can help delay early setting times and accelerators increase them. In areas where the risk of environmental damage is high, corrosion reducers can decrease the likelihood of rebar corrosion.

2.2.4.1 Water Reducers

Water reducing admixtures have become common in HPC to increase slump and create easily placeable concrete from stiff, low w/cm mixtures. Water reducers are available in two ranges: normal, which will reduce water demand five to ten percent and high range or superplasticizers; which reduce water demand twelve to thirty percent. (25) ASTM C 494 lists several types of chemical admixtures with Types A, D, E, F, and G all water reducers. Types D and G contain both a water reducer and a set retarding agent while Type E contains a water reducer and set accelerator. (26)

Water reducers are a viable way to increase slump without the loss of compressive strength or permeability associated with increased water content. (25) High range water reducers may affect the air content of HPC concrete causing it to be difficult to control. It may be advisable to add a portion of the water reducer at the plant and the remainder at the site to ensure desired slump and avoid variations in air content. (27) The addition of the admixture after five minutes of mixing during batching is recommended to reduce unmixed clumps. (28) Often using a combination of normal and high range water reducers can reduce costs since normal range reducers can cost less than half the cost of their high range counterparts. (25)

2.2.4.2 Air Entraining Agents

Air entraining agents (AEA) increase air content by stabilizing air within the concrete mixture. Air entrainment bubbles are smaller than one mm and are evenly distributed throughout the mixture. In contrast, entrapped air bubbles incorporated during normal mixing processes are larger and randomly spaced. (29) Air entraining agents reduce the risk of freeze-thaw damage by providing a space where water pressure caused by freezing water can be relieved. The use of AEA is standard practice in bridge deck construction due to increased risk from exposure to saturated conditions. However, entrained air reduces compressive strength but increases workability. Air entraining agents should conform to ASTM C 260 or AASHTO M 154. (25)

Concrete containing both air entraining agents and high range water reducers should be test batched to ensure the air content is not affected. The need for air entrainment has been questioned for very low w/cm ratio concretes but it is generally agreed that bridge decks should be air entrained. (23) Air contents are generally specified between five and eight percent for bridge deck applications.

2.2.4.3 Set Retarders/Accelerators

Set retarders and accelerators are chemical admixtures that affect the setting time of concrete. Set retarders (AASHTO Type B) lengthen the setting time while set accelerators (AASHTO Type C) shorten it. Set retarders are used in hot weather when concrete tends to set too rapidly and when early age strengths are not required. Set retarders can also be used for concrete that must travel an extended distance to the jobsite. The longer the time between addition of water and addition of set retarder to concrete, the longer the set time will be delayed. (30)

Set accelerators are used in cold weather and when high early strengths are a priority. The most effective type of set accelerator is calcium chloride but it should not be used in reinforced concrete, concrete exposed to sulfate, or concrete subject to alkali-aggregate reaction. (25)

Set accelerators are not commonly used in HPC since the use of high range water reducers can cause a rapid loss of slump and subsequent finishing problems without a set retarder. Water reducers Type D and G contain a set retarder. (25) Set retarders and accelerators can help to give more control under extreme temperature conditions or transportation times.

2.2.4.4 Corrosion Reducers

Corrosion reducers are used in structures exposed to harsh conditions. Corrosion reducers increase the chloride threshold level at which corrosion starts and reduce the rate of corrosion after it begins. Corrosion reducers are primarily used in areas exposed to high levels of deicing salts or in marine conditions. (26)

2.3 HPC SPECIFICATIONS

Traditionally most concrete mixture designs are prescriptive in nature. Specifications quantify the amounts of materials to be used and require specific test values. HPC concrete uses prescriptive requirements but headway is being made towards developing performance based specifications that will allow contractors flexibility designing HPC to meet broader durability and physical characteristics. Often during early experimentation with HPC concrete, prescriptive specifications are used, then as experience is gained with the material, performance based specifications are developed. (30)

2.3.1 Prescriptive Specifications

Prescriptive specifications are those requirements specifying quantities or amounts that must be adhered to in order to satisfy design characteristics. The most common prescriptive specifications are air content, compressive strength, and slump.

2.3.1.1 Air Content

The air content of concrete affects many of its mechanical properties such as compressive strength and freeze-thaw durability. Increased air content decreases compressive strength 2%-5% for each 1% in entrained air. However, a certain level of air is desired in order to resist freeze-thaw damage.

The standard practice for specifying air content is a prescriptive amount specifying an acceptable range of percent air to be tested on each batch with ASTM C 231. In general this range is between five to eight percent air of the total concrete.

Another concern is air void spacing, although this has been less commonly used in specifications. This issue has been growing in the past few years as it is believed that the spacing entrained air can have more of an affect on efficiency of freeze-thaw resistance than percent air. Air void spacing is difficult to test in fresh concrete and in hardened concrete is tested by coring the structure. In general air voids spaced with a maximum allowable average spacing factor of .250 mm (.0098 in) are considered acceptable. Most concrete with entrained air meeting the percent specifications has little problem also meeting the air void spacing specification. (31)

2.3.1.2 Compressive Strength

The material now called HPC concrete began as high strength concrete. The name was adapted to include the focus on durability in addition to compressive strength. However, the compressive strength of concrete is still an important factor in design of any structure. Many highway departments specified high strength concrete be used for bridge decks before the focus on durability began. It has been decided from experience in the field that bridge decks using HPC concrete do not need a minimum compressive strength over four thousand to six thousand psi at 28-days. However, the use of supplementary cementitious materials, low w/cm ratios, and high range water reducers can have a side benefit of increased compressive strength over the required level. When using supplementary cementitious materials, it may be advisable to specify a 56-day compressive strength rather than 28-day strength since a delay in early strength gain but an increase in late strength gain is possible. (32)

2.3.1.3 Slump

The slump test (ASTM C 143) is the most common test for concrete workability used in the industry. A higher slump usually translates into more workable, and thus easily placed, concrete; though extremely high slump concrete can run the risk of segregation. The use of water reducers allows HPC concrete to achieve good slumps despite its low w/cm ratios. Most often only a minimum slump is specified, although an increasing number of designs are also specifying a maximum slump in order to address the use of high range water reducers. A minimum slump of five inches is desirable, a seven inch slump is considered optimal. The maximum slump for HPC concrete is generally nine inches. (5)

2.3.1.4 Modulus of Elasticity

The modulus of elasticity of hardened concrete is a relative measure of stiffness that is affected by both the cement paste and stiffness of aggregates. The elastic modulus of concrete increases with increasing compressive strength. (24) When higher levels of structural stiffness are needed it is wise to closely consider the modulus of elasticity. The FHWA HPC Performance Grade lists three grades of HPC for modulus of elasticity ranging from 24 GPa (3480 Ksi) to over 50 GPa (7255 Ksi). (1)

2.3.2 Performance Specifications

Performance specifications are those requirements that target long term properties such as durability rather than physical characteristics alone. There are many factors that can lead to premature degradation of concrete and performance specifications focus on these aspects. Performance specifications are based upon: freeze-thaw durability, abrasion resistance, scaling resistance, and low permeability. Performance specifications are increasing in use since they give the contractor a wider scope in which to create concrete mixture designs that meet criteria, which if done properly can result in superior concrete at a lower cost.

2.3.2.1 Freeze-Thaw Durability

Freeze-thaw durability is the ability of concrete to resist cracking, scaling, and flaking due to the expansion of water trapped in the pores when saturated concrete freezes. The main method used to counteract freeze-thaw damage is air entrainment, which allows the water to expand into entrained air bubbles. Another method to reduce freeze-thaw damage is to reduce the permeability of the concrete and thereby decrease the amount of water allowed to seep into the concrete. Freeze-thaw durability can be measured by ASTM C 666 Procedure A or AASHTO T 161 and is usually denoted by a durability factor. The durability is a percentage based upon durability (computed by changes in the dynamic modulus of elasticity) through 300 freeze-thaw cycles. (1) Some have complained that ASTM C 666 is too harsh a test and not truly representative of field conditions. A field freezing and thawing cycle is defined as a temperature of 28˚ F or below followed by a rise over freezing in saturated concrete. The FHWA HPC Concrete Performance Grade defines a durability factor after 300 cycles of 60%-80% as Grade 1 and a durability factor of over 80% as Grade 2. (1) Some HPC concrete bridge deck applications specify a durability factor of at least 90%. (11) It is becoming increasingly popular to specify a durability factor in addition to specifying for air entrainment. (5)

2.3.2.2 Abrasion Resistance

Abrasion resistance is simply the resistance to wear on concrete surfaces caused by traffic load. Abrasion resistance increases with increasing strength and lower w/cm ratios. (23) Abrasion is not normally a controlling factor in HPC concrete bridge deck design except in areas that permit the use of studded tires. Abrasion resistance can be tested through ASTM C 944. HPC concrete characteristics are generally considered more than adequate to resist normal abrasion levels from traffic, deicing salts, and flowing water. (1)

2.3.2.3 Permeability

Permeability is a very important factor in concrete durability. Permeability characteristics can affect freeze-thaw damage and corrosion of internal members, both of which can cause flaking, scaling, and spalling. Concrete permeability can be reduced by lowering the w/cm ratio, using supplementary cementitious materials, and by using high range water reducers- all of which are characteristic of HPC concrete. Low permeability is a high priority in almost all HPC concrete bridge deck applications. There is no direct method to measure concrete permeability, but two methods that measure chloride ion penetration are believed to reasonably approximate permeability. The two test methods are the rapid chloride permeability test (ASTM C 1202, AASHTO T 277) and the chloride ion penetration, or ponding, test (AASHTO T 259). A recently developed test is the rapid migration test which like ASTM C 1202 exposes a saturated concrete specimen to an electrical field. (33)

The rapid chloride permeability test (RCPT) is performed on the top two inches of four-inch cores of hardened concrete. (34) This test is also known as the Rapid Chloride

Ion Penetrability Test (RCIP). Theoretically, the test measures the number of chloride ions that pass through a sample of concrete in a six-hour period of time. In general, the lower the permeability of the concrete the lower the amount of coulombs passed. Therefore, concrete with a high permeability will pass more coulombs. Questions as to whether the test is effective or concrete containing silica fume or other supplementary cementitious materials have been raised but tests investigating this have produced mixed results. (35) Less than 2000 coulombs for the RCPT is considered to be in the low category. Most conventional concrete score between 3000 and 4000 coulombs, which is the moderate category. (34) RCPT is the most common permeability test specified for construction applications. Many bridge projects specify values less than 1500 coulombs. The chloride ion penetration test, or the ponding test, is performed on specimens ponded with a three percent solution of sodium chloride for ninety days. This test is considered a more accurate estimation of concrete permeability than the rapid chloride permeability test but because of the three months required to be completed, it is not commonly specified for construction applications.

2.4 PRECONSTRUCTION REQUIREMENTS

HPC concrete is not a difficult material to work with once experience is gained; but more care should be put into planning and preconstruction than with conventional concrete. It is important to have preconstruction requirements involving all parties who will be involved in batching, placing, or finishing the concrete to ensure that all parties understand their responsibilities and the time constraints they will be under to perform their tasks. (36)

2.4.1 Contractor and Ready Mix Supplier Requirements

In order to guarantee design specifications are met, it is vital to provide concrete suppliers and contractors with clear guidelines of expectations and the tests that must be completed in order to satisfy specifications.

2.4.1.1 Trial Mixes

It is important to perform a trial mix of any HPC concrete design. (28) Trial batches can ensure there are no unexpected interactions between chemical and mineral admixtures used in HPC. (25) A trial batch will also give experience in batching the material to determine if dosages of water reducers, air entrainment, or other admixtures are sufficient.

2.4.1.2 Trial Slabs

Many departments of transportation consider it vital for the contractor to provide a trial slab prior to concrete placement. This allows the contractor to familiarize himself with HPC concrete placement and can demonstrate whether the contractor has suitable placement and finishing techniques for working with HPC concrete. Trial slabs are generally required to be the same width and thickness as the deck to be cast. The contractor should use the same placing, finishing and curing methods, and crew that will be used in installation. (31)

2.4.1.3 Penalties & Bonuses

A technique that is gaining favor is the use of a system of penalties and bonuses to encourage contractors to meet or even surpass requirements. Since the main focus of HPC concrete in bridge deck applications is durability, a number of departments of transportation use penalties to ensure that concrete durability is not impaired by excessive cracking, poor consolidation, or improper finishing. The most common penalty is the requirement that the contractor repair cracks of a size greater than an allowable size. (31) Bonuses are beginning to be offered for construction that excels in desirable qualities.

2.4.2 Preconstruction Meetings

Preconstruction meetings are a vital step in ensuring the smooth completion of any HPC concrete project. It is essential to include everyone involved in the project in these meetings so that all members of the project are informed of the latest information. Since the importance of finishing and curing HPC is impossible to stress enough, it is especially critical that the contractor be fully aware of all expectations. (36)

2.5 HPC PLACEMENT

Despite the amount of planning that has gone into the mixture design and specifications, if HPC concrete is not placed well its durability advantages can be lost. It is essential to ensure that all placement and finishing techniques have been planned well in advance and that all equipment needed for placement, finishing, and curing will be on site prior to the beginning of concrete placement. There are many techniques to ensure proper placement and curing such as the use of fog misters and evaporation retarders to prevent concrete over drying.

2.5.1 Placement

Concrete placement is important to the end result of concrete characteristics. If placement conditions are not suitable for HPC concrete, concrete can dry out too quickly resulting in plastic shrinkage cracking which can seriously reduce the concrete’s durability. Also concrete could have difficulty reaching required early set if conditions are too cold. (37) One way to ensure a proper placement environment is to specify a maximum temperature for placement and a maximum evaporation rate to control drying problems. (28)

2.5.1.1 Temperature Restrictions

The main concern with HPC concrete placement is high air temperature since the material has very little bleed water and is extremely susceptible to premature drying. In some cases the placement of HPC concrete is not allowed over temperatures of 80-90˚F (38), and in Canada this temperature is often restricted to 77˚F. (27) In areas with a warm year round climate or hot summers, the preferred option is to place concrete at night to comply with this restriction.

In extremely cold climates concern should be taken as to keeping HPC concrete warm enough to achieve full hydration. (37) For colder environments concrete is prohibited from being placed if the air temperature is under 35˚F unless the water and aggregate have a temperature of 70˚F or higher and concrete is insulated after placement. (39) An increasingly common practice is to also specify maximum internal concrete temperatures in order to control strength gains and thermal strains.

2.5.1.2 Maximum Evaporation Rates

Evaporation rates can be determined from the equation or tables according to ACI 308 Section 1.2.1 or by onsite tests. Evaporation rates take into account air temperature, relative humidity, and wind speed. Evaporation rates over 0.1 pound per square foot per hour or wind speeds over 10 mph, relative humidity less than 50%, or temperatures over 85˚F call for special precautions to compensate against the rapid loss of surface moisture. (40) These measures may include placing concrete at night, the use of wind screens, evaporation retarders, or fogging equipment.

2.5.2 Finishing

There are many concrete finishing techniques that can be used for HPC concrete and some special restrictions applied to projects. It is important remember that the same evaporation precautions employed during placement should be continued throughout finishing.

2.5.2.1 Methods & Restrictions

There are many methods of surface finishing such as screeding, troweling, bullfloating, and broom finishing or tining. In certain HPC concrete applications, the use of bullfloating has been prohibited for concern that the surface will tear during the process. The use of a self-propelled finishing machine is fairly standard. Attaching a burlap drag to the back of the finishing pan can texture the concrete quickly. (41) Texturing can also be accomplished by tining of the surface during finishing or saw cut grooving applied to hardened concrete. In order to hasten finishing and curing so that concrete does not have time to overdry, it is recommended that the concrete be placed no farther than five to eight feet ahead of the finishing machine. (14)

2.5.3 Curing

The curing of HPC concrete is perhaps the most important of all phases of construction. Without proper curing techniques the advantages that HPC can offer can be destroyed in a very short amount of time. It is impossible to overstress the care that must be put into curing HPC concrete bridge decks in order to give superior results. HPC concrete is very dependent upon curing conditions due to the usage of supplementary cementitious materials which are highly sensitive to water loss and poor curing practices. (24)

2.5.3.1 Curing Methods

There are a number of curing methods available for application. Concrete can be cured by moist curing- the addition of water to the concrete surface to restore moisture, or by evaporation reducers- the application of materials designed to slow the loss of water from concrete surfaces. It is vital to HPC concrete that a moist cure method be used. (42) The use of curing compounds is not acceptable since it has been shown that curing compounds are less effective than any moist curing technique. (43) The use of curing compounds as an intermediate between finishing and curing is also discouraged since the curing compound can impede the progress of moisture back into the concrete during curing. If desired a curing compound may be applied at the end of the moist curing period to extend curing time. (44)

The best method of curing HPC concrete is a moist curing method that will keep concrete saturated. This can be achieved through ponding, spraying, or the use of wet burlap or wet cotton mats. (42) The use of soaker hoses under plastic sheeting over burlap or cotton mats can keep concrete saturated easily and is a preferred method. (38)

2.5.3.2 Duration of Curing

When the curing of HPC should begin and how long it should continue is a major point of discussion for HPC concrete. It is agreed that curing of HPC concrete should begin as close to the end of finishing as possible since the surface will dry out quickly and crack due to lack of bleedwater. The best way to protect concrete from cracking is to begin water curing within fifteen minutes after concrete is placed in any portion of the deck (44); some projects restrict this time to as little as ten minutes after finishing. (18) This means the contractor should have the wet materials on site and ready to be placed before concrete placement begins. (45) If a delay prevents the immediate application of curing after finishing, an evaporation retarder can be applied or fogging should be used to keep the surface moist. (44)

HPC concrete projects have specified curing durations ranging from as little as four days to over two weeks. The generally accepted specification for most projects requires seven days of wet curing. (44) However recent research has shown that a wet curing duration of fourteen days will ensure optimal strength and durability characteristics. (43) One method of this is seven days of wet curing followed by seven days of curing with a liquid membrane. (18) Any inconvenience due to extended curing time will be offset by the improved lifespan associated with high durability concrete.

2.6 RESULTS OF HPC PROJECTS

Since a large number of HPC concrete bridge projects have been completed in the past ten years there is a wealth of information regarding construction with this material. An examination of some problems experienced and the solutions formulated by a number of these projects shed light on some issues to consider carefully before designing a HPC concrete project. These issues fall into three categories: problems with mix designs, problems with concrete placement, and problems with curing. Most of the problems encountered in HPC concrete projects are due to inexperience in working with the material and can be solved easily.

2.6.1 HPC Mix Problems and Solutions

Mix design problems can be attributed to lack of experience by the design engineer, concrete supplier, or both parties. It has been suggested that concrete containing silica fume requires longer mixing times than conventional concrete, therefore a HPC concrete may take an extended mixing time to be properly batched without microsilica balling. (14) Microsilica balling was also a problem during a HPC project in Minnesota when silica fume slurry was improperly mixed. (13) The use of the dry-densified form of silica fume rather than slurry can reduce the risk of this problem. During the reconstruction of Wacker Drive in Chicago, problems caused by the interactions of high range water reducers and air entraining agents were solved by adding a portion of the water reducer while batching and the remainder onsite. (27)

2.6.2 HPC Placement Problems and Solutions

Placement and curing problems are more common than mixture problems in HPC concrete projects due to sensitivity in these areas. HPC concrete should be placed in a low evaporation environment to prevent plastic shrinkage cracking and the formation of a "skin" on concrete- experienced by projects in New York and Utah. (46,11) Over-finishing while attempting to close a surface can lead to scaling problems as experienced in New York. (46) The use of silica fume can sometimes produce concrete that is sticky and difficult to finish but this problem can be alleviated by allowing an increased slump and creating a low evaporation environment. For a project in Hawaii the inclusion of fly ash in the mixture also helped promote bleedwater and ease the finishing problems. (47)

2.6.3 HPC Curing Problems and Solutions

Curing problems are the most common problem in HPC concrete bridge deck applications. These problems are usually due to not beginning curing soon enough after placement or not maintaining saturated conditions for a long enough period of time. In a 1999 HPC bridge deck, the Minnesota department of transportation experienced map cracking when fogging employed between finishing and curing was unable to cope with increased wind speeds and the increased rate of evaporation.

Another problem with cracking occurred again in a 2002 project in which the contractor did not have the equipment ready for immediate application of wet burlap. (13) In an Idaho HPC bridge project using silica fume, slabs were covered in a curing compound but wet burlap was not placed until 45 minutes later causing severe cracking. (45) When wet burlap was not maintained in contact with the deck surface in a project in Ohio, differential shrinkage cracking occurred. (48)

Practically all of these problems could have been prevented by following the specifications or changing project requirements to reflect the needs of HPC concrete. Many projects that have adopted and enforced strict guidelines regarding HPC concrete curing have been rewarded by the production of virtually crack free bridge decks with minimal complications.

2.7 OTHER APPLICATIONS OF HPC

The applications of HPC concrete to highway structures are not limited to bridge decks alone. Bridge supports and substructures can also benefit from increased strength and durability characteristics.

2.7.1 Girders

HPC prestressed concrete bridge girders are used in a number of states and countries around the world. In Texas nine out of ten bridges constructed are concrete. (6) The primary advantage of using HPC concrete in bridge girders is the ability to increase span length and decrease the number of girders in each span due to increased strength. (49) Sizeable technical and economic benefits have been experienced using precast, prestressed HPC girders for short and medium span bridges. (36) HPC concrete girders also benefit from increased durability. Unlike steel girders that require painting or sealing to resist corrosion, HPC concrete girders are inherently corrosion resistant due to low permeability. (6) Finally, research has implied that concrete decks supported on concrete girders outperform those supported by steel girders. (50)

2.7.2 Substructure

HPC concrete adds the same advantages to substructure that it does to bridge decks and girders. Substructures and footings can benefit from increased strength and durability and the application of HPC concrete to these areas can also help increase the service life of bridge structures.

2.8 CONCLUSION

HPC concrete is a material that holds great promise for the bridge construction industry and is delivering on those promised today. With only a little study and knowledge of the characteristics and components of HPC concrete it can be applied to almost any bridge project successfully. Although experience may be needed before the techniques of creating superior HPC are perfected, the benefits- longer service lives and economic advantages- will outweigh the initial learning curve. HPC concrete offers increased durability, increased strength, and long and short term cost benefits with only a small initial change. With minor adaptations in terms of the amounts and types of supplementary cementitious materials and chemical admixtures allowed, HPC concrete can be produced by any contractor. Curing practices and procedures must be extremely carefully monitored but any inconvenience incurred will be far outweighed by the benefits HPC concrete can offer. HPC concrete is a material of the future that is beginning to come to the forefront of construction.

CHAPTER 3

SURVEY RESULTS AND CONCLUSIONS

3.1 INTRODUCTION

In order to gain insight into the use of HPC in bridge decks in the United States, a survey was sent to all Departments of Transportation in July 2003. The survey consisted of 5 major parts including mixture proportions, chemical admixtures, mix specifications, finishing and curing, and results from previous projects.

3.2 SURVEY QUESTIONS

The questions asked in the survey are shown in Appendix A. Each question asked for information regarding the use of concrete for bridge decks. The second part of the survey asked questions regarding the mixture proportions for concrete used on bridge decks. Third, questions were asked regarding the use of chemical admixtures in mixtures. Fourth a section on mix specifications was asked. This section was broken down into prescriptive, performance, and testing. The fifth section of the survey asked questions regarding finishing and curing techniques for concrete used on bridge decks. The final section asks the officials for information regarding results from previous bridge deck construction using HPC.

3.3 RESULTS AND DISCUSSION

Officials from 35 states replied to the survey. The states replying to the survey are listed in Table 1. Some officials gave more in depth responses than others, but in general all questions were answered with good clarity. The first part of the survey asked questions regarding current and future use of HPC in bridge deck applications. Of the 35 states responding, 25 have already implemented the use of HPC in some bridge decks; some on an experimental basis. Of the remaining 10 states, seven states (Arizona, Mississippi, Montana, Nebraska, North Carolina, Oklahoma, and Tennessee) reported they were currently researching HPC or had projects planned in the near future. Arizona reported that although there were no bridge decks constructed entirely with HPC, HPC is being used for bridge deck rehabilitation. All survey responses are located in Appendix B.

Table 1. States Replying to Survey

State	Current Use of HPC in Bridge Decks
Alaska	Yes
Arizona	No
California	Yes
Connecticut	Yes
Delaware	Yes
Hawaii	No
Idaho	Yes (one project)
Illinois	Yes (experimental)
Indiana	Yes
Iowa	Yes
Massachusetts	Yes
Michigan	Yes
Minnesota	Yes
Mississippi	No
Missouri	Yes
Montana	No
Nebraska	No
Nevada	Yes
New Hampshire	Yes
New Jersey	Yes
New York	Yes
North Carolina	No
North Dakota	No
Oklahoma	No
Oregon	Yes
Rhode Island	Yes
South Carolina	No
Tennessee	No
Texas	Yes
Utah	Yes
Vermont	Yes
Virginia	Yes
Washington	Yes
West Virginia	Yes
Wisconsin	Yes

3.3.1 Mixture Proportions

The first question in the mixture proportioning section pertained to maximum or minimum cement content. Unless noted, all responses were assumed to be minimum cement contents per cubic yard. Of the 35 states responding, five did not list a minimum or maximum limit for cement content. The other states ranged anywhere from a minimum of 390 lb/yd^3 to a maximum of 800 lb/yd^3. Ten states placed limits on the maximum amount of cement. These maximum limits were likely placed to reduce shrinkage cracks that result from large quantities of cement in a mixture. For example, the state of Idaho limits the amount of cementitious material in HPC bridge decks to 583 lb/yd^3. While other states, such as Indiana, allow as little as 390 lb/yd^3 of cement. All information regarding mixture proportions is included in Table 2.

The second question in the mixture proportioning section asked if the DOT specified a maximum or minimum w/cm. Unless noted in Table 2, all responses regarding w/cm were assumed to be maximum w/cm allowed. All but three states specified a maximum w/cm for their concrete in bridge decks. The remaining states specified a maximum w/cm between 0.40 and 0.49. The reported aggregate sizes ranged from 0.75 in. to 1.5 in. Idaho was the only state that specified a maximum ratio of fine aggregate to total aggregate content.

Table 2. Mixture Proportions.

State	Cement Content (lb/yd^3) Minimum	Cement Content (lb/yd^3) Maximum	Maximum w/cm	N.M.S.A. (in.)
Alaska	658	-	0.44	0.75, 1.0, 1.5
Arizona	-	-	-	-
California	674	800	[1]	1.5 (max.)
Connecticut	675	-	0.40	0.75
Delaware	658	752	0.40	100 % passing 1.5
Hawaii	610	800	0.49	0.75 (max.)
Idaho		583[2]	0.40	0.38[3]
Illinois	605	-	0.44	1.0
Indiana	390[4]	-	0.42[4]	1.0
Iowa	624	-	0.42[5]	1.0
Massachusetts	685[6]	-	0.40	0.75
Michigan		715[4]	0.49	1.0
Minnesota	611	-	0.44	0.75
Mississippi	-	-	0.45	Dependent on thickness/spacing
Missouri	600	-	0.45	1.0
Montana	-	-	0.40	0.75
Nebraska	658	-	0.42	1.0
Nevada	611	752	0.44	1.0
New Hampshire	-	-	-	0.75
New Jersey	-	-	0.40	1.5
New York	682	-	0.40	1.0
North Carolina	639	715	0.41[7]	1.5
North Dakota	611	-	[8]	1.5
Oklahoma	611	-	0.44	1.0
Oregon	630	-	0.40	0.75[9]
Rhode Island	709	799	0.40	0.75
South Carolina	611	-	0.40[10]	0.75, 1.0, 1.5
Tennessee	620	-	0.40	1.5
Texas	-	700	0.45	1.5
Utah	611	-	0.44	Function of geometrics
Vermont	660[11]	-	0.44	0.75
Virginia	635	-	0.45	1.0
Washington	660	-	0.39	No. 5
West Virginia	[13]	[13]	0.40[12]	1.0, 1.5
Wisconsin	565	-	0.45	1.5

1. 308 lb/yd^3 + 33.7 lb. per 168 lb. of cement over 548 lb.
2. Cementitious material content.
3. Maximum ratio of fine aggregate to total aggregate content.
4. For HPC mixtures.
5. Maximum w/cm.

6. Target value.
7. 0.41 for concrete with fly ash, and a max of 0.426 for all other.
8. Maximum water content of 5 gallons/sack of cement.
9. Minimum coarse aggregate solid volume = 0.40 m^3/m^3 of concrete.
10. Maximum water content of 244 lbs.
11. Required cementitious material.
12. Required w/cm.
13. Two HPC options; 470 lb/yd^3 or 423 lb/yd^3.

Another question in this portion of the survey concerned the use of supplementary cementing materials (SCM). Most states allow the use of SCM in bridge decks, with fly ash being the most common. The survey asked if SCM were required and if maximum or minimum limits of SCM were specified. Once again, unless otherwise noted, the responses were assumed to be maximum allowable replacement rates. The replacements rates shown in Table 3 are either mandatory rates (for example Idaho), but for most states, the rates listed are maximum replacement rates. Fly ash replacement rates ranged from 15 to 35 percent, and slag cement contents ranged from 20 to 50 percent. Additionally, silica fume content ranged from 3 to 10 percent. Though not specifically asked, some states gave additional information regarding the use of ternary mixtures. The detail information regarding replacement rates is shown in the surveys contained in Appendix B.

Table 3. Use of SCM.

State	Are SCM required in HPC?	SCM (maximum replacement percentage)			Ternary Combinations
		fly ash	Slag cement	Silica fume	
Alaska	No	20		7.3[1]	
Arizona	-	-	-	-	
Arkansas	-				
California	-	35[2]			
Connecticut	Yes	20	-	6	
Delaware	Yes	-	50	7-10	
Hawaii	No	-	-	-	
Idaho	Yes	20	-	5	Yes
Illinois	No	15	25	-	
Indiana	-	20-30	-	5-7	Yes
Iowa	Yes	15	35	-	
Massachusetts	Yes	15	25-40	5-7	
Michigan	No	25	40		40%
Minnesota	No	15-30	-	-	
Mississippi	-	-	-	-	
Missouri	Yes	25	40	6-8	40%
Montana	-	-	-	-	-
Nebraska	Yes	15-25	-	-	-
Nevada	-	-	-	3-7	-
New Hampshire	Yes	25	50	-	-
New Jersey	Yes[3]	-	-	-	-
New York	Yes	20	20	6	Yes
North Carolina	Yes[4]	20	35-50	4-8	-
North Dakota	No	-	-	-	-
Oklahoma	No	-	-	-	-
Oregon	Yes	30-35	-	4.0-4.6	34%
Rhode Island	-	-	20	50 lbs/yd^3	-
South Carolina	No	-	-	-	-
Tennessee	No	25[5]	35	-	-
Texas	Yes[4]	25-35	50	-	-
Utah	Yes	20	-	-	-
Vermont	Yes	20	25	6	Yes
Virginia	-	30[6]	50	10[7]	-
Washington	Yes	75 lbs/yd^3	-	-	-
West Virginia	Yes	[8]	[8]	[8]	Yes
Wisconsin	Yes	15	30	-	-

1. For microsilica concrete overlay.
2. If CaO < 2%.
3. No limits have been set.
4. Required in some cases, optional in others.

5. Class C fly ash.
6. Class F fly ash.
7. Used in overlays not in decks.
8. Two options; 1.75 bags of fly ash and 30 lbs of microsilica, or 2.25 bags of GGBFS and 30 lbs of microsilica.

3.3.2 Mixture Specifications-Prescriptive

The specified compressive strength, slump, and air content are shown in Table 4. Of the states responding, 20 require a minimum compressive strength of 4000 psi for bridge decks. Seven states require compressive strengths between 4000-4500psi. Four states require compressive strengths of 5000 psi, and one state requires 3600 psi. All but two states have a specification for required slump. State specifications for slump were reported in a wide range and are given in Table 4. The wide range in slumps accounts for the usage of high range water reducers. All states with the exception of two reported required air contents. Specified air contents ranged from 2 to 10 percent.

Table 4 Mixture Specifications - Prescriptive.

State	Compressive Strength (psi)	Slump (in.)	Air Content (%)
Alaska	5000	1 - 3	5 -8
California	3600	2.5 – 3.0[3]	Not specified
Connecticut	4000	3 - 4	5 - 8
Delaware	4500	2 – 4, 8[4]	5 - 9
Hawaii	4000	0 - 3	2 - 4
Idaho	4000	1.5 - 3.5[5]	6.5 ± 1.5
Illinois	4000	2 - 4; 7[4]	5 – 8
Indiana	4000	4 - 7.5	4 - 10[1]
Iowa	5000[1]	1 - 4	6.5 - 1
Massachusetts	5000	3 - 6	6 - 8
Michigan	4500	[6]	5 - 8
Minnesota	4300	2.5 - 7[6]	5 - 8
Mississippi	4000	3 - 8[6]	4 - 6
Missouri	3200 - 4000[2]	4.5	5 min.
Montana	4500	1.5 - 3	5 - 7
Nebraska	4000	0.75 - 4	5 - 7.5
Nevada	4500	1 - 2.5	5 - 7
New Hampshire	4000	not specified	5 - 9
New Jersey	4000	2 - 4	4.5 - 7.5
New York	not specified	3 - 5	5 - 8
North Carolina	4500	3.5 max.	4.5 - 7.5
North Dakota	4000	not specified	5 - 8
Oklahoma	4000	1 - 3[7]	5 - 8
Oregon	4350	3 - 8[6]	4.5 - 7.5[8]
Rhode Island	5000	3 - 8	6.5 ± 1.5
South Carolina	4000	1 - 4	3 - 6
Tennessee	4000	3 - 8[6]	5 - 8
Texas	4000	5.5 max.	3 - 8
Utah	4000	3 - 5	3 - 7
Vermont	4000	7 max.	4.5 - 7.5
Virginia	4000	2 - 7[6]	4 - 8
Washington	4000	6 - 9	Not specified
West Virginia	4000	7 max.	4.5 - 8.5
Wisconsin	4000	4 max.	4.5 - 8.5

1. For HPC bridge decks only.
2. Dependant upon construction loads.
3. Dependent on thickness.
4. With the use of HRWR.
5. Before the addition of water reducers.
6. Dependent on admixtures.
7. Except when admixtures are used.
8. Dependent on elevation.

3.3.3 Mixture Specifications-Performance

States specifying permeability, shrinkage, or freeze-thaw durability are shown in Table 5. Only ten states specify an allowable permeability for the deck. For the ten states, permeability was assessed by AASHTO T 277 or ASTM C 1202 (rapid chloride ion penetrability test). Maximum coulombs allowed by the states ranged from 750 - 4000. Concrete in this range would be classified as very low permeability concrete (passing 750 coulombs) to concrete with moderate permeability (passing less than 4000 coulombs). Permeability classifications based on coulombs passed are show in Table 6.

Only four of the responding states measure freeze-thaw resistance. The required durability factors are reported in Table 6. The durability factor is the percent change in the dynamic modulus of elasticity. For example, a concrete mixture with a durability factor of 60 has a dynamic modulus that is 60 percent of what it was prior to testing. Acceptable freeze-thaw durability is defined as concrete having a durability factor greater than 60 or a spacing factor less than 0.008 inches. (51, 52)

New Jersey and Idaho were the only states to specify a maximum allowable shrinkage. New Jersey was the only state making specifications for abrasion or scaling resistance. All responses for performance are listed in Table 6.

Table 6. Permeability, Durability Factor, and Shrinkage Requirements.

	Maximum Permeability (coulombs)	Freeze-thaw Durability Factor	Maximum Shrinkage (microstrains)
California	Not specified	[7]	Not specified
Delaware	1500	Not measured	Not specified
Idaho	1500	Not measured	400
Indiana	4000[1]	Not measured	Not specified
Illinois	Not specified	Not measured	Not specified
Iowa	1500[2]	Not measured	Not specified
Massachusetts	1500[3]	Not measured	Not specified
Minnesota	Not specified	[8]	Not specified
Nevada	2000	Not measured	Not specified
New Hampshire	4000	Not measured	Not specified
New Jersey	2000	80	600
Oklahoma	Not specified	50 @350 cycles	Not specified
Rhode Island	Not specified	Not measured	Not specified[10]
Tennessee	Being researched	Not measured	Being researched
Texas	[4]	Not measured	Not measured
Utah	Yes[5]	Not measured	Not specified
Virginia	2500	60 @ 300 cycles[9]	Not specified
West Virginia	750	Not measured	Not specified[11]
Wisconsin	[6]	Not measured	Not specified

1. Or as determined during trial batching.
2. Target for HPC mixtures.
3. For trial batch concrete.
4. Only required if the mix design is different than the mixture prescriptively specified for HPC.
5. Performance based spec./design build.
6. Low permeability is assumed based on data from previous mixtures.
7. Evaluated by measuring the soundness of the aggregates.
8. Past performance is good; therefore tests not necessary.
9. Freeze-thaw tests for research purposes and new materials.
10. Not specified, but shrinkage reducing admixture and fibers are required.
11. No limits are specified, but tests are performed.

Table 6. Permeability Classification Based on Coulombs Passed.

Charge Passed (coulombs)	Chloride Ion Penetrability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

3.3.4 Mixture Specifications-Testing

The required concrete tests are shown in Table 7. The majority of the states require slump, temperature, and air content tests on the fresh content. It was surprising that seven states require unit weight of the fresh concrete. Unit weight tests in the field are not common, because it requires a scale. However, measuring unit weight can identify problems with the mixtures. Two states, Idaho and New Hampshire, measure the w/cm of the fresh concrete. A copy of New Hampshire's procedure for measuring w/cm is located with their survey in Appendix B. The most specified hardened concrete test was compressive strength. When a respondent stated "cylinders" or "strength", the authors assumed the respondent meant compressive strength.

Table 7. Required Fresh and Hardened Concrete Tests.

State	Concrete Tests
Alaska	Slump, air content, temperature, compressive strength
California	Uniformity (Kelly Ball), air content, unit weight, compressive strength
Connecticut	Slump, air content, temperature, compressive strength
Delaware	Slump, air content, temperature, compressive strength (7 & 28), permeability
Hawaii	Slump, compressive strength (7 & 28)
Idaho	Slump, air content, compressive strength, permeability, shrinkage, w/cm
Illinois	Slump, air content, compressive strength
Indiana	Air content, unit weight, compressive strength,
Iowa	Slump, air content, flexural and compressive strength
Massachusetts	Slump, air content, temperature, compressive strength
Michigan	Slump, air content, temperature, compressive strength
Minnesota	Slump, air content, temperature, compressive strength, and some permeability
Mississippi	Slump, air content, temperature, unit weight (yield), compressive strength,
Missouri	Slump, air content, compressive strength
Montana	Slump, air content, temperature, compressive strength
Nebraska	Slump, air content, compressive strength
Nevada	Slump, air content, unit weight,
New Hampshire	Slump, air content, temperature, compressive strength, w/cm, cover, permeability
New Jersey	Slump, air content, compressive strength, permeability
New York	Slump, air content, compressive strength
North Carolina	Slump, air content, compressive strength
North Dakota	Slump, air content, unit weight, compressive strength,
Oklahoma	Slump, air content, compressive strength, depth of cover to top rebar
Oregon	Slump, air content, temperature, density, yield, compressive strength, w/cm
Rhode Island	Slump, air content, temperature, unit weight, compressive strength
South Carolina	Slump, air content, compressive strength
Tennessee	Slump, air content, temperature, compressive strength, smoothness
Texas	Slump, air content, temperature, compressive strength
Utah	Slump, air content, compressive strength
Vermont	Slump, air content, compressive strength
Virginia	Slump, air content, temperature, compressive strength, permeability-if low permeability special provisions are included.
Washington	Compressive strength
West Virginia	Slump, air content, compressive strength, permeability, shrinkage
Wisconsin	Slump, air content, compressive strength

3.3.5 Finishing and Curing

The final section of the survey focused on finishing, curing, and lessons learned from constructing HPC bridge decks. Shown in Table 8 are the allowable ambient temperatures and evaporation rates that were reported. The allowable ambient temperatures ranged from a low of 20 F to a high of 90 F. Unless otherwise specified in the responses, the reported evaporation rates were assumed to be the maximum allowable evaporation rate. The allowable evaporation rates ranged from 0.10 lb/ft^2-hr to 0.20 lb/ft^2-hr. Above an evaporation rate of 0.10 lb/ft^2-hr, some states, such as Illinois and Indiana, require fogging.

Table 8. Temperature and Evaporation Rate Requirements.

State	Ambient Temp. Requirements		Evaporation rates (lb/ft^2-hr)
	Minimum	Maximum	
Alaska	40[1]	90[1]	0.20[2]
California	50	86	-
Connecticut	50	85	0.10
Delaware	45	85	0.15
Hawaii	-	90[3]	-
Idaho	-	85	0.10
Illinois	45	-	0.10[2]
Indiana	-	-	0.10[2]
Iowa	40	-	0.15
Massachusetts	-	90[4]	0.15
Michigan	-	-	0.20
Minnesota	-	80[5]	0.15[6]
Missouri	-	85	-
Montana	37	90	-
Nebraska	-	90	PCA nomograph
New Hampshire	-	-	0.10
New Jersey	20	75[7]	0.15
New York	-	-	0.25
North Carolina	35	-	-
North Dakota	35	-	-
Oklahoma	50	85	-
Oregon	-	-	0.15
South Carolina	50[8]	90[4]	-
Tennessee	-	-	0.20
Texas	35	85	PCA nomograph
Utah	-	90	-
Vermont	-	90	-
Virginia	-	-	0.10
West Virginia	50	-	0.10[9]
Wisconsin	-	90[4]	0.20

1. Special provisions are required if ambient temperatures are not within 40 to 90 F.
2. If specified evaporation rate is exceeded, special provisions are required.
3. Special provisions required if maximum temperature is exceeded.
4. Maximum concrete temperature.
5. For low slump overlays.
6. For HPC mixtures containing silica fume.
7. Hot weather measures required if temperature is above 75 F.
8. Air around concrete must be maintained at 50 F.
9. If above 0.10, special provisions are required.

The use of fogging, curing type, and curing regimen are shown in Table 9. The survey asked if fogging was required during construction. Fogging refers to the application of a fine mist to increase the relative humidity over the concrete to reduce plastic shrinkage cracks. Fogging is normally applied after the concrete has been finished but before final curing. Twenty-two states require the use of fogging. Some states require fogging under special circumstances. For example, Illinois and Indiana require fogging when the evaporation rate is greater than 0.10 lb/ft^2-hr, and Minnesota requires fogging when the concrete contains silica fume.

A wide range of curing methods was reported, but many similarities exist amongst the states. Most require wet burlap or cotton mats placed on the concrete for seven days. Many respondents emphasized that these mats should be prewetted before they are placed on the deck.

There were some differences amongst states when it came to curing duration. Massachusetts, New York, Oregon, and Washington specify 14 days. Some states, such as Oklahoma and Texas, require additional days of curing if SCM are used in the bridge deck. The final question related to curing asked if there were any special curing requirements that the DOT thought should be listed. Many respondents stated that wet curing should be applied as soon as possible. The respondent from Iowa DOT stated that wet curing should begin within 10 minutes of final finishing. Likewise, the respondent from Vermont DOT stated that the cure should be applied within 10 minutes of finishing by the screed machine.

Table 9. Curing Regimens.

State	Fogging Required?	Type of curing	Duration (days)
Alaska	No	Water curing –burlap or cotton	7
California	No	Wet curing and compound	7
Connecticut	Yes	Fog spray, moist cotton mats, soaker hoses with plastic sheeting	7
Delaware	Yes	Wet burlap	3 days wet[1]
Hawaii	No	Water curing & impervious membrane	7
Illinois	Yes[2]	Cotton mats – soaker hoses	7
Indiana	Yes[2]	Wet burlap covered with plastic	7
Iowa		2 layers of prewetted burlap placed within 10 minutes of final finishing and continuous wet sprinkling	7[3]
Massachusetts	Yes	2 layers of prewetted burlap	14
Michigan	No	Curing agents followed by wet burlap with polyethylene and soaker hoses	7
Minnesota	Yes[4]	Membrane + burlene	7[3]
Mississippi	Yes	Ponding, wet burlap, cotton mats	7
Missouri	No	Dissipating liquid membrane and curing mats	7
Montana	Yes	Wet burlap cure	14
Nebraska	Yes[5]	Curing compound and wet burlap	4
Nevada	Yes	Burlene, burlap, burlap w/polyethylene, cotton mats	10
New Hampshire	No	Wet burlap or cotton mats applied with 30 minutes	7
New Jersey	Yes	Wet burlap	7
New York	No	Wet burlap w/soaker hoses	14
North Carolina	No[6]	Water method or membrane curing	7
North Dakota	Yes	Wet burlap	7 or 10[7]
Oklahoma	Yes	Liquid membrane followed by cotton mats	7 or 10[7]
Oregon	Yes	Evaporation reducer followed wet burlap or curing blanket	14
Rhode Island	Yes	Wet burlap	7
South Carolina	Yes	Curing compound and blankets	7
Tennessee		Curing compound and burlap	5
Texas	Yes[8]	Liquid membrane followed by wet cotton mats	8 to 10[7]
Utah	No	Curing agent and wet burlap	7
Vermont	Yes	Pre-wetted burlap or cotton mats	10
Virginia	Yes[9]	Wet and curing compound	7[10]
Washington	Yes	Curing compound & wet burlap	14
West Virginia	Yes	Wet burlap	7
Wisconsin	Yes	Wet burlap with continuous water	7

1. Wet burlap for 3 days then curing compound.
2. When evaporation rate exceeds 0.10 lb/ft^2 – hr.
3. For HPC bridge decks.
4. For mixtures containing silica fume.
5. When evaporation exceeds 0.15 lb/ft^2 – hr.
6. A fogger must be on site if evaporation becomes a problem
7. If SCM ate used.
8. Evaporation retardant also used
9. To prevent the surface from drying until covered.
10. 7 days and 0.70f'c.

3.3.6 Previous Results from HPC Bridge Decks

Of the states responding to the survey, 29 states constructed bridge decks with HPC. The survey asked each state if they had experienced cracking in their bridge decks and if a solution had been developed. Nineteen states reported cracking in the decks. Their responses are shown in Table 10. Strategies to reduce cracking ranged from changing the cement content to increasing the wet curing time. States that reported problems with scaling, difficulties in finishing HPC bridge decks, and their written responses are shown in Table 11. Missouri, New Hampshire, New York, and Vermont were the only states to report scaling on bridge decks. Eight states reported finishing or placement problems. These problems were different in each case and are listed in Table 11.

The final question in the survey asked if there was any other information that was not covered that they would like to share. The respondent from Michigan stated that they were planning a bridge deck using a ternary mixture and an optimized aggregate gradation with the intent to reduce cracking and permeability. The respondent from Missouri stated that low early strength concrete which also has low modulus of elasticity was designed for their HPC bridge decks. The low strength and low modulus of elasticity mixtures would be less brittle and could understand more movement than concretes with higher early strength. Missouri has lowered the total cementitious material content and incorporated SCM which has reduced cracking in their HPC bridge decks. Finally, the respondent from Texas provided information on specifications for HPC. In addition to performance based specifications, TxDOT also has a prescriptive approach where several concrete mixture designs are provided. The respondent stated that when the contractors are given a choice, they choose the prescriptive method over the performance based specifications.

Table 10. States Experiencing HPC Deck Cracking.

State	Responses to Questions Concerning Cracking
California	Sporadic instances – adding proper amounts of SRA following good curing practice have helped
Connecticut	Some hairline cracking
Delaware	Very little cracking – we think it was a curing issue.
Illinois	Yes. The cracking is a combination of the Department's mix design and current methods used for structural design.
Massachusetts	Yes. Most common problem are transverse oriented shrinkage cracks spaced about 3' on center. We have proposed a reduction in required 28 day strength to 4000 psi and cementitious content to 585 pcy.
Michigan	Some cracking but appears to be due to curing or design (ex. skewed angles at joints)
Minnesota	Very little cracking in HPC mixtures
Missouri	Yes. Decreased cement content from 7.5 to 6.5 sk./yd^3. Changed existing placing and curing specifications to address temp, evaporation loss, and wet curing time. Some cracking due to design issues and pouring sequences.
Nebraska	They developed shrinkage cracks
New Jersey	Yes. Transverse cracking. Cement content a concern
New York	Yes with all decks, not just HPC. Have tried longer cure time with limited success.
Oregon	Some
Rhode Island	Multispan continuous deck placed in one pour experienced transverse cracks while the other bound was placed in shorter segments without cracking
South Carolina	Yes, but reducing the total cementitious material reduced cracks
Texas	Minor to moderate amount. Seal cracks with gravity feed epoxy.
Utah	Length of time from batching and contractor inexperience major contributors. Fogging found to help on other projects.
Vermont	Occasionally we experience cracking and the primary cause is late or insufficient curing
Virginia	No difference than conventional decks
Wisconsin	Yes, avoid superplasticizers

Table 11. States with HPC Bridge Deck Scaling and Difficulty Finishing.

State	Scaling	Placement/finishing problems & Responses
Connecticut	No	HPC is more difficult to finish smoothly. Some contractor difficulty in keeping concrete moist during finishing
Missouri	Yes	Yes. One deck. With low w/cm was very sticky. The minimum slump was increased from 4.5 to 6 inches.
New Hampshire	Yes	Yes, only when contractors were first getting use to HPC
New York	Yes	Yes
Oregon	No	Some at concrete temps greater than 75
South Carolina	No	Concrete tended to tear when screeded, adjusted aggregate to eliminate tearing
Utah	No	Yes, difficult and sticky. Experience helped.
Vermont	some	Few problems, dependent on the quality of the finishing machine. Drag pan was removed, and fogging helps prevent evaporation so finishing became easier.
Virginia	No	No difference than conventional decks
West Virginia	No	No, field personnel expressed the ease in placement and finishing

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 SCOPE

As discussed in Chapter 1, a bridge deck survey was sent to all DOTs in July 2003. The first time the survey was mailed, 26 states responded. The survey was again mailed out to the 24 states who had not responded. An additional nine states responded. The survey consisted of 5 major parts including mixture proportions, chemical admixtures, mix specifications, finishing and curing, and results from previous projects.

The ultimate goal of this research is to provide AHTD with a state of the art report on use of HPC bridge decks and possibly a performance based specification. This can be achieved if the specification for deck class concrete not only permits but also promotes the use of HPC.

4.2 RECOMMENDATIONS

The results of the survey have identified the following areas where changes could be made to current specifications.

1. AHTD could provide several proven mixture proportions that have low permeability, low shrinkage, good freeze-thaw durability, and adequate workability. The contractor would have the option of choosing a mixture with

known properties instead of relying on a ready-mix company to develop a mixture with the required properties.

2. For concrete mixtures containing fly ash, slag cement, or silica fume, increase the length of wet cure from 7 to 14 days.
3. Current AHTD Specifications (section 802.17) requires "*the concrete, immediately after finishing, shall be covered with one of the curing materials listed above and shall be kept continuously and thoroughly wet for a period of not less than 7 days after the concrete is placed*." Some states specify a time interval between final finishing and application of the curing material. This time interval for most states ranged from 10 minutes to 30 minutes.
4. Current AHTD Specifications (802.17) states "*the concrete….shall be kept continuously and thoroughly wet*". The use of soaker hoses or continuous water sprinklers could be specified to maintain the wet cure.
5. Consider specifying a maximum evaporation rate. Many states limit the evaporation rate to 0.10 lb/ft^2-hr. If the specified evaporation rate is exceeded, require fogging. If fogging is specified, a clear meaning of what constitutes fogging should be developed.
6. Consider specifying a maximum concrete permeability of 2000 coulombs or less at 56 days of age.
7. Consider specifying a maximum concrete shrinkage of 400 microstrains at 28 days of age.

8. Current AHTD Specifications require at least 6.5 bags of cement per cubic yard. Consider decreasing the required cement content to 5.5 or 6.0 bags per cubic yard.

BIBLIOGRAPHY

1. Goodspeed, C., Vanikar, S., Cook, R. "High-Performance Concrete (HPC) Define for Highway Structures." Concrete International. Volume 18. Issue 2. February 1996.
2. Triandafilou, Louis. "HPC Implementation Status." HPC Bridge Views. Issue No. 32. March/April 2004
3. Fossier, P. "Charenton Canal Bridge- Louisiana's First HPC Bridge." HPC Bridge Views. Issue No. 8. March/April 2000.
4. Smith, D.C. "The Promise of High-Performance Concrete." United States Department of Transportation. Federal Highway Administration. Volume 60. No. 2. Fall 1996. http://www.tfhrc.gov/pubrds/fall96/p96au31.htm. Accessed September 24, 2004.
5. Meeks, K., Carino, N. "Curing of High-Performance Concrete: Report of the State-of-the-Art." United States Department of Commerce Technology Administration. National Institure of Standards and Technology. March 1999.
6. Kuennen, T. "Transportation Research Targets HPC Durability." May 2003. http://concreteproducts.com/mag/concrete_transportation_research_targets/. Accessed June 14, 2004.
7. Edwards, D., "HPC Concrete the Florida Experience." HPC Bridge Views. Issue No. 11. September/October 2000.
8. "What is a pozzolan?" http://www.geocities.com/CapeCanaveral/Launchpad/2095/pozzolan.htm. Accessed August 20, 2004.
9. Russell, H. "Mineral Admixtures for HPC Concrete." Concrete Products. April 2002. http://concreteproducts.com/mag/concrete_mineral_admixtures_high/. Accessed June 14, 2004.
10. Oh, B., Cha, S., Jang, B., Jane, S. "Development of high-performance concrete having high resistance to chloride penetration." Nuclear Engineering and Design. Volume 212, Issue 1-3. pg. 221-231
11. Tracy, S., Conolly, J. "High-performance concrete for the reconstruction of Wacker drive." HPC materials in bridges: proceeding of the international conference. 2003.
12. Cook, R. "HPC on the I-15 Reconstruction Project." HPC Bridge Views. Issue No. 23. September/October 2002.
13. Kivisto, P. "HPC Concrete Bridge Decks in Minnesota." HPC Bridge Views. Issue No. 28. July/August 2003.
14. Streeter, D., "A Look at Applying High-Performance Concrete." Bridge Builder Magazine. Jan/Feb 2001.
15. Morin, R., Haddad, G., Aitcin, P.C., "Crack-fee, High-performance Concrete Structures." Concrete International. Volume 24. Issue 9. September 2002. pg. 43-48.
16. "Utilization of Recycled Materials in Illinois Highway Construction." The United States Department of Transportation. Federal Highway Administration. http://www.fhwa.dot.gov/pavement/recfly.htm. Accessed September 24, 2004.

17. Ramakrishnan, V., Sigl, A. "Evaluation of HPC Concrete in Four Bridge Decks as Well as Prestressed Girders for Two Bridges." South Dakota Department of Transportation. December 2001.
18. Capers, H.A. "New Jersey's Move to HPC" HPC Bridge Views. Issue No. 31. Jan/Feb 2004.
19. "What, Why, & How? Supplementary Cementitious Materials." National Ready Mix Concrete Association. 2000. http://www.nrmca.org/aboutconcrete/cips/CIP30p.pdf. Accessed September 24, 2004.
20. Bharatkumar, B.H., Narayanan, R., Raghuprasad, B.K., Ramachandramurthy, D.S., "Mix proportioning of HPC concrete." Cement & Concrete Composites. Vol.23. No. 1. Feb 2001. pg. 71-80.
21. Basheer, P.A.M., McCabe, C.C. and Long, A.E. "Properties of concretes containing Metakaolin." http://www.qub.ac.uk/civeng/research/Intro/research_areas/durability/metakaolin1.html. Accessed July 22, 2004.
22. "Rice Husk Ash Can Be Substitute For Cement" Department of Science and Technology. S & T Media Service. http://www.dost.gov.ph/media/article.php?sid=182. Accessed July 22, 2004.
23. Zia, P., Ahmad, S., Leming, M. "High-Performance Concretes: A State of the Art Report (1989-1994)." Publication FHWA-RD-97-030. FHWA , U.S. Department of Transportation. 1994.
24. Myers, J., Yang, Y. "Practical Issues for the Application of High-Performance Concrete to Highway Structures." Journal of Bridge Engineering. November/December 2001. pg. 613-627.
25. Caldarone, M.A. "Benefits of Chemical Admixtures in HPC." HPC Bridge Views. Issue No. 22. July/August 2002.
26. Russell, H.G. "Admixtures for HPC concrete." Concrete Products. July 2002. http://concreteproducts.com/mag/concrete_admixtures_high_performance/. Accessed June 14, 2004.
27. Schultz, K. "The Contractor's Perspective." HPC Bridge Views. Issue No. 27. May/June 2003. pg. 2.
28. Bickley, J.A., Mitchell, D. "A State-of-the-Art Review of HPC Concrete Structures Built in Canada: 1990-2000." http://www.cement.org/bridges/SOA_HPC.pdf. May 2001. Accessed June 14, 2004.
29. Russell, H.G. "Air entrainment and HPC." Concrete Products. December 2001. http://concreteproducts.com/mag/concrete_air_entrainment_hpc/. Accessed June 14, 2004.
30. Hansen, M.R., Flottmeyer, B.L. "Field Performance of Concrete Admixtures." South Dakota Department of Transportation. Report No. SD97-09-F. June 30, 1998. http://www.state.sd.us/Applications/HR19ResearchProjects/Projects/SD1997_09_final_report.pdf. Accessed September 25, 2004.
31. Schell, H.C., Konecny, J. "Ensuring the Quality of HPC." Concrete International. Volume 25. Issue 7. July 2003. pg. 79-84.

32. Hassan, K.E., Cabrera, R.S., Maliehe, R.S. "The effect of mineral admixture on the properties of high-performance concrete." Cement & Concrete Composites. Volume 22. No 4. August 2000. pg. 267-271.
33. Stanish, K., Hooten, R.D., Thomas, M.D.A. "The Rapid Migration Test- An Alternative to AASHTO T 277." HPC Bridge Views. Issue No. 13. January/February 2001.
34. Sprinkel, M.M, Ozyildirim, C. "Evaluation of HPC Concrete Overlays Placed on Route 60 over Lynnhaven Inlet in Virginia." Virginia Transportation Research Council. Federal Highway Administration. August 2000.
35. Hooten, D., Nagi, M.A., Ozyildirim, C.H. "The Rapid Chloride Permeability Test." HPC Bridge Views. Issue No. 12. November/December 2000.
36. Fung, Rico. "HPC Bridges in Canada." HPC Bridge Views. Issue No. 24. November/December 2002.
37. Ozyildirim, C. "Performance of the First Structure Built With HPC Concrete in Virginia." Virginia Transportation Research Council. Federal Highway Administration. VRTC 02-R1. October 2001.
38. Kaderbek, S.L. "HPC for Wacker Drive Reconstruction." HPC Bridge Views. Issue No.27. May/June 2003.
39. Khaleghi, B., Weigel, J. "HPC Bridge Decks in Washington State." HPC Bridge Views. Issue No. 15. May/June 2001.
40. Prisby, R.A. "Global Warming You Say? OK, But What About My Concrete?" Concrete International. January 2001. http://www.pavement.com/techserv/ACI-GlobalWarming.PDF. Accessed August 2, 2004.
41. Waszczuk, C.M. "Crack-Free HPC Bridge Deck- New Hampshire's Experience." HPC Bridge Views. Issue No. 4. July/August 1999.
42. Russell, H.G. "Curing HPC Concrete Slabs." Concrete Products. February 2000. http://concreteproducts.com/mag/concrete_curing_highperformance_concrete/. Accessed June 14, 2004.
43. "Research underscores need for moist curing of HPC decks." Concrete Products. March 2002. http://concreteproducts.com/mag/concrete_research_underscores_need/. Accessed June 14, 2004.
44. "Specification Changes for HPC- Curing Concrete Bridge Decks." HPC Bridge Views. Issue No. 25. January/February 2003.
45. Praul, M.F. "Curing for HPC Bridge Decks- Bring on the Water!" HPC Bridge Views. Issue No. 15. May/June 2001.
46. Streeter, D.A. "HPC in New York State Bridge Decks." HPC Bridge Views. Issue No. 6. November/December 1999.
47. Abrahams, M.J. "Use of HPC on Admiral Clarey Bridge, Hawaii." HPC BridgeViews. Issue No. 7. January/February 2000.
48. Miller, R.A. "From Three Spans to One with HPC." HPC Bridge Views. Issue No. 4. July/August 1999.
49. Koch, Tom. "NCDOT's Experience with HPC." HPC Bridge Views. Issue No. 20. March/April 2002.

50. Rabbat, B.G. "Group Promotes Benefits Of HPC Concrete Bridges." http://www.pci.org/markets/bridges/rabbat.cfm. Accessed June 14, 2004.

APPENDIX A

SURVEY

PERFORMANCE OF HPC BRIDGE DECKS

Please mail or fax your replies to:

Dr. Micah Hale
Assistant Professor
4190 Bell Engineering Center
Department of Civil Engineering
University of Arkansas
Fayetteville, AR 72701
Tel : (479)-575-6348
Fax: (479)-575-7168
micah@uark.edu

Thank you for your consideration. The results of this survey will be used to create a new performance based specification for high performance concrete bridge decks based upon the results of previously constructed decks.

Please complete and return by December 15, 2004. Use additional paper/materials if needed.

Would you like to receive a copy of the results of this survey?

Yes_______ No_______

Name and Address (Mail or electronic)

____

____

____

____

____

BASIC INQUIRIES

Does your state DOT currently use high performance concrete (HPC) in bridge deck applications?

Yes_______ No_______

Does your state DOT intend to implement the use of HPC for such applications in the near future?

____

Unless otherwise noted all questions refer only to concrete (conventional, specially proportioned, or HPC) used for bridge decks.

PROPORTIONING MIXTURES

1. Do you have a maximum or minimum limit for cement content? If the answer is yes for any of the following please specify.

   ____

2. Do you have a maximum/minimum limit for w/cm ratio? If yes specify.

   ____

3. Do you require the use of mineral admixtures such as fly ash, silica fume, or ground granulated blast furnace slag (GGBFS)? Do you specify maximum/minimum amounts? If yes specify.

   ____

4. Do you specify a nominal maximum aggregate size for coarse aggregate? If yes please detail.

   ____

5. Do you specify the type of portland cement used? Please detail.

____

CHEMICAL ADMIXTURES

1. Do you require air entrainment for bridge decks? If so what amount?

____

2. What types and amounts of water reducing, superplasticizing and/or high range water reducing agents do you allow?

____

3. Do you allow or specify the use of set retarding/accelerating admixtures?

____

4. Do you allow the use of corrosion reducing admixtures?

____

MIX SPECIFICATIONS

Prescriptive

1. Do you specify a minimum/maximum compressive strength for bridge decks? If yes please detail.

____

2. Do you prescribe a min/max slump? If yes please specify.

____

3. Do you have a specified air content range? If yes please list.

____

Performance

1. Is allowable permeability of the deck specified? If so is the Rapid Chloride Ion test (ASTM C 1202, AASHTO T 277) used for determination and what level is required?

   ____

2. Is freeze-thaw resistance measured? What the minimum durability factor or number of freeze/thaw cycles specified?

   ____

3. Do you specify a maximum allowable shrinkage?

   ____

4. Do you specify for abrasion or scaling resistance? Please explain.

   ____

   ____

Testing

1. Do you require the contractor to provide trial batches? If so please explain.

   ____

   ____

   ____

2. What tests do you require on concrete after and during placement?

   ____

   ____

   ____

   ____

FINISHING AND CURING

1. What consolidation techniques do you use for bridge decks?

2. How soon after placement is concrete finished?

3. What requirements for concrete placement do you specify with regards to air temperature and evaporation rates?

4. Do you require the use of fogging or other such special treatments during placing and finishing?

5. What type of curing do you use? (ponding, wet burlap, cotton mats, curing agents, etc.)

6. What is the minimum duration of curing that is required?

7. Are there any special curing requirements you think should be listed?

RESULTS FROM PREVIOUS CONSTRUCTION

1. Are there completed projects that involve HPC bridge decks in your state?

   Yes________ No________

If yes please continue, if no thank you very much for your time and attention.

2. Have you experienced problems with cracking? If so please detail and if a solution has been determined share.

   ____
   ____
   ____
   ____
   ____

3. Have you experienced problems with scaling?

   ____
   ____
   ____
   ____
   ____

4. Have you experienced placement/finishing problems?

   ____
   ____
   ____
   ____
   ____

5. For what design life were the decks designed? Are they performing up to this?

6. Is there any important information not covered relating to this project you wish to share?