COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

PENNDOT RESEARCH

PENNDOT

BEST PRACTICES GUIDE TO QUALITY CONCRETE CONSTRUCTION

University-Based Research, Education and Technology Transfer Program
AGREEMENT NO. RFQ NO. 03-01 (C07)
AGREEMENT NO. 359704, WORK ORDER 81

MARCH 18, 2003 (Revised March 30, 2005)

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FINAL REPORT

Prepared for
Commonwealth of Pennsylvania
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In partial fulfillment of

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16. Abstract This document provides a revised working guide to the design and construction of concrete structures using attainable high standards rather than common practice. High quality concrete can be designed, produced and placed as economically as marginally controlled concrete operations, and in many cases more economically. The improvements obtained through engineering, quality control and reduction in material expenses often lead to more efficient operations, less waste and higher production rates. Together these produce long-lasting structures that are more efficient to construct and maintain. This is a step toward a sustainable infrastructure, both economically and environmentally.			
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CHAPTER 1. INTRODUCTION

This document provides a working guide to the design and construction of concrete structures using attainable high standards rather than common practice. High quality concrete can be designed, produced and placed as economically as marginally controlled concrete operations and in many cases more economically. The improvements obtained through engineering, quality control and reduction in material expenses often lead to more efficient operations, less waste and higher production rates. Together, these produce long-lasting structures that are more efficient to construct and maintain. This is the first step toward a sustainable infrastructure, both economically and environmentally.

Annually, billions of dollars are invested in repair, replacement and rehabilitation of concrete bridges across the United States. The average life of the approximately 22,000 bridges in Pennsylvania that are on the U.S. National Bridge Inventory is 28 years. Resources are available to repair or replace about 270 bridges per year, resulting in an inventory of bridges that has 24.5 percent classified as structurally deficient and 18.6 percent classified as functionally obsolete [NBI, 2000]. Changes in design and construction that make use of the latest state of practice procedures can increase design life and reduce life cycle costs, thereby enabling the more efficient use of transportation funds. With the available resources, new bridges must have an average life nearly three times longer than the existing inventory. The economical technologies, engineering practices and construction procedures exist to meet this goal with little increase in initial capital costs. Bringing together the technology, engineering and construction practices is possible in Pennsylvania and could be fully implemented within 5 years.

In addition, the implementation of the practices described herein will move Pennsylvania toward the goals of environmentally friendly and sustainable development. While concrete structures are both economical and essential to our transportation infrastructure, they use massive amounts of natural resources and energy to construct and generate a large portion of construction waste and greenhouse gases (CO_2). Cement and concrete production produce nearly 8% of the worldwide CO_2 emissions and nearly 50% of the construction waste. Of the construction waste generated, about 18% is attributed to material that was delivered to the site and never used. Reducing the number of times a structure has to be rebuilt has the single greatest impact on a greener environment and a sustainable future for our infrastructure.

Objective

The primary objective of this document is to provide guidelines for designing and producing durable concrete structures with 75 to 100 years of design life. Essential procedures to achieve this objective include:

- Identification of the structural and environmental design requirements
- Design and specification of performance consistent with the identified structural and environmental requirements
- Design and reliable production of concrete meeting the specifications
- Implementation of a detailed quality control plan during construction
- Oversight, inspection, and enforcement of construction specifications

CHAPTER 2. PERFORMANCE-BASED CONCRETE DESIGN

2.1 INTRODUCTION

Performance-based concrete is concrete produced to meet a set of design criteria based on a set of engineering and environmental exposure conditions. Concrete for homes and commercial buildings is typically specified by slump, water-cementitious materials ratio (w/cm), and 28-day compressive strength. This is not adequate for most transportation structures or applications. The desired structural requirements and life expectancy in severe environmental conditions require a more comprehensive view of the building materials. In particular, the transportation agency, the structural and materials engineers, and the constructors must clearly understand what is expected of the transportation structure. This requires a commitment to communication, assessment, quality control, inspection and enforcement through contractual discounts and incentives for field performance.

To improve the transportation infrastructure, engineers must systematically evaluate both the structural design requirements and environmental exposure conditions that may lead to premature deterioration. The results of these evaluations must be used to develop higher standards for design details, material performance and construction quality. The integration of these standards into the transportation infrastructure leads to the design, production, transportation, placement and curing of concrete meeting the goal of a longer life cycle design. Figure 2.1 shows a conceptual path to life cycle design. The path starts with the highway department defining in the broadest terms its expectations for particular structures (desired life, economic and environmental values, commercial uses, and desired function of the structure). From this information, the engineer defines the load combinations based on code requirements and special conditions and exposure conditions based on local environmental factors and maintenance practices. Loadings and exposure are determined by expert opinions, often expressed in design codes. The engineer must use design tools that use measure values or expert systems to assist in estimating loadings or exposures, where they are not explicitly stated in the design code.

2.2 AGENCY NEEDS

The initial step in performance-based design understands the needs of the transportation agency. The highway department must broadly define the desired outcome for bridges and other structures. These policy decisions provide a framework for which the engineer and contractor can design and construct a structure to meet the needs of the agency. The typical needs that must be defined are those related to the desired function of the structure, the economic resources, timeframe the structure is expected to be in service and the acceptance of the structure being out of service. Table 2.1 may be used as a template to define the needs of a bridge. This table is essential is setting up goals for the bridge inventory and future financial planning. It also provides engineers with a standard on which design decisions can be based. The agency and engineers understand that the life of a structure and its anticipated loadings and exposures are a matter of probability.

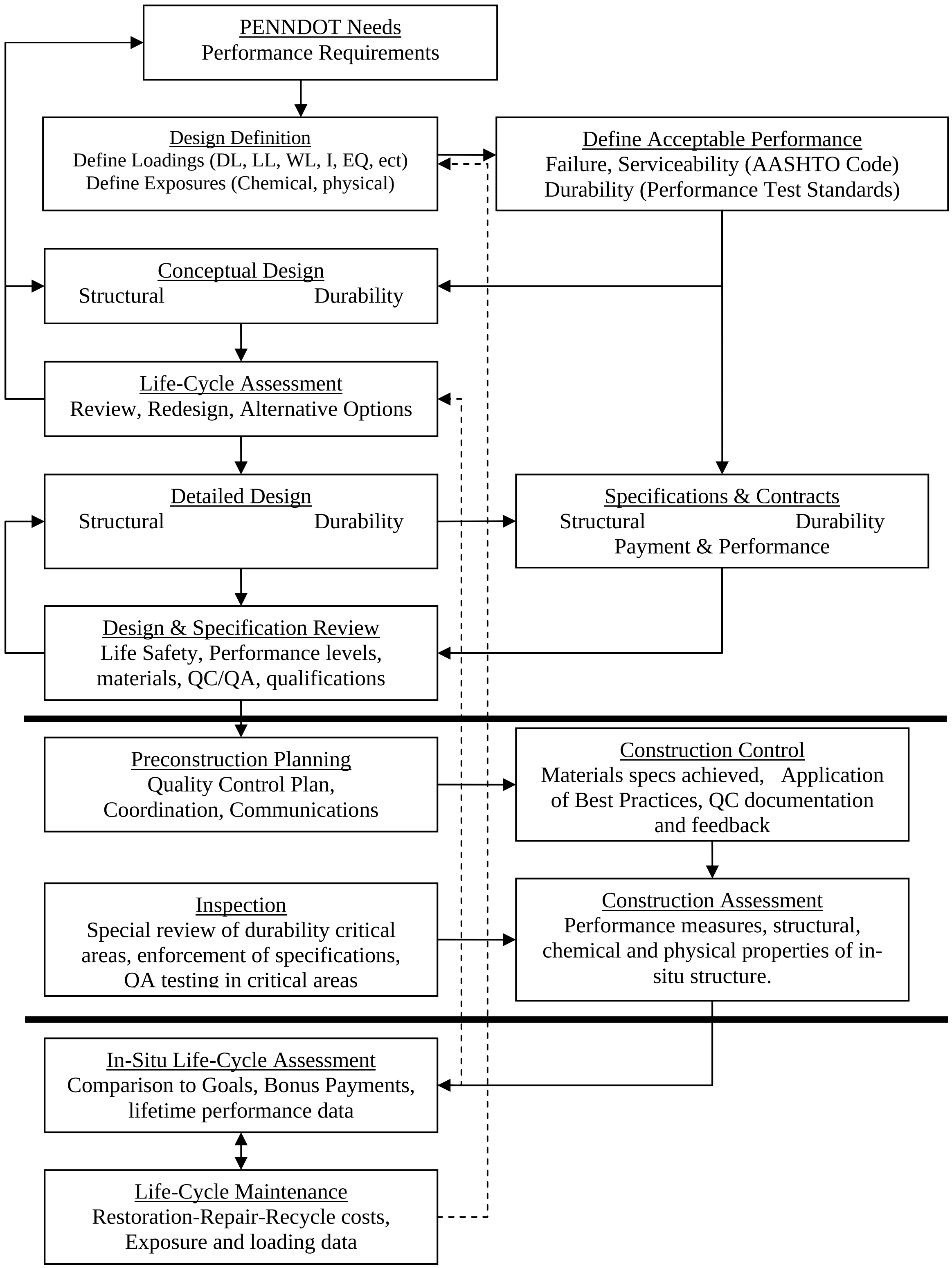

Figure 2.1. Conceptual path to life cycle design.

For example, an agency could choose average numbers (50% chance) for funding and expected years of service or choose a more refined number (e.g., 75% of not exceeding anticipated funding and 90% of exceeding expected years of service). Structures that are part of a new long-term transportation system may have a life of 75 to 100 years with current technologies. As the agency obtains more information and feedback on the life cycle costs of needs decisions, they may revise goals or add additional items to the table.

Table 2.1. Sample agency needs table.

Need			
Function of the Structure	*Structure to cross small stream along I-99 Route*		
Anticipated Funding	*$3,000,000*	Max. Additional Funding	*$300,000*
Desired Opening Date	*6/1/2005*	Expected Years of Service	*75*
Critical Nature of Opening (1-5)*	*1*	Critical Nature of Early Deterioration (1-5)*	*3*

* Scale: 1 = not critical – alternatives are acceptable, 3 = important but not a life safety issue, and 5 = extremely critical, life safety issue.

2.3 DESIGN DEFINITION

After becoming fully aware of the needs of the agency, the designer must translate these needs into loads, load combinations and exposures. Loads and load combinations are covered in the AASHTO code and the agency design manual. Exposures must define, through an environmental assessment of the particular site of the structure, the conditions under which the structure will be in service. This requires basic knowledge of the annual weather conditions, local geotechnical and soil properties, local air and water exposures, standardized design details and local construction material that may interact with the environment. In addition, the engineer must be able to predict maintenance or external operations that will change the environment over the life of the structure.

Table 2.2 is a template for designers to define the structural environment. The designer must be able to fill out a table of environmental conditions for any design element of a structure. This information is shared between the structural designer and the materials engineer. During the course of designing a structure, the designer may choose to change design details, building materials or maintenance practices to better serve the agency's design goals. The information in Table 2.2 is the first step in defining the performance of the concrete element. Both the structural properties and the environmental exposures are defined in the table.

2.4 DEFINING ACCEPTABLE PERFORMANCE

Compiling the agency needs, information on local construction materials, and the environmental assessment data brings together the needed information for the first iteration of defining performance. This is not an easy task. It requires that the engineer(s) have a basic understanding of material science, structural design, quality control, probability and local construction material sources. Defining acceptable performance is not in the design code but, rather, requires engineering judgment. The designer must use the environmental data and agency needs to define quantifiable performance criteria using life cycle design principles.

Table 2.2. Sample Environmental Assessment Table

Structural Designer	**Materials Designer**
Element Type____________	Reactivity of Aggregate: High Medium Low
Reinforced Yes No	Exposed to freezing or thawing Yes No
Reinforcement type: Black ECR Galvanized	Saturated while Freezing Yes No
f_c'at 28 days ____________	Average Number of F-T/year = ________
Early age f_c_____@____days	Average dosage of deicer salt______ tons/lm/yr
Clear cover = in.	Contact to studded tires or chains Yes No
Clear spacing between rebars = in.	Acceleration or deceleration zone Yes No
Desired Design Life: 25 40 50 75 100 yrs	Exposed to salt or seawater Yes No
Design Fatigue Cycles	Exposed to SO_4 or seawater Yes No
	Tidal Zone Yes No

One of the most important concepts to remember in performance-based design is that not all aspects of a material or structure need to be optimized. If a structural element is never exposed to aggressive chemical agents, then it does not have to have low permeability, and permeability does not need to be a performance criterion. Likewise, if higher than normal stiffness is not required, then the modulus of elasticity does not need to be a performance criterion.

2.5 ENGINEERING GUIDELINES AND DESIGN AIDS

Design tools can assist the engineer in developing the desired levels of performance and the standards by which they can be measured. This section provides an engineering design tool for the development of performance specifications for reinforced concrete highway structures. The following guide addresses the use of performance criteria for designing reinforced concrete structures for highway applications. It is emphasized that higher performance grades do not necessarily result in better concrete for all applications. Appropriate performance grades should be selected based on the guidelines described below.

The decision tree used in this design tool leads to a series of yes/no answers. If the designer answers "yes," there is another question to further clarify the performance needs. This continues until a recommended grade of performance is reached. The tool in this section is developed for 75- to 100-year design life structures. The designer would have to use engineering judgment and further expert opinion to extend the tool to shorter or longer life structures.

2.5.1 Compressive Strength

The compressive strength of concrete is generally determined by the structural design requirements. For most highway structures, the concrete compressive strength is between 3500 psi and 5000 psi at 28 days (CS-Grade 1), as determined from testing standard cylinders moist cured at 73°F (23°C). Grade 2 is high strength concrete for piers and prestressed concrete girders. Grade 3 is typically applicable to early opening and repair applications. The questions below are those that should be considered when determining if high strength or high early strength concrete is needed.

<table>
<tr><td rowspan="4">CS

Compressive Strength</td><td rowspan="4">Is the concrete used in either a structure or a pavement?</td><td rowspan="3">Yes</td><td rowspan="3">Is the member optimized for high strength?</td><td rowspan="2">Yes</td><td rowspan="2">Is the member optimized for high early strength?</td><td>Yes. Specify within CS - Grade 3</td></tr>
<tr><td>No. Specify within CS - Grade 2</td></tr>
<tr><td colspan="3">No. Specify within CS - Grade 1</td></tr>
<tr><td colspan="5">No. Specify a minimum of 3500 psi at 28 days (24 MPa)</td></tr>
</table>

	Test Method	Grade 1	Grade 2	Grade 3
CS Compressive Strength, ksi (MPa)	AASHTO T 22	3.5≤X<8.0 @ 28 days (24≤X<55)	8.0≤X @ 28 days (55≤X)	3.5 ≤X @ time (24≤X)

Sample PENNDOT specification language for CS Grade 1 should read as follows:

SECTION 704.1 (c) **Design Basis** - Make trial mixtures and computations for the concrete mixture, including the molding and curing of test specimens. Prepare and compute each mixture design in accordance with Bulletin 5, except the compressive strength shall have a minimum compressive strength, f_c' (28 days) and f_{cr}' (28 days) as specified below:

Minimum f_c' (28 days) = ___________

Required Average Compressive Strength, f_{cr}' (28 days) = the larger value computed from Equation 1 and 2, computing the standard deviation according to ACI 318 Section 5.3.1.

$$f_{cr}' \text{ (28 days)} = f_c' \text{ (28 days)} + 1.34\sigma \qquad (1)$$

$$f_{cr}' \text{ (28 days)} = 0.9 f_c' \text{ (28 days)} + 2.33\sigma \qquad (2)$$

The final mixture design approval will be based on a full batch trial mixture using the approved mixture design and the type of mixer and the mixing procedure detailed in the contractors quality control plan. The Bureau of Construction and Materials, Materials Testing Division may conduct a quality assurance test of the compressive strength before the mixture will be approved and during the course of the contract.

The specification language for grades 2 and 3 are more specialized and should be tailored to the particular needs of the structure.

2.5.2 Strength Development

The strength development of concrete is a strong indicator of the early heat evolution and orderly formation of the cementitious matrix. For most highway structures, the concrete strength development will be SD-Grade 2 because this represents concrete elements exposed to environmental factors. Prestressed concrete, concrete for early openings, and repair applications generally do not require this performance criterion because rapid strength gain is the dominant criterion in their engineering applications.

<table>
<tr><td rowspan="4">SD
Strength Development</td><td rowspan="4">Is a specified concrete strength required in the first 6 days after being cast?</td><td rowspan="3">Yes</td><td rowspan="3">Is durability an important factor in this element?</td><td rowspan="2">Yes</td><td rowspan="2">Is the member greater than 3 feet in thickness?</td><td>Yes.
Specify SD-Grade 3</td></tr>
<tr><td>No.
Specify SD-Grade 2</td></tr>
<tr><td colspan="3">No. Specify SD- Grade 1</td></tr>
<tr><td colspan="5">No. SD grade should not be specified.</td></tr>
</table>

	Test Method	Grade 1	Grade 2	Grade 3
SD Strength ratio $\frac{28 \text{ day } f_c}{7 \text{ day } f_c}$	AASHTO T 22	X≥1.15	X≥1.33	X≥1.45

Sample PENNDOT specification language for SD Grade 2 should read as follows:

SECTION 704.1 © Design Basis…….

> The concrete mixture design shall have a 28 day to 7 day compressive stress ratio greater than or equal to 1.33, as determined by standard test cylinders moist cured at 73°F (23°C). The final mixture design approval will be based on a full batch trial mixture using the approved mixture design and the type of mixer and the mixing procedure detailed in the contractors quality control plan. The Bureau of Construction and Materials, Materials Testing Division may conduct a quality assurance test of the strength development before the mixture will be approved and during the course of the contract.

The specifications are for grades 1 and 3 would be identical except for the insertion of the ratios 1.15 or 1.45, respectively. Grade 1 is typically applicable to elements not directly exposed to chemical and physical exposures (diaphragms, pier caps, columns, slabs and beams within office buildings). Grade 3 is typically applicable to massive concrete members that have a potential for large thermal gradients, e.g., large piers, abutments, foundations and dams.

2.5.3. Chloride Penetration

Chlorides from deicing salts or seawater enter concrete through dual mechanisms. The salts are absorbed into the small surface pores and diffused through the concrete over time. Repeated wetting/drying or freezing/thawing contributes to the concentration of the absorbed salts, which drives the diffusion mechanism. Concrete can be designed to have a lower diffusion rate through the use of chemical admixtures, pozzolans, lower w/cm ratios and/or longer curing times. The decision tree below and the AASHTO T277 performance test are tools to assist the engineer with the later three. When using chemical admixtures to reduce diffusion, alternative measures are needed.

<table>
<tr><td rowspan="4">CP
Chloride Penetration Durability</td><td rowspan="4">Is the concrete exposed to chloride salts or soluble sulfate environments?</td><td rowspan="3">Yes</td><td rowspan="3">Is the member exposed to an environment of wet/dry cycles?</td><td rowspan="2">Yes</td><td rowspan="2">Will the member be saturated completely during freezing?</td><td>Yes.
Specify CP-Grade 3</td></tr>
<tr><td>No.
Specify CP-Grade 2</td></tr>
<tr><td colspan="3">No. Specify CP- Grade 1</td></tr>
<tr><td colspan="5">No. CP grade should not be specified.</td></tr>
</table>

	Test Method	HPC Grade 1	HPC Grade 2	HPC Grade 3
CP Chloride penetration, Coulombs	AASHTO T 277*	4000≥X	1500≥X	800≥X

*Mixtures containing permeability reducing admixtures or corrosion inhibiting admixtures need to be evaluated using alternative procedures.

Sample PENNDOT specification language for SD Grade 2 should read as follows:

SECTION 704.1 © Design Basis…….

> The concrete mixture design shall have a chloride penetration less than 1500 coulombs, as determined by standard samples moist cured at 73°F (23°C) for 60 days. The final mixture design approval will be based on a full batch trial mixture using the approved mixture design and the type of mixer and the mixing procedure detailed in the contractors quality control plan. The Bureau of Construction and Materials, Materials Testing Division may conduct a quality assurance test of the chloride penetration before the mixture will be approved and during the course of the contract.

The specification for grade 1 or 3 would be identical to this specification, with the exception that 4000 or 800 would be inserted, respectively. Grade 1 is suitable for most exposed structural elements that have passive exposures to salts or do not absorb additional salts from wet/dry cycling, e.g., beams and piers. Grade 2 is for elements that have direct exposure to salts but are not typically saturated during freezing and thawing, e.g., bridge decks. Grade 3 is typically specified for areas that would be fully saturated during freezing. This compounds the damage from internal pressures from freezing water and salt concentrations.

2.5.4 Shrinkage

Concrete shrinks by three primary mechanisms, i.e., plastic shrinkage, autogenous shrinkage, and drying shrinkage. Proper construction practices can prevent plastic shrinkage. Autogenous shrinkage is relatively small at w/cm above 0.40, the lower bound in most highway specifications. Drying shrinkage can be controlled through the selection of mixture design proportions (aggregate size and gradation, w/cm, cementitious materials). Creating "crack-free" structures without post-tensioning is both expensive and unnecessary in most applications. The decision tree below provides an engineer with a tool for specifying reasonable performance limits for different applications.

<table>
<tr><td rowspan="4">SH
Shrinkage</td><td rowspan="4">Is the concrete exposed to moisture, chloride salts or soluble sulfate environments?</td><td rowspan="3">Yes</td><td rowspan="3">Is the member constructed without joints?</td><td rowspan="2">Yes</td><td rowspan="2">Is the member designed to be watertight or crack free?</td><td>Yes.
Specify SH-Grade 3</td></tr>
<tr><td>No.
Specify SH-Grade 2</td></tr>
<tr><td colspan="3">No. Specify SH- Grade 1</td></tr>
<tr><td colspan="5">No. SH grade should not be specified.</td></tr>
</table>

	Test Method	HPC Grade 1	HPC Grade 2	HPC Grade 3
SH Shrinkage (microstrain)	ASTM C 157	$800 \geq X$	$500 \geq X$	$200 \geq X$

Sample PENNDOT specification language for SH Grade 2 should read as follows:

SECTION 704.1 © Design Basis…….

> The concrete mixture design must have a shrinkage less than 500 microstrain, as determined by standard samples moist cured at 73°F (23°C) for 14 days. The final mixture design approval will be based on a full batch trial mixture using the approved mixture design and the type of mixer and the mixing procedure detailed in the contractors quality control plan. The Bureau of Construction and Materials, Materials Testing Division may conduct a quality assurance test of the shrinkage before the mixture will be approved and during the course of the contract.

Grade 1 and 3 specifications would have an identical format with limits of 800 and 200, respectively. The time of the curing should be same as that used on the project. If the member is constructed with regularly spaced sawed joints (2*thickness, in. = spacing, ft.), then Grade 1 would typically be specified. Grade 3 is a special situation for fluid retention structures.

2.5.5 Alkali Silica Reaction

Alkali silica reaction (ASR) occurs when reactive silica within local aggregates reacts with the alkalis from the cementitious material and water from the environment to cause a swelling that eventually cracks the concrete structure. Reactive aggregates exist throughout North American and cannot be reasonably avoided in construction. The swelling is largely avoidable by changes to the concrete mixture design (selection of cement, addition of pozzolans, and selection of aggregate source). The decision tree below is a tool for specifying the appropriate grade of performance for a particular concrete element.

<table>
<tr><td rowspan="4">AS
Alkali Silica Reaction Durability</td><td rowspan="4">Does the concrete contain reactive aggregates?</td><td rowspan="3">Yes</td><td rowspan="3">Is the concrete exposed to moisture?</td><td rowspan="2">Yes</td><td rowspan="2">Will the member be saturated during freezing?</td><td>Yes.
Specify AS - Grade 3</td></tr>
<tr><td>No.
Specify AS - Grade 2</td></tr>
<tr><td colspan="3">No. Specify AS - Grade 1</td></tr>
<tr><td colspan="5">No. AS grade should not be specified.</td></tr>
</table>

	Test Methods	HPC Grade 1	HPC Grade 2	HPC Grade 3
AS Alkali-silica reaction	AASHTO T 303	X <0.10% At 14 Days	X <0.10% At 14 Days	X <0.10% At 14 Days
	ASTM C 441	X >50% Reduction in Expansion At 56 Days	X>60% Reduction in Expansion At 56 Days	X >70% Reduction in Expansion At 56 days

Sample PENNDOT specification language for AS Grade 2 should read as follows:

SECTION 704.1 © Design Basis…….

> The aggregate used in the mixture design must have an expansion less than 0.10 percent in 14 days according to AASHTO T303, or the cement/pozzolan combination must have an expansion 60 percent less than that of the control according to ASTM C441. The cementitious combination used in the concrete mixture design approval will be that used in the approved mixture design detailed in the contractor's quality control plan. The Bureau of Construction and Materials, Materials Testing Division may conduct a quality assurance test of the resistance of the cementitious material to alkali silica reaction during the course of the contract.

Grade 1 and 3 specifications would read in an identical manner except for the 50 or 70 percent reduction in expansion, respectively.

2.5.6 Freezing and Thawing Durability

Freeze thaw cycling of saturated concrete causes internal cracking and surface spalling, as well as accelerates the ingress of salts, moisture, and sulfate. It is an avoidable form of distress. The use of chemical admixtures as air-entraining agents, to develop a dispersed noninterconnected matrix of air bubbles, provides buffer space for the expanding water during freezing, thus avoiding internal pressures that cause cracking. The total volume of air as measured by a pressure air meter on a construction site is not sufficient to ensure that the matrix of bubbles is present. The performance test, AASHTO T161, provides a harsh test environment to verify the resistance of the concrete. The decision tree below is a tool for engineers to use to develop performance specifications for concrete elements in different environments.

<table>
<tr><td rowspan="4">FT

Freeze Thaw Durability</td><td rowspan="4">Is the concrete exposed to freezing and thawing environments?</td><td rowspan="3">Yes</td><td rowspan="3">Is the member exposed to deicing salts?</td><td rowspan="2">Yes</td><td rowspan="2">Will the member be saturated during freezing?</td><td>Yes.
Specify FT-Grade 3</td></tr>
<tr><td>No.
Specify FT-Grade 2</td></tr>
<tr><td colspan="3">No. Specify FT- Grade 1</td></tr>
<tr><td colspan="5">No. FT grade should not be specified.</td></tr>
</table>

	Test Method	HPC Grade 1	HPC Grade 2	HPC Grade 3
FT Freeze-thaw durability (relative modulus, 300 cycles)	AASHTO T 161 Proc. A	60%≤X	80%≤ X	90%≤ X

Sample PENNDOT specification language for FT Grade 2 should read as follows:

SECTION 704.1 © Design Basis…….

> The concrete mixture design must maintain a relative dynamic modulus of 80 percent of the original value, as tested according to AASHTO T161 procedure A. The final mixture design approval will be based on a full batch trial mixture using the approved mixture design and the type of mixer and the mixing procedure detailed in the contractors quality control plan. The Bureau of Construction and Materials, Materials Testing Division may conduct a quality assurance test of the freeze-thaw durability before the mixture will be approved and during the course of the contract.

Specifications for Grades 1 and 3 would be identical except for 60 and 90 percent limits, respectively.

2.5.7 Scaling Resistance

Scaling is a surface deterioration that occurs during the freezing and thawing of concrete with concentrated salt solutions near the surface. The deterioration is preventable by reducing the absorptive capability of the surface of the concrete and by providing a proper air-entrained structure, as required for freeze-thaw resistance. This type of deterioration is most common on horizontal surfaces in highway structures exposed directly to deicing salts or seawater. However, it can also occur on vertical surfaces that are subjected to tidal scour or wicking of salt water solutions.

<table>
<tr><td rowspan="4">SR

Scaling Durability</td><td rowspan="4">Is the concrete exposed to deicing salts or seawater?</td><td rowspan="3">Yes</td><td rowspan="3">Is the exposure a direct application of salt?</td><td rowspan="2">Yes</td><td rowspan="2">Will the member be subjected to severe surface loading?</td><td>Yes.
Specify SR-Grade 3</td></tr>
<tr><td>No.
Specify SR-Grade 2</td></tr>
<tr><td colspan="3">No. Specify SR - Grade 1</td></tr>
<tr><td colspan="5">No. SR grade should not be specified</td></tr>
</table>

	Test Method	HPC Grade 1	HPC Grade 2	HPC Grade 3
SR Scaling resistance (visual rating, 50 cycles)	ASTM C 672	X≤3	X≤1	X=0

Sample PENNDOT specification language for SR Grade 2 should read as follows:

SECTION 704.1 © Design Basis…….

> The concrete mixture design must maintain a scaling resistance less than or equal to 1.0 after 50 cycles, as tested according to ASTM C672. The final mixture design approval will be based on a full batch trial mixture using the approved mixture design and the type of mixer and the mixing procedure detailed in the contractors quality control plan. The Bureau of Construction and Materials, Materials Testing Division may conduct a quality assurance test of the scaling resistance before the mixture will be approved and during the course of the contract.

Specifications for grades 1 and 3 would be identical except for scaling resistance level equal to or less than 3 for Grade 1 and equal to 0 for Grade 3. The Grade 3 is a very severe limitation to meet.

2.5.8 Sulfate Resistance

Sulfate attack is a form of distress that gradually softens the concrete to a point at which it cracks and spalls, leaving the rebar exposed to corrosive elements. It is caused by soluble sulfates in soils, seawater or other environmental sources. The sulfate reacts with aluminate compounds in hardened concrete that cause large expansions. Sulfate attack is completely avoidable if its potential is identified during the design phase. In most moderate to severe conditions, combinations of ordinary portland cement and certain pozzolans (silica fume, class F fly ash or slag) can be used, as well as ASTM C150 Type II cement or ASTM C1157 MS cement.

<table>
<tr><td rowspan="4">SU

Sulfate Resistance</td><td rowspan="4">Is the concrete exposed to more than 0.10 percent soluble sulfates?</td><td rowspan="3">Yes</td><td rowspan="3">Is the member exposed to more than 0.20 percent soluble sulfates?</td><td rowspan="2">Yes</td><td rowspan="2">Is the member exposed to wet-dry cycles?</td><td>Yes.
Specify SU - Grade 3</td></tr>
<tr><td>No.
Specify SU - Grade 2</td></tr>
<tr><td colspan="3">No. Specify SU - Grade 1</td></tr>
<tr><td colspan="5">No. SU grade should not be specified.</td></tr>
</table>

	Test Method	HPC Grade 1	HPC Grade 2	HPC Grade 3
SU Sulfate resistance (expansion)	ASTM C 1012	X<0.10% At 6 months	X<0.10% At 12 months	X<0.10% At 18 months

Sample PENNDOT specification language for SU Grade 2 should read as follows:

SECTION 704.1 © Design Basis…….

> The cementitious materials used in the mixture design must maintain a sulfate resistance less than 0.10 percent expansion in 12 months, as tested according to ASTM C1012. The cementitious combination used in the concrete mixture design approval will be that used in the approved mixture design detailed in the contractor's quality control plan. The Bureau of Construction and Materials, Materials Testing Division may conduct a quality assurance test of the sulfate resistance on the cementitious material during the course of the contract.

Specifications for grades 1 and 3 would be identical except for sulfate resistance level less than 0.10% at 6 months and 18 months, respectively.

There are other performance characteristics that can be optimized under special situations. Extensive trial batching and importing special materials is often required to optimize these characteristics. While these characteristics may not be economically viable for small projects, they may serve special needs of designers for large engineering projects.

2.5.9 Abrasion Resistance

Abrasion of highway structures is caused by surface friction forces acting on the concrete. The resistance of the concrete to these forces is primarily a function of concrete compressive strength and the contractor's finishing and curing operations.

<table>
<tr><td rowspan="4">AB
Abrasion Resistance</td><td rowspan="4">Is the concrete exposed to surface abrasion?*</td><td rowspan="3">Yes</td><td rowspan="3">Is the member subjected to other than tire wear?</td><td rowspan="2">Yes</td><td rowspan="2">Will the member be exposed to tire studs or chains?</td><td>Yes.
Specify AB-Grade 3</td></tr>
<tr><td>No.
Specify AB-Grade 2</td></tr>
<tr><td colspan="3">No. Specify AB- Grade 1</td></tr>
<tr><td colspan="5">No. AB grade should not be specified.</td></tr>
</table>

* Hydraulic structures subjected to abrasion should be design according to ACI 210.

	Test Method	HPC Grade 1	HPC Grade 2	HPC Grade 3
AB Abrasion resistance (wear depth, mm)	ASTM C 994	2.0≥X	1.0≥X	0.5≥X

Sample PENNDOT specification language for AB Grade 2 should read as follows:

SECTION 704.1 © Design Basis…….

> The concrete mixture design must maintain an abrasion resistance less than or equal to 1.0 mm of wear depth, as tested according to ASTM C994. The final mixture design approval will be based on a full batch trial mixture using the approved mixture design, the type of mixer, the mixing procedure, finishing operation and curing detailed in the contractors quality control plan. The Bureau of Construction and Materials, Materials Testing Division may conduct a quality assurance test of the abrasion resistance before the mixture will be approved and during the course of the contract.

Specifications for grades 1 and 3 would be identical except for abrasion resistance level equal to or less than 2.0 for Grade 1 and equal to or less than 0.5 for Grade 3. Grade 3 is a very severe limitation to meet.

2.5.10 Modulus of Elasticity

The modulus of elasticity of concrete is not typically a design option in reinforced concrete structures. While it is important for the structural engineer to know or estimate the modulus of elasticity, it is not used to optimize the design of most highway structures. However, there may be particular structural elements that need additional stiffness. The table below can assist an engineer in determining if modulus of elasticity can assist in optimizing the design.

<table>
<tr><td rowspan="4">ME
Modulus of Elasticity</td><td rowspan="4">Is there a structural need to specify stiffness?</td><td rowspan="3">Yes</td><td rowspan="3">Is there a particular benefit to a higher than normal stiffness?</td><td rowspan="2">Yes</td><td rowspan="2">Is high stiffness critical to the structural design?</td><td>Yes.
Specify within ME - Grade 3</td></tr>
<tr><td>No.
Specify within ME - Grade 2</td></tr>
<tr><td colspan="3">No. Specify within ME - Grade 1</td></tr>
<tr><td colspan="5">No. ME grade should not be specified.</td></tr>
</table>

	Test Method	HPC Grade 1	HPC Grade 2	HPC Grade 3
ME Modulus of Elasticity, Msi (GPa)	ASTM C 469	2.9≤X<4.3 (20≤X<30)	4.3≤X<6.5 (30≤X<45)	6.5≤X (45≤X)

Sample PENNDOT specification language for ME Grade 1 should read as follows:

SECTION 704.1 © Design Basis…….

The concrete mixture design shall have a 28 day modulus of elasticity greater than 2.9 x 10^6 psi and less than 4.3 x 10^6 psi, as determined by standard cylinder tests of moist cured samples at 73°F (23°C). The final mixture design approval will be based on a full batch trial mixture using the approved mixture design and the type of mixer and the mixing procedure detailed in the contractors quality control plan. The Bureau of Construction and Materials, Materials Testing Division may conduct a quality assurance test of the modulus of elasticity before the mixture will be approved and during the course of the contract.

2.5.11 Creep Coefficient

Creep coefficient is used in calculating long-term deflections and in calculating prestressed concrete losses. While it can be designed, it is typically calculated from a mixture design optimized for other characteristics. The w/cm ratio and the aggregate properties play the largest role in determining whether the creep coefficient. The table below may assist engineers in determining whether the specification of creep coefficient is necessary to optimize a design.

<table>
<tr><td rowspan="4">CC

Creep Coefficient</td><td rowspan="4">Is there a significant advantage to specifying creep coefficient in the design?</td><td rowspan="3">Yes</td><td rowspan="3">Is there an advantage in relieving large stresses or strains?</td><td rowspan="2">No</td><td rowspan="2">Is creep detrimental to the concrete element or surrounding elements?</td><td>Yes.
Specify CC - Grade 3</td></tr>
<tr><td>No.
Specify CC - Grade 2</td></tr>
<tr><td colspan="3">Yes. Specify CC - Grade 1</td></tr>
<tr><td colspan="5">No. CC grade should not be specified.</td></tr>
</table>

	Test Method	HPC Grade 1	HPC Grade 2	HPC Grade 3
CC Creep Coefficient strain/strain	ASTM C 512*	2<X	2>X≥1.4	1.4>X

*Alternatively, creep coefficient can be estimated using ACI 209 or AASHTO LRFD Bridge Design Specifications

Sample PENNDOT specification language for CC Grade 1 should read as follows:

SECTION 704.1 © Design Basis…….

The concrete mixture design shall have a creep coefficient greater than 2.0, as determined by ASTM C512. The final mixture design approval will be based on a full batch trial mixture using the approved mixture design and the type of mixer and the mixing procedure detailed in the contractors quality control plan. The Bureau of Construction and Materials, Materials Testing Division may conduct a quality assurance test of the creep coefficient during the course of the contract.

2.5.12 Tensile Strength

The tensile strength of concrete is not typically a design feature of reinforced concrete structures. The reinforcing steel carries the tension, and this may require the concrete to exceed its tensile capacity in several areas to fully utilize the steel. However, in unreinforced concrete and prestressed concrete, the tensile strength is used in design.

<table>
<tr><td rowspan="4">TS
Tensile Strength</td><td rowspan="4">Does the design depend on concrete to carry tension?</td><td rowspan="3">Yes</td><td rowspan="3">Does the structural performance rely on tensile strength?</td><td rowspan="2">Yes</td><td rowspan="2">Is there a design need for TS > 6 MPa?</td><td>Yes.
Specify within TS-Grade 3</td></tr>
<tr><td>No.
Specify within TS-Grade 2</td></tr>
<tr><td colspan="3">No. Specify TS - Grade 1</td></tr>
<tr><td colspan="5">No. TS grade should not be specified.</td></tr>
</table>

	Test Method	Grade 1	Grade 2	Grade 3
TS Tensile strength psi (MPa)	ASTM C 496	580≤X (4≤X)	720≤X (5≤X)	870≤X (6≤X)

Sample PENNDOT specification language for TS Grade 1 should read as follows:

SECTION 704.1 © Design Basis…….

The concrete mixture design shall have a 28 day tensile strength greater than 580 psi, as determined by standard split cylinder tests of moist cured samples at 73°F (23°C). The final mixture design approval will be based on a full batch trial mixture using the approved mixture design and the type of mixer and the mixing procedure detailed in the contractors quality control plan. The Bureau of Construction and Materials, Materials Testing Division may conduct a quality assurance test of the tensile strength before the mixture will be approved and during the course of the contract.

CHAPTER 3. CONSTRUCTION PRACTICES

3.1. INTRODUCTION

Durable concrete is achieved by using quality constituents with optimized concrete mixture designs and carefully controlled construction practices—proportioning, batching, mixing, placing, consolidating and curing. The integration of these practices is the key to longer life structures. The contractor cannot use "standard practice" as the guide to building long life highway structures. A higher standard is required. The higher standard requires a well-trained workforce and a commitment to quality control.

3.2. QUALITY CONTROL AND QUALITY ASSURANCE

Quality control and quality assurance are essential to constructing long life concrete structures. Quality control (QC) provides the process and information to reliably produce, transport, place, consolidate, finish and cure concrete that meets the performance requirements of well-designed concrete. Quality assurance (QA) provides an independent evaluation of the performance of the contractor and the concrete materials. High performance concrete for most highway structures is meant to convey concrete designed for a long service life under specified exposure conditions or designed to meet special structural requirements. The performance life or special structural properties are highly dependent on exercising quality controlled sound construction practices.

Completion of long life structures, or specialized structural concrete elements, from conceptual stage through design, construction and maintenance over a lifetime of use requires communication among the several skilled personnel at different stages and phases of construction. Proper coordination among all the personnel involved in various components of the project is critical for the successful completion of the project. Constructing long life concrete structures involves the use of performance-based specifications and standards for both design and construction.

Planning for long life and/or structural applications is critical to the success of the project. Planning provides an overall view of all the activities and the steps necessary to carry them out. A basic construction planning scheme for performance-based concrete structures is as follows:

- Organizational structure defining lines of communication, time scheduling, quality control responsibility, contractual oversight and definition and assignment of duties

- Detailed quality control plan, including a corporate template for continuous quality improvement
- Training and certification of employees
- Inspection and maintenance of equipment
- Approval of plant and employee certifications by the Transportation Agency
- Design meeting on the agency's performance requirements for concrete
- Material selection and approval
- Reinforcement planning, design, fabrication, and procurement
- Concrete mixture proportioning, laboratory mixture designs, and performance testing
- Full-scale truck trials with QA testing
- Planned timeline for concrete delivery and fresh concrete testing
- Planned timeline for placement, consolidation, finishing and curing
- Planned targets and action items for QC testing

3.3 DESIGNING PERFORMANCE-BASED CONCRETE MIXTURES

Most new concrete mixture designs for transportation agencies begin with quality control records kept by the ready-mix concrete producer. The experience of the producer and the QC records provides a basis by which local materials and specific batch equipment combine to produce concrete throughout the year. The performance-based concrete mixture design should begin in the same manner. As a supplier produces more performance-based concrete mixtures, they will gain additional experience and quantitative data on the performance of the mixture designs. This experience and data will lead to the technical and economic optimization of the performance-based concrete.

The development of performance-based concrete mixture designs has some fundamental differences from past concrete mixture design practices. The first difference is that one property is no longer the driving force in the design (e.g., compressive strength). The mixture design must meet multiple criteria, and each is as important as the other. The tests that are conducted for mixture design approval are more technical than a compression test. This requires more technical knowledge by the ready-mix producer and contractor and more technical capability by testing laboratories. The second difference is that there are no longer prescriptive requirements for concrete. Since there are multiple means to meet the performance requirements, the producer is free to optimize the economics of cementitious materials, admixtures and aggregates.

Meeting any number of performance requirements simultaneously requires that the concrete mixture designer understands the options that are available to meet each performance requirement individually. Overlaying these options typically provides a path to selecting materials for the first trial batches. As with ACI 211 methods, the second (or third) trial batch serves to refine the deficient or marginal performance properties by changing single variables in the direction of improved performance. Initially, excess performance, i.e., higher performance than desired, should be expected with some performance characteristics as the designer brings all characteristics above their respective performance standard. As a producer gains more experience with the new materials combinations, additional fine tuning can take place as part of the continuous quality improvement program.

3.4 SITE PREPARATION

The placement area should be properly prepared and inspected prior to the arrival of concrete. Inspections should be completed to verify that reinforcing steel and formwork are in the proper location and condition. Reinforcing steel depth-check measurements should be completed to ensure that the reinforcing steel is in the proper location within a ½-inch tolerance. Holidays in epoxy-coated bars should be cleaned and repaired in accordance with AASHTO M284 provisions. Reinforcing steel should not be bent on-site unless specified by the engineer. Reinforcing steel should be tied together in a manner to avoid damage to the epoxy coating on the rebars and fully arrest slippage and movement during the concrete placement. All ice and debris should be removed from formwork and reinforcing steel. Underlying media should be damp but free of excess water.

3.5 CERTIFICATION OF READY-MIX CONCRETE PLANTS AND TRUCKS

Ready-mix concrete plants that are accepted for infrastructure concrete projects should be held to the standards of practice detailed in ACI 304, Guide for Measuring, Mixing, Placing and Transporting Concrete. The plants should be inspected annually by a Registered Professional Engineer, according to the certification requirements of the National Ready Mixed Concrete Association prior to the delivery of concrete. This inspection process covers multiple aspects of a ready-mixed plant, including material storage and handling equipment, batching equipment, central mixer, ticketing system, and the delivery fleet including truck mixers, agitators, and non-agitating units. Plant recertification should be completed annually at a minimum. In addition to the plants, the trucks delivering the concrete should be inspected to meet the standards of NRMCA and the Truck Mixer Manufacturers Bureau (TMMB). TMMB has issued a list of standards and specifications for delivery fleet units, including sizes, volume limitations, and standards for water tank and measuring devices, mixing and agitation speeds, and mix uniformity (TMMB, 2001). A thorough inspection and certification of the concrete plants and trucks supplying the project is a necessary measure for ensuring the quality of concrete construction. Concrete suppliers should be encouraged to include training of concrete plant standards in their quality control plans.

3.6 PRODUCING AND TRANSPORTING CONCRETE

Producing quality concrete for highway construction is not a passive process. It requires that the concrete plant operators monitor and adjust constituents on a continuous basis.

Concrete production starts with the quality control of materials. The plant operators must be confident of the material properties, cleanliness and gradation of the aggregates, the quality of the water and chemical admixtures and the consistency of the cementitious materials. The moisture content and absorption of the aggregates must be predictable and near constant. In-line moisture and temperature meters that can be read by the batch operator are essential tools in maintaining real-time knowledge of aggregate properties. Regular moisture content tests must be performed according to ASTM C127 and C128 at least every 2 hours during continuous casting. These data should be used to verify or calibrate the in-line meters. The cementitious materials (portland cement, fly ash, silica fume, and blast furnace slag) should be delivered with uniform properties throughout the year. They should be dry and cool. Temperature sensors in the cementitious discharge should be monitored by the batch operator. The quality and nature of the water is important in the production of quality concrete. Fresh, potable water with or without a component of recycled water can be used to produce excellent concrete. When recycled water is used, it should be tested regularly for uniformity and pH. Chemical admixtures are used in most concrete. The admixtures should be stored and metered according to the manufacturer's recommendations. The metering devices should be certified and accurate.

Batching is the process of measuring and introducing the ingredients for a batch of concrete into a mixer in a specific sequence. To produce concrete of uniform quality, the constituents must be measured accurately and reliably for each batch. The important issues that must be addressed to ensure conformance to the selected mixture proportions are as follows:

- Batching of solid ingredients must be done by mass rather than by volume. Scales must be accurate and reliable. Either weight or volume can be used to batch liquid ingredients; however, the method must be consistent.
- The temperature of batching materials should be carefully monitored. Cementitious materials should be kept below 120˚F (49˚C). Aggregates should be cooled in the summer and prevented from freezing in the winter. The temperature of fresh concrete should be kept between 50˚F and 75˚F (10 ^{o}C and 24 ^{o}C) throughout the year.
- Each constituent of the concrete is required to be batched within specific tolerance limit as specified in ASTM C94. For standard batches these tolerances are as follows:

- Cementitious materials	+/- 1 percent of the specified mass
- Water	+/- 1 percent of the specified quantity
- Aggregates	+/- 2 percent of the specified mass
- Admixtures	+/- 3 percent of the specified quantity

- Moisture content of the aggregates being batched must be determined accurately and monitored in real-time. Appropriate adjustment in the total batch water content is critical to ensure the specified w/cm. Water used to wash the mixer between the loads must be completely discharged prior to loading the next batch. If used, ice as partial replacement for water to decrease concrete temperatures must be included in the w/cm.
- Appropriate facilities for storage and handling should be provided to maintain the properties of each of the concrete constituents.
- All batching devices should be checked for accuracy and function on a regular basis, according to NRMCA guidelines and ACI 304.
- All devices should be regularly calibrated and inspected to ensure proper discharge of the constituents into the mixer.

Materials must be thoroughly mixed to achieve uniform dispersion of the individual constituents into a homogeneous mixture. Inadequate mixing may result in decreased concrete performance and batch-to-batch variability. Over-mixing, however, does not improve the concrete quality. Important factors to ensure the performance of the mixing operation are as follows:

- Constituents must be loaded into the mixer in a consistent and appropriate sequence, and proper blending must be assured. Improper sequencing will cause "cement balling" and non-uniform concrete.

- Deposition of the hardened concrete or excessive wear on mixer blades reduces mixing efficiency. Worn blades must be replaced, and hardened concrete should be removed regularly.
- Mixers should not be loaded above the rated capacity and should be operated at approximately the speed for which they were designed. Mixers should be loaded to a sufficient level to promote batch uniformity.
- The nature of the constituent materials also influences the mixing operation. Concretes made with angular aggregate need longer mixing than those made with rounded gravels. Lean mixtures or those with specialized ingredients require longer mixing times.
- Trial batches using job materials and mixing procedures should be used to assess efficiency and batch-to-batch variations.

Concrete should be transported from the plant to the site of placement without adversely affecting the water content, w/cm, workability, air void system, homogeneity and temperature of the concrete. The change in slump and air content during transportation should be consistent from truck to truck. Concrete should typically lose no more than 2 inches of slump or 2% air during transport. Excess loss of air or slump is an indication of quality control problems or incorrect use of admixtures.

Various types of equipment can be used for transportation depending on the distance to be traveled and the ambient conditions. Longer distances require the use of equipment capable of agitating the concrete in the field. In hot climates, the use of white or light- colored drums can prevent excessive rise in concrete temperature.

3.7 PLACING AND CONSOLIDATING

Construction practices significantly influence the performance of hardened concrete. Each operation must be performed in a timely manner with appropriate procedures to ensure a quality product.

Efficient placement can enhance the long-term performance of concrete. Concrete should be placed without significant delay. As a rule, concrete should not be accepted if it has been in a truck for more than 90 minutes. In addition, concrete should be tested promptly when a truck arrives on site. Concrete trucks should not “rest” on site in hopes they will come into compliance with specifications. If the concrete does not meet specifications, then additional revolutions may be added up to the maximum allowed, and it should be retested promptly.

The following are the primary factors considered during placement of the concrete:

- Workability is the field measurement of the concrete's flow characteristics. While slump is used to measure workability, it is only a quality control tool to verify the mixture design. Slump addresses the ease at which concrete begins to move; it indicates very little about its flow once it starts moving. High slump concrete can flow poorly, and low slump concrete can flow well. While high slump concrete can be produced for ease of placement, it can lead to subsidence in reinforced concrete sections. A slump of 3-6 inches at the point of placement is the most desirable range for long-life concrete bridge decks. Massive structures and areas of high reinforcement congestion may require higher slumps. High slump concrete should be specially designed and handled by specially trained and experienced placing and finishing crews.
- Entrained air is designed into concrete mixtures to abate freeze-thaw problems for the life of the structure. Most concrete for highway applications in freeze-thaw climates must contain approximately 6 percent total air by volume. Of this air, 4-4.5 percent is typically entrained air bubbles, i.e., less than 0.04 inches in diameter with an average spacing of less than 0.008 inches. Larger entrapped air bubbles comprise about 1.5 percent of the measured air content. Some admixtures entrap air, increasing the measured air content. This should be accounted for in the design of the concrete mixture. Concrete placement crews should not place concrete that has highly variable or low air contents. The entrained air aides in the workability and finishing process, making it easier to move and finish to the desired texture. Normal vibration, screeding and finishing practices do not reduce the entrained air content in any way. The loss of entrapped air during these processes is part of the normal consolidation process and is beneficial to concrete.
- Segregation is a common problem encountered during placement. Some of the key construction procedures to prevent segregation are as follows:
  - Free fall of concrete of more than 4 feet can cause segregation and should be avoided; drop chutes should be used for vertical placements.
  - Concrete should be placed as close as possible to its final position to avoid any horizontal movement.
  - Concrete should not be deposited in separate piles and then leveled or worked.
- Concrete pumping procedures may affect air-void structure. Pumped concrete mixtures should be proportioned for the specific pump equipment. Pumping can reduce the total air and affect the air void system. Samples from the pumping line at point of placement should be tested for mixture qualification and quality control.
- To avoid cold joints, the rate of placement of subsequent layers should be rapid enough to ensure that the concrete has not yet set when the new layer is placed. Alternatively, modifications to the mixture design can be considered.
- Concrete should be placed horizontally in layers of uniform thickness to allow proper consolidation.

Concrete should be consolidated into the corners of the forms and around the reinforcing bars. Removal of entrapped air-voids is a benefit of consolidation. Adequate consolidation is essential for the durability of concrete. Concrete that has not been consolidated properly will have excessive entrapped air voids. Inadequate consolidation also causes honeycombs and rock pockets. Over-consolidation of concrete brings the excess paste to the surface, enhances bleeding and causes loss of entrained air. The lower the workability of the concrete, the more difficult it is to consolidate and finish it.

3.8 FINISHING

The objective of finishing is to produce a dense, compacted, well-graded surface with minimum manipulations. Insufficient finishing will leave a surface open to deterioration and rapid ingress of water and salts. Finishing operations should include the following:

- Vibrating screed after the initial placement and vibratory compaction. This levels the surface to the desired profile and provides some additional compaction to the surface.
- For bridge deck placements, a bridge-deck finishing machine should be used to prepare the surface for texturing (if any) and curing. The screed should be set in a manner so that minimal bullfloating or further finishing will be required to prepare the surface.
- Bull float the surface in one or two passes. This operation evens out the surface, implants coarse aggregate, and removes bugholes and surface defects. Care should be taken not to overwork the surface.
- Wood or magnesium floats may be used to even out areas that are not accessible by the screed or bull float. Magnesium floats should be used for concrete with entrained air.
- The surface should be tined or broom textured as desired before initial set. Since low w/cm concrete may have little or no bleed water, this operation may immediately follow the bull float operation to expedite the curing measures. However, in high slump concrete, tining or texturing must be delayed until the surface is sufficiently stiff to hold the texture firmly.

Overworking of the surface will weaken the concrete surface through several factors:

- Increased paste content at the surface causes greater shrinkage in the concrete at the surface, making it more susceptible to cracking. The excess surface paste also reduces the abrasion resistance of the concrete.
- Overworking may result in the loss of air content in the surface concrete, which significantly reduces the freeze-thaw and scaling resistance of the surface concrete.
- Trowel finishing in the presence of water on the surface causes an increase in w/cm in the surface concrete, reducing its strength and durability. Water should never be added to the surface.
- Steel trowels should be not be used for compacting or initial finishing prior to the emergence of bleed water that may seal the surface, thereby increasing the w/cm at the surface.

Saw cutting is the last of the finishing operations and should be carried out after the concrete has gained sufficient strength. The saw cut are contraction joints, designed to accommodate shrinkage and thermal movements of the bridge deck.

3.9 CURING

Curing is the maintenance of satisfactory moisture and temperature in conditions during a defined period immediately following finishing, assuring development of the desired properties. The long-term performance of concrete significantly depends on the initial development of the concrete properties.

The term moist curing refers to concrete that has 95-100 percent relative humidity surrounding the concrete. This includes the edges, corners and exposed surfaces. Failure to provide moist curing to the entire concrete placement may result in the following:

- Cracks from moisture or temperature differentials
- Shrinkage cracks
- Self-desiccation of the paste structure
- Increased permeability of the concrete
- Reduced long-term strength and stiffness

Curing requirements are primarily influenced by the climatic conditions, cross-section of the element, structural application and concrete mixture characteristics (w/cm, cement type, application of pozzolans and GGBFS, etc.).

- Hot and arid weather increases the evaporation rate and therefore hastens the evaporation of water from concrete. Figure 3.1 provides an estimation of the evaporation rate on concrete in ambient environments. The curing measures should limit the evaporation to less than 0.1 $lbs/ft^2/hr$.
- Relatively thin sections have large surface areas compared to their volumes. This accelerates the loss of water from the concrete and enhances the need for moist curing.
- Timely implementation of curing is critical for structural concrete with w/cm less than 0.50 to keep the paste saturated during the hydration of cementitious material.
- Finer cements, due to large surface area, have higher initial heat of hydration and therefore have higher rate of moisture loss through evaporation.
- Concrete with pozzolan as partial replacement of portland cement typically exhibit less bleeding and are sensitive to early age moisture loss. Early age moisture loss is a major contributing factor in plastic shrinkage.

Desired performance of high-performance concretes is influenced by the timely and appropriate moist curing. Several construction measures must be controlled throughout the concrete placement:

- The key to timely curing is minimizing the time gap between the placing and finishing and application of the curing. In most situations, this requires fogging measures throughout the placing and finishing operations.
- Duration of continuous moist cure is important. Provide wet burlap or equivalent curing for 10-14 days, and ensure continuous wetting of the burlap for the entire curing period followed by the application of curing compound. Saturated cotton mats with plastic covers or continuous soaker hoses that ensure the saturation of burlap covered with plastic are equally effective.
- For short-term curing applications, the application of curing compounds should be used only after initial set of the concrete. The concrete must be fog-cured until initial set is reached. Two light coats of pigmented approved curing compounds should be applied in perpendicular directions. This is also recommended after the removal of wet curing measures.

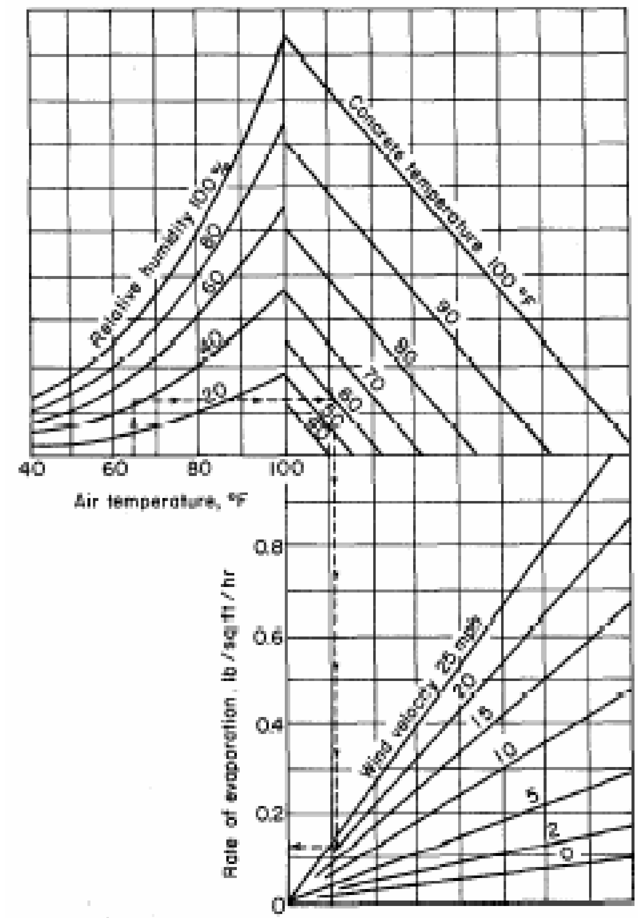

Figure 3.1 Evaporation rate of surface water (Menzel, PCA, 1954)

CHAPTER 4. ENGINEERING LONG-LIFE CONCRETE HIGHWAY STRUCTURES

4.1 INTRODUCTION

Highway structures can be designed and constructed for long lives. From an engineering level, it requires that structural and materials engineers within the transportation agency and its consultant consider durability on an equal basis with strength considerations. During the construction process, the requirements are a higher quality standard than for conventional commercial building construction, trained supervision and certified personnel executing the production, testing, placement, finishing and curing of concrete. This includes diligent inspection and an appropriate reward/penalty system that encourages continuous quality improvement. This chapter briefly summarizes some of the most important aspects of building long-life highway structures.

4.2. DURABLE BRIDGE DECKS

The use of performance-based criteria enables the designer to address each characteristic influencing the desired performance. For long-life bridge decks, low permeability, moderate shrinkage, minimal or no cracking, normal compressive strength and possibly other site-specific characteristics are typically desired. There are several key factors in the construction process that contribute to the longevity of bridge decks.

- Optimization of concrete mixture designs for the appropriate performance grade of each of these variables is one of the keys to achieving durable and economic concrete. Bridge decks in northern climates should be designed for a high level of performance for freeze-thaw durability, scaling resistance and chloride penetration. Bridge decks require a moderate level of performance for shrinkage, alkali-silica reactivity and abrasion resistance, dependent on project specific conditions (reactive aggregates, studded tires, etc.).
- The structural design should specify compressive strength and shear restraint between the girder and decks that is suitable for the load requirements. Excessive compressive strength or shear restraint added by the designer or contractor is not desirable.
- Rebar design details can contribute to the cracking and the size of cracks in bridge decks. A maximum size of #5 reinforcing steel (#4 if possible) should be used in the top mat of bridge decks, and the top and bottom transverse steel, as well as splice details, should be offset to avoid planes of weakness. Longitudinal steel should be specified as the outermost layer of steel on top of the bridge deck.
- The sequence by which the deck of a continuous bridge is cast has a profound impact on the early age cracking of a bridge deck. The sequence should be considered carefully to avoid generating tensile stresses in concrete at early ages. Even small tensile stresses from construction operations may crack the bridge deck prematurely, effectively reducing its life. The following are suggested guidelines for bridge specifications:
    - The complete deck should be placed at one time whenever possible.

  - If the bridge consists of multiple simple spans, each span should be placed in one placement.
  - Simply supported spans that cannot be placed in one deck placement should be longitudinally divided and placed in two deck placements.
  - In simply supported bridges, when single placements cannot be made over the full span, place the center of the span first.
  - For continuous span bridges, positive moment regions should be placed first and in consecutive order from one end of the bridge to the other. A minimum 72-hour delay should be observed before negative moment region placements.
- Wet curing of bridge decks should be specified for up to 14 days, when practical. The wet curing acts to optimize the tensile strength development, reduce the thermal gradients and reduce the permeability of the concrete.

A typical bridge deck in Pennsylvania will be subjected to the following environmental exposures:

- 10-40 annual freeze-thaw cycles
- 3-6 tons of deicing salt/lane mile/year
- 90-100 °F ambient temperature changes
- moderately reactive aggregates
- wet and dry cycles throughout the year

The engineer is required to consider local environmental conditions when designing bridges. The local conditions could be more or less severe than the typical conditions. The engineer must also consider the effects of structural details and construction stresses on the life of each bridge. In designing and approving details of a particular bridge, the question should be asked and answered as to whether the detail will increase the potential of cracking in the bridge deck. A bridge deck and any reinforced concrete element should be expected to crack if it is not in flexural or direct compression. The frequency and size of the cracks is of greater importance in design and constructing long life structures. With the use of epoxy-coated reinforcing, the probability of a "holiday" in the epoxy coating or near the location of crack must be minimized. The reduced probability, i.e., longer life, comes from larger spacing between cracks and reducing the number of holidays in the epoxy coating.

4.3. HIGH STRENGTH BRIDGE GIRDERS

Concrete designed for high compressive strength, high early strength development, and high modulus of elasticity enables the design of longer spans for a given loading or less girders for a given span. The option of designing with long prestressed bridge girders provides the designer the benefits of fewer piers and wider clearances for the roads and waterways. For the contractor, larger spans may provide fewer environmental impacts, expedited schedules, additional transportation logistics, lower foundation costs and fewer connections.

Through material optimization and high levels of quality control, it is possible for many prestressed concrete plants to produce concrete that can obtain 9500 psi compressive strength in 18 hours and 11,000 psi compressive strength in 28 days. Prestress concrete plants use controlled steam curing at early ages to maximize early age hydration before release times while avoiding delayed ettringite formation and thermal distress. The high-strength prestressed girders are highly durable, provided appropriate cover is maintained and they are not damaged during transport or placement.

4.4 SUBSTRUCTURES, CULVERTS AND FOUNDATIONS

Bridge substructures, culverts and foundations are some of the most variable environments in the highway infrastructure. The chemical characterization of the soil and groundwater is essential in defining the environment for the concrete elements. The engineer should pay special attention to the following items:

- groundwater table level
- presence of sulfate compounds
- pH of soil
- ground or surface water movement and speed
- drainage
- presence of potential wet/dry, tidal or saturated areas
- soil physical properties

Each of these presents a means by which the substructure, culvert or foundation could be compromised in its expected design life. Proper drainage in areas where concrete is in direct contact with soil is essential in minimizing the exposure. Areas subjected to scour and tidal movements should considered the most susceptible areas to distress.

4.5. REDUCED LIFE CYCLE COST

Concrete designed for the appropriate performance grade for each of the desired characteristics and implemented with the specified construction practices yields more economical concrete structures. This is especially true for durability characteristics. Concrete resistant to the aggressive environmental exposure conditions will last longer than standard concrete. The modest initial investment in HPC will reduce the repair, rehabilitation and replacement of bridges and consequently deliver a substantial reduction in the life cycle cost of bridges.

APPENDIX A: MATERIAL SPECIFICATIONS

Standard test methods recommended for the materials used for High-Performance Concrete are as follows:

Material	ASTM Specification
Cement	C 150, C 595, C 1157
Aggregate	C 29, C 33, C 127, C 128, C 131, C 136, C 289, C 1260
Water	C 94
Silica Fume	C 1240
Fly Ash	C 618
Ground Granulated Blast Furnace Slag (GGBFS)	C 989
Water Reducer Admixtures	C 494
Air-Entraining Admixture	C 260
Other Chemical Admixtures	C 494
Fresh Concrete	C 138, C 143, C 172, C 173, C 231, C 1064

APPENDIX B: HOT WEATHER CONCRETE

B.1 INTRODUCTION

Hot weather creates unique challenges in producing, transporting and placing concrete. Considering most highway bridges and pavements are constructed in the summer months, these challenges must be addressed by highway agencies and contractors. The issue in hot weather is not simply high ambient temperatures but, rather, high concrete temperature, low relative humidity, wind speed, evaporation rate, and solar radiation. The effects of hot weather on fresh concrete include a reduction in the life of the hardened concrete through losses in durability. The majority of the problems arise from the increased rate of hydration and the rapid evaporation of water from the freshly mixed or surface of the newly placed concrete. Additional strains may be associated with thermal differentials from solar radiation on the surface of the newly placed concrete.

The hydration of portland cement is a chemical reaction that transforms the portland cement powder into a complex series of calcium silicate hydrates, calcium aluminate sulfate hydrates and other similar compounds. Heat is an important component in these reactions. Each of these reactions generates heat, and each of these reactions is accelerated by heat. Under normal temperatures, the reactions produce a series of fine glassy structures that bind the aggregates together in a nearly impervious structure. However, at elevated temperatures, the reactions accelerate rapidly to form larger, less refined structures. These larger binding structures have larger voids between them, making the concrete more pervious to outside agents. Several other factors contribute to the heat of hydration, including fineness of cement, cement composition, percentage and types of pozzolans, curing conditions and the chemical admixtures used. In hot weather conditions, the control of several of these factors can offset the effect of elevated temperature to produce durable concrete.

The rapid evaporation of water from concrete during placing and finishing is a major cause of both workability problems and early-age cracking. The rapid evaporation of water from the surface of freshly placed concrete induces large plastic shrinkage cracks. The apparent wind speed, relative humidity and temperature at the exposed surface of the concrete control the evaporation of water.

B.2 FRESH CONCRETE PROBLEMS

The proportioning, mixing, transporting and placing of concrete in hot weather presents a series of problems for nearly all concrete producers and contractors. These problems are not difficult to solve but require a higher level of quality control, detailed measures to prevent to loss of water and a well-trained work force to execute the concrete placement and curing measures in a timely manner. From a craftsman’s standpoint, hot weather conditions produce a higher demand for water. The evaporation of water and the acceleration of the hydration reactions during the mixing, transportation and placement processes are the causes of the higher water demand. The resulting conditions lead to a loss of workability, increased rate of setting and variations in the entrained air content. Subsequently, field testing and retesting takes longer, and field personnel tend to add water to the concrete to regain the desired properties. The delays in placement exacerbate the slump loss and increase the possibility of cold joints. The combined effects lead to fresh concrete that is difficult to place, susceptible to plastic shrinkage cracks and cold joints, and may have marginal freeze-thaw resistance.

B.3 HARDENING CONCRETE PROBLEMS

After the concrete is placed, the effects of the addition of water and hot weather conditions decrease the desired properties of the concrete. The additional water increases the drying shrinkage, increases the permeability and reduces the compressive strength of the concrete. The increased drying shrinkage causes more frequent cracks that allow the ingress of moisture and salt solutions. The reduced permeability increases the rate of carbonation and the rate by which salt may diffuse through the concrete cover to the level of the reinforcing steel. The reduction in long-term strength affects both its structural performance and resistance to surface loadings. The combined effect on the hardened concrete is the probability of a diminished life expectancy and early replacement of the structure.

B.4 SOLVING THE PROBLEMS OF HOT WEATHER CONCRETING

Each of the identified problems of producing, transporting, placing, and finishing concrete in hot weather has a solution. The solutions are not particularly difficult to implement but require additional planning, quality control, training, manpower and coordination. The most successful approach of hot weather concreting is to mitigate the environmental effect through planning and preparation. The concrete materials, mixing process, transportation, testing, placing, finishing, protection and curing measures must all be considered in a coordinated manner to mitigate the generation of heat or loss of water.

Planning starts with a detailed section in the quality control plan on the procedures that must be followed when casting concrete in hot weather conditions. The quality control plan should cover the following items:

1. Preparation of aggregates. The aggregates for hot weather concrete should be stored in a cool, moist environment. This may require misting the stockpiles and protecting them from direct sunlight. Using large stockpiles that have been created in cool weather conditions will assist in keeping the aggregate cool. The aggregates should be stored in a near surface saturated dry condition (SSD). The moisture condition of the aggregates should be monitored in real time with in-line moisture sensors and tested according to standardized procedures every two hours. This information should be available to the batch operator.
2. Selection of cementitious materials (blended or portland cement, fly ash, silica fume, slag). The cementitious materials have multiple effects on both the early age and the long-term durability properties of concrete. The quantity, fineness, alkali content, chemical composition, temperature at delivery, and consistency all play a significant role in the properties of the concrete. Portland cements, blended cements and supplementary cementitious materials react at different rates when subjected to different temperatures and material combinations. The slowest setting cement in the summer months may be the fastest in the winter months. Experienced contractors and concrete producers must develop detailed quality control records to predict the behavior of concrete mixtures at

early ages. Adding a greater mass of cementitious material is rarely the desired solution in hot weather conditions.

3. Means of controlling temperatures of cementitious materials and aggregates. The delivery of hot portland cement can be a significant contributing factor to the overall concrete temperature. The delivery of cements in excess of 150ºF is not uncommon in the summer months, when demand for cement is high. Newly manufactured cement is often delivered shortly after the grinding process. Such cement still retains a portion of the heat from the kiln and has not had the time to dissipate the heat. For a typical highway concrete mixture, this translates into 5ºF rise in concrete temperature for every 40ºF the cement is above the desired temperature. The hot cement also reacts faster when put into contact with water, further accelerating the heat evolution of the concrete. The use of supplemental cementitious materials, such as fly ash or blast furnace slag, is an effective means of reducing the temperature of the concrete. Several factors contribute to this effectiveness. Initially, the fly ash and blast furnace slag react at a slower rate, thereby not generating the heat of portland cement. Second, the use of supplementary cementitious materials reduces the amount of portland cement used in the mix, thereby reducing the effect of cement delivered at elevated temperatures and the effect of cement hydration on heat generation.
4. Evaluation of need for ice. When the temperature of the concrete cannot be controlled by the aggregates and cementitious materials, the temperature control of the water can be used to lower the temperature of the concrete. Controlling the water temperature is one of the easiest methods of controlling temperature, but has a relatively high expense. Lowering the temperature of the mixing water by 40ºF will generally reduce the temperature of the concrete by 10ºF. While this is effective in controlling concrete temperature in moderate conditions, it may not be sufficient in hot weather. In contrast, if half the water is introduced as ice (no cooling of other water) the reduction in concrete temperature would be more than 20ºF. The ice should be finely crushed, shaved or chipped and limited to 75 percent of the total mixing water.
5. Batching sequence and times. Batch sequence is often a function of the specifics of the plant and the admixtures used in the concrete mixture. However, the best effects of mixing are usually obtained by ribboning the cementitious and aggregate materials simultaneously in central mixing plants and avoiding the packing of cement and sand at the head of the drum in truck mixing plants. This can be done by adding a portion of the coarse aggregate first and/or following the procedures detailed in ACI 304. In no case should the cementitious materials be preblended with the only the sand or water.
6. Environmental control (erection of windbreaks, fogging devices, solar protection, etc). The control of the curing environment during the construction process is critical to maintaining the long-term quality of the concrete. The curing becomes increasingly important as the concrete temperature rises. For hot weather conditions, the ambient temperature, humidity and wind speed must be monitored to define the adequate curing conditions. The concrete temperature and the relative humidity have strong influences on the evaporation rate, and the concrete temperature and the ambient temperature have the strongest influences on the rate of hydration. When the ambient temperature is above 80ºF and the relative humidity is below 50 percent, the concrete temperature should be maintained at least 5ºF less than the high ambient temperature at time of placement, with

limitations of 10 mph on wind speed. Additional guidance for concrete temperatures and hot weather control can be calculated from the evaporation chart in ACI 305R.

7. Preparation of forms and subgrade. The forms, subgrade, reinforcing steel, and inserts should be dampened immediately before concrete placement. Metal forms, subgrade aggregates and reinforcing should be shaded or cooled before casting to reduce the temperature of the exposed metal. This can be accomplished by using a fogger to raise the humidity, thereby creating a cooling effect from the evaporation of the fogged moisture.
8. Transportation time and rate of delivery. Normal practice allows 90 minutes to mix, transport and place concrete. If the concrete producer uses cooled aggregates or ice to reduce the temperature of the concrete to 75ºF, this 90 minutes remains a good estimate of the working time. However, if the concrete temperature rises above 80ºF, a reduction in time should be imposed.
9. Monitoring of temperature, time and QC test results. The monitoring of the environmental parameters during the cast is essential to ensure that proper measures are taken to avoid early-age problems. The field temperatures and relative humidity should be monitored approximately 5 feet higher than the concrete surface on the windward side shielded from the sun. The wind speed should be monitored at a height of 20 inches above the concrete surface.
10. Placement crew training and experience. During hot weather conditions, the efficiency of the crew is essential in avoiding problems. The contractor's supervisory personnel and at least half of the crew should be experienced in the standard practices of hot weather concrete. The experienced personnel should have completed organized training on concrete placement, such as ACI-or PENNDOT-approved training.
11. Placement equipment preparation and maintenance. Mechanical breakdowns in hot weather are especially detrimental to the quality of the concrete. Equipment should be well maintained and checked immediately before starting the cast. Spare equipment should be available, and preparations should be in place to stop casting at any time.
12. Protection after placement. The loss of surface water must be reduced to avoid plastic shrinkage and to mitigate the problems of early-age hot weather problems. Evaporation rates exceeding 0.15 lb/ft^2/hr greatly increase the probability of forming plastic shrinkage cracks or early-age strains associated with plastic shrinkage. The concrete must be protected from the loss of surface moisture through the use of wind breaks, fogging devices and well- organized, efficient placement of the concrete. In highway concrete, where the w/cm is typically below 0.45 for durability reasons, this becomes critical. There is only a small amount of water available for evaporation, and the bleed may be very limited. Many high-performance concretes do not bleed. The combinations of these factors dry the surface rapidly unless measures are taken to protect the surface from the loss of moisture.
13. Finishing requirements and logistics. The finishing requirements of concrete should be carefully considered. If the concrete is placed by a Bidwell or paving machine, then minimal finishing should be required. A few passes of a bullfloat with a magnesium head may be needed to remove small surface void and implant aggregate particles. Additional finishing delays the required curing measures and potentially "closes" the surface. This will weaken the top layer of the concrete and encourage plastic shrinkage.

14. Protection after finishing. Immediately after finishing, curing measures should be placed on the concrete. The time between the completion of the placement operations and the curing measures should be minimized in hot weather (10-15 minutes). This requires minimal finishing operations and preparation by the field crew. If winds are high, a wind break should be erected to prevent the freshly placed concrete from loss of surface moisture.
15. Curing measures. Wet burlap or thick cotton mats should be used to cure concrete in hot weather. Light-colored polyethylene sheets should be used to cover the placed burlap or cotton mats to prevent the loss of water. Overlapping seams of the burlap, cotton mats and polyethylene sheets should be staggered. The burlap must cover all edges and be kept wet at all times during the curing period. The recommended curing period is 14 days.
16. Maintenance of curing measures. The curing measures should be inspected every four hours during the daytime hours during the curing period, including weekends. Soaking hoses or water should be provided 24 hours a day to keep the burlap wet. In the case of thick cotton mats, the water content should be checked regularly and saturated to maintain 98% relative humidity at the surface of the concrete.
17. Evaluation of entire process after concrete is cured. Upon removal of the curing measure, a cracking survey should be conducted. Additional cracking surveys should be conducted at 30 and 60 days after the removal of the curing measures. The information from the evaluation should be integrated into the improvement of the quality control plan.