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DEPARTMENT OF TRANSPORTATION

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BEST ENGINEERING PRACTICES GUIDE FOR BRIDGE DECK DURABILITY

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

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PENNSTATE

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BEST ENGINEERING PRACTICES GUIDE FOR BRIDGE DECK DURABILITY

FINAL REPORT

Prepared for
Commonwealth of Pennsylvania
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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.

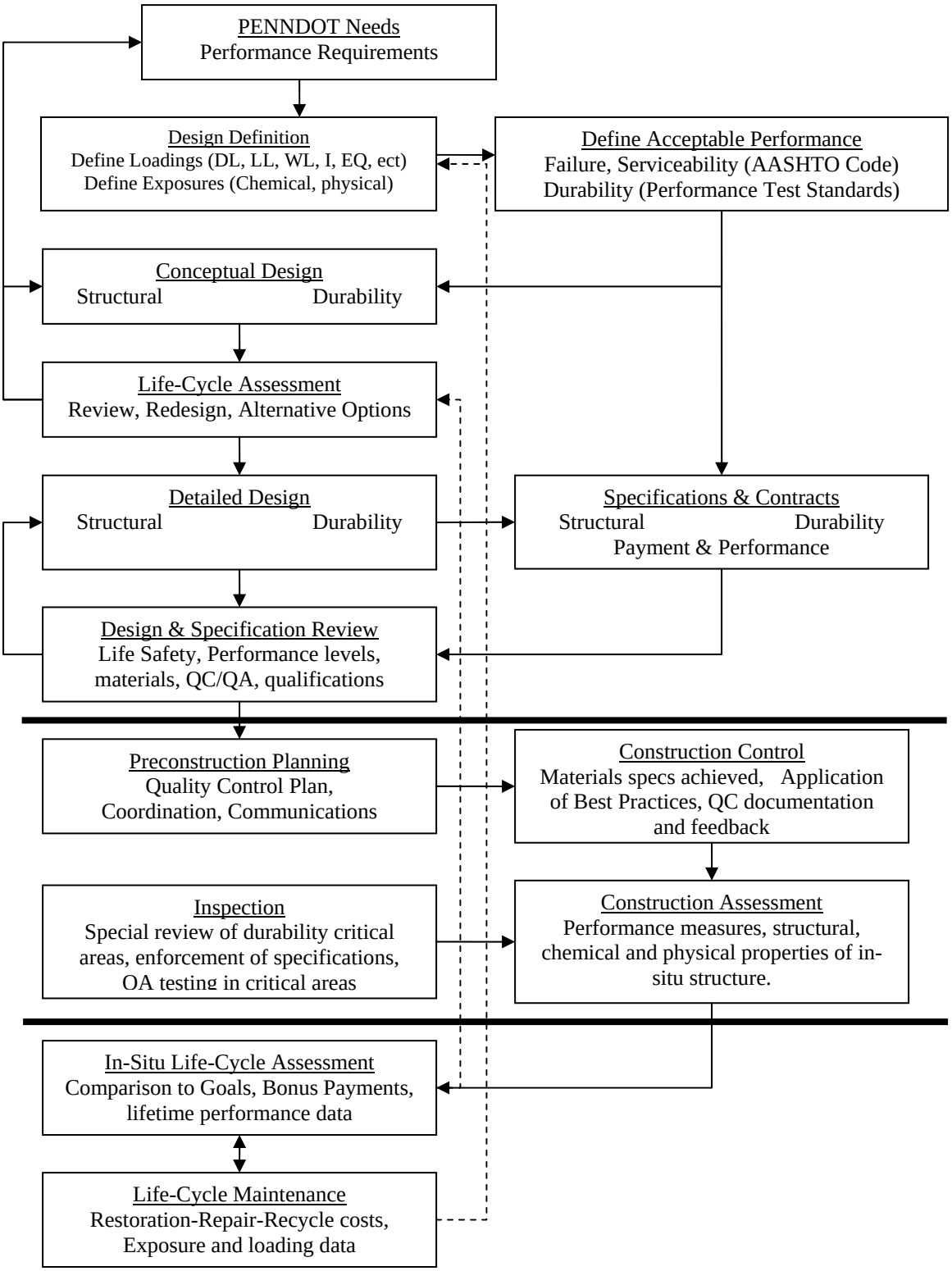

Figure 2.1. Conceptual path to life cycle design.

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="2">No. Specify within CS - Grade 1</td></tr>
<tr><td colspan="4">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<12.0 @ 28 days (55≤X82)	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}' (28 days)= f_c' (28 days)+1.34σ (1)
>
> f_{cr}' (28 days)= 0.9f_c' (28 days)+2.33σ (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="2">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 $\frac{\text{28 day } f_c}{\text{7 day } f_c}$	AASHTO T 22	X≥1.1	X≥1.3	X≥1.5

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 1.1 or 1.5, respectively. Grade 1 is typically applicable to elements not directly exposed to chemical and physical exposures (prestressed beams and columns/slabs 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="2">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 56 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="2">Yes</td><td rowspan="2">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="2">No. Specify SH- Grade 1</td></tr>
<tr><td colspan="4">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≥X	500≥X	200≥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="2">No. Specify AS - Grade 1</td></tr>
<tr><td colspan="4">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="2">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="2">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≤2	X=1

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 2.0 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 1 for Grade 3. The Grade 3 is a 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="2">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="2">Yes</td><td rowspan="2">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="6">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="2">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="2">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="2">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. ENGINEERING LONG-LIFE CONCRETE HIGHWAY STRUCTURES

3.1 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.

3.2 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.

3.3 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 12,000 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.

3.4 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.

3.5 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.