Specifying high performance concrete for durable bridges

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The problem of deficient bridges in the U.S. can be mitigated by widespread use of high performance concrete (HPC) for new bridges. One of the main hurdles in achieving this objective is the absence of a guide specification for HPC. The Federal Highway Administration (FHWA), USA, encourages the use of HPC to improve the long-term performance of the nation's infrastructure at lower life-cycle costs. For its purposes, the FHWA uses 11 performance criteria to define high performance concrete, and it designates three levels of performance for each criterion, with Grade 3 being the most stringent. For FHWA projects, the specifier is expected to select the criteria necessary for a given element, and then select an appropriate performance grade. It is not necessary or desirable to specify the same performance grade for all characteristics.

The paper presents an overview of the Portland Cement Association's "Guide Specification for High Performance Concrete for Bridges"1 which provides mandatory language that the specifier can cut and paste into project specifications, as well as guidance on what characteristics should be specified in a given case, and what criterion is needed to ensure satisfactory performance. It includes commentary that tells how to obtain the desired performance for each characteristic. In cases where two performance criteria are in conflict, the commentary advises the user how to balance conflicting requirements.

Keywords: *Abrasion resistance, alkali-silica reactivity, chloride ion penetration, compressive strength, concrete mixture design, consistency, creep and shrinkage, freeze-thaw durability, guide specification, high performance concrete, modulus of elasticity, performance specification, service life, scaling resistance, sulphate resistance.*

Rising traffic volume in the United States is exacerbating a problem that has been brewing for decades. Congestion is becoming intolerable and the cost of traffic slowdown is increasing every year. Congestion slows America's clean air progress, increases greenhouse gas emissions, impedes the flow of products to market and keeps us away from our jobs and our families. The poor condition of the bridges contributes significantly to highway congestion; over a third of highway bridges are deficient. Moderate increases in funding over the past decade have barely kept pace with inflation and have not alleviated the problem.

High performance concrete bridges offer cost efficiencies, time savings, and twice the lifespan of conventionally built bridges. As traffic volume on U.S. highways continues to outweigh capacity, community leaders are persistently challenged to find solutions for preventing delays caused by roadway maintenance. Highway bridges are too often at the crux of the matter. Thirty six percent of highway bridges – a total of 173,000 bridges – are structurally deficient or functionally obsolete[2].

The inherent strengths of HPC allow for greater design efficiencies, shorter construction cycles, and lower life-cycle costs. And HPC is environmentally efficient; it's recyclable and it incorporates recovered industrial materials which include wastes and byproducts such as fly ash, slag cement, and silica fume. Widespread implementation of HPC for bridges can help solve the problem of deficient bridges in the U.S. One of the hurdles in making HPC a routine practice is the unavailability of a guide specification for HPC.

Service life versus design life

AASHTO's LRFD Bridge Design Specifications define service life as the period over which a bridge is expected to be in service. And, the design life is defined as the period over which the transient loads are expected not to exceed the nominal value. Though the specifications specify a design life of 75 years, they are silent on the target value for the service life.

Due to degradation, a bridge's ability to provide its intended function could be compromised. Major causes of degradation are high transient loads and severe environmental conditions. Proper structural design usually addresses the effects of transient loads through adequate member proportioning and design details.

Environmental conditions which cause degradation include carbonation, sulphate attack, alkali silica reaction, freeze-thaw cycles, and ingress of chlorides and other harmful fluids. Adverse environmental conditions, if not properly addressed, typically invade concrete's pore structure and initiate physical and/or chemical reactions with expansive by-products. The most damaging consequence of these reactions is depassivation and eventual corrosion of reinforcing steel causing scaling, spalling, and cracking of concrete. The end of the service life of the structure occurs when the accumulated damage in the bridge materials exceeds the tolerance limit. However, the service life is typically extended by performing periodic repairs to restore the serviceability of the structure.

Chlorides from deicing salts penetrate concrete by several transport mechanisms: ionic diffusion, capillary absorption, permeation, dispersion, and wick action. During the last several years computer models have been developed to predict the service life of a concrete bridge exposed to chlorides. Several service life prediction models assume diffusion to be the most dominant mode of transport for chloride ions. The time taken by chlorides to reach reinforcing steel and accumulate to a level exceeding the corrosion threshold is known as "Time to Initiation of Corrosion" (TIC). Typically, TIC is computed by modelling chloride ingress according to Fick's second law of diffusion. TIC depends on many factors; major among them are diffusivity of concrete, concrete cover, temperature, and the degree of exposure.

The propagation time – from initiation of corrosion to intolerable accumulation of damage – depends not only on the rate of the corrosion process, but also on the definition of "unacceptable damage" which is typically project specific. The corrosion rate is influenced by many factors such as the nature of reinforcing steel, properties of surrounding concrete, composition of concrete's pore solution, and environmental conditions.

Designing for a specific service life for concrete bridges exposed to chlorides typically involves specifying minimum cover and maximum permeability for concrete. There are several models available for predicting the service life of concrete structures[3]. This technique was used for designing bridges for 75 to 100 years service life, for example, Confederation Bridge, Prince Edward Island, Canada designed for 100 years[4], Wacker Drive Reconstruction Project, Chicago designed for 75 years service life[5], and Cooper River Bridge, Charleston, South Carolina designed for 100 years service life6. Depending on the span, loading, and exposure conditions other properties of concrete such as creep and shrinkage, resistance to abrasion, freeze-thaw, and scaling, also play an important role in extending the service life of bridges with minimal maintenance.

The Federal Highway Administration (FHWA) encourages the use of high performance concrete to improve the long-term performance of the nation's infrastructure at lower life-cycle costs. FHWA defines high performance concrete on the basis of 11 performance criteria, with three levels of performance laid out for each for each criterion. For FHWA projects, the specifier is expected to select the criteria necessary for each element of the structure, and then select an appropriate performance grade. Specifying engineers may be tempted to require the highest performance grade for every criterion in the hope of obtaining the best possible result. This practice can lead to problems by:

1. incurring excess cost to achieve non-essential performance, and

2. possibly establishing mutually exclusive criteria that make full compliance impossible.

FHWA encourages the use of high performance concrete to improve the long-term performance of the nation's infrastructure at lower life-cycle costs

Another common problem is to depend on compressive strength as a measure for all performance criteria. This may also be problematic in cases where potential durability and compressive strength are not controlled by the same factors.

To assist specifiers in selecting what is important in HPC for bridges, the authors have worked to develop a "Guide Specification for High Performance Concrete for Bridge Elements. This document provides mandatory language that the specifier can cut and paste into project specifications. It also includes guidance on what characteristics should be specified in a given case, and what performance limit is needed to ensure satisfactory performance for a given element or environment. In cases where two performance criteria are in conflict, the commentary advises the user how to balance these conflicting requirements. Using the guide, specifiers should be able to select all of the criteria necessary for their structures, and then, using the commentary, apply appropriate performance limits for each element.

The Guide Specification was published by the Portland Cement Association (PCA) in 2005.

Overview of HPC guide specification

The following overview of PCA's guide specification for HPC for bridges was published in American Concrete Institute's (ACI) publication SP228 and is copyrighted by ACI7.

The Guide Specification is set up in two parts. Part 1 is a model specification, in mandatory language that sets out requirements for each parameter that may be considered important for the structure in question. The specifier can then cut and paste the needed clauses into the specification. Where numerical limits are required in the specification, they are left blank so that the specifier can choose values appropriate for the project.

Part 2, the associated commentary, is laid out using the same numbering system, and guides the specifier in selecting the clauses that are relevant to a particular project, and the limits that are appropriate under particular circumstances. The limits are generally based on the three classes FHWA uses in its definitions of high performance concrete. The commentary also provides guidance on when a requirement should be omitted.

It would not be advisable to specify extremely low permeability for concrete in a massive element that is not exposed to an aggressive environment

Specifiers are often tempted to select the highest grade for every parameter with the intention of achieving "high performance concrete." This practice is undesirable and, in some cases, produces mutually incompatible requirements. It also leads to excessive costs as suppliers attempt to meet unnecessary criteria. The commentary helps to prevent this practice by providing guidance on the criteria needed for a given element in a given environment.

For instance, low permeability is normally achieved by using high cement contents and low watercement ratios. This, however, increases shrinkage and heat of hydration and thus increases the risk of thermal cracking. It would therefore not be advisable to specify extremely low permeability for concrete in a massive element that is not exposed to an aggressive environment.

Similarly, requiring high resistance to freezing and thawing in a structure built in a temperate environment will add unnecessary cost. Moreover, in this case the suppliers may be unused to working with air-entrained concrete, and so may compromise strength, uniformity, and surface finish as they seek to meet an unnecessary restriction.

Different requirements apply, not only between structures and climate zones, but also between elements within a single structure. A bridge deck in a northern location will require freeze-thaw resistance and low chloride penetration. The beams supporting that deck, however, are unlikely to be exposed to road salts, and compressive strength and creep may be the only parameters that need to be addressed. Likewise, the supporting columns are likely to be massive and will require attention to the heat of hydration and crack prevention.

Specifiers should therefore set out only those parameters that are necessary, using appropriate limits for the elements being specified. The commentary provides a wealth of information to help them do just that, including references to many existing specifications and standard methods, and to the relevant literature.

Using the guide specification

The first part of the Guide Specification provides mandatory language for each of a suite of parameters that may be needed in a given specification. Specifiers select the criteria necessary for their structures, and insert the appropriate clauses into their own specifications. The specifier will also have to select the appropriate limits for each criterion, for each element of the structure.

The Guide Specification provides clauses and guidance for the criteria discussed below.

Materials and concrete performance

The following are materials-related criteria that may need to be specified.

1. ***Abrasion resistance:*** Limits are required for bridge decks and perhaps for piers exposed to water-borne abrasion.

2. ***Chloride ion penetration:*** This criterion needs to be addressed for bridge decks and other structural elements exposed to deicing salts, and for all bridge elements exposed to seawater.

3. ***Compressive strength:*** Strength is the factor that engineers are most familiar with. Limits are necessary for structural requirements, including during construction phase. Strength should not be used as a control parameter for other criteria unless a correlation has been established for the mix in question.

4. ***Creep and modulus of elasticity:*** These criteria may be necessary for structural elements, particularly prestressed or slender elements.

5. ***Freeze-thaw durability:*** Limits are needed only for concrete exposed to freezing and thawing in saturated or near-saturated conditions. This would potentially exclude vertical elements protected from standing water.

6. ***Scaling resistance:*** Bridge decks, and possibly other elements, exposed to deicing salts require specifications that address their performance under a scaling environment.

7. ***Shrinkage:*** There is little correlation between the standard shrinkage test and structural movement. Limits imposed are largely used as an indicator of the risk of shrinkage-related cracking.

8. ***Sulphate resistance:*** This criterion need only be imposed for foundations and substructures in areas where sulphates are present in the soil or groundwater.

9. ***Consistency:*** The specifier can elect not to specify a consistency, but rather allow the contractor to elect a value appropriate to the construction practices used on the site. In that case, a limit on variability may be required.

10. ***Alkali-silica reactivity:*** Limits are needed in areas where aggregates are potentially reactive.

Submission

The Guide Specification covers submissions that should be considered as part of the pre-construction verification programme:

1. The contractor submits concrete mixture designs, along with verification that the concrete meets performance requirements, for the engineer's approval.

2. Production facility certification serves to assure the owner and engineer that the concrete delivered will consistently comply with the requirements of the specification.

3. Material sample retention recommendations allow the subsequent evaluation of actual materials used when incompatibilities or other problems occur. Forensic evaluations of similar but not representative materials can be inconclusive.

4. A temperature control plan is essential to minimise thermal cracking in massive structures. Concrete elements that require this attention include those that have a minimum dimension of 1.83 m (6 ft) or more.

6. A crack control plan is needed for elements where the risk of cracking is high, including those with a large surface-to-volume ratio (such as slabs on grade), and those where restraint is significant (such as long walls bonded to the foundation).

7. A curing plan is required to maximise performance and minimise cracking in high performance concrete.

Pre-qualification of mixes is essential. Trial batches of every potential material combination should be pre-qualified

Quality management

The Guide Specification addresses and defines quality management issues, assigning responsibility for quality control and quality assurance tasks and spelling out particular step to be taken at each stage of construction.

Production

The Guide Specification lists production-related issues that can be addressed to increase the likelihood of acceptable performance in the finished concrete. These criteria derive from problems commonly experienced in the past.

1. ***Equipment quality:*** This criterion can reduce the risk of non-uniform and unacceptable concrete produced using equipment that is poorly maintained or calibrated, unsuitable for the task, or unsuitably sized for the scope of the project.

2. ***Mixing procedures and timing:*** The order of batching and the amount of mixing time influence the concrete's workability, rate of slump loss, and air void system. It is important to identify a satisfactory system and use it consistently, particularly in HPC systems that contain high cementitious materials contents, combinations of chemical admixtures, and supplementary cementitious materials.

3. ***Temperature limits:*** Concrete's temperature strongly influences the rate of change in its fresh properties, while also affecting strength gain and the risk of deleterious chemical reactions. In extremes of ambient temperature, limiting the temperature of the concrete is necessary.

4. ***Trial batches:*** These can minimise risk of the surprises in the field. In ever more complex concrete systems, otherwise acceptable materials may interact in an unacceptable way, often resulting in problems with rate of stiffening and setting, or in the air void system. Preparing trial batches using the field materials at approximate field temperatures can help predict whether problems are likely to occur.

5. ***Site addition of water or chemicals:*** Later addition of water or chemicals (even within the limits of the original mix design) can drastically influence the concrete's final performance and possibly increase the risk of air void clustering. Specifications should limit the amount of materials that can be added to the mixture in the field.

6. ***Tickets and records:*** As part of the quality system, accurate data should be kept of what was used when, and where. When a problem is found with a given truck load,

it becomes important to know where that concrete was placed.

7. ***Measurement methods and tolerances:*** Disputes often result from a lack of clarity on what test methods should be used and how their data should be interpreted. These need to be laid out in the specification.

Examples

Following are examples that show how the concrete for two particular bridge elements –the deck and the pier – might be specified. These examples illustrate concrete performance criteria. They do not include the clauses that address constituent materials, such as the need to test aggregates for alkali reactivity. The kind and frequency of constituent material tests should be defined in the specification, usually as QA/QC activities. Some parameters, however, such as the aggregate's risk of alkali silica reaction, need only be determined at the mix qualification stage.

If the sources of materials change during the course of the contract, then the pre-qualification needs to be redone for the new mixture. Some materials specifications are so broad that changing a supplier for the same material can result in different properties. This is why trial batches of every potential materials combination should be pre-qualified.

The specification clauses below include test methods, specimen-handling details, and pass/fail limits for each test.

Bridge deck

A bridge deck exposed to deicing salts needs to resist chloride ion penetration in order to delay the onset of chloride-induced corrosion for as long as possible. Both freeze/thaw durability and scaling resistance also are necessary if the bridge is in a cold region. Depending on structural requirements, the deck may need to have some minimum strength at the age when the bridge is opened to traffic; however, too high a strength or modulus requirement may increase the tendency of the deck to crack.

Cracking would be detrimental to durability, particularly in an environment conducive to corrosion. In such a case, the specifier might elect to include only the minimum strength requirement. The concrete specification would then be as follows:

1. ***Abrasion resistance:*** The coarse aggregate shall be tested according to AASHTO T 96 (ASTM C 131). The result shall not exceed 40 percent. For bridge decks or surface courses, aggregates known to polish shall not be used.

2. ***Chloride ion penetration:*** The concrete shall have a charge passed in six hours of 1500 coulombs or less when tested according to AASHTO T 277 at age 56 days. The specimens shall be moist-cured up to the age of 7 days, after which they shall be stored at 23 ±2°C (73.4 ±3°F) and 50 ±4 percent RH until the time of test.

3. ***Compressive strength:*** The concrete shall have a compressive strength of at least 281 kg/cm^2 (4,000 lb/in^2) when tested according to AASHTO T 22 at age 28 days. The specimens shall be moist-cured to age 7 days, after which they shall be stored at 23 ±2°C (73.4 ±3°F) and 50 ± 4 percent RH until the time of test. Either 100 × 200 mm (4×8 in.) or 150 × 300 mm (6×12 in.) cylinders may be used.

4. ***Freeze/thaw durability:*** The concrete shall have a durability factor of 90 percent or greater when tested according to AASHTO T 161, Procedure A.

5. ***Scaling resistance:*** The concrete shall have a visual rating of 1 or less when tested in accordance with ASTM C 672, except that the concrete shall be moistcured to an age of 28 days, after which it shall be stored in air for 14 days at 23 ±2°C (73.4 ±3°F) and 50 ±4 percent RH, before being exposed to deicing chemicals. Note that ASTM C 672 normally uses a solution of 4 g anhydrous $CaCl_2$ per 100 mL solution as the deicing medium, but allows the use of other deicing chemicals. If the owner routinely uses a different deicing chemical, the specification should require that deicing chemical to be used in the test.

Bridge piers and foundations

For massive members such as bridge piers and foundations, the generation and slow dissipation of the heat of hydration may result in internal stresses sufficient to cause cracking. Crack control methods are discussed in the Guide Specification and commentary, but are not covered in this paper. Note, however, that high concrete strengths, particularly at early ages, are usually attained through the use of high cement contents, which generate significant heat of hydration at early ages, with consequently high thermal stresses. Thus cracking is difficult to avoid.

In general, high early strengths are not required for piers and foundations at early ages. Strength requirements should be kept as low as is structurally acceptable and as late as possible without interfering with the construction schedule. Piers and foundations may be subject to sulphate exposure, either from sulphate soils or from seawater, which is considered a moderate sulphate exposure. In that case, the maximum limit on the water-cementitious materials ratio or the minimum limit on compressive strength may govern the strength for design. When selecting cementitious materials, consider the need to provide sulphate resistance without generating excessive heat. Liberal use of slag cement or lowcalcium fly ash is recommended. These materials may be components of a blended cement or added separately at the mixer, or both. For a bridge pier or foundation subject to severe sulphate exposure due to sulphate soils, the specification might be as follows:

1. ***Compressive strength:*** The concrete shall have a compressive strength of at least 281 kg/cm^2 (4,000 lb/in^2) when tested according to AASHTO T 22 at the age of 56 days. The specimens shall be moist-cured to age 7 days, after which they shall be stored at 23 ±2°C (73.4 ±3°F) and 50 ±4 percent RH until the time of test. Either 100 × 200

mm (4×8 in.) or 150 × 300 mm (6×12 in.) cylinders may be used.

2. ***Crack control:*** The method(s) to be used to control cracking due to shrinkage or thermal stresses shall be submitted to the Engineer. Unless engineering analysis can demonstrate that it is not detrimental to the structure, the maximum temperature differential between the interior and exterior concrete shall be limited to 19°C (35°F).

3. ***Sulphate resistance:*** The combination of cementitious materials in the proportions proposed shall have sulphate resistance at least equivalent to that of a Type II cement, and the water-cementitious materials ratio shall not exceed 0.5.

Conclusion

The Guide Specification for High Performance Concrete for Bridge Elements will facilitate the design of long-lasting, durable concrete bridges by helping specifiers first to determine the appropriate performance criteria for each structural element, and then to write clear specifications to ensure the criteria are met.

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