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1. Introduction

Annually, billions of dollars are invested in repair, replacement and rehabilitation of concrete bridges across the United States. The average life of the approximately 28,000 bridges in Pennsylvania is 28 years. Resources are available to repair or replace about 270 bridges per year, resulting in a large number of newly deficient structures. High-Performance Concrete (HPC) bridge decks can increase design life and reduce life cycle costs, thereby enabling the more efficient use of transportation funds.

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

- Identification of the required structural design properties
- Identification of the potential contributing factors for concrete distress
- Definition of the severity of each contributing distress factor
- Specification of performance levels consistent with the defined structural requirements and distress factors
- Production, testing, and inspection of concrete to meet requirements

This document provides succinct descriptions of the factors affecting concrete performance, describing deterioration mechanisms and structural properties. In addition, guidelines for the production of high-performance concrete are included.
2. High-Performance Concrete Defined

High-performance concrete is concrete produced to meet multiple design criteria for a given set of engineering and exposure conditions. Merely specifying slump, water-cementitious materials ratio (w/cm), and 28-day compressive strength, is not adequate for most transportation applications. Specifications for concrete vary based on construction, structural, and durability requirements.

It is not necessary to design every concrete mixture to be resistant to all types of deterioration and optimized for all engineering properties. For example, bridge deck concrete requires resistance to freezing and thawing, corrosion and scaling, whereas prestressed concrete for bridge girders requires optimization for strength, release times and stiffness.

To improve the transportation infrastructure, engineers must systematically evaluate both the structural design requirements and exposure conditions that may lead to premature deterioration. The results of these evaluations must be used to specify the required concrete properties. The final and most important step in improving the transportation infrastructure is designing, producing and maintaining concrete of appropriate grade. This requires a commitment to quality control, inspection and contractual discounts and incentives for field performance.
3. Goals

The primary goal of the HPC Program is to produce bridges with a design life of 75 to 100 years. The benefits of HPC are specifically focused at economically extending the life of bridges so as to address the needs for a safe and reliable transportation system.

3.1. Engineering Guidelines and Design Aids

The Engineer will find that design aids can expedite the development of appropriate specifications. This is especially true for performance-based specifications. Appendix A is a decision tree design aid that will assist the engineer in determining characteristics that should be specified and the level of performance that is required for the desired result. The designer should be able to fill out a table of conditions for any design element of a structure. Table 1 is an example table of conditions for a structural element.

<table>
<thead>
<tr>
<th>Structural Designer</th>
<th>Materials Designer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element Type_______</td>
<td>Reactive Aggregate HR MR NR</td>
</tr>
<tr>
<td>Reinforced</td>
<td>Yes No</td>
</tr>
<tr>
<td>Exposed to freezing or thawing</td>
<td>Yes No</td>
</tr>
<tr>
<td>Exposed to salt or seawater</td>
<td>Yes No</td>
</tr>
<tr>
<td>Exposed to SO₄</td>
<td>Yes No</td>
</tr>
<tr>
<td>Saturated</td>
<td>Yes No</td>
</tr>
<tr>
<td>Tidal Zone</td>
<td>Yes No</td>
</tr>
<tr>
<td>$f'_c$ at 28 days</td>
<td>____________</td>
</tr>
</tbody>
</table>

3.2. Durable Bridge Decks

The use of performance-based criteria enables the designer to address each characteristic influencing the desired performance. For bridge decks, low permeability, moderate shrinkage, normal compressive strength and possibly other site-specific characteristics are typically desired. Optimization of concrete mixture designs for the appropriate performance grade of each of these variables is the key to achieving durable and economic concrete. Bridge decks in Pennsylvania 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 designer specifies compressive strength. Other performance criteria do not typically apply.

3.3. High Strength Bridge Girders

HPC 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 less environmental impacts, expedited schedules, additional transportation logistics, lower foundation costs and fewer connections.

3.4. Reduced Life Cycle Cost

HPC 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.
4. Objectives

Once the desired characteristics of the structural element are defined, the next task is to determine the standards that must be met to realize the goals. In order to produce HPC bridges the engineer must specify the appropriate performance grades for the desired concrete characteristics based on the anticipated environmental and loading conditions. The main properties of HPC are listed below and Appendix A. The optimization of these properties can be used to define a specific level of performance.

1. Compressive strength
2. Strength development
3. Tensile strength
4. Modulus of elasticity
5. Creep coefficient
6. Chloride penetration
7. Shrinkage
8. Alkali – silica reaction
9. Freeze – thaw durability
10. Scaling resistance
11. Abrasion resistance
12. Sulfate resistance
13. Other considerations
5. Performance Characteristics of High-Performance Concrete

High-performance concrete is optimized for the concrete characteristics associated with the anticipated exposure conditions and the desired structural properties. The primary characteristics that may be optimized for specific applications are described in this chapter. It is typical for two to four of the characteristics to be optimized beyond grade 1 for a given element. It is generally not recommended to specify more than 4 HPC characteristics beyond grade 1 for a single element.

5.1 Compressive Strength

Probably the most often specified concrete property, compressive strength has high importance in optimizing structural designs. Many concrete properties are empirically related to the compressive strength of the concrete, e.g. tensile strength, modulus of elasticity, and flexural strength. High compressive strength generally indicates higher values for these properties. High compressive strength alone does not necessarily enhance durability of the concrete. In fact, it may be detrimental for some applications.

High early strength concrete is defined as concrete that reaches 8,000 pounds per square inch (psi) within 24 hours. This is used in fast track construction, limited access applications and prestressed concrete. Very high early strength concrete reaches 8,000 psi within six hours and is listed in rapid repair applications and emergency support conditions.

Applications:

Among the most frequent applications for high strength concrete are bridge girders, piers, abutments, and foundations. Some benefits include:

- Long span girders
- Reduction in the number of piers
- Smaller cross-section of piers
- Low depth girders allowing more vertical clearance underneath
• Reduction in the number of girders
• Reduction of dead weight

Influencing Factors:

• W/cm- Compressive strength increases with decreasing w/cm.
• Cement- Strength gain varies with type and fineness of cement. Although concrete made with different types of cement can exhibit different strength characteristics, the order of increasing strength at early ages is generally type II, type I, type III. At later ages, the trend is typically reversed. Concrete made with finer cement usually exhibits higher strength at early ages and lower strengths at later ages, provided that moisture is available for continued hydration.
• Aggregate- Compressive strength varies with the mineralogy, size and shape of the aggregate. Smaller, angular aggregates with rough textures will generally yield a higher compressive strength potential.
• Pozzolans and ground granulated blast-furnace slag (GGBFS)- Pozzolans and GGBFS used as partial replacement for portland cement enhance long-term compressive strengths.
• Construction practices- An effective quality control plan is essential to assure appropriate mixing, placement, consolidation and finishing techniques. Inconsistent batch sequencing may result in strength variability.
• Curing- Proper curing measures must be employed to achieve full strength potential.
• Temperature- Low early age temperatures will result in higher long-term compressive strength. However, higher early age temperatures will generally increase the rate of strength gain.
• Air content- Higher air content will generally yield lower compressive strengths.
• Chemical Admixtures- Various chemical admixtures may have different affects on concrete strength. A list of some chemical admixtures and their usual affects on strength is provided:
  • Accelerators – Increased early age strength but decreased later age strength
• Retarders – Increased later age strength and either increased or decreased early age strength
• Water reducers – Increased strength as a result of decreased water demand and dispersion

5.2. Strength Development

The rate of strength development, as measured by the 28 to 7-day compressive strength ratio, influences the durability of the concrete by affecting the organization and porosity of the cementitious paste. Current specifications not only allow, but encourage the delivery of 28-day strength at early ages. Cement chemistry, fineness, and temperature influence the rate of cement hydration. Rapid hydration may increase autogenous shrinkage at early ages. Autogenous shrinkage strains and the higher porosity of rapidly hydrated cement combine to reduce the durability of concrete. Rapid hydration of cement will result in incompletely hydrated cement particles and microcracks, decreasing the efficiency and quality of the concrete.

Refined pore structure of the cementitious matrix has an important role in the durability of the concrete since many deterioration mechanisms are either initiated or exacerbated due to ingress of water, deicing salts and other harmful species from external sources. 28 to 7-day compressive strength ratio is a practical means of quantifying the rate of hydration.

Strength development rate is influenced by several parameters including proportioning, mixing, placing and curing. The primary factors affecting the strength development rate are as follows:

Influencing Factors:
• W/cm- Higher w/cm yields higher 28 to 7-day compressive strength ratios.
• Cement- Coarse cements and cements with high C₅S contents generate less heat during the early hydration process and gain strength over a longer period. Coarse cements generally exhibit reduced autogenous shrinkage.

• Pozzolans and GGBFS. Fly ash or GGBFS generate up to 80 percent less heat than type I portland cement. Concrete containing Class F fly ash exhibits relatively slow strength gain during the first four days however, 28-day strengths are nearly equal to type I portland cement concrete. GGBFS has similarly slow strength gain in cooler temperatures, but in hot temperatures the strength gain is greater than that of portland cement. Silica fume provides rapid strength gain in the first seven days. This is not typically detrimental provided the heat of hydration remains below that of normal portland cement.

• Admixtures- Certain chemical admixtures can affect strength development. The extent of these effects are ascertained through testing.

• Curing- Proper and adequate moist curing encourages heat dissipation and continued hydration. High curing temperatures accelerate the hydration process, decreasing the 28 to 7 day compressive strength ratio. This is especially apparent with temperatures increases greater than 30 °C above placement temperature.

5.3. Tensile Strength

Concrete tensile strength is generally estimated to be between 7 and 11 percent the compressive strength, and for this reason is generally neglected in the design of normal reinforced concrete. Tensile strength increases at a slower rate than compressive strength, and accepted values for tensile strength range from $3\sqrt{f'c}$ for prestressed concrete to $7.5\sqrt{f'c}$ for normal reinforced concrete. Adequate tensile strength is necessary for cracking resistance of concrete. As tensile strain capacity is developed, the potential for shrinkage cracking can be reduced.

Influencing Factors:
Factors influencing tensile strength of concrete are similar to those affecting the compressive strength. In general, a factor that increases concrete compressive strength will increase tensile strength as well.

5.4. Modulus of Elasticity

The modulus of elasticity, the elastic ratio between stress and strain, is a fundamental and important mechanical property of concrete. It is empirically related to compressive strength of concrete and fundamentally related to the modulus of the constituent aggregate. High modulus of elasticity is advantageous wherever reduced deflections are desired. In bridge construction, girders and columns may benefit from concrete with high modulus of elasticity. Higher modulus concrete however, is not always beneficial, as it exhibits higher cracking potential from environmental strain. This makes concrete with a high elastic modulus undesirable for bridge decks or concrete elements subject to high environmental strains.

Influencing Factors:

- W/cm- Concrete with lower w/cm generally has higher modulus of elasticity.
- Cement- Modulus varies with type and fineness of cement. The variations are similar to those described for compressive strength.
- Aggregate- Higher aggregate content (for normal-weight aggregates) and high modulus aggregate increase the modulus of concrete.
- Other factors- Pozzolans and GGBFS, curing, temperature, admixtures and air content affect modulus of elasticity in a manner similar to that of compressive strength.

5.5. Creep Coefficient

Creep is the time-dependant deformation of concrete under sustained load. This deformation can act to decrease internal strains, increase deflections, and/or relieve restrained stresses. Creep can be advantageous in some applications, such as where stress
relief is beneficial. However, a significant disadvantage lies in the magnification of elastic deformations in other applications. Creep in concrete is a direct result of the relocation of water molecules under stress, as well as other mechanisms. Creep can be divided into two categories. Basic creep occurs in the absence of drying. Drying creep occurs while the concrete element is drying.

The two most common quantifications of creep are specific creep and creep coefficient. Specific creep is defined as creep strain per unit stress. Creep coefficient refers to a ratio of creep strain to initial elastic strain at a given stress. This method may be preferable in that it accounts for the elastic properties of aggregate. In addition to physical tests, analytical models may be used to estimate creep coefficient. Creep coefficient is a highly variable property and is influenced by many factors.

**Influencing Factors:**

- **W/cm**: As w/cm increases, creep coefficient generally increases.
- **Aggregate**: As fine aggregate percentage increases, creep coefficient increases.
- **Air content**: As air content increases, creep coefficient increases.
- **Ambient conditions**: As relative humidity increases, creep coefficient decreases.
- **Volume-to-surface area ratio**: As the v/s of the member increases, creep coefficient decreases.
- **Loading conditions**: Creep coefficient is greater when loading occurs at an earlier age. In addition, creep coefficient increases with time under load.

**5.6. Chloride Penetration**

Concrete deterioration is usually caused by a combination of factors; however, permeability is a characteristic of concrete that influences almost all of the deterioration processes. Ingress of water, chloride ions and other harmful chemical elements from external sources adversely affect the performance of the concrete. In the past few decades, corrosion of rebar has become a challenging problem for the performance of reinforced concrete and prestressed concrete elements. Bridge decks are typically
reinforced and exposed to a large quantity of deicing salts and therefore must be highly resistant to chloride ion penetration.

The w/cm plays an important role in reducing permeability. Although porosity and permeability are very different properties, concrete that has low porosity will typically have lower permeability. This is because low permeability is a result of poor connectivity between pores. In low w/cm concrete, the bleed water is minimized and therefore there are very few bleed water channels connecting one pocket of excess mixing water to the others. If concrete is porous, water, air and salts can penetrate to the level of the steel. The ingress of chlorides into concrete is primarily diffusion controlled. Other mechanisms such capillary absorption and hydrostatic pressure also contribute on a smaller scale.

**Influencing Factors:**

- **W/cm-** Concrete with lower w/cm generally has lower chloride-ion permeability.
- **Cement-** Chloride-ion permeability increases moderately with increased fineness.
- **Aggregates-** Proper gradation is important in creating concrete with low chloride-ion permeability.
- **Pozzolans and GGBFS-** The addition of pozzolans or GGBFS will decrease the chloride-ion permeability to varying levels. The beneficial effects of fly ash and GGBFS are generally not realized until later ages. Concrete with silica fume as an addition generally has low chloride-ion permeability both at early and late ages. Mixtures with a combination of silica fume and GGBFS, or silica fume and fly ash typically have significantly decreased permeability at both early and late ages.
- **Construction processes-** Proper consolidation is essential to creating concrete with low chloride-ion permeability.
- **Curing-** Adequate curing promotes full hydration and aids in the isolation of pores, thereby decreasing chloride-ion permeability.
• Temperature- Increased temperature (after exposure to normal placement temperatures) increases the rate of hydration, thereby producing lower chloride-ion permeability concrete at earlier ages.

• Admixtures- Certain types of chemical admixtures (primarily those containing sodium silicates) promote reduction in chloride-ion permeability through the conversion of hydration products.

5.7. Shrinkage

Shrinkage is a primary cause of cracks in a concrete structure. Tensile strains begin to accumulate after placement. If these strains exceed the strain capacity of the restrained concrete, cracks will develop. Concrete shrinkage can be divided into three major categories: plastic shrinkage, autogenous shrinkage, drying shrinkage. The w/cm plays a major role in each type of shrinkage.

Autogenous shrinkage occurs when cementious materials react with water to form reaction products. The shrinkage is due to the removal of water from capillaries into the gel space, and the relative decrease in volume of the reaction. This type of shrinkage is generally insignificant compared to other shrinkage phenomena, except where low w/cm or silica fume replacements are used, and for mass concrete structures.

Plastic shrinkage occurs when the evaporation rate in the atmosphere exceeds the bleed rate. This excess evaporation leads to extraction of water from the surface. This leads to wide surface tears during the plastic stage.

Drying shrinkage occurs due to the loss of capillary water in hardened concrete. It begins after the curing measures have been removed and is substantially complete after a year. In flatwork, differential drying shrinkage may result in curling and potentially cracking from restraint or external loads.
Influencing Factors:

- **W/cm**- Drying shrinkage increases with an increase in w/cm. However, the effects of autogenous shrinkage decrease with an increase in w/cm. Low w/cm exacerbates plastic shrinkage due to inadequate bleed water.

- **Water content**- Increased water content increases drying shrinkage, but decreases the likelihood of plastic shrinkage.

- **Cement**- Heat of hydration increases with the fineness of cement due to the larger surface area of the cement. This raises the concrete temperature and hence aggravates the effects of autogenous shrinkage. Cement properties have little effect on drying shrinkage. Increased cement fineness will generally increase plastic shrinkage potential. High alkali cements may decrease plastic shrinkage due to earlier setting times.

- **Pozzolans and GGBFS**- Silica fume significantly reduces bleed, and hence increases the potential for plastic shrinkage. In addition, the potential for autogenous shrinkage is increased by the presence of silica fume. Replacement of cement with pozzolans and GGBFS will result in an increased paste fraction, thereby increasing shrinkage potential.

- **Aggregate**- Shrinkage is primarily a function of the cementitious paste content, and therefore is significantly influenced by the gradation, total volume, and maximum size of the aggregate. The aggregate restrains the shrinkage of the paste and therefore concrete with higher aggregate content exhibit less shrinkage. Further, concrete with aggregates of higher modulus of elasticity and of rough surface exhibit higher shrinkage resistance. Excessive fines will increase the potential for plastic shrinkage.

- **Curing**- Plastic shrinkage can be prevented by appropriate curing measures. Curing does not significantly affect total drying shrinkage.

- **Admixtures**- Shrinkage reducing admixtures reduce the total drying shrinkage potential, however, should not be used in freeze-thaw environments. Water reducing admixtures affect shrinkage to varying degrees. Set controlling admixtures can reduce plastic shrinkage by altering the time in the plastic state.
- Ambient conditions - Higher relative humidity substantially reduces plastic shrinkage potential. High temperature and high wind speed increase the evaporation rate and raise the plastic shrinkage potential. Concrete in continuously moist environments will not experience drying shrinkage. If subbase material or formwork is dry, shrinkage may be accelerated.

- Volume-to-surface area ratio - Structural components with large surface areas lose capillary water more easily in low humidity environments and therefore exhibit greater plastic shrinkage. Higher volume-to-surface area ratios will alter the drying shrinkage rate but not the total drying shrinkage.

To diminish the effects of shrinkage on concrete, it is recommended that the w/cm be maintained between 0.40 and 0.45, and that moist curing be applied as soon as possible and maintained for ten to 14 days.

5.8. Alkali-Silica Reaction

Alkali-aggregate reactivity (AAR) can cause excessive expansion in the concrete, which results in progressive deterioration of the concrete. AAR may involve alkali-silica reactivity (ASR) or alkali-carbonate reactivity (ACR) depending on the type of aggregate (siliceous or carbonate). ACR typically only occurs with the use of specific dolomitic aggregates.

The three basic conditions for the alkali-silica reaction to take place are as follows:

- High alkali content in the pore solution,
- Moisture, more than 80 percent internal relative humidity of the concrete
- Reactive siliceous aggregate.

The rate of reaction however, increases with the increase in temperature for a given aggregate and alkali content.

Common sources of external alkalis are deicing salts, seawater, ground water and water from industrial processes.
Influencing Factors:

- W/cm- Lower w/cm decreases permeability, thereby indirectly decreasing ASR potential.
- Cement- Use of low alkali cements can reduce the potential of the expansion due to alkali-silica reactivity. ASTM C150 recommends cements with an equivalent sodium oxide less than 0.60 percent (Na$_2$O + 0.658 percent K$_2$O).
- Pozzolans and GGBFS- The use of pozzolans (silica fume and class F fly ash) and ground granulated blast furnace slag as part of the cementitious material will mitigate the alkali-silica reactivity. However, class C fly ash may actually increase ASR potential in some instances.
- Aggregate- Silicious aggregates are necessary for ASR. In addition, particle size, form of silica, and aggregate fraction affect ASR potential interdependently.
- Curing- Proper curing procedures enhance the microstructure, thereby retarding the ingress of water and deleterious species, thus reducing ASR potential.
- Admixtures- Several lithium based chemical admixtures, including lithium nitrate, are used as ASR inhibitors.
- Ambient conditions- Alkali-silica gel can form in entrained air voids thereby reducing the freezing and thawing durability of concrete. In addition, cracks formed through ASR expansion can promote the ingress and expansion of water upon freezing. Increased humidity and temperature increase potential and rate of ASR. Alternate wetting and drying cycles accelerate the migration of foreign alkalis, resulting in a concentration in the drying zone. Alkalis introduced from external sources such as deicing salts can contribute to ASR.

5.9. Freezing and Thawing Durability

Concrete exposed to repeated freeze-thaw cycles is susceptible to cracking from excessive internal pressures. There are a number of theories describing the mechanisms of frost action. The basic mechanism involves the nine percent expansion of water upon freezing, and the destructive nature of this volume change. The freezing temperature of
water varies with the size of the capillaries and presence of impurities. Pure water and water in large voids freezes before impure water or water in smaller voids.

An amount of air is intentionally entrained in concrete that will be exposed to freezing and thawing cycles. In addition to an adequate quantity of air, a proper air void system characterized by void spacing and size is essential.

**Influencing Factors:**

- **W/cm:** Decreased w/cm will increase freezing and thawing durability.
- **Admixtures:** The use of air-entraining admixtures to produce a proper air void system will improve freezing and thawing durability. Other admixtures have varying effects on the air void system.
- **Ambient conditions:** Increased freezing and thawing cycles will compound to accumulate damage. These effects are worsened with increased saturation and exposure to deicing salts.
- **Air content:** A proper air void system, characterized by small, non-interconnected, well spaced voids will improve freezing and thawing durability.

When numerous freezing and thawing cycles are expected, it is recommended that the w/cm be maintained below 0.45 and that an appropriate air void system be maintained. The properties of an effective air void system include:

- Maximum air void spacing factor less than 0.2mm (0.008 in.)
- Maximum air void size shall be less than 1mm in diameter
- At least six percent total air content
- Minimum air content of hardened concrete shall be greater than nine percent of the mortar fraction.
5.10. Scaling Resistance

Concrete bridge decks exposed to repeated freeze-thaw cycles in the presence of deicing salts may suffer severe surface scaling. Poor workmanship on the concrete surface, thermal gradients and moisture differences between the surface concrete and the bulk concrete can also cause scaling. Scaling can cause deterioration as deep as 20 mm depending on the severity of the scaling. Scaling resistance of concrete is significantly influenced by the microstructure of the surface concrete since the phenomenon of scaling is limited to this area.

Influencing Factors:

- W/cm- The w/cm directly affects the pore structure in the concrete and hence affects the scaling resistance. Decrease in w/cm can significantly diminish scaling. Excessive bleeding, especially coupled with poor workmanship, increases the w/cm at the surface and leaves bleed channels, which reduces the scaling resistance of concrete. Bleeding is primarily controlled by using appropriate aggregate gradation, admixtures and water content.

- Pozzolans- The use of silica fume as a partial replacement for portland cement significantly decreases bleed rate and strengthens concrete at all ages, thereby decreasing scaling potential. Fly ash and GGBFS also generally have a beneficial effect on scaling resistance.

- Curing- Adequate curing measures significantly improve scaling resistance. High placement temperatures are detrimental to the scaling resistance of concrete since they yield a relatively coarse micro-structure. Temperature differentials between the bulk concrete and surface concrete can also promote scaling, especially at early ages.

- Construction practices- Over-finishing the surface reduces the quality of the air-void structure and increases the w/cm near the concrete surface thereby increasing the potential for scaling. Premature finishing prior to evaporation of bleed water also increases the w/cm and therefore scaling potential. Pumping of concrete might reduce the air content, potentially decreasing scaling resistance.
Ambient conditions- Rapid rates of freezing, and longer periods of freezing may result in increased scaling. Exposure to deicing salts significantly increases the potential for scaling, especially if this exposure occurs at early ages.

Air content- A proper entrained air void system at the surface of the concrete is essential for scaling resistance.

5.11. Abrasion Resistance

Abrasion resistance is the ability of a surface to resist being worn away by friction. In transportation applications, concrete surfaces are subjected to acceleration and deceleration of vehicles, chains, tire studs, and hydraulic scour. Abrasion initiates at the surface layer of the concrete, therefore properties of the surface concrete are most critical for abrasion resistance.

Influencing Factors:

• W/cm- Abrasion resistance increases with decrease in w/cm at the surface. Low w/cm generally leads to higher compressive strength and therefore improves the abrasion resistance.

• Aggregate- Abrasion resistance of concrete varies with the content, hardness, and gradation of the aggregates. Well-graded and larger maximum size aggregates improve the abrasion resistance through the associated reduction in water demand. Hard aggregates provide enhanced abrasion resistance.

• Pozzolans and GGBFS- The use of silica fume as a partial replacement for portland cement greatly decreases bleeding and increases compressive strength, and thus increases abrasion resistance. Excessive bleeding increases the w/cm of the surface concrete and creates voids in the form of bleed water channels. This reduces the strength of the surface concrete and thus reduces the abrasion resistance.

• Curing- Adequate curing measures improve the pore structure of surface concrete, increasing abrasion resistance.

• Construction practices- Segregation causes significant reduction in the aggregate content in the surface concrete, thereby reducing abrasion resistance. Steel
trowelling will provide a uniform, dense finish, greatly increasing abrasion resistance.

5.12. Sulfate Resistance

Sulfates from internal and external sources can promote damage caused by expansive chemical reactions and physical degradation. Internal sulfate attack may occur in oversulfonated systems or when exposed to elevated curing temperatures. This damage is caused by the expansive conversion of hydration products into gypsum, ettringite and other compounds. These expansive products induce internal stresses and soften the paste, diminishing integrity. Concrete in sulfate-rich environments such as certain soils and saltwater is susceptible to similar deterioration. Physical salt attack occurs when sulfate salts crystallize at an evaporation front thereby causing distress.

Influencing Factors:

- W/cm- Susceptibility to sulfate attack is decreased as w/cm is decreased.
- Cement- Cement with lower C₃A content will produce concrete with increased sulfate resistance.
- Aggregates- Proper aggregate gradation is essential in optimizing cement and water contents, increasing sulfate attack resistance.
- Pozzolans and GGBFS- Use of pozzolans and GGBFS decrease the permeability, thereby diminishing the ingress of external sulfates. Also, as pozzolans and GGBFS replace a portion of the Portland cement, the overall C₃A content is effectively reduced.
- Curing- Proper curing measures are essential in providing sulfate resistant concrete.
- Construction practices- Proper placement, compaction, and finishing techniques reduce the ingress of water carrying external sulfates.
- Temperature- Increased curing temperature may cause internal sulfate attack.
For concrete exposed to moderate sulfate environments (soluble sulfate concentration between 0.10 and 0.20 percent), it is recommended that the w/cm be maintained below 0.45. In addition, the use of moderate sulfate resistant cement (type II), class F fly ash or GGBFS is recommended.

5.13. Other Considerations

In addition to the parameters outlined in the high performance grades, other properties exist that may affect the performance of concrete. Two of the more important and difficult to quantify properties include workability and steel corrosion.

5.13.1. Workability

Workability describes the ease of placement, consolidation and finishing of plastic concrete. Adequate workability is important to obtain dense concrete in full contact with the steel reinforcement. The mixture should be easy to vibrate without causing segregation. Consistency is the ability of fresh concrete to flow and plasticity is the ease of molding. Workability is often estimated in the field using the slump test.

The most influential factors affecting workability include water content, aggregate properties, cementitious materials properties, construction practices and use of admixtures. As water content increases, workability generally increases. However, segregation may occur with excessive water content. Workability increases with decrease in aggregate size. However, small aggregates enhance the paste demand due to increased surface area. Round shapes are more workable than angular. Proper gradation is important in the minimization of segregation and producing workable concrete. Fly ash increases workability whereas silica fume decreases workability. Pumping decreases workability and may encourage segregation. The use of water reducing admixtures will increase concrete workability. To a lesser extent, air-entraining admixtures also will increase workability.
5.13.2. Corrosion

A primary reason for considering chloride penetration involves the corrosion of reinforcing steel. The pore solution in concrete normally creates an atmosphere with a pH of 12.5 or higher, and therefore promotes a corrosion-preventive passive layer around the embedded reinforcing steel. The mechanism of steel corrosion is initiated by the reduction in pH from phenomena such as carbonation, or increased chloride ion concentration in the presence of moisture and oxygen at the level of reinforcing steel. This increased chloride concentration may be due to ingress from external sources such as deicing salts, or seawater. Once initiated, corrosion continues to form rust as the final product, which has substantially higher volume than the rebar volume (about five to ten percent higher). This induces stresses in the surrounding concrete eventually causing cracking. Corrosion continues until all of the reinforcing steel has deteriorated. The following conditions are required at the reinforcing steel level for corrosion initiation:

- Chloride ion concentration above the threshold level of 0.2 percent by mass of the portland cement or pH less than ten
- Moisture
- Oxygen
6. MATERIALS

6.1. Cementitious Materials

6.1.1. Hydraulic Cements

Hydraulic cements are those that set and harden as a result of chemical reactions with water, and can do so in the presence of external water. A vast majority of the hydraulic cement produced in the world is portland cement; however, other hydraulic cements are available for specialty applications.

6.1.1.1. Portland Cement

Portland cement is produced through the pulverization of clinkers consisting of primarily of hydraulic calcium silicates (C₃S and C₂S), calcium aluminates (C₃A) and aluminoferrites (C₄AF) and the addition of inter-ground calcium sulfate (gypsum). The calcium silicates are the primary cementitious constituents in cement and are the main contributors to mechanical property development. When combined with water, cement undergoes a chemical transformation referred to as hydration. Among the products of hydration are calcium silicate hydrate, calcium hydroxide, and derivatives of calcium aluminates. Occupying a majority of the paste volume and resulting from the hydration of the calcium silicates, calcium silicate hydrate is responsible for the cementing properties of hardened paste. Because of its relatively high solubility in water, calcium hydroxide has the propensity to create problems with durability.

Properties of portland cement that contribute to concrete performance include fineness and composition. ASTM C 150 outlines the physical and chemical requirements of different types of portland cement, including the three that are commercially available in the United States: type I, type II, and type III. In addition, type IV and type V cements are designated, but not commonly produced. Type I cement is classified as general use. Type II is classified as having both moderate heat of hydration and moderate sulfate
resistance, and is attained by reducing the amount of C₃A and combined amounts of C₃A and C₃S. Type III is classified as being high early strength and is achieved through increased fineness and the use of clinker with increased C₃S and possibly C₃A contents. The general rank of these cements in terms of decreasing adiabatic temperature rise, decreasing expansion due to sulfate attack and increasing early age strength and decreasing later age strength is: type III, type I, and type II.

6.1.1.2. Other Hydraulic Cements

In addition to the aforementioned portland cements, there are also other hydraulic cements that can be satisfactorily used to produced durable concrete in the United States. For transportation applications, blended portland cements as outlined in ASTM C 595, performance-based cements as outlined in ASTM C 1157, and expansive cements such as those covered in ASTM C 845 also may be used in certain circumstances.

Blended cements are those containing portland cement and additions of pozzolans or GGBFS that are intimately and uniformly blended, and are typically ground finer than regular portland cements. These cements are used to reduce the heat of hydration and increase durability, and promote the use of recycled materials. Refer to section 6.1.2 for a description of pozzolans and GGBFS.

Performance-based cements are those prepared without restriction on cement composition, only on the resulting performance. Cements that achieve high early strength, varying levels of sulfate resistance, or varying levels of reduced heat of hydration can be prepared by using blended cements and/or other components.

Expansive cements create internal expansion within concrete at early ages and act to offset subsequent drying shrinkage and eradicate the associated cracks. The expansion is obtained by using calcium aluminate compounds, calcium oxide and/or calcium sulfates in appropriate proportions.
6.1.2. Pozzolans and GGBFS

Pozzolans and GGBFS are often used as partial replacements for portland cement in concrete. Pozzolans are siliceous or siliceous and aluminous materials that possess little or no cementitious value but will chemically react with calcium hydroxide to form hydrated compounds possessing cementitious properties. GGBFS reacts in a manner similar to pozzolans; however, unlike pozzolans, GGBFS has some intrinsic cementitious value. The effect of these materials on the durability characteristics of concrete depends on the amount used, compatibility with chemical admixtures, mixing & placing procedures, and curing practices.

6.1.2.1. Silica Fume

Silica fume is a by-product resulting from the reduction of high-purity quartz with coal or coke and wood chips in an electric arc furnace during the production of silicon metal or ferrosilicon alloys. It is available in loose bulk form, slurry form, and in the form of blended portland-silica fume cement. Silica fume that is used as part of the cementitious material in concrete must meet the requirements of ASTM C 1240. Silica fume can be used at replacement percentages as low as three percent and above ten percent in high strength applications. The particles are spherical and on the order of 100 times finer than portland cement. Silica fume modifies the physical characteristics of fresh cement paste as well as microstructure of the paste after hardening. Due to the high specific surface area, the use of silica fume increases the water demand of concrete, and is therefore usually used with a high-range water-reducing admixture.

The use of silica fume as a partial replacement of portland cement significantly affects various mechanical and durability properties. Compressive strength, tensile strength, and modulus of elasticity of silica fume concrete are increased at all ages through its densification of the matrix and improvement of the interface between paste and aggregate. The strength ratio and creep coefficient are typically decreased. Durability
properties, especially permeability and alkali-silica reactivity, are typically improved through the addition of silica fume.

Concretes containing silica fume shows significantly reduced bleeding. The reduced bleeding enhances the potential for plastic shrinkage cracks unless appropriate curing practices are exercised. Fogging, using evaporation retarders, erecting windbreaks, and immediate curing are necessary practices for the prevention of initial water loss from concrete containing silica fume.

6.1.2.2 Fly Ash

Fly ash is a finely divided by-product obtained from burning coal, typically at electric power generation plants. ASTM C 618 classifies fly ash into Class F and Class C designations based on the chemical composition of the ash and source of the coal. Class C Fly ashes, produced from subbituminous and lignite coals often contain more than 20 percent CaO and have both pozzolanic and cementitious properties. Class F fly ashes are produced from bituminous and anthracite coals and typically contain less than five percent CaO.

Fly ash particles are predominantly amorphous and spherical in nature. Replacement percentages for the use of fly ash generally vary between twenty and thirty-five percent. Mechanical properties of concrete with fly ash as a partial replacement are typically retarded at early ages, but at later ages exceed the properties of concrete with 100 percent portland cement. The use of class F fly ash improves all durability properties of concrete. Class C fly ash may worsen ASR and sulfate durability and should be used with caution.

Class F fly ashes have a higher loss on ignition (LOI) value than class C fly ashes and may adversely affect the air void system in fresh concrete. Fly ash concretes typically exhibit improved workability and are generally cost efficient. In addition, fly ash concretes generate less heat during hydration.
6.1.2.3. Ground Granulated Blast Furnace Slag (GGBFS)

Blast furnace slag is a glassy by-product of the production of iron in blast furnaces. The slag is rapidly chilled and then ground to appropriate fineness to produce GGBFS. ASTM C 989 classifies GGBFS into three grades: Grade 80, Grade 100, and Grade 120, depending on the strength when blended with an equal mass of the portland cement. Grade 120 GGBFS is the strongest, and finest of these grades. Generally, GGBFS is finer than portland cement.

Concrete containing 35-50 percent GGBFS as part of the cementitious material content, may yield improved workability as compared to the concrete without GGBFS for a given design mixture. At early ages, mechanical properties of concrete containing GGBFS are similar to those of portland cement concrete. However, at 28 days and later, GGBFS concretes with up to 50 percent GGBFS content exhibit increased compressive strengths and strength development rate with the GGBFS content. Increased durability properties will typically result from the use of GGBFS as a partial replacement for portland cement.

6.2. Aggregates

Aggregates occupy approximately 65 to 80 percent of a concrete mixture, and thus significantly contribute to the properties of the concrete. Fresh concrete properties, hardened concrete mechanical and durability properties, and mixture economy are all affected by aggregates. Although generally inert in nature, certain aggregates can contribute to freezing and thawing damage and alkali-silica reactivity, and to other durability problems resulting from impurities.

Aggregates are designated as coarse and fine. Coarse aggregates are retained on the number 4 sieve. Fine aggregates pass the number 4 sieve and are predominantly retained on the on the number 200 sieve. Among the aggregate properties of interest when optimizing a concrete mixture are: type and composition, shape and texture, density and
absorption, reactivity, soundness and hardness, cleanliness, temperature and moisture content. The combined aggregate gradation and total amount of aggregate are important issues in proportioning a concrete mixture, as they affect the overall workability.

6.3. Water

Water used in concrete mixtures should be potable and free of excessive impurities. Chlorides and other deleterious chemicals should not be present in mixing water.

6.4. Chemical Admixtures

The durability of concrete can be significantly enhanced by various chemical admixtures. They can improve freeze-thaw resistance and chemical durability, decrease shrinkage, reduce permeability, and improve workability. When chemical admixtures are used in concrete, the compatibility of the combination of admixtures must be tested prior to use in the field. Admixtures are typically most effective when added at a specified stage in the mixing process and care should be taken to follow the manufacturer’s recommendations. Many chemical admixtures are covered in the specifications of ASTM C 494. The following sections summarize the influence of chemical admixtures on the performance of concrete.

6.4.1. Air-Entraining Admixtures

Air-entraining agent is an addition for hydraulic cement or an admixture for concrete that causes the entrainment of air during mixing. Air entrainment acts to provide freezing and thawing durability and scaling resistance. Air entraining admixtures are generally organic materials classified as surfactants. Surfactants are molecules with a hydrophilic (has an affinity for water) end and a hydrophobic (repels water) end. The hydrophilic end can be anionic (negative charged), cationic (positive charged) or non-ionic (neutral); however, the most frequently encountered groups are anionic. A proper air void system, in
addition to entrained air volume, is necessary for resisting deterioration. Proper air void systems are defined by ASTM C 260.

The purpose of air-entraining agents is to create stabilized air bubbles, formed during the mixing of concrete. Entrained air develops from the mechanical stirring, kneading and folding actions during mixing of the concrete when the batch falls between the baffles in the drum and the entrapped air is broken down and dispersed into the system as air bubbles. Once formed, these bubbles are stabilized by the air-entraining agents. The air-entraining agents reduce the surface tension of water, and enable the shear stresses developed by the mixer to create small bubbles.

Addition of an air-entraining agent increases workability of the concrete by reducing friction between the fine particles in the paste. In low cement concretes, addition of air-entraining agents significantly reduces the water requirement to produce the specified slump. A drawback with air entrainment is the associated reduction in strength.

6.4.2. Water-Reducing Admixtures

Water-reducing admixtures are designed to reduce the water requirement for a desired workability or improve the workability for constant water content. ASTM C 494 gives an overview of the physical properties and test methods of these admixtures. For typical transportation applications, mid range and high range water reducers are commonly used.

Water-reducing admixtures may reduce the water content requirement by five percent and high-range water reducing admixtures can achieve water content reduction of 15 to 30 percent. Several types of materials and their combinations are found in the commercially available admixtures. In general, normal range water reducing admixtures include those containing salts and modifications of hydroxylated carboxylic acids, those containing salts and modifications of lignosulfonic acids, and those containing carbohydrates and polysaccharides. The high range water reducers, commonly called superplasticizers, normally contain salts of high molecular weight: naphthalene sulfonic
acid formaldehyde condensates, salts of melaminesulfonic acid formaldehyde condensates, or salts and modifications of ligninsulfonic acids.

Water reducing admixtures function by dispersing the cement particles evenly and consequently reduce the viscosity of the paste, making the concrete more fluid. The effect of water reducing admixtures of both types can be significantly influenced by cement, aggregates, other materials used in the design mixture, weather conditions and construction practices.

Achieving the desired slump with less water content at a constant cement content can improve the strength, impermeability, and hence the durability of concrete. However, the use of some high range water reducing admixtures may manifest in slump loss. The lower water content associated with the use of high range water reducers, reduces bleed and may result in problems in finishing and increases the potential for plastic shrinkage cracking. Immediate application of curing as specified by ACI 308 becomes critical to prevent the moisture loss through evaporation.

6.4.3. Set Modifying Admixtures

Chemical admixtures can be used to alter the setting time of concrete. Accelerators are chemical admixtures that decrease the setting time of concrete, while retarders are those that increase the setting time.

Accelerators can be classified as chloride and non-chloride. Calcium chloride is a typical chloride-based accelerator, and calcium nitrite is a typical non-chloride based accelerator. Chloride accelerators increase early-age strength but increases drying shrinkage and susceptibility to corrosion and scaling. In addition, resistance to ASR and sulfate attack is diminished with the use of accelerators. The use of accelerating admixtures serves to accelerate the project schedule, and is particularly useful in cold weather applications.
Retarders are typically comprised of carbohydrate derivatives, organic acids or inorganic salts. These admixtures decrease the rate of early hydration, and typically increase long-term strength. Retarders are most useful in hot weather applications, and whenever delayed setting time is advantageous.

6.4.4. Durability Enhancing Admixtures

Several chemical admixtures can be used to enhance the durability of concrete. Common durability enhancing admixtures include corrosion inhibitors, ASR inhibitors, shrinkage reducers, and permeability reducers. These admixtures are briefly discussed in this section.

Corrosion inhibiting admixtures protect the steel embedded in concrete by reducing the onset and/or rate of corrosion in the presence of chloride ions. These admixtures limit either the anodic or cathodic electrochemical reactions involved in the corrosion process. Corrosion inhibitors may be inorganic or organic in nature. Inorganic inhibitors work by stabilizing the passivation layer, whereas organic inhibitors serve as a protective layer to chlorides. Commercially available corrosion inhibiting admixtures are calcium nitrite, sodium nitrite, and a mixture of amines and esters, dimethyl ethanol amine, amines, and phosphates.

Soluble salts of lithium, barium, and certain air-entraining agents and some water-reducing set-retarding admixtures have been reported to result in reduction in ASR expansion. Lithium nitrate is the most common ASR inhibitor. Lithium ions combine with soluble silica from aggregates to promote the formation of an insoluble gel, preventing the formation of expansive gel. The dosage of the admixture mainly depends on the amount of alkali in the concrete and therefore the required amount should be determined by testing.
Shrinkage reducing admixtures effectively reduce surface tension of pore water solution, thereby reducing tensile strains generated during drying. The use of shrinkage reducing admixtures will reduce drying shrinkage, shrinkage cracking, and slab curling.

Permeability of concrete is of prime concern since it significantly influences durability. Some chemical admixtures such as polymer-emulsion, reduce the permeability of concrete. The polymer particles coalesce into a continuous film, which reduces permeability. Another class of admixtures yielding reduced permeability concrete includes admixtures containing sodium silicates or silica desiccants. The mechanism by which these admixtures decrease permeability and improve durability is essentially a densification of the paste.

6.5. Reinforcement

One of the most highly regarded benefits of utilizing concrete in engineering applications is its ability to resist compressive loadings. Reinforcements of various types have been developed to aid the concrete in the resistance of tensile forces. The result is the two materials acting in combination, producing composite action.

Reinforcement is generally distinguished as either steel reinforcement or polymer reinforcement. Steel reinforcement consists of the following:

- Unaltered reinforcing steel- Uncoated reinforcement with only rust, mill scale or a combination of the both on its surface
- Epoxy-coated reinforcing steel- Covered with an epoxy resin to aid in corrosion protection
- Galvanized reinforcing steel- Reinforcement that has been coated in zinc for corrosion protection
- Microcomposite or dual phase reinforcing steel- Relatively new technology designed at the microstructural level to improve properties such as corrosion resistance
Reinforcing bars are round in shape with added deformations to aid in bond. Cleanliness also affects the bond developed between the steel and the concrete. Several specifications (ASTM A 615, ASTM A 616, ASTM A 617, and ASTM A 706) describe dimensions and chemical and mechanical properties. Reinforcing bars are generally available in four grades based on yield strengths of 40, 50, 60, and 75 ksi, referred to as Grades 40, 50, 60, and 75, respectively.

Other types of steel reinforcement include steel wire, steel fibers, and welded wire fabric. Steel wire may be placed singularly or in groups often times used as prestressing strands. Steel fibers or welded wire fabrics are commonly placed at layers to add ductility and to distribute shrinkage cracks. In addition, welded wire fabric can be used to resist punching shear.

Fiber reinforced polymers (FRP) are alternatives to traditional steel reinforcing methods. FRP products may be fabricated to produce bars, cables, grids, sheets, or simply placed loosely as chopped fibers. Common FRP products include:

- Polyester resin- Commonly used to produce large composite structural parts
- Epoxy resin- Flowable form of reinforcement used for both reinforcement and repair applications
- Glass fiber- Produced with different compositions by utilizing glass chemistry to achieve the desired properties
- Carbon fiber- Relatively strong and stiff material used in specialty applications
7. Construction Practices

Durable concrete can be 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.

7.1. Quality Assurance and Quality Control

Quality control (QC) assures the reliability of performance of the designed concrete. High performance concrete for most highway structures is concrete designed for a long service life under specified exposure conditions. The performance life is highly dependent on exercising quality control sound construction practices.

Completion of HPC structures from conceptual stage through design, construction and a lifetime of use, requires communications 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. HPC involves the use of complex specifications and standards not only for design but also for the construction.

Planning for HPC applications is critical since it provides an overall view of all the activities involved. The steps to be carried out are as follows:

- Organizational preparation involving planning, time scheduling, contract details and definition and assignment of duties
- Material selection and approval
- Detailed quality control plan and certification of employees and inspection of equipment
- Reinforcement planning, design, fabrication, and procurement
- Concrete mixture proportioning, laboratory mixture designing, and coordination with the design engineers
• Timely concrete delivery and fresh concrete testing
• Timely moist curing and surface treatment of the hardened concrete
• Quality control tests of the hardened concrete

7.2. Batching, Mixing, and Transporting

Batching is the process of measuring and introducing the ingredients for a batch of concrete into the mixer in a specified sequence. To produce concrete of uniform quality, the constituents must be measured accurately 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 100°F (38°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 °C and 24 °C) throughout the year.

• Each constituent of the concrete is required to be batched within specific tolerance limit. These tolerances are
  - 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. 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.
• 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. Usually, prolonged mixing can reduce the air content and could result in the breakdown of aggregate. 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.
• 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 might 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. 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.

7.3. Placing, Consolidating, and Finishing

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 appreciably the performance of concrete. Concrete should be placed without significant delay. The following are the primary factors considered during placement of the concrete:

- Segregation is a common problem encountered during placement. Some of the key construction procedures to prevent segregation are outlined below:
  - Free fall of concrete of more than a few feet can cause segregation and should be avoided.
  - 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 and 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.

The objective of finishing is to produce a dense, compacted, well-graded surface with minimum manipulations. Overworking of the surface is detrimental to the performance of concrete surfaces due to the following factors:

- Increased paste content at the surface makes the concrete more susceptible to cracking. This 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 frost and scaling resistance of the concrete.
- Trowelling in the presence of water on the surface causes increase in w/cm in the surface concrete and hence reduces its strength and durability.
- Steel trowelling prior to the emergence of bleed water seals 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.

7.4. Curing

Curing is the maintenance of satisfactory moisture and temperature in conditions during a defined period immediately following finishing to assure 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.
- Relatively thin sections have large surface areas as compared to their volume. This accelerates the loss of water from the concrete and enhances the need for moist curing.
- Timely implementation of curing is critical for low w/cm concretes 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. This makes timely application of curing essential for the performance of concrete.
- Concrete with pozzolan as partial replacement of portland cement or with low w/cm typically exhibit less bleeding. Therefore, they require timely curing to prevent the loss of surface moisture.

Desired performance of high-performance concretes is influenced by the timely and appropriate moist curing.

- The key to timely curing is minimizing the time gap between the placing & finishing and application of the curing. Provide wet curing within 10 minutes from the concrete placement.
Duration of continuous moist cure is also important. Provide wet burlap or equivalent curing for 14 days and ensure continuous wetting of the burlap for the entire curing period followed by the application of curing compound.
8. High Performance Concrete Design Guide for Pennsylvania Bridge Decks

The following guide addresses the use of performance criteria for designing HPC for bridge decks in Pennsylvania. It is important to realize 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. Decisions are indicated in red italics.

Compressive Strength

<table>
<thead>
<tr>
<th>CS Compressive Strength</th>
<th>Is the concrete structural or a pavement?</th>
<th>Is the member optimized for high strength?</th>
<th>Yes. Specify within CS - Grade 3</th>
<th>No. Specify within CS - Grade 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is the member optimized for high strength?</td>
<td>Yes</td>
<td>Is the member optimized for high early strength?</td>
<td>No. Specify within CS - Grade 1</td>
<td></td>
</tr>
<tr>
<td>No. Specify a minimum of 21 MPa at 28 days (3000 psi)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Test Method | HPC Grade 1 | HPC Grade 2 | HPC Grade 3 |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CS Compressive Strength, MPa (ksi)</td>
<td>AASHTO T 22</td>
<td>24≤X&lt;55 @ 28 days (3.5≤X&lt;8.0)</td>
<td>55≤X @ 28 days (8.0≤X)</td>
</tr>
</tbody>
</table>

Is the concrete structural or a pavement?
Yes. Bridge decks are structural elements.

Is the member optimized for high strength?
No. Typically, bridge decks are not optimized for high strength; however, in some instances, they might be. In fact, high strength might be detrimental in terms of facilitating strain relaxation.

Specification:
CS Grade 1. Specify a compressive strength between 24 and 55 MPa at 28 days.
Strength Development

<table>
<thead>
<tr>
<th>SD</th>
<th>Will the concrete go into service after a minimum of 7 days after being cast?</th>
<th>Is a reduced rate of strength gain advantageous?</th>
<th>Is the member greater than 3 feet in thickness?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes, Specify SD-Grade 3</td>
</tr>
<tr>
<td>No</td>
<td>No, Specify SD-Grade 2</td>
<td>No</td>
<td>No, Specify SD-Grade 1</td>
</tr>
</tbody>
</table>

No. SD grade should not be specified.

<table>
<thead>
<tr>
<th>Test Method</th>
<th>HPC Grade 1</th>
<th>HPC Grade 2</th>
<th>HPC Grade 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD Strength ratio</td>
<td>AASHTO T 22</td>
<td>X≥1.15</td>
<td>X≥1.33</td>
</tr>
</tbody>
</table>

**Will the concrete go into service after a minimum of 7 days after being cast?**

**Yes.** Usually, bridge decks are not put into service before seven days; however, in fast track applications, this may be necessary.

**Is a reduced rate of strength gain advantageous?**

**Yes.** Slow development of properties generally improves long-term performance.

**Is the member greater than 3 feet in thickness?**

**No.**

**Specification:**

**SD Grade 2.** Specify a minimum 28 to 7-day compressive strength ratio of 1.33.
Tensile Strength

<table>
<thead>
<tr>
<th>TS Tensile Strength</th>
<th>Does the design depend on concrete to carry tension?</th>
<th>Yes</th>
<th>Does the structural performance rely on tensile strength?</th>
<th>Yes</th>
<th>Is there a design need for TS &gt; 6 MPa?</th>
<th>Yes. Specify within TS-Grade 3</th>
<th>No. Specify within TS-Grade 2</th>
<th>No. Specify TS - Grade 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS Tensile strength MPa (psi)</td>
<td>Test Method</td>
<td>HPC Grade 1</td>
<td>HPC Grade 2</td>
<td>HPC Grade 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS Tensile strength MPa (psi)</td>
<td>ASTM C 496</td>
<td>4 &gt;X≥5 (580≤X&lt;720)</td>
<td>5 &gt;X≥6 (720≤X&lt;870)</td>
<td>X &gt; 6 (870≤X )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Does the design depend on concrete to carry tension?*

No.

*Specification:*

Do not specify TS Grade.
Modulus of Elasticity

<table>
<thead>
<tr>
<th>ME</th>
<th>Modulus of Elasticity</th>
<th>Is there a structural need to specify stiffness?</th>
<th>Yes</th>
<th>Is there a particular benefit to a higher than normal stiffness?</th>
<th>Yes</th>
<th>Is high stiffness critical to the structural design?</th>
<th>Yes, Specify within ME - Grade 3</th>
<th>No, Specify within ME - Grade 2</th>
<th>No, Specify ME - Grade 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

No. ME grade should not be specified.

<table>
<thead>
<tr>
<th>Test Method</th>
<th>HPC Grade 1</th>
<th>HPC Grade 2</th>
<th>HPC Grade 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME Modulus of Elasticity, GPA (Msi)</td>
<td>ASTM C 469</td>
<td>20 ≤ X ≤ 30 (2.9 ≤ X ≤ 4.3)</td>
<td>30 ≤ X ≤ 45 (4.3 ≤ X ≤ 6.5)</td>
</tr>
</tbody>
</table>

Is there a structural need to specify stiffness?

No.

Specification:

Do not specify ME Grade.
## Creep Coefficient

<table>
<thead>
<tr>
<th>Creep Coefficient</th>
<th>Is there a significant advantage to specifying creep coefficient in the design?</th>
<th>Is there an advantage in relieving large stresses or strains?</th>
<th>Is creep detrimental to the concrete element or surrounding elements?</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>Yes. Specify CC - Grade 1</td>
<td>Yes. Specify CC - Grade 3</td>
<td></td>
</tr>
</tbody>
</table>

*No. CC grade should not be specified.*

<table>
<thead>
<tr>
<th>Test Method</th>
<th>HPC Grade 1</th>
<th>HPC Grade 2</th>
<th>HPC Grade 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>ASTM C 512*</td>
<td>2 \leq X</td>
<td>2\times X \geq 1.4</td>
</tr>
</tbody>
</table>

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

Is there a significant advantage to specifying creep coefficient in the design?

No.

**Specification:**

CC grade should not be specified
Chloride Penetration

<table>
<thead>
<tr>
<th>CP</th>
<th>Chloride Penetration Durability</th>
<th>Is the concrete exposed to chloride salts or soluble sulfate environments?</th>
<th>Yes</th>
<th>Is the member exposed in a potentially moist environment?</th>
<th>Yes</th>
<th>Will the member be saturated completely during freezing?</th>
<th>Yes. Specify CP-Grade 3</th>
<th>No. Specify CP-Grade 2</th>
<th>No. Specify CP-Grade 1</th>
<th>No. CP grade should not be specified.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test Method</th>
<th>HPC Grade 1</th>
<th>HPC Grade 2</th>
<th>HPC Grade 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP Chloride penetration, Coulombs</td>
<td>AASHTO T 277*</td>
<td>4000≥X</td>
<td>2000≥X</td>
</tr>
</tbody>
</table>

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

**Is the concrete exposed to chloride salts or soluble sulfate environments?**

**Yes.** Bridge decks in Pennsylvania are often exposed to chloride deicing salts.

**Is the member exposed in a potentially moist environment?**

**Yes.** Exposure to deicing salts is often accompanied by moist conditions.

**Will the member continuously be saturated completely during freezing?**

**No.** Adequate drainage is provided to disperse water from the bridge surface.

**Specification:**

**CP Grade 2.** Specify a maximum total charge passed of 2000 Coulombs.
**Shrinkage**

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

<table>
<thead>
<tr>
<th>SH Shrinkage (microstrain)</th>
<th>Test Method</th>
<th>HPC Grade 1</th>
<th>HPC Grade 2</th>
<th>HPC Grade 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM C 157</td>
<td>800≥X</td>
<td>500≥X</td>
<td>200≥X</td>
<td></td>
</tr>
</tbody>
</table>

**Is the concrete exposed to moisture, chloride salts or soluble sulfate environments?**

**Yes.** Bridge decks in Pennsylvania are often exposed to chloride deicing salts and moisture.

**Is the member constructed without joints?**

**Yes.** Construction joints are not typically used in bridge decks.

**Is the member designed to be watertight or crack free?**

**No.** These design criteria are not typical for Pennsylvania bridge decks.

**Specification:**

**SH Grade 2.** Specify a maximum shrinkage value of 500 microstrain.
Alkali Silica Reaction

<table>
<thead>
<tr>
<th>AS</th>
<th>Alkali Silica Reaction Durability</th>
<th>Does the concrete contain reactive aggregates?</th>
<th>Yes</th>
<th>Is the concrete exposed to moisture?</th>
<th>Yes</th>
<th>Will the member be saturated during freezing?</th>
<th>Yes, Specify AS - Grade 3</th>
<th>Yes, Specify AS - Grade 2</th>
<th>No, Specify AS - Grade 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Concrete produced in Pennsylvania often includes reactive siliceous fine aggregate.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Does the concrete contain reactive aggregates?**

**Yes.** Concrete produced in Pennsylvania often includes reactive siliceous fine aggregate.

**Is the concrete exposed to moisture?**

**Yes.** Bridge decks in Pennsylvania are exposed to moisture.

**Will the member be subjected to external alkalis?**

**Yes.** Bridge decks in Pennsylvania are commonly subjected to external alkalis from deicing salts.

**Specification:**

**AS Grade 3.** Specify a maximum expansion of 0.10% at 14 days (AASHTO T 303) and a minimum of 70% reduction in expansion at 56 days (ASTM C 441).
Freezing & Thawing Durability

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

<table>
<thead>
<tr>
<th>Test Method</th>
<th>HPC Grade 1</th>
<th>HPC Grade 2</th>
<th>HPC Grade 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT</td>
<td>AASHTO T 161 Proc. A</td>
<td>60%≤X</td>
<td>80%≤X</td>
</tr>
</tbody>
</table>

Is the concrete exposed to freezing and thawing environments?  
Yes. Pennsylvania experiences cycllical freezing and thawing during winter months.

Is the member exposed to deicing salts?  
Yes. Deicing salts are commonly applied to bridge decks in Pennsylvania.

Will the member be saturated during freezing?  
Yes. Bridge decks in Pennsylvania are commonly saturated during freezing.

Specification:  
**FT Grade 3.** Specify a minimum of 90% relative modulus at 300 cycles of freezing and thawing.
### Scaling Resistance

<table>
<thead>
<tr>
<th>SR</th>
<th>Is the concrete exposed to deicing salts?</th>
<th>Is the exposure a direct application of salt?</th>
<th>Will the member be subjected to severe surface loadings?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

| SR Grade 2. | Specify a maximum visual surface rating of 1 after 50 cycles of freezing and thawing. |

<table>
<thead>
<tr>
<th>Test Method</th>
<th>HPC Grade 1</th>
<th>HPC Grade 2</th>
<th>HPC Grade 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM C 672</td>
<td>X≤3</td>
<td>X≤1</td>
<td>X=0</td>
</tr>
</tbody>
</table>

**Is the concrete exposed to deicing salts?**

**Yes.** Deicing salts are commonly applied to bridge decks in Pennsylvania.

**Is the exposure a direct application of salt?**

**Yes.** Deicing salts are applied directly to bridge decks.

**Will the member be subjected to severe surface loadings?**

**No.** Tires are not considered to impose severe loading.

**Specification:**

**SR Grade 2.** Specify a maximum visual surface rating of 1 after 50 cycles of freezing and thawing.
Abrasión Resistencia

<table>
<thead>
<tr>
<th>AB</th>
<th>Abrasion Resistance</th>
<th>Is the concrete exposed to surface abrasion?</th>
<th>Yes</th>
<th>Is the member subjected to other than tire wear?</th>
<th>Yes</th>
<th>Will the member be exposed to tire studs or chains?</th>
<th>Yes, Specify AB-Grade 3</th>
<th>No. Specify AB-Grade 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. AB grade should not be specified.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test Method</th>
<th>HPC Grade 1</th>
<th>HPC Grade 2</th>
<th>HPC Grade 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB Abrasion resistance (wear depth, mm)</td>
<td>ASTM C 994</td>
<td>2.0≥X</td>
<td>1.0≥X</td>
</tr>
</tbody>
</table>

**Is the concrete exposed to surface abrasion?**

**Yes.** Bridge decks are exposed to surface abrasion from traffic loading.

**Is the member subjected to other than tire wear?**

**No.** Pennsylvania bridge decks are normally only exposed to tire wear.

**Specification:**

**AB Grade 1.** Specify a maximum wear depth of 2.0 mm.
### Sulfate Resistance

<table>
<thead>
<tr>
<th>SU Sulfate Resistance</th>
<th>Is the concrete exposed to more than 0.10 percent soluble sulfates?</th>
<th>Yes</th>
<th>Is the member exposed to more than 0.20 percent soluble sulfates?</th>
<th>Yes</th>
<th>Is the member exposed to wet-dry cycles?</th>
<th>Yes. Specify SU - Grade 3</th>
<th>No. Specify SU - Grade 2</th>
<th>No. Specify SU - Grade 1</th>
</tr>
</thead>
</table>

**Test Method**

- **SU Sulfate resistance (expansion)**: ASTM C 1012
  - HPC Grade 1: $X < 0.10\%$ at 6 months
  - HPC Grade 2: $X < 0.10\%$ at 12 months
  - HPC Grade 3: $X < 0.10\%$ at 18 months

**Is the concrete exposed to surface abrasion?**

**No.** Bridge decks are not exposed to soluble sulfates.

**Specification:**

**Do not specify SU Grade.**
## Engineering Guide to Specifying HPC Performance Grades

### CS - Compressive Strength

<table>
<thead>
<tr>
<th>Question</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is the concrete structural or a pavement?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is the member optimized for high strength?</td>
<td>Yes</td>
<td>No. Specify within CS - Grade 1</td>
</tr>
<tr>
<td>Is the member optimized for high early strength?</td>
<td>Yes. Specify within CS - Grade 3</td>
<td>No. Specify within CS - Grade 2</td>
</tr>
</tbody>
</table>

No. Specify a minimum of 21 MPa at 28 days (3000 psi)

### SD - Strength Development

<table>
<thead>
<tr>
<th>Question</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Will the concrete go into service after a minimum of 7 days after being cast?</td>
<td>Yes</td>
<td>No. Specify SD- Grade 1</td>
</tr>
<tr>
<td>Is a reduced rate of strength gain advantageous?</td>
<td>Yes</td>
<td>No. Specify SD-Grade 3</td>
</tr>
<tr>
<td>Is the member greater than 3 feet in thickness?</td>
<td>Yes. Specify SD-Grade 2</td>
<td>No. Specify SD-Grade 1</td>
</tr>
</tbody>
</table>

No. SD grade should not be specified.

### TS - Tensile Strength

<table>
<thead>
<tr>
<th>Question</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Does the design depend on concrete to carry tension?</td>
<td>Yes</td>
<td>No. Specify TS - Grade 1</td>
</tr>
<tr>
<td>Does the structural performance rely on tensile strength?</td>
<td>Yes</td>
<td>No. Specify TS-Grade 3</td>
</tr>
<tr>
<td>Is there a design need for TS &gt; 6 MPa?</td>
<td>Yes. Specify TS-Grade 2</td>
<td>No. Specify TS-Grade 1</td>
</tr>
</tbody>
</table>

No. TS grade should not be specified.

### ME - Modulus of Elasticity

<table>
<thead>
<tr>
<th>Question</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is there a structural need to specify stiffness?</td>
<td>Yes</td>
<td>No. Specify ME - Grade 1</td>
</tr>
<tr>
<td>Is there a particular benefit to a higher than normal stiffness?</td>
<td>Yes</td>
<td>No. Specify within ME - Grade 3</td>
</tr>
<tr>
<td>Is high stiffness critical to the structural design?</td>
<td>Yes. Specify within ME - Grade 2</td>
<td>No. Specify within ME - Grade 1</td>
</tr>
</tbody>
</table>

No. ME grade should not be specified.
<table>
<thead>
<tr>
<th>Component</th>
<th>Question</th>
<th>Grade 1</th>
<th>Grade 2</th>
<th>Grade 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CC</strong></td>
<td>Is there a significant advantage to specifying creep coefficient in the design?</td>
<td>Yes</td>
<td>No</td>
<td>Yes, Specify CC - Grade 3</td>
</tr>
<tr>
<td></td>
<td>Is there an advantage in relieving large stresses or strains?</td>
<td>Yes</td>
<td>No</td>
<td>No, Specify CC - Grade 2</td>
</tr>
<tr>
<td></td>
<td>Is creep detrimental to the concrete element or surrounding elements?</td>
<td>Yes</td>
<td>No</td>
<td>Yes, Specify CC - Grade 1</td>
</tr>
<tr>
<td></td>
<td>No. CC grade should not be specified.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CP</strong></td>
<td>Is the concrete exposed to chloride salts or soluble sulfate environments?</td>
<td>Yes</td>
<td>No</td>
<td>Yes, Specify CP-Grade 3</td>
</tr>
<tr>
<td></td>
<td>Is the member exposed in a potentially moist environment?</td>
<td>Yes</td>
<td>No</td>
<td>No, Specify CP-Grade 2</td>
</tr>
<tr>
<td></td>
<td>Will the member be saturated completely during freezing?</td>
<td>Yes</td>
<td>No</td>
<td>No. Specify CP-Grade 1</td>
</tr>
<tr>
<td></td>
<td>No. CP grade should not be specified.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SH</strong></td>
<td>Is the concrete exposed to moisture, chloride salts or soluble sulfate environments?</td>
<td>Yes</td>
<td>No</td>
<td>Yes, Specify SH-Grade 3</td>
</tr>
<tr>
<td></td>
<td>Is the member constructed without joints?</td>
<td>Yes</td>
<td>No</td>
<td>No, Specify SH-Grade 2</td>
</tr>
<tr>
<td></td>
<td>Is the member designed to be watertight or crack free?</td>
<td>Yes</td>
<td>No</td>
<td>No. Specify SH-Grade 1</td>
</tr>
<tr>
<td></td>
<td>No. SH grade should not be specified.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AS</strong></td>
<td>Does the concrete contain reactive aggregates?</td>
<td>Yes</td>
<td>No</td>
<td>Yes, Specify AS - Grade 3</td>
</tr>
<tr>
<td></td>
<td>Is the concrete exposed to moisture?</td>
<td>Yes</td>
<td>No</td>
<td>No, Specify AS - Grade 2</td>
</tr>
<tr>
<td></td>
<td>Will the member be saturated during freezing?</td>
<td>Yes</td>
<td>No</td>
<td>No. Specify AS - Grade 1</td>
</tr>
<tr>
<td></td>
<td>No. AS grade should not be specified.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FT</td>
<td>Freeze Thaw Durability</td>
<td>Is the concrete exposed to freezing and thawing environments?</td>
<td>Yes</td>
<td>Is the member exposed to deicing salts?</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>SR</td>
<td>Scaling Durability</td>
<td>Is the concrete exposed to deicing salts?</td>
<td>Yes</td>
<td>Is the exposure a direct application of salt?</td>
</tr>
<tr>
<td>AB</td>
<td>Abrasion Resistance</td>
<td>Is the concrete exposed to surface abrasion?</td>
<td>Yes</td>
<td>Is the member subjected to other than tire wear?</td>
</tr>
<tr>
<td>SU</td>
<td>Sulfate Resistance</td>
<td>Is the concrete exposed to more than 0.10 percent soluble sulfates?</td>
<td>Yes</td>
<td>Is the member exposed to more than 0.20 percent soluble sulfates?</td>
</tr>
</tbody>
</table>
Parameters to be achieved for durable bridge decks:

<table>
<thead>
<tr>
<th>Performance Characteristics</th>
<th>Standard Test Method</th>
<th>Proposed HPC performance grade</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CS</strong> Compressive Strength, MPa (ksi)</td>
<td>AASHTO T 22</td>
<td>24≤X&lt;55 @ 28 days (3.5≤X&lt;8.0)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>55≤X @ 28 days (8.0≤X)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24≤X @ specified time &lt; 48 hrs. (3.5≤X)</td>
</tr>
<tr>
<td><strong>SD</strong> Strength ratio 28 day fy, 7 day f_y</td>
<td>AASHTO T 22</td>
<td>X≥1.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X≥1.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X≥1.45</td>
</tr>
<tr>
<td><strong>TS</strong> Tensile strength MPa (psi)</td>
<td>ASTM C 496</td>
<td>4 &gt;X≤5 (580≤X&lt;720)</td>
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<td>20≤X&lt;30 (2.9≤X&lt;4.3)</td>
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<td></td>
<td>30≤X&lt;45 (4.3≤X&lt;6.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45≤X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(6.5≤X)</td>
</tr>
<tr>
<td><strong>CC</strong> Creep Coefficient Micro strain/micro strain</td>
<td>ASTM C 512*</td>
<td>2≤X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2&gt;X≥1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.4&gt;X</td>
</tr>
<tr>
<td><strong>CP</strong> Chloride penetration, Coulombs</td>
<td>AASHTO T 277*</td>
<td>4000≤X</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>800≤X</td>
</tr>
<tr>
<td><strong>SH</strong> Shrinkage (micro strain)</td>
<td>ASTM C 157</td>
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</tr>
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<td></td>
<td></td>
<td>500≤X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200≤X</td>
</tr>
<tr>
<td><strong>AS</strong> Alkali-silica reaction</td>
<td>AASHTO T 303</td>
<td>X&lt;0.10% At 14 Days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X&lt;0.10% At 14 Days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X&lt;0.10% At 14 Days</td>
</tr>
<tr>
<td></td>
<td>ASTM C 441</td>
<td>X&gt;50% Reduction in Expansion At 56 Days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X&gt;60% Reduction in Expansion At 56 Days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X&gt;70% Reduction in Expansion At 56 Days</td>
</tr>
<tr>
<td><strong>FT</strong> Freeze-thaw durability (relative modulus, 300 cycles)</td>
<td>AASHTO T 161 Proc. A</td>
<td>60%≤X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80%≤ X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90%≤ X</td>
</tr>
<tr>
<td><strong>SR</strong> Scaling resistance (visual rating of surface 50 cycles)</td>
<td>ASTM C 672</td>
<td>X≤3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X≤1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X=0</td>
</tr>
<tr>
<td><strong>AB</strong> Abrasion resistance (wear depth, mm)</td>
<td>ASTM C 994</td>
<td>2.0≤X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0≥X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5≥X</td>
</tr>
<tr>
<td><strong>SU</strong> Sulfate resistance (expansion)</td>
<td>ASTM C 1012</td>
<td>X&lt;0.10% At 6 months</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X&lt;0.10% At 12 months</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X&lt;0.10% At 18 months</td>
</tr>
</tbody>
</table>
Appendix A2. Material Specifications

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

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