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High-Performance Concrete Defined for Highway Structures

by Charles H. Goodspeed,
Suneel Vanikar,
and Raymond A. Cook

From the High-Performance Concrete Committee Special Report No. 4

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High-Performance Concrete Defined for Highway Structures

by Charles H. Goodspeed, Suneel Vanikar, and Raymond A. Cook

The Strategic Highway Research Program (SHRP) has investigated more than 60 concrete and structural products.[1] To stimulate the use of selected products by state highway agencies, the Federal Highway Administration (FHWA) is using a "Showcase" to demonstrate these and other new product technologies. Products selected for showcasing include those contributing to the production and performance evaluation of higher quality concrete.

To establish a clear understanding of high performance concrete (HPC), the FHWA is proposing to define HPC by using long-term performance criteria. The proposed definition consists of four durability and four strength parameters. Associated with each definition parameter are performance criteria, testing procedures to measure performance, and recommendations to relate performance to adverse field conditions. To specify an HPC concrete mixture using the FHWA definition of the material, a user states the level of performance desired for each performance characteristic, based on field conditions. Updates will be required to keep the definition current with improvements in technology and with field experience.

FHWA's primary purpose in offering a "Showcase" and preparing the HPC definition is to stimulate the use of higher quality concrete in highway structures. A recent study conducted in the Chicago area evaluated the performance characteristics of commercially available concrete ranging in strength from 70 to 140 MPa (10 to 20 ksi).[2] This study demonstrated that a significant improvement in concrete durability resulted from an increase in strength. That HPC is not specified more frequently may be because engineers do not have confidence that higher strength concrete is more durable, that it can be reliably achieved in the field, that the higher strength can not always be used, or combinations thereof.

The FHWA's "Showcase" addresses these issues by illustrating cost-effective state-of-the art procedures for producing, evaluating, and designing with HPC. The FHWA is sponsoring a number of state highway agency demonstration projects over the next several years to illustrate the use of HPC.

This article presents the performance definition of HPC by using three tables: Table 1 gives the parameters and performance criteria; Table 2 identifies standard tests to evaluate performance, and Table 3 relates recommended performance to exposure conditions.

Approach

A SHRP study[3] defined HPC as consisting of: 1) a maximum water-cementitious ratio (*w/c*) of 0.35; 2) a minimum durability factor of 80 percent as determined by ASTM C 666, Procedure A; and 3) a minimum strength criteria of either: a) 21 MPa (3000 psi) within 4 hours after placement (very early strength, VES); b) 34 MPa (5000 psi) within 24 hours (high early strength, HES); or c) 69 MPa (10,000 psi) within 28 days (very high strength, VHS).

An American Concrete Institute committee has defined HPC (see Preface of ACI Special Publication SP-140, *High-Performance Concrete in Severe Environments*) as concrete that meets special performance and uniformity requirements that can not always be obtained using conventional ingredients, normal mixing procedures, and typical curing practices. These requirements may include the following enhancements:

- Ease of placement and consolidation without affecting strength,
- Long-term mechanical properties,
- Early high strength,
- Toughness,
- Volume stability, and
- Longer life in severe environments.

The SHRP definition uses *w/c* as a mixture proportion criterion to define

Table 1 — Grades of performance characteristics for high performance structural concrete[1]

Performance characteristic[2]	Standard test method	FHWA HPC performance grade[3]				
		1	2	3	4	N/A
Freeze-thaw durability[4] (x=relative dynamic modulus of elasticity after 300 cycles	AASHTO T 161 ASTM C 666 Proc. A	$60\% \leq x < 80\%$	$80\% \leq x$			
Scaling resistance[5] (x=visual rating of the surface after 50 cycles)	ASTM C 672	x=4,5	x=2,3	x=0,1		
Abrasion resistance[6] (x=avg. depth of wear in mm)	ASTM C 944	$2.0 > x \geq 1.0$	$1.0 > x \geq 0.5$	$0.5 > x$		
Chloride penetration[7] (x=coulombs)	AASHTO T 277 ASTM C 1202	$3000 \geq x > 2000$	$2000 \geq x > 800$	$800 \geq x$		
Strength (x=compressive strength)	AASHTO T 2 ASTM C 39	$41 \leq x < 55$ MPa ($6 \leq x < 8$ ksi)	$55 \leq x < 69$ MPa ($8 \leq x < 10$ ksi)	$69 \leq x < 97$ MPa ($10 \leq x < 14$ ksi)	$x \geq 97$ MPa ($x \geq 14$ ksi)	
Elasticity[10] (x=modulus of elasticity)	ASTM C 469	$28 \leq x < 40$ GPa ($4 \leq x < 6x10^6$ psi)	$40 \leq x < 50$ GPa ($6 \leq x < 7.5x10^6$ psi)	$x \geq 50$ GPa ($x \geq 7.5x10^6$ psi)		
Shrinkage[8] (x=microstrain)	ASTM C 157	$800 > x \geq 600$	$600 > x \geq 400$	$400 > x$		
Creep[9] (x=microstrain/pressure unit)	ASTM C 512	$75 \geq x > 60$/MPa ($0.52 \geq x > 0.41$/psi)	$60 \geq x > 45$/MPa ($0.41 \geq x > 0.31$/psi)	$45 \geq x > 30$/MPa ($0.31 \geq x > 0.21$/psi)	30 MPa$\geq x$ (0.21 psi$\geq x$)	

[1]This table does not represent a comprehensive list of all characteristics that good concrete should exhibit. It does list characteristics that can quantifiably be divided into different performance groups. Other characteristics should be checked. For example, HPC aggregates should be tested for detrimental alkali silica reactivity according to ASTM C 227, cured at 38 C, and tested at 23 C and should yield less than 0.05 percent mean expansion at 3 months and less than 0.10% expansion at 6 months (based on SHRP C-342, p. 83). Due consideration should also be paid to (but not necessarily limited to) acidic environments and sulfate attack.

[2]All tests to be performed on concrete samples moist or submersion cured for 56 days. See Table 2for additional information and exceptions.

[3]A given HPC mix design is specified by a grade for each desired performance characteristic. For example, a concrete may perform at Grade 4 in strength and elasticity, Grade 3 in shrinkage and scaling resistance, and Grade 2 in all other categories.

[4]Based on SHRP C/FR-91-103, p. 3.52.

[5]Based on SHRP S-360.

[6]Based on SHRP C/FR-91-103.

[7]Based on *PCA Engineering Properties of Commercially Available High-Strength Concretes.*

[8]Based on SHRP C/FR-91-103, p. 3.25.

[9]Based on SHRP C/FR-91-103, p. 3.30.

[10]Based on SHRP C/FR-91-103, p. 3.17.

HPC. The ACI committee cites fresh concrete properties, and both refer to long-term performance parameters. By restricting the definition to long-term performance parameters, concrete mixture designers may be more willing to incrementally modify mixture designs, change concrete curing procedures, and use admixtures and alternate hydraulic cements such as granulated ground blast furnace slag (gbfs). Use of a performance definition alone can not, however, address all deterioration mechanisms. There is insufficient experience to relate laboratory test results with resistance to the wide range and combination of field conditions. Deterioration stemming from poor quality materials subjected to an adverse environment can also represent problems of quality control and quality assurance.

For bridge engineers to adopt a HPC performance definition it must include adequate durability and strength parameters.[4] The proposed HPC definition uses eight parameters and relates four to deterioration resistance. It also cites standard tests to evaluate the performance of each parameter.

Durability, strength parameters

The definition has an adequate number of performance parameters to facilitate its applications as a guide when specifying concrete mixtures. The HPC definition resulted from an investigation of general field conditions that cause concrete structures to deteriorate. Field conditions can be divided into three categories: climate, exposure effects, and loads. Climatic conditions include temperature fluctuations, cycles of freezing and thawing, and relative humidity. Exposure conditions include the presence of salts (applied for deicing or suspended in water) and aggressive chemicals (sulfates, acids, and carbon dioxide). Loading conditions include traffic, wind, earthquake, and other factors inducing applied loads.

Climate may cause adverse thermal expansion, an undesirable moisture content, or a deterioration of strength due to cycles of freezing and thawing. Exposure to aggressive chemical agents may cause scaling, destructive expansion within the concrete, or corrosion of reinforcing steel. Stresses due

Table 2 — Details of test methods for determining HPC performance grades

Performance Characteristic	Standard Test Method	Notes[1]
Freeze/Thaw Durability	AASHTO T 161 ASTM C 666 Proc. A	1. Test specimen 76.2 x 76.2 x 279.4 mm (3 x 3 x 11 in.) as cast or cut from 152.4 x 304.8 mm (6 x 12 in.) cylinder. 2. Acoustically measure dynamic modulus until 300 cycles.
Scaling Resistance	ASTM C 672	1. Test specimen to have a surface area of 46,451 mm^2 (72 $in.^2$). 2. Perform visual inspection after 50 cycles.
Abrasion	ASTM C 944	1. Concrete shall be tested at 3 different locations. 2. At each location, 98 Newtons, for three, 2 minute, abrasion periods shall be applied for a total of 6 minutes of abrasion time per location. 3. The depth of abrasion shall be determined per ASTM C 799 Procedure B.
Chloride Penetration	AASHTO T 277 ASTM C 1202	1. Test per standard test method.
Strength	AASHTO T 22 ASTM C39	1. Molds shall be rigid metal or one time use rigid plastic. 2. Cylinders shall be 100 mm dia. x 200 mm long (3.9 x 7.8 in.) or 150 mm dia. x 300 mm long (5.9 x 11.2 in.). 3. Ends shall be capped with high strength capping compound, ground parallel, or placed onto neoprene pads per AASHTO Specifications for Concretes. 4. Use of neoprene pads on early age testing of concrete exceeding 70 MPa at 56 days should use neoprene pads on the 56 day tests. 5. The 56 day strength is recommended.
Elasticity	ASTM C 469	1. Test per standard test method.
Shrinkage	ASTM C 157	1. Use 76.2 x 76.2 x 285 mm (3 x 3 x 11.25 in.) specimens. 2. Shrinkage measurements are to start 28 days after moist curing and be taken for a drying period of 180 days.
Creep	ASTM C 512	1. Use 152 x 305 mm (6 x 12 in.) specimens. 2. Cure specimens at 73 F and 50 percent RH after 7 days until loading at 28 days. 3. Creep measurements to be taken for a creep loading period of 180 days.

[1]See footnote to Table 1 for the curing period to be used before testing.

to loading may result in unacceptable creep, deflection, capacity, or cracking. Each field condition was evaluated to identify independent concrete performance parameters that represent an acceptable durability or strength characteristic for defining HPC.

Climatic conditions: Temperature affects concrete by thermal expansion and contraction from heating and cooling, and also by freezing water that induces internal stresses. Structural designs normally consider thermally induced expansion and contraction. Thermal expansion and contraction are not typically considered in specifying a mixture.

Mixture ingredients and proportions thereof, mixing sequence, curing conditions and concrete permeability affect the ability of concrete in a saturated condition to resist deterioration when subjected to freezing and thawing. Important characteristics include the air-void system, soundness of the aggregate, and concrete maturity. Although these concrete characteristics can be measured independently, it is the combined effect of these characteristics that results in overall long term performance.[5] It is the combined effect that must be represented in a long term HPC definition.

Exposure conditions: The application of road salts results in a pore water solution high in chloride ions. Over time these solutions promote corrosion of reinforcing steel. The corrosive reaction is expansive and causes tensile stress in the concrete. When the tensile stresses exceed concrete tensile strength, the concrete begins to spall. Steel corrosion occurs in concrete when the acid-soluble chloride content minus the background chloride reaches 0.72 g/m^3 (1.2 lb/yd^3), when pore water exists, and when oxygen is present.[6,7] The presence of all three is required for corrosion to occur. Concrete with low permeability slows the corrosion process by reducing the rate of chloride ion diffusion into the concrete. Reducing the presence of this one corrosion ingredient is often sufficient to adequately delay the onset of corrosion. Thus, it can represent resistance to corrosion.

Aside from causing steel corrosion, the repeated application of deicing chemicals has the potential to create scaling, pitting, spalling, and flaking of concrete surfaces. The exact cause of these problems is not completely understood. However, when deicing chemicals are used to melt ice, the following process occurs: the ice melts, the concrete thaws, the melt water is absorbed, the surface concrete becomes more fully saturated, the melt water is diluted; if the concrete surface freezes again it undergoes a freezing and thawing cycle that it would not have experienced had it remained frozen. This cycle can repeat and deteriorate concrete lacking adequate freezing and thawing resistance in one winter, whereas the same concrete when not exposed may not show any frost damage. Furthermore, endothermic nature of melting ice with salt is detrimental to concrete. The melting absorbs energy that causes the temperature of the concrete to drop rapidly just below the ice surface. This may result in damage from the effects of rapid freezing and differential thermal strains. Curing history, water-cementitious ratio, air content, moisture content, characteristics of the freezing and thawing cycle, and salt concentration may affect concrete scaling resistance. Again, it is the combined effect that rep-

Table 3 — Recommendations for the application of HPC grades

	Recommended HPC Grade for Given Exposure Condition				
Exposure condition	N/A[2]	Grade 1	Grade 2	Grade 3	Grade 4
Freeze/Thaw Durability Exposure (x = F/T cycles per year)[1]	$x < 3$	$3 \leq x < 50$	$50 \leq x$		
Scaling Resistance Applied Salt[3] (x = tons/lane-mile-year)	$x < 5.0$	$5.0 \leq x$			
Abrasion Resistance (x = average daily traffic, studded tires allowed)	no studs/chains	$x \leq 50{,}000$	$50{,}000 < x < 100{,}000$	$100{,}000 \leq x$	
Chloride Penetration Applied Salt[3] (x = tons/lane-mile-year)	$x < 1$	$1.0 \leq x < 3.0$	$3.0 \leq x < 6.0$	$6.0 \leq x$	

[1]F/T stands for "freeze/thaw." A freeze/thaw cycle is defined as an event where saturated concrete is subjected to an ambient temperature which drops below -2.2°C (28°F) followed by a rise in temperature above freezing.
[2]N/A stands for "not applicable" and indicates a situation in which specification of an HPC performance grade is unnecessary.
[3]As defined in SHRP S-360.

resents performance against scaling and should all be represented in a definition scaling parameter.

Care must be taken to investigate the effect of aggressive chemicals when field conditions warrant. Highway structures can be exposed to a wide range of aggressive chemicals that deteriorate concrete. The diversity of chemical attack makes it difficult to represent concrete resistance to aggressive chemicals by a single durability performance parameter. Thus, it is considered the responsibility of the designer to address the potential effects of ambient project conditions. The need to be aware of aggressive chemicals is footnoted in Table 1.

Loading conditions: Concrete durability and strength parameters are not necessarily independent. An increase in a durability parameter can result in a jump in strength and vice versa. Loading conditions may not warrant the strength developed in concrete proportioned to meet durability criteria. Structural designers may specify concrete performance in terms of limiting volume change (i.e., creep and shrinkage) and achieving a minimum modulus of elasticity. These characteristics along with strength are generally sufficient to represent the mechanical concrete properties used in structural design. Other characteristics, such as modulus of rupture, can generally be estimated using these primary characteristics. Other parameters can be calculated or may need to be experimentally determined.

The action of vehicular traffic or solids suspended in flowing water abrade concrete surfaces. Surface wear is normally not a controlling factor in deck and roadway performance. However, in areas where the use of studded tires is permitted, abrasion can be significant. In these situations the ability of the concrete to resist abrasion is an important performance parameter.

Deterioration resistance

Eight parameters were identified as sufficient to represent HPC long-term performance (Table 1). To use the definition as a basis for specifying concrete, relationships were required to establish the performance parameter and the resistance to exposure conditions. To accomplish this, it was necessary to identify desired performance grades for the definition parameters and their relationship to project field conditions. Each parameter grade must represent a measure of performance when subjected to a field condition. Using grades to represent performance, an engineer can specify a mixture to yield a desired concrete service life. Each parameter can be independently specified by grade. An example is a mixture for a bridge deck subjected to high usage of deicing salts, high frequency of freezing and thawing cycles, and narrow beam spacing. This may be specified by a high grade to resist freezing and thawing distress, a medium to high grade to combat scaling, abrasion, and chloride penetration, and a low grade to obtain strength and elasticity.

Performance is represented by test variables such as the percentage of dynamic modulus of elasticity remaining after 300 prescribed cycles of freezing and thawing or a range of compressive strengths. Grades start at low performance levels and small enough increments are defined to allow engineers to incrementally begin specifying higher quality concrete. The strength grades start at a performance level that is easily attainable and spans to a superior grade. The definition is intended to cover all grades of concrete that can be readily used by the highway industry.

Testing procedures

Standard test methods were identified to ascertain performance for the eight definition parameters. These procedures and specimen preparation not specified in the standard test procedures are given in Table 2. To achieve uniformity in evaluating performance, the following specimen and curing procedures were stipulated for each test, except as noted elsewhere in this article:

- Cylinders: 100 mm diameter x 200 mm long (4 x 8 in.), or 150 mm diameter x 300 mm long (6 x12 in.).
- Curing: non-steam cured products; moist cure specimens for 56 days or until test age, or match cure and use a maturity meter. For steam cured products, cure specimens with the member or match cure until test age.

The standard tests, performance parameter variables, and respective grades are described:

Resistance to freezing and thawing, ASTM C666, Procedure A, or AASHTO T 161: The test procedure is to be continued for 300 cycles or until the relative dynamic modulus of elasticity drops below 60 percent. Two HPC grades of resistance to freezing and thawing are delineated by the percentage of dynamic modulus of elasticity after 300 cycles. Grade 1 is defined as 60 to 80 percent remaining of the original dynamic modulus of elasticity and Grade 2 is defined as greater than 80 percent of the original dynamic modulus of elasticity.

Scaling test, ASTM C 672: This test must be done for 50 cycles. Scaling performance is evaluated after 50 cycles by visually inspecting specimens as prescribed by C 672. Grade 1 is defined by a visual inspection rating of 4 or 5, Grade 2 by a rating of 2 or 3, and Grade 3 by 0 or 1.

Abrasion, ASTM C 944: Test areas should receive a light trowel finish. Specimens should be field cured for 56 days and air dried for two hours before testing. The tests should then be carried out on three different cylinders or at three different areas on the surface of a concrete structure. A 196 N force for three two minutes periods for a total of six minutes should be used for each abrasion test. A wear depth is then measured. The grades are inversely proportional to wear; a low performance grade is assigned to the higher measurements of wear and a high grade is assigned to the lower measurements of wear.

Chloride test, AASHTO T277, ASTM C 1202: Chloride test specimens should be moist cured for 56 days. Grades are shown in Table 1.

Strength, AASHTO T 22: Strength test specimens must be cast in metal or rigid plastic molds. Compression specimens should have the ends capped, ground parallel, or be tested using neoprene pads per AASHTO or ASTM specifications. The diversity of strength needs and the variation of strengths used in practice necessitates a wide range of strength grades starting at 41 MPa (6 ksi) for Grade 1 to greater than 97 Mpa (14 ksi) for Grade 4. Bridge engineers currently specifying strengths less than Grade 1 can begin the transition to a higher durability and strength concrete by stipulating minimum HPC performance grades. The highest level is specified to define the state of the art in highway concrete usage.

Static modulus of elasticity, ASTM C 469: Standard test procedures should be followed for this test. Grades range from a low of 28 GPa (4 x 10^6 psi) for Grade 1 to greater than 50 GPa (7.5 x 10^6 psi) for Grade 3.

Creep and shrinkage, ASTM C 512 and ASTM C 157: Creep and shrinkage specimens should be moist cured for 28 days, and then tests performed for an additional 180 days. Creep test loading and air storage of shrinkage specimens should start at the 28 day age. Grades of performance are as shown in Table 1.

Test performance, field conditions

Grades of performance were defined for each of the eight parameters in the HPC definition. Field condition severity was estimated for the full range of potential field conditions occurring in the United States (Table 3).

Freeze and thawing: A field freezing and thawing cycle is defined as a decrease in temperature to -2.2 C (28 F) or below followed by a thaw.[8] This field condition is recorded throughout the United States by the Geological Society and is reported by the number of occurrences per year and shown on a national map.[9] A relationship between the deteriorating effect of a field cycle and a laboratory cycle, per AASHTO T 161, is estimated. The currently recommended relationship is as follows: when fewer than three field cycles occur per year no consideration is required; between three and 50 field cycles per year, the use of Grade 1 is recommended; and Grade 2 for above 50 field cycles. This relationship is recommended as a lower bound for specifying HPC.

Scaling: Data are not available to substantiate a strong recommendation between performance grade and field severity. The relationship given should be taken as a suggestion until further research is available.

Abrasion: Normal surface abrasion from rubber tires typically does not warrant abrasion resistance consideration assuming that there is well-cured concrete of appropriate strength. However, the use of studded tires on highways does warrant such consideration. A Grade 1 is recommended for less than a 50,000 average daily traffic count, Grade 2 for greater than 50,000 and less than 100,000, and Grade 3 for greater than 100,000 when steel studded tires are permitted. Similar estimates can be made by local engineers if the use of car chains is prevalent. Recommendations for other abrasion conditions such as a stream flow laden with abrasive materials are the responsibility of the project engineer.

Chloride penetration: Coulombs measured in the rapid chloride permeability test were used in this research to estimate performance grades relative to steel corrosion. Grade 1 was defined between 2000 and 3000 coulombs, Grade 2 between 800 and 2000, and Grade 3 less than 800 coulombs. A corrosion model to predict service life based on chloride content in the concrete were recommended, using the following assumptions: a 30-year life span; 2 in. of cover with a standard deviation of 0.3 in.; and a range of applied quantities of deicing salt.

Mechanical properties: Grades of performance are designated in Table 1. Material and structural designers can select and specify appropriate grades for a project.

Conclusions

The HPC definition presented here identifies a set of concrete performance characteristics sufficient to estimate long-term concrete durability and strength for highway structures. Standard laboratory tests, specimen preparation procedures, and grades of performance were suggested for each definition parameter. Relationships between performance and severity of field conditions were estimated to assist designers in selecting the grade of HPC for a particular project. Because there is a lack of information correlating field condition severity and laboratory performance, these relationships serve only as suggestions. Thus, this definition is a guide and identifies areas in which additional research is needed.

Bridge engineers and other concrete designers are encouraged to begin using the definition as a tool in expanding their understanding and confidence in concrete with high performance. It is anticipated that research and experience gained from the FHWA demonstration projects and other sources will result in continued updates to these tables. Note that specified relationships between laboratory performance data and resistance to field conditions are only suggestions. Information gained from local experience should receive careful consideration.

In the transportation industry, it has always been the goal to use concrete with characteristics at appropriate levels to insure satisfactory performance for the intended service life. Though success has often been achieved, attention seems to focus on those cases without such desirable conclusions. When concrete does not perform as desired, either the specifications were inadequate or not followed properly. Modern QC/QA procedures should greatly increase the likelihood that specifications are met when followed.

At a recent HPC workshop, it was suggested that if the concrete to be used was produced to strictly comply with relevant code requirements it should be a high-performance concrete.[11] The intent of high-performance concrete, as defined here, is not to produce a high cost product but simply to provide the means for making concrete that will perform satisfactorily with only reasonable maintenance costs for intended service life.[12]

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Selected for reader interest by the editors.

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Abrasion resistance[6] (x=avg. depth of wear in mm)	ASTM C 944	$2.0 > x \ge 1.0$	$1.0 > x \ge 0.5$	$0.5 > x$		
Chloride penetration[7] (x=coulombs)	AASHTO T 277 ASTM C 1202	$3000 \ge x > 2000$	$2000 \ge x > 800$	$800 \ge x$		
Strength (x=compressive strength)	AASHTO T 2 ASTM C 39	$41 \le x < 55$ MPa ($6 \le x < 8$ ksi)	$55 \le x < 69$ MPa ($8 \le x < 10$ ksi)	$69 \le x < 97$ MPa ($10 \le x < 14$ ksi)	$x \ge 97$ MPa ($x \ge 14$ ksi)	
Elasticity[10] (x=modulus of elasticity)	ASTM C 469	$28 \le x < 40$ GPa ($4 \le x < 6 \times 10^6$ psi)	$40 \le x < 50$ GPa ($6 \le x < 7.5 \times 10^6$ psi)	$x \ge 50$ GPa ($x \ge 7.5 \times 10^6$ psi)		
Shrinkage[8] (x=microstrain)	ASTM C 157	$800 > x \ge 600$	$600 > x \ge 400$	$400 > x$		
Creep[9] (x=microstrain/pressure unit)	ASTM C 512	$75 \ge x > 60$/MPa ($0.52 \ge x > 0.41$/psi)	$60 \ge x > 45$/MPa ($0.41 \ge x > 0.31$/psi)	$45 \ge x > 30$/MPa ($0.31 \ge x > 0.21$/psi)	30 MPa$\ge x$ (0.21 psi$\ge x$)	

[1]This table does not represent a comprehensive list of all characteristics that good concrete should exhibit. It does list characteristics that can quantifiably be divided into different performance groups. Other characteristics should be checked. For example, HPC aggregates should be tested for detrimental alkali silica reactivity according to ASTM C 227, cured at 38 C, and tested at 23 C and should yield less than 0.05 percent mean expansion at 3 months and less than 0.10% expansion at 6 months (based on SHRP C-342, p. 83). Due consideration should also be paid to (but not necessarily limited to) acidic environments and sulfate attack.

[2]All tests to be performed on concrete samples moist or submersion cured for 56 days. See Table 2for additional information and exceptions.

[3]A given HPC mix design is specified by a grade for each desired performance characteristic. For example, a concrete may perform at Grade 4 in strength and elasticity, Grade 3 in shrinkage and scaling resistance, and Grade 2 in all other categories.

[4]Based on SHRP C/FR-91-103, p. 3.52.

[5]Based on SHRP S-360.

[6]Based on SHRP C/FR-91-103.

[7]Based on *PCA Engineering Properties of Commercially Available High-Strength Concretes.*

[8]Based on SHRP C/FR-91-103, p. 3.25.

[9]Based on SHRP C/FR-91-103, p. 3.30.

[10]Based on SHRP C/FR-91-103, p. 3.17.

HPC. The ACI committee cites fresh concrete properties, and both refer to long-term performance parameters. By restricting the definition to long-term performance parameters, concrete mixture designers may be more willing to incrementally modify mixture designs, change concrete curing procedures, and use admixtures and alternate hydraulic cements such as granulated ground blast furnace slag (gbfs). Use of a performance definition alone can not, however, address all deterioration mechanisms. There is insufficient experience to relate laboratory test results with resistance to the wide range and combination of field conditions. Deterioration stemming from poor quality materials subjected to an adverse environment can also represent problems of quality control and quality assurance.

For bridge engineers to adopt a HPC performance definition it must include adequate durability and strength parameters.[4] The proposed HPC definition uses eight parameters and relates four to deterioration resistance. It also cites standard tests to evaluate the performance of each parameter.

Durability, strength parameters

The definition has an adequate number of performance parameters to facilitate its applications as a guide when specifying concrete mixtures. The HPC definition resulted from an investigation of general field conditions that cause concrete structures to deteriorate. Field conditions can be divided into three categories: climate, exposure effects, and loads. Climatic conditions include temperature fluctuations, cycles of freezing and thawing, and relative humidity. Exposure conditions include the presence of salts (applied for deicing or suspended in water) and aggressive chemicals (sulfates, acids, and carbon dioxide). Loading conditions include traffic, wind, earthquake, and other factors inducing applied loads.

Climate may cause adverse thermal expansion, an undesirable moisture content, or a deterioration of strength due to cycles of freezing and thawing. Exposure to aggressive chemical agents may cause scaling, destructive expansion within the concrete, or corrosion of reinforcing steel. Stresses due to loading may result in unacceptable creep, deflection, capacity, or cracking. Each field condition was evaluated to identify independent concrete performance parameters that represent an acceptable durability or strength characteristic for defining HPC.

Climatic conditions: Temperature affects concrete by thermal expansion and contraction from heating and cooling, and also by freezing water that induces internal stresses. Structural designs normally consider thermally induced expansion and contraction. Thermal expansion and contraction are not typically considered in specifying a mixture.

Mixture ingredients and proportions thereof, mixing sequence, curing conditions and concrete permeability affect the ability of concrete in a saturated condition to resist deterioration when subjected to freezing and thawing. Important characteristics include the air-void system, soundness of the aggregate, and concrete maturity. Although these concrete characteristics can be measured independently, it is the combined effect of these characteristics that results in overall long term performance.[5] It is the combined effect that must be represented in a long term HPC definition.

Exposure conditions: The application of road salts results in a pore water solution high in chloride ions. Over time these solutions promote corrosion of reinforcing steel. The corrosive reaction is expansive and causes tensile stress in the concrete. When the tensile stresses exceed concrete tensile strength, the concrete begins to spall. Steel corrosion occurs in concrete when the acid-soluble chloride content minus the background chloride reaches 0.72 g/m^3 (1.2 lb/yd^3), when pore water exists, and when oxygen is present.[6,7] The presence of all three is required for corrosion to occur. Concrete with low permeability slows the corrosion process by reducing the rate of chloride ion diffusion into the concrete. Reducing the presence of this one corrosion ingredient is often sufficient to adequately delay the onset of corrosion. Thus, it can represent resistance to corrosion.

Table 2 — Details of test methods for determining HPC performance grades

Performance Characteristic	Standard Test Method	Notes[1]
Freeze/Thaw Durability	AASHTO T 161 ASTM C 666 Proc. A	1. Test specimen 76.2 x 76.2 x 279.4 mm (3 x 3 x 11 in.) as cast or cut from 152.4 x 304.8 mm (6 x 12 in.) cylinder. 2. Acoustically measure dynamic modulus until 300 cycles.
Scaling Resistance	ASTM C 672	1. Test specimen to have a surface area of 46,451 mm^2 (72 in.^{2}). 2. Perform visual inspection after 50 cycles.
Abrasion	ASTM C 944	1. Concrete shall be tested at 3 different locations. 2. At each location, 98 Newtons, for three, 2 minute, abrasion periods shall be applied for a total of 6 minutes of abrasion time per location. 3. The depth of abrasion shall be determined per ASTM C 799 Procedure B.
Chloride Penetration	AASHTO T 277 ASTM C 1202	1. Test per standard test method.
Strength	AASHTO T 22 ASTM C39	1. Molds shall be rigid metal or one time use rigid plastic. 2. Cylinders shall be 100 mm dia. x 200 mm long (3.9 x 7.8 in.) or 150 mm dia. x 300 mm long (5.9 x 11.2 in.). 3. Ends shall be capped with high strength capping compound, ground parallel, or placed onto neoprene pads per AASHTO Specifications for Concretes. 4. Use of neoprene pads on early age testing of concrete exceeding 70 MPa at 56 days should use neoprene pads on the 56 day tests. 5. The 56 day strength is recommended.
Elasticity	ASTM C 469	1. Test per standard test method.
Shrinkage	ASTM C 157	1. Use 76.2 x 76.2 x 285 mm (3 x 3 x 11.25 in.) specimens. 2. Shrinkage measurements are to start 28 days after moist curing and be taken for a drying period of 180 days.
Creep	ASTM C 512	1. Use 152 x 305 mm (6 x 12 in.) specimens. 2. Cure specimens at 73 F and 50 percent RH after 7 days until loading at 28 days. 3. Creep measurements to be taken for a creep loading period of 180 days.

[1]See footnote to Table 1 for the curing period to be used before testing.

Aside from causing steel corrosion, the repeated application of deicing chemicals has the potential to create scaling, pitting, spalling, and flaking of concrete surfaces. The exact cause of these problems is not completely understood. However, when deicing chemicals are used to melt ice, the following process occurs: the ice melts, the concrete thaws, the melt water is absorbed, the surface concrete becomes more fully saturated, the melt water is diluted; if the concrete surface freezes again it undergoes a freezing and thawing cycle that it would not have experienced had it remained frozen. This cycle can repeat and deteriorate concrete lacking adequate freezing and thawing resistance in one winter, whereas the same concrete when not exposed may not show any frost damage. Furthermore, endothermic nature of melting ice with salt is detrimental to concrete. The melting absorbs energy that causes the temperature of the concrete to drop rapidly just below the ice surface. This may result in damage from the effects of rapid freezing and differential thermal strains. Curing history, water-cementitious ratio, air content, moisture content, characteristics of the freezing and thawing cycle, and salt concentration may affect concrete scaling resistance. Again, it is the combined effect that rep-

Table 3 — Recommendations for the application of HPC grades

Exposure condition	Recommended HPC Grade for Given Exposure Condition: N/A[2]	Grade 1	Grade 2	Grade 3	Grade 4
Freeze/Thaw Durability Exposure (x = F/T cycles per year)[1]	$x < 3$	$3 \le x < 50$	$50 \le x$		
Scaling Resistance Applied Salt[3] (x = tons/lane-mile-year)	$x < 5.0$	$5.0 \le x$			
Abrasion Resistance (x = average daily traffic, studded tires allowed)	no studs/chains	$x \le 50{,}000$	$50{,}000 < x < 100{,}000$	$100{,}000 \le x$	
Chloride Penetration Applied Salt[3] (x = tons/lane-mile-year)	$x < 1$	$1.0 \le x < 3.0$	$3.0 \le x < 6.0$	$6.0 \le x$	

[1]F/T stands for "freeze/thaw." A freeze/thaw cycle is defined as an event where saturated concrete is subjected to an ambient temperature which drops below -2.2°C (28°F) followed by a rise in temperature above freezing.
[2]N/A stands for "not applicable" and indicates a situation in which specification of an HPC performance grade is unnecessary.
[3]As defined in SHRP S-360.

resents performance against scaling and should all be represented in a definition scaling parameter.

Care must be taken to investigate the effect of aggressive chemicals when field conditions warrant. Highway structures can be exposed to a wide range of aggressive chemicals that deteriorate concrete. The diversity of chemical attack makes it difficult to represent concrete resistance to aggressive chemicals by a single durability performance parameter. Thus, it is considered the responsibility of the designer to address the potential effects of ambient project conditions. The need to be aware of aggressive chemicals is footnoted in Table 1.

Loading conditions: Concrete durability and strength parameters are not necessarily independent. An increase in a durability parameter can result in a jump in strength and vice versa. Loading conditions may not warrant the strength developed in concrete proportioned to meet durability criteria. Structural designers may specify concrete performance in terms of limiting volume change (i.e., creep and shrinkage) and achieving a minimum modulus of elasticity. These characteristics along with strength are generally sufficient to represent the mechanical concrete properties used in structural design. Other characteristics, such as modulus of rupture, can generally be estimated using these primary characteristics. Other parameters can be calculated or may need to be experimentally determined.

The action of vehicular traffic or solids suspended in flowing water abrade concrete surfaces. Surface wear is normally not a controlling factor in deck and roadway performance. However, in areas where the use of studded tires is permitted, abrasion can be significant. In these situations the ability of the concrete to resist abrasion is an important performance parameter.

Deterioration resistance

Eight parameters were identified as sufficient to represent HPC long-term performance (Table 1). To use the definition as a basis for specifying concrete, relationships were required to establish the performance parameter and the resistance to exposure conditions. To accomplish this, it was necessary to identify desired performance grades for the definition parameters and their relationship to project field conditions. Each parameter grade must represent a measure of performance when subjected to a field condition. Using grades to represent performance, an engineer can specify a mixture to yield a desired concrete service life. Each parameter can be independently specified by grade. An example is a mixture for a bridge deck subjected to high usage of deicing salts, high frequency of freezing and thawing cycles, and narrow beam spacing. This may be specified by a high grade to resist freezing and thawing distress, a medium to high grade to combat scaling, abrasion, and chloride penetration, and a low grade to obtain strength and elasticity.

Performance is represented by test variables such as the percentage of dynamic modulus of elasticity remaining after 300 prescribed cycles of freezing and thawing or a range of compressive strengths. Grades start at low performance levels and small enough increments are defined to allow engineers to incrementally begin specifying higher quality concrete. The strength grades start at a performance level that is easily attainable and spans to a superior grade. The definition is intended to cover all grades of concrete that can be readily used by the highway industry.

Testing procedures

Standard test methods were identified to ascertain performance for the eight definition parameters. These procedures and specimen preparation not specified in the standard test procedures are given in Table 2. To achieve uniformity in evaluating performance, the following specimen and curing procedures were stipulated for each test, except as noted elsewhere in this article:

- Cylinders: 100 mm diameter x 200 mm long (4 x 8 in.), or 150 mm diameter x 300 mm long (6 x12 in.).
- Curing: non-steam cured products; moist cure specimens for 56 days or until test age, or match cure and use a maturity meter. For steam cured products, cure specimens with the member or match cure until test age.

The standard tests, performance parameter variables, and respective grades are described:

Resistance to freezing and thawing, ASTM C666, Procedure A, or AASHTO T 161: The test procedure is to be continued for 300 cycles or until the relative dynamic modulus of elasticity drops below 60 percent. Two HPC grades of resistance to freezing and thawing are delineated by the percentage of dynamic modulus of elasticity after 300 cycles. Grade 1 is defined as 60 to 80 percent remaining of the original dynamic modulus of elasticity and Grade 2 is defined as greater than 80 percent of the original dynamic modulus of elasticity.

Scaling test. ASTM C 672: This test must be done for 50 cycles. Scaling performance is evaluated after 50 cycles by visually inspecting specimens as prescribed by C 672. Grade 1 is defined by a visual inspection rating of 4 or 5. Grade 2 by a rating of 2 or 3. and Grade 3 by 0 or 1.

Abrasion. ASTM C 944: Test areas should receive a light trowel finish. Specimens should be field cured for 56 days and air dried for two hours before testing. The tests should then be carried out on three different cylinders or at three different areas on the surface of a concrete structure. A 196 N force for three two minutes periods for a total of six minutes should be used for each abrasion test. A wear depth is then measured. The grades are inversely proportional to wear; a low performance grade is assigned to the higher measurements of wear and a high grade is assigned to the lower measurements of wear.

Chloride test. AASHTO T277, ASTM C 1202: Chloride test specimens should be moist cured for 56 days. Grades are shown in Table 1.

Strength. AASHTO T 22: Strength test specimens must be cast in metal or rigid plastic molds. Compression specimens should have the ends capped, ground parallel, or be tested using neoprene pads per AASHTO or ASTM specifications. The diversity of strength needs and the variation of strengths used in practice necessitates a wide range of strength grades starting at 41 MPa (6 ksi) for Grade 1 to greater than 97 Mpa (14 ksi) for Grade 4. Bridge engineers currently specifying strengths less than Grade 1 can begin the transition to a higher durability and strength concrete by stipulating minimum HPC performance grades. The highest level is specified to define the state of the art in highway concrete usage.

Static modulus of elasticity. ASTM C 469: Standard test procedures should be followed for this test. Grades range from a low of 28 GPa (4 x 10^6 psi) for Grade 1 to greater than 50 GPa (7.5 x 10^6 psi) for Grade 3.

Creep and shrinkage. ASTM C 512 and ASTM C 157: Creep and shrinkage specimens should be moist cured for 28 days, and then tests performed for an additional 180 days. Creep test loading and air storage of shrinkage specimens should start at the 28 day age. Grades of performance are as shown in Table 1.

Test performance, field conditions

Grades of performance were defined for each of the eight parameters in the HPC definition. Field condition severity was estimated for the full range of potential field conditions occurring in the United States (Table 3).

Freeze and thawing: A field freezing and thawing cycle is defined as a decrease in temperature to -2.2 C (28 F) or below followed by a thaw.[8] This field condition is recorded throughout the United States by the Geological Society and is reported by the number of occurrences per year and shown on a national map.[9] A relationship between the deteriorating effect of a field cycle and a laboratory cycle, per AASHTO T 161, is estimated. The currently recommended relationship is as follows: when fewer than three field cycles occur per year no consideration is required; between three and 50 field cycles per year, the use of Grade 1 is recommended; and Grade 2 for above 50 field cycles. This relationship is recommended as a lower bound for specifying HPC.

Scaling: Data are not available to substantiate a strong recommendation between performance grade and field severity. The relationship given should be taken as a suggestion until further research is available.

Abrasion: Normal surface abrasion from rubber tires typically does not warrant abrasion resistance consideration assuming that there is well-cured concrete of appropriate strength. However, the use of studded tires on highways does warrant such consideration. A Grade 1 is recommended for less than a 50,000 average daily traffic count. Grade 2 for greater than 50,000 and less than 100,000, and Grade 3 for greater than 100,000 when steel studded tires are permitted. Similar estimates can be made by local engineers if the use of car chains is prevalent. Recommendations for other abrasion conditions such as a stream flow laden with abrasive materials are the responsibility of the project engineer.

Chloride penetration: Coulombs measured in the rapid chloride permeability test were used in this research to estimate performance grades relative to steel corrosion. Grade 1 was defined between 2000 and 3000 coulombs, Grade 2 between 800 and 2000, and Grade 3 less than 800 coulombs. A corrosion model to predict service life based on chloride content in the concrete were recommended, using the following assumptions: a 30-year life span; 2 in. of cover with a standard deviation of 0.3 in.; and a range of applied quantities of deicing salt.

Mechanical properties: Grades of performance are designated in Table 1. Material and structural designers can select and specify appropriate grades for a project.

Conclusions

The HPC definition presented here identifies a set of concrete performance characteristics sufficient to estimate long-term concrete durability and strength for highway structures. Standard laboratory tests, specimen preparation procedures, and grades of performance were suggested for each definition parameter. Relationships between performance and severity of field conditions were estimated to assist designers in selecting the grade of HPC for a particular project. Because there is a lack of information correlating field condition severity and laboratory performance, these relationships serve only as suggestions. Thus, this definition is a guide and identifies areas in which additional research is needed.

Bridge engineers and other concrete designers are encouraged to begin using the definition as a tool in expanding their understanding and confidence in concrete with high performance. It is anticipated that research and experience gained from the FHWA demonstration projects and other sources will result in continued updates to these tables. Note that specified relationships between laboratory performance data and resistance to field conditions are only suggestions. Information gained from local experience should receive careful consideration.

In the transportation industry, it has always been the goal to use concrete with characteristics at appropriate levels to insure satisfactory performance for the intended service life. Though success has often been achieved, attention seems to focus on those cases without such desirable conclusions. When concrete does not perform as desired, either the specifications were inadequate or not followed properly. Modern QC/QA procedures should greatly increase the likelihood that specifications are met when followed.

At a recent HPC workshop, it was suggested that if the concrete to be used was produced to strictly comply with relevant code requirements it should be a high-performance concrete.[11] The intent of high-performance concrete, as defined here, is not to produce a high cost product but simply to provide the means for making concrete that will perform satisfactorily with only reasonable maintenance costs for intended service life.[12]

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