CHAPTER 19

High-Performance Concrete

High-performance concrete (HPC) exceeds the properties and constructability of normal concrete. Normal and special materials are used to make these specially designed concretes that must meet a combination of performance requirements. Special mixing, placing, and curing practices may be needed to produce and handle high-performance concrete. Performance tests are usually required to demonstrate compliance with specific project needs (ASCE 1993, Russell 1999, and Bickley and Mitchell 2001). High-performance concrete has been primarily used in bridges, and tall buildings for its durability, strength, and high modulus of elasticity (Figure 19-1). It has also been used in shotcrete repair, poles, tunnels, parking garages, and agricultural applications.

High-performance concrete characteristics are defined, categorized, or developed for particular applications and environments (Goodspeed, Vanikar, and Cook 1996 and Russell and Ozyildirim 2006); some of the characteristics that may be required include:

- Enhanced Durability
  - High abrasion resistance
  - Low permeability and diffusion
  - Resistance to chemical attack
  - High resistance to freeze-thaw, and deicer scaling damage
  - Resistance to alkali silica reactivity
- Enhanced Engineering Properties
  - High strength
  - High early strength
  - High modulus of elasticity
  - Toughness and impact resistance
  - Volume stability

Figure 19-1. High-performance concrete is often used in bridges and tall buildings. (left) I-35W St. Anthony Falls bridge in Minneapolis, Minnesota. (right) 311 W. Wacker Drive, Chicago, Illinois.

- Other Enhanced Properties
  - Ease of placement
  - Temperature control
  - Compaction without segregation
  - Inhibition of bacterial and mold growth

High-performance concretes are made with carefully selected high-quality ingredients and optimized mixture designs; these are batched, mixed, placed, compacted and cured to the highest industry standards. Typically, they will have low water-cementing materials ratios of 0.20 to 0.45. High-range water reducers (or superplasticizers) are usually used to make these concretes fluid and workable at lower w/cm.

High-performance concrete almost always has greater durability than normal concrete. This greater durability may be accompanied by normal strength or it may be partnered with high strength. Note that strength is not always the primary required property. For bridge decks, a normal strength concrete with very high durability and very low permeability is considered high performance concrete (Lane 2010). Table 19-1 lists materials often used in high-performance concrete and their selection criteria. Table 19-2 lists properties that can be selected for high-performance concrete. Typical mix designs and member properties for many bridges can be found in the FHWA report compiling results for HPC bridges (Russell and others 2006). Not all properties can be achieved concurrently.

High-performance concrete specifications should be performance oriented. However, many specifications are a combination of performance requirements (such as permeability or strength limits) and prescriptive requirements (such as air content limits or dosage of SCMs) (Ferraris and Lobo 1998 and Caldarone and others 2005). Table 19-3 provides examples of high-performance concrete mixtures used in a variety of structures. Selected high-performance concretes are presented in this chapter.

Table 19-1. Materals Used in High-Performance Concrete

Material	Primary contribution/desired property
Portland cement	Cementing material/durability
Blended cement	Cementing material/durability/high strength
Fly ash	Cementing material/durability/high strength
Slag cement	Cementing material/durability/high strength
Silica fume	Cementing material/durability/high strength
Calcined clay	Cementing material/durability/high strength
Metakaolin	Cementing material/durability/high strength
Calcined shale	Cementing material/durability/high strength
Expanded shale, clay, and/or slate	Lightweight
Superplasticizers	Flowability
High-range water reducers	Reduce water to cement ratio
Hydration control admixtures	Control setting
Retarders	Control setting
Accelerators	Accelerate setting
Corrosion inhibitors	Control steel corrosion
Water reducers	Reduce cement and water content
Shrinkage reducers	Reduce shrinkage
ASR inhibitors	Control alkali-silica reactivity
Polymer/latex modifiers	Durability
Optimally graded aggregate	Improve workability and reduce paste demand

Table 19-2. Selected Properties of High-Performance Concrete

Property	Test method	Criteria that may be specified
High compressive strength	ASTM C39 (AASHTO T 22)	55 to 140 MPa (8000 to 20,000 psi) at 28 to 91 days
High-early compressive strength	ASTM C39 (AASHTO T 22)	20 to 41 MPa (3000 to 6000 psi) at 3 to 18 hours, or 1 to 3 days
High-early tensile strength	ASTM C78 (AASHTO T 97)	2 to 4 MPa (300 to 600 psi) at 3 to 12 hours, or 1 to 3 days
Abrasion resistance	ASTM C944	0 to less than 2 mm depth of wear
Low permeability	ASTM C1202 (AASHTO T 277)	500 to 2500 coulombs
Reduced chloride penetration	ASTM C1543 (AASHTO T 259 and AASHTO T 260)	Less than 0.07% Cl at 6 months
High resistivity	ASTM G59	
Low absorption	ASTM C642	2% to 5%
Low diffusion coefficient	ASTM C1556	1000 x 10^{-13} m/s
Resistance to chemical attack	Expose concrete to saturated solution in wet/dry environment	No deterioration after 1 year
Resistance to sulfate attack	ASTM C1012	Mild Exposure: 0.10% max expansion at 6 months; Moderate Exposure: 0.10% max. expansion at 12 months; Severe Exposure: 0.10% max expansion at 18 months;
High modulus of elasticity	ASTM C469	34 to more than 48 GPa (5 to more than 7 million psi)
High resistance to freezing and thawing damage	ASTM C666, Procedure A (AASHTO T 161)	Relative dynamic modulus of elasticity after 300 cycles of 70% to more than 90%
High resistance to deicer scaling	ASTM C672	Visual rating of the surface after 50 cycles of 0 to 3
Low shrinkage	ASTM C157	Less than 800 millionths (microstrain) to less than 400 millionths (microstrain)
Low creep	ASTM C512	70 microstrain/MPa to less than 30 microstrain/MPa (0.52 microstrain/psi to less than 0.21 microstrain/psi)
Increased workability	ASTM C143 (AASHTO T 119)	Slump more than 190 mm (7.5 in)
Increased workability for SCC	ASTM C1611	Slump flow ≤ 600 mm (24 in)
Resistance to alkali silica reactivity	ASTM C441	Expansion at 56 days of 0.20% to less than 0.10%
Resistance to delayed ettringite formation	Maximum internal curing tempera-ture (within concrete)	Less than 70°C (158°F)

Table 19-3 (Metric). High-Performance Concrete Mixtures Used in Various Structures

Mixture Number/Mixture Ingredient	1	2	3	4	5	6	7	8	9
Water, kg/m³	151	145	135	145	130	130	119	157	151
Cement, kg/m³	311	398*	500	335*	513	315	530	387	371
Fly ash, kg/m³	31	45	—	—	—	40	—	68	59
Slag, kg/m³	47	—	—	125	—	—	—	—	—
Silica fume, kg/m³	16	32*	30	40*	43	23	—	—	30
Coarse aggregate, kg/m³	1068	1030	1100	1130	1080	1140	949	973	997
Fine aggregate, kg/m³	676	705	700	695	685	710	766	652	801
Water reducer, L/m³	1.6	1.7	—	1.0	—	1.5	—	—	—
Retarder, L/m³	—	—	1.8	—	—	—	—	—	—
Water reducing/Retarding Admixture, L/m³	—	—	—	—	—	—	—	0.6	—
Shrinkage-Reducing Admixture, L/m³	—	—	—	—	—	—	—	4.8	—
Hydration Stabilizer, L/m³	—	—	—	—	—	—	—	0.9	—
Air Entraining Admixture, L/m³	—	—	—	—	—	—	1.4	0.3	—
Air, %	7 ± 1.5	5 – 8	—	—	—	5.5	—	—	—
HRWR or plasticizer, L/m³	2.1	3	14	6.5	15.7	5.0	2.4	0.7	0 to 3090
Water to cementitious materials ratio	0.37	0.30	0.27	0.29	0.25	0.34	0.22	0.35	0.33
Comp. strength at 28 days, MPa	59	—	93	99	119	—	61	—	76
Comp. strength at 91 days MPa	—	60	107	104	145	—	—	36	—
Permeability at 56 days, coulombs	—	—	—	—	—	—	—	—	Less than 800

1. Wacker Drive bi-level roadway, Chicago, 2001.
2. Confederation Bridge, Northumberland Strait, Prince Edward Island/New Brunswick, 1997.
3. La Laurentienne Building, Montreal, 1984.
4. BCE Place Phase 2, Toronto, 1993.
5. Two Union Square, Seattle, 1988.
6. Great Belt Link, East Bridge, Denmark, 1996.
7. Girders, Angeles Crest Bridge (Higareda 2010).
8. Deck, Angeles Crest Bridge.
9. Pontoon, Hood Canal Floating Bridge (Gaines and Tragesser 2008).

* Originally used a blended cement containing silica fume. Portland cement and silica fume quantities have been separated for comparison purposes.

Table 19-3 (Inch-Pound Units). High-Performance Concrete Mixtures Used in Various Structures

Mixture Number/Mixture Ingredient	1	2	3	4	5	6	7	8	9
Water, lb/yd^3	254	244	227	244	219	219	200	265	255
Cement, lb/yd^3	525	671*	843	565*	865	531	893	652	625
Fly ash, lb/yd^3	53	76	—	—	—	67	—	115	100
Slag, lb/yd^3	79	—	—	211	—	—	—	—	—
Silica fume, lb/yd^3	27	54*	51	67	72	39	—	—	50
Coarse aggregate, lb/yd^3	1800	1736	1854	1905	1820	1921	1600	1640	1680
Fine aggregate, lb/yd^3	1140	1188	1180	1171	1155	1197	1292	1099	1350
Water reducer, oz/yd^3	41	47	—	27	—	38	—	—	—
Retarder, oz/yd^3	—	—	48	—	—	—	—	—	—
Water reducing/Retarding Admixture, oz/yd^3	—	—	—	—	—	—	—	15	—
Shrinkage-Reducing Admixture, oz/yd^3	—	—	—	—	—	—	—	123	—
Hydration Stabilizer, oz/yd^3	—	—	—	—	—	—	—	23	—
Air Entraining Admixture, oz/yd^3	—	—	—	—	—	—	37	8.5	
Air, %	7 ± 1.5	5 – 8	—	—	—	5.5			
HRWR or plasticizer, oz/yd^3	55	83	975	175	420	131	63	18	0 to 80
Water to cementitious materials ratio	0.37	0.30	0.27	0.29	0.25	0.34	0.22	0.35	0.33
Comp. strength at 28 days, psi	8590	—	13,500	14,360	17,250	—	8750		11,000
Comp. strength at 91 days psi	—	8700	15,300	15,080	21,000	—		5190	
Permeability at 56 days, coulombs	—	—	—	—	—	—			Less than 800

1. Wacker Drive bi-level roadway, Chicago, 2001.
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High-Durability Concrete

HPC concrete today is more on concretes with high durability in mild, moderate, or severe environments. For example, the Confederation Bridge across the Northumberland Strait between Prince Edward Island and New Brunswick, Canada has a 100-year design life (see Mix No. 2 in Table 19-3). This bridge contains HPC designed to efficiently protect the embedded reinforcement. The concrete had a diffusion coefficient of 4.8 x 10^{-13} at six months (a value 10 to 30 times lower than that of conventional concrete). The electrical resistivity was measured at 470 Ω-m to 530 Ω-m, compared to 50 Ω-m for conventional concrete. The design required that the concrete be rated at less than 1000 coulombs. The high concrete resistivity in itself will result in a rate of corrosion that is potentially less than 10% of the corrosion rate for conventional concrete (Dunaszegi 1999). The following sections review durability issues that high-performance concrete can address.

Abrasion Resistance

Abrasion resistance is related to the strength of concrete. This makes high strength HPC ideal for abrasive environments. The abrasion resistance of HPC incorporating silica fume is especially high. This makes silica fume concrete particularly useful for spillways and stilling basins, bridge decks subject to studded tires or tires with chains, and concrete pavements or concrete pavement overlays subjected to heavy or abrasive traffic.

Holland and others (1986) describe how severe abrasion-erosion had occurred in the stilling basin of a dam. Repairs using fiber-reinforced concrete were not durable. The new HPC mixtures used to repair the structure the second time contained 386 kg/m^3 (650 lb/yd^3) of cement, 70 kg/m^3 (118 lb/yd^3) of silica fume, and admixtures; had a water-to-cementitious materials ratio of 0.28; and had a 90-day compressive strength exceeding 103 MPa (15,000 psi).

Berra, Ferrara, and Tavano (1989) studied the addition of fibers to silica fume mortars to optimize abrasion resistance. The best results were obtained with a mixture using slag cement, steel fibers, and silica fume. Mortar strengths ranged from 75 MPa to 100 MPa (11,000 psi to 14,500 psi). In addition to better erosion resistance; less drying shrinkage, high freeze-thaw resistance, and good bond to the substrate were achieved.

In Norway steel studs are allowed in tires. This causes severe abrasion wear on pavement surfaces, with resurfacing required within one to two years. Tests using an accelerated road-wear simulator showed that in the range of 100 MPa to 120 MPa (14,500 psi to 17,000 psi), concrete had the same abrasion resistance as granite (Helland 1990). Abrasion-resistant highway mixtures usually contain between 320 kg/m^3 and 450 kg/m^3 (539 lb/yd^3 and 758 lb/yd^3) of cement, plus silica fume or fly ash. They have water to cementing materials ratios of 0.22 to 0.36 and compressive strengths in the range of 85 MPa to 130 MPa (12,000 psi to 19,000 psi). Applications have included new pavements and overlays to existing pavements.

Blast Resistance

High-performance concrete can be designed to have excellent blast resistance properties. These concretes often have a compressive strength exceeding 120 MPa (14,500 psi) and contain steel fibers. Blast-resistant concretes are often used in bank vaults, military applications, and some transportation structures.

Permeability

The durability and service life of steel reinforced concrete exposed to weather is related to the permeability of the concrete cover protecting the reinforcement. HPC typically has very low permeability to air, water, and chloride ions. Low permeability is often specified through the use of a coulomb value, such as a maximum of 1000 coulombs.

Test results obtained on specimens from a concrete column specified to be 70 MPa (10,000 psi) at 91 days and which had not been subjected to any wet curing were as follows (Bickley and others 1994):

Water permeability of vacuum-saturated specimens:

Age at test:	7 years
Applied water pressure:	0.69 MPa
Permeability:	7.6 x 10^{-13} cm/s

Rapid chloride permeability (ASTM C1202):

Age at test, years	Coulombs
1	303
2	258
7	417

The dense pore structure of high-performance concrete, gives it characteristics that make it eminently suitable for uses where a high quality concrete would not normally be considered. Ternary mixtures achieve lower permeabilities more easily for a given w/cm (Bouzoubaa and others 2004). Latex-modified HPC is able to achieve these same low levels of permeability at normal strength levels without the use of supplementary cementing materials.

Diffusion

Aggressive ions, such as chloride, in contact with the surface of concrete will diffuse through the concrete until a state of equilibrium is achieved. If the concentration of ions at the surface is high, diffusion may result in corrosion-inducing concentrations at the level of the reinforcement.

The lower the water-cementing materials ratio the lower the diffusion coefficient will be for any given set of materials. Supplementary cementing materials, particularly silica fume, further reduce the diffusion coefficient. Typical values for diffusion for HPC are as follows:

Type of Concrete	Diffusion Coefficient (ASTM C1556)
Portland cement-fly-ash silica fume mix:	1000×10^{-15} m²/s
Portland cement-fly ash mix:	1600×10^{-15} m²/s

Carbonation

HPC has a very good resistance to carbonation due to its low permeability. It was determined that after 17 years the concrete in the CN Tower in Toronto had carbonated to an average depth of 6 mm (0.24 in.) (Bickley, Sarkar, and Langlois 1992). The concrete mixture in the CN Tower had a water-cement ratio of 0.42. For a cover to the reinforcement of 35 mm (1.4 in.), this concrete would provide corrosion protection for 500 years. For the lower water-cementing materials ratios common to HPC, significantly longer times to corrosion would result, assuming a crack free structure. In practical terms, uncracked HPC cover concrete is immune to carbonation to a depth that would cause corrosion.

Freeze-Thaw Resistance

Because of its very low water-cementing materials ratio (0.20 to 0.45), it is widely believed that HPC should be highly resistant to both scaling and physical breakup due to freezing and thawing. There is ample evidence that properly air-entrained high performance concretes are highly resistant to freezing and thawing and to scaling.

Gagne, Pigeon, and Aïtcin (1990) tested 27 mixtures using cement and silica fume with water-cementing materials ratios of 0.30, 0.26, and 0.23 and a wide range of quality in air-voids systems. All specimens performed exceptionally well in salt-scaling tests, confirming the durability of high-performance concrete, and suggesting that air-entrainment is not needed. Tachitana and others (1990) conducted ASTM C666 (Procedure A) tests on non-air-entrained high performance concretes with water-cementing materials ratios between 0.22 and 0.31. All were found to be extremely resistant to freeze-thaw damage and again it was suggested that air-entrainment is not needed.

Pinto and Hover (2001) found that non-air-entrained concrete with a w/c of 0.25 was deicer-scaling resistant with no supplementary cementing materials present. They found that higher strength portland cement concretes needed less air than normal concrete to be frost and scale resistant.

Burg and Ost (1994) found that of the six mixtures tested in Table 19-5 using ASTM C666, only the silica fume concrete (Mix 4) with a water to cementing materials ratio of 0.22 was frost resistant.

Sidewalks constructed in Chicago in the 1920s used 25-mm (1-in.) thick toppings made of no-slump dry-pack mortar rammed into place. The concrete contained no air entrainment. Many of these sidewalks are still in use today; they are in good condition (minus some surface weathering exposing fine aggregate) after 90 plus years of exposure to frost and deicers. No documentation exists on the water to cement ratio; however, it can be assumed that the water-to-cement ratio was comparable to that of modern HPC.

While the above experiences prove the excellent durability of certain high-performance concretes to freeze-thaw damage and salt scaling, it is considered prudent to use air-entrainment. No well-documented field experiments have been made to prove that air-entrainment is not needed. Until such data are available, current practice for air-entrainment should be followed. It has been shown that the prime requirement of an air-void system for HPC is a preponderance of air bubbles of 200 µm size and smaller. If the correct air bubble size and spacing can be assured, then a moderate air content will ensure durability and minimize strength loss. The best measure of air-entrainment is the spacing factor.

Chemical Attack

For resistance to chemical attack on most structures, HPC offers a much improved performance. Resistance to various sulfates is achieved primarily by the use of a dense, strong concrete of very low permeability and low water-to-cementing materials ratio; these are all characteristics of HPC. Similarly, as discussed by Gagne, Chagnon, and Parizeau (1994), resistance to acid from wastes is also much improved.

Alkali-Silica Reactivity

Reactivity between certain siliceous aggregates and alkali hydroxides can affect the long-term performance of concrete. Two characteristics of HPC that help combat alkali-silica reactivity are:

1. HPC concretes at very low water to cement ratios can self desiccate (dry out) to a level that does not allow ASR to occur (relative humidity less than 80%). Burg and Ost (1994) observed relative humidity values ranging from 62% to 72% for their six mixtures in Table 19-5. The low permeability of HPC also minimizes external moisture from entering the concrete.
2. HPC concretes can use significant amounts of supplementary cementing materials that may have the ability to control alkali-silica reactivity. However, this must be demonstrated by test. HPC concretes can also use ASR inhibiting admixtures to control ASR.

HPC concretes are not immune to alkali-silica reactivity and appropriate precautions must be taken. Procedures are available for determining the potential reactivity of aggregates and limiting ASR (Thomas, Fournier, and Folliard, 2008).

Resistivity

HPC, particularly that formulated with silica fume, has very high resistivity, up to 20 to 25 times that of normal concrete. This increases resistance to the flow of electrical current and reduces corrosion rates. Particularly if dry, HPC acts as an effective dielectric. Where cracking occurs in HPC, the corrosion is localized and minor; this is due to the high resistivity of the concrete which suppresses the development of a macro corrosion cell.

High-Early-Strength Concrete

High-early-strength concrete, also called fast-track concrete, achieves its specified strength at an earlier age than normal concrete. The time period in which a specified strength should be achieved may range from a few hours (or even minutes) to several days. High-early-strength can be attained using traditional concrete ingredients and concreting practices, although sometimes special materials or techniques are needed.

High-early-strength can be obtained using one or a combination of the following, depending on the age at which the specified strength must be achieved and on job conditions:

1. Type III or HE high-early-strength cement
2. High cement content (400 kg/m^3 to 600 kg/m^3 [675 lb/yd^3 to 1000 lb/yd^3])
3. Low water-cementing materials ratio (0.20 to 0.45 by mass)
4. Higher freshly mixed concrete temperature
5. Higher curing temperature (Note: Keep internal member temperature under 70°C [158°F] to help prevent delayed ettringite formation)
6. Chemical admixtures
7. Silica fume (or other supplementary cementing materials)
8. Steam or autoclave curing (see note on 5)
9. Insulation to retain heat of hydration (see note on 5)
10. Special rapid hardening cements

High-early-strength concrete is used for prestressed concrete to allow for early stressing, precast concrete for rapid production of elements, high-speed cast-in-place construction, rapid form reuse, cold-weather construction, rapid repair of pavements (to reduce traffic downtime), fast-track paving, and several other uses.

In fast-track paving, use of high-early-strength mixtures allows traffic to open just hours after concrete is placed. An example of a fast-track concrete mixture used for a bonded concrete highway overlay consisted of 380 kg (640 lb) of Type III cement, 42 kg (70 lb) of Type C fly ash, 6½% air, a water reducer, and a water-to-cementing materials ratio of 0.4. Strength data for this 40-mm (1½ in.) slump concrete are given in Table 19-4. Figures 19-2 and 19-3 illustrate early strength development of concretes designed to open to traffic within 4 hours after placement. Figure 19-4 illustrates the benefits of blanket curing to develop early strength for patching or fast-track applications.

Table 19-4. Strength Data for Fast-Track Bonded Overlay

Age	Compressive strength, MPa (psi)	Flexural strength, MPa (psi)	Bond strength, MPa (psi)
4 hours	1.7 (252)	0.9 (126)	0.9 (120)
6 hours	7.0 (1020)	2.0 (287)	1.1 (160)
8 hours	13.0 (1883)	2.7 (393)	1.4 (200)
12 hours	17.6 (2546)	3.4 (494)	1.6 (225)
18 hours	20.1 (2920)	4.0 (574)	1.7 (250)
24 hours	23.9 (3467)	4.2 (604)	2.1 (302)
7 days	34.2 (4960)	5.0 (722)	2.1 (309)
14 days	36.5 (5295)	5.7 (825)	2.3 (328)
28 days	40.7 (5900)	5.7 (830)	2.5 (359)

Adapted from Knutson and Riley 1987.

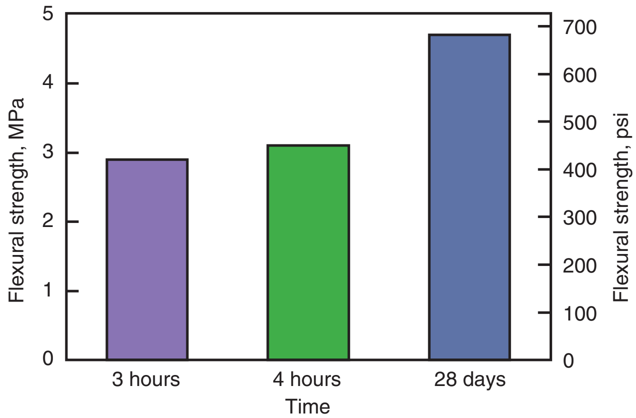

Figure 19-2. Strength development of a high-early strength concrete mixture using 390 kg/m³ (657 lb/yd³) of rapid hardening cement, 676 kg/m³ (1140 lb/yd³) of sand, 1115 kg/m³ (1879 lb/yd³) of 25 mm (1 in.) nominal max. size coarse aggregate, a water to cement ratio of 0.46, a slump of 100 to 200 mm (4 to 8 in.), and a plasticizer and retarder. Initial set was at one hour (Pyle 2001).

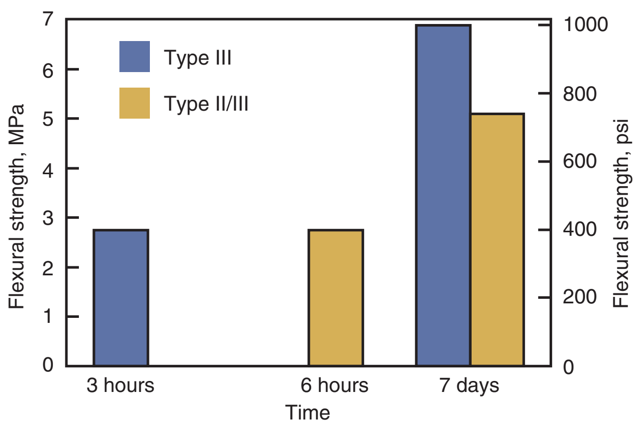

Figure 19-3. Strength development of high-early strength concrete mixtures made with 504 to 528 kg/m³ (850 to 890 lb/yd³) of Type III or Type II/III cement, a nominal maximum size coarse aggregate of 25 mm (1 in.), a water to cement ratio of 0.30, a plasticizer, a hydration control admixture, and an accelerator. Initial set was at one hour (Pyle 2001).

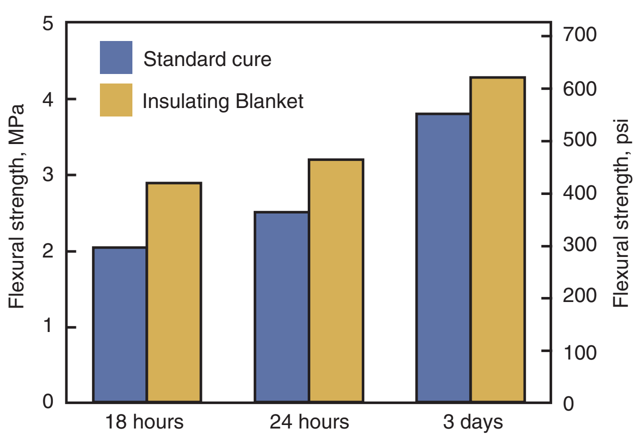

Figure 19-4. Effect of blanket insulation on fast-track concrete. The concrete had a Type I cement content of 421kg/m³ (710 lb/yd³) and a water to cement ratio of 0.30 (Grove 1989).

When designing early-strength mixtures, strength development is not the only criteria that should be evaluated; durability, early stiffening, camber of pretensioned members, autogenous shrinkage, drying shrinkage, temperature rise, and other properties also should be evaluated for compatibility with the project. Special curing procedures, such as fogging, may be needed to control plastic shrinkage cracking.

High-Strength Concrete

The definition of high strength changes over the years as concrete strength used in the field increases. This publication considers high-strength concrete (HSC) as a strength significantly beyond what is used in normal practice. About 90% of ready mixed concrete has a 28-day specified compressive strength ranging from 20 MPa (3000 psi) to 40 MPa (6000 psi), with most of it between 20 MPa (3000 psi) and 35 MPa (5000 psi).

Most high-strength concrete applications are designed for compressive strengths of 70 MPa (10,000 psi) or greater as shown in Tables 19-3 and 19-5. For bridges, the AASHTO LRFD Specifications (2010) state that the minimum allowable compressive strength for bridge decks and prestressed concrete members is 28 MPa (4000 psi). Therefore, HSC considered here has a minimum design strength of at least 55 MPa (8000 psi). For high strength concrete, stringent application of the best practices is required. Compliance with the guidelines and recommendations for preconstruction laboratory and field-testing procedures described in ACI 363.2 are essential. Concrete with a design strength of 131 MPa (19,000 psi) has been used in buildings (Figure 19-5).

Figure 19-5. The Two Union Square building in Seattle used concrete with a designed compressive strength of 131 MPa (19,000 psi) in its steel tube and concrete composite columns. High-strength concrete was used to meet a design criterion of 41 GPa (6 million psi) modulus of elasticity.

Table 19-5 (Metric). Mixture Proportions and Properties of Commercially Available High-Strength Concrete (Burg and Ost 1994)

Units	Mix number					
	1	**2**	**3**	**4**	**5**	**6**
Cement, Type I, kg/m³	564	475	487	564	475	327
Silica fume, kg/m³	—	24	47	89	74	27
Fly ash, kg/m³	—	59	—	—	104	87
Coarse aggregate SSD (12.5 mm crushed limestone), kg/m³	1068	1068	1068	1068	1068	1121
Fine aggregate SSD, kg/m³	647	659	676	593	593	742
HRWR Type F, liters/m³	11.6	11.6	11.22	20.11	16.44	6.3
HRWR Type G, liters/m³	—	—	—	—	—	3.24
Retarder, Type D, liters/m³	1.12	1.05	0.97	1.46	1.5	—
Water to cementing materials ratio	0.28	0.29	0.29	0.22	0.23	0.32
Fresh concrete properties						
Slump, mm	197	248	216	254	235	203
Density, kg/ m³	2451	2453	2433	2486	2459	2454
Air content, %	1.6	0.7	1.3	1.1	1.4	1.2
Concrete temp., °C	24	24	18	17	17	23
Compressive strength, 100 x 200-mm moist-cured cylinders						
3 days, MPa	57	54	55	72	53	43
7 days, MPa	67	71	71	92	77	63
28 days, MPa	79	92	90	117	100	85
56 days, MPa	84	94	95	122	116	—
91 days, MPa	88	105	96	124	120	92
182 days, MPa	97	105	97	128	120	—
426 days, MPa	103	118	100	133	119	—
1085 days, MPa	115	122	115	150	132	—
Modulus of elasticity in compression, 100 x 200-mm moist-cured cylinders						
91 days, GPa	50.6	49.9	50.1	56.5	53.4	47.9
Drying shrinkage, 75 by 75 x 285-mm prisms						
7 days, millionths	193	123	100	87	137	—
28 days, millionths	400	287	240	203	233	—
90 days, millionths	573	447	383	320	340	—
369 days, millionths	690	577	520	453	467	—
1075 days, millionths	753	677	603	527	523	—

Traditionally, the specified strength of concrete has been based on 28-day test results. However, in high-rise concrete structures, the process of construction is such that the structural elements in lower floors are not fully loaded for periods of a year or more. For this reason, compressive strengths based on 56- or 91-day test results are commonly specified in order to achieve significant economy in material costs. For bridges, the specified strength of concrete has also been based on 28-day test results. However, because of the use of fly ash and slag cement, which may hydrate slower than the cement, 56-day strengths have been specified on bridge projects.

When later ages are specified, supplementary cementing materials are usually incorporated into the concrete mixture. This produces additional benefits in the form of reduced heat generation during hydration.

With use of low-slump or no-slump mixtures, high compressive-strength concrete is produced routinely under careful control in precast and prestressed concrete plants. These stiff mixtures are placed in ruggedly-built forms and consolidated by prolonged vibration or shock methods. However, cast-in-place concrete uses more fragile forms that do not permit the same compaction procedures. Hence, more workable concretes are necessary to achieve the required compaction and to avoid segregation and honeycomb. Superplasticizing admixtures are invariably added to HPC mixtures to produce workable and often flowable mixtures.

Production of high-strength concrete may or may not require the purchase of special materials. The producer must know the factors affecting compressive strength and know how to vary those factors for best results. Each variable should be analyzed separately in developing a mix

Table 19-5 (Inch-Pound Units). Mixture Proportions and Properties of Commercially Available High-Strength Concrete (Burg and Ost 1994)

Units	Mix number					
	1	2	3	4	5	6
Cement, Type I, lb/yd³	950	800	820	950	800	551
Silica fume, lb/yd³	—	40	80	150	125	45
Fly ash, lb/yd³	—	100	—	—	175	147
Coarse aggregate SSD (½ in. crushed limestone), lb/yd³	1800	1800	1800	1800	1800	1890
Fine aggregate SSD, lb/yd³	1090	1110	1140	1000	1000	1251
HRWR Type F, fl oz/yd³	300	300	290	520	425	163
HRWR Type G, fl oz/yd³	—	—	—	—	—	84
Retarder, Type D, fl oz/yd³	29	27	25	38	39	—
Water to cementing materials ratio	0.28	0.29	0.29	0.22	0.23	0.32
Fresh concrete properties						
Slump, in.	7¾	9¾	8½	10	9¼	8
Density, kg/ lb/ft³	153.0	153.1	151.9	155.2	153.5	153.2
Air content, %	1.6	0.7	1.3	1.1	1.4	1.2
Concrete temp., °F	75	75	65	63	62	74
Compressive strength, 4 x 8-in. moist-cured cylinders						
3 days, psi	8220	7900	7970	10,430	7630	6170
7 days, psi	9660	10,230	10,360	13,280	11,150	9170
28 days, psi	11,460	13,300	13,070	17,000	14,530	12,270
56 days, psi	12,230	13,660	13,840	17,630	16,760	—
91 days, psi	12,800	15,170	13,950	18,030	17,350	13,310
182 days, psi	14,110	15,160	14,140	18,590	17,400	—
426 days, psi	14,910	17,100	14,560	19,230	17,290	—
1085 days, psi	16,720	17,730	16,650	21,750	19,190	—
Modulus of elasticity in compression, 4 x 8-in. moist-cured cylinders						
91 days, million psi	7.34	7.24	7.27	8.20	7.75	6.95
Drying shrinkage, 3 by 3 x 11.5-in. prisms						
7 days, millionths	193	123	100	87	137	—
28 days, millionths	400	287	240	203	233	—
90 days, millionths	573	447	383	320	340	—
369 days, millionths	690	577	520	453	467	—
1075 days, millionths	753	677	603	527	523	—

design. When an optimum or near optimum is established for each variable, it should be incorporated as the remaining variables are studied. An optimum mix design is then developed keeping in mind the economic advantages of using locally available materials. Many of the materials considerations discussed below also apply to most high-performance concretes.

Cement

Selection of cement for high-strength concrete should not be based only on mortar-cube tests but should also include tests of comparative strengths of concrete at 28, 56, and 91 days. Cement that yields the highest concrete compressive strength at extended ages (91 days) is preferable. For high-strength concrete, the cement should produce a minimum 7-day mortar-cube strength of approximately 30 MPa (4350 psi).

Trial mixtures with cement contents between 400 kg/m³ and 550 kg/m³ (675 lb/yd³ to 930 lb/yd³) should be made for each cement being considered for the project. Amounts will vary depending on target strengths. Other than decreases in sand content as cement content increases, the trial mixtures should be as nearly identical as possible.

Supplementary Cementing Materials

Fly ash, silica fume, or slag cement are frequently used and are sometimes mandatory in the production of high-performance concrete. The strength gain obtained with these supplementary cementing materials cannot be attained by using additional cement alone. The addition of these supplementary cementitious materials greatly reduces permeability and improves durability. These supplementary cementing materials are usually added at dosage rates of 5% to 20% or higher by mass of cementing material. Some specifications only permit use of up to 10% silica fume, unless evidence is available indicating that concrete produced with a larger dosage rate will have satisfactory strength, durability, and volume stability. The water-to-cementing materials ratio should be adjusted so that equal workability becomes the basis of comparison between trial mixtures. For each set of materials, there will be an optimum cement-plus-supplementary cementing materials content at which strength does not continue to increase with greater amounts and the mixture becomes too sticky to handle properly. Blended cements containing fly ash, silica fume, slag, or calcined clay can be used to make high-strength concrete with or without the addition of supplementary cementing materials.

Aggregates

In high-strength concrete, careful attention must be given to aggregate size, shape, surface texture, mineralogy, and cleanness. For each source of aggregate and concrete strength level there is an optimum-size aggregate that will yield the most compressive strength per unit of cement. To find the optimum size, trial batches should be made with 19 mm (¾ in.) and smaller coarse aggregates and varying cement contents. Many studies have found that 9.5 mm to 12.5 mm (⅜ in. to ½ in.) nominal maximum-size aggregates give optimum strength. Combining single sizes of aggregate to produce the required grading is recommended for close control and reduced variability in the concrete.

In high-strength concretes, the strength of the aggregate itself and the bond or adhesion between the paste and aggregate become important factors. Tests have shown that crushed-stone aggregates produce higher compressive strength in concrete than gravel aggregate using the same size aggregate and the same cementing materials content. This is probably due to a superior aggregate-to-paste bond when using rough, angular, crushed material. For specified concrete strengths of 70 MPa (10,000 psi) or higher, the potential of the aggregates to meet design requirements must be established prior to use.

Coarse aggregates used in high-strength concrete should be free from detrimental coatings of dust and clay. Removing dust is important since it may affect the quantity of fines and consequently the water demand of a concrete mixture. Clay may affect the aggregate-paste bond. Washing of coarse aggregates may be necessary.

The quantity of coarse aggregate in high-strength concrete should be the maximum consistent with required workability. Because of the high percentage of cementitious material in high-strength concrete, an increase in coarse aggregate content beyond values recommended in standards for normal-strength mixtures is necessary and allowable.

In high-rise buildings and in bridges, the stiffness of the structure is an important structural concern. On certain projects a minimum static modulus of elasticity has been specified as a means of increasing the stiffness of a structure (Figure 19-5). The modulus of elasticity is not necessarily proportional to the compressive strength of a concrete. There are code formulas for normal-strength concrete and suggested formulas for high-strength concrete. The modulus achievable is affected significantly by the properties of the aggregate and also by the mixture proportions (Baalbaki and others 1991). If an aggregate has the ability to produce a high modulus, then the optimum modulus in concrete can be obtained by using as much of this aggregate as practical, while still meeting workability and cohesiveness requirements. If the coarse aggregate used is a crushed rock, and manufactured fine aggregate of good quality is available from the same source, then a combination of the two can be used to obtain the highest possible modulus.

Due to the high amount of cementitious material in high-strength concrete, the role of the fine aggregate (sand) in providing workability and good finishing characteristics is not as critical as in conventional strength mixtures. Sand with a fineness modulus (FM) of about 3.0 – considered a coarse sand—has been found to be satisfactory for producing good workability and high compressive strength. For specified strengths of 70 MPa (10,000 psi) or greater, FM should be between 2.8 and 3.2 and not vary by more than 0.10 from the FM selected for the duration of the project. Finer sand, say with a FM of between 2.5 and 2.7, may produce lower-strength, sticky mixtures.

High performance lightweight concrete has been used for bridges. This concrete typically uses normal-weight sand and lightweight coarse aggregate. Its lower mass also makes it an attractive option in seismic regions (Murugesh 2008 and Gilley 2008).

Admixtures

The use of chemical admixtures such as water reducers, retarders, high-range water reducers, or superplasticizers is necessary. They make more efficient use of the large amount of cementitious material in high-strength concrete and help to obtain the lowest practical water to cementing materials ratio. Chemical admixture efficiency must be evaluated by comparing strengths of trial batches. Also, compatibility between cement and supplementary cementing materials, as well as water-reducing and other admixtures, must be investigated by trial batches. From these trial batches, it will be possible to determine the workability, setting time, and amount of water reduction for given admixture dosage rates and times of addition.

The use of air-entraining admixtures where durability in a freeze-thaw environment is required is mandatory. However, air is not necessary or desirable in high-strength concrete protected from the weather, such as interior columns and shear walls of high-rise buildings. Because air entrainment decreases concrete strength of rich mixtures, testing to establish optimum air contents and spacing factors may be required. Certain high-strength concretes may not need as much air as normal-strength concrete for equivalent frost resistance. Pinto and Hover (2001) found that non-air-entrained, high-strength concretes had good frost and deicer-scaling resistance at a water to portland cement ratio of 0.25. Burg and Ost (1994) found good frost resistance with non-air-entrained concrete containing silica fume at a water to cementing materials ratio of 0.22 (Mix No. 4 in Table 19-5). However, this was not the case with other mixtures, including a portland-only mixture with a water to cement ratio of 0.28.

High-Performance Concrete Construction

Proportioning

The trial mixture approach is best for selecting proportions for high-performance concrete. To obtain high performance, it is necessary to use a low water to cementing materials ratio and, often, a high portland cement content. The unit strength obtained for each unit of cement used in a cubic meter (yard) of concrete can be plotted as strength efficiency to evaluate mixture designs.

The water requirement of concrete increases as the fine aggregate content is increased for any given size of coarse aggregate. Because of the high cementing materials content of these concretes, the fine aggregate content can be kept low. However, even with well-graded aggregates, a low water-cementing materials ratio may result in concrete that is not sufficiently workable for the job. If a superplasticizer is not used, the design should be revised. A slump of around 200 mm (8 in.) will provide adequate workability for most applications. ACI Committee 211 (2008), Farny and Panarese (1994), Nawy (2001), and Caldarone (2009) provide additional guidance on proportioning.

Mixing

High-performance concrete has been successfully mixed in transit mixers and central mixers. However, many of these concretes that have higher cementitious contents tend to be sticky and may cause build-up in these mixers, especially when silica fume is used. Where dry, uncompacted silica fume has been batched into a mixture, "balling" of the mixture has occurred and mixing has been incomplete. In these instances it has been necessary to experiment with the charging sequence, and the percentage of each material added at each step in the batching procedure. Batching and mixing sequences should be optimized during the trial mix phase. Where truck mixing is unavoidable, the best practice is to reduce loads to 90% of the rated capacity of the trucks.

Where there is no recent history of HPC mixtures that meet specified requirements, it is essential to first make laboratory trial mixtures to establish optimum proportions. At this stage, the properties of the mixture, such as workability, air content, density, strength, and modulus of elasticity can be determined. It is also important to determine how admixtures interact and their effects on concrete properties. Once laboratory mixture proportions have been determined, field trials using full loads of concrete are essential. They should be delivered to the site or to a mock-up to establish and confirm the suitability of the batching, mixing, transporting, and placing systems to be used.

For large projects or a mass concrete structure, a trial member may be required. One or more loads of the proposed mixture is cast into a trial member or mock-up. The fresh concrete is tested for slump, air content, temperature, and density. Casting the trial member or mock-up provides the opportunity to assess the suitability of the mixture for placing, compaction, and temperature gain. The trial member or mock-up can be instrumented to record temperatures and temperature gradients. It can also be cored and tested to provide correlation with standard cylinder test results. The cores can be tested to provide the designer with in-place strength and modulus values for reference during construction. The heat characteristics of the mixture can also be determined using a computer program, and the data used to determine how curing technology should be applied to the project.

Placing, Consolidation, Finishing, and Curing

Close liaison between the contractor and the concrete producer allows concrete to be discharged rapidly after arrival at the jobsite. Final adjustment of the concrete should be supervised by the concrete producer's technicians at the site, by a concrete laboratory, or by a consultant familiar with the performance and use of high-strength concrete.

Delays in delivery and placing must be eliminated. Sometimes it may be necessary to reduce batch sizes if placing procedures are slower than anticipated. Rigid surveillance must be exercised at the jobsite to prevent any addition of retempering water. Increases in workability should only be achieved by the addition of a superplasticizer. This should be done by the supplier's technician. The contractor must be prepared to receive the concrete and understand the consequences of exceeding the specified slump and water-cementitious materials ratio.

Consolidation is very important in achieving the potential of high-performance concrete. Concrete must be vibrated as quickly as possible after placement in the forms. High-frequency vibrators should be small enough to allow sufficient clearance between the vibrating head and reinforcing steel. Over-vibration of workable normal-strength concrete often results in segregation, loss of entrained air, or both. On the other hand, high-performance concrete without a superplasticizer will be relatively stiff and contain little air. Consequently, inspectors should be more concerned with under-vibration rather than over-vibration. Most high-strength concrete, particularly very high-strength-concrete, is placed at slumps of 180 mm to 220 mm (7 in. to 9 in.). Even at these slumps, some vibration is required to ensure compaction. The amount of compaction should be determined by onsite trials.

High-performance concrete can be difficult to finish. High cementitious materials contents, large dosages of admixtures, low water contents, and air entrainment all contribute to the concrete sticking to the trowels and other finishing equipment. When this occurs, finishing activities should be minimized. The finishing sequence should be modified to include the use of a fresno trowel in place of a bullfloat.

Curing of high-performance concrete is even more important than curing normal-performance concrete. Providing adequate moisture and favorable temperature conditions are recommended for a prolonged period, particularly when 56- or 91-day concrete strengths are specified.

Additional curing considerations apply with HPC. Where very low water-cement ratios are used in flatwork (slabs and overlays), and particularly where silica fume is used in the mixture, there will be little if any bleeding before or after finishing. In these situations it is imperative that fog curing or evaporation retarders be applied to the concrete immediately after the surface has been struck off. This is necessary to avoid plastic shrinkage cracking of horizontal surfaces and to minimize crusting. Fog curing, followed by 7 days of wet curing, has proven to be very effective.

It is inevitable that some vertical surfaces, such as columns, may be difficult to cure effectively. Where projects are fast-tracked, columns are often stripped at an early age to allow raising of self-climbing form systems. Concrete is thus exposed to early drying, sometimes within eleven hours after casting. Because of limited access, providing further curing is difficult and impractical.

Tests were conducted on column concrete to determine if such early exposure and lack of curing have any harmful effects. The tests showed that for a portland cement-slag-silica fume mixture with a specified strength of 70 MPa (10,000 psi), the matrix was sound and a very high degree of impermeability to water and chloride ions had been achieved (Bickley and others 1994). Nevertheless, the best curing possible is recommended for all HPC.

The temperature history of HPC is an integral part of its curing process. Advantage should also be taken of recent developments in curing technology. Temperature increases and gradients that will occur in a concrete placement can be predicted by procedures that provide data for this purpose. With this technique, measures to heat, cool, or insulate a concrete placement can be determined and applied to significantly reduce both micro- and macro-cracking of the structure and assure durability. The increasing use of these techniques will be required in most structures using HPC to assure that the cover concrete provides long term protection to the steel, to meet the intended service life of the structure.

Temperature Control

The quality, strength, and durability of HPC are highly dependent on its temperature history from the time of delivery to the completion of curing. In principle, favorable construction and placing methods will enable: (1) a low temperature at the time of delivery; (2) the smallest possible maximum temperature after placing; (3) minimum temperature gradients after placing; and (4) a gradual reduction to ambient temperature after maximum temperature is reached. Excessively high temperatures and gradients can cause excessively fast hydration and micro- and macro-cracking of the concrete. Keeping member temperature under 70°C (158°F) internal curing temperature helps prevent delayed ettringite formation (DEF) (see Chapter 11).

It has been a practice on major high-rise structures incorporating concrete with specified strengths of 70 MPa to 85 MPa (10,000 psi to 12,000 psi) to specify a maximum delivery temperature of 18°C (64°F) (Ryell and Bickley 1987). In summertime it is possible that this limit could only be met using liquid nitrogen to cool the concrete (see Chapter 16). Experience with very-high-strength concrete suggests that a delivery temperature of no more than 25°C (77°F), preferably 20°C (68°F), should be allowed. The specifier should state the required delivery temperature.

In HPC applications such as high-rise buildings, column sizes are large enough to be classified as mass concrete. Normally, excessive heat generation in mass concrete is controlled by using a low cement content. When high-cement-content HPC mixtures are used under these conditions, other methods of controlling maximum concrete temperature must be employed. Burg and Ost (1994) recorded temperature rise for 1220-mm (4-ft) concrete cubes using the mixtures in Table 19-5. A maximum temperature rise of 9.4°C to 11.7°C for every 100 kg of cement per cubic meter of concrete (10°F to 12.5°F for every 100 lb of cement per cubic yard of concrete) was measured. Burg and Fiorato (1999) monitored temperature rise in high-strength concrete caissons; they determined that in-place strength was not affected by temperature rise due to heat of hydration.

Quality Control

A comprehensive quality-control program is required at both the concrete plant and onsite to guarantee consistent production and placement of high-performance concrete. Inspection of concreting operations from stockpiling of aggregates through completion of curing is important. Closer production control than is normally obtained on most projects is necessary. Also, routine sampling and testing of all materials is particularly necessary to control uniformity of the concrete.

While tests on concrete should always be made in strict accordance with standard procedures, some additional requirements are recommended, especially where specified strengths are 70 MPa (10,000 psi) or higher. In testing high-strength concrete, some changes and more attention to detail are required. For example, cardboard cylinder molds, which can cause lower strength-test results, should be replaced with reusable steel or plastic molds. Capping of cylinders must be done with great care using appropriate capping compounds. Lapping (grinding) the cylinder ends is an alternative to capping. For specified strengths of 70 MPa (10,000 psi) or greater, end grinding to a flatness tolerance of 0.04 mm is recommended (Calderone and Burg 2009).

The physical characteristics of a testing machine can have a major impact on the result of a compression test. It is recommended that testing machines be extremely stiff, both longitudinally and laterally.

The quality control necessary for the production of high compressive strength concrete will, in most cases, lead to low variance in test results. Strict vigilance in all aspects of quality control on the part of the producer and quality testing on the part of the laboratory are necessary on high-strength concrete projects. For concretes with specified strengths of 70 MPa (10,000 psi) or greater, the coefficient of variation is the preferred measure of quality control.

Self-Consolidating Concrete

Self-consolidating concrete (SCC), also referred to as self-compacting concrete, is able to flow and consolidate under its own weight. At the same time it is cohesive enough to fill spaces of almost any size and shape without segregation or bleeding. This makes SCC particularly useful wherever placing is difficult, such as in heavily-reinforced concrete members or in complicated formwork.

This technology, developed in Japan in the 1980s, is based on increasing the amount of fine material, for example fly ash or limestone filler, without changing the water content. This changes the rheological behavior of the concrete. SCC must have a low yield value to ensure high flowability; a low water content ensures high viscosity, so the coarse aggregate can float in the mortar without segregating. To achieve a balance between deformability and stability, the total content of particles finer than the 150 µm (No. 100) sieve is typically high, usually about 520 kg/m³ to 560 kg/m³ (880 lb/yd³ to 950 lb/yd³). Generally, the higher the required flowability of the SCC, the higher the amount of fine material needed to produce a stable mixture. However, in some cases, a viscosity-modifying admixture (VMA) can be used instead of, or in combination with, an increased fine content to stabilize the concrete mixture. High-range water reducers based on polycarboxylate ethers are typically used to plasticize the mixture. Figure 19-6 shows an example of mixture proportions used in self-consolidating concrete as compared to a conventional concrete mixture.

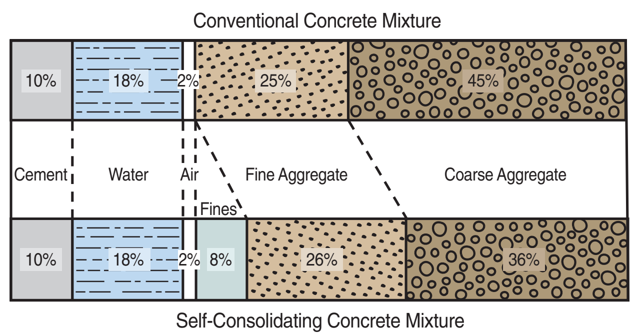

Figure 19-6. Examples of materials used in conventional concrete and self-consolidating concrete by absolute volume.

Since SCC is characterized by special fresh concrete properties, many new tests have been developed to measure flowability, viscosity, blocking tendency, self-leveling, and stability of the mixture (Skarendahl and Peterson 1999 and Ludwig and others 2001). The slump flow test (ASTM C1611, *Standard Test Method for Slump Flow of Self-Consolidating Concrete*) is performed to measure filling ability and stability. The test is performed similarly to the conventional slump test (ASTM C143). However, instead of measuring the slumping distance vertically, the mean diameter of the resulting concrete patty is measured horizontally. This number is recorded as the slump flow. The J-Ring test (ASTM C1621, *Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring*) measures passing ability. The J-Ring consists of a ring of reinforcing bar such that it will fit around the base of a standard slump cone (Figure 19-7). The slump flow with and without the J-Ring is measured, and the difference calculated.

ASTM C1610, *Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique*, evaluates static stability of a concrete mixture by quantifying aggregate segregation. A column is filled with concrete and allowed to sit after placement. The column is then separated into three pieces. Each section is removed individually and the concrete from that section is washed

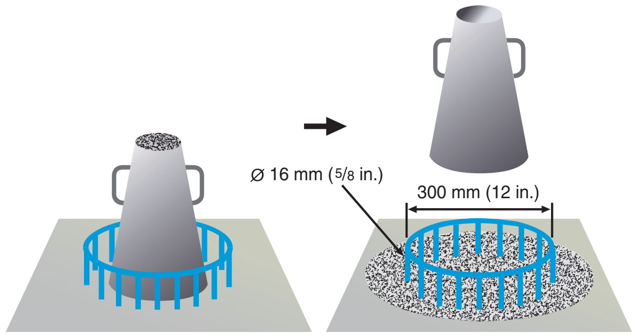

Figure 19-7. J-ring test. Photo courtesy of VDZ.

over a 4.75 mm (No. 4) sieve and the retained aggregate weighed. A non-segregating mixture will have a consistent aggregate mass distribution in each section. A segregating mixture will have higher concentrations of aggregate in the lower sections.

An earlier assessment of the segregation resistance is ASTM C1712, *Standard Test Method for Rapid Assessment of Static Segregation Resistance of Self-Consolidating Concrete Using Penetration Test*. A 45 g hollow cylinder device is placed on top of an inverted slump mold containing SCC. The distance the weight sinks in 30 seconds correlates to the static segregation resistance of the mixture. If the penetration depth is less than 10 mm, the mixture is considered segregation resistant. A penetration value above 25 mm signals a mixture that is probably prone to segregation.

Strength and durability of well-designed SCC are almost similar to conventional concrete. Without proper curing, SCC tends to have higher plastic shrinkage cracking than conventional concrete (Grube and Rickert 2001). Research indicates greater tensile creep for SCC, resulting in a reduced tendency to crack (Bickley and Mitchell 2001). The use of fly ash as a filler compared to limestone as a filler seems to be advantageous; it results in higher strength and higher chloride resistance (Bouzoubaa and Lachemi 2001 and Ludwig and others 2001).

The production of SCC is more expensive than regular concrete and it is difficult to keep SCC in the desired consistency over a long period. However, construction time is shorter and production of SCC is environmentally friendly (little noise, no vibration). Furthermore, SCC produces a good surface finish. These advantages make SCC particularly attractive for use in precasting plants.

SCC has been used successfully in tall buildings including the Trump International Hotel and Tower in Chicago, Illinois (Figure 19-8). Cast-in-place SCC has been used in the construction of inclined pylons for a cable-stayed pedestrian bridge, in Virginia (Lwin 2008). It has also been used for many drilled shaft foundations for bridges, including those of the new I-35W St. Anthony Falls Bridge in Minneapolis, Minnesota (Phipps 2008). SCC was also used to speed construction of precast prestressed bulb-tee girders in the replacement of the Biloxi Bay Bridge in Mississippi after the original bridge was destroyed by Hurricane Katrina (Carr 2008).

SCC has also been successfully used in a number of rehabilitation projects in Canada (Bickley and Mitchell 2001). Refer to ACI Committee 237, Khayat and Mitchell (2009), and Szecsy and Mohler (2009) for more information on SCC.

Figure 19-8. Completed in 2009, the 92 story Trump International Hotel and Tower, which was constructed with high-performance SCC, is the tallest building (at 1170 ft [1389 ft to the top of the spire]) built in North America since the completion of the Sears Tower in 1974.

Ultra-High Performance Concrete

Ultra-high performance concrete (UHPC) is also known as reactive powder concrete. Reactive-powder concrete was first patented by a French construction company in 1994. It is characterized by high strength and very low permeability, obtained by optimized particle packing and by a low water content.

The properties of UHPC are achieved by: (1) eliminating the coarse aggregates – only very fine powders are used (sand, crushed quartz, and silica fume), all with particle sizes between 0.02 and 300 µm; (2) optimizing the grain size distribution to densify the mixture; (3) using post-set heat-treatment to improve the microstructure; (4) addition of steel and synthetic fibers (about 2% by volume); and (5) use of superplasticizers to decrease the water to cement ratio – usually to less than 0.2 – while improving the rheology of the paste. See Figure 19-9 for a typical fresh UHPC.

Figure 19-9. Freshly-mixed ultra-high performance concrete.

The compressive strength of UHPC is typically around 200 MPa (29,000 psi), but can be produced with compressive strengths up to 810 MPa (118,000 psi) (Semioli 2001). However, the low comparative tensile strength requires prestressing reinforcement in severe structural service. Table 19-6 compares hardened concrete properties of RPC with those of an 80-MPa (11,600-psi) concrete.

The Federal Highway Administration (FHWA) studied multiple properties of UHPC, namely compressive and tensile strengths, creep and shrinkage, chloride ion penetration, and freeze-thaw durability. The 28-day compressive strengths ranged from 126 to 193 MPa (18,000 to 28,000 psi), depending upon whether or not a secondary heat treatment was used to further develop compressive strength. The tensile strength was approximately 6.2 MPa (900 psi) without secondary heat treatment and 9.0 MPa (1,300 psi) after secondary heat treatment. The UHPC showed excellent resistance to chloride ion penetration, exhibited good long-term creep and shrinkage behavior, and held up well in freeze-thaw testing (Graybeal 2006).

UHPC has been used in the beams and decks of U.S. bridges. The first bridge in the U.S. to use UHPC was the Mars Hill Bridge in Wapello County, Iowa. This 33.5-m (110-ft.) bridge used three 107-cm (42-in.) modified Iowa bulb-tee girders, and opened to traffic in 2006. The second bridge was the Cat Point Creek Bridge in Richmond County, Virginia. This ten-span bridge opened to traffic in 2008 and contained one span with five UHPC bulb-tee girders. The third bridge was the Jakway Park Bridge in

Figure 19-10. The Sherbrooke footbridge in Quebec, built in 1997, is North America's first reactive-powder ultra-high performance concrete structure.

Table 19-6. Typical Mechanical Properties of Reactive Powder Concrete (RPC) Compared to an 80-MPa Concrete (Perry 1998)

Property	Unit	80 MPa	RPC
Compressive strength	MPa (psi)	80 (11,600)	200 (29,000)
Flexural strength	MPa (psi)	7 (1000)	40 (5800)
Tensile strength	MPa (psi)		8 (1160)
Modulus of Elasticity	GPa (psi)	40 (5.8 x 10^6)	60 (8.7 x 10^6)
Fracture Toughness	10^3 J/m^2	<1	30
Freeze-thaw, ASTM C666	RDF	90	100
Carbonation depth: 36 days in CO_2	mm	2	0
Abrasion	10^{-12} m^2/s	275	1.2

Buchanan County, Iowa. This 15.7-m (51.5-ft.) long bridge used UHPC pi-girders. (Graybeal 2009), (Bierwagen 2009). Other uses for UHPC in bridges include waffle deck panels in Iowa and cast-in-place UHPC connections between full-depth deck panels in New York. See Li and Li (2010) for repair applications and Li (2010) for infrastructure applications. UHPC has also been used in pedestrian bridges (Figure 19-10) (Bickley and Mitchell 2001 and Semioli 2001). The low porosity of RPC also gives excellent durability and transport properties, which makes it a suitable material for the storage of nuclear waste (Matte and Moranville 1999). A low-heat type of reactive-powder concrete has been developed to meet needs for mass concrete pours for nuclear reactor foundation mats and underground containment of nuclear wastes (Gray and Shelton 1998).

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