

Report on High-Strength Concrete

Reported by ACI Committee 363



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Report on High-Strength Concrete

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Report on High-Strength Concrete

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This report summarizes currently available information about high-strength concrete (HSC). Topics discussed include selection of materials, concrete mixture proportions, ordering, batching, mixing, transporting, placing, quality control, concrete properties, structural design, economic considerations, and applications.

Keywords: concrete properties; economic considerations; high-strength concrete; material selection; mixture proportions; structural applications; structural design; quality control.

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CHAPTER 1—INTRODUCTION

1.1—Historical background

The use and definition of high-strength concrete (HSC) has seen a gradual and continuous development over many years. In the 1950s, concrete with a compressive strength of 5000 psi (34 MPa) was considered high strength. In the 1960s, concrete with compressive strengths of 6000 and 7500 psi (41 and 52 MPa) were produced commercially. In the early 1970s, 9000 psi (62 MPa) concrete was produced. Today, compressive strengths approaching 20,000 psi (138 MPa) have been used in cast-in-place buildings. Laboratory researchers using special materials and processes have achieved “concretes” with compressive strengths in excess of 116,000 psi (800 MPa) (Schmidt and Fehling 2004). As materials technology and production processes evolve, it is likely the maximum compressive strength of concrete will continue to increase and HSC will be used in more applications.

Demand for and use of HSC for tall buildings began in the 1970s, primarily in the U.S.A. Water Tower Place in Chicago, IL, which was completed in 1976 with a height of 859 ft (260 m) and used 9000 psi (62 MPa) specified compressive strength concrete in the columns and shear walls. The 311 South Wacker building in Chicago, completed in 1990 with a height of 961 ft (293 m), used 12,000 psi (83 MPa) specified compressive strength concrete for the columns. In their time, both buildings held the record for the world's tallest concrete building. Two Union Square in Seattle, WA, completed in 1989, holds the record for the highest specified compressive strength concrete used in a building at 19,000 psi (131 MPa).

High-strength concrete is widely available throughout the world, and its use continues to spread, particularly in the Far East and Middle East. All of the tallest buildings constructed in the past 10 years have some structural contribution from HSC in vertical column and wall elements. The world's tallest building, at 1670 ft (509 m), is Taipei 101 in Taiwan, completed in 2004. The structural system uses a mix of steel and concrete elements, with specified concrete compressive strengths up to 10,000 psi (69 MPa) in composite columns. Petronas Towers 1 and 2, completed in 1998 in Kuala Lumpur, Malaysia, used concrete with specified cube strengths up to 11,600 psi (80 MPa) in columns and shear walls. At the time of this report, these towers are the second and third tallest buildings in the world, both at 1483 ft (452 m). The world's tallest building constructed entirely with a reinforced concrete structural system is the CITIC Plaza

building in Guangzhou, People's Republic of China, with a height of 1283 ft (391 m). Trump World Tower in New York City, reportedly the world's tallest residential building at 861 ft (262 m) and completed in 2001, is constructed using a concrete system alone with columns having specified compressive strengths up to 12,000 psi (83 MPa). In 2005, construction began on Burj Dubai tower in Dubai, UAE. With a height exceeding 1969 ft (600 m), this all-concrete residential structure, scheduled for completion in 2009, will use concrete with specified cube strengths up to 11,600 psi (80 MPa).

The use of HSC in bridges began in the U.S. in the mid-1990s through a series of demonstration projects. The highest specified concrete compressive strength is 14,700 psi (101 MPa) for prestressed concrete girders of the North Concho River Overpass in San Angelo, TX. High-strength concrete has also been used in long-span box-girder bridges and cable-stayed bridges. There are also some very significant applications of HSC in offshore structures. These include projects such as the Glomar Beaufort Sea I drilling structure, the Heidrun floating platform in the North Sea, and the Hibernia offshore concrete platform in Newfoundland, Canada. In many offshore cases, HSC is specified because of the harsh environments in which these structures are located (Kopczynski 2008).

1.2—Definition of high-strength concrete

In 2001, Committee 363 adopted the following definition of HSC:

concrete, high-strength—concrete that has a specified compressive strength for design of 8000 psi (55 MPa) or greater.

When the original version of this report was produced in 1992, ACI Committee 363 adopted the following definition of HSC:

concrete, high-strength—concrete that has a specified compressive strength for design of 6000 psi (41 MPa) or greater.

The new value of 8000 psi (55 MPa) was selected because it represented a strength level at which special care is required for production and testing of the concrete and at which special structural design requirements may be needed. As technology progresses and the use of concrete with even higher compressive strengths evolves, it is likely that the definition of high-strength concrete will continue to be revised.

Although 8000 psi (55 MPa) was selected as the lower limit, it is not intended to imply that there is a drastic change in material properties or in production techniques that occur at this compressive strength. In reality, all changes that take place above 8000 psi (55 MPa) represent a process that starts with the lower-strength concretes and continues into higher-strength concretes. Many empirical equations used to predict concrete properties or to design structural members are based on tests using concrete with compressive strengths of 8000 to 10,000 psi (55 to 69 MPa). The availability of data for higher-strength concretes requires a reassessment of the equations to determine their applicability with higher-strength concretes. Consequently, caution should be exercised in extrapolating empirical relationships from lower-strength to higher-strength concretes. If necessary, tests should be

made to develop relationships for the materials or applications in question.

The committee also recognized that the definition of HSC varies on a geographical basis. In regions where concrete with a compressive strength of 9000 psi (62 MPa) is already being produced commercially, HSC might range from 12,000 to 15,000 psi (83 to 103 MPa) compressive strength. In regions where the upper limit on commercially available material is currently 5000 psi (34 MPa) concrete, 9000 psi (62 MPa) concrete is considered high strength. The committee recognized that material selection, concrete mixture proportioning, batching, mixing, transporting, placing, curing, and quality-control procedures are applicable across a wide range of concrete strengths. The committee agreed, however, that material properties and structural design considerations given in this report should be concerned with concretes having high compressive strengths. The committee has tried to cover both aspects in developing this report.

1.3—Scope of report

Because the definition of HSC has changed over the years, the following scope was adopted by Committee 363 for this report: "The immediate concern of Committee 363 shall be concretes with specified compressive strengths for design of 8000 psi (55 MPa) or greater, but for the present time, considerations shall not include concrete made using exotic materials or techniques." The word "exotic" was included so that the committee would not be concerned with concretes such as polymer-impregnated concrete, epoxy concrete, ultra-high-performance concrete; concrete with artificial, normal, and heavyweight aggregates; and reactive powder concrete. In addition to focusing on concretes made with nonexotic materials or techniques, the committee also attempted to focus on concretes that were commercially viable rather than concretes that have only been produced in the laboratory.

CHAPTER 2—NOTATION, DEFINITIONS, AND ACRONYMS

2.1—Notation

A_b	=	area of a single spliced bar (or wire), in. ² (mm ²)
A_{cp}	=	area enclosed by outside perimeter of concrete cross section, in. ² (mm ²)
A_g	=	gross area of concrete section, in. ² (mm ²). For a hollow section, A_g is the area of concrete only and does not include the area of the void(s)
A_s	=	area of nonprestressed longitudinal tension reinforcement, in. ² (mm ²)
A_{sp}	=	area of transverse reinforcement crossing the potential plane of splitting through the reinforcement being developed, in. ² (mm ²)
A_{st}	=	total area of nonprestressed longitudinal reinforcement, in. ² (mm ²)
A_{tr}	=	total cross-sectional area of all transverse reinforcement with spacing s that crosses the potential plane of splitting through the reinforcement being developed, in. ² (mm ²)

A_{Vmin} = minimum area of shear reinforcement within spacing s , in.² (mm²)
 B = width of compression face of member, in. (mm)
 b = width of the cross section, in. (mm)
 b_w = web width, or diameter of circular section, in. (mm)
 C_c = creep coefficient
 D = distance from extreme compression fiber to centroid of longitudinal reinforcement, in. (mm)
 d = distance from extreme compression fiber to centroid of tension reinforcement, in. (mm)
 E_c = modulus of elasticity of concrete, psi (MPa)
 f_2' = concrete confinement stress produced by spiral, psi (MPa)
 f_c' = specified compressive strength of the concrete, psi (MPa)
 $\bar{f}_c$ = compressive strength of spirally reinforced concrete column, psi (MPa)
 f_c'' = compressive strength of unconfined concrete column, psi (MPa)
 f_{cr}' = required average compressive strength of concrete used as the basis for selection of concrete proportions, psi (MPa)
 f_r = modulus of rupture of concrete, psi (MPa)
 f_{sp} = splitting cylinder strength of concrete, psi (MPa)
 f_y = specified yield strength of reinforcement, psi (MPa)
 I_{cr} = moment of inertia of cracked transformed to concrete, in.⁴ (mm⁴)
 I_g = moment of inertia of gross concrete section about centroidal axis, neglecting reinforcement, in.⁴ (mm⁴)
 k_1 = ratio of average to maximum compressive stress in beam
 k_2 = ratio of depth to compressive resultant to neutral axis depth
 k_3 = ratio of maximum stress in beam to maximum stress in corresponding axially loaded cylinder
 M_a = maximum moment in member due to service loads at stage deflection is computed, in.-lb (N·mm)
 M_{cr} = cracking moment, in.-lb (N·mm)
 M_n = nominal flexural strength at section, in.-lb (N·mm)
 M_u = factored moment at section, in.-lb (N·mm)
 n = number of spliced bars ($n = 1$ for a single bar)
 s_s = sample standard deviation, psi (MPa)
 T_{cr} = cracking torsional moment, in.-lb (N·mm)
 V_c = nominal shear strength provided by concrete, lb (N)
 V_u = factored shear force at section, lb (N)
 w_c = unit weight of normalweight concrete or equilibrium density of lightweight concrete, lb/ft³ (kg/m³)
 w/cm = water-cementitious material ratio
 α_1 = stress block parameter as defined in Fig. 7.2
 β_1 = factor relating depth of equivalent rectangular compressive stress block to neutral axis depth
 δ_c = specific creep (unit creep coefficient)
 Δ_u = beam deflection at failure load, in. (mm)
 Δ_y = beam deflection at the load producing yielding of tensile steel, in. (mm)

$\epsilon_{initial}$ = initial strain upon application of load, in./in. (mm/mm)
 ϵ_{creep} = additional time-dependent strain due to creep, in./in. (mm/mm)
 λ_Δ = multiplier for additional deflection due to long-term effects
 μ = ductility index
 ξ = time-dependent factor for sustained load taken from ACI 318
 $\sigma_{initial}$ = initial stress due to sustained load, psi (MPa)
 ρ' = reinforcement ratio for non-prestressed compression reinforcement; ratio of A_s' to bd
 ρ_{cp} = outside perimeter of concrete cross section
 ρ_{min} = minimum reinforcement ratio; ratio of $A_{s,min}'$ to bd
 ρ_s = ratio of volume of spiral reinforcement to total volume of concrete core confined by the spiral (measured out-to-out of spirals)
 ψ_u = cross-section curvature at failure load
 ψ_y = cross-section curvature at the load producing yielding of tensile steel
 ω = tension reinforcement index

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology” (<http://terminology.concrete.org>) (American Concrete Institute 2009). Definitions provided here complement that resource.

admixture—a material other than water, aggregates, hydraulic cement, and fiber reinforcement, used as an ingredient of a cementitious mixture to modify its freshly mixed, setting, or hardened properties and that is added to the batch before or during its mixing.

admixture, air-entraining—an admixture that causes the development of a system of microscopic air bubbles in concrete, mortar, or cement paste during mixing, usually to increase its workability and resistance to freezing and thawing.

admixture, water-reducing (high-range)—a water-reducing admixture capable of producing large water reduction or great flowability without causing undue set retardation or entrainment of air in mortar or concrete.

aggregate—granular material, such as sand, gravel, crushed stone, crushed hydraulic-cement concrete, or iron blast-furnace slag, used with a hydraulic cementing medium to produce either concrete or mortar.

concrete, high-strength—concrete that has a specified compressive strength for design of 8000 psi (55 MPa) or greater.

creep—time-dependent deformation due to sustained load.

heat of hydration—heat evolved by chemical reactions with water, such as that evolved during the setting and hardening of portland cement, or the difference between the heat of solution of dry cement and that of partially hydrated cement.

materials, cementitious—pozzolans and hydraulic cements used in concrete and masonry construction.

modulus of elasticity—the ratio of normal stress to corresponding strain for tensile or compressive stresses below the proportional limit of the material, also referred to as

elastic modulus, Young's modulus, and Young's modulus of elasticity; denoted by the symbol E .

modulus of rupture—a measure of the load-carrying capacity of a beam and sometimes referred to as rupture modulus or rupture strength; it is calculated for apparent tensile stress in the extreme fiber of a transverse test specimen under the load that produces rupture.

permeability to water, coefficient of—the rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and standard temperature conditions, usually 70°F (20°C).

ratio, Poisson's—the absolute value of the ratio of transverse (lateral) strain to the corresponding axial (longitudinal) strain resulting from uniformly distributed axial stress below the proportional limit of the material; the value will average approximately 0.2 for concrete and 0.25 for most metals.

resistance, abrasion—ability of a surface to resist being worn away by rubbing and friction.

resistance, fire—the property of a material or assembly to withstand fire or give protection from it; as applied to elements of buildings, it is characterized by the ability to confine a fire or, when exposed to fire, to continue to perform a given structural function, or both.

scaling—local flaking or peeling away of the near-surface portion of hardened concrete or mortar; also peeling or flaking of a layer from metal.

shrinkage—decrease in either length or volume. Note: may be restricted to the effects of moisture content or chemical changes.

strength, fatigue—the greatest stress that can be sustained for a given number of stress cycles without failure.

strength, splitting tensile—tensile strength of concrete determined by a splitting tensile test.

quality assurance—actions taken by an organization to provide and document assurance that what is being done and what is being provided are in accordance with the contract documents and standards of good practice for the work.

quality control—actions taken by an organization to provide control and documentation over what is being done and what is being provided so that the applicable standard of good practice and the contract documents for the work are followed.

water-cement ratio—the ratio of the mass of water, exclusive only of that absorbed by the aggregates, to the mass of portland cement in concrete, mortar, or grout, stated as a decimal and abbreviated as w/c . (See also **water-cementitious material ratio**.)

water-cementitious material ratio—the ratio of the mass of water, exclusive only of that absorbed by the aggregate, to the mass of cementitious material (hydraulic) in concrete, mortar, or grout, stated as a decimal and abbreviated as w/cm . (See also **water-cement ratio**.)

2.3—Acronyms

CCHRB	Chicago Committee on High-Rise Buildings
CSH	calcium silicate hydrate
CTE	coefficient of thermal expansion

FHWA	Federal Highway Administration
HRM	high-reactivity metakaolin
HRWRA	high-range water-reducing admixture
HSC	high-strength concrete
MRWRA	mid-range water-reducing admixture
SCM	supplementary cementitious material

CHAPTER 3—SELECTION OF MATERIAL

3.1—Introduction

Producing high-strength concrete (HSC) that consistently meets requirements for workability and strength development places stringent requirements on material selection compared with conventional concretes. Quality materials are needed, and specifications require enforcement. High-strength concrete has been produced using a wide range of constituent materials. Trial batching, in both the laboratory and field, is necessary to assess the quality and suitability of constituent materials in HSC. This chapter cites the state of knowledge regarding material selection and provides a baseline for the subsequent discussion of mixture proportions in Chapter 4.

3.2—Cementitious materials

3.2.1 Portland cement—Portland cement is by far the most widely used type of cement in the manufacture of hydraulic-cement concrete, and HSC is no exception. The choice of portland cement for HSC is extremely important (Freedman 1971; Hester 1977). Portland cement for use in HSC should be selected based on performance needs. For example, unless high early strength is required, such as in prestressed concrete, there is no need to use high-early-strength portland cement, such as ASTM C150/C150M Type III. Furthermore, because of the significant variations in properties that are permitted in cement specifications within a given cement type, different brands of cement will have different strength development characteristics. Differences in compressive strength among mixtures containing different cements are more pronounced at an age of 1 day than at 56 days (Myers and Carrasquillo 1998). Also, cement characteristics will generally have a larger influence on compressive strength than modulus of elasticity (Freyne et al. 2004).

Initially, manufacturers' mill certificates for the previous 6 to 12 months should be obtained from potential suppliers. This will give an indication of strength characteristics from ASTM C109/C109M mortar cube tests, and more importantly, it will provide an indication of cement uniformity. The cement supplier should be required to report uniformity in accordance with ASTM C917. Variations in chemical and physical properties over time should be tightly controlled. For example, in the case of a portland cement, if the tricalcium silicate content varies by more than 4%, the ignition loss by more than 0.5%, or the fineness by more than 171 ft²/lb (35 m²/kg) (Blaine), then objectionable variability in strength performance may result (Hester 1977). Sulfur trioxide (SO₃) levels should not vary by more than ±0.20 percentage points from that in the cement used for the mixture development process.

Although mortar cube tests can be a good indication of potential strength, mortar cube test results alone should not

be the sole basis for selecting cement for use in concrete, particularly in HSC. A reliable estimate of cement performance in HSC can be achieved by assessing the cements' normal consistency and setting times along with cube strength (ASTM C191; ASTM C109/C109M). Concrete tests, however, should be run on trial batches of concrete made with proposed aggregates, supplementary cementitious materials (SCMs), and chemical admixtures, and evaluated under simulated job conditions. Unless the objective is only to achieve high early strength, in most cases, strengths should be determined through at least 56 days. The effect of cementitious material characteristics on water demand is more pronounced in HSCs because of higher cementitious materials contents and low water-cementitious material ratios (w/cm).

The type and amount of cementitious materials in a HSC mixture can have a significant effect on temperature development within the concrete. For example, the Chicago Committee on High-Rise Buildings (CCHRB 1997) reported that the temperature in the 4 ft (1.2 m) square columns used in Water Tower Place, which had a cement content of 846 lb/yd³ (502 kg/m³), rose to 150 from 75°F (66 from 24°C) during hydration. The heat was dissipated within 6 days without harmful effects. When temperature rise is expected to be a problem, however, slower-reacting, low-heat-of-hydration materials, such as Type II portland cement, SCMs such as slag or Class F fly ash, or blended hydraulic cements incorporating slag or Class F fly ash can be used provided they meet strength and heat of hydration requirements. Additional practices that can alleviate problems associated with temperature rise and related hot weather conditions are discussed in ACI 305R.

A further consideration is optimization of the cement-admixture system. Optimization in terms of the balance of cement and admixtures is the level at which the cement, cementitious admixtures, and chemical admixtures are minimized from a cost perspective. The exact effect of a water-reducing chemical admixture on water requirement, for example, will depend on cement characteristics. Strength development depends on both the characteristics of the cementitious materials and the w/cm (ACI 211.4R).

3.2.2 Supplementary cementitious materials—In the past, fly ash, silica fume, and natural pozzolans were frequently called mineral admixtures. In North America today, these materials and others, such as slag cement, are now covered under the term “supplementary cementitious materials” (SCMs). Supplementary cementitious materials for use in concrete are materials that have mineral oxides similar to those found in portland cement, but in different proportions and possibly different mineral phases. Supplementary cementitious materials are widely used in the production of HSC because their presence alters the mineral constituents in the binding (paste) system to allow attainment of high strengths.

Supplementary cementitious materials consisting of certain pozzolans or slags are extremely well-suited for use in HSC. Supplementary cementitious materials can be predominantly hydraulic, pozzolanic, or possess properties of both a hydraulic and pozzolanic material. Similar to portland

cement, hydraulic SCMs set and harden when in contact with water. Pozzolans are siliceous or siliceous and aluminous materials that, by themselves, possess little or no cementitious value. In finely divided form and in the presence of moisture, however, they will chemically react with calcium hydroxide released by cement hydration to form additional calcium silicate hydrate (CSH) gel, the glue that binds aggregate particles together. In addition to the pozzolanic effect, some SCMs improve the particle packing of the binder system (Brewe and Myers 2005).

With a good understanding of their individual properties and an understanding of how these materials interact with the other mixture constituents (ACI 232.2R; ACI 233R; ACI 234R), appropriate use of SCMs can significantly improve strength in concrete, particularly HSC. In fact, without their use, achieving extremely high strength levels that are routinely available in many construction markets would be significantly more difficult, if not impossible. In many cases, workability, pumpability, finishability, durability, and economy can also be improved through the proper use of these materials.

It is important that all cementitious materials be tested for acceptance and uniformity, and carefully investigated for strength-producing properties and compatibility with the other materials in the mixture, particularly chemical admixtures, before they are used in the work.

3.2.2.1 Fly ash—Specifications for fly ash are covered in ASTM C618. There are two fly ash classifications: Class F and Class C. Class F fly ash is normally produced from burning anthracite or bituminous coal and has strong pozzolanic properties, but little or no hydraulic properties. Class C fly ash is normally produced from burning lignite or sub-bituminous coal, and in addition to having pozzolanic properties, has some hydraulic properties. The major difference between these two classes of fly ash is the amounts of silicon dioxide (silica) and calcium oxide they contain. Class C fly ash, having an abundance of both silica and calcium oxide, is capable of producing CSH when it alone comes into contact with water. Class F fly ash, though high in silica, lacks a sufficient quantity of calcium oxide to produce CSH when it alone comes into contact with water. Class C fly ash is more reactive than Class F fly ash. In general, Class F fly ash has been used predominantly in the eastern and western regions of the U.S. and Canada, and Class C fly ash has been used mostly in the Midwestern and South Central regions of the U.S. (ACI 232.2R).

In addition to its chemical and physical properties and how it interacts with admixtures and other cementitious materials in the mixture, the optimum quantity of fly ash in a HSC depends to a large extent on the target strength level and the age at which strength is desired. For example, the optimum quantity of a Class C fly ash in conventional concrete having a specified compressive strength of 4000 psi (28 MPa) at 28 days and containing 450 lb/yd³ (225 kg/m³) of cementitious material might be 25% (by mass) of the cementitious material content. In a concrete having a specified compressive strength of 10,000 psi (69 MPa) at 56 days and containing 900 lb/yd³ (450 kg/m³) of cementitious material, the

optimum quantity of the same fly ash might be 40% or more (Caldarone 2008).

Methods for sampling and testing fly ash are given in ASTM C311 and C618. Variations in chemical or physical properties, although within the tolerances of these specifications, may cause appreciable variations in HSC properties. Such variations can only be minimized by changes in the coal burning and fly ash collection process employed at the power plant.

3.2.2.2 Silica fume—Silica fume has been used in structural concrete and repair applications where high strength, low permeability, or high abrasion resistance are advantageous. Major advancements in the areas of high-strength and high-performance concrete have been largely possible through the use of silica fume. Silica fume is a by-product resulting from the reduction of high-purity quartz with coal in electric arc furnaces in the production of silicon and ferrosilicon alloys. The fume, which has high amorphous silicon dioxide content and consists of very fine spherical particles, is collected from the gases escaping the furnaces. Specifications for silica fume are covered in standards, such as ASTM C1240 and EN 13263.

Silica fume is composed mostly of amorphous silica particles, and its specific gravity is expected to be approximately 2.20, the most commonly accepted value for amorphous silica (Malhotra et al. 2000). ELKEM (1980) reported the specific surface area of silica fume is on the order of 88,000 to 107,500 ft²/lb (18,000 to 22,000 m²/kg) when measured by nitrogen adsorption techniques. Nebesar and Carette (1986) reported an average value of 97,700 ft²/lb (20,000 m²/kg). Particle-size distribution of typical silica fume shows most particles are smaller than 1 micrometer (1 μm), with the majority being on the order of 0.1 to 0.3 μm, which is approximately 100 times smaller than the average cement particle. The specific gravity of silica fume is typically 2.2, but may be as high as 2.5. The bulk density as collected is 10 to 20 lb/ft³ (160 to 320 kg/m³). Silica fume for commercial applications is available in either densified or slurry form. Silica fume in slurry form, however, is not readily available in some markets. Silica fume is generally dark gray to black in color.

Silica fume, because of its extreme fineness and high silica content, is highly reactive and effective pozzolanic material. In addition to the pozzolanic reaction, the fine particle size of silica fume also helps to increase paste density by filling voids between the cement grains, thereby improving particle packing and pore size distribution (Brewer and Myers 2005). Because of its extreme fineness, the increased water demand resulting from its use is quite high; therefore, using a high-range water-reducing admixture (HRWRA) is usually required. Silica fume contents typically range from 5 to 10% of the cementitious materials content. The use of silica fume to produce high-strength concrete increased dramatically, starting in the 1980s, with much success. Laboratory and field experience indicates that concrete incorporating silica fume exhibits reduced bleeding but has an increased tendency to develop plastic shrinkage cracks. Thus, it is necessary to quickly cover the surfaces of freshly placed

silica-fume concrete to prevent surface drying. An in-depth discussion of silica fume for use in concrete can be found in ACI 234R and the *Silica Fume User's Manual* (Holland 2005).

3.2.2.3 High-reactivity metakaolin—High-reactivity metakaolin (HRM) is a reactive alumino-silicate pozzolan formed by calcining purified kaolin (china) clay at a specific temperature range. Unlike most other SCMs, such as fly ash, slag cement, and silica fume, which are by-products of major industry, HRM is a specifically manufactured material. It is nearly white in color, and usually supplied in powder form. Specifications for HRM are covered under ASTM C618, Class N.

High-reactivity metakaolin is a highly reactive pozzolan suitable for applications where high strength or low permeability is required in structural or repair materials. High-reactivity metakaolin particles are significantly smaller than most cement particles, but are not as fine as silica fume. The average particle size of a HRM produced for concrete applications is approximately 2 μm, or approximately 20 times the average particle size of silica fume. Because of its larger particle size, the increased water demand associated with HRM is not quite as high as it is with silica fume (Caldarone et al. 1994); however, measures to preclude surface drying and plastic cracking may still need to be employed due to a reduction in bleeding rate. HRM contents typically range from 5 to 15% (by mass) of the cementitious materials content used. The specific gravity of HRM is approximately 2.5 (Caldarone et al. 1994).

3.2.2.4 Slag cement—Slag cement is produced only in certain areas of the U.S. and Canada, but is generally available in many North American markets. Specifications and classifications for this material are covered in ASTM C989. Slag appropriate for use in concrete is the nonmetallic product developed in a molten condition simultaneously with iron in a blast furnace. Iron blast-furnace slag essentially consists of silicates and alumino-silicates of calcium and other bases.

When properly quenched and processed, iron blast-furnace slag acts hydraulically in concrete and can be used as a partial replacement for portland cement. According to ACI 233R, most slag cement is batched as a separate constituent at the concrete production plant. Blended hydraulic cements are also produced consisting of slag cement and portland cement produced through intergrinding or intermixing processes. It is the committee's experience that slag cement contents typically range from 30 to 50% (by mass) of the cementitious material content, though higher contents are frequently used for special applications, such as in mass concrete where minimal heat of hydration is desired. The use of HSCs consisting of ternary combinations of portland cement, slag cement, and pozzolans, such as fly ash and silica fume, is also common.

3.2.3 Evaluation and selection—Cementitious materials, like any material in a HSC mixture, should be evaluated using laboratory trial batches to establish optimum desirable qualities. Materials representative of those that will be employed in the actual construction should be used. Care should be taken to ensure that the materials used are representative, come from the same source, and are handled

in the same manner as those for the proposed work. For example, if a certain silica fume is to be supplied in bulk form, the material should not be evaluated using a sample that has gone through a bagging process. This general method applies to all constituent materials, including portland cement.

Generally, several trial batches are made using varying cementitious materials contents and chemical admixture dosages to establish curves that can be used to select the optimum amount of cementitious material and admixture required to achieve desired results. Optimum performance results may be characterized in terms of any single or multiple mechanical properties, material properties, or both. For HSC, compressive strength is often an optimum performance property.

3.3—Admixtures

3.3.1 General—Admixtures, particularly chemical admixtures, are widely used in the production of HSC. Chemical admixtures are generally produced using lignosulfonates, hydroxylated carboxylic acids, carbohydrates, melamine and naphthalene condensates, and organic and inorganic accelerators in various formulations. Air-entraining admixtures are generally surfactants that will develop an air-void system appropriate for enhanced durability. Chemical admixtures are most commonly used for water reduction and set time alteration, and can additionally be used for purposes such as corrosion inhibition, viscosity modification, and shrinkage control. Selection of type, brand, and dosage rate of all admixtures should be based on performance with the other materials being considered or selected for use on the project. Significant increases in compressive strength, control of rate of hardening, accelerated strength gain, improved workability, and durability can be achieved with the proper selection and use of chemical admixtures. Reliable performance on previous work and compatibility with the proposed cementitious materials and between chemical admixtures should be considered during the selection process. Specifications for chemical admixtures and air-entraining admixtures are covered under ACI 212.3R, ASTM C494/C494M and C260.

3.3.2 Chemical admixtures

3.3.2.1 Retarding chemical admixtures (ASTM C494/C494M, Types B and D)—High-strength concrete mixtures incorporate higher cementitious materials contents than conventional-strength concrete. Retarding chemical admixtures are highly beneficial in controlling early hydration, particularly as it relates to strength (ACI 212.3R). With all else being equal, increased hydration time results in increased long-term strength. Retarding chemical admixtures are also beneficial in improving workability. Adding water to retemper a HSC mixture and maintain or recover workability will result in a marked strength reduction. Structural design frequently requires heavy reinforcing steel and complicated forming with difficult placement of concrete. A retarding admixture can control the rate of hardening in the forms to eliminate cold joints and provide more flexibility in placement schedules. The dosage of a retarding admixture can be adjusted to give the desirable rate of hardening under anticipated temperature conditions.

Retarding admixtures frequently provide a strength increase proportional to the dosage rate, although the selected dosage rate is significantly affected by ambient temperatures conditions (ACI 212.3R). Mixture proportions can be tailored to ambient conditions with a range of retarding admixture dosages corresponding to the anticipated temperature conditions. During summer months, an increase in retarder dosage can effectively mitigate temperature-induced strength reduction. During winter months, dosage rates are often decreased to prevent objectionably long setting times. Transition periods between summer and winter conditions may be handled with a corresponding adjustment in the retarding admixture dosage.

When the retarding effect of the admixture has diminished, normal or slightly faster rates of heat liberation usually occur. Depending on the type and dosage of retarding admixture used, early hydration can be effectively controlled while maintaining favorable 24-hour strengths. Extended retardation or cool temperatures may adversely affect early strengths.

3.3.2.2 Normal-setting chemical admixtures (ASTM C494/C494M, Type A)—Type A water-reducing chemical admixtures, commonly called normal-setting or conventional chemical admixtures, can provide strength increases while having minimal effect on rates of hardening. Their selection should be based on strength performance. Dosages increased above the manufacturer's recommended amounts generally increase strengths, but may extend setting times.

3.3.2.3 High-range water-reducing chemical admixtures (ASTM C494/C494M, Types F and G)—One potential advantage of HRWRAs is decreasing the w/cm and providing high-strength performance, particularly at early (24-hour) ages (Mindess et al. 2003). Matching the chemical admixture to cementitious materials both in type and dosage rate is important. Slump loss characteristics of the concrete will determine whether the HRWRA should be introduced at the plant, at the site, or at both locations. With the advent of newer-generation products, however, sufficient slump retention can be achieved through plant addition in most cases (ACI 212.3R).

High-range water-reducing admixtures may serve the purpose of increasing strength through a reduction in the w/cm while maintaining equal slump, increasing slump while maintaining equal w/cm , or a combination thereof. The method of addition should distribute the admixture uniformly throughout the concrete. Adequate mixing is critical to achieve uniformity in performance. Problems resulting from nonuniform admixture distribution or batch-to-batch dosage variations include inconsistent slump, rate of hardening, and strength development. Proper training of site personnel is essential to the successful use of a HRWRA at the project site.

3.3.2.4 Accelerating chemical admixtures (ASTM C494/C494M, Types C and E)—Accelerating admixtures are not normally used in HSC unless early form removal or early strength development is absolutely critical. High-strength concrete mixtures can usually be proportioned to provide strengths adequate for vertical form removal of walls and columns at an early age. Accelerators used to increase the rate

of hardening will normally be counterproductive to long-term strength development.

3.3.2.5 Air-entraining admixtures (ASTM C260)—The use of air entrainment is recommended to enhance durability when concrete will be subjected to freezing and thawing while critically saturated or in the presence of deicers. Critical saturation is when the moisture content within the capillaries or pores exceeds 91.7%. To reach critical saturation, concrete requires direct contact with moisture for long periods. Exterior exposure alone does not justify the use of air entrainment in HSC. Periodic precipitation, such as rain or snow against a vertical surface alone, does not constitute conditions conducive to critical saturation. In 1982, Gustaferrero et al. (1983) inspected 20 out of 50 concrete bridges built on the Illinois Tollway in 1957. They observed minimal freezing-and-thawing damage in the non-air-entrained, precast, prestressed concrete bridge beams. Even though the bridges were geographically located in a severe freezing-and-thawing region and subjected to deicer chemicals from the adjacent roadway, a non-air-entrained mixture was selected because tollway engineers were concerned that air-entrained HSC could not be economically achieved on a daily basis. Entrained air can significantly reduce the strength of high-strength mixtures and increase potential for strength variability as air contents in the concrete vary; therefore, extreme caution should be exercised with respect to its use. Even though many state departments of transportation require entrained air in prestressed precast HSC bridge girders, air entrainment in HSC should be avoided unless absolutely necessary. Refer to Sections 4.6 and 6.12.

3.3.2.6 Chemical admixture combinations—Combining HRWRAs with water-reducing or retarding chemical admixtures has become common practice to achieve optimum performance at lowest cost. With optimized combinations, improvements in strength development and control of setting times and workability are possible. When using a combination of admixtures, they should be dispensed individually as approved by the manufacturer(s). Air-entraining admixtures, if used, should never directly contact chemical admixtures during the batching process.

3.4—Aggregates

3.4.1 General—Production of HSC requires purposeful selection of quality aggregates. Both fine and coarse aggregates used for HSC should, as a minimum, meet the requirements of ASTM C33/C33M; however, there are several exceptions that discussed in this section that have been found to be beneficial for HSC.

3.4.2 Fine aggregate—Fine aggregates with a rounded particle shape and smooth texture have been found to require less mixing water in concrete; for this reason, they are preferable in HSC (Wills 1967; Gaynor and Meininger 1983). The optimum gradation of fine aggregate for HSC is determined more by its effect on water requirement than on physical packing. Blick (1973) reported that sand with a fineness modulus below 2.50 gave the concrete a sticky consistency, making it difficult to compact. Sand with an

fineness modulus of approximately 3.0 gave the best workability and compressive strength. Also, refer to Section 4.7.1.

High-strength concretes typically contain such high contents of fine cementitious materials that the grading of the fine aggregates used is less critical compared with conventional concrete. However, the fine aggregate may be used to enhance the particle packing aspects of the mixture design. It is sometimes helpful, however, to increase the fineness modulus. A National Crushed Stone Association report (1975) made several recommendations in the interest of reducing the water requirement. The amounts passing the No. 50 (300 μ m) and No. 100 (150 μ m) sieves should be kept low, but within the requirements of ASTM C33/C33M, and mica or clay contaminants should be avoided. In the same study, it was reported that sand gradation had no significant effect on early strengths but that “at later ages and consequently higher levels of strength, the gap-graded sand mixes exhibited lower strengths than the standard mixes.”

3.4.3 Coarse aggregate—Coarse aggregate mineralogical characteristics, grading, shape, surface texture, elastic modulus (stiffness), and cleanliness can influence concrete properties. Many varieties of coarse aggregates have proved suitable for high-strength concrete production, but some aggregates are more suitable than others. No simple guidance on the selection of coarse aggregate is available (Neville 1996). Coarse aggregate may have a more pronounced effect in high-strength concrete than in conventional concrete (Mokhtarzadeh and French 2000a). In conventional concrete, compressive strength is typically limited by the cement paste capacity or by the capacity of the bond between coarse aggregate and cement paste. In high-strength concrete, where the cement paste and coarse aggregate and cement paste bond are enhanced by design of a low w/cm and use of SCMs, ultimate strength potential may be limited by the intrinsic strength of the coarse aggregate itself (deLarrard and Belloc 1997; Aïtcin and Neville 1993; Cetin and Carrasquillo 1998; Sengul et al. 2002).

Coarse aggregates occupy the largest volume of any of the constituent materials in concrete. In HSC, coarse aggregate volumes typically range between 50 and 70%. The optimum amount depends on the maximum size of coarse aggregate and the fineness modulus of the fine aggregate. As the maximum size of coarse aggregate increases, the optimum amount of coarse aggregate in concrete also increases. As the fineness modulus of the fine aggregate increases, the optimum amount of coarse aggregate in concrete decreases (Freyne 2000).

Past studies (Blick 1973; Perenchio 1973) have shown that for optimum compressive strength with high cementitious material contents and low w/cm , the maximum size of coarse aggregate should be kept to a minimum, at 1/2 or 3/8 in. (13 or 10 mm). Maximum sizes of 3/4 and 1 in. (19 and 25 mm) have also been used successfully (Cook 1982).

Maximum aggregate sizes of 1/2 in. (13 mm), or smaller sizes of coarse aggregate and crushed coarse aggregate, are recommended for use in HSC. Smaller sizes of coarse aggregate have greater surface area for given aggregate content, which improves coarse aggregate and cement paste

bond and enhances ultimate strength potential. The crushing process eliminates potential zones of weakness within the parent rock with the effect that smaller particles are likely to be stronger than larger ones (deLarrard and Belloc 1997). Smaller aggregate sizes are also considered to produce higher concrete strengths because of less severe concentrations of stress around the particles, which are caused by differences between the elastic moduli of the paste and the aggregate. Coarse aggregate with a rough surface texture is generally more suitable for use in HSC than coarse aggregate with a smooth surface texture because of the superior bond that it provides (Mokhtarzadeh et al. 1995; Neville 1997).

Optimum strength in an HSC mixture can most often be achieved through the use of smaller-sized aggregates. The governing factor for selecting HSC for a structure, however, may be a property other than strength. For example, in a tall building, modulus of elasticity may be the primary reason that HSC is specified. In such cases, a larger-sized aggregate, though yielding lower strength, may provide a higher modulus of elasticity.

Studies have shown that crushed stone produces higher strengths than rounded gravel (Perenchio 1973; Walker and Bloem 1960; Harris 1969). The likely reason for this is the greater mechanical bond that can develop with angular particles. Accentuated angularity, however, is to be avoided because of the attendant high water requirement and reduced workability. Aggregate should be clean, cubical, angular, 100% crushed aggregate with a minimum of flat and elongated particles. Refer to Section 4.7.2.

3.4.3.1 Paste-aggregate homogeneity—Neville (1996) reported that designing HSC to act more like a homogeneous material can enhance ultimate strength potential. This can be achieved by increasing the similarity between the elastic moduli of coarse aggregate and cement paste. Having like elastic moduli will reduce stress at the paste-aggregate interface. Using a coarse aggregate with greater stiffness has been found to increase the elastic modulus of concrete, but it is sometimes detrimental to ultimate strength potential (Cetin and Carrasquillo 1998; Myers 1999; Tadros et al. 1999).

3.4.4 Intrinsic aggregate strength—High-strength concrete often uses higher-strength and higher-quality aggregates to generate the targeted compressive strength level. Using normal-strength or low-quality aggregates will result in fracture of the aggregate before fully developing strength potential of the paste matrix or bond strength of the aggregate-paste transition zone. Developing a paste matrix and selecting an aggregate type that has a compatible relative strength and stiffness will yield high-compressive-strength concrete as further discussed in Section 6.3.

3.5—Water

The requirements for mixing water quality for HSC are no more stringent than those for conventional concrete. Specifications for standard and optional compositional and performance requirements for water used as mixing water in hydraulic cement concrete are covered in ASTM C1602/C1602M. Potable water is permitted to be used as mixing water in

concrete without testing for conformance to the requirements of ASTM C1602/C1602M.

As a result of environmental regulations that prevent the discharge of runoff water from production facility properties, use of nonpotable water or water from concrete production operations is increasing. Nonpotable water includes water containing quantities of substances that discolor it, make it smell, or have objectionable taste. Water from concrete production operations includes wash water from mixers or water that was part of a concrete mixture that was reclaimed from a concrete recycling process, water collected in a basin as a result of storm water runoff at a concrete production facility, or water that contains quantities of concrete ingredients. Water from these sources should not be used to produce HSC unless it has been shown that their use will not adversely affect the properties of the concrete.

CHAPTER 4—CONCRETE MIXTURE PROPORTIONS

4.1—Introduction

Concrete mixture proportions for HSC have varied widely. Factors influencing mixture proportions include the strength level required, test age, material characteristics, and type of application. In addition, economics, structural requirements, manufacturing practicality, anticipated curing environment, and even the time of year have affected the selection of mixture proportions. Much information on proportioning concrete mixtures is available in ACI 211.1, which deals specifically with proportioning HSC containing fly ash.

High-strength concrete mixture proportioning is a more critical process than proportioning normal-strength concrete mixtures. Frequently, the use of SCMs and chemical admixtures, and the attainment of a low w/cm are considered essential in high-strength mixture proportioning. Many trial batches are often required to generate the data that enable optimum mixture proportions to be identified.

4.2—Strength required

4.2.1 ACI 318—As with most structural concretes, HSC is usually specified in terms of its compressive strength. ACI 318 specifies concrete strength requirements. Structural concrete is normally proportioned so that the average compressive strength test results exceed specified strength f'_c by an amount sufficiently high to minimize the frequency of test results below the specified compressive strength (refer to ACI 214R).

An average value can be calculated for any set of measurement data. The fraction of individual test values that deviate from the average is usually quantified by the standard deviation. The standard deviation of test results can be valuable in predicting future variability.

Many factors can influence the variability of compressive strength test results, including variations in testing equipment and procedures, constituent materials, production facilities, delivery equipment, inspection agencies, and environmental conditions. All factors that may affect the variability of measured strength should be considered when selecting mixture proportions and establishing the acceptable standard deviation for strength results. Carrasquillo (1994) identified

principal factors affecting compressive strengths of normal- and high-strength concretes, including specimen moisture condition, specimen size, and end conditions. Burg et al. (1999) investigated the effect of end conditions, curing methods, specimen size, and testing machine properties for HSC. Refer to ACI 363.2R for additional information on quality control and testing of HSC.

High-strength concrete is more sensitive to variations in mixture proportions and testing than normal-strength concrete, and is recognized to be more challenging to evaluate accurately than lower-strength concretes. A high variability in test results will dictate a higher required average strength. If variability is predicted to be relatively low, but proves to be higher, the frequency of test results below the specified strength may be unacceptably high. Therefore, when computing a standard deviation, the concrete producer should use the most realistic test record.

ACI 318 recognizes that some test results are likely to be lower than the specified strength. Acceptance criteria are designed to limit the frequency of tests allowed to fall below the specified strength. ACI 318-05, Section 5.6.3.3 considers the strength level of an individual class of concrete satisfactory if both of the following requirements are met:

- a) Every arithmetic average of any three consecutive strength tests (average of two cylinders) equals or exceeds f'_c ; and
- b) No individual strength test (average of two cylinders) falls below f'_c by more than 500 psi (3.4 MPa) when f'_c is 5000 psi (34 MPa) or less, or by more than $0.10f'_c$ when f'_c is more than 5000 psi (34 MPa).

When f'_c exceeds 5000 psi (34 MPa), and when strength data are available to establish a standard deviation s_s , the required average strength f'_{cr} used as the basis for selection of mixture proportions should be based on the larger value computed from the following equations (ACI 318-05, Table 5.3.2.1):

$$f'_{cr} = f'_c + 1.34s_s \quad (\text{SAE units, psi}) \quad (4-1)$$

$$f'_{cr} = 0.90f'_c + 2.33s_s \quad (\text{SAE units, psi}) \quad (4-2)$$

When strength data are not available to establish a standard deviation, the required average strength f'_{cr} , used as the basis for selection of concrete proportions when f'_c exceeds 5000 psi (34 MPa), should be based on the following equation (ACI 318-05, Table 5.3.2.2):

$$f'_{cr} = 1.10f'_c + 700 \quad (\text{SAE units, psi}) \quad (4-3)$$

ACI 318 allows mixtures to be proportioned based on field experience or by laboratory trial batches. When the concrete producer chooses to select HSC mixture proportions based upon laboratory trial batches, mixture performance under field conditions should also be confirmed before proceeding with the work.

4.2.2 ACI 214R—Once sufficient test data have been generated from the project, a reevaluation of mixture

proportions based on actual test results is required. Refer to ACI 214R for methods of monitoring strength test results during production. Analyses affecting reportioning of mixtures based upon test histories are described in Chapter 5.

4.2.3 Other requirements—In some situations, considerations other than compressive strength may influence mixture proportions. A detailed discussion of the mechanical properties of HSC, including flexural strength, tensile strength, modulus of elasticity, shrinkage, and creep is given in Chapter 6. Chapter 6 also presents a discussion on material properties that influence HSC.

4.3—Test age

Selection of mixture proportions can be influenced by the testing age or early-age strength requirements. Testing age depends upon construction requirements. Testing age is usually the age at which acceptance criteria are established, for example, at 56 or 90 days. Testing, however, can be conducted before the age of acceptance testing, or after that age, depending on the type of information desired.

4.3.1 Early age—Pretensioned concrete operations may require very high strengths in 12 to 24 hours. Special applications for early use of machinery foundations, pavement traffic lanes, or slipformed concrete have required high strength at early ages. Post-tensioned concrete is often stressed at ages of 2 to 3 days or more, and requires high strength at later ages. Generally, once the effect of set-retarding admixtures have subsided, early-age strength development can be significant. The optimum materials and mixture proportions selected, however, may vary for different test ages. For example, mixtures with Type III cement have been used for high early strength, compared with Types I, II, or V cement for high later-age strength. Early-age strengths may be more variable due to the influence of curing temperature and the early age strength development characteristics of the specific cement, SCM, or chemical admixture. Therefore, mixture proportions should be evaluated for a higher required average strength. The effects of SCMs and chemical admixtures on early-age strength are addressed further in Section 4.8 (Leming et al. 1993a; Zia et al. 1993a,b; Ahmad and Zia 1997).

4.3.2 Twenty-eight days—A common test age for compressive strength of normal-strength concrete is 28 days. Performance of structures has been empirically correlated with the strength of moist-cured concrete cylinders, usually 6 x 12 in. (150 x 300 mm) or 4 x 8 in. (100 x 200 mm) prepared according to ASTM C31/C31M and C192/C192M. This has produced good results for normal-strength concretes not requiring early strength or early evaluation.

4.3.3 Later age—High-strength concretes made with SCMs may gain considerable strength at later ages and, therefore, are typically evaluated at later ages, such as 56 or 90 days, when construction requirements allow the concrete more time to develop strength before loads are imposed. High-strength concrete has been placed frequently in columns or shear walls of high-rise buildings. Therefore, it has been desirable to take advantage of long-term strength gains so that efficient use of construction materials is achieved. This has often been justified in applications such as

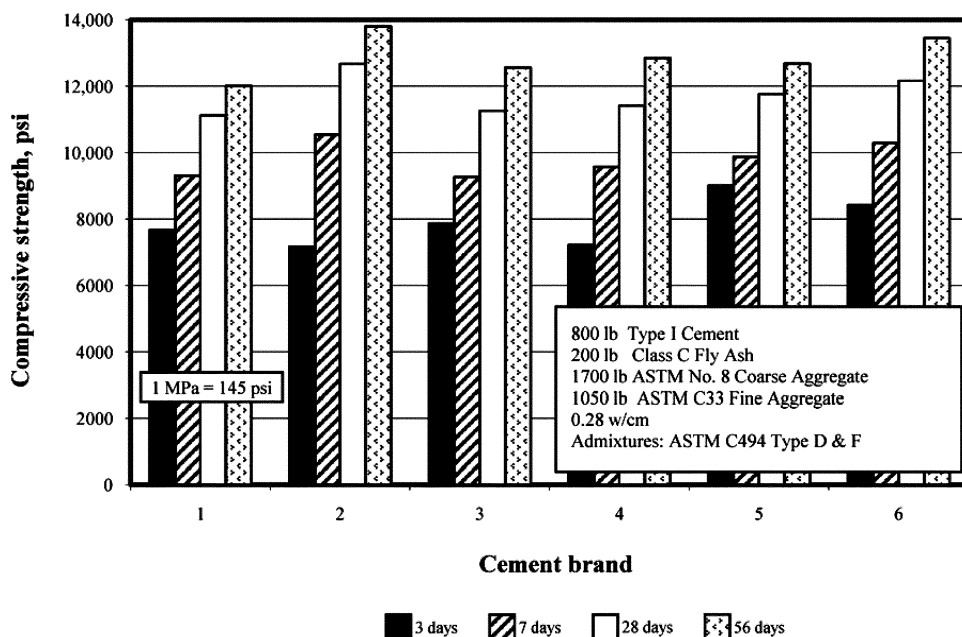


Fig. 4.1—Effects of various brands of cement on concrete compressive strength.

high-rise buildings where full loading may not occur until significantly later ages.

In cases where later-age acceptance criteria are specified, it may be advantageous for the concrete supplier to develop early-age or accelerated strength test data to estimate later-age strengths, refer to ASTM C684 and C918/C918M. In such cases, correlation data should be developed for the materials and proportions to be used in the work. These tests may not always accurately estimate later-age strengths, but they can provide an early identification of lower-strength trends before a long history of noncompliance is realized.

Extra test cylinders should be prepared and held for testing at ages later than the specified acceptance age. In cases where the specified compressive strength is not achieved, subsequent testing of later-age or “hold” cylinders may justify acceptance of the concrete in question.

4.3.4 Test age in relationship to curing—When selecting mixture proportions, the type of curing anticipated should be considered along with the test age, especially when designing for high early strengths. Concrete gains strength as a function of maturity, which is defined as a function of curing time and curing temperature. This is particularly important for steam-cured precast concrete.

4.4—Water-cementitious material ratio

4.4.1 Nature of w/cm in high-strength concrete—When SCMs such as pozzolans or slag cement are used in concrete, a w/cm by mass has been considered in place of the traditional w/c by mass.

The relationship between the w/cm and compressive strength, which has been identified in lower-strength concretes, is applicable to higher-strength concretes as well. Higher cementitious materials contents and lower water contents have produced higher strengths. In many cases, however, using larger amounts of cementitious material

increases water demand. Depending on properties of the cementitious materials used, increasing the cementitious material content beyond a certain point has not always resulted in increased compressive strength. Other factors that may limit maximum contents of cementitious materials are discussed in Section 5.5.3. The use of HRWRAs has enabled concrete to be placed at flowing and self-consolidating consistencies with lower w/cm . HRWRAs are discussed in Section 4.8.2.2.

Water-cementitious material ratios by mass for HSCs have ranged typically from 0.25 to 0.40. The quantity of water contained in liquid admixtures, particularly HRWRAs, should always be included in determining the w/cm .

As the w/cm changes, the density of the concrete also changes. By incrementally decreasing the w/cm , less cementitious material is available to hydrate (Mindess et al. 2003). As long as decreasing the w/cm increases density, strength should also increase. Any unhydrated cementitious material will merely act as mineral filler.

4.4.2 Estimating compressive strength—The compressive strength that a concrete will develop at a given w/cm depends on the cementitious materials, aggregates, and admixtures employed.

Principal causes of variations in compressive strengths at a given w/cm include the strength-producing capabilities of the cement and the hydraulic or pozzolanic activity of SCMs, if used. Figure 4.1 shows the effects of various brands of Type I portland cement on compressive strength.

Specific information pertaining to the range of values of compressive strengths of portland cements is published in ASTM C917. Depending on their chemical and physical properties, fly ashes and natural pozzolans may vary in their pozzolanic activity index from 75 to 110% compared to the portland cement control. The pozzolanic activity index for

fly ash and natural pozzolans is specified in ASTM C618. Similarly, the strength activity indexes for silica fume and various grades of slag cement are given in ASTM C1240 and C989, respectively. Proprietary pozzolans containing silica fume have been reported to have activity indexes in excess of 200% (Gaynor 1980).

The water requirement of the particular pozzolan employed can vary significantly, and generally increases with increasing fineness of the pozzolan. For example, as a result of the nearly spherical shape of fly ash particles, the water requirement for concrete containing fly ash is usually lower than for concrete made only with portland cement, which helps in lowering the w/cm .

Perenchio and Klieger (1978) reported variations in compressive strength at given w/cm in laboratory-prepared concretes, depending on the aggregates used. In addition, these laboratory results differed from results achieved in actual production with materials from the same area. In total, three aggregate sources were used in their study. Maximum aggregate size was 3/8 in. (10 mm) for the Elgin and Dresser aggregates and 1/2 in. (13 mm) for the Romeoville limestone used. Examples of strengths reported at given w/cm are presented in Fig. 4.2. Trial batches with materials actually to be used in the work were found to be necessary. Generally, laboratory trial batches have produced strengths higher than are achievable in production, as seen in Fig. 4.3.

4.5—Cementitious material content

The quantity of cementitious material proportioned in a HSC mixture is best determined by making trial batches. The required content of cementitious material in a HSC mixture is usually governed by the required w/cm . Typical cementitious materials contents in HSC test programs have ranged from 650 to 1000 lb/yd³ (386 to 593 kg/m³). In evaluating optimum cementitious materials contents, trial mixtures usually are proportioned to equal consistencies. This can be achieved either by allowing the admixture dosage to vary and keeping the water content fixed, or by allowing the water content to vary and keeping the admixture dosage fixed.

4.5.1 Cement strength—The strength for any given cement or cementitious materials content will vary with the water demand of the mixture and the strength-producing characteristics of the particular combination of cementitious material, as shown in Fig. 4.1. Figure 4.1 illustrates a variation in compressive strength on the order of 10% when comparing different cement brands. Strength-producing characteristics of cements at a given age can vary depending on the mixture proportions and compatibility with other materials, particularly SCMs and chemical admixtures. The relative strength performance of cement can differ depending on the strength level of the concrete, as shown in Fig. 4.4. High-strength concrete is more sensitive to cement brand than normal-strength concrete. This may be attributed to the varied interaction of the cement and the mixture constituent chemical and mineral admixtures. For example, cement that exhibits one level of relative strength performance in a 4000 psi (27 MPa) concrete mixture may perform quite differently in a 10,000 psi (69 MPa) mixture.

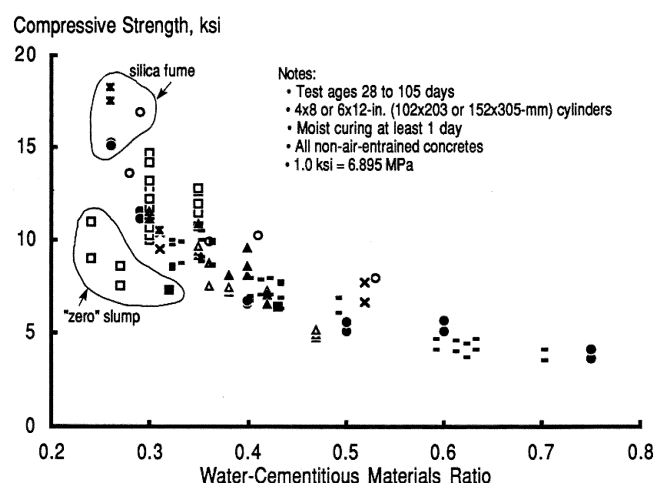


Fig. 4.2—Strength versus w/cm of various mixtures (adapted from Fiorato [1989]).

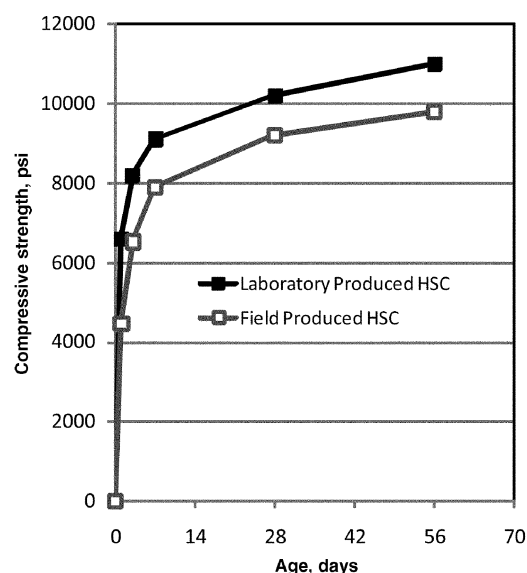


Fig. 4.3—Laboratory-molded concrete strengths versus ready mixed field-molded concrete strengths for 9000 psi (62 MPa) concrete (adapted from Myers [1999]).

Concrete strength depends on the gel-space ratio, which is defined as the “ratio of the volume of hydrated cement paste to the sum of the volumes of the hydrated cement and of the capillary pores” (Neville 1981; Leming et al. 1993b).

Although mortar cube tests (ASTM C109/C109M) can be extremely useful in monitoring the strength uniformity of cement over time, the performance of cement in a mortar cube can be quite different than its strength performance in concrete. Therefore, strength characteristics of various cements and combinations of cement and SCMs should be evaluated in concrete rather than mortar.

4.5.2 Optimization—A principal consideration in establishing the desired cementitious material content is the determination of material combinations that will produce optimum strengths. Ideally, evaluations of each potential source of cementitious materials, aggregates, and chemical admixtures in varying quantities would indicate the optimum



Fig. 4.4—Effects of various brands of cement on concrete compressive strength using different mixture proportions. (Mixture proportions shown in Tables 4.1(a) and (b).)

Table 4.1(a)—Laboratory mixtures used in Fig. 4.4 study (U.S. Customary units)

	Mixture no.			
	1	2	3	4
Specified strength, psi	4000	4000	6000	10,000
Type I cement, lb/yd ³	423	564	588	800
Class C fly ash, lb/yd ³	80	0	125	200
ASTM C33 fine aggregate, lb/yd ³	1500	1450	1320	1050
3/4 in. coarse aggregate, lb/yd ³	1750	1750	1750	0
3/8 in. coarse aggregate, lb/yd ³	0	0	0	1700
Type A WR, oz/yd ³	12.7	0	17.6	0
Type D WR, oz/yd ³	0	0	0	32
Type F HRWR	0	0	0	Varied
Water, lb/yd ³	Varied	Varied	Varied	280
w/cm	Varied	Varied	Varied	0.28
Target slump, in.	5	5	5	8

cementitious materials content and optimum combination of constituent materials. Testing costs and time requirements have usually limited the completeness of evaluation programs, but particular attention has been given to evaluation of the type and brand of cement to be used with the type and source of SCMs.

The strength efficiency of cementitious material combinations will vary for different nominal maximum-size aggregates at different strength levels. Higher cementitious material efficiencies are achieved at high strength levels with smaller maximum aggregate sizes. Figure 4.5 illustrates this principle. For example, a nominal maximum aggregate size of approximately 3/8 in. (10 mm) yields the highest cement efficiency for a 7000 psi (48 MPa) mixture.

Incorporating SCMs and chemical admixtures can significantly increase concrete strength (Myers and Carrasquillo 2000). Today, HSCs with specified compressive strengths up to 16,000 psi (110 MPa) at 56 days have been produced successfully

Table 4.1(b)—Laboratory mixtures used in Fig. 4.4 study (SI units)

	Mixture no.			
	1	2	3	4
Specified strength, MPa	28	28	41	69
Type I cement, kg/m ³	251	335	349	475
Class C fly ash, kg/m ³	47	0	74	119
ASTM C33 fine aggregate, kg/m ³	890	860	783	623
19 mm coarse aggregate, kg/m ³	1038	1038	1038	0
9.5 mm coarse aggregate, kg/m ³	0	0	0	1009
Type A WR, mL/m ³	492	0	681	0
Type D WR, mL/m ³	0	0	0	1239
Type F HRWR	0	0	0	Varied
Water, kg/m ³	Varied	Varied	Varied	166
w/cm	Varied	Varied	Varied	0.28
Target slump, mm	125	125	125	200

using crushed aggregate having a nominal maximum size of 3/8 in. (10 mm) with corresponding cementitious efficiency values of 17 psi/lb/yd³ (0.29 MPa/kg/m³).

4.5.3 Limiting factors—There are several factors that may limit the maximum quantity of cementitious material that may be desirable in a high-strength mixture. Concrete strength may decrease if the cementitious materials content exceeds optimum value. The maximum desirable content of cementitious material may vary considerably depending upon the efficiency of dispersing agents, such as MRWRAs or HRWRAs, in promoting deflocculation of cementitious particles.

Extremely low w/cm or high cementitious material contents can have a significant effect on the rheology of the concrete mixture. Stickiness and loss of workability may increase as higher amounts of cementitious materials are incorporated into the mixture. Combinations of constituent materials should be evaluated for their effect on the ability to place, consolidate, and finish the mixture. As discussed in

Section 4.9.3, combinations of chemical admixtures such as MRWRAs and HRWRAs may reduce stickiness and improve workability. To date, no standard test methods are available to evaluate finishing characteristics.

The maximum temperature permitted in the concrete element may limit the quantity or type of cementitious material. It may be helpful to use materials that are capable of reducing the initial temperature and, subsequently, the peak temperature, such as ice, chilled water, and liquid nitrogen. Furthermore, the temperature rise and, subsequently, the peak temperature, can be reduced by using slag cement and pozzolans.

Mixtures with high cementitious materials contents may frequently have higher water demands, particularly if the cementitious material is composed of extremely finely divided particles, such as silica fume. Under some circumstances, it may be preferable to reduce the amount of cementitious material in the mixture and to rely more upon careful selection of aggregates and aggregate proportions.

The amount of early stiffening (loss of workability) can vary depending on the type and quantity of cementitious materials and chemical admixtures used. In some cases, loss of workability has been attributed to poor constituent material compatibility. As the use of retempering water can result in significant strength loss, it should not be permitted as a remedy to loss of workability.

4.6—Air entrainment

4.6.1 Resistance to freezing and thawing—There are advantages and disadvantages associated with the use of air entrainment. The primary advantage of having entrained air is the protection it provides in the event that the moisture content within the capillaries or pores exceeds critical saturation. As the water within concrete freezes, it expands approximately 9% by volume. Without a system of tiny, uniformly distributed air bubbles throughout the mortar fraction, this expansion can produce hydraulic and osmotic pressures within the capillaries and pores of the paste and aggregate that will damage the concrete.

To reach critical saturation, concrete has to be in direct contact with moisture for long periods. Obviously, horizontal members are significantly more susceptible to critical saturation than vertical members. Periodic precipitation, such as rain or snow against a vertical surface alone, does not constitute conditions conducive to saturation. Because of the significantly detrimental effects it can have on strength, air entrainment should be used in HSC only when absolutely necessary.

Additional discussions on the freezing-and-thawing resistance of HSC are provided in Chapter 6.

4.6.2 Effect on strength—The primary disadvantage of air entrainment is its negative effect on strength. To achieve equal strength, air-entrained concrete generally requires a lower w/cm and, therefore, a higher quantity of cementitious material than non-air-entrained concrete. The quantity of cementitious material needed to attain equal strength varies depending on the strength class of the concrete. For example, it is the committee's experience that a 4000 psi (27 MPa) air-entrained concrete mixture may require only an additional

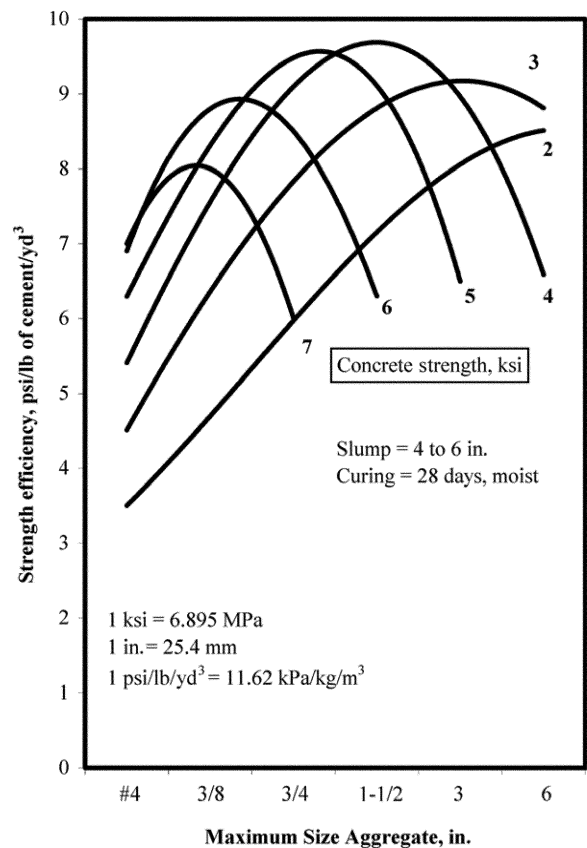


Fig. 4.5—Maximum-size aggregate for strength efficiency envelope (adapted from Cordon and Gillespie [1963]).

50 lb/yd³ (30 kg/m³) of cementitious material than a non-air-entrained mixture to attain equal strength, whereas a 6000 psi (41 MPa) air-entrained mixture might require an additional 150 lb/yd³ (90 kg/m³) of cementitious material than its non-air-entrained counterpart. The specific difference depends on the characteristics of the local constituent materials. Beyond 6000 psi (41 MPa), however, the decrease in strength due to the inclusion of entrained air becomes so large that it is usually necessary to include SCMs such as silica fume or high-reactivity metakaolin.

The decrease in strength for each incremental increase in air content becomes larger as the specified strength f'_c of the concrete increases. For example, in a 4000 psi (27 MPa) concrete mixture, an air content increase from 5 to 7% may reduce compressive strength by 200 to 400 psi (1.4 to 2.8 MPa), or 5 to 10%. In a 10,000 psi (69 MPa) mixture, the same air content increase may reduce strength by 2000 to 3000 psi (6.9 to 13.8 MPa), or 20 to 30%. The effect of increasing air content on the compressive strength of various concretes is demonstrated in Fig. 4.6(a) (Gaynor 1968). Ekenel et al. (2004) observed a similar trend for HSC mixtures, although the scatter of data appear to be more sensitive to the mixture constituents and SCMs used (Fig. 4.6(b)).

Because normal fluctuations in air content will have a significantly more dramatic effect on strength of HSC, higher variations in strength should be expected. As a result, the required average strength f'_t of air-entrained HSC is expected to be higher than for non-air-entrained HSC.

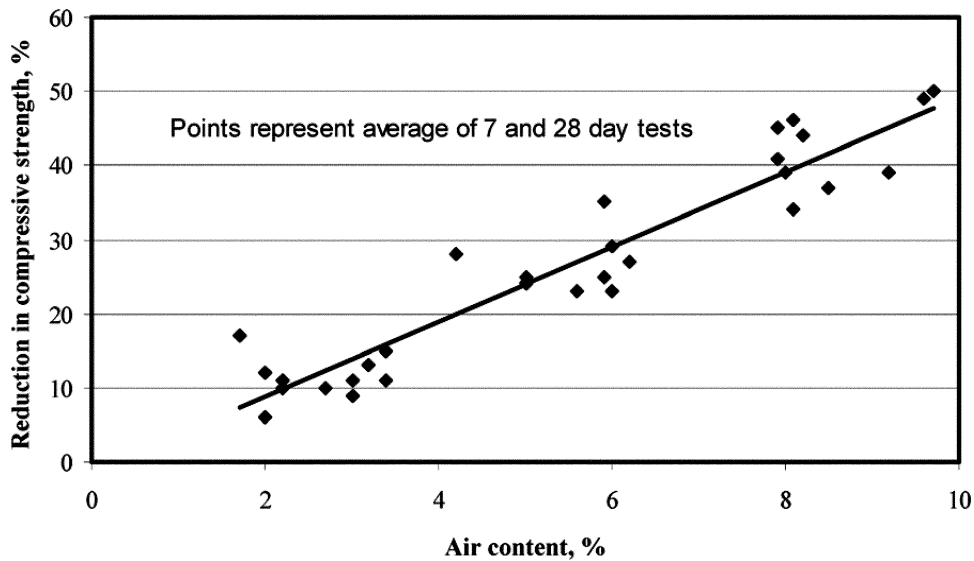


Fig. 4.6(a)—Strength reduction by air entrainment (adapted from Gaynor [1968]).

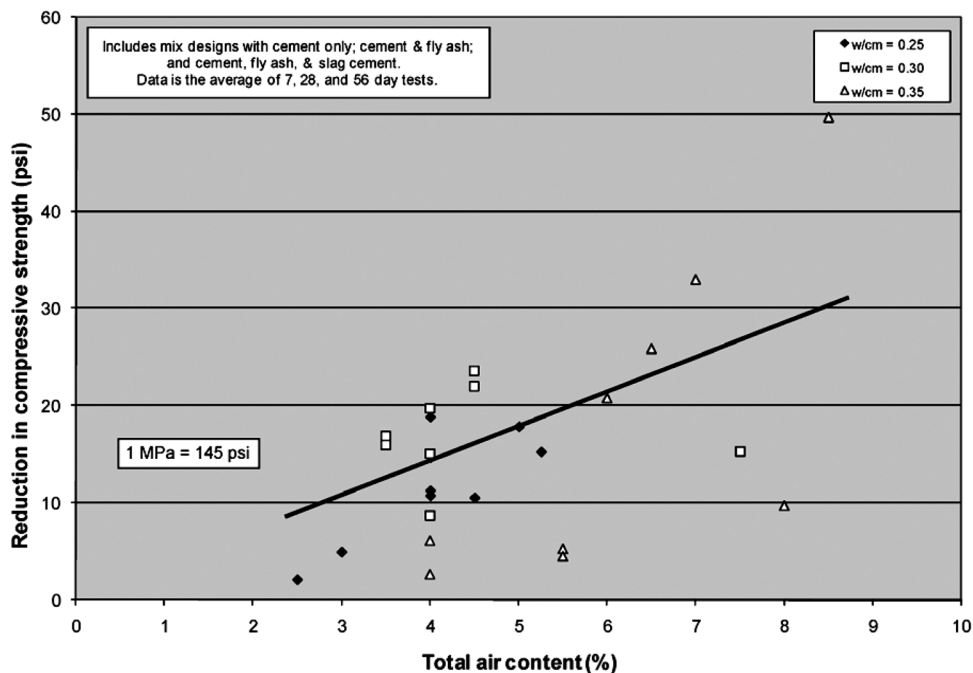


Fig. 4.6(b)—Strength reduction by air entrainment (adapted from Ekenel et al. [2004]).

As a result of the potentially detrimental effects it can have on the strength of HSC, air entrainment should be considered only when truly warranted. Reduction of air content by 1% for concrete compressive strength greater than 5000 psi is permitted by ACI 318-08, Section 4.4.1.

4.7—Aggregate proportions

Aggregates are an important consideration in proportioning HSC because they occupy the largest volume of the constituent ingredients in the concrete. Usually, HSCs have been produced using normal-density aggregates. Shideler (1957), Holm (1980), and Hoff (1992) reported on lightweight, high-strength structural concrete. Mather (1965) reported on high-strength, high-density concrete using high-density aggregate.

4.7.1 Fine aggregates—Fine aggregate or sand has a significant effect on mixture proportions. Fine aggregate contains a much higher surface area for a given mass than the coarse aggregate. Because the surface area of aggregate particles is coated with a cementitious paste, the proportion of fine-to-coarse aggregate can have a direct effect on paste requirements. Furthermore, fine aggregate particles may be spherical, subangular, or very angular. Particle shape can alter paste requirements even though net volume of the fine aggregate remains the same.

The gradation of the fine aggregate plays an important role in properties of fresh and hardened concrete. For example, if the gradation has an overabundance of particles retained on the No. 50 and 100 (300 and 150 μ m) sieve sizes, workability

will be improved, but more paste will be needed to compensate for the increased surface area. This could result in a more expensive mixture, or if water were added to increase the paste volume, there would be a serious loss in strength. It is sometimes possible to blend fine aggregates from different sources to improve their gradation and capacity to produce higher-strength concrete. High-strength concretes have been produced using blends of manufactured and natural fine aggregates.

Low fine aggregate contents with high coarse aggregate contents have resulted in a reduction in paste requirements and have typically been more economical. Such proportions also have made it possible to produce higher strengths for a given amount of cementitious materials. If the proportion of fine aggregate is too low, however, there may be serious problems in workability.

Consolidation with mechanical vibrators may help overcome the effects of an under-sanded mixture, and using power finishing equipment can help offset the lack of finishability. Also, refer to Section 3.4.2.

4.7.2 Coarse aggregates—In proportioning normal-strength concrete mixtures, the maximum size of coarse aggregate is usually controlled by clearance requirements in the structure, and the optimum amount of coarse aggregate depends on the fineness modulus of the fine aggregate. In HSC, however, it has been found that the highest strengths for a given w/cm are obtained by using smaller maximum-size coarse aggregate. To maintain workability, this results in a lower volume fraction of coarse aggregate. The selection of coarse aggregate size and content for HSC, however, may be influenced by requirements such as modulus of elasticity, creep, shrinkage, and heat of hydration. For these cases, larger aggregate sizes may be more desirable. Also, refer to Section 3.4.3.

4.7.3 Proportioning aggregates—The amounts of coarse aggregate suggested in Table 4.2 are recommended for initial proportioning. The values given represent the fractional volume of coarse aggregate in the dry-rodded condition as a function of the nominal maximum size and for fine aggregate with a fineness modulus between 2.5 and 3.2.

In general, the least amount of fine aggregate consistent with necessary workability gives the best strength for a given paste. Mixtures with objectionably high coarse aggregate contents, however, may exhibit poor pumpability or may be significantly more prone to segregation during placement and consolidation.

4.8—Proportioning with supplementary cementitious materials and chemical admixtures

4.8.1 Supplementary cementitious materials—High-strength mixtures have been successfully made with ternary blends consisting of highly reactive SCMs such as silica fume or HRM used in combination with materials such as fly ash and slag cement (Caldarone et al. 1994). Silica fume and HRM are commonly used at 5 to 15% by mass of the total cementitious materials content. In addition, high-strength mixtures have been produced using ternary blends composed

Table 4.2—Recommended volume of coarse aggregate per unit volume of concrete*

	Optimum coarse aggregate contents for nominal maximum sizes of aggregates to be used with sand with fineness modulus (FM) of 2.5 to 3.2			
Nominal maximum size, in.	3/8	1/2	3/4	1
Fractional volume [†] of oven-dry rodded coarse aggregate	0.65	0.68	0.72	0.75

*Table 4.2 taken from ACI 211.4R-93, Table 4.3.3.

[†]Volumes are based on aggregates in oven-dry rodded condition as described in ASTM C29 for unit weight of aggregates.

Notes: Refer to ASTM C136 for calculation of fineness modulus. 1 in. = 25.4 mm.

of portland cement, conventional fly ash, and ultra-fine fly ash (Obla et al. 2001).

Using fly ash often causes a slight reduction in the water demand of the mixture. Although generally ground finer than portland cement, the water demand of slag cement is usually about the same as that of portland cement. The opposite relationship has been found for other pozzolans. Dosages above approximately 5% of total cementitious material silica fume, for example, increase water demand, which makes the use of HRWRAs a requirement. Proprietary products containing silica fume may include carefully balanced chemical admixtures as well (Wolsiefer 1984). These SCMs often have other characteristics that are beneficial for HSC applications, such as temperature control, enhanced workability, or both.

4.8.2 Chemical admixtures—Chemical admixture specifications are covered in ASTM C494/C494M. Advancements in chemical admixture technology have contributed significantly to the evolution of HSC. Chemical admixtures are used to control consistency (slump or slump flow), setting, rate of slump loss, water demand, rate of strength gain, and the effects of elevated temperatures.

4.8.2.1 Conventional and mid-range water-reducing admixtures (MRWRAs)—The amount of conventional or mid-range water-reducing admixtures used in HSC varies depending upon the particular admixture and application. In addition to controlling water demand, the ability of these admixtures to control the rate of hydration as it relates to strength is of critical importance in the successful production of HSC.

Conventional WRAs generally reduce water demand approximately 5 to 10%. Mid-range water-reducing admixtures are designed to be used at higher dosages than conventional WRAs, and can reduce water demand by as much as 18% without the retardation associated with using higher dosages of conventional WRAs.

Generally, set-neutral WRAs or accelerating WRAs will not be as beneficial to long-term strength development as WRAs that retard setting. As the specified design strength increases, the ability of set-retarding admixtures to effectively control hydration as it relates to strength becomes increasingly important.

4.8.2.2 High-range water-reducing admixtures (HRWRAs)—High-range water-reducing admixtures are frequently called superplasticizers, and are classified in ASTM C494/C494M as Types F and G. Water adjustments

to HSC made with HRWRAs have been similar to those adjustments made when conventional WRAs are used. These adjustments have typically been larger due to the larger amount of water reduction, approximately 12 to 30%.

Self-consolidating HSC mixtures are frequently produced using HRWRAs in conjunction with viscosity-modifying admixtures, such as cellulose ether or welan or diutan gum (ACI 212.4R; BASF 2008). Generally, slump retention, batch-to-batch slump uniformity, and admixture efficiency can be increased when concrete is proportioned with a sufficient quantity of water such that measurable slump is produced without the HRWRA. For example, a mixture proportioned with enough water to produce a 1 to 2 in. (25 to 50 mm) slump (without the chemical admixture) would be expected to exhibit longer slump retention than a mixture proportioned with less water.

Unlike earlier melamine or naphthalene-based HRWRAs that performed more consistently after prewetting the cement, new-generation HRWRAs based on polycarboxylate chemistry can frequently be introduced without prewetting the cement. Therefore, once the water content has been established, new-generation admixtures can be introduced during the beginning phases of batching rather than at the end.

In HSC mixtures, HRWRAs are primarily used to lower the w/cm while maintaining workability. Due to the relatively large quantity of liquid that is frequently added in the form of HRWRAs, the water content of these admixtures should be included in the calculation of the w/cm .

4.8.3 Combinations—Nearly all HSCs incorporate combinations of SCMs and chemical admixtures. Changes in the type, quantities, and combinations of these materials can affect both the fresh and hardened properties of HSC. Therefore, as discussed in Chapter 3, special attention has been given to their effects. Careful adjustments to mixture proportions have been made when there have been changes in admixture type, quantities, or combinations. Material characteristics have varied extensively, making experimentation with the candidate materials necessary.

High-range water-reducing admixtures frequently perform better in HSCs when used in combination with conventional WRAs or retarding WRAs. This is because of the increased slump retention and hydration control achievable through their use.

4.9—Workability

Workability is defined as “that property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogeneous condition” (American Concrete Institute 2009).

4.9.1 Consistency—ASTM C143/C143M describes a standard test method for determining the slump of hydraulic-cement concrete that has been used to quantify the consistency of plastic, cohesive concrete mixtures. This test method is generally not relevant to stiff mixtures having measured slump values below 1/2 in. (13 mm), or flowing concrete mixtures having measured slump values above 7-1/2 in. (190 mm).

Other test methods such as the Vebe consistometer have been used with very stiff mixtures and may be a better aid in

evaluating mixture proportions for some HSCs. Slump flow or spread is more relevant for determining the consistency of flowing or self-consolidating concretes than is the slump test (Aggoun et al. 2002).

Without uniform placement, structural integrity may be compromised. Without proper attention, high-strength mixtures tend to exhibit more early stiffening than lower-strength concrete. Concrete should be discharged before the mixture becomes unworkable. If adjustments in the field become necessary, it should be done using compatible chemical admixtures, not retempering water.

4.9.2 Placeability—High-strength concrete, often designed with 1/2 in. (13 mm) or smaller nominal maximum-size aggregate and with a high cementitious material content, is inherently placeable provided that proper attention is given to optimizing the ratio of fine-to-coarse aggregate. Local material characteristics can have a marked effect on mixture proportions. The particle size distribution of cementitious fines can influence the character of the mixture. Admixtures have been found to significantly improve the placeability of HSC mixtures.

Placeability has been evaluated in mock-up forms before final approval of the mixture proportions. At that time, placement procedures, consolidation methods, and scheduling should be established because they can greatly affect the end product and will influence the apparent placeability of the mixture.

4.9.3 Flow properties and cohesion—Slump values needed for desired flow characteristics can be designed for the concrete; however, full attention should be given to aggregate selection and proportioning to achieve the optimum slump. Elongated aggregate particles and poorly graded coarse and fine aggregates are examples of characteristics that have negative effects on flow and increase water demand for placeability with a corresponding reduction in strength.

Stickiness is inherent in mixtures with high cementitious materials contents. Certain cements or combinations of cementitious materials and admixtures have been found to cause undue stickiness that impairs workability. The cementitious materials content of the mixture has normally been the minimum quantity required for strength development combined with the maximum quantity of coarse aggregate within the requirements for workability. Using a MRWRA in addition to a HRWRA may reduce stickiness and improve workability of HSC (Nmai et al. 1998).

Mixtures that were designed properly but appear to change in character and become stickier should be considered suspect and quickly checked for proportions, possible false setting of cement, undesirable entrained air, or other changes. A change in the character of a high-strength mixture could be a warning sign for quality control. This is an example where a subjective judgment may sometimes be as meaningful as quantitative parameters.

4.10—Trial batches

Frequently, the development of a HSC mixture requires a large number of trial batches. Because each batch and project is unique, a number of laboratory and field evaluations

are frequently necessary to develop mixtures having suitable materials and proportions (Hester and Leming 1989). To minimize the number of trial batches needed to define the optimum combination and quantity of materials, a statistical approach using a central-composite design technique has been used on some projects (Luciano et al. 1991).

In addition to laboratory trial batches, larger-sized trial batches have been used to simulate typical production conditions. Care should be taken that all material samples are taken from bulk production and are typical of the materials that will be used in the work. To avoid accidental testing bias, some investigators have sequenced trial mixtures in a randomized order.

4.10.1 Laboratory trial batch investigations—Laboratory trial batches are prepared to achieve several goals. They should be prepared according to ASTM C192/C192M. In addition, timing, handling, and environmental conditions similar to those that are likely to be encountered in the field should be considered in the evaluation process. Often, the mixing and resting periods prescribed in ASTM C192/C192M require modification for a longer final mixing time.

Selection of material sources has been facilitated by comparative testing, with all variables except the candidate materials being held constant. In nearly every case, particular combinations of materials have proven to be best. By testing for optimum quantities of optimum materials, the investigator is likely to define the best combination and proportions of materials to be used.

Once a promising mixture has been established, further laboratory trial batches may be required to quantify the relevant characteristics of those mixtures. Strength characteristics at various test ages may be defined. Rate of slump loss, amount of bleeding, segregation, and setting time can be evaluated. The density (unit weight) of the mixture should be determined. Density monitoring can be a valuable quality control tool. Structural properties such as shrinkage and modulus of elasticity may also be determined. Although degrees of workability and placeability may be difficult to measure, at least a subjective evaluation should be attempted.

4.10.2 Field-production trial batches—Once a desirable mixture has been formulated in the laboratory, field testing with production-sized batches is recommended. Laboratory trial batches frequently exhibit significantly higher strength than can be reasonably achieved in production, as shown in Fig. 4.3. Actual field water demand, and therefore concrete yield and w/cm , has varied significantly from laboratory design. Ambient temperatures and weather conditions have affected concrete performance. Practicality of production and of quality-control procedures has been evaluated better when production-sized trial batches were prepared using the equipment and personnel to be used in the actual work.

CHAPTER 5—ORDERING, BATCHING, MIXING, TRANSPORTING, PLACING, CURING, AND QUALITY-CONTROL PROCEDURES

5.1—Introduction

Qualified producers, contractors, and testing laboratories are essential for successful construction with HSC. The

batching, mixing, transporting, placing, and quality-control procedures for HSC are not different in principle from those procedures used for lower-strength concrete; however, some changes, refinements, and emphasis on critical points are necessary. Maintaining the unit water content as low as possible, consistent with placing requirements, is good practice for all concrete; for HSC, it is critical. Because the production of HSC will normally involve using relatively large cementitious materials contents with resulting greater heat generation, some of the recommendations on production, delivery, placing, and curing given in ACI 305R may also be applicable.

5.2—Ordering

5.2.1 Batch size—When ordering HSC, every effort should be made to divide the quantity of concrete produced and delivered into equally sized batches to help ensure both uniformity and consistency. For example, if 10 yd³ (8 m³) of concrete is required for a given placement, and the delivery equipment has a rated capacity of 9 yd³ (7 m³) each, it would be more prudent to batch two 5 yd³ (3.5 m³) batches rather than one 9 yd³ (7 m³) batch and one 1 yd³ (0.8 m³).

5.2.2 Lead time—Orders for HSC should be placed at least several days in advance to allow ample time to inventory raw materials and schedule testing and inspection services.

5.3—Batching

5.3.1 Control, handling, and storage of materials—Quality control, handling, and storage of raw materials need not be substantially different from the procedures used for conventional concrete as outlined in ACI 304R. As with all concrete, proper stockpiling of aggregates, uniformity of moisture in the batching process, and good sampling practice are essential.

In the committee's opinion, the moisture content of aggregates should be uniform, and the temperature of all ingredients should be kept such that the mixture design temperature is maintained between 65 to 75°F (18 to 24°C). The moisture content of fine aggregates should be monitored continuously through the use of calibrated moisture metering devices. If not automatically monitored, the moisture content of coarse aggregates should be routinely determined at least once per day, or whenever it is suspected that the moisture content is different from the value being used during production. It may be prudent to place a maximum limit of 150°F (66°C) on the temperature of the cementitious materials as batched, particularly under hot-weather concreting conditions. Maximum temperatures for concrete are specified in ACI 305R and ACI 301.

5.3.2 Measuring—Materials for the production of HSC may be batched in manual, semiautomatic, or automatic plants. To maintain the proper w/cm necessary to secure HSC, accurate moisture determination in the fine aggregate is essential.

5.3.3 Charging of materials—Batching procedures have important effects on the ease of producing thoroughly mixed, uniform concrete in both stationary and truck mixtures. The uniformity of concrete produced in central mixers is generally enhanced by loading the aggregate, cement, and water simultaneously (ribbon loading). High-