ACI 211.4R-08

Guide for Selecting Proportions for High-Strength Concrete Using Portland Cement and Other Cementitious Materials

Reported by ACI Committee 211

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Guide for Selecting Proportions for High-Strength Concrete Using Portland Cement and Other Cementitious Materials

Reported by ACI Committee 211

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This guide presents general methods for selecting mixture proportions for high-strength concrete and optimizing these mixture proportions on the basis of trial batches. The methods are limited to high-strength concrete containing portland cement and fly ash, silica fume, or slag cement (formerly referenced as ground-granulated blast-furnace slag) and produced using conventional materials and production techniques.

Recommendations and tables are based on current practice and information provided by contractors, concrete suppliers, and engineers who have been involved in projects dealing with high-strength concrete.

Keywords: aggregate; fly ash; high-range water-reducing admixture; high-strength concrete; mixture proportion; quality control.

CONTENTS

ACI 211.4R-08 supersedes ACI 211.4R-93 and was adopted and published December 2008.

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

ACI 211.1 describes methods for selecting proportions for normal-strength concrete in the range of 2000 to 6000 psi. This guide supplements ACI 211.1 by presenting several methods for selecting mixture proportions for high-strength concrete and for optimizing these proportions on the basis of trial batches. Usually, for high-strength concrete mixtures specially selected cementitious materials and chemical admixtures are used, and achieving a low water-cementitious material ratio (*w/cm*) is considered essential. Many trial mixtures are often required to generate the data necessary to identify optimum mixture proportions.

1.2—Scope

Discussion in this guide is limited to high-strength concrete produced using conventional materials and production methods.

While high-strength concrete is defined in ACI 363.2R as concrete that has a specified compressive strength f_c' of 8000 psi or greater, this guide provides methods for selecting mixture proportions for f_c' greater than 6000 psi. The following recommendations are based on accepted ACI 211.1 methods, current practice, and information from contractors, concrete suppliers, and engineers who have been involved in projects dealing with high-strength concrete. The reader may refer to ACI 363R for a more complete list of publications and references available on this topic.

CHAPTER 2—NOTATION AND DEFINITIONS

ACI provides a comprehensive list of acceptable notation and definitions through an online resource, "ACI Concrete Terminology" (American Concrete Institute 2008).

2.1—Notation

f_c' = compressive strength
f_{cr}' = required average compressive strength

2.2—Definitions

cement, slag—granulated blast-furnace slag that has been finely ground and that is hydraulic cement. Note: before March 1, 2003, defined as: "hydraulic cement consisting mostly of an intimate and uniform blend of granulated blast-furnace slag and portland cement, hydrated lime, or both, in which the slag constituent is at least 70% by mass of the finished product."

fly ash—the finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gases from the combustion zone to the particle removal system.

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

pozzolan—a siliceous or siliceous and aluminous material that in itself possesses little or no cementitious value but that will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds having cementitious properties; there are both natural and artificial pozzolans.

silica fume—very fine noncrystalline silica produced in electric arc furnaces as a by-product of the production of elemental silicon or alloys containing silicon.

strength—the ability of a material to resist strain or rupture induced by external forces.

The following terms are defined herein for the purpose of clarification and used throughout this report:

binary mixtures—concrete mixtures that contain two supplementary cementitious materials.

high strength—specified compressive strength f_c' greater than 6000 psi.

normal strength—specified compressive strength f_c' equal to or less than 6000 psi.

quad blends—concrete mixtures that contain four supplementary cementitious materials.

slag index—percent of compressive strength increase resulting from the slag cement dosage relative to the 28-day compressive strength of the same mixture without slag cement.

ternary mixtures—concrete mixtures that contain more than three supplementary cementitious materials.

CHAPTER 3—PERFORMANCE REQUIREMENTS

3.1—Test age

The selection of mixture proportions can be influenced by the age at which the strength level is required. Because most high-strength concrete mixtures use fly ash, silica fume, slag cement, or other cementitious materials, high-strength concrete can gain considerable strength after the normally specified 28-day age. To take advantage of this characteristic, many specifications for the compressive strength of high-strength concrete have been modified from the typical 28-day criterion to 56 days, 90 days, or later ages.

3.2—Required average compressive strength f'_{cr}

ACI 318 allows concrete mixtures to be proportioned based on field experience or laboratory trial batches. To meet the specified compressive strength requirement, f'_c, the concrete should be designed to achieve the required average compressive strength f'_{cr}. To do so, the concrete mixture is proportioned in such a manner that the average compressive strength results of field tests exceed f'_c by an amount high enough to reduce the number of low test results.

3.2.1 *Proportioning based on field experience*—When the concrete producer chooses to select high-strength concrete mixture proportions based on field experience, the required average compressive strength f'_{cr}, used as the basis for the selection of concrete proportions, should be the larger of the values calculated from the following two equations

$$f'_{cr} = f'_c + 1.34s \quad (3\text{-}1)$$

$$f'_{cr} = 0.90f'_c + 2.33s \quad (3\text{-}2)$$

where s is a sample standard deviation from 30 tests.

Equation (3-1) is Eq. (5-1) of ACI 318. Equation (3-2) is Eq. (5-3) of ACI 318. Equation (3-1) is based on the probability of 1-in-100 that the average of three consecutive tests may be below f'_c. Equation (3-2) is based on the same probability that an individual test may be less than $0.90f'_c$. These equations use the population standard deviation, appropriate for an infinite or very large number of tests. At least 30 tests are preferred to estimate the population standard deviation. Refer to ACI 214R when fewer tests are available.

3.2.2 *Proportioning based on trial batches*—When the concrete producer selects high-strength concrete proportions on the basis of laboratory trial batches, f'_{cr} may be determined from

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

Where the average strength documentation is based on laboratory trial mixtures, it may be appropriate to increase f'_{cr} from Eq. (3-3) in accordance with ACI 214R to allow for a reduction in strength from laboratory trials to actual concrete production.

To assume that the average strength of field-produced concrete will equal the strength of a laboratory-batched concrete is contrary to experience because many factors controlled in the laboratory can influence the strength and variability measurements in the field. Initial use of a high-strength concrete mixture in the field may require some adjustments in proportions for air content and yield and for the requirements listed in Section 3.3, as appropriate. Once sufficient data have been generated from the job, mixture proportions can be reevaluated using ACI 214R and adjusted accordingly.

3.3—Other requirements

Considerations of properties other than compressive strength may influence the selection of materials and mixture proportions, including creep, drying shrinkage, resistance to freezing and thawing, electrical conductivity, finishability, heat of hydration, method of placement, modulus of elasticity, peak temperature differential, permeability, pumpability, tensile strength, time of setting, and workability. More than one requirement may apply to a concrete mixture. In this event, the best acceptable overall solution to proportioning the concrete mixture becomes the goal.

In many cases, the attainment of specific properties can be correlated to strength, and thereafter a strength requirement may become the acceptance criterion for the other properties. For example, if a project specification requires a specific value for modulus of elasticity, and a significant number of compressive strength results are found to correlate strongly with elastic modulus results for a specific concrete mixture, then the compressive strength results could be used as the acceptance criterion.

CHAPTER 4—CONCRETE MATERIALS

4.1—Introduction

Carefully selecting, controlling, and proportioning all of the ingredients will achieve effective production of high-strength concrete. To achieve higher-strength concrete, optimum proportions should be selected, considering the cement and other cementitious material characteristics, aggregate quality, aggregate gradation, paste volume, aggregate-paste interaction, admixture type and dosage rate, and mixing. Evaluating cement and other cementitious materials, chemical admixtures, and aggregates from various potential sources in varying proportions will indicate the optimum combination of materials. Variations in the chemical composition and physical properties of any of these materials will affect the concrete compressive strength. The supplier of high-strength concrete should implement a program to ensure uniformity and acceptance tests for all materials used in the production of high-strength concrete.

4.2—Portland cement

Proper selection of the type and source of cement is one of the most important steps in the production of high-strength concrete. For more information, refer to ACI 363R and ACI Compilation 17, *High-Strength Concrete*, on high-strength concrete. For any given set of materials, there is an optimum cement content beyond which little or no additional increase in strength is achieved from increasing the cement content.

4.3—Fly ash

For use in concrete, ASTM C618 specifies the requirements for Class F and Class C fly ashes and Class N for raw or calcined natural pozzolans. Fly ash, a by-product of coal combustion, is widely used as a cementitious and pozzolanic ingredient in concrete. According to "ACI Concrete Terminology," fly ash is "the finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gases from the combustion zone to the particle removal systems" (American Concrete Institute 2008). The terminology guide defines pozzolans as "a siliceous or siliceous and aluminous material that in itself possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds having cementitious properties." All fly ashes contain pozzolanic materials; however, some ashes exhibit varying degrees of cementitious properties in the absence of calcium hydroxide or portland cement because they contain some lime. For more information on fly ash in concrete, refer to ACI 232.2R.

Fly ash in concrete makes efficient use of the hydration products of portland cement by consuming calcium hydroxide to produce additional cementing compounds. When concrete containing fly ash is properly cured, fly-ash reaction products partially fill in the spaces originally occupied by mixing water that were not filled by the hydration products of the cement, thus lowering the concrete permeability to water and aggressive chemicals (Manmohan and Mehta 1981; ACI 232.2R).

Initially, fly ash was used as a partial mass or volume replacement of portland cement for economical reasons. As fly ash usage increased, researchers recognized the potential for improved properties of concrete containing fly ash. Because fly ash reacts with the alkali hydroxides in portland cement paste, it reduces alkali-aggregate reactions. In addition, fly ash may increase resistance to deterioration when exposed to sulfates, improve workability, reduce permeability, and reduce peak temperatures in mass concrete.

Due to their generally spherical shape, fly ash particles normally permit a reduction in water content for a given workability and improve pumpability and finishability. Bleeding may be reduced due to increased paste volume, lower water content for a given workability, and greater solid particle surface area. Other mechanisms by which fly ash reduces water can be referenced in ACI 232.2R.

On an equal mass replacement basis of portland cement with fly ash, early compressive strengths (less than 7 days) may be lower, particularly when using a Class F fly ash. If equivalent early strengths are required, the mixture proportions may need to be modified. Methods by which early-strength equivalency can be achieved include reducing the *w/cm*, adjusting the cementitious materials content, adjusting the chemical admixture dosage, modifying the fly ash content, the addition of silica fume, or a combination of all of the above. The 56- and 90-day strengths of fly ash concrete generally surpass mixtures of only portland cement. The ability of fly ash to aid in achieving high ultimate strengths has made it a very useful ingredient in the production of high-strength concrete (Kosmatka et al. 2002). After the rate of strength contribution of portland cement slows, the continued pozzolanic reactivity of fly ash contributes to increased strength gain at later ages if the concrete is kept moist; therefore, concrete containing fly ash at an equivalent or lower strength at early ages may have an equivalent or higher strength at later ages than concrete without fly ash. This strength gain will continue with time and result in higher later-age strengths than can be achieved by using additional cement (Berry and Malhotra 1980; ACI 232.2R).

4.4—Silica fume

Silica fume is a by-product resulting from the reduction of high-purity quartz with coal or coke and wood chips in an electric arc furnace during the production of silicon metal or ferrosilicon alloys. The silica fume, which condenses from the gases escaping from the furnaces, has a very high content of amorphous silicon dioxide, and consists of very fine spherical particles.

Ferrosilicon alloys are produced with nominal silicon contents of 61 to 98%. When the silicon content reaches 98%, the product is called elemental silicon rather than ferrosilicon. As the silicon content increases in the alloy, the SiO_2 content will increase in the silica fume. The majority of published data and the field use of silica fume have been with silica fume produced from alloys of 75% elemental silicon or higher. ASTM C1240 defines this silica fume as having a minimum 85% amorphous silicon dioxide. Limited applications have been made using fume produced from lower silicon content alloys. The U.S. Environmental Protection Agency considers silica fume to be a valuable recyclable material for use in federally funded concrete construction. For more information about silica fume in concrete, refer to ACI 234R.

Silica fume is also collected as a by-product in the production of other elemental alloys. Little published data are available on the properties of these fumes. The use of these fumes should be avoided unless data on their favorable performance in concrete are available.

Silica fume was initially viewed as a cement replacement material, and, in some parts of the world, is still used as such. In general, for low-permeable concrete applications, part of the cement may be replaced by a much smaller quantity of silica fume. For example, one part of silica fume replaces three to four parts of cement (mass to mass) without loss of strength, provided that the water content remains constant. The replacement of cement by silica fume may not affect all hardened concrete properties to the same degree.

Due to its high surface area and because silica fume is highly pozzolanic, its addition to the concrete usually increases water demand and results in a more cohesive concrete mixture. If it is desired to maintain the same *w/cm* (by mass), water-reducing admixtures (WRAs), high-range water-reducing admixtures (HRWRAs), or both, should be used to obtain the required workability. To maintain the same apparent degree of workability, an increase in slump of 1 to 2 in. will normally be required for silica-fume concrete.

Because of the limited availability and higher cost (relative to portland cement and other pozzolans), silica fume is being used primarily as a property-enhancing material for concrete. In this role, silica fume has been used to provide concrete with higher compressive strengths. Silica-fume concrete has been used in numerous high-strength concrete applications.

Silica fume is available commercially in several forms: dry or densified dry, each with or without chemical admixtures. Silica fume or products containing silica fume are available in bulk, drums, and bags, depending on the supplier. For more information on silica fume, refer to ACI 234R.

4.5—Slag cement

Slag cement, sometimes referred to as granulated blast-furnace slag, is produced during the iron production process. In the production of iron, the blast furnace is continuously charged from the top with iron oxide (ore, pellets, sinter), fluxing stone (limestone and dolomite), and fuel (coke). Two products are obtained from the furnace: molten iron that collects in the bottom of the furnace (hearth) and liquid iron blast-furnace slag floating on the pool of iron. Both are periodically tapped from the furnace at a temperature of approximately 2730° F.

The composition of blast-furnace slag is determined by that of the ores, fluxing stone, and impurities in the coke charged into the blast furnace. Typically, silicon, calcium, aluminum, magnesium, and oxygen constitute 95% or more of the blast-furnace slag.

Quenching with water is the most common process for granulating slag to be used as cementitious materials. The blast-furnace slag is quenched almost instantaneously to a temperature below the boiling point of water, producing particles of highly glassy material. The resulting product is called granulated blast-furnace slag or slag cement. Other methods used to formulate slag cement are described in detail in ACI 233R.

When slag cement is mixed with water, initial hydration is much slower than portland cement mixed with water; therefore, portland cement or alkali salts or lime are used to increase the reaction rate. Hydration of slag cement in the presence of portland cement depends largely on breakdown and dissolution of the glassy slag structure by hydroxyl ions released during the hydration of the portland cement. In the hydration of slag cement, the slag reacts with alkali and calcium hydroxide ($Ca(OH)_2$) to produce additional CSH. Regourd (1987) showed that a very small immediate reaction also takes place when slag is mixed with water, preferentially releasing calcium and aluminum ions to solution. The reaction is limited, however, until additional alkali, calcium hydroxide, or sulfates are available for reaction.

Slag cement concrete has demonstrated compatibility with pozzolanic materials such as fly ash, silica fume, and other materials that may be used in high-performance concrete.

More information about slag cement and its use in concrete is available in ACI 233R.

4.6—Combinations of other cementitious materials

Combinations of cementitious materials, such as rice hull ash, diamataeous earth, metakaolin, and calcium-aluminate cement have been used with portland cement in the production of high-strength concrete. Some of these materials can help control the temperature rise in concrete at early ages, and may reduce the water demand of high-strength concrete. For more information about the use of other cementitious materials in concrete, refer to ACI 232.1R.

With increasing demand for high-performance concrete, enhanced durability, and environmental sustainability, the use of combinations of cements and supplementary cementing materials is becoming more common. Three- and four-part cementitious materials mixtures, often referred to as ternary and quad blends, respectively, may be used to impart specific plastic and hardened characteristics to the concrete. Quad-blend cements are sold as engineers' cement in Australia and as marine cement in China.

In such concrete mixtures, the purpose of the design is specific to certain performance criteria. This can be for lower heat of hydration, controlled setting characteristics and rate of strength gain, reduced permeability, or other strength and durability enhancements. Often the attempt is to develop an engineered design of the concrete mixture to offset deficiencies in the properties of a portland cement or binary mixture. This does not preclude achieving higher strengths. Actually, the extended duration of the pozzolanic and cementitious action of the combination can often result in very high strengths at later ages. Common examples of such blends would be:

1. Portland cement + fly ash + silica fume;
2. Portland cement + slag cement + silica fume;
3. Portland cement + slag cement + fly ash; and
4. Portland cement + slag cement + fly ash + silica fume.

The supplementary cementitious materials and possible portland-cement content in these blends are often at lower percentages than when used in simple binary combinations (Elkem 2003b). This often leads to optimized mixture proportions and lower cost, either in terms of materials or constructibility.

Ternary blends are in worldwide use. In addition to everyday use in the United States and Canada, international projects, including the Storebælt Link in Denmark, the Tsing Ma and Ting Kau bridges in Hong Kong, LNG tanks at Dahej, and the Bandra Worli Sealink project in India, all used ternary blends (Elkem 2001a,b; 2003a).

With the increasing focus on the reuse of by-products from various industrial processes, the advent of other pozzolanic or filler materials within the marketplace is to be expected. This will increase the possibility of further blends.

Due to the many possible combinations of these materials and the percentages used, this document does not cover the proportioning methods for such blends. Typically, the starting point for these mixtures is an existing portland cement only or binary mixture that is then modified to achieve the specific requirements of a project. If such multiple cementitious mixtures are specified or being considered for a project, reference should be made to the ready mixed concrete producer or suppliers of the cementitious materials for technical assistance in the mixture design process. Constraints such as the material storage and batching capabilities, material availability, and potential setup costs relative to the size of a proposed project should be considered before ternary or quad blends are specified.

4.7—Mixing water

Potable water is usually acceptable. When other sources of water are to be used, they should meet the water quality standards stated in ASTM C1602/C1602M. Water sources should be tested for suitability to be used in concrete mixtures in accordance with ASTM C1603.

4.8—Coarse aggregate

In the proportioning of high-strength concrete, the aggregates require special consideration because they occupy the largest volume of any ingredient in the concrete, and they greatly influence the strength and other properties of the concrete. The coarse aggregate will significantly influence the strength and structural properties of the concrete. For this reason, a coarse aggregate should be chosen that is sufficiently sound, free of fissures or weak planes, clean, and free of surface coatings. Coarse aggregate properties also affect aggregate-mortar bond characteristics and mixing-water requirements (Kosmatka et al. 2002).

High-strength concrete may be manufactured with a broad array of coarse aggregate sizes and mineral compositions. ACI Committee 211 recommends that the user investigate the impact of type, shape, size, gradation, and aggregate mineralogy on the compressive strength of concrete in the prospective local market by conducting trial batches.

4.9—Fine aggregate

The grading and particle shape of the fine aggregate are significant factors in the production of high-strength concrete. Particle shape and surface texture of the fine aggregate can have as great an effect on mixing-water requirements and compressive strength of concrete as do those of the coarse aggregate (Kosmatka et al. 2002).

The quantity of paste required per unit volume of a concrete mixture decreases as the relative volume of coarse versus fine aggregate increases. Because the amount of cementitious material contained in high-strength concrete is large, the volume of fines (materials passing the No. 100 sieve) tends to be high. Consequently, the volume of fine aggregate can be kept to the minimum necessary to achieve the needed workability and consolidation. In this manner, it will be possible to produce higher-strength concrete for a given cementitious material content. Fine aggregate contents of high-strength concrete mixtures are usually lower than those in normal-strength concrete. The coarser fine aggregate sizes and reduced total fine aggregate volume contribute to reduced water demand and increased concrete strength.

The fine aggregate should meet the requirements of ASTM C33. Generally, for high-strength concrete, fine aggregate with a higher fineness modulus (FM) is preferred. FMs in the range of 2.5 to 3.2 or higher are typical. Concrete mixtures made with a fine aggregate that has an FM of less than 2.5 may cause the concrete to be sticky and result in poor workability and a higher water demand. It is sometimes possible to blend fine aggregates from different sources to improve their grading and their capacity to produce higher strengths. If manufactured fine aggregates are used, consideration should be given to a possible increase in water demand for workability. The particle shape and the increased surface area of manufactured fine aggregates over natural fine aggregates can significantly affect water demand.

4.10—Chemical admixtures

The use of chemical admixture to increase the effectiveness of the cementitious materials either by reducing the water requirements and/or by dispersing the cementitious materials will result in higher strength. Chemical admixtures should meet the requirements of ASTM C494/C494M.

In this guide, chemical admixture dosage rates are based on fluid ounces per 100 lb (oz/cwt) of total cementitious material. If powdered admixtures are used, dosage rates are on a dry mass basis. The use of chemical admixtures may control slump loss and the rate of hardening resulting in improved workability, extended time from batching to placing (particularly in hot weather concrete), accelerated strength gain, and better durability.

High-range water-reducing admixtures (HRWRAs) are most effective in concrete mixtures that are rich in cement and other cementitious materials. HRWRAs help in dispersing cement particles, and they can reduce mixing water requirements by more than 30%, thereby increasing concrete compressive strengths.

Generally, high-strength concrete can contain one or more of the following admixtures: water-reducing/retarding admixture, high-range water-reducing admixtures, and hydration stabilizers. The dosage rates of admixtures will most likely be different from the manufacturer's published recommended dosage rates for normal-strength concrete mixtures. It is recommended that the admixture manufacturer be consulted regarding the applicability of the use of the specific admixtures and admixture combinations for high-strength concrete mixtures.

Although only limited information is available, high-strength concrete also has been produced using a combination of chemical admixtures, such as a high dosage rate of a normal-set water-reducer and a set accelerator. The performance of the admixtures is influenced by the types of cementitious materials used. The optimum dosage of an admixture or combination of admixtures should be determined by trial mixtures using varying amounts of admixtures.

Air-entraining admixtures are seldom used in high-strength concrete building applications when there are no freezing and thawing concerns other than during the construction period. If entrained air is required because of severe exposure, it will reduce the compressive strength of the concrete. Information on the reduction in concrete strength as a result of air entrainment can be found in ACI 211.1. For guidance on the amount of air needed in high-strength concrete, reference ACI 318.

CHAPTER 5—HIGH-STRENGTH CONCRETE MIXTURE PROPERTIES

5.1—Introduction

The procedure described in ACI 211.1 for proportioning normal-strength concrete is similar to that required for high-strength concrete. The procedure consists of a series of steps that, when completed, provide a mixture meeting workability, *w/cm*, strength, and durability requirements based on the combined properties of the individually selected and proportioned components. In the development of a high-strength concrete mixture, obtaining the optimum proportions is based on a series of trial batches having different proportions and cementitious material contents.

5.2—Water-cementitious material ratio

Because most high-strength concrete mixtures contain other cementitious materials, a *w/cm* should be considered in place of the traditional *w/c*. The *w/cm*, like the *w/c*, should be calculated on a mass basis. The mass of water in an HRWRA should be included in the *w/cm*.

The relationship between *w/cm* and compressive strength, which has been identified in normal-strength concrete, is valid for high-strength concrete as well. The use of chemical admixtures and other cementitious materials has been proven generally essential to producing placeable concrete with a low *w/cm*; see Table 6.5.

5.3—Workability

For the purpose of this guide, workability is that property of freshly mixed concrete that determines the ease with which it can be properly mixed, placed, consolidated, and finished without segregation.

5.3.1 *Slump*—In general, high-strength concrete should be placed at the lowest slump that can be properly handled and consolidated in the field. High-strength concrete is commonly placed at slumps in excess of 7 in. with HRWRAs without segregation. Placement conditions, pumping requirements, reinforcement spacing, and form details should be considered before development of concrete mixtures.

Because of high coarse aggregate and cementitious material contents and low *w/cm*, high-strength concrete can be difficult to place. Flowing concrete with slumps in excess of 8 in. that incorporate HRWRAs are very effective in filling the voids between closely-spaced reinforcement.

CHAPTER 6—HIGH-STRENGTH CONCRETE MIXTURE PROPORTIONING USING FLY ASH

6.1—Fundamental relationship

When concrete containing fly ash is properly cured, fly ash reaction products partially fill in the spaces, originally occupied by mixing water, that are not filled by the hydration products of the cement, thus lowering the concrete permeability to water and aggressive chemicals (Manmohan and Mehta 1981).

6.1.1 *Materials selection*—Fly ash is normally used at 15 to 35% by mass of total cementitious material. Class C fly ashes often exhibit a higher rate of reaction at early ages than Class F fly ashes.

6.1.2 *Special consideration*—When concrete is kept moist, the continued pozzolanic activity of fly ash provides strength gain at later ages after the rate of strength gain of portland cement has slowed. Concrete containing fly ash may achieve higher strengths at later ages than concrete without fly ash. This strength gain will continue with time as long as moisture is available and will result in higher later-age strength than can be achieved by using additional cement (Berry and Malhotra 1980). The ability of fly ash to aid in achieving high ultimate strengths has made it a very important ingredient in the production of high-strength concrete.

Table 6.1—Recommended slump for concrete with and without HRWRA

Concrete made using HRWRA*	
Slump before adding HRWRA	1 to 2 in.
Concrete made without HRWRA	
Slump	2 to 4 in.

*Adjust slump to that desired in the field through the addition of HRWRA.

6.2—Concrete mixture proportioning

6.2.1 *Purpose*—Proper proportioning is required for all materials used. Because the performance of high-strength concrete is highly dependent on the properties of its individual components, the proportioning procedure is meant to produce mixture proportions based on the performance of adjusted laboratory and field trial batches. This procedure further ensures that the properties and characteristics of the materials used in the trial mixtures are adequate to achieve the desired concrete compressive strength. Guidelines for the selection of materials for producing high-strength concrete are provided in ACI 363.2R.

The project specifications should be reviewed before starting the proportioning of high-strength concrete mixtures. The review will establish the design criteria for specified strengths, the age when strengths are to be attained, and other testing acceptance criteria.

6.2.2 *Introduction*—Because fly ash properties vary depending on the source, type, and class, the most effective method to establish proper mixture strength and performance for a specific application using fly ash in the concrete mixture is a trial batch program (ACI 211.1).

6.2.3 *Mixture proportioning procedure*—Completion of the following steps will result in a set of high-strength concrete laboratory trial proportions. These proportions will then provide the basis for field testing concrete batches from which the optimum mixture proportions may be chosen.

6.2.3.1 *Step 1: Select slump and required concrete strength*—Recommended values for concrete slump are given in Table 6.1. Although high-strength concrete with HRWRA has been produced successfully without a measurable initial slump, an initial starting slump of 1 to 2 in. before adding HRWRA is recommended. This will ensure an adequate amount of water is available for mixing and hydration and allows the HRWRA to be effective. Slump values after addition of HRWRA of at least 2 in. are recommended because concrete with a slump less than 2 in. is difficult to consolidate.

For high-strength concrete made without HRWRA, a recommended slump range of 2 to 4 in. may be chosen according to the type of work to be done. A minimum value of 2 in. of slump is recommended for concrete without HRWRA.

HRWRA dosage should be adequate for both the anticipated contribution to strength and the desired workability. Slump after adding HRWRA should be enough for proper placement and consolidation, but not so much as to cause segregation.

Table 6.2—Suggested maximum-size coarse aggregate

Required concrete strength, psi	Suggested maximum-size coarse aggregate, in.
<9000	3/4 to 1
>9000	3/8 to 1/2*

*When using HRWRA and selected coarse aggregate, concrete compressive strengths in the range of 9000 to 12,000 psi can be attained using larger-than-recommended nominal maximum-size coarse aggregates of up to 1 in.

Table 6.3—Recommended volume of coarse aggregate per unit volume of concrete

Optimum coarse aggregate contents for nominal maximum sizes of aggregates to be used with fine aggregates with fineness modulus 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 (VCA)	0.65	0.68	0.72	0.75

*Volumes are based on aggregates in oven-dry-rodded condition as described in ASTM C29/C29M for unit mass or bulk density of aggregates.

Because this slump is chemically induced and not the result of added water, traditional slump limits do not apply.

The required concrete strength to use in the trial mixture procedure should be determined using the guidelines provided in Chapter 2.

6.2.3.2 *Step 2: Select maximum size of aggregate*—Based on strength requirements, the recommended nominal maximum sizes for coarse aggregates are given in Table 6.2. Also, ACI 318 states the maximum size of an aggregate should not exceed 1/5 of the narrowest dimension between sides of forms, 1/3 of the depth of slabs or concrete element, nor 3/4 of the minimum clear spacing between individual reinforcing bars, bundles of bars, or prestressing tendons or ducts.

6.2.3.3 *Step 3: Select optimum coarse aggregate content*—The optimum content of the coarse aggregate depends on its strength, potential characteristics, and maximum size.

In proportioning normal-strength concrete mixtures, the optimum content of coarse aggregate is given as a function of the maximum size and fineness modulus of the fine aggregate. High-strength concrete mixtures, however, have a high content of cementitious material and thus are not so dependent on the fine aggregate to supply fines for lubrication and consolidation of the fresh concrete.

The recommended coarse aggregate contents, expressed as a fraction of the bulk density, are given in Table 6.3 as a function of nominal maximum size. The values given in Table 6.3 are recommended for use with fine aggregates having fineness modulus values from 2.5 to 3.2.

Once the coarse aggregate content has been chosen from Table 6.3, the required mass of the coarse aggregate per cubic yard of concrete can be calculated using Eq. (6-1)

$$\text{Mass of coarse aggregate} = \text{VCA} \times \text{bulk density} \times 27 \quad (6\text{-}1)$$

where VCA is the fractional volume from Table 6.3.

6.2.3.4 *Step 4: Estimate mixing water and air content*—The quantity of water per unit volume of concrete required to produce a given slump is dependent on many factors, including the maximum size, particle shape, and grading of the aggregate; the quantity of cement; the amount of fly ash; and the type of chemical admixture used. Therefore, the most effective way to determine the best proportions for a given set of ingredients is through the process of trial batching. If an HRWRA is used, the water content in this admixture is calculated to be a part of the *w/cm*. Table 6.4 gives estimates of required mixing water for high-strength concrete made with 3/8 to 1 in. maximum-size aggregates before adding any chemical admixture. Also given are the corresponding estimated values for entrapped air content. These quantities of mixing water are maximums for reasonably well-shaped, clean, angular coarse aggregates, well-graded within the limits of ASTM C33. Because particle shape and surface texture of a fine aggregate can significantly influence its voids content, mixing water requirements may be different from the values given.

Table 6.4—First estimate of mixing water requirement and air content of freshly mixed concrete based on using fine aggregate with 35% voids

Slump, in.	Mixing water, lb/yd^3*			
	Maximum-size coarse aggregate, in.			
	3/8	1/2	3/4	1
1 to 2	310	295	285	280
2 to 3	320	310	295	290
3 to 4	330	320	305	300
Entrapped air content	3 (2.5)†	2.5 (2.0)†	2 (1.5)†	1.5 (1.0)†

*Values given must be adjusted for fine aggregates with voids other than 35% using Eq. (6-3).
†Mixtures made using HRWRA.

The void content of a fine aggregate may be calculated using Eq. (6-2)

$$\textbf{Void content } V, \% = \left(1 - \frac{\text{bulk density}}{\text{relative density} \times 62.4}\right) \times 100 \quad (6\text{-}2)$$

When a fine aggregate with a void content other than 35% is used, an adjustment is made to the recommended mixing water content. This adjustment (the amount to be added or reduced) may be calculated using Eq. (6-3)

$$\text{Mixing water adjustment, lb/yd}^3 = (V - 35) \times 8 \quad (6\text{-}3)$$

The use of Eq. (6-3) results in a water adjustment of 8 lb/yd^3 of concrete for each 1% deviation from 35% void content.

6.2.3.5 *Step 5: Select* w/cm—The *w/cm* is calculated by dividing the mass of the mixing water by the combined mass of the cement and fly ash (and other cementitious materials).

In Table 6.5, recommended maximum *w/cm* is given as a function of maximum-size aggregate to achieve different compressive strengths at either 28 or 56 days. The use of an HRWRA generally increases the compressive strength of concrete. The *w/cm* values given in Table 6.5 are for concrete made with and without HRWRA.

The committee is aware of high-strength concrete proportioned without the use of HRWRA, however, the use

Table 6.5—Recommended maximum *w/cm* for high-strength concrete

Required average compressive strength f'_{cr},* psi		*w/cm*							
		Maximum-size coarse aggregate, in.							
		3/8		1/2		3/4		1	
		with HRWRA	without HRWRA	with HRWRA	without HRWRA	with HRWRA	without HRWRA	with HRWRA	without HRWRA
7000	28-day	0.50	0.42	0.48	0.41	0.45	0.40	0.43	0.39
	56-day	0.55	0.46	0.52	0.45	0.48	0.44	0.46	0.43
8000	28-day	0.44	0.35	0.42	0.34	0.40	0.33	0.38	0.33
	56-day	0.48	0.38	0.45	0.37	0.42	0.36	0.40	0.35
9000	28-day	0.38	0.30	0.36	0.29	0.35	0.29	0.34	0.28
	56-day	0.42	0.33	0.39	0.32	0.37	0.31	0.36	0.30
10,000	28-day	0.33	0.26	0.32	0.26	0.31	0.25	0.30	0.25
	56-day	0.37	0.29	0.35	0.28	0.33	0.27	0.32	0.26
11,000	28-day	0.30	—	0.29	—	0.27	—	0.27	—
	56-day	0.33	—	0.31	—	0.29	—	0.29	—
12,000	28-day	0.27	—	0.26	—	0.25	—	0.25	—
	56-day	0.30	—	0.28	—	0.27	—	0.26	—

*$f'_{cr} = 1.10 f'_c + 700$ psi.

of HRWRA is recommended. A comparison of the values contained in Table 6.5 permits the following conclusions:

1. For a given *w/cm*, the field strength of concrete is greater with the use of HRWRA than without it, and this greater strength is reached within a shorter period of time; and

2. With the use of HRWRA, a given concrete field strength can be achieved in a given period of time using less cementitious material than would be required when not using HRWRA.

6.2.3.6 *Step 6: Calculate content of cementitious material*—The mass of cementitious material required per cubic yard of concrete can be determined by dividing the amount of mixing water per cubic yard of concrete (Step 4) by the *w/cm* (Step 5). If the specifications include a maximum or minimum limit on the amount of cementitious material per cubic yard of concrete, however, this must be satisfied. Therefore, the mixture should be proportioned to contain the larger quantity of cementitious material required.

6.2.3.7 *Step 7: Proportion basic mixture with no other cementitious material*—One trial mixture should be made with portland cement as the only cementitious material. The following steps should be followed to complete this basic mixture proportion:

1. *Cement content*—For this mixture, because no other cementitious material is to be used, the mass of cement equals the mass of cementitious material calculated in Step 6; and

2. *Fine aggregate content*—After determining the masses per cubic yard of coarse aggregate, cement, water, and the percentage of air content, the fine aggregate content can be calculated to produce 27.0 ft^3 using the absolute volume method.

6.2.3.8 *Step 8: Proportion companion mixtures using fly ash*—To determine optimum mixture proportions, the user needs to prepare several trial mixtures having different combinations and percentages of cementitious materials.

The use of fly ash in producing high-strength concrete can result in lowered water demand, reduced concrete temperature, and reduced cost. Due to variations in the chemical properties of fly ash, however, the strength-gain characteristics of the concrete might be affected. It is therefore recommended that at least two different fly ash contents be used for the companion trial mixtures. The following steps should be completed for each companion trial mixture to be proportioned:

Table 6.6—Recommended values for fly ash replacement of portland cement

Fly ash	Recommended replacement (percent by mass)
Class F	15 to 25
Class C	20 to 35

1. *Fly ash type*—Due to differing chemical compositions, the water-reducing and strength-gaining characteristics of fly ash will vary with the type used and its source. Therefore, these characteristics, as well as availability, should be considered when choosing the fly ash to be used;

2. *Fly ash content*—The amount of cement to be replaced by fly ash depends on the type of material to be used. The recommended limits for replacement are given in Table 6.6 for the two classes of fly ash. For each companion trial mixture to be designed, a replacement percentage should be chosen from Table 6.6;

3. *Fly ash mass*—Once the percentages for replacement have been chosen, the mass of the fly ash to be used for each companion trial mixture can be calculated by multiplying the total mass of cementitious materials (Step 6) by the replacement percentages previously chosen. The remaining mass of cementitious material corresponds to the mass of cement. Therefore, for each mixture, the mass of fly ash plus the mass of cement should equal the mass of cementitious materials calculated in Step 6;

4. *Volume of fly ash*—Due to the differences in relative density of portland cement and fly ash, the volume of cementitious materials per cubic yard will vary with the fly ash content, even though the mass of the cementitious material remains constant. Therefore, for each mixture, the volume of

cementitious material should be calculated by adding the volume of cement and the volume of fly ash; and

5. *Fine aggregate content*—Having determined the volume of cementitious material per cubic yard of concrete for each companion trial mixture, and given the previously determined volumes per cubic yard of coarse aggregate, water, and entrapped air (Step 7), the fine aggregate content of each companion trial mixture is calculated using the absolute volume method.

6.2.3.9 *Step 9*: *Trial mixtures*—For each of the trial mixtures proportioned in Steps 1 through 8, a laboratory trial batch should be produced to determine the workability and strength characteristics of the mixtures. The masses of fine aggregate, coarse aggregate, and water should be adjusted to correct for the moisture condition of the aggregates used. Each trial batch should be such that, after a thorough mixing, a uniform concrete mixture of at least 3.0 ft^3, or larger if necessary, to conduct the freshly mixed concrete testing, and fabricate the required number of test specimens.

6.2.3.10 *Step l0: Adjust trial mixture proportions*—If the desired properties of the concrete are not obtained, the original trial mixture proportions should be adjusted according to the following guidelines to produce the desired workability.

1. *Initial slump*—If the initial slump of the trial mixture is not within the desired range, the mixing water or the admixture dosage should be adjusted. The mass of cementitious material in the mixture should be adjusted to maintain the desired *w/cm*. The fine aggregate content should then be adjusted to ensure proper yield of the concrete;

2. *HRWRA dosage rate*—If HRWRA is used, different dosage rates should be tried to determine the effect on strength and workability of the concrete mixture. Because of the nature of high-strength concrete mixtures, higher dosage rates than those recommended by the admixture manufacturer may still function without segregation. Also, because the time of addition of the HRWRA and concrete temperature can impact the effectiveness of the admixture, its use in laboratory trial mixtures may have to be adjusted for field conditions. In practice, redosing with HRWRA to restore workability results in increased strengths at nearly all test ages; however, an excessive dosage of HRWRA can retard the initial setting time of concrete, which may increase the potential for plastic shrinkage cracking on flatwork applications;

3. *Coarse aggregate content*—Once the concrete trial mixture has been adjusted to the desired slump, it should be determined if the mixture is too harsh for job placement or finishing requirements. If needed, the coarse aggregate content may be reduced, and the fine aggregate content adjusted accordingly to ensure proper yield. This may, however, increase the water demand of the mixture, thereby increasing the required content of cementitious material to maintain a given *w/cm*. In addition, a reduction in coarse aggregate content may result in a lower modulus of elasticity for the hardened concrete;

4. *Air content*—If air entrainment is required and the measured air content differs significantly from the designed proportion calculations, then the dosage should be adjusted to maintain yield; and

5. *w/cm*—If the required concrete compressive strength is not achieved using the *w/cm* recommended in Table 6.5, additional trial mixtures with lower *w/cm* should be tested. If this does not result in increased compressive strengths, the adequacy of the materials used should be reviewed.

6.2.3.11 *Step 11: Select optimum mixture proportions*—Once the trial mixture proportions have been adjusted to produce the desired properties, strength specimens should be cast from trial batches made under the expected field conditions according to the requirements of ACI 318. Practicalities of production and quality control procedures are better evaluated when production-size trial batches are prepared using the equipment and procedures that are to be used in the actual work.

6.3—Sample calculations

6.3.1 *Introduction*—An example is presented herein to illustrate the mixture proportioning procedure for high-strength concrete discussed in the preceding section. Laboratory trial batch results will depend on the actual materials used. In this example, Type I cement having a relative density of 3.15 is used.

6.3.2 *Example*—High-strength concrete is required for the columns in the first three floors of a high-rise office building. The specified compressive strength is 9000 psi at 28 days. Due to the close spacing of steel reinforcement in the columns, the largest nominal maximum-size aggregate that can be used is 1/2 in. A fine aggregate that meets ASTM C33 limits will be used, which has the following properties:

1. FM = 2.9 fineness modulus;
2. RD_{Od} = 2.59 relative density, based on oven-dry;
3. Abs = 1.1% absorption, based on oven-dry;
4. BD = 105 lb/ft^3 bulk density; and
5. HRWRA and a set-retarding admixtures will be used.

6.3.2.1 *Step 1: Select slump and required concrete strength*—Because an HRWRA is used, the concrete will be designed based on a slump of 1 to 2 in. before the addition of the HRWRA according to Table 6.1.

In this example, the ready mixed concrete producer has no previous history with high-strength concrete, and therefore should select proportions based on laboratory trial mixtures. Using Eq. (3-3), the required average strength used for selection of concrete proportions is

$$f'_{cr} = 1.10 \times (9000) + 700 = 10{,}600 \text{ psi} \qquad (3\text{-}3)$$

6.3.2.2 *Step 2: Select maximum size of aggregate*—Based on the guidelines in Table 6.2, a crushed limestone having a nominal maximum size of 1/2 in. will be used. The crushed limestone properties are as follows:

1. RD_{Od} = 2.76 relative density, based on oven-dry;
2. Abs = 0.7% absorption, based on oven-dry; and
3. BD = 101 lb/ft^3 bulk density.

The grading of the aggregate should comply with ASTM C33, No. 7, 1/2 in. coarse aggregate.

6.3.2.3 *Step 3: Select optimum coarse aggregate content*—The optimum coarse aggregate content, selected from Table 6.3, is 0.68 per unit volume of content. The dry mass of coarse aggregate per cubic yard of concrete, W_{dry}, is then

$$(0.68) \times (101) \times (27) = 1854 \text{ lb}$$

6.3.2.4 *Step 4: Estimate mixing water and air contents*—Based on a slump of 1 to 2 in. and 1/2 in. maximum-size coarse aggregate, the first estimate of the required mixing water chosen from Table 6.4 is 295 lb/yd^3 of concrete, and the entrapped air content, for mixtures made using HRWRA, is 2.0%.

To correct for void content other than 35%, Eq. (6-2) is first used to compute the voids content of the fine aggregate to be used

$$\left[1 - \frac{105}{(2.59) \times (62.4)}\right] \times 100 = 35.03\%$$

The mixing water adjustment, calculated using Eq. (6-3), is

$$(35.03 - 35) \times 8 = +0.24 \text{ lb/yd}^3 \text{ of concrete}$$

The adjustment to the mixing water per cubic yard of concrete is negligible; therefore, 295 lb of water will be used. This required mixing water is not adjusted for the water in the HRWRA or other chemical admixtures.

6.3.2.5 *Step 5: Select* w/cm—For concrete to be made using HRWRA, 1/2 in. nominal maximum-size aggregate, and achieving an average compressive strength of 10,600 psi at 28 days in the field based on laboratory trial mixtures, the required *w/cm* chosen from Table 6.5 is interpolated to be 0.30. The compressive strengths listed in Table 6.5 are required average field strengths.

6.3.2.6 *Step 6: Calculate content of cementitious material*—The mass of cementitious material per cubic yard of concrete is

$$\left(\frac{295}{0.30}\right) = 983.3 \text{ lb}$$

The specifications do not set a minimum for cementitious materials content; thus, 984 lb/yd^3 of cement will be used.

6.3.2.7 *Step 7: Proportion basic mixture with cement only*

1. Cement content per cubic yard = 984 lb; and
2. The volumes per cubic yard of all materials, except fine aggregate, are as follows:

Cement	(984)/(3.15 × 62.4) =	5.01 ft^3
Coarse aggregate	(1854)/(2.76 × 62.4) =	10.77 ft^3
Water	(295)/(62.4) =	4.73 ft^3
Air	(0.02) × (27) =	0.54 ft^3
Total volume		21.04 ft^3

Therefore, the required volume of fine aggregate per cubic yard of concrete is (27.0 – 21.04) = 5.96 ft^3. Converting this to mass of fine aggregate in a dry condition, per cubic yard of concrete, the required mass of fine aggregate is

$$(5.96) \times (62.4) \times (2.59) = 963 \text{ lb}$$

Cement	984 lb
Fine aggregate, dry	963 lb
Coarse aggregate, dry	1854 lb
Water, including 3 oz/cwt* admixture	295 lb

*Hundred mass of cement.

6.3.2.8 *Step 9: Proportion companion mixtures using cement and fly ash*

1. An ASTM Class C fly ash with a relative density of 2.64 is selected;
2. The recommended limits for replacement given in Table 6.6 for Class C fly ash are from 20 to 35%. Four companion mixtures should be proportioned, having fly ash replacement percentages as follows:

Companion mixture No. 1	20%
Companion mixture No. 2	25%
Companion mixture No. 3	30%
Companion mixture No. 4	35%

3. For companion mixture No. 1, the mass of Class C fly ash per cubic yard of concrete is (0.20) × (984) = 197 lb. Therefore, the cement mass is (984) – (197) = 787 lb. The masses of cement and fly ash per cubic yard of concrete for the remaining companion mixtures are calculated in a similar manner. The values are as follows:

Companion mixture	Percent	Cement, lb	Class C fly ash, lb	Total, lb
No. 1	20	787	197	984
No. 2	25	738	246	984
No. 3	30	689	295	984
No. 4	35	640	344	984

4. For the first companion mixture, the volume of cement per cubic yard of concrete is (787)/(3.15 × 62.4) = 4.00 ft^3, and the fly ash per cubic yard is (197)/(2.64 × 62.4) = 1.2 ft^3. The volumes of cement, fly ash, and total cementitious material for each companion mixture are:

Companion mixture	Cement, ft^3	Class C fly ash, ft^3	Total, ft^3
No. 1	4.00	1.20	5.20
No. 2	3.75	1.49	5.24
No. 3	3.50	1.79	5.29
No. 4	3.25	2.09	5.34

5. For all companion mixtures, the volumes of coarse aggregate, water, and air per cubic yard of concrete are the same as the basic mixture that contains no other cementitious material; however, the volume of cementitious material varies with each mixture. The required mass of fine aggregate per cubic yard of concrete for companion mixture No. 1 is calculated as follows:

Component	Volume (per cubic yard of concrete, ft^3)
Cementitious material	5.20
Coarse aggregate	10.77

Water (including 2.5 oz/cwt retarding mixture)	4.73
Air	0.54
Total volume	21.24

The required volume of fine aggregate is (27.0 – 21.24) = 5.76 ft^3. Converting this to the mass of fine aggregate (dry) per cubic yard of concrete, the required mass is (5.76) × (62.4) × (2.59) = 931 lb.

The mixture proportions per cubic yard of concrete for each companion mixture are as follows:

Materials	Basic, lb	Companion mixtures, lb			
		No. 1	No. 2	No. 3	No. 4
Cement	984	787	738	689	640
Fly ash, Class C	—	197	246	295	344
Fine aggregate, dry	963	931	924	916	908
Coarse aggregates, dry	1854	1854	1854	1854	1854
Water (including 2.5 oz/cwt retarding admixture)	295	295	295	295	295

During trial batches, the proportioner needs to be aware of the possible need to make the necessary adjustment of the proper dosage rates for all chemical admixtures. In this example, the dosage rate of chemical retarding admixture was adjusted from 3.0 to 2.5 oz/cwt to account for the retarding action of the fly ash.

6.3.2.9 *Step 9: Trial mixtures*—Trial mixtures should be conducted for the basic mixture and each of the four companion mixtures. If the fine aggregate is found to have 6.4% total moisture, and the coarse aggregate is found to have 0.5% total moisture, based on dry conditions, aggregate masses are adjusted by increasing batch weight per cubic yard as follows:

Fine aggregate, wet = (963) × (1 + 0.064) = 1024 lb
Coarse aggregate, wet = (1854) × (1 + 0.005) =1863 lb
Water = (295) – (963)(0.064 – 0.011) – (1854)(0.005 – 0.007) = 248 lb

Thus, the batch mass of water is corrected to account for the moisture contributed by the aggregates, which is the total moisture minus the absorption of the aggregate.

Basic mixture	Dry masses, lb	Batch masses, lb
Cement	984	984
Fine aggregate	963	1024
Coarse aggregate	1854	1863
Water (including 3 oz/cwt retarding admixture)	295	248
Companion mixture No. 1	**Dry masses, lb**	**Batch masses, lb**
Cement	787	787
Fly ash	197	197
Fine aggregate	931	992
Coarse aggregate	1854	1863
Water (including 2.5 oz/cwt retarding mixture)	295	250
Companion mixture No. 2	**Dry masses, lb**	**Batch masses, lb**
Cement	738	738
Fly ash	246	246
Fine aggregate	924	984
Coarse aggregate	1854	1863
Water (including 2.5 oz/cwt retarding admixture)	295	250

Companion mixture No. 3	Dry masses, lb	Batch masses, lb
Cement	689	689
Fly ash	295	295
Fine aggregate, dry	917	975
Coarse aggregate, dry	1854	1863
Water (including 2.5 oz/cwt retarding admixture)	295	250
Companion mixture No. 4	**Dry masses, lb**	**Batch masses, lb**
Cement	640	640
Fly ash, Class C	344	344
Fine aggregate	909	967
Coarse aggregate	1854	1863
Water (including 2.5 oz/cwt retarding admixture)	295	251

The size of the trial mixture is selected to be 3.0 ft^3. The reduced batch mass for the basic mixture to yield 3.0 ft^3 is calculated as follows:

Cement = 984 × (3/27) = 109.33 lb
Fine aggregate = 1024 × (3/27) = 113.90 lb
Coarse aggregate = 1863 × (3/27) = 207.00 lb
Water = 248 × (3/27) = 27.52 lb

The reduced batch mass for the basic and the companion mixtures to yield 3.0 ft^3 are presented herein:

Materials	Basic	Companion mixture			
		No. 1	No. 2	No. 3	No. 4
Cement, lb	109.30	87.60	82.00	76.50	71.10
Fly ash, Class C, lb	—	21.87	27.33	32.78	38.27
Fine aggregate, lb	113.90	110.20	109.28	108.36	107.43
Coarse aggregate, lb	207.00	207.00	207.00	207.00	207.00
Water, lb	27.52	27.70	27.75	27.80	27.84
Chemical admixtures (included as part of the mixing water)					

6.3.2.10 *Step 10: Adjust trial mixture proportions*—Trial mixture proportions will require adjustment and the batch mass for each trial mixture will be adjusted during the batching to obtain the desired slump, before and after the addition of the HRWRA, and the desired workability. The adjustments to the batch mass for the basic mixture and companion mixture No. 4 will be shown in detail. Those for the other three companion mixtures will be summarized.

6.3.2.10.1 *Basic mixture*

1. Although the amount of water required to produce a 1 to 2 in. slump was calculated to be 27.52 lb, actually 28.50 lb (including 2.5 oz/cwt retarding admixture) was needed to produce the desired slump. The actual batch mass for the basic mixture was then:

Component	Volume (per cubic yard of concrete, ft^3)
Cement	109.00 lb
Fine aggregate	114.00 lb
Coarse aggregate	207.00 lb
Water	28.50 lb

Correcting these to dry mass gives:

Basic mixture		Mass, lb
Cement	N/A	109.00
Fine aggregate, dry	(114.00)/(1.064) =	107.14
Coarse aggregate, dry	(207.00)/(1.005) =	205.97
Batch water	(28.50 + 5.68* – 0.41†) =	33.77

*Fine aggregate moisture correction.
†Coarse aggregate moisture correction.

The actual yield of the trial mixture was:

Basic mixture		Volume, ft^3
Cement	(109.00)/(3.15 × 62.4) =	0.55
Fine aggregate	(107.14)/(2.59 × 62.4) =	0.66
Coarse aggregate	(205.97)/(2.76 × 62.4) =	1.20
Water	(33.77)/(62.4) =	0.54
Air	(0.02 × 3.0) =	0.06
	Total volume	3.01

Adjusting the mixture proportions to yield 27.0 ft^3 gives:

Cement	= 109.00 × (27/3) × (3/3.01)	= 976 lb
Fine aggregate	= 107.14 × (27/3) × (3/3.01)	= 1021 lb
Coarse aggregate	= 205.97 × (27/3) × (3/3.01)	= 1854 lb
Water	= 33.77 × (27/3) × (3/3.01)	= 302 lb

Basic mixture	Mass, lb
Cement	976
Fine aggregate, dry	960
Coarse aggregate, dry	1845
Water (including 2.5 oz/cwt retarding admixture)	302

The new mixture proportions result in a *w/cm* of (302)/(976) = 0.31. To maintain the desired ratio of 0.30, the mass of cement should be increased to (302)/(0.30) = 1007 lb/yd^3 of cement. The increase in volume due to the adjustment of the mass of cement is (1007 – 976)/(3.15 × 62.4) = 0.158 ft^3, which should be adjusted for by removing an equal volume of fine aggregate. The mass of fine aggregate to be removed is 0.158 × 2.59 × 62.4 = 26 lb. The resulting adjusted mixture proportions are:

Basic mixture	Mass, lb
Cement	1007
Fine aggregate, dry	934
Coarse aggregate, dry	1845
Water (including 2.5 oz/cwt retarding admixture)	302

2. For placement in the heavily reinforced columns, a flowing concrete having a slump of at least 9 in. is desired. The dosage rate recommended by the manufacturer of the HRWRA ranged between 8 and 16 oz/cwt of cementitious material. In a laboratory having an ambient temperature of 75 °F, adding HRWRA to the adjusted mixture at a dosage rate of 8 oz/cwt produced a slump of 6 in., 11 oz/cwt produced a slump of 10 in., and 16 oz/cwt caused segregation of the fresh concrete. When using all three HRWRA rates, a constant dosage rate of retarding admixture of 2.5 oz/cwt was also added to the mixture with the mixing water. The HRWRA was added approximately 15 minutes after initial mixing;

3. The concrete mixture with a 10 in. slump had adequate workability for proper placement, so no adjustment was necessary to the coarse aggregate content;

4. The air content of the HRWRA mixture was measured at 1.8%, so no correction was necessary;

5. The addition of significant amounts of HRWRA requires an adjustment in the mixing water to account for water contributed by the HRWRA and accommodate for the yield variation resulting from the admixture water. For HRWRA dosage rate of 11 oz/cwt with 20% solids, the water correction is:

Water contributed by HRWRA:

$$11 \times (1007/100)(0.80)/16 = 5.54 \text{ lb of water}$$

The impact of the solids part of the chemical admixture on the weight and yield are often negligible and can be ignored in mixture proportioning as long as the admixture water is considered in weight and mixture yield. The amount of mixing water should be reduced by 5.54 lb contributed by the admixtures; and

6. The 28-day compressive strength of the basic mixture was 11,750 psi, which satisfied the required strength of 10,600 psi.

6.3.2.10.2 *Companion mixture No. 4*

1. The actual amount of mixing water required to produce a 1 to 2 in. slump was less than that calculated for this trial mixture (3.0 ft^3). The actual batch masses were:

Mixture No. 4	Mass, lb
Cement	71.07
Fly ash, Class C	38.27
Fine aggregate	107.43
Coarse aggregate	207.00
Batch water	26.50

Correcting these by dry masses gives:

Mixture No. 4	Mass, lb
Cement	71.07
Fly ash, Class C	38.27
Fine aggregate, dry	100.97
Coarse aggregate, dry	205.97
Batch water	31.78

The actual yield of the trial mixture was:

Material	Volume calculation	Volume, ft^3
Cement	(70.56)/(3.15 × 62.4) =	0.36
Fly ash, Class C	(38.00)/(2.64 × 62.4) =	0.23
Fine aggregate	(99.10)/(2.59 × 62.4) =	0.62
Coarse aggregate	(205.97)/(2.76 × 62.4) =	1.20
Water	(32.67)/(62.4) =	0.51
Air	(0.02)/(3.0) =	0.06
	Total volume	2.98

Adjusting the mixture proportions to yield 27.0 ft^3 gives:

Mixture No. 4	Mass, lb
Cement	635
Fly ash, Class C	342
Fine aggregate, dry	898
Coarse aggregate, dry	1866
Water (including 2.5 oz/cwt retarding admixture)	296

The new mixture proportions result in a *w/cm* of 0.29. The desired ratio was 0.30; so the mass of cementitious material may be reduced. The percentage of fly ash for this mixture is 35%, and should be maintained. The new mass of cementitious material is (296)/(0.30) = 959 lb. Of this, 35% should be fly ash, giving 335 lb of fly ash and 623 lb of cement. The change in volume due to the reduction in cementitious material is

$$(643 - 623)/(3.15 \times 62.4) + (342 - 335)/(2.64 \times 62.4) = 0.167 \text{ ft}^3$$

Therefore, 0.167 ft^3 of fine aggregate should be added, which increases the mass of fine aggregate by (0.167)(2.59)(62.4) = 19 lb/yd^3 of concrete. The adjusted mixture proportions are:

Cement	623 lb
Fly ash	335 lb
Fine aggregate, dry	859 lb
Coarse aggregate, dry	1854 lb
Water (including 2.5 oz/cwt retarding admixture)	288 lb

2. In adding HRWRA to the adjusted mixture to produce a flowing concrete, it was found that 9 oz/cwt of cementitious material produced a slump of 9-1/2 in. under laboratory conditions. A retarding admixture (2.5 oz/cwt) was added to the concrete with mixing water, and the HRWRA was added approximately 15 minutes after initial mixing;

3. The HRWRA mixture had adequate workability; thus, no adjustment to the coarse aggregate content was necessary;

4. The air content of the HRWRA mixture was measured at 2.1%; thus, no correction was necessary; and

5. The average 28-day compressive strength of specimens cast from the laboratory trial mixture was 11,370 psi.

6.3.2.10.3 *Summary of trial mixture performance*—Table 6.7 is a summary of the results of the adjusted laboratory trial mixtures.

6.3.2.11 *Step 11: Select optimum mixture proportions*—All mixtures produced a 28-day laboratory compressive strength in excess of the required laboratory compressive strength of 10,600 psi. Therefore, any of the companion mixtures No. 1 through 4 can be selected for use on this project.

Because experience shows that the average strength of field production concrete will be different than the strength of a laboratory trial batch, the contractor properly elected to make field trial batches for the basic and the companion mixtures to verify the anticipated compressive strength in the field. The mixtures were adjusted to the desired slumps, both before and after addition of the HRWRA, and compressive strength specimens were made. Concrete temperatures were also recorded. The test results are shown as follows.

Table 6.7—Adjusted companion mixtures

Materials	Basic mixture—no ash	Companion mixture			
		No. 1	No. 2	No. 3	No. 4
		20% ash	25% ash	30% ash	35% ash
Cement, lb	1007	788	738	684	617
Fly ash, Class C, lb	—	197	243	287	332
Fine aggregate, dry, lb	934	875	867	859	896
Coarse aggregate, dry, lb	1845	1845	1845	1845	1858
Water, lb*	302	296	294	294	285
Slump, in., before HRWRA	1.00	1.25	1.00	1.50	1.00
Retarder, oz/cwt	3.0	2.5	2.5	2.0	2.0
HRWRA, oz/cwt	11.0	11.0	10.0	9.5	9.0
Water from HRWRA, lb	5.60	5.60	4.80	4.60	4.30
Slump, in., after HRWRA	10.00	10.50	9.00	10.25	9.50
Laboratory strength, 28-day, psi	11,750	11,500	11,900	11,600	11,370

*Does not include water in HRWRA.

Mixture	28-day compressive strength, psi	Concrete temperature, °F
Basic	11,160	94
Companion mixture No. 1	10,920	93
Companion mixture No. 2	10,820	89
Companion mixture No. 3	10,790	84
Companion mixture No. 4	10,290	82

With the exception of Companion Mixture No. 4, all mixtures produced field compressive strengths exceeding the laboratory compressive strength of 10,600 psi (73 MPa) at 28 days. The reduced concrete temperature and cementitious material content of Companion Mixture No. 3 made it more desirable to the ready mixed concrete producer. As ambient conditions or material properties vary, additional field adjustments may be necessary.

CHAPTER 7—HIGH-STRENGTH CONCRETE MIXTURE PROPORTIONING USING SILICA FUME

7.1—Fundamental relationships

Silica fume has a pronounced effect on concrete properties. This is especially so for high-strength concrete because of its physical and chemical properties. Silica fume increases the strength of concrete largely because it increases the strength of the bond between the cement paste and the aggregate particles (Mindess 1988). Silica fume combines with calcium hydroxide Ca(OH), a weak by-product of the cement hydration process, which results in additional cementing products, thus increasing concrete strength and significantly reducing its permeability. Refer to ACI 234R for current and more comprehensive information on mechanism by which silica fume modifies cement paste, mortar, and concrete.

7.1.1 *Cement and silica fume*—Various types of portland cement have been used in conjunction with silica fume to meet specific project requirements, including high strength. Mixture proportions with portland cement that meets ASTM C150, for Type I or II and silica fume that meets the requirements of ASTM C1240 are most commonly used. Concrete mixtures for high-strength concrete typically contain 600 to

850 lb/yd^3 of cementitious materials plus 5 to 15% silica fume by mass of cement with a *w/cm* as low as 0.20.

7.1.1.1 *Chemical admixtures*—Silica fume increases water demand and, without HRWRA, silica fume concrete mixtures can be difficult to mix, place, pump, and finish. ACI 211.1 and 363R recommend the use of chemical admixtures when using silica-fume concrete. Water-reducing and set-controlling admixtures should meet the requirements of ASTM C494/C494M.

When using silica fume in concrete mixtures, it is expected that more admixture is required for a desired slump than would otherwise be required in a conventional concrete mixture. The addition of the WRA or HRWRA should be made at the ready mixed concrete plant to batch the concrete at approximately 1 to 2 in. slump higher than required on the job site. This will allow the silica fume concrete to be thoroughly mixed on the way to the job site. Slump adjustment on site should be made using only HRWRA, provided that all mixing water allowed in the concrete mixture has been added during concrete batching.

The dosage of air-entraining admixture needed to produce a required volume of air in concrete usually increases with increasing amounts of silica fume due to the very high surface area of silica fume (Carette and Malhotra 1983b). The amount of air-entraining agent needs to be verified through trial batches.

Silica fume used in high-strength concrete mixtures may contain corrosion-inhibiting admixtures for protection of reinforcing steel. An example of such application is concrete columns in parking garages. Some corrosion-inhibiting admixtures are added to silica fume concrete in dosages up to 6 gal./yd^3. It is important that the amount of water contributed by these admixtures to the silica-fume concrete should be accounted for during the proportioning process, and should be subtracted from batch water.

7.1.1.2 *Water demand*—The water demand of concrete containing silica fume increases with increasing amounts of silica fume (Scali and Burke 1987; Carette and Malhotra 1983a,b). This increase is due primarily to the high surface area of the silica fume. Therefore, the amounts of mixing water recommended of Table 6.6.3 in ACI 211.1 are not applicable for silica fume concrete mixtures. The increase in water demand may be equal to the mass of the silica fume added (Transportation Research Board 1990). HRWRAs are commonly used to help achieve the desired *w/cm* and workability of silica fume concrete. The dosage of the HRWRA will depend on the amount of silica fume and the type of water-reducing admixture used (Jahren 1983).

7.1.1.3 *Aggregate*—The recommendations for coarse aggregate bulk volume per unit volume used in high-strength concrete containing silica fume should be according to Table 6.3.

7.1.1.4 *Workability and slump*—Freshly mixed concrete containing silica fume is more cohesive and less prone to segregation than concrete without silica fume. As silica fume content increases, concrete may appear to become sticky. To maintain the same apparent workability, industry experience has shown that it is necessary to increase the initial slump of the concrete with silica fume 1 to 2 in. (Jahren 1983) above that required for conventional portland cement concrete. Silica fume use in concrete can improve both workability and finishability. The added cohesiveness of silica fume concrete can improve the placement-by-pumping properties of concrete, while the absence of surface bleed water allows for faster finishing and curing.

The presence of silica fume by itself will not significantly change the rate of slump loss of a given concrete mixture. Because silica fume is used in conjunction with WRAs, HRWRAs, or both, there may be a change in slump-loss characteristics that is actually caused by the chemical admixture selected. Different chemical admixtures produce differing rates of slump loss. Trial batches using proposed project materials are recommended to establish slump-loss characteristics for a particular situation.

7.1.2 *Special considerations*—On average, a particle of silica fume is approximately 100 times smaller than portland cement (Silica Fume Association 2005). As with aggregates, decreasing particle size increases surface area and the water demand. Without an HRWRA, silica fume would require extra conveyance water to obtain a reasonable slump. The extra water would increase the total amount of water and the *w/cm*, reducing the concrete strength.

7.2—Concrete mixture proportioning

7.2.1 *Purpose*—The purpose of this method is to determine the appropriate and most economical materials that can be used in a trial batch that will approximate the desired concrete properties. This proportioning method provides a starting point for a concrete mixture that will be modified and adjusted as needed to meet the desired concrete properties.

7.2.2 *Introduction*—The procedure described in ACI 211.1 for proportioning normal-strength concrete may not be entirely applicable for high-strength concretes containing silica fume, low *w/cm* with the incorporation of normal- and high-range water-reducers, or both. These high-strength concretes most often contain one or more supplementary cementitious materials that possibly replace a significant amount of cement. Silica fume alters the properties and behavior of fresh and hardened concrete. As an example, a large majority of silica fume concrete mixture proportions have slump values generated mainly by the addition of WRAs. The use of silica fume will usually increase the water demand of the concrete proportionally to the amount of silica fume added. Therefore, the recommendations for approximating mixing water listed in ACI 211.1 are not applicable in silica fume concrete. The entire mass of the silica fume should be added to the mass of all other cementitious materials present to determine the *w/cm*.

Another common approach is to start with mixture proportions that have been used successfully on other projects with similar requirements. Given this starting point, trial mixtures can be made in the laboratory and under field conditions to verify performance with actual project materials. Some examples of silica fume concrete mixture proportions, excerpted from the *Silica Fume User's Manual* (Silica Fume Association 2005), are shown in Table 7.1.

Table 7.1—Recommended starting mixture proportions for high-strength concrete with silica fume (Silica Fume Association 2005)

	Key Tower, Cleveland	Scotia Plaza, Toronto	Bridge deck, Ohio DOT	Wet shotcrete repair	Bridge girders, Colorado DOT	Test mixture	Test mixture
Silica Fume Manual references	1	2	4	5	7	9	10
Compressive strength*	12,000 psi at 28 days	10,000 psi at 28 days	7000 psi at 28 days	6000 psi at 28 days	6500 psi at release 10,000 psi ultimate	12,840 psi at 28 days 16,760 psi at 3 years	15,520 psi at 28 days 18,230 psi at 3 years
Other requirements	Pumpable to 57 stories	N/A	N/A	100 lb/yd^3 steel fiber to increase toughness	N/A	N/A	N/A
Entrained air†	N/A	N/A	5 ± 1.5	8 to 10% as delivered; 4 to 6% in place	Unknown	N/A	N/A
Slump, in.	>10 in.	4 in.	4 to 8 in.	2 to 4 in.	Unknown	10 in.	9.5 in.
Maximum aggregate size, in.	0.5	1.5	3/4	3/8	Unknown	0.5	0.5
Cement, lb/yd^3	684	532	700	682	730	800	800
Fly ash, lb/yd^3	0	0	0	0	0	100, Class C	175, Class C
Slag cement, lb/yd^3	285	197	0	0	0	0	0
Silica fume, lb/yd^3	79	62	70	70	35	40	125
Maximum *w/cm*	0.24	0.31	0.36	0.45	0.28	0.29	0.23
Water, lb/yd^3‡	251	244	277	338	214	270	255

*Strength shown is f_c' except for Mixtures 9 and 10, which are the actual measured strengths. Add appropriate overdesign for mixture development.
†Allowed reduction in air content for strength above 6000 psi has taken place.
‡Include water in HRWRA for mixtures with very low *w/cm*.

7.2.3 *Mixture proportioning procedure*

7.2.3.1 *Proportioning*—Although there is no empirical method available for proportioning, the following step-by-step procedure has evolved over many years and has proven effective. This procedure is taken from *Silica Fume User's Manual* (Silica Fume Association 2005). The following steps are recommended procedures for mixture proportioning.

7.2.3.1.1 *Step 1: Determine project requirements*—Read the project specifications carefully. Look for requirements not only for concrete performance but also for concrete proportioning. Items to note include:

- Compressive strength;
- Chloride exposure;
- Freezing and thawing exposure;
- Chemical exposure;
- Abrasion resistance;
- Temperature restrictions;
- Water-cementitious material ratio (*w/cm*);
- Maximum water content;
- Cementitious materials content; and
- Percentages of fly ash, slag cement, and silica fume.

7.2.3.1.2 *Step 2: Coordinate with the contractor who will be placing the concrete*—Get input from the contractor early in the mixture proportioning process. Items to consider include:

- Special constructibility requirements;
- Placing and finishing methods;
- Maximum allowable aggregate size;
- Slump restrictions: increase the slump for silica fume concrete (Section 7.1.1.4); and
- Responsibility for adding chemical admixtures on the site, if necessary.

7.2.3.1.3 *Step 3: Select starting mixture*—Table 7.1 contains a number of silica fume concrete mixtures that have been developed for a variety of applications. This table can be used to find a concrete mixture that meets requirements similar to those on your project. The mixture values in the table include all water in chemical admixtures. Failure to account for all the water contributed by these chemicals will result in the concrete with different *w/cm* and may impact compressive strength along with other properties.

7.2.3.1.4 *Step 4: Determine the volume of entrained air required*—It is essential that silica fume concrete that will be exposed to freezing and thawing while saturated be air entrained. Use industry standard tables such as those found in ACI 301, 201.2R, and 318 to determine the volume of air required.

7.2.3.1.5 *Step 5: Incorporate local aggregates into the original trial mixture*—There are two items to consider herein:

- Calculate a total aggregate volume that will yield the correct amount of concrete for your project. Concrete is sometimes proportioned not to yield the same volume; some producers proportion slightly higher than 27.0 ft^3 per cubic yard to provide a safety factor against air loss and its impact on yield; and
- Use a fine-to-coarse aggregate ratio that works well for local materials. Because this ratio has an influence on workability, it may be adjusted once trial mixtures are made in the laboratory.

7.2.3.1.6 *Step 6: Prepare laboratory trial mixtures*

- The amount of silica fume is relatively small when compared with the rest of the concrete ingredients. For the silica fume to perform, it should disperse throughout the concrete. Sometimes it is difficult to get adequate dispersion when using small, often less efficient, laboratory concrete mixers. This is particularly true for the densified form of silica fume (Lagerblad and Utkin 1993). The densified silica fume particles should be broken down and uniformly distributed throughout the concrete. The mixing times for silica fume concrete are often double those given in ASTM C192/C192M;

- Batch the concrete at the maximum allowed water content provided by the mixture proportion and the maximum allowable *w*/*cm* requirements. In some cases, the maximum allowable water may not produce any measurable slump. Use chemical admixtures to achieve the necessary slump; and
- Review the properties of the fresh concrete and adjust mixture proportions as necessary to produce the desired workability, air content, and other properties. Reducing the fine aggregate content and increasing the coarse aggregate content may help reduce the stickiness of the concrete mixture. Once the fresh properties are achieved, make specimens for hardened concrete testing to verify project requirements. Further proportioning adjustment may be necessary.

7.2.3.1.7 *Step 7: Conduct full-scale testing*—There are always differences between proportions developed in the laboratory and those that result from concrete production, particularly in chemical admixture dosages. Making truck-sized batches of the concrete is the best way to confirm the required fresh and hardened properties. Full-scale testing is also an excellent way to confirm other properties that may be of particular interest to the project, such as finishability, shrinkage, temperature rise, and quality of the finished surface. It is also an opportunity for the entire production team to work together to identify any last-minute problems before going into full production. The following should be kept in mind:

- Do not attempt to economize by making very small batches. Make enough concrete to be representative of what will be made during the project. It takes a large amount of paste to coat the inside of a concrete mixer drum or central mixer. If too small a batch of concrete is made, a significant amount of paste can be lost to the drum. When conducting full-scale testing, batch at least 3.0 yd^3 of concrete;
- Test to determine whether the concrete meets the freshly mixed and hardened concrete requirements for the project. Adjustment of the concrete mixture proportioning is expected when conducting full-scale batching of the laboratory mixture. Because a mixture has been fine-tuned in the laboratory, however, major adjustments should not be expected; and
- Make more than one batch in the field. It is always prudent to know that the performance of a particular concrete mixture can be repeated.

7.3—Sample calculations

7.3.1 *Introduction*—High-strength concrete mixture proportioning is a more complex process than proportioning normal-strength concrete mixtures. In addition to silica fume, other supplementary cementitious materials may also be incorporated into the mixture as well as WRAs or HRWRAs necessary to achieve the low *w*/*cm* needed to produce high-strength concrete.

7.3.2 *Examples*—Step-by-step procedure for proportioning a high-strength concrete mixture for columns:

7.3.2.1 *Step 1: Determine project requirements*—A review of the project specification determines the following requirements:

- Design compressive strength of 14,000 psi at 28 days; and
- No exposure to freezing and thawing.

7.3.2.2 *Step 2: Coordinate with contractor*—Discussions with the contractor may yield additional requirements, such as:

- Maximum size of coarse aggregate is 1/2 in.;
- Desired slump is 8 to 10 in.; and
- Concrete will primarily be placed by pump.

7.3.2.3 *Step 3: Select a starting mixture*—From Table 7.1, the high-strength mixture in Column 5 is selected as a good starting mixture.

This mixture has the following characteristics:

Cement	800 lb/yd^3
Fly ash	175 lb/yd^3
Silica fume	125 lb/yd^3
Maximum *w*/*cm*	0.23

7.3.2.4 *Step 4: Determine volume of air required*—None. Assume that 1.5% will be entrapped in this mixture.

7.3.2.5 *Step 5: Incorporate local aggregates*—First, determine the volume the paste will occupy as shown in the following table:

Material	Mass, lb	Relative density	Volume, ft^3
Cement	800	3.15	4.07
Fly ash	175	2.5	1.12
Silica fume	125	2.2	0.91
Water	255	1	4.08
Air, 1.5%	—	—	0.41
		Total volume	10.58

Second, calculate aggregate volumes and masses:

Coarse aggregate bulk specific gravity	2.58
Fine aggregate bulk specific gravity	2.60
Fine aggregate	38% of total aggregate volume
Aggregate volume	= 27.00 – 10.58 = 16.42 ft^3
Fine aggregate volume	= 0.38 × 16.42 = 6.24 ft^3
Fine aggregate mass	= 6.24 × 62.4 × 2.60 = 1012 lb/yd^3
Coarse aggregate volume	= 16.42 – 6.24 = 10.18 ft^3
Coarse aggregate mass	= 10.18 × 62.4 × 2.58 = 1639 lb/yd^3

7.3.2.6 *Step 6: Prepare laboratory trial mixtures*—When preparing laboratory trial mixtures, several items should be remembered:

- Thorough and uniform silica fume dispersion is necessary;
- Account for all moisture on the aggregates and in admixtures used;
- At a minimum, double the mixing times defined in ASTM C192/C192M;
- Conduct necessary testing on freshly mixed and hardened concrete; and
- Adjust the mixture as necessary to obtain the required freshly mixed concrete properties.

7.3.2.7 *Step 7: Conduct full-scale testing*—Once the properties of the concrete mixture produced in the laboratory trials are satisfactory, conduct full-scale production testing. Consider these points:

- Use large enough batches to be representative of a full load;
- Test production batches more than once to ensure repeatability and uniformity; and
- Understand that these trial batches may coincide with the contractor's need for placing, finishing, and curing trials as required.

CHAPTER 8—HIGH-STRENGTH CONCRETE MIXTURE PROPORTIONING USING SLAG CEMENT

8.1—Fundamental relationships

The selection of mixture proportions can be influenced by the testing age. High-strength concrete can gain considerable strength after 28 days, particularly when slag cement is used (Fig. 8.1). To take advantage of this characteristic, many specifications for compressive strength are revised from criteria at 28 days to 56 days, 91 days, or later ages.

8.1.1 *Selection of materials*—Carefully selecting, controlling, and proportioning of all the ingredients enhances reliable production of a high-strength concrete mixture. Guidance concerning effectively addressing these factors is given in the following.

It is advisable to focus first upon finding a combination of materials (local or otherwise) that provide the required level of performance. Then optimization of the mixture proportioning may include a broader evaluation of the potentially more cost-effective options. In most cases, if local experience indicates that practice other than that cited as follows is appropriate, it is generally preferred to initially defer to the local experience.

8.1.1.1 *Portland cement*—In general, portland cement, regardless of type, is compatible with slag cement. Type I or II portland cement is generally evaluated first, largely because most concrete producers usually have a dedicated silo for one or the other. Type III portland cement has also been used with slag cement, particularly to increase early-age strength performance.

Certain chemical and physical properties for portland cement can be of benefit when slag cement is used. For example, relative to concrete mixtures without slag cement, a higher total alkali content from the portland cement may be acceptable when the slag cement is used.

8.1.1.2 *Chemical admixtures*—As portland cement is replaced with traditional levels of 40 to 50% of slag cement, the water demand typically stays about the same or is moderately reduced. The use of WRA, HRWRA, or both produces about the same or higher slump when the mixture contains slag cement as a partial cement replacement. Accelerators generally work as well with slag cement concrete as with concrete without slag cement.

A slightly higher air-entraining admixture dosage is needed to achieve specific air content. In the first trial batch of slag cement concrete, the required air-entraining admixture

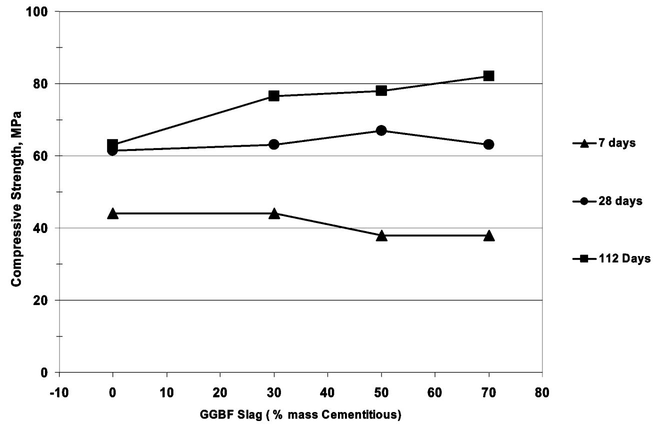

Fig. 8.1—Influence of testing age: slab cement Blaine fineness (2010 ft²/lb) (Brooks et al. 1992). (Note: 1 MPa = 145 psi.)

dosage may be the same or slightly higher (often by about 20%) than concrete without slag cement.

8.1.1.3 *Coarse aggregates*—It is generally possible to produce high-strength concrete containing slag cement with nominal maximum-size coarse aggregate as large as 1 in., and the use of even larger aggregate sizes may be possible.

The selection of coarse aggregate size may be influenced by requirements other than high strength, such as size of the concrete element, spacing of reinforcement, method of placement, elastic modulus, creep, drying shrinkage, or limiting the heat of hydration.

8.1.1.4 *Slag cement*—Slag cement used to produce high-strength concrete should meet the requirements of ASTM C989 or AASHTO M-302. Slag cement that meets other slag cement-related specifications (from countries other than the United States) and is essentially equivalent to ASTM C989-compliant slag cement may also be used.

The amount of slag cement is traditionally expressed as a percentage by mass of the total cementitious materials content of a concrete mixture. For example, for a concrete mixture with 674 lb/yd^3 of cementitious material and a slag cement content of 40%, the amount of slag cement will be 270 lb/yd^3.

Generally, all other factors being equal, the more finely ground the slag cement incorporated in the mixture, the higher the early age and ultimate strength of the concrete. This trend is shown in Table 8.1.

8.1.1.4.1 *Slag activity index of slag cement*—Increasing fineness of slag cement is commonly associated with increasing strength. Specification ASTM C989 lists the three slag cement grades as 80, 100, and 120. (Refer to Table 8.1 for examples of fineness versus performance). In ASTM C989, the slag activity index (SAI), also known as slag component index (SCI), is determined by dividing compressive strength of the 50% slag mixture by the compressive strength of the reference portland-cement-only mixture. The higher the grade number, the higher the SAI (Table 8.1).

ASTM C989 classifies slag by performance according to its slag activity test in three grades: 80, 100, and 120. According to ASTM C989 and Table 8.1, a Grade 120 slag cement is required to achieve an average 28-day compressive

Table 8.1—Slag activity index requirements for various grades of slag cement per ASTM C989

Grade	Slag activity index (SAI), minimum percent: Average of last five consecutive samples	Slag activity index (SAI), minimum percent: Any individual sample
	7-day index, %	
80	—	—
100	75	70
120	95	90
	28-day index, %	
80	75	70
100	95	90
120	115	110

strength (average of five samples) of a minimum of 115% of the compressive strength of the reference portland cement mixture. In the United States, Grade 120 slag cement typically averages well above the specified minimum level. SAI values for Grade 120 slag cement of 130% are common, and for Grade 100 slag cement, achieving SAI levels above 110% is common as well.

8.1.1.4.2 *Density and handling of slag cement*—The density of a Grade 100 or 120 slag cement typically is between 0.102 and 0.107 lb/in.^{3}. Slag cement is handled, stored, and batched in the same manner as portland cement. When slag cement is used in amounts up to 30%, it is known to improve the transition zone of the paste-aggregate interface by reducing zone thickness and diminishing or eliminating preferred orientation of calcium hydroxide crystals. This improvement in paste-aggregate interface assists in achieving higher strength, particularly tensile strength, compared with concrete not containing slag cement. One important implication of the improved transition zone is that slag cement concrete may employ somewhat larger-size coarse aggregate compared with concrete not containing slag cement for a given strength. Because of the lower density, replacement on a mass basis results in slightly higher paste volume.

8.1.2 *Special considerations*—The use of slag cement in concrete usually improves workability and finishability. The presence of slag cement concrete does not adversely affect the pumpability of the concrete. Slump of slag cement concrete is as stable as the slump of portland cement concrete without slag cement. Slump loss of slag cement concrete may be more influenced by factors other than the slag cement. Among these other factors are the inherent slump loss tendencies of the portland cement, the impact of using combinations of chemical admixtures, and the stability of the air content in the unhardened concrete.

8.2—Concrete mixture proportioning

8.2.1 *Purpose*—The purpose of this section is to provide the user a guide of methods and examples to proportioning concrete mixtures using slag cement.

8.2.2 *Introduction*—The user is encouraged to use local materials and the performance history of concrete mixtures in developing concrete mixtures using slag cement.

8.2.2.1 *Selecting initial slag cement grade and proportions*—ASTM C989 Grades 100 and 120 slag cement

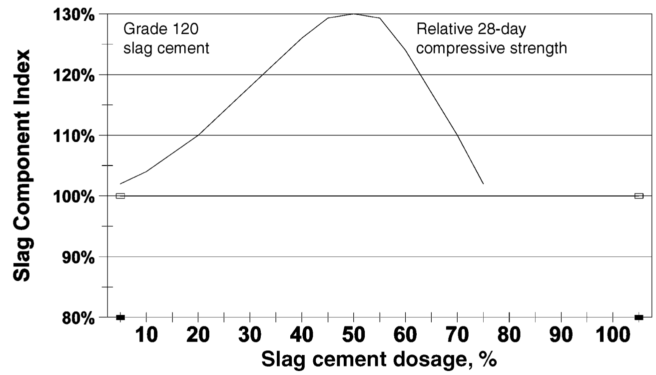

Fig. 8.2—Idealized 28-day compressive strength curve for concrete mixtures made with portland cement and the indicated percent of ASTM C989, Grade 120 slag cement.

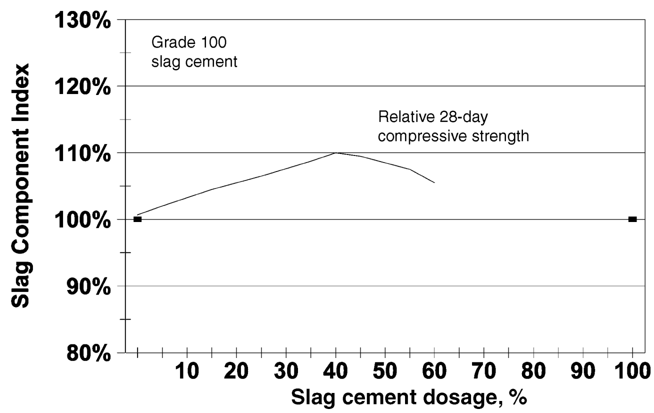

Fig. 8.3—Idealized 28-day compressive strength curve for concrete mixtures made with portland cement and the indicated percent of ASTM C989, Grade 100 slag cement.

have been used successfully in high-strength concrete. Only limited information is available about the use of Grade 80 slag cement in high-strength concrete. Grade 120 and Grade 100 slag cement materials, which are the widely used slag cement grades in the United States, are recommended for developing high-strength concrete mixtures.

For combinations of slag cement with portland cement, a 40 to 50% by mass replacement of portland cement with slag cement is usually associated with the highest 28-day strength. The concept behind first selecting the slag cement content from within the 40 to 50% range is shown in Fig. 8.2 and 8.3. The 40 to 50% range should be investigated first, unless local information indicates that some other slag cement content is more likely to maximize compressive strength. For specifications with 56-day, 91-day, or later specified compressive strengths, a slag cement amount somewhat higher than 40 to 50% may be optimum.

Some high-strength concrete will have performance requirements other than just compressive strength that will influence the optimum slag cement amount. For example, high-strength concrete used in mass concrete may need a slag cement amount higher than the 40 to 50% range (commonly into the 60 to 80% range) to reduce the rise in concrete temperature resulting from heat of hydration. Early-age strength may be reduced with increasing slag cement content.

Table 8.2—Slag cement content for specific applications (Grades 100 and 120 slag cement)

Application	Slag cement*
Maximum high-strength	
More common	40 to 50%
Less common	35 to 55%

*Slag cement content is expressed as percent replacement of portland cement by mass.
Note: When information demonstrates that a specific slag cement material provides equivalent-or-better sulfate resistance with lower slag cement content, the lower content may be used.

8.2.2.2 *Development of relative compressive strength: slag cement content curve*—A tool useful for proportioning high-strength concrete containing slag cement is a compressive strength versus slag cement content curve. A diagram can present the effect of slag cement content on the relative 28-day compressive strength of the slag cement-portland cement concrete as compared with the portland-cement-only concrete. Where all other factors, such as *w/cm*, air content, material sources, and sizes, are kept equal, the compressive strength versus slag cement quantity curve is a useful tool in proportioning concrete mixtures. Similar to a three-point *w/c* curve, which has a long history of use in proportioning concrete where no previous experience record exists, the x-axis includes several slag cement percentages, but the compressive strength is calculated relative to a 0% slag cement, which is 100% portland cement.

Figure 8.2 represents an idealized curve for a Grade 120 slag cement with an average 28-day relative compressive strength index of 130%. Figure 8.3 is an idealized curve for a Grade 100 slag cement with an average 28-day relative compressive strength index of 110%. The total cementitious materials content, by mass, should remain constant to reduce variation in the curve shape.

Figures 8.2 and 8.3 are developed using local concrete materials with different grades of slag cement. The slag component index is the percent of compressive strength increase resulting from the slag cement dosage relative to the 28-day compressive strength of the same mixture without slag cement. The curves in Fig. 8.2 and 8.3 demonstrate the variance in compressive strength versus slag cement dosage.

Ages later than 28 days, such as 56 or 91 days, can be considered for relative compressive strength versus slag cement content curves. The strength of the slag cement concretes relative to the reference portland cement concrete will continue to increase after the 28-day age.

The most useful relative compressive strength slag cement content curves are those derived from information using the same materials (especially the portland cement) and methods that will be employed on the project. The purpose of constructing a curve is to create a reliable reference of existing information, and to use the curve as a starting point for selecting the proportions for the mixture for a trial batch. The desired characteristics, such as a compressive strength overdesign, can be targeted as a function of the total cementitious material, water, and admixture combinations in the subsequent trial batches.

8.2.3 *Mixture proportioning methods*—Two mixture-proportioning methods (Methods A and B) for concrete made with slag cement-portland cement are recommended.

Both Methods A and B rely on ACI 211.1 procedures for most of the proportioning steps, particularly as they apply to developing the basic mixture using portland cement as the only cementitious material.

All of the examples use local aggregates in their saturated surface-dry (SSD) state. The SSD relative density of the coarse aggregate is 2.72; for the fine aggregate, it is 2.63.

8.2.3.1 *Method A*—This method begins with historical slag cement concrete information to determine the expected increase in strength (in percent) attributed to the slag cement when compared with a reference portland cement mixture without slag cement. The expected strength increase attributed to the slag cement is subtracted from the required average compressive strength f'_{cr}. ACI 211.1 is then followed to proportion a portland cement mixture (the basic mixture) for this lower strength level. Subsequently, the appropriate amount of portland cement is replaced with slag cement on a mass basis, and the aggregate content is adjusted to maintain yield.

The steps associated with Method A are as follows:

8.2.3.1.1 *Step 1*—The specified compressive strength f'_c from the project specification for the class of concrete that is being proportioned should be identified, as well as mixture performance requirements such as slump, maximum *w/cm*, air content (if applicable), or other requirements as in Section 3.3. Also, it should be determined whether the project specification requires that a specific slag cement grade should be used, or whether a specific range in percentage of slag cement is prescribed.

8.2.3.1.2 *Step 2*—The required average compressive strength f'_{cr} should be calculated according to Section 3.2.

8.2.3.1.3 *Step 3*—A relative compressive strength-slag cement content diagram relating the compressive strength to the percent of slag cement at the specified maturity or age of test should be located or developed. Refer to Fig. 8.2 or 8.3. Unless the slag cement content is specified (from Step 1), the slag cement content at the maximum-strength index point on the curve that lies within the acceptable slag cement content range as specified should be selected. In the event that the project specification does not prescribe a slag cement content range, Table 8.2 lists common slag cement contents for Grades 100 and 120 slag cements for selected specific applications.

8.2.3.1.4 *Step 4*—From the x-axis on the relative compressive strength (RCS) slag cement content diagram, the y-intercept that determines the maximum percent increase in compressive strength attributed to the optimum slag cements content should be located.

8.2.3.1.5 *Step 5*—*PC* is defined as the portion of the required average compressive strength which is attributed to portland cement and it should be calculated using the following equation

$$PC_{,\text{psi}} = (f'_{cr})(100\%/\text{RCS}\%) \quad (8\text{-}1)$$

8.2.3.1.6 *Step 6*—A basic mixture that contains only portland cement for the cementitious material according to ACI 211.1 or Section 6.2.3 without incorporating slag cement should be proportioned. The portland cement portion of the required compressive strength, as calculated in Step 5, should be used as the required average compressive strength f'_{cr} for this basic mixture. Also, the applicable mixture requirements identified in Step 1 such as slump, temperature, and air content should be taken into consideration.

8.2.3.1.7 *Step 7*—With the basic mixture developed in Step 6, the portland cement by mass should be replaced with the amount of slag cement selected in Step 3. For example: if a 45% slag cement content was selected in Step 3, then the mass of portland cement should be multiplied by 0.45 to quantify the mass of the slag cement. The mass of slag cement should be subtracted from the original mass of portland cement to obtain the portland cement portion of the mixture proportions. The yield will increase slightly because the slag cement has a lower density than portland cement. (Refer to Section 8.1.1.4.2.)

8.2.3.1.8 *Step 8*—The yield should be adjusted to the desired amount by reducing the fine aggregate content or by adjusting the combinations of coarse and fine aggregates. The now-completed slag cement trial batch mixture can be used as one of several mixtures needed to describe the *w/cm* characteristics.

8.2.3.1.9 *Step 9*—Two or more slag cement mixtures, each with incrementally lower *w/cm*, should be developed. *w/cm* increments of 0.02 or 0.03 are common. Admixtures should be used as required to achieve the same slump and yield. Other factors, such as air content and concrete temperature, should also be held constant.

8.2.3.1.10 *Step 10*—Make the trial batch for concrete mixture(s) with slag cement and for the basic mixture without slag cement to confirm the expected performance and assumptions.

8.2.3.1.11 *Step 11*—If necessary, the trial batch mixture(s) should be adjusted using the absolute volume method of ACI 211.1.

8.2.3.2 *Method B*—Starting with an existing portland cement concrete mixture of known properties, a modified mixture with slag cement can be developed as follows.

8.2.3.2.1 *Steps 1 through 5*—Follow the same steps as in Method A.

8.2.3.2.2 *Step 6*—An existing portland cement concrete mixture, referred to as the existing basic mixture, should be selected that achieves the portion of the required average compressive strength f'_{cr}, which is expected from portland cement $PC_{,psi}$.

8.2.3.2.3 *Step 7*—Using the existing basic mixture, the mass of portland cement should be reduced by the mass of slag cement selected in Step 3. The yield will increase slightly because the slag cement has a lower density than portland cement. (Refer to Section 8.1.1.4.2.)

8.2.3.2.4 *Steps 8 through 11*—Follow the same steps as in Method A.

8.3—Sample calculations

8.3.1 *Introduction*—The sample calculations presented herein are taken from an actual project. The examples follow a step-by-step proportioning procedure of a typical concrete mixture using slag cement.

8.3.2 *Examples*

8.3.2.1 *Example 1, Method A*—A project has a 28-day specified compressive strength of 7250 psi for a class of interior concrete. Type I portland cement is specified. The maximum allowable slump is 6 in., and the nominal maximum-aggregate size specified is 1 in. Trial batches were conducted with Grade 100 slag cement and several Type I portland cements. Recent experience, available from other projects for the same specific class of concrete, revealed that at a 50% slag cement content with portland cement, the 28-day compressive strengths of the slag cement mixtures average about 13% higher than the plain portland cement mixtures. Trial batch work is done in a laboratory.

8.3.2.1.1 *Step 1*—f'_c = 7250 psi; maximum slump = 6 in.; Grade 100 slag cement will be used.

8.3.2.1.2 *Step 2*—Because there is no prior history for this mixture, trial batches will be made in the laboratory and Eq. (3-3) applies. Therefore

$$f'_{cr} = 1.1f'_c + 700 \text{ psi} \quad (3\text{-}3)$$

$$f'_{cr} = 1.1(7250) + 700$$

$$f'_{cr} = 8680 \text{ psi}$$

8.3.2.1.3 *Step 3*—Because Grade 100 slag cement will be used, Fig. 8.3 is used as an example of a SCI-slag cement content curve. The point representing 50% slag cement and 113% relative 28-day compressive strength (from the recent experience of the concrete producer) is placed on a copy of Fig. 8.3, and a curve is drawn through this point (refer to Fig. 8.4). The maximum-strength point lies at the 45% slag cement content, and is selected as the slag cement content for the trial batch.

8.3.2.1.4 *Step 4*—From the SCI-slag cement content curve that was drawn in Step 3 (Fig. 8.4), the maximum relative compressive strength should be 114% of the strength of the plain portland cement mixture.

8.3.2.1.5 *Step 5*—Calculate the portion of the required average compressive strength f'_{cr}, which is relegated to portland cement $PC_{,psi}$ as follows

$$PC_{,psi} = (f'_{cr})(100/[\text{SCI }\%])$$

$$= (8680)(100/114)$$

$$= 8680(0.8772)$$

$$= 7610 \text{ psi}$$

8.3.2.1.6 *Step 6*—Using Section 6.2.3, the basic concrete mixture should be developed.

From Table 6.5, for the 28-day age, a nominal maximum aggregate size of 1 in. and interpolating for f'_{cr} = 7610 psi, a *w/cm* of 0.41 is needed.

From Table 6.4, the estimated mixing water to achieve an initial slump of 1 to 2 in., using a 1 in. nominal maximum coarse aggregate size, is 280 lb/yd^3.

The bulk density of the coarse aggregate is given as 100 lb/ft^3. From Table 6.3, and for a nominal maximum coarse aggregate size of 1 in., the fractional volume of dry-rodded coarse aggregate per unit volume of concrete is 0.75. The coarse aggregate amount is calculated to be 2025 lb/yd^3 as

$$0.75(100 \text{ lb/ft}^3)(27 \text{ ft}^3/\text{yd}^3) = 2025 \text{ lb/yd}^3$$

The portland cement content is computed by dividing the estimated water by the w/cm = 280 lb/yd^3/0.41 = 683 lb/yd^3.

To increase slump from 2 in. (before HRWRA) to 6 in. (after HRWRA), HRWRA will need to be added to the mixture. A WRA and HRWRA combination may be employed, and the combined volume of admixtures used should be considered.

The basic concrete mixture is as follows:

Materials	Mass, lb/yd^3	Relative density	Volume, ft^3
Portland cement	683	3.15	3.475
Coarse aggregate (saturated surface-dry) at 1% absorption	2045	2.72	12.049
Water	280	—	4.487
Anticipated entrapped air content	1.5%	—	0.405
HRWRA, oz	9.2	1.2	0.123
			Subtotal = 20.539

Therefore, 20.5 ft^3 is the total materials volume without fine aggregate.

Applying the absolute volume method, the volume of the fine aggregate is the total volume of 27.0 ft^3 less the combined volume of all other ingredients, 20.5 ft^3, equals 6.46 ft^3.

The computations for the fine aggregate mass for the trial batch basic mixture are as follows:

Fine aggregate volume required to yield

$$27.0 \text{ ft}^3 - 20.539 \text{ ft}^3 = 6.461 \text{ ft}^3$$

Mass of fine aggregate at saturated surface-dry

$$6.461 \times (2.63 \times 62.4) = 1060 \text{ lb}$$

Basic mixture Method A			
Materials	Mass, lb/yd^3	Relative density	Volume, ft^3
Portland cement	683	3.15	3.475
Coarse aggregate (saturated surface-dry)	2045	2.72	12.049
Fine aggregates	1060	2.63	6.461
Water	280	—	4.487
Anticipated entrapped air content	1.5%	—	0.405
Admixtures	9.2	1.2	0.123
			Subtotal = 27.00

8.3.2.1.7 *Step 7—*

Amount of slag cement = 683 lb/yd^3(0.45) = 307 lb/yd^3

Amount of portland cement =
683 lb/yd^3 – 307 lb/yd^3 = 376 lb/yd^3

Total cementitious material = 683 lb/yd^3

8.3.2.1.8 *Step 8*—Finally, the yield for first trial mixture containing slag cement is adjusted as follows:

Trial mixture Method A			
Materials	Mass, lb/yd^3	Relative density	Volume, ft^3
Portland cement	376	3.15	1.913
Slag cement	307	2.85	1.726
Coarse aggregates (saturated surface-dry)	2045	2.72	12.049
Fine aggregates	1033	2.63	6.297
Water	280	—	4.487
Anticipated entrapped air content	1.5%	—	0.405
Admixtures	9.2	1.2	0.123
			Subtotal = 27.00

The mass of the fine aggregate has been adjusted from 1060 to 1033 lb to adjust for the volume changes resulting from replacing a percentage of the portland cement with slag cement.

8.3.2.1.9 *Step 9*—The results of this trial mixture should be reviewed before considering if other mixtures (that is, with different w/cm) will be needed.

8.3.2.1.10 *Step 10*—Both the basic mixture and the slag cement trial mixture should be prepared and evaluated.

8.3.2.1.11 *Step 11*—No other adjustments were needed. The trial batch amounts of admixtures are reported along with all other results. Scaling up to full-size loads and seasonal variations may require further adjustments.

8.3.2.2 *Example 1, Method B*—For the same scenario as presented in Example 1, Method A, several portland-cement concrete mixtures without slag cement are on file that could potentially be used in developing a first trial batch for a slag cement concrete mixture.

Steps 1 through 5 are the same as for Example 1, Method A. Abbreviated, these steps are as follows:

8.3.2.2.1 *Step 1*—f'_c = 7250 psi; maximum slump = 6 in. Grade 100 slag cement will be used.

8.3.2.2.2 *Step 2—*

$$f'_{cr} = 1.1f'_c + 700 \text{ psi} \quad (3\text{-}3)$$

$$f'_{cr} = 1.1(7250) + 700$$

$$f'_{cr} = 8680 \text{ psi}$$

8.3.2.2.3 *Step 3*—From Fig 8.4, the maximum strength point lies at the 45% slag cement content.

8.3.2.2.4 *Step 4*—From Fig. 8.4, the maximum strength point is 114% of the strength of the mixture without slag cement.

8.3.2.2.5 *Step 5*—The portion of the required average compressive strength f'_{cr}, which is relegated to portland cement $PC_{,\text{psi}}$, is

$$PC_{,\text{psi}} = (f'_{cr})(100/[\text{SCI }\%])$$

$$= (8680)(100/114)$$

$= 8680(0.8772)$

$= 7610 \text{ psi}$

8.3.2.2.6 *Step 6*—The concrete producer already has a portland cement concrete mixture that achieves 8700 psi, as follows:

Materials	Mass, lb/yd^3	Relative density	Volume, ft^3
Portland cement	705	3.15	3.587
Coarse aggregate (saturated surface-dry)	1830	2.72	10.782
Fine aggregate (saturated surface-dry)	1355	2.63	8.258
Water	240	1.00	3.846
Admixture WRA	1.35	1.2	0.018
Admixture HWRA	7.8	1.2	0.104
Anticipated entrapped air content	1.5%	—	0.405
			Total = 27.00
Final *w/cm* = 0.34			

8.3.2.2.7 *Step 7*—

Amount of slag cement = 705(0.45) = 317 lb/yd^3

Amount of portland cement = 705 – 317 = 388 lb/yd^3

8.3.2.2.8 *Step 8*—Finally, the yield for first trial mixture containing slag cement is adjusted as follows:

Trial mixture Method B			
Materials	Mass, lb/yd^3	Relative density	Volume, ft^3
Portland cement	388	3.15	1.974
Slag cement, Grade 100	317	2.85	1.783
Coarse aggregate (saturated surface-dry)	1830	2.72	10.782
Water	240	1.00	3.846
Admixture WRA	1.35	1.2	0.018
Admixture HRWRA	7.80	1.2	0.104
Anticipated entrapped air content	1.5%	-	0.405
			Subtotal = 18.912
Fine aggregate required to adjust yield = 27.0 – 18.912 = 8.088 ft^3			
Mass of fine aggregate at saturated surface-dry = 8.088 × 2.63 × 62.4 = 1327 lb			
Final *w/cm* = 0.34			

8.3.2.2.9 *Step 9*—The results of the trial mixture should be reviewed. Additional batches with different *w/cm* may be needed. The construction schedule may warrant the preparation of several trial batches initially.

8.3.2.2.10 *Step 10*—Because the basic mixture information is already known, the basic mixture need not be batched.

8.3.2.3 *Example 2, Method B*—A project has a 56-day specified compressive strength of 8700 psi for one class of interior concrete. The maximum allowed slump is 8 in. Grade 120 slag cement will be used.

8.3.2.3.1 *Step 1*—f_c' = 8700 psi at 56 days; slump = up to 8 in.; no air entrainment is needed.

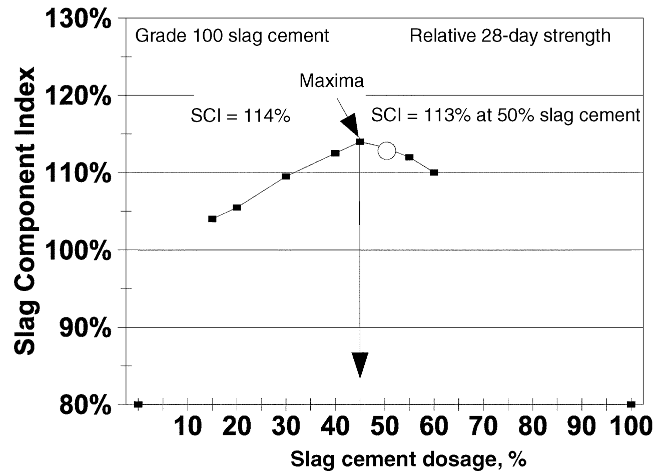

Fig. 8.4—Expected relative 28-day compressive strength curve for concrete mixtures made with portland cement and the indicated percent of ASTM C989, Grade 100 slag cement.

8.3.2.3.2 *Step 2*—Because this will be a laboratory trial batch mixture that has never been produced before with the given materials, Eq. (3-3) applies. Therefore

$$f'_{cr} = 1.1f'_c + 700 \quad (3\text{-}3)$$

$$f'_{cr} = 1.1(8700) + 700$$

$$f'_{cr} = 10{,}271 \text{ psi}$$

8.3.2.3.3 *Step 3*—A slag component index/slag cement content diagram has not been developed, and a Grade 120 slag cement was initially considered for the project. The slag cement has a relative density of 2.85, and it usually achieves approximately 30% more strength than reference portland cement concrete mixtures. For an optimized mixture proportion, an SCI curve similar to that shown in Fig. 8.2 is needed. Several trial batches with a range of 40 to 50% slag cement would be prepared and tested in expectation of a peak similar to that in Fig. 8.2. An arbitrary selection of 40% slag cement content by the concrete producer is used herein.

8.3.2.3.4 *Step 4*—Figure 8.5 indicates that at the arbitrarily selected 40% slag cement content, the compressive strength of the 40% slag cement mixture may be expected to be 128% of the compressive strength of the basic mixture.

8.3.2.3.5 *Step 5*—Calculate the portion of the required average compressive strength f'_{cr} that is relegated to portland cement.

$$PC_{,\text{psi}} = (f'_{cr})(100/[\text{SCI }\%])$$

$$= (10{,}270)(100/128)$$

$$= 10{,}270(0.78125)$$

$$= 8020 \text{ psi}$$

8.3.2.3.6 *Step 6*—A portland cement mixture (basic mixture) achieving 8700 psi at 28 days that uses all of the concrete materials initially considered for use on the project is located. Because the specification has a 56-day strength

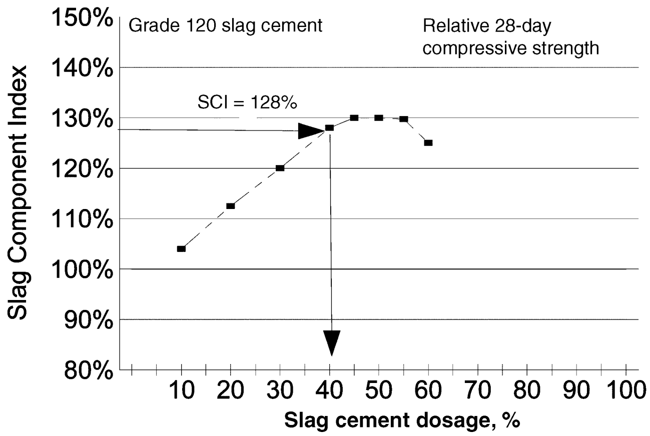

Fig. 8.5—Estimated relative 28-day compressive strength curve for concrete mixtures made with various amounts of portland cement and the indicated percent of ASTM C989, Grade 120 slag cement and the expected results of the trial batch with 40% slag cement.

requirement, using a mixture achieving 8700 psi at 28 days will be conservative. The mixture is shown in Table 8.3 as the actual job record.

Basic mixture Method B			
Materials	Mass, lb/yd^3	Relative density	Volume, ft^3
Portland cement	705	3.15	3.587
Coarse aggregate (saturated surface-dry)	1830	2.72	10.782
Fine aggregate (saturated surface-dry)	1355	2.63	8.257
Water	240	1.00	3.846
Admixture WRA	1.35	1.2	0.018
Admixture HRWRA	7.8	1.2	0.104
Anticipated entrapped air content	1.5%		0.405
			Total = 27.00
Final *w/cm* = 0.34			

8.3.2.3.7 *Step 7*—

Amount of slag cement = 705 (0.40) = 282 lb/yd^3

Amount of portland cement = 705 – 282 = 423 lb/yd^3

8.3.2.3.8 *Step 8*—The slag cement trial batch proportions:

Materials	Mass, lb/yd^3	Relative density	Volume, ft^3
Portland cement	423	3.15	2.152
Slag cement, Grade 120	282	2.85	1.586
Coarse aggregate at saturated surface-dry	1830	2.72	10.782
Water	240	1.00	3.846
Admixture WRA	1.35	1.20	0.018
Admixture HRWRA	7.8	1.20	0.104
Anticipated air content	1.5%		0.405
			Subtotal = 18.893
Fine aggregate required to adjust yield = 27.0 – 18.893 = 8.107 ft^3			
Fine aggregate at saturated surface-dry = 8.107 × 2.63 × 62.4 = 1330 lb			
Final *w/cm* = 0.34			

Table 8.3—Reference mixtures

		Basic mixture		Slag cement mixture	
Units	Relative density	Amount, lb/yd^3	Volume, ft^3	Amount, lb/yd^3	Volume, ft^3
Portland cement	3.15	750	3.82	450	2.29
Slag cement	2.85	—	—	300	1.69
Coarse aggregate (saturated surface-dry)	2.68	1720	10.29	1720	10.29
Fine aggregate (saturated surface-dry)	2.63	1352	8.24	1326	8.08
Water	1.0	232	3.72	232	3.72
WRA, oz/yd^3	1.2	22	0.02	22	0.02
HRWRA, oz/yd^3	1.2	114	0.1	114	0.1
Entrapped air content	—	3%	0.81	3%	0.81
	Total	27.00			27.00
	Slump, in.	6		8	
Compressive strength	Age, days	psi		psi	
	1	4130		2450	
	3	6910		6670	
	7	7870		8630	
	28	9210		10,150	
	56	9450		11,600	
	90	11,060		13,480	

CHAPTER 9—REFERENCES

9.1—Referenced standards and reports

The standards and report listed below were the latest editions at the time this document was prepared. Because these standards and reports are revised frequently, the reader is advised to contact the proper sponsoring group for the latest version.

American Concrete Institute

201.2R Guide to Durable Concrete

211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete

214R Evaluation of Strength Test Results of Concrete

232.1R Use of Raw or Processed Natural Pozzolans in Concrete

232.2R Use of Fly Ash in Concrete

233R Slag Cement in Concrete and Mortar

234R Guide for the Use of Silica Fume in Concrete

301 Specifications for Structural Concrete

318 Building Code Requirements for Structural Concrete

363R Report on High-Strength Concrete

363.2R Guide to Quality Control and Testing of High-Strength Concrete

ASTM International

C29/C29M Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate

C33 Specification for Concrete Aggregates

C150 Specification for Portland Cement

C192/C192M Practice for Making and Curing Concrete Test Specimens in the Laboratory

C494/C494M	Specification for Chemical Admixtures for Concrete
C618	Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete
C989	Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars
C1240	Specification for Silica Fume Used in Cementitious Mixtures
C1602/C1602M	Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete
C1603	Test Method for Measurement of Solids in Water

AASHTO

M-302	Ground Iron Blast-Furnace Slag for Use in Concrete and Mortars

The above publications can be obtained from the following organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094
www.concrete.org

ASTM International
100 Barr Harbor Dr.
West Conshohocken, PA 19428-2959
www.astm.org

AASHTO
444 N. Capitol Street NW Suite 249
Washington, DC 20001
www.transportation.org

9.2—Cited references

ACI Committee 318, 2005, "Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (318R-05)," American Concrete Institute, Farmington Hills, MI, 430 pp.

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Guide for Selecting Proportions for High-Strength Concrete Using Portland Cement and Other Cementitious Materials