

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

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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.

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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

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

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

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

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

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 ($\text{Ca}(\text{OH})_2$) 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, diatomaceous 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

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.

(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.

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 to properly place and consolidate, but not so fluid as to cause segregation.