Guide for Selecting Proportions for High-Strength Concrete with Portland Cement and Fly Ash

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This guide presents a generally applicable method for selecting mixture proportions for high-strength concrete and optimizing these mixture proportions on the basis of trial batches. The method is limited to high-stmngth concrete 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: aggregates; capping; chemical admixtures; fine aggregates; **fIy ash**; **high-strength concretes**; **mixture proportioning**; quality control; specimen size; strength requirements; superplasticizers.

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CHAPTER l-INTRODUCTION

1.1.Purpose

The current ACI 211.1 mixture proportioning proce-

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dure describes methods for selecting proportions for normal strength concrete in the range of 2000 to 6000 psi. Mixture proportioning is more critical for high-strength concrete than for normal strength concrete. Usually, specially selected pozzolanic and chemical admixtures are employed, and attainment of a low water-to-cementitious material ratio (*w/c+p*) is considered essential. Many trial mixtures are often required to generate the data necessary to identify optimum mixture proportions. The purpose of this guide is to present a generally applicable method for selecting mixture proportions for high-strength concrete and for optimizing these mixture proportions on the basis of trial batches.

1.2-Scope

Discussion in this guide is limited to high-strength concrete produced using conventional materials and production methods. Consideration of silica fume and ground granulated blast furnace slag (GGBFS) is beyond the scope of this document. Information on proportioning of silica fume concrete is limited at this time. ACI Committee 234, Silica Fume in Concrete, is developing information on the use of silica fume for a committee report. Proportioning GGBFS concrete is discussed in ACI 226-1R (now ACI Committee 233). When additional data becomes available, it is expected that an ACI guide for proportioning concrete with these materials will be developed. Currently, silica fume and GGBFS suppliers, as well as experienced concrete suppliers, represent the best source of proportioning information for these materials.

High-strength concrete is defined as concrete that has a specified compressive strength f_c' of 6000 psi or greater. This guide is intended to cover field strengths up to 12,000 psi as a practical working range, although greater strengths may be obtained. Recommendations are based on current practice and information from contractors, concrete suppliers, and engineers who have been involved in projects dealing with high-strength concrete. For a more complete list of references and available publications on the topic, the reader should refer to ACI 363R.

CHAPTER 2-PERFORMANCE REQUIREMENTS

2.1-Test age

The selection of mixture proportions can be influenced by the testing age. High-strength concretes can gain considerable strength after the normally specified 28-day age. To take advantage of this characteristic, many specifications for compressive strength have been modified from the typical 28-day criterion to 56 days, 91 days, or later ages. Proportions of cementitious components usually have been adjusted to produce the desired strength at the test age selected.

2.2-Required strength

ACI 318 allows concrete mixtures to be proportioned based on field experience or laboratory trial batches. To meet the specified strength requirements, the concrete must be proportioned in such a manner that the average compressive strength results of field tests exceed the specified design compressive strength f_c' by an amount sufficiently high to make the probability of low tests small. When the concrete producer chooses to select high-strength concrete mixture proportions based upon field experience, it is recommended that the required average strength f_{cr}' used as the basis for selection of concrete proportions be taken as the larger value calculated from the following equations

$$f_{cr}' = f_c' + 1.34s \qquad (2\text{-}1)$$

$$f_{cr}' = 0.90 f_c' + 2.33s \qquad (2\text{-}2)$$

where s = sample standard deviation in psi.

Eq. (2-l) is Eq. (5-l) of the ACI 318 Building Code. Eq. (2-2) is a modified version of Eq. (5-2) ($f_{cr}' = f_c' + 2.33s - 500$) of ACI 318 because, to date, job specifications for high-strength concrete have usually been modified to allow no more than 1 in 100 individual tests to fall below 90% of the specified strength. When job specifications cite ACI 318 acceptance criteria, Eq. (5-2) of ACI 318 should be used instead of Eq. (2-2) of this report.

When the concrete producer selects high-strength concrete proportions on the basis of laboratory trial batches, the required average strength f_{cr}' may be determined from the equation

$$f_{cr}' = \frac{(f_c' + 1400)}{0.90} \qquad (2\text{-}3)$$

Eq. (2-3) gives a higher required average strength value than that required in Table 5.3.2.2 of the ACI Building Code (ACI 318). Experience has shown that strength tested under ideal field conditions attains only 90 percent of the strength measured by tests performed under laboratory conditions. To assume that the average strength of field production concrete will equal the strength of a laboratory trial batch is not realistic, since many factors can influence the variability of strengths and strength 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 below, as appropriate. Once sufficient data have been generated from the job, mixture proportions should be reevaluated using ACI 214 and adjusted accordingly.

2.3-Other requirements

Considerations other than compressive strength may influence the selection of materials and mixture proportions. These include: a) modulus of elasticity, b) flexural and tensile strengths, c) heat of hydration, d) creep and drying shrinkage, e) durability, f) permeability, g) time of setting, h) method of placement, and i) workability.

CHAPTER 3-FUNDAMENTAL RELATIONSHIPS

3.1-Selection of materials

Effective production of high-strength concrete is achieved by carefully selecting, controlling, and proportioning all of the ingredients. To achieve higher strength concretes, optimum proportions must be selected, considering the cement and fly ash characteristics, aggregate quality, paste proportion, aggregate-paste interaction, admixture type and dosage rate, and mixing. Evaluating cement, fly ash, chemical admixture, and aggregate from various potential sources in varying proportions will indicate the optimum combination of materials. The supplier of high-strength concrete should implement a program of uniformity and acceptance tests for all materials used in the production of high-strength concrete.

3.1.1 *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. ASTM C 917 may be useful in considering cement sources. Variations in the chemical composition and physical properties of the cement affect the concrete compressive strength more than variations in any other single material. 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.

3.1.2 *Other cementitious materials*-Finely divided cementitious materials other than portland cement, consisting mainly of fly ash, ground blast furnace slag, or silica fume (microsilica), have been considered in the production of high-strength concrete because of the required high cementitious materials content and low *w/(c+p)*. These materials can help control the temperature rise in concrete at early ages and may reduce the water demand for a given workability. However, early strength gain of the concrete may be decreased.

ASTM C 618 specifies the requirements for Class F and Class C fly ashes, and for raw or calcined natural pozzolans, Class N, for use in concrete. Fly ash properties may vary considerably in different areas and from different sources within the same area. The preferred fly ashes for use in high-strength concrete have a loss on ignition no greater than 3 percent, have a high fineness, and come from a source with a uniformity meeting ASTM C 618 requirements.

3.13 *Mixing water*-The acceptability of the water for high-strength concrete is not of major concern if potable water is used. Otherwise, the water should be tested for suitability in accordance with ASTM C 94.

3.1.4 *Coarse aggregate*--In the proportioning of high-strength concrete, the aggregates require special consideration since they occupy the largest volume of any ingredient in the concrete, and they greatly influence the strength and other properties of the concrete. Usually, high-strength concretes are produced with normal weight aggregates. However, there have been reports of high-strength concrete produced using lightweight aggregates for structural concrete and heavyweight aggregates for high-density concrete.

The coarse aggregate will influence significantly the strength and structural properties of the concrete. For this reason, a coarse aggregate should be chosen that is sufficiently hard, 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. Smaller size aggregates have been shown to provide higher strength potential.

For each concrete strength level, there is an optimum size for the coarse aggregate that will yield the greatest compressive strength per pound of cement. A 1 or 3/4-in. nominal maximum-size aggregate is common for producing concrete strengths up to 9000 psi; and ½ or 3/8-in. above 9000 psi. In general, the smallest size aggregate produces the highest strength for a given *w/c+p*. However, compressive strengths in excess of 10,000 psi are feasible using a l-in. nominal maximum-size aggregate when the mixture is proportioned with chemical admixtures. The use of the largest possible coarse aggregate is an important consideration if optimization of modulus of elasticity, creep, and drying shrinkage are important.

3.1.5 *Fine aggregate*-The grading and particle shape of the fiie aggregate are significant factors in the production of high-strength concrete. Particle shape and surface texture can have as great an effect on mixing water requirements and compressive strength of concrete as do those of coarse aggregate. Fine aggregates of the same grading but with a difference of 1 percent in voids content may result in a 1 gal. per yd^3 difference in water demand. More information can be found in ACI 211.1.

The quantity of paste required per unit volume of a concrete mixture decreases as the relative volume of coarse aggregate versus fine material increases. Because the amount of cementitious material contained in high-strength concrete is large, the volume of fines tends to be high. Consequently, the volume of sand can be kept to the minimum necessary to achieve workability and compactibility. In this manner, it will be possible to produce higher strength concretes for a given cementitious material content.

Fine aggregates with a fineness modulus (FM) in the range of 2.5 to 3.2 are preferable for high-strength concretes. Concrete mixtures made with a fine aggregate that has an FM of less than 2.5 may be “sticky” and result in poor workability and a higher water requirement. It is sometimes possible to blend sands from different sources to improve their grading and their capacity to produce higher strengths. If manufactured sands 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 sands over natural sands can significantly affect water demand.

3.1.6 *Chemical admixtures*-In the production of concrete, decreasing the *w/(c+p)* by decreasing the water requirement rather than by increasing the total cementitious materials content, will usually produce higher compressive strengths. For this reason, use of chemical admixtures should be considered when producing high-strength concrete (see ACI 212.3R and ASTM C 494). In this guide, chemical admixture dosage rates are based on fluid oz per 100 lb of total cementitious material (oz/cwt). If powdered admixtures are used, dosage rates are on a dry weight basis. The use of chemical admixtures may improve and control the rate of hardening and slump loss, and result in accelerated strength gain, better durability, and improved workability.

High-range water-reducing admixtures (HRWR), also known as superplasticizers, are most effective in concrete mixtures that are rich in cement and other cementitious materials. HRWR help in dispersing cement particles, and they can reduce mixing water requirements by up to 30 percent, thereby increasing concrete compressive strengths.

Generally, high-strength concretes contain both a conventional water-reducing or water-reducing and retarding admixture and an HRWR. The dosage of the admixtures will most likely be different from the manufacturer's recommended dosage. Although only limited information is available, high-strength concrete has also 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 particular cementitious materials used. The optimum dosage of an admixture or combination of admixtures should be determined by trial mixtures using varying amounts of admixtures. The best results are achieved generally when an HRWR is added after the cement has been wetted in the batching and mixing operation.

Air-entraining admixtures are seldom used in high-strength concrete building applications when there are no freeze-thaw concerns other than during the construction period. If entrained air is required because of severe environments, it will reduce significantly the compressive strength of the concrete.

3.2-Water-cementitious material ratio (*w/(c +p)*)

Many researchers have concluded that the single most important variable in achieving high-strength concrete is the water-cement ratio (*w/c*). Since most high-strength concrete mixtures contain other cementitious materials, a *w/(c+p)* ratio must be considered in place of the traditional *w/c*. The *w/(c+p)*, like the *w/c*, should be calculated on a weight basis. The weight of water in HRWR should be included in the *w/(c+p)*.

The relationship between *w/c* and compressive strength, which has been identified in normal strength concretes, has been found to be valid for higher strength concretes as well. The use of chemical admixtures and other cementitious materials has been proven generally essential to producing placeable concrete with a low *w/c*. *w/(c+p)* for high-strength concretes typically have ranged from 0.20 to 0.50.

3.3-Workability

3.3.1 *Introduction*-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.

3.3.2 *Slump*-In general, high-strength concretes should be placed at the lowest slump which can be properly handled and consolidated in the field. A slump of 2 to 4 in. provides the required workability for most applications. However, reinforcement spacing and form details should be considered prior to development of concrete mixtures.

Because of a high coarse aggregate and cementitious materials content and low *w/(c+p)*, high-strength concrete can be difficult to place. However, high-strength concrete can be placed at very high slumps with HRWR without segregation problems. Flowing concretes with slumps in excess of 8 in., incorporating HRWR, are very effective in filling the voids between closely spaced reinforcement. In delivery situations where slump loss may be a problem, a placeable slump can be restored successfully by redosing the concrete with HRWR. A second dosage of HRWR results in increased strengths at nearly all test ages. This practice has been advantageous especially in using HRWR for hot-weather concreting.

3.4-Strength measurements

3.4.1 *Test method*-standard ASTM or AASHTO test methods are followed except where changes are indicated by the characteristics of the high-strength concrete (ACI 363R). The potential strength for a given set of materials can be established only if specimens are made and tested under standard conditions. A minimum of two specimens should be tested for each age and test condition.

3.4.2 *Specimen size*-Generally, 6 x 12-in. cylindrical specimens are specified as the standard for strength evaluation of high-strength concrete. However, some 4 x 8-in. cylinders have been used for strength measurements. The specimen size used by the concrete producer to determine mixture proportions should be compatible with the load capacity of the testing machine and consistent with the cylinder size specified by the designer for acceptance. Measurements of strength using 6 x 12-in. cylinders are not interchangeable with those obtained when using 4 x 8-in. cylinders.

3.4.3 *Type of molds*--The type of mold used will have a significant effect on the measured compressive strength. In general, companion specimens cast using steel molds achieve more consistent compressive strengths than those cast using plastic molds. Molds made of cardboard material are not recommended for casting high-strength concrete specimens. Single-use rigid plastic molds have been used successfully on high-strength concrete projects.

Regardless of the type of mold material, it is important that the type used for establishing mixture proportions be the same type as that used for fiial acceptance testing.

3.4.4 *Specimen capping*--Prior to testing a cylinder, the ends usually are capped to provide for a uniform transmission of force from a testing machine platen into the specimen body. Sulfur mortar is the most widely used capping material and, when properly prepared, is economical, convenient, and develops a relatively high strength in a short period of time.

Cap thickness should be as thin as practical, in the range of **1/16 to ⅛ in.** for high-strength concrete specimens. A commercially available high-strength sulfur capping material has been used to determine concrete strengths in excess of 10,000 psi, with cap thicknesses maintained at approximately ⅛ in. When using a sulfur capping material on high-strength concrete specimens, it is important that irregular end conditions are corrected prior to capping. Irregular end conditions and air voids between the cap and the cylinder end surfaces can adversely affect the measured compressive strength. Some concrete technologists prefer to form or grind specimen ends to ASTM C 39 tolerance when compressive strengths are greater than 10,000 psi.

3.4.5 *Testing machines*--Testing machine characteristics, mainly load capacity and stiffness, can have a significant influence on measured strength results. Good test results and minimum variation have been obtained when testing high-strength concrete cylinders using a testing machine with a minimum lateral stiffness of 10^5 lb/in. and a longitudinal stiffness of at least 10^7 lb/in. Testing machines that are laterally flexible can reduce the measured compressive strength of a specimen.

CHAPTER 4-HIGH-STRENGTH CONCRETE MIXTURE PROPORTIONING

4.1-Purpose

This guide procedure for proportioning high-strength concrete mixtures is applicable to normal weight, non-air-entrained concrete having compressive strengths between 6000 and 12,000 psi (f_{cr}'). When proportioning high-strength concrete mixtures, the basic considerations are still to determine the ingredient quantities required to produce a concrete with the desired plastic properties (workability, finishability, etc.) and hardened properties (strength, durability, etc.) at the lowest cost. 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, this proportioning procedure is meant to be a reasonable process to produce submittal mixture proportions based on the performance of adjusted laboratory and field trial batches. Guidelines for the adjustment of mixture proportions are provided at the end of this chapter. This procedure further assumes 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 selections of materials for producing high-strength concrete are provided in ACI 363R.

Table 4.3.1 — Recommended slump for concretes with and without HRWR

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

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

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

4.2-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, which when completed provides a mixture meeting strength and workability requirements based on the combined properties of the individually selected and proportioned components. However, 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 contents of cementitious materials.

4.3-Mixture proportioning procedure

Completion of the following steps will result in a set of adjusted 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.

4.3.1 *Step 1-Select slump and required concrete strength*-Recommended values for concrete slump are given in Table 4.3.1. Although high-strength concrete with HRWR has been produced successfully without a measurable initial slump, an initial starting slump of 1 to 2 in. prior to adding HRWR is recommended. This will insure an adequate amount of water for mixing and allow the superplasticizer to be effective.

For high-strength concretes made without HRWR, 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 HRWR. Concretes with less than 2 in. of slump are difficult to consolidate due to the high coarse aggregate and cementitious materials content.

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

4.3.2 *Step 2-Select maximum size of aggregate*-Based on strength requirements, the recommended maximum

Table 4.3.2— Suggested maximum-size coarse aggregate

Required concrete strength, psi	Suggested maximum-size coarse aggregate, in.
<9000	¾ to 1
>9000	⅜ to ½*

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

Table 4.3.3— Recommended volume of coarse aggregate per unit volume of concrete

Optimum coarse aggregate contents for nominal maximum sizes of aggregates to be used with sand 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	0.65	0.68	0.72	0.75

* Volumes are based on aggregates in oven-dry rodded condition as described in ASTM C 29 for unit weight of aggregates.

sixes for coarse aggregates are given in Table 4.3.2. ACI 318 states the maximum size of an aggregate should not exceed one-fifth of the narrowest dimension between sides of forms, one-third of the depth of slabs, nor three-quarters of the minimum clear spacing between individual reinforcing bars, bundles of bars, or prestressing tendons or ducts.

4.3.3 *Step 3-Select optimum coarse aggregate content* -The optimum content of the coarse aggregate depends on its strength potential characteristics and maximum size. The recommended optimum coarse aggregate contents, expressed as a fraction of the dry-rodded unit weight (DRUW), are given in Table 4.3.3 as a function of nominal maximum size.

Once the optimum coarse aggregate content has been chosen from Table 4.3.3, the oven-dry (OD) weight of the coarse aggregate per yd^3 of concrete can be calculated using Eq. (4-l)

weight of coarse aggregate = (coarse aggregate factor x DRUW) x 27 (4-l)

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 fiies for lubrication and compactibility of the fresh concrete. Therefore, the values given in Table 4.3.3 are recommended for use with sands having fineness modulus values from 2.5 to 3.2.

4.3.4 *Step 4-Estimate mixing water and air contents*-The quantity of water per unit volume of concrete required to produce a given slump is dependent on the maximum size, particle shape, and grading of the aggregate, the quantity of cement, and type of water-reducing admixture used. If an HRWR is used, the water content in this admixture is calculated generally to be a part of the *w/(c+p)*. Table 4.3.4 gives estimates of required mixing water for high-strength concretes made with ⅜ to 1 in. maximum-size aggregates prior to the addition of any chemical admixture. Also given are the corresponding 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 C 33. 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 4.3.4 —First estimate of mixing water requirement and air content of fresh concrete based on using a sand with 35 percent voids

Slump, in.	Mixing water, lb/yd^3 — Maximum-size coarse aggregate, in. ⅜	½	¾	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 sands with voids other than 35 percent using Eq. 4-3.
† Mixtures made using HRWR.

The values for the required mixing water given in Table 4.3.4 are applicable when a fine aggregate is used that has a void content of 35 percent. The void content of a fine aggregate may be calculated using Eq. (4-2)

$$\text{Void content, } V, \% = \left(1 - \frac{\text{Oven-dry rodded unit weight}}{\text{Bulk specific gravity (dry) x 62.4}}\right) \times 100 \quad (4\text{-}2)$$

When a fine aggregate with a void content not equal to 35 percent is used, an adjustment must be made to the recommended mixing water content. This adjustment may be calculated using Eq. (4-3)

$$\text{Mixing water adjustment, lbs/yd}^3 = (V - 35) \times 8 \quad (4\text{-}3)$$

Use of Eq. (4-3) results in a water adjustment of 8 lb/yd^3 of concrete for each percent of voids deviation from 35 percent.

4.3.5 *Step 5-Select w/(c+p)*-In high-strength concrete mixtures, other cementitious material, such as fly ash, may be used. The *w/(c+p)* is calculated by dividing the weight of the mixing water by the combined weight of the cement and fly ash.

In Tables 4.3.5(a) and (b), recommended maximum *w/(c+p)* are given as a function of maximum-size aggregate

Table 4.3.5(a)— Recommended maximum *w/(c + p)* for concretes made without HRWR

Field strength f_{cr}'*, psi		*w/(c + p)* Maximum-size coarse aggregate, in. ⅜	½	¾	1
7000	28-day	0.42	0.41	0.40	0.39
	56-day	0.46	0.45	0.44	0.43
8000	28-day	0.35	0.34	0.33	0.33
	56-day	0.38	0.37	0.36	0.35
9000	28-day	0.30	0.29	0.29	0.28
	56-day	0.33	0.32	0.31	0.30
10,000	28-day	0.26	0.26	0.25	0.25
	56-day	0.29	0.28	0.27	0.26

* $f_{cr}' = f_c' + 1400$.

Table 4.3.5(b)— Recommended maximum *w/(c + p)* ratio for concretes made with HRWR

Field strength f_{cr}'*, psi		*w/(c + p)* Maximum-size coarse aggregate, in. ⅜	½	¾	1
7000	28-day	0.50	0.48	0.45	0.43
	56-day	0.55	0.52	0.48	0.46
8000	28-day	0.44	0.42	0.40	0.38
	56-day	0.48	0.45	0.42	0.40
9000	28-day	0.38	0.36	0.35	0.34
	56-day	0.42	0.39	0.37	0.36
10,000	28-day	0.33	0.32	0.31	0.30
	56-day	0.37	0.35	0.33	0.32
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

* $f_{cr}' = f_c' + 1400$.

Note: A comparison of the values contained in Tables 4.3.5(a) and 4.3.5(b) permits, in particular, the following conclusions:

1. For a given water cementitious material ratio, the field strength of concrete is greater with the use of HRWR than without it, and this greater strength is reached within a shorter period of time.

2. With the use of HRWR, 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 HRWR.

to achieve different compressive strengths at either 28 or 56 days. The use of an HRWR generally increases the compressive strength of concrete. The *w/(c +p)* values given in Table 4.3.5(a) are for concretes made without HRWR, and those in Table 4.3.5(b) are for concretes made using an HRWR.

The *w/(c+p)* may be limited further by durability requirements. However, for typical applications, high-strength concrete would not be subjected to severe exposure conditions.

When the cementitious material content from these tables exceed 1000 lb, a more practical mixture may be produced using alternative cementitious materials or proportioning methods.

4.3.6 *Step 6-Calculate content of cementitious material*-The weight of cementitious material required per yd^3 of concrete can be determined by dividing the amount of mixing water per yd^3 of concrete (Step 4) by the *w/(c+p)* ratio (Step 5). However, if the specifications include a minimum limit on the amount of cementitious material per yd^3 of concrete, this must be satisfied. Therefore, the mixture should be proportioned to contain the larger quantity of cementitious material required. When the cementitious material content from the following tables exceeds 1000 lb, a more practical mixture may be produced using alternate cementitious materials or proportioning methods. This process is beyond the scope of this guide.

4.3.7 *Step 7-Proportion basic mixture with no other cementitious material*-To determine optimum mixture proportions, the proportioner needs to prepare several trial mixtures having different fly ash contents. Generally, one trial mixture should be made with portland cement as the only cementitious material. The following steps should be followed to complete the basic mixture proportion.

1. *Cement content*-For this mixture, since no other cementitious material is to be used, the weight of cement equals the weight of cementitious material calculated in Step 6.

2. *Sand content*-After determining the weights per yd^3 of coarse aggregate, the cement and water, and the percentage of air content, the sand content can be calculated to produce 27 ft^3, using the absolute volume method.

4.3.8 *Step 8--Proportion companion mixtures using fly ash*-The use of fly ash in producing high-strength concrete can result in lowered water demand, reduced concrete temperature, and reduced cost. However, due to variations in the chemical properties of fly ash, the strength-gain characteristics of the concrete might be affected. Therefore, it is 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:

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 4.3.6, for the two classes of fly ash. For each companion trial mixture to be designed, a replacement percentage should be chosen from this table.

3. *Fly ash weight*-Once the percentages for replacement have been chosen, the weight of the fly ash to be used for each companion trial mixture can be calculated by multiplying the total weight of cementitious materials (Step 6) by the replacement percentages previously cho-

Table 4.3.6— Recommended values for fly ash replacement of portland cement

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

sen. The remaining weight of cementitious material corresponds to the weight of cement. Therefore, for each mixture, the weight of fly ash plus the weight of cement should equal the weight of cementitious materials calculated in Step 6.

4. *Volume of fly ash*-Due to the differences in bulk specific gravities of portland cement and fly ash, the volume of cementitious materials per **yd^3** will vary with the fly ash content, even though the weight of the cementitious materials remains constant. Therefore, for each mixture, the volume of cementitious materials should be calculated by adding the volume of cement and the volume of fly ash.

5. *Sand content*-Having found the volume of cementitious materials per **yd^3** of concrete, the volumes per **yd^3** of coarse aggregate, water, and entrapped air (Step 7), the sand content of each mixture can be calculated using the absolute volume method.

Using the preceding procedure, the total volume of cement and fly ash plus sand per **yd^3** of concrete is kept constant. Further adjustments in the mixture proportions may be needed due to changes in water demand and other effects of fly ash on the properties of the concrete. These adjustments are determined during trial mixing, as discussed in Section 4.3.10.

4.3.9 *Step 9--Trial mixtures*-For each of the trial mixtures proportioned in Steps 1 through 8, a trial mixture should be produced to determine the workability and strength characteristics of the mixtures. The weights of sand, coarse aggregate, and water must be adjusted to correct for the moisture condition of the aggregates used. Each batch should be such that, after a thorough mixing, a uniform mixture of sufficient size is achieved to fabricate the number of strength specimens required.

4.3.10 *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 should be adjusted. The weight of cementitious material in the mixture should be adjusted to maintain the desired *w/(c+p)*. The sand content should then be adjusted to insure proper yield of the concrete.

2. *HRWR dosage rate*-If HRWR 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 be tolerated without segregation. Also, since the time of addition of the HRWR and concrete temperature have been found to affect the effectiveness of the admixture, its use in laboratory trial mixtures may have to be adjusted for field conditions. In general, it has been found that redosing with HRWR to restore workability results in increased strengths at nearly all test ages.

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 sand content adjusted accordingly to insure proper yield. However, this may increase the water demand of the mixture, thereby increasing the required content of cementitious materials to maintain a given *w/(c+p)*. In addition, a reduction in coarse aggregate content may result in a lower modulus of elasticity of the hardened concrete.

4. *Air content*-If the measured air content differs significantly from the designed proportion calculations, the dosage should be reduced or the sand content should be adjusted to maintain a proper yield.

5. *w/(c+p)*-If the required concrete compressive strength is not attained using the *w/(c+p)* recommended in Table 4.3.5(a) or (b), additional trial mixtures having lower *w/(c+p)* should be tested. If this does not result in increased compressive strengths, the adequacy of the materials used should be reviewed.

4.3.11 *Step 11-Select optimum mixture proportions*-Once the trial mixture proportions have been adjusted to produce the desired workability and strength properties, strength specimens should be cast from trial batches made under the expected field conditions according to the ACI 211.1 recommended procedure for making and adjusting trial batches. Practicality of production and quality control procedures have been better evaluated when production-sized trial batches were prepared using the equipment and personnel that were to be used in the actual work. The results of the strength tests should be presented in a way to allow the selection of acceptable proportions for the job, based on strength requirements and cost.

CHAPTER 5-SAMPLE CALCULATIONS

5.1-Introduction

An example is presented here to illustrate the mixture proportioning procedure for high-strength concrete discussed in the preceding chapter. Laboratory trial batch results will depend on the actual materials used. In this example, Type I cement having a bulk specific gravity of 3.15 is used.

5.2-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 3/4 in. A natural sand that meets ASTM C 33 limits will be used, which has the following properties: fineness modulus *FM* = 2.90; bulk specific gravity based on oven-dry weight *BSGdry* = 2.59; absorption based on oven-dry weight *Abs* = 1.1 percent; dry-rodded unit weight *DRUW* = 103 lb/ft^3. Also, a HRWR and a set-retarding admixture will be used.

5.2.1 *Step 1-Select slump and required concrete strength*-Since an HRWR is to be used, the concrete will be designed based on a slump of 1 to 2 in. prior to the addition of the HRWR.

The ready-mix producer has no prior history with high-strength concrete, and therefore will select proportions based on laboratory trial mixtures. Using Eq. (2.3), the required average strength used for selection of concrete proportions is

$$f'_{cr} = \frac{(9000 + 1400)}{0.90} = 11{,}556\ psi\ ,...\ i.e.,\ 11{,}600\ psi$$

5.2.2 *Step 2-Select maximum size of aggregate*—Based on the guidelines in Table 4.3.2, a crushed limestone having a nominal maximum size of 1/2 in. is to be used. Its material properties are as follows: bulk specific gravity at oven-dry, BSG_{dry}= 2.76; absorption at oven-dry, *Abs* = 0.7 percent; dry-rodded unit weight, *DRUW* = 101 lb/ft^3. The grading of the aggregate must comply with ASTM C 33 for size designation No. 7 coarse aggregate.

5.2.3 *Step 3-Select optimum coarse aggregate content*-The optimum coarse aggregate content, selected from Table 4.3.3, is 0.68 per unit volume of concrete. The dry weight of coarse aggregate per yd^3 of concrete W_{dry}, is then

$$(0.68) \times (101) \times (27) = 1854 \text{ lb, using Eq. (4.1)}$$

5.2.4 *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 4.3.4 is 295 lb/yd^3 of concrete, and the entrapped air content, for mixtures made using HRWR, is 2.0 percent.

However, using Eq. (4-2), the voids content of the sand to be used is

$$\left[1 - \frac{103}{(2.59) \times (62.4)}\right] \times 100 = 36\ percent$$

The mixing water adjustment, calculated using Eq. (4-3), is

$$(36 - 35) \times 8 = +8 \text{ lb/yd}^3 \text{ of concrete}$$

Therefore, the total mixing water required per yd^3 of concrete is 295 + 8 or 303 lb. This required mixing water includes the retarding admixture, but does not include the water in the HRWR.

5.2.5 *Step 5 - Select w/(c+p)*-For concrete to be made using HRWR and 1/2-in. maximum-size aggregate, and having an average compressive strength based on laboratory trial mixtures of 11,600 psi at 28 days, the required *w/c+p* chosen from Table 4.3.5(b) is interpolated to be 0.31. It should be noted that the compressive strengths listed in Tables 4.3.5(a) and (b) are required average field strengths. Therefore, although the required strength of laboratory trial mixtures is 11,600 psi, the value to be used in the tables is

$$(0.90) \times (11{,}600) = \approx 10{,}400 \text{ psi}$$

5.2.6 *Step 6--Calculate content of cementitious material*--The weight of cementitious material per yd^3 of concrete is

$$\left(\frac{303}{0.31}\right) = 977\ lb$$

The specifications do not set a minimum for cementitious materials content, so 977 lb/yd^3 of concrete will be used.

5.2.7 *Step 7-Proportion basic mixture with cement only*

1. Cement content per yd^3 = 977 lb.

2. The volumes per yd^3 of all materials except sand are as follows:

Cement = (977)/(3.15 x 62.4) =	4.97 ft^3
Coarse aggregate = (1854)/(2.76 x 62.4) =	10.77 ft^3
Water = (303)/(62.4) =	4.86 ft^3
Air = (0.02) x (27) =	0.54 ft^3
Total volume =	21.14 ft^3

Therefore, the required volume of sand per yd^3 of concrete is (27 - 21.14) = 5.86 ft^3. Converting this to weight of sand, dry, per yd^3 of concrete, the required weight of sand is

$$(5.86) \times (62.4) \times (2.59) = 947 \text{ lb.}$$

Cement	977 lb
Sand, dry	947 lb
Coarse aggregate, dry	1854 lb
Water, including 3 oz/cwt* retarding admixture	303 lb

* Hundred weight of cement.

5.2.8 *Step 8-Proportion companion mixtures using cement and fly ash*

1. An ASTM Class C fly ash is to be used which has a bulk specific gravity of 2.64.

2. The recommended limits for replacement given in Table 4.3.6 for Class C fly ash are from 20 to 35 percent. Four companion mixtures will be proportioned, having fly ash replacement percentages as follows:

Companion mixture #1	20 percent
Companion mixture #2	25 percent
Companion mixture #3	30 percent
Companion mixture #4	35 percent

3. For companion mixture #l, the weight of fly ash per **yd**^{3} of concrete is (0.20) x (977) = 195 lb. therefore the cement is (977) - (195) = 782 lb. The weights of cement and fly ash per **yd**^{3} of concrete for the remaining companion mixes are calculated in a similar manner. The values are as follow:

Companion mixture	Cement, lb	Fly ash, lb	Total, lb
#1	782	195	977
#2	733	244	977
#3	684	293	977
#4	635	342	977

4. For the first companion mixture, the volume of cement per yd^3 of concrete is (782)/(3.15 x 62.4) = 3.98 **ft**^{3}, and the fly ash per yd^3 is (195)/(2.64 x 62.4) = 1.18 **ft**^{3}. The volume of cement, fly ash, and total cementitious material for each companion mixture are:

Companion mixture	Cement, ft^3	Fly ash, ft^3	Total, ft^3
#1	3.98	1.18	5.16
#1	3.73	1.48	5.21
#3	3.48	1.78	5.26
#4	3.23	2.08	5.31

5. For all of the companion mixtures, the volumes of coarse aggregate, water, and air per **yd**^{3} of concrete are the same as for the basic mixture that contains no other cementitious material. However, the volume of cementitious material varies with each mixture. The required weight of sand per **yd**^{3} of concrete for companion mixture #1 is calculated as follows:

Component	Volume (per cubic yard of concrete. ft^3)
Cementitious material	5.16
Coarse aggregate	10.77
Water (including 2.5 oz/cwt retarding mixture)	486
Air	0.54
Total volume	21.33

The required volume of sand is (27 - 21.33) = 5.67 **ft**^{3}. Converting this to the weight of sand (dry) per **yd**^{3} of concrete, the required weight is: (5.67) x (62.4) x (2.59) = 916 lb.

The mixture proportions per **yd**^{3} of concrete for each companion mixture are as follows:

Companion mixture. #1	
Cement	782 lb
Fly ash	195 lb
Sand, dry	916 lb
Coarse aggregate, dry	1854 lb
Water (including 2.5 oz/cwt retarding mixture)	303 lb

Companion mixture #2	
Cement	733 lb
Fly ash	244 lb
Sand, dry	908 lb
Coarse aggregate, dry	1854 lb
Water (including 2.5 oz/cwt retarding admixture)	303 lb

Companion mixture #3	
Cement	684 lb
Fly ash	293 lb
Sand, dry	900 lb
Coarse aggregate, dry	1854 lb
Water (including 2.5 oz/cwt retarding admixture)	303 lb

Companion mixture #4	
Cement	635 lb
Fly ash	342 lb
Sand, dry	892 lb
Coarse aggregate, dry	1854 lb
Water (including 2.5 oz/cwt retarding admixture)	303 lb

As shown in this example, the dosage rate of chemical admixture may or may not need to be adjusted when other cementitious materials are used. There are no existing guidelines to be followed when doing this adjustment other than experience. The proportioner needs to be aware of the possible need for this adjustment. During trial batches, verify proper dosage rates for all chemical admixtures.

5.2.9 *Step 9-Trial mixtures*-Trial mixtures are to be conducted for the basic mixture and each of the four companion mixtures. The sand is found to have 6.4 percent total moisture, and the coarse aggregate is found to have 0.5 percent total moisture, based on dry conditions. Corrections to determine batch weights for the basic mixtures are done as follows: sand, wet = (947) x (1 + 0.064) = 1008 lb; coarse aggregate, wet = (1854) x (1 + 0.005) = 1863 lb; and water, correction = (303) - (947) (0.064 - 0.011) - (1854)(0.005 - 0.007) = 257 lb.

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

Basic mixture	Dry weights	Batch weights
Cement	977 lb	977 lb
Sand	947 lb	1008 lb
Coarse aggregate	1854 lb	1863 lb
Water (including 2.5 oz/cwt retarding admixture)	303 lb	259 lb

Companion mixture #1	Dry weights	Batch weights
Cement	782 lb	782 lb
Fly ash	195 lb	195 lb
Sand	916 lb	975 lb
Coarse aggregate	1854 lb	1863 lb
Water (including 2.5 oz/cwt retarding admixture)	303 lb	259 lb

Companion mixture #2	Dry weights	Batch weights
Cement	733 lb	733 lb
Fly ash	244 lb	244 lb
Sand	908 lb	966 lb
Coarse aggregate	1854 lb	1863 lb
Water (including 25 oz/cwt retarding admixture)	303 lb	259 lb

Companion mixture #3	Dry weights	Batch weights
Cement	684 lb	684 lb
Fly ash	293 lb	293 lb
Sand	900 lb	958 lb
Coarse aggregate	1854 lb	1863 lb
Water (including 2.5 oz/cwt retarding admixture)	303 lb	259 lb

Companion mixture #4	Dry weights	Batch weights
Cement	635 lb	635 lb
Fly ash	342 lb	342 lb
Sand	892 lb	949 lb
Coarse aggregate	1854 lb	1863 lb
Water (including 2.5 oz/cwt retarding admixture)	303 lb	259 lb

The size of the trial mixture is to be **3.0 ft^3**. The reduced batch weights to yield 3.0 **ft^3** are as follows:

Mixture	Basic	Comp #1	Comp #2	Comp #3	Comp #4
Cement, lb	108.56	86.89	81.44	76.00	70.56
Fly ash, lb	—	21.67	27.11	32.56	38.00
Sand, lb	112.00	108.33	107.33	106.44	105.44
Coarse aggregate, lb	207.00	207.00	207.00	207.00	207.00
Water, lb	28.56	28.67	28.67	28.78	28.78
Chemical admixtures (included as part of the mixing water)					

5.2.10 *Step 10--Adjust trial mixture proportions*-The batch weights for each trial mixture were adjusted to obtain the desired slump, before and after the addition of the HRWR, and the desired workability. The adjustments to the batch weights for the basic mixture and companion mixture #4 will be shown in detail. Those for the other three companion mixtures will be summarized.

5.2.10.1 *Basic mixture*

1. Although the amount of water required to produce a 1 to 2-in. slump was calculated to be 28.56 lb, it was found that 29.56 lb (including 2.5 oz/cwt retarding admixture) were actually needed to produce the desired slump. The actual batch weights then were:

Cement	108.56 lb
Sand	112.00 lb
Coarse aggregate	207.00 lb
Water	29.56 lb

Correcting these to dry weights gives:

Cement		108.56 lb
Sand, dry	(112.00)/(1.064) =	105.26 lb
Coarse aggregate, dry	(207.00)/(1.005) =	205.97 lb
Batch water	(29.56 + 5.58* – 0.41†) =	34.73 lb

* = Sand moisture correction.
† = C/A moisture correction.

The actual yield of the trial mixture was:

Cement	(108.56)/(3.15 x 62.4) =	0.55 ft^3
Sand	(105.26)/(2.59 x 62.4) =	0.65
Coarse aggregate	(205.97)/(2.76 x 62.4) =	1.20
Water	(34.73)/(62.4) =	0.56
Air	(0.02)(3.0) =	0.06
	Total volume	3.02 ft^3

Adjusting the mixture proportions to yield 27 **ft^3** gives:

Cement	971 lb
Sand, dry	941 lb
Coarse aggregate, dry	1841 lb
Water (including 2.5 oz/cwt retarding admixture)	311 lb

The new mixture proportions result in a $w/(c+p)$ of 0.32. To maintain the desired ratio of 0.31, the weight of cement should be increased to (311)/(0.31) = 1003 **lb/yd^3** of concrete. The increase in volume due to the adjustment of the weight of cement is (1003 – 971)/(3.15 x 62.4) = 0.16 **ft^3**, which should be adjusted for by removing an equal volume of sand. The weight of sand to be removed is 0.16 x 2.59 x 62.4 = 26 lb. The resulting adjusted mixture proportions are:

Cement	1003 lb
Sand, dry	915 lb
Coarse aggregate, dry	1841 lb
Water (including 2.5 oz/cwt retarding admixture)	311 lb

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 HRWR ranged between 8 and 16 oz/100 lb of cementitious material. In a laboratory having an ambient temperature of 75 F, it was found that adding

HRWR 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. In all cases, a constant dosage rate of retarding admixture (2.5 oz/cwt) was also added to the mixture with the mixing water. The HRWR at a dosage rate of 11 oz/cwt was added approximately 15 min after initial mixing.

3. It was determined that 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 HRWR mixture was measured at 1.8 percent, so no correction was necessary.

5. Note that the addition of the HRWR might require an adjustment in the cementitious content and yield of the mixture to account for the additional volume of admixture. Under normal dosage rates, 10 to 15 oz/cwt, the correction needed is negligible and not shown in this example.

6. The 28-day compressive strength of the basic mixture was found to be 11,750 psi, which satisfied the required laboratory test strength of 11,600 psi.

5.2.10.2 *Companion mixture #4*

1. The actual amount of mixing water required (including 2 oz/cwt retarding admixture) to produce a 1 to 2-in. slump was less than that calculated for this mixture. The actual batch weights were:

Cement	70.56 lb
Fly ash	38.00 lb
Sand	105.44 lb
Coarse aggregate	207.00 lb
Water	27.83 lb

Correcting these by dry weights gives:

Cement	70.56 lb
Fly ash	38.00 lb
Sand, dry	99.10 lb
Coarse aggregate, dry	205.97 lb
Batch water	32.67 lb

The actual yield of the trial mixture was:

Cement	(70.56)/(3.15 x 62.4) =	0.36 ft^3
Fly ash	(38.00)/(2.64 x 62.4) =	0.23
Sand	(99.10)/(2.59 x 62.4) =	0.61
Coarse aggregate	(205.97)/(2.76 x 62.4) =	1.20
Water	(32.67)/(62.4) =	0.52
Air	(0.02)(3.0) =	0.06
	Total volume	2.98 ft^3

Adjusting the mixture proportions to yield 27 ft^3 gives:

Cement	639 lb
Fly ash	344 lb
Sand, dry	898 lb
Coarse aggregate, dry	1866 lb
Water (including 2.5 oz/cwt retarding admixture)	296 lb

The new mixture proportions result in a *w/(c+p)* of 0.30. The desired ratio was 0.31, so the weight of cementitious material may be reduced. The percentage of fly ash for this mixture is 35 percent, and should be maintained. The new weight of cementitious material is (296)/(0.31) = 955 lb. Of this, 35 percent should be fly ash, giving 334 lb of fly ash and 621 lb of cement. The change in volume due to the reduction in cementitious material is:

$$(639 - 621)/(3.15 \times 62.4) + (344 - 334)/(2.64 \times 62.4) = 0.15 \text{ ft}^3$$

Therefore, 0.15 ft^3 of sand should be added, which increases the weight of sand by (0.15)(2.59)(62.4) = 24 lb/yd^3 of concrete. The adjusted mixture proportions are:

Cement	621 lb
Fly ash	334 lb
Sand, dry	922 lb
Coarse aggregate, dry	1866 lb
Water (including 2.5 oz/cwt retarding admixture)	296 lb

2. In adding HRWR to the adjusted mixture to produce a flowing concrete, it was found that 9 oz of HRWR per 100 lb. of cementitious material produced a slump of 9 1/2 in. under laboratory conditions. A retarding admixture (2 oz/cwt) was added to the concrete with mixing water, and the HRWR was added approximately 15 min after initial mixing.

3. The HRWR mixture had adequate workability, so no adjustment to the coarse aggregate content was necessary.

4. The air content of the HRWR mixture was measured at 2.1 percent.

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

5.2.10.3 *Summary of trial mixture performance*-The following is a summary of the results of the adjusted laboratory trial mixtures.

Mixture	Basic	C.M.* #1	C.M. #2	C.M. #3	C.M. #4
Cement, lb	1003	782	738	671	621
Fly ash, lb	—	195	246	287	334
Sand, dry, lb	915	916	914	917	922
Coarse aggregate dry, lb	1841	1854	1866	1854	1866
Water, lb	311	303	301	297	296
Slump, in.	1.00	1.25	1.00	1.50	2.00

Retarder, oz/cwt	3.0	2.5	2.5	2.0	2.0
HRWR, oz/cwt	11.0	11.0	10.0	9.5	9.0
Slump, in.	10.0	10.50	9.00	10.25	9.50
28-day psi	11,750	11,500	11,900	11,600	11,370

* C.M. =companion mix.
Note: This table has intentionally omitted the water in HRWR to avoid confusion. Section 3.2 of this guide suggests this be done to properly determine *w/(c + p)*.

5.3.11 *Step 11-Select optimum mixture proportions*-Companion mix (c.m.) #4 was the only trial mixture that was significantly less than the required compressive strength of 11,600 psi at 28 days. Field trial batches were made for all of the others. The mixtures were adjusted to the desired slumps, both before and after addition of the HRWR, and strength specimens were cast. Concrete temperatures were also recorded. The test results are shown below.

Mixture	28-day compressive strength, psi	Concrete temperature, deg F
Basic	10,410	94
C.M. #1	10,570	93
C.M. #2	10,530	89
C.M. #3	10,490	84

Although all mixtures produced the required field strength of 10,400 psi at 28 days, the reduced concrete temperature and cementitious material content of companion mix #3 made it more desirable to the ready-mix producer. As ambient conditions or material properties vary, additional field adjustments may be necessary.

CHAPTER 6-REFERENCES

6.1-Recommended references

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation.

The preceding publications may be obtained from the following organizations.

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

ASTM International
100 Barr Harbor Dr.
West Conshohocken, PA 19428

American Concrete Institute (ACI)
211.1 Standard Practice for Selecting Proportions for Normal, Heavy Weight, and Mass Concrete
212.3R Chemical Admixtures for Concrete
214 Recommended Practice for Evaluation of Strength Test Results of Concrete
226.1R Ground Granulated Blast Furnace Slag As a Cementitious Constituent in Concrete
301 Specifications for Structural Concrete for Buildings
318 Building Code Requirements for Reinforced Concrete
363R State-of-the-Art Report on High-Strength Concrete

American Society for Testing and Materials (ASTM)
C 29 Standard Test Method for Unit Weight and Voids in Aggregates
C 33 Standard Specification for Concrete Aggregates
C 39 Test Method for Cylindrical Strength of Cylindrical Concrete Specimens
C 94 Specification for Ready Mixed Concrete
C 494 Standard Specification for Chemical Admixtures for Concrete
C 618 Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete
C 917 Standard Method of Evaluation of Cement Strength Uniformity from a Single Source

CONVERSION FACTORS

1 in. = 25.4 mm
1 psi = 6.8 kPa
1 $lb/in.^3$ = 2.768×10^{-5} kg/mm^3
1 lb/yd^3 = 0.59 kg/m^3

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