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Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91)

(Reapproved 2002)

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Describes, with examples, two methods for selecting and adjusting proportions for normal weight concrete, both with and without chemical admixtures pozzolanic, and slag materials. One method is based on an estimated weight of the concrete per unit volume; the other is based on calculations of the absolute volume occupied by the concrete ingredients. The procedures take into consideeration the requirements for placeability, consistency, strength, and durability. Example calculations are shown for both methods, including adjustments based on the cheracteristics of the first trial batch.

The proportioning of heavyweight concrete for such purposes as radiation shielding and bridge counterweight structures is described in an appendix. This appendix uses the absolute volume method, which is generally accepted and is more convenient for heavyweight concrete.

There is also an appendix that provides information on the proportioning of mass concrete. The absolute volume method is used because of its general acceptance.

Keywords: absorption; admixtures; aggregates; blast-furnace slag; cementitious materials; concrete durability; concretes; consistency; durability; exposure; fine aggregates: fly ash; heavyweight aggregates; heavyweight concretes; mass concrete; mix proportioning; pozzolans; quality control; radiation shielding; silica fume; slump tests; volume; water-cement ratio; water-cementitious ratio; workability.

CONTENTS

* Members of Subcommittee A who prepared this standard. The committee acknowledges the significant contribution of William L. Barringer to the work of the subcommittee.

† Members of Subcommittee A who prepared the 1991 revision.

This standard supersedes ACI 211.1-89. It was revised by the Expedited Standardization procedure, effective Nov. 1, 1991. This revision incorporates provisions related to the use of the mineral admixture silica fume in concrete. Chapter 4 has been expanded to cover in detail the effects of the use of silica fume on the proportions of concrete mixtures. Editorial changes have also been made in Chapters 2 through 4, and Chapters 6 through 8.

CHAPTER 1 - SCOPE

1.1 This Standard Practice describes methods for selecting proportions for hydraulic cement concrete made with and without other cementitious materials and chemical admixtures. This concrete consists of normal and/or high-density aggregates (as distinguished from lightweight aggregates) with a workability suitable for usual cast-in-place construction (as distinguished from special mixtures for concrete products manufacture). Also included is a description of methods used for selecting proportions for mass concrete. Hydraulic cements referred to in this Standard Practice are portland cement (ASTM C 150) and blended cement (ASTM C 595). The Standard does not include proportioning with condensed silica fume.

1.2 The methods provide a first approximation of proportions intended to be checked by trial batches in the laboratory or field and adjusted, as necessary, to produce the desired characteristics of the concrete.

1.3 U.S. customary units are used in the main body of the text. Adaption for the metric system is provided in Appendix 1 and demonstrated in an example problem in Appendix 2.

1.4 Test methods mentioned in the text are listed in Appendix 3.

CHAPTER 2 -- INTRODUCTION

2.1 Concrete is composed principally of aggregates, a portland or blended cement, and water, and may contain other cementitious materials and/or chemical admixtures. It will contain some amount of entrapped air and may also contain purposely entrained air obtained by use of an admixture or air-entraining cement. Chemical admixtures are frequently used to accelerate, retard, improve workability, reduce mixing water requirements, increase strength, or alter other properties of the concrete (see ACI 212.3R). Depending upon the type and amount, certain cementitious materials such as fly ash, (see ACI 226.3R) natural pozzolans, ground granulated blast-furnace (GGBF) slag (see ACI 226.1R) and silica fume may be used in conjunction with portland or blended cement for economy or to provide specific properties such as reduced early heat of hydration, improved late-age strength development, or increased resistance to alkali-aggregate reaction and sulfate attack, decreased permeability, and resistance to the intrusion of aggressive solutions (See ACI 225R and ACI 226.1R).

2.2 The selection of concrete proportions involves a balance between economy and requirements for placeability, strength, durability, density, and appearance. The required characteristics are governed by the use to which the concrete will be put and by conditions expected to be encountered at the time of placement. These characteristics should be listed in the job specifications.

2.3 The ability to tailor concrete properties to job needs reflects technological developments that have taken place, for the most part, since the early 1900s. The use of water-cement ratio as a tool for estimating strength was recognized about 1918. The remarkable improvement in durability resulting from the entrainment of air was recognized in the early 1940s. These two significant developments in concrete technology have been augmented by extensive research and development in many related areas, including the use of admixtures to counteract possible deficiencies, develop special properties, or achieve economy (ACI 212.2R). It is beyond the scope of this discussion to review the theories of concrete proportioning that have provided the background and sound technical basis for the relatively simple methods of this Standard Practice. More detailed information can be obtained from the list of references in Chapter 8.

2.4 Proportions calculated by any method must always be considered subject to revision on the basis of experience with trial batches. Depending on the circumstances, the trial mixtures may be prepared in a laboratory, or, perhaps preferably, as full-size field batches. The latter procedure, when feasible, avoids possible pitfalls of assuming that data from small batches mixed in a laboratory environment will predict performance under field conditions. When using maximum-size aggregates larger than 2 in., laboratory trial batches should be verified and adjusted in the field using mixes of the size and type to be used during construction. Trial batch procedures and background testing are described in Appendix 3.

2.5 Frequently, existing concrete proportions not containing chemical admixtures and/or materials other than hydraulic cement are reproportioned to include these materials or a different cement. The performance of the reproportioned concrete should be verified by trial batches in the laboratory or field.

CHAPTER 3 -- BASIC RELATIONSHIP

3.1 Concrete proportions must be selected to provide necessary placeability, density, strength, and durability for the particular application. In addition, when mass concrete is being proportioned, consideration must be given to generation of heat. Well-established relationships governing these properties are discussed next.

3.2 *Placeability* -- Placeability (including satisfactory finishing properties) encompasses traits loosely accumulated in the terms "workability" and "consistency." For the purpose of this discussion, workability is considered to be that property of concrete that determines its capacity to be placed and consolidated properly and to be finished without harmful segregation. It embodies such concepts as moldability, cohesiveness, and compactability. Workability is affected by: the grading, particle shape, and proportions of aggregate; the amount and qualities of cement and other cementitious materials; the presence of entrained air and chemical admixtures; and the consistency of the mixture. Procedures in this Standard Practice permit these factors to be taken into account to achieve satisfactory placeability economically.

3.3 *Consistency* -- Loosely defined, consistency is the relative mobility of the concrete mixture. It is measured in terms of slump -- the higher the slump the more mobile the mixture -- and it affects the ease with which the concrete will flow during placement. It is related to but not synonymous with workability. In properly proportioned concrete, the unit water content required to produce a given slump will depend on several factors. Water requirement increases as aggregates become more angular and rough textured (but this disadvantage may be offset by improvements in other characteristics such as bond to cement paste). Required mixing water decreases as the maximum size of well-graded aggregate is increased. It also decreases with the entrainment of air. Mixing water requirements usually are reduced significantly by certain chemical water-reducing admixtures.

3.4 *Strength* -- Although strength is an important characteristic of concrete, other characteristics such as durability, permeability, and wear resistance are often equally or more important. Strength at the age of 28 days is frequently used as a parameter for the structural design, concrete proportioning, and evaluation of concrete. These may be related to strength in a general way, but are also affected by factors not significantly associated with strength. In mass concrete, mixtures are generally proportioned to provide the design strength at an age greater than 28 days. However, proportioning of mass concrete should also provide for adequate early strength as may be necessary for form removal and form anchorage.

3.5 *Water-cement or water-cementitious ratio [w/c or w/(c + p)]* -- For a given set of materials and conditions, concrete strength is determined by the net quantity of water used per unit quantity of cement or total cementitious materials. The net water content excludes water absorbed by the aggregates. Differences in strength for a given water-cement ratio *w/c* or water-cementitious materials ratio *w/(c + p)* may result from changes in: maximum size of aggregate; grading, surface texture, shape, strength, and stiffness of aggregate particles; differences in cement types and sources; air content; and the use of chemical admixtures that affect the cement hydration process or develop cementitious properties themselves. To the extent that these effects are predictable in the general sense, they are taken into account in this Standard Practice. In view of their number and complexity, it should be obvious that accurate predictions of strength must be based on trial batches or experience with the materials to be used.

3.6 *Durability* -- Concrete must be able to endure those exposures that may deprive it of its serviceability -- freezing and thawing, wetting and drying, heating and cooling, chemicals, deicing agents, and the like. Resistance to some of these may be enhanced by use of special ingredients: low-alkali cement, pozzolans, GGBF slag, silica fume, or aggregate selected to prevent harmful expansion to the alkali-aggregate reaction that occurs in some areas when concrete is exposed in a moist environment; sulfate-resisting cement, GGBF slag, silica fume, or other pozzolans for concrete exposed to seawater or sulfate-bearing soils; or aggregate composed of hard minerals and free of excessive soft particles where resistance to surface abrasion is required Use of low water-cement or cementitious materials ratio *[w/c or w/(c + p)]* will prolong the life of concrete by reducing the penetration of aggressive liquids. Resistance to severe weathering, particularly freezing and thawing, and to salts used for ice removal is greatly improved by incorporation of a proper distribution of entrained air. Entrained air should be used in all exposed concrete in climates where freezing occurs. (See ACI 201.2R for further details).

3.7 *Density* -- For certain applications, concrete may be used primarily for its weight characteristic. Examples of applications are counterweights on lift bridges, weights for sinking oil pipelines under water, shielding from radiation, and insulation from sound. By using special aggregates, placeable concrete of densities as high as 350 lb/ft^3 can be obtained--see Appendix 4.

3.8 *Generation of heat* -- A major concern in proportioning mass concrete is the size and shape of the completed structure or portion thereof. Concrete placements large enough to require that measures be taken to control the generation of heat and resultant volume change within the mass will require consideration of temperature control measures. As a rough guide, hydration of cement will generate a concrete temperature rise of 10 to 15 F per 100 lb of portland cement/yd^3 in 18 to 72 hours. If the temperature rise of the concrete mass is not held to a minimum and the heat is allowed to dissipate at a reasonable rate, or if the concrete is subjected to severe temperature differential or thermal gradient, cracking is likely to occur. Temperature control measures can include a relatively low initial placing temperature, reduced quantities of cementitious materials, circulation of chilled water, and, at times, insulation of concrete surfaces as may be required to adjust for these various concrete conditions and exposures. It should be emphasized that mass concrete is not necessarily large-aggregate concrete and that concern about generation of an excessive amount of heat in concrete is not confined to massive dam or foundation structures. Many large structural elements may be massive enough that heat generation should be considered, particularly when the minimum cross-sectional dimensions of a solid concrete member approach or exceed 2 to 3 ft or when cement contents above 600 lb/yd^3 are being used.

CHAPTER 4--EFFECTS OF CHEMICAL ADMIXTURES, POZZOLANIC, AND OTHER MATERIALS ON CONCRETE PROPORTIONS

4.1 *Admixtures* -- By definition (ACI 116R), an admixture is "a material other than water, aggregates, hydraulic cement, and fiber reinforcement used as an ingredient of concrete or mortar and added to the batch immediately before or during its mixing." Consequently, the term embraces an extremely broad field of materials and products, some of which are widely used while others have limited application. Because of this, this Standard Practice is restricted to the effects on concrete proportioning of air-entraining admixtures, chemical admixtures, fly ashes, natural pozzolans, and ground granulated blast-furnace slags (GGBF slag).

4.2 *Air-entraining admixture* -- Air-entrained concrete is almost always achieved through the use of an air-entraining admixture, ASTM C 260, as opposed to the earlier practice in which an air-entraining additive is interground with the cement. The use of an air-entraining admixture gives the concrete producer the flexibility to adjust the entrained air content to compensate for the many conditions affecting the amount of air entrained in concrete, such as: characteristics of aggregates, nature and proportions of constituents of the concrete admixtures, type and duration of mixing, consistency, temperature, cement fineness and chemistry, use of other cementitious materials or chemical admixtures, etc. Because of the lubrication effect of the entrained air bubbles on the mixture and because of the size and grading of the air voids, air-entrained concrete usually contains up to 10 percent less water than non-air-entrained concrete of equal slump. This reduction in the volume of mixing water as well as the volume of entrained and entrapped air must be considered in proportioning.

4.3 *Chemical admixtures* -- Since strength and other important concrete qualities such as durability, shrinkage, and cracking are related to the total water content and the *w/c* or $w/(c + p)$, water-reducing admixtures are often used to improve concrete quality. Further, since less cement can be used with reduced water content to achieve the same *w/c* or $w/(c + p)$ or strength, water-reducing and set-controlling admixtures are used widely for reasons of economy (ACI 212.2R).

Chemical admixtures conforming to ASTM C 494, Types A through G, are of many formulations and their purpose purposes for use in concrete are as follows:

Type A -- Water-reducing
Type B -- Retarding
Type C -- Accelerating
Type D -- Water-reducing and retarding
Type E -- Water-reducing, and accelerating
Type F -- Water-reducing, high-range
Type G -- Water-reducing, high-range, and retarding

The manufacturer or manufacturer's literature should be consulted to determine the required dosage rate for each specific chemical admixture or combination of admixtures. Chemical admixtures have tendencies, when used in large doses, to induce strong side-effects such as excessive retardation and, possibly, increased air entrainment, in accordance with ASTM C 1017. Types A, B, and D, when used by themselves, are generally used in small doses (2 to 7 oz/100 lb of cementitious materials), so the water added to the mixture in the form of the admixture itself can be ignored. Types C, E, F, and G are most often used in large quantities (10 to 90 oz/100 lb of cementitious materials) so their water content should be taken into account when calculating the total unit water content and the *w/c or* $w/(c + p)$. When Types A, B, and D admixtures are used at higher than normal dosage rates in combination or in an admixture system with an accelerating admixture (Type C or E), their water content should also be taken into account.

Although chemical admixtures are of many formulations, their effect on water demand at recommended dosages is governed by the requirements of ASTM C 494. Recommended dosage rates are normally established by the manufacturer of the admixture or by the user after extensive tests. When used at normal dosage rates, Type A water-reducing, Type D water-reducing and retarding, and Type E water-reducing and accelerating admixtures ordinarily reduce mixing-water requirements 5 to 8 percent, while Type F water-reducing, high-range, and Type G water-reducing, high-range, and retarding admixtures reduce water requirements 12 to 25 percent or more. Types F and G water-reducing, high-range admixtures (HRWR) are often called "superplasticizers."

High-range, water-reducing admixtures are often used to produce flowing concrete with slumps between about 7$^1/_2$ or more with no increase in water demand other than that contained in the admixture itself. Types A, B, or D admixtures at high dosage rates, in combination with Types C or E (for acceleration), may also be used to produce the same effect. When flowing concrete is so produced, it is sometimes possible to increase the amount of coarse aggregate to take advantage of the fluidity of the concrete to flow into place in constricted areas of heavy reinforcement. Flowing concrete has a tendency to segregate; therefore, care must be taken to achieve a proper volume of mortar in the concrete required for cohesion without making the concrete undesirably sticky.

ASTM C 494 lists seven types of chemical admixtures as to their expected performance in concrete. It does not classify chemical admixtures as to their composition. ACI 212.2R lists five general classes of materials used to formulate most water-reducing, set-controlling chemical admixtures. This report, as well as ACI 301 and ACI 318, should be reviewed to determine when restrictions should be placed upon the use of certain admixtures for a given class of concrete. For example, admixtures containing purposely added calcium chloride have been found to accelerate the potential for stress-corrosion of tensioned cables imbedded in concrete when moisture and oxygen are available.

4.4 *Other cementitious materials* -- Cementitious materials other than hydraulic cement are often used in concrete in combination with portland or blended cement for economy, reduction of heat of hydration, improved workability, improved strength and/or improved durability under the anticipated service environment. These materials include fly ash, natural pozzolans (ASTM C 618), GGBF slag (ASTM C 989), and silica fune. Not all of these materials will provide all of the benefits listed.

As defined in ASTM C 618, pozzolans are: "Siliceous or siliceous and aluminous materials which in themselves 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 possessing cementitious properties . . . " Fly ash is the "finely divided residue that results from the combustion of ground or powdered coal . . . ' Fly ash used in concrete is classified into two categories: Class F, which has pozzolanic properties, and Class C, which, in addition to having pozzolanic properties, also has some cemetitious properties in that this material may be self-setting when mixed with water. Class C fly ash may contain lime (CaO) amounts higher than 10 percent. The use of fly ash in concrete is more fully described and discussed in ACI 226.3R.

Blast-furnace slag is a by-product of the production of pig iron. When this slag is rapidly quenched and ground, it will possess latent cementitious properties. After processing, the material is known as GGBF slag, whose hydraulic properties may vary and can be separated into grades noted in ASTM C 989. The grade classification gives guidance on the relative strength potential of 50 percent GGBF slag mortars to the reference portland cement at 7 and 28 days. GGBF slag grades are 80, 100, and 120, in order of increasing strength potential.

Silica fume,* as used in concrete, is a by-product resulting from the reduction of high-purity quartz with coal 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 fiie spherical particles.

Uses of silica fume in concrete fall into three general categories:

a. Production of low permeability concrete with enhanced durability.
b. Production of high-strength concrete.
c. As a cement replacement (The current economics of cement costs versus silica fume costs do not usually make this a viable use for silica fume in the U.S.).

* Other names that have been used include silica dust, condensed or pre-compacted silica fume and micro silica; the most appropriate is silica fume.

Silica fume typically has a specific gravity of about 2.2. The lower specific gravity of silica fume compared with that of portland cement means that when replacement is based on weight (mass), a larger volume of silica fume is added than the volume of cement removed. Thus, the volume of cementitious paste increases and there is actually a lowering of the water-cementitious materials ratio on a volume basis.

The particle-size distribution of a typical silica fume shows that most particles are smaller than one micrometer (1 **μm** with an average diameter of about 0.1 **μm,** which is approximately one hundred times smaller than the average size cement particle).

The extreme fineness and high silica content of silica fume make it a highly effective pozzolanic material. The silica fume reacts pozzolanically with the calcium hydroxide produced during the hydration of cement to form the stable cementitious compound, calcium silicate hydrate (CSH).

Silica fume has been successfully used to produce very high strength (over 18,000 psi), low permeability, and chemically resistant concretes. Such concretes contain up to 25 percent silica fume by weight (mass) of cement. The use of this high amount of silica fume generally makes the concrete difficult to work. The mixing water demand of a given concrete mixture incorporating silica fume increases with increasing amounts of silica fume.

To maximize the full strength-producing potential of silica fume in concrete, it should always be used with a water-reducing admixture, preferably a high-range, water-reducing (HRWR) admixture. the dosage of the HRWR will depend on the percentages of silica fume and the type of HRWR used.

When proportioning concrete containing silica fume, the following should be considered:

a. Mixing -- The amount of mixing will depend on the percentage of silica fume used and the mixing conditions. Mixing time may need to be increased to achieve thorough distribution when using large quantities of silica fume with low water content concrete. The use of HRWR assists greatly in achieving uniform dispersion.
b. Air-entrainment -- The amount of air-entraining admixture to produce a required volume of air in concrete may increase with increasing amounts of silica fume due to the very high surface area of the silica fume and the presence of any carbon within the silica fume. Air entrainment is not usually used in high strength concretes unless they are expected to be exposed to freezing and thawing when saturated with water or to deicing salts.
c. Workability -- Fresh concrete containing silica fume is generally more cohesive and less prone to segregation than concrete without silica fume. This increase in cohesiveness and reduction to bleeding can provide improved pumping properties. Concrete containing silica fume in excess of 10 percent by

weight (mass) of the cementitious materials may become sticky. It may be necessary to increase the slump 2 to 5 in. to maintain the same workability for a given length of time.

d. Bleeding -- Concrete containing silica fume exhibits reduced bleeding. This reduced bleeding is primarily caused by the high surface area of the silica fume particles, resulting in very little water being left in the mixture for bleeding. As the result of reduced bleeding of concrete containing silica fume, there is a greater tendency for plastic shrinkage cracking to occur.

Typically, the materials listed previously are introduced into the concrete mixer separately. In some cases, however, these same materials may be blended with portland cement in fixed proportions to produce a blended cement, ASTM C 595. Like air-entraining admixtures added to the concrete at the time of batching, the addition of GGBF slag also gives the producer flexibility to achieve desired concrete performance.

When proportioning concrete containing a separately batched, cementitious material such as fly ash, natural pozzolan, GGBF slag, or silica fume, a number of factors must be considered. These include:

a. Chemical activity of the cementitious material and its effect on concrete strength at various ages.
b. Effect on the mixing-water demand needed for workability and placeability.
c. Density (or specific gravity) of the material and its effect on the volume of concrete produced in the batch.
d. Effect on the dosage rate of chemical admixtures and/or air-entraining admixtures used in the mixture.
e. Effect of combinations of materials on other critical properties of the concrete, such as time of set under ambient temperature conditions, heat of hydration, rate of strength development, and durability.
f. Amount of cementitious materials and cement needed to meet the requirements for the particular concrete.

4.4.1 Methods for proportioning and evaluating concrete mixtures containing these supplementary cementitious materials must be based on trial mixtures using a range of ingredient proportions. By evaluating their effect on strength, water requirement, time of set, and other important properties, the optimum amount of cementitious materials can be determined. In the absence of prior information and in the interest of preparing estimated proportions for a first trial batch or a series of trial batches in accordance with ASTM C 192, the following general ranges are given based on the percentage of the ingredients by the total weight of cementitious material used in the batch for structural concrete:

Class F fly ash -- 15 to 25 percent
Class C fly ash -- 15 to 35 percent
Natural pozzolans -- 10 to 20 percent
Ground granulated blast-furnace slag -- 25 to 70 percent
Silica fume -- 5 to 15 percent

For special projects, or to provide certain special required properties, the quantity of the materials used per yd^3 of concrete may be different from that shown above.

In cases where high early strengths are required, the total weight of cementitious material may be greater than would be needed if portland cement were the only cementitious material. Where high early strength is not required higher percentages of fly ash are frequently used.

Often, it is found that with the use of fly ash and GGBF slag, the amount of mixing water required to obtain the desired slump and workability of concrete may be lower than that used in a portland cement mixture using only portland cement. When silica fume is used, more mixing water is usually required than when using only portland cement. In calculating the amount of chemical admixtures to dispense for a given batch of concrete, the dosage should generally be applied to the total amount of cementitious material. Under these conditions the reduction in mixing water for conventional water-reducing admixtures (Types A, D, and E) should be at least 5 percent, and for water-reducing, high-range admixtures at least 12 percent. When GGBF slag is used in concrete mixtures containing some high-range water-reducing admixtures, the admixture dosage may be reduced by approximately 25 percent compared to mixtures containing only portland cement.

4.4.2 Due to differences in their specific gravities, a given weight of a supplementary cementitious material will not occupy the same volume as an equal weight of portland cement. The specific gravity of blended cements will be less than that of portland cement. Thus, when using either blended cements or supplementary cementitious materials, the yield of the concrete mixture should be adjusted using the actual specific gravities of the materials used.

4.4.3 Class C fly ash, normally of extremely low carbon content, usually has little or no effect on entrained air or on the air-entraining admixture dosage rate. Many Class F fly ashes may require a higher dosage of air-entraining admixture to obtain specified air contents; if carbon content is high, the dosage rate may be several times that of non-fly ash concrete. The dosage required may also be quite variable. The entrained air content of concrete containing high carbon-content fly ash may be difficult to obtain and maintain. Other cementitious materials may be treated the same as cement in determining the proper quantity of air-entraining admixtures per yd^3 of concrete or per 100 lb of cementitious material used.

4.4.4 Concrete containing a proposed blend of cement, other cementitious materials, and admixtures should be tested to determine the time required for setting at various temperatures. The use of most supplementary cementitious materials generally slows the time-of-set of the concrete, and this period may be prolonged by higher percentages of these materials in the cementitious blend, cold weather, and the presence of chemical admixtures not formulated especially for acceleration.

Because of the possible adverse effects on finishing time and consequent labor costs, in some cold climates the proportion of other cementitious materials in the blend may have to be reduced below the optimum amount for strength considerations. Some Class C fly ashes may affect setting time while some other cementitious materials may have little effect on setting time. Any reduction in cement content will reduce heat generation and normally prolong the setting time.

CHAPTER 5 -- BACKGROUND DATA

5.1 To the extent possible, selection of concrete proportions should be based on test data or experience with the materials actually to be used. Where such background is limited or not available, estimates given in this recommended practice may be employed.

5.2 The following information for available materials will be useful:

5.2.1 Sieve analyses of fine and coarse aggregates.

5.2.2 Unit weight of coarse aggregate.

5.2.3 Bulk specific gravities and absorptions of aggregates.

5.2.4 Mixing-water requirements of concrete developed from experience with available aggregates.

5.2.5 Relationships between strength and water-cement ratio or ratio of water-to-cement plus other cementitious materials, for available combinations of cements, other cementitious materials if considered, and aggregates.

5.2.6 Specific gravities of portland cement and other cementitious materials, if used.

5.2.7 Optimum combination of coarse aggregates to meet the maximum density gradings for mass concrete as discussed in Section 5.3.2.1 of Appendix 5.

5.3 Estimates from Tables 6.3.3 and 6.3.4, respectively, may be used when items in Section 5.2.4 and Section 6.3.5 are not available. As will be shown, proportions can be estimated without the knowledge of aggregate-specific gravity and absorption, Section 5.2.3.

CHAPTER 6 -- PROCEDURE

6.1 The procedure for selection of mix proportions given in this section is applicable to normal weight concrete. Although the same basic data and procedures can be used in proportioning heavyweight and mass concretes, additional information and sample computations for these types of concrete are given in Appendixes 4 and 5, respectively.

6.2 Estimating the required batch weights for the concrete involves a sequence of logical, straightforward steps which, in effect, fit the characteristics of the available materials into a mixture suitable for the work. The question of suitability is frequently not left to the individual selecting the proportions. The job specifications may dictate some or all of the following:

6.2.1 Maximum water-cement or water-cementitious material ratio.

6.2.2 Minimum cement content.

6.2.3 Air content.

6.2.4 Slump.

6.2.5 Maximum size of aggregate.

6.2.6 Strength.

6.2.7 Other requirements relating to such things as strength overdesign, admixtures, and special types of cement, other cementitious materials, or aggregate.

6.3 Regardless of whether the concrete characteristics are prescribed by the specifications or are left to the individual selecting the proportions, establishment of batch weights per yd^3 of concrete can be best accomplished in the following sequence:

6.3.1 *Step 1. Choice of slump* -- If slump is not specified, a value appropriate for the work can be selected from Table 6.3.1. The slump ranges shown apply when vibration is used to consolidate the concrete. Mixes of the stiffest consistency that can be placed efficiently should be used.

Table 6.3.1 — Recommended slumps for various types of construction*

Types of construction	Slump, in. Maximum+	Slump, in. Minimum
Reinforced foundation walls and footings	3	1
Plain footings, caissons, and substructure walls	3	1
Beams and reinforced walls	4	1
Building columns	4	1
Pavements and slabs	3	1
Mass concrete	2	1

*Slump may be increased when chemical admixtures are used, provided that the admixture-treated concrete has the same or lower water-cement or water-cementitious material ratio and does not exhibit segregation potential or excessive bleeding.
+May be increased 1 in. for methods of consolidation other than vibration.

6.3.2 *Step 2. Choice of maximum size of aggregate* -- Large nominal maximum sizes of well graded aggregates have less voids than smaller sizes. Hence, concretes with the larger-sized aggregates require less mortar per unit volume of concrete. Generally, the nominal maximum size of aggregate should be the largest that is economically available and consistent with dimensions of the structure. In no event should the nominal maximum size exceed one-fifth of the narrowest dimension between sides of forms, one-third the depth of slabs, nor three-fourths of the minimum clear spacing between individual reinforcing bars, bundles of bars, or pretensioning strands. These limitations are sometimes waived if workability and methods of consolidation are such that the concrete can be placed without honeycomb or void. In areas congested with reinforcing steel, post-tension ducts or conduits, the proportioner should select a nominal maximum size of the aggregate so concrete can be placed without excessive segregation, pockets, or voids. When high strength concrete is desired, best results may be obtained with reduced nominal maximum sizes of aggregate since these produce higher strengths at a given water-cement ratio.

Table 6.3.3 — Approximate mixing water and air content requirements for different slumps and nominal maximum sizes of aggregates

	Water, lb/yd³ of concrete for indicated nominal maximum sizes of aggregate							
Slump, in.	⅜ in.*	½ in.*	¾ in.*	1 in.*	1-½ in.*	2 in.*,†	3 in.†,‡	6 in.†,‡
Non-air-entrained concrete								
1 to 2	350	335	315	300	275	260	220	190
3 to 4	385	365	340	325	300	285	245	210
6 to 7	410	385	360	340	315	300	270	—
More than 7*	—	—	—	—	—	—	—	—
Approximate amount of entrapped air in non-air-entrained concrete, percent	3	2.5	2	1.5	1	0.5	0.3	0.2
Air-entrained concrete								
1 to 2	305	295	280	270	250	240	205	180
3 to 4	340	325	305	295	275	265	225	200
6 to 7	365	345	325	310	290	280	260	—
More than 7*	—	—	—	—	—	—	—	—
Recommended averages§ total air content, percent for level of exposure:								
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5**,††	1.0**,††
Moderate exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5**,††	3.0**,††
Severe exposure‡‡	7.5	7.0	6.0	6.0	5.5	5.0	4.5**,††	4.0**,††

*The quantities of mixing water given for air-entrained concrete are based on typical total air content requirements as shown for "moderate exposure" in the table above. These quantities of mixing water are for use in computing cement contents for trial batches at 68 to 77 F. They are maximum for reasonably well-shaped angular aggregates graded within limits of accepted specifications. Rounded aggregate will generally require 30 lb less water for non-air-entrained and 25 lb less for air-entrained concretes. The use of water-reducing chemical admixtures, ASTM C 494, may also reduce mixing water by 5 percent or more. The volume of the liquid admixtures is included as part of the total volume of the mixing water. The slump values of more than 7 in. are only obtained through the use of water-reducing chemical admixture; they are for concrete containing nominal maximum size aggregate not larger than 1 in.

†The slump values for concrete containing aggregate larger than 1½ in. are based on slump tests made after removal of particles larger than 1½ in. by wet-screening.

‡These quantities of mixing water are for use in computing cement factors for trail batches when 3 in. or 6 in. nominal maximum size aggregate is used. They are average for reasonably well-shaped coarse aggregates, well-graded from coarse to fine.

§Additional recommendations for air-content and necessary tolerances on air content for control in the field are given in a number of ACI documents, including ACI 201, 345, 318, 301, and 302. ASTM C 94 for ready-mixed concrete also gives air-content limits. The requirements in other documents may not always agree exactly, so in proportioning concrete consideration must be given to selecting an air content that will meet the needs of the job and also meet the applicable specifications.

**For concrete containing large aggregates that will be wet-screened over the 1½ in. sieve prior to testing for air content, the percentage of air expected in the 1½ in. minus material should be as tabulated in the 1½ in. column. However, initial proportioning calculations should include the air content as a pecent of the whole.

††When using large aggregate in low cement factor concrete, air entrainment need not be detrimental to strength. In most cases mixing water requirement is reduced sufficiently to improve the water-cement ratio and to thus compensate for the strength-reducing effect of air-entrained concrete. Generally, therefore, for these large nominal maximum sizes of aggregate, air contents recommended for extreme exposure should be considered even though there may be little or no exposure to moisture and freezing.

‡‡These values are based on the criteria that 9 percent air is needed in the mortar phase of the concrete. If the mortar volume will be substantially different from that determined in this recommended practice, it may be desirable to calculate the needed air content by taking 9 percent of the actual mortar volume.

6.3.3 *Step 3. Estimation of mixing water and air content* -- The quantity of water per unit volume of concrete required to produce a given slump is dependent on: the nominal maximum size, particle shape, and grading of the aggregates; the concrete temperature; the amount of entrained air; and use of chemical admixtures. Slump is not greatly affected by the quantity of cement or cementitious materials within normal use levels (under favorable circumstances the use of some finely divided mineral admixtures may lower water requirements slightly -- see ACI 212.1R). Table 6.3.3 provides estimates of required mixing water for concrete made with various maximum sizes of aggregate, with and without air entrainment. Depending on aggregate texture and shape, mixing water requirements may be somewhat above or below the tabulated values, but they are sufficiently accurate for the first estimate. The differences in water demand are not necessarily reflected in strength since other compensating factors may be involved. A rounded and an angular coarse aggregate, both well and similarly graded and of good quality, can be expected to produce concrete of about the same compressive strength for the same cement factor in spite of differences in w/c or $w/(c + p)$ resulting from the different mixing water requirements. Particle shape is not necessarily an indicator that an aggregate will be either above or below in its strength-producing capacity.

Chemical admixtures -- Chemical admixtures are used to modify the properties of concrete to make it more workable, durable, and/or economical; increase or decrease the time of set; accelerate strength gain; and/or control temperature gain. Chemical admixtures should be used only after an appropriate evaluation has been conducted to show that the desired effects have been accomplished in the particular concrete under the conditions of intended use. Water-reducing and/or set-controlling admixtures conforming to the requirements of ASTM C 494, when used singularly or in combination with other chemical admixtures, will reduce significantly the quantity of water per unit volume of concrete. The use of some chemical admixtures, even at the same slump, will improve such qualities as workability, finishability, pumpability, durability, and compressive and flexural strength. Significant volume of liquid admixtures should be considered as part of the mixing water. The slumps shown in Table 6.3.1, "Recommended Slumps for Various Types of Construction," may be increased when chemical admixtures are used, providing the admixture-treated concrete has the same or a lower water-cement ratio and does not exhibit segregation potential and excessive bleeding. When only used to increase slump, chemical admixtures may not improve any of the properties of the concrete.

Table 6.3.3 indicates the approximate amount of entrapped air to be expected in non-air-entrained concrete in the upper part of the table and shows the recommended average air content for air-entrained concrete in the lower part of the table. If air entrainment is needed or desired, three levels of air content are given for each aggregate size depending on the purpose of the entrained air and the severity of exposure if entrained air is needed for durability.

Mild exposure -- When air entrainment is desired for a beneficial effect other than durability, such as to improve workability or cohesion or in low cement factor concrete to improve strength, air contents lower than those needed for durability can be used. This exposure includes indoor or outdoor service in a climate where concrete will not be exposed to freezing or to deicing agents.

Moderate exposure -- Service in a climate where freezing is expected but where the concrete will not be continually exposed to moisture or free water for long periods prior to freezing and will not be exposed to deicing agents or other aggressive chemicals. Examples include: exterior beams, columns, walls, girders, or slabs that are not in contact with wet soil and are so located that they will not receive direct applications of deicing salts.

Severe exposure -- Concrete that is exposed to deicing chemicals or other aggressive agents or where the concrete may become highly saturated by continued contact with moisture or free water prior to freezing. Examples include: pavements, bridge decks, curbs, gutters, sidewalks, canal linings, or exterior water tanks or sumps.

The use of normal amounts of air entrainment in concrete with a specified strength near or about 5000 psi may not be possible due to the fact that each added percent of air lowers the maximum strength obtainable with a given combination of materials.' In these cases the exposure to water, deicing salts, and freezing temperatures should be carefully evaluated. If a member is not 'continually wet and will not be exposed to deicing salts, lower air-content values such as those given in Table 6.3.3 for moderate exposure are appropriate even though the concrete is exposed to freeziug and thawing temperatures. However, for an exposure condition where the member may be saturated prior to freezing, the use of air entrainment should not be sacrificed for strength. In certain applications, it may be found that the content of entrained air is lower than that specified, despite the use of usually satisfactory levels of air-entraining admixture. This happens occasionally, for example, when very high cement contents are involved. In such cases, the achievement of required durability may be demonstrated by satisfactory results of examination of air-void structure in the paste of the hardened concrete.

When trial batches are used to establish strength relationships or verify strength-producing capability of a mixture, the least favorable combination of mixing water and air content should be used. The air content should be the maximum permitted or likely to occur, and the concrete should be gaged to the highest permissrble slump. This will avoid developing an over-optimistic estimate of strength on the assumption that average rather than extreme conditions will prevail in the field. If the concrete obtained in the field has a lower slump and/or air content, the proportions of ingredients should be adjusted to maintain required yield. For additional information on air content recommendations, see ACI 201.2R, 301, and 302.1R.

6.3.4 *Step 4. Selection of water-cement or water-cementitious materials ratio* -- The required *w/c* or *w/(c + p)* is determined not only by strength requirements but also by factors such as durability. Since different aggregates, cements, and cementitious materials generally produce different strengths at the same *w/c* or *w/(c + p)*, it is highly desirable to have or to develop the relationship between strength and *w/c* or *w/(c + p)* for the materials actually to be used. In the absence of such data, approximate and relatively conservative values for concrete containing Type I portland cement can be taken from Table 6.3.4(a). With typical materials, the tabulated *w/c* or *w/(c + p)* should produce the strengths shown, based on 28-day tests of specimens cured under standard laboratory conditions. The average strength selected must, of course, exceed the specific strength by a sufficient margin to keep the number of low tests within specific limits -- see ACI 214 and ACI 318.

Table 6.3.4(a) — Relationship between water-cement or water-cementitious materials ratio and compressive strength of concrete

Compressive strength at 28 days, psi*	Water-cement ratio, by weight	
	Non-air-entrained concrete	Air-entrained concrete
6000	0.41	—
5000	0.48	0.40
4000	0.57	0.48
3000	0.68	0.59
2000	0.82	0.74

*Values are estimated average strengths for concrete containing not more than 2 percent air for non-air-entrained concrete and 6 percent total air content for air-entrained concrete. For a constant *w/c* or *w/(c+p)*, the strength of concrete is reduced as the air content is increased. 28-day strength values may be conservative and maychange when various cementitious materials are used. The rate at which the 28-day strength is developed may also change.

Strength is based on 6 x 12 in. cylinders moist-cured for 28 days in accordance with the sections on "Initial Curing" and "Curing of Cylinders for Checking the Adequacy of Laboratory Mixture Proportions for Strength or as the Basis for Acceptance or for Quality Control" of ASTM method C 31 for Making and Curing Concrete Specimens in the Field. These are cylinders cured moist at 73.4 ± 3 F (23 ± 1.7 C) prior to testing.

The relationship in this table assumes a nominal maximum aggregate size of about 3/4 to 1 in. For a given source of aggregate, strength produced at a given *w/c* or *w/(c+ p)* will increase as nominal maximum size of aggregate decreases: see Sections 3.4 and 6.3.2.

For severe conditions of exposure, the *w/c* or *w/(c + p)* ratio should be kept low even though strength requirements may be met with a higher value. Table 6.3.4(b) gives limiting values.

When natural pozzolans, fly ash, GGBF slag, and silica fume, hereafter referred to as pozzolanic materials, are used in concrete, a water-to-cement plus pozzolanic materials ratio (or water-to-cement plus other cementitious materials ratio) by weight must be considered in place of the traditional water-cement ratio by weight. There are two ap-

Table 6.3.4(b) — Maximum permissible water-cement or water-cementitious materials ratios for concrete In severe exposures*

Type of structure	Structure wet continuously or frequently and exposed to freezing and thawing+	Structure exposed to sea water or sulfates
Thin sections (railings, curbs, sills, ledges, ornamental work) and sections with less than 1 in. cover over steel	0.45	0.40+
All other structures	0.50	0.45+

*Based on report of ACI Committee 201. Cementitious materials other than cement should conform to ASTM C 618 and C 989.
"Concrete should also be air-entrained.
+If sulfate resisting cement (Type II or Type V of ASTM C 150) is used, permissible water-cement or water-cementitious materials ratio may be increased by 0.05.

proaches normally used in determining the $w/(c+p)$ ratio that will be considered equivalent to the w/c of a mixture containing only portland cement: (1) equivalent weight of pozzolanic materials or (2) equivalent absolute volume of pozzolanic materials in the mixture. For the first approach, the weight equivalency, the total weight of pozzolanic materials remains the same [that is, $w/(c+p) = w/c$ directly]: but the total absolute volume of cement plus pozzolanic materials will normally be slightly greater. With the second approach, using the Eq. (6.3.4.2), a $w/(c+p)$ by weight is calculated that maintains the same absolute volume relationship but that will reduce the total weight of cementitious material since the specific gravities of pozzolanic materials are normally less than that of cement.

The equations for converting a target water-cement ratio w/c to a weight ratio of water to cement plus pozzolanic materials $w/(c+p)$ by (1) weight equivalency or (2) volume equivalency are as follows:

Eq. (6.3.4.1)--Weight equivalency

$$\frac{w}{c+p} \text{ weight ratio, weight equivalency} = \frac{w}{c}$$

where

$\frac{w}{c+p}$ = *weight of water divided by weight of cement + pozzolanic materials*

$\frac{w}{c}$ = *target water-cement ratio by weight*

When the weight equivalency approach is used, the percentage or fraction of pozzolanic materials used in the cementitious material is usually expressed by weight. That is, F_w, the pozzolanic materials percentage by weight of total cement plus pozzolanic materials, expressed as a decimal factor, is

$$F_w = \frac{p}{c+p}$$

where

F_w = pozzolanic materials percentage by weight, expressed as a decimal factor
p = weight of pozzolanic materials
c = weight of cement

(Note: If only the desired pozzolanic materials percentage factor by absolute volume F_v, is known, it can be converted to F_w as follows

$$F_w = \frac{1}{1 + \left(\frac{3.15}{G_p}\right)\left(\frac{1}{F_v} - 1\right)}$$

where

F_v = pozzolanic materials percentage by absolute volume of the total absolute volume of cement plus pozzolanic materials expressed as a decimal factor
G_p = specific gravity of pozzolanic materials
3.15 = specific gravity of portland cement [use actual value if known to be different])

Example 6.3.4.1 -- Weight equivalency

If a water-cement ratio of 0.60 is required and a fly ash pozzolan is to be used as 20 percent of the cementitous material in the mixture by weight *($F_w = 0.20$)*, then the required water-to-cement plus pozzolanic material ratio on a weight equivalency basis is

$$\frac{w}{c+p} = \frac{w}{c} = 0.60, \textit{ and}$$

$$F_w = \frac{p}{c+p} = 0.20$$

Assuming an estimated mixing-water requirement of 270 lb/yd^3, then the required weight of cement + pozzolan is 270 ÷ 0.60 = 450 lb; and the weight of pozzolan is (0.20)(450) = 90 lb. The weight of cement is, therefore, 450 - 90 = 360 lb. If instead of 20 percent fly ash by weight, 20 percent by absolute volume of cement plus pozzolan was specified (F_v = 0.20), the corresponding weight factor is computed as follows for a fly ash with an assumed gravity of 2.40:

$$F_w = \frac{1}{1+\left(\frac{3.15}{G_p}\right)\left(\frac{1}{F_v}-1\right)}$$

$$\frac{1}{1+\left(\frac{3.15}{2.40}\right)\left(\frac{1}{0.2}-1\right)}$$

$$F_w = \frac{1}{1+(1.31)(4)} = \frac{1}{1+5.24} = \frac{1}{6.24} = 0.16$$

In this case 20 percent by absolute volume is 16 percent by weight, and the weight of pozzolan in the batch would be (0.16)(450) = 72 lb, and the weight of cement 450 - 72 = 378 lb.

Eq. (6.3.4.2) -- Absolute volume equivalency

$\frac{W}{c+p}$ *weight ratio, absolute volume equivalency* =

$$\frac{3.15\frac{w}{c}}{3.15(1-F_v)+G_p(F_v)}$$

where

$\frac{w}{c+p}$ = weight of water divided by weight of cement + pozzolanic materials

$\frac{w}{c}$ = target water-cement ratio by weight

3.15 = specific gravity of portland cement (use actual value if known to be different)

F_v = pozzolan percentage by absolute volume of the total absolute volume of cement plus poxzolan, expressed as a decimal factor

(Note: If only the desired pozzolan percentage by weight F_w is known, it can be converted to F_v as follows

$$F_v = \frac{1}{1+\left(\frac{G_p}{3.15}\right)\left(\frac{1}{F_w}-1\right)}$$

where these symbols are the same as defined previously.)

Example 6.3.4.2 -- Absolute volume equivalency

Use the same basic data as Example 6.3.4.1, but it should be specified that the equivalent water-to-cement plus pozzolan ratio be established on the basis of absolute volume, which will maintain, in the mixture, the same ratio of volume of water to volume of cementitious material when changing from cement only to cement plus pozzolan. Again the required water-cement ratio is 0.60, and it is assumed initially that it is desired to use 20 percent by absolute volume of fly ash ($F_v = 0.20$). The specific gravity of the fly ash is assumed to be 2.40 in this example

$$\frac{w}{c+p} = \frac{3.15\left(\frac{w}{c}\right)}{3.15(1-F_v)+G_p(F_v)}$$

$$= \frac{(3.15)(0.60)}{(3.15)(0.80)+(2.40)(0.20)}$$

$$\frac{1.89}{+2.52+0.48} = \frac{1.89}{3.00} = 0.63$$

So the target weight ratio to maintain an absolute volume equivalency is $w/(c+p) = 0.63$. If the mixing water is again 270 lb/y$_3$, then the required weight of cement + pozzolan is 270 ÷ 0.63 = 429 lb, and, since the corresponding weight percentage factor for $F_v = 0.20$ is $F_w = 0.16$ as calculated in Example 6.3.4.1, the weight of fly ash to be used is (0.16)(429) = 69 lb and the weight of cement is 429 - 69 = 360 lb. The volume equivalency procedure provides lower weights of cementitious materials. Checking the absolute volumes

$$\textit{fly ash} = \frac{69}{(2.40)(62.4)} = 0.461 ft^3$$

$$\textit{cement} = \frac{360}{(3.15)(62.4)} = 1.832 ft^3$$

total = 0,461 + 1.832 = 2.293ft3

$$\textit{percent pozzolan by volume} = \frac{0.461 \times 100}{2.293} = 20 \textit{ percent}$$

If, instead of 20 percent fly ash by volume ($F_v = 0.20$), a weight percentage of 20 percent was specified ($F_w = 0.20$), it could be converted to F_v using $G_p = 2.40$ and the appropriate formula

$$F_v = \frac{1}{1+\left(\frac{G_p}{3.15}\right)\left(\frac{1}{F_w}-1\right)}$$

$$F_v = \frac{1}{1+\left(\frac{2.40}{3.15}\right)\left(\frac{1}{0.2}-1\right)}$$

$$F_v = \frac{1}{1+(0.762)(4)} = \frac{1}{4.048} = 0.247$$

In this case 20 percent by weight is almost 25 percent by absolute volume. The equivalent w/(c + p) ratio by volume will have to be recomputed for this condition since F_v has been changed from that originally assumed in this example

$$\frac{W}{c+p} = \frac{3.15\left(\frac{w}{c}\right)}{3.15(1-F_v) \quad G_p(F_v)}$$

$$= \frac{(3.15)(0.60)}{3.15(0.75) + 2.40(0.25)}$$

$$= \frac{1.89}{2.36 + 0.60} = \frac{1.89}{2.96} = 0.64$$

Total cementitious material would be 270 ÷ 0.64 = 422 lb. Of this weight 20 percent (F_w = 0.20) would be fly ash; (422)(0.20) = 84 lb of fly ash and 422 - 84 = 338 lb of cement.

6.3.5 *Step 5. Calculation of cement content* -- The amount of cement per unit volume of concrete is fixed by the determinations made in Steps 3 and 4 above. The required cement is equal to the estimated mixing-water content (Step 3) divided by the water-cement ratio (Step 4). If, however, the specification includes a separate minimum limit on cement in addition to requirements for strength and durability, the mixture must be based on whichever criterion leads to the larger amount of cement.

The use of pozzolanic or chemical admixtures will affect properties of both the fresh and hardened concrete. See ACI 212.

6.3.6 *Step 6. Estimation of coarse aggregate content* -- Aggregates of essentially the same nominal maximum size and grading will produce concrete of satisfactory workability when a given volume of coarse aggregate, on an oven-dry-rodded basis, is used per unit volume of concrete. Appropriate values for this aggregate volume are given in Table 6.3.6. It can be seen that, for equal workability, the volume of coarse aggregate in a unit volume of concrete is dependent only on its nominal maximum size and the fineness modulus of the fine aggregate. Differences in the amount of mortar required for workability with different aggregates, due to differences in particle shape and grading, are compensated for automatically by differences in oven-dry-rodded void content.

The volume of aggregate in ft^3, on an oven-dry-rodded basis, for a yd^3 of concrete is equal to the value from Table 6.3.6 multiplied by 27. This volume is converted to dry weight of coarse aggregate required in a yd^3 of concrete by multiplying it by the oven-dry-rodded weight per ft^3 of the coarse aggregate.

6.3.6.1 For more workable concrete, which is sometimes required when placement is by pump or when concrete must be worked around congested reinforcing steel, it may be desirable to reduce the estimated coarse aggregate content determined using Table 6.3.6 by up to 10 percent. However, caution must be exercised to assure that the resulting slump, water-cement or water-cementitious materials ratio, and strength properties of the concrete are consistent with the recommendations in Sections 6.3.1 and 6.3.4 and meet applicable project specification requirements.

6.3.7 *Step 7. Estimation of fine aggregate content* -- At completion of Step 6, all ingredients of the concrete have been estimated except the fine aggregate. Its quantity is determined by difference. Either of two procedures may be employed: the weight method (Section 6.3.7.1) or the absolute volume method (Section 6.3.7.2).

6.3.7.1 If the weight of the concrete per unit volume is assumed or can be estimated from experience, the required weight of fine aggregate is simply the difference between the weight of fresh concrete and the total weight of the other ingredients. Often the unit weight of concrete is known with reasonable accuracy from previous experience with the materials. In the absence of such information, Table 6.3.7.1 can be used to make a first estimate. Even if the estimate of concrete weight per yd^3 is rough, mixture proportions will be sufficiently accurate to permit easy adjustment on the basis of trial batches as will be shown in the examples.

Table 6.3.6 — Volume of coarse aggregate per unit of volume of concrete

Nominal maximum size of aggregate, in.	Volume of oven-dry-rodded coarse aggregate* per unit volume of concrete for different fineness moduli of fine aggregate†			
	2.40	2.60	2.80	3.00
3/8	0.50	0.48	0.46	0.44
1/2	0.59	0.57	0.55	0.53
3/4	0.66	0.64	0.62	0.60
1	0.71	0.69	0.67	0.65
1 1/2	0.75	0.73	0.71	0.69
2	0.78	0.76	0.74	0.72
3	0.82	0.80	0.78	0.76
6	0.87	0.85	0.83	0.81

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

These volumes are selected from empirical relationships to produce concrete with a degree of workability suitable for usual reinforced construction. For less workable concrete, such as required for concrete pavement construction, they may be increased about 10 percent. For more workable concrete see Section 6.3.6.1.

†See ASTM C 1.36 for calculation of fineness modulus.

Table 6.3.7.1 — First estimate of weight of fresh concrete

Nominal maximum size of aggregate, in.	First estimate of concrete weight, lb/yd³*	
	Non-air-entrained concrete	Air-entrained concrete
3/8	3840	3710
1/2	3890	3760
3/4	3960	3840
1	4010	3850
1 1/2	4070	3910
2	4120	3950
3	4200	4040
6	4260	4110

*Values calculated by Eq. (6-l) for concrete of medium richness (550 lb of cement per yd^3) and medium slump with aggregate specific gravity of 2.7. Water requirements based on values for 3 to 4 in. slump in Table 6.3.3. If desired, the estimated weight may be refined as follows if necessary information is available: for each 10 lb difference in mixing water from the Table 6.3.3 values for 3 to 4 in. slump, correct the weight per yd^3 15 lb in the opposite direction; for each 100 lb difference in cement content from 550 lb, correct the weight per yd^3 15 lb in the same direction; for each 0.1 by which aggregate specific gravity deviates from 2.7, correct the concrete weight 100 lb in the same direction. For air-entrained concrete the air content for severe exposure from Table 6.3.3 was used. The weight can be increased 1 percent for each percent reduction in air content from that amount.

If a theoretically exact calculation of fresh concrete weight per yd³ is desired, the following formula can be used

$$U = 16.85 \; G_a (100 - A) + c(1 - G_a/G_c) \; w(G_a - 1) \qquad (6\text{-}1)$$

where

U = weight in lb of fresh concrete per yd³
G_a = weighted average specific gravity of combined fine and coarse aggregate, bulk SSD*
G_c = specific gravity of cement (generally 3.15)
A = air content, percent
w = mixing water requirement, lb/yd³
c = cement requirement, lb/yd³

6.3.7.2 A more exact procedure for calculating the required amount of fine aggregate involves the use of volumes displaced by the ingredients. In this case, the total volume displaced by the known ingredients--water, air, cementitious materials, and coarse aggregate--is subtracted from the unit volume of concrete to obtain the required volume of fiie aggregate. The volume occupied in concrete by any ingredient is equal to its weight divided by the density of that material (the latter being the product of the unit weight of water and the specific gravity of the material).

6.3.8 *Step 8. Adjustments for aggregate moisture* -- The aggregate quantities actually to be weighed out for the concrete must allow for moisture in the aggregates. Generally, the aggregates will be moist and their dry weights should be increased by the percentage of water they contain, both absorbed and surface. The mixing water added to the batch must be reduced by an amount equal to the free moisture contributed by the aggregate -- i.e., total moisture minus absorption.

6.3.8.1 In some cases, it may be necessary to batch an aggregate in a dry condition. If the absorption (normally measured by soaking one day) is higher than approximately one percent, and if the pore structure within the aggregate particles is such that a significant fraction of the absorption occurs during the time prior to initial set, there may be a noticeable increase in the rate of slump loss due to an effective decrease in mixing water. Also, the effective water-cement ratio would be decreased for any water absorbed by the aggregate prior to set; this, of course, assumes that cement particles are not carried into aggregate particle pores.

6.3.8.2 Laboratory trial batch procedures according to ASTM C 192 allow the batching of laboratory air-dried aggregates if their absorption is less than 1.0 percent with an allowance for the amount of water that will be absorbed from the unset concrete. It is suggested by ASTM C 192 that the amount absorbed may be assumed to be 80 percent of the difference between the actual amount of water in the pores of the aggregate in their air-dry state and the nominal 24-hr absorption determined by ASTM C 127 or C 128. However, for higher-absorption aggregates, ASTM C 192 requires preconditioning of aggregates to satisfy absorption with adjustments in aggregate weight based on total moisture content and adjustment to include surface moisture as a part of the required amount of mixing water.

6.3.9 *Step 9. Trial batch adjustments* -- The calculated mixture proportions should be checked by means of trial batches prepared and tested in accordance with ASTM C 192 or full-sized field batches. Only sufficient water should be used to produce the required slump regardless of the amount assumed in selecting the trial proportions. The concrete should be checked for unit weight and yield (ASTM C 138) and for air content (ASTM C 138, C 173, or C 231). It should also be carefully observed for proper workability, freedom from segregation, and finishing properties. Appropriate adjustments should be made in the proportions for subsequent batches in accordance with the following procedure.

6.3.9.1 Re-estimate the required mixing water per yd³ of concrete by multiplying the net mixing water content of the trial batch by 27 and dividing the product by the yield of the trial batch in ft³. If the slump of the trial batch was not correct, increase or decrease the re-estimated amount of water by 10 lb for each 1 in. required increase or decrease in slump.

6.3.9.2 If the desired air content (for air-entrained concrete) was not achieved, re-estimate the admixture content required for proper air content and reduce or increase the mixing-water content of Paragraph 6.3.9.1 by 5 lb for each 1 percent by which the air content is to be increased or decreased from that of the previous trial batch.

6.3.9.3 If estimated weight per yd³ of fresh concrete is the basis for proportioning, re-estimate that weight by multiplying the unit weight in lb/ft³ of the trial batch by 27 and reducing or increasing the result by the anticipated percentage increase or decrease in air content of the adjusted batch from the first trial batch.

6.3.9.4 Calculate new batch weights starting with Step 4 (Paragraph 6.3.4), modifying the volume of coarse aggregate from Table 6.3.6 if necessary to provide proper workability.

CHAPTER 7 -- SAMPLE COMPUTATIONS

7.1 Two example problems will be used to illustrate application of the proportioning procedures. The following conditions are assumed:

7.1.1 Type I non-air-entraining cement will be used and its specific gravity is assumed to be 3.15.†

* SSD indicates saturated-surface-dry basis used in considering aggregate displacement. The aggregate specific gravity used in calculations must be consistent with the moisture condition assumed in the basic aggregate batch weights -- i.e., bulk dry if aggregate weights are stated on a dry basis, and bulk SSD if weights are stated on a saturated-surface-dry basis.

† The specific gravity values are not used if proportions are selected to provide a weight of concrete assumed to occupy 1 yd³.

7.1.2 Coarse and fine aggregates in each case are of satisfactory quality and are graded within limits of generally accepted specifications. See ASTM C 33.

7.1.3 The coarse aggregate has a bulk specific gravity of 2.68* and an absorption of 0.5 percent.

7.1.4 The fine aggregate has a bulk specific gravity of 2.64,* an absorption of 0.7 percent, and a fineness modulus of 2.8.

7.2 *Example 1* -- Concrete is required for a portion of a structure that will be below ground level in a location where it will not be exposed to severe weathering or sulfate attack. Structural considerations require it to have an average 28-day compressive strength of 3500 psi.† On the basis of information in Table 6.3.1, as well as previous experience, it is determined that under the conditions of placement to be employed, a slump of 3 to 4 in. should be used and that the available No. 4 to M-in. coarse aggregate will be suitable. The dry-rodded weight of coarse aggregate is found to be 100 lb/ft^3. Employing the sequence outlined in Section 6, the quantities of ingredients per yd^3 of concrete are calculated as follows:

7.2.1 *Step 1* -- As indicated previously, the desired slump is 3 to 4 in.

7.2.2 *Step 2* -- The locally available aggregate, graded from No. 4 to $1\frac{1}{2}$ in., has been indicated as suitable.

7.2.3 *Step 3* -- Since the structure will not be exposed to severe weathering, non-air-entrained concrete will be used. The approximate amount of mixing water to produce 3 to 4-in. slump in non-air-entrained concrete with M-in aggregate is found from Table 6.3.3 to be 300 lb/yd^3. Estimated entrapped air is shown as 1 percent.

7.2.4 *Step 4* -- From Table 6.3.4(a), the water-cement ratio needed to produce a strength of 3500 psi in non-air-entrained concrete is found to be about 0.62.

7.2.5 *Step 5* -- From the information derived in Steps 3 and 4, the required cement content is found to be 300/0.62 = 484 lb/yd^3.

7.2.6 *Step 6* -- The quantity of coarse aggregate is estimated from Table 6.3.6. For a fine aggregate having a fineness modulus of 2.8 and a $1\frac{1}{2}$ in. nominal maximum size of coarse aggregate, the table indicates that 0.71 ft^3 of coarse aggregate, on a dry-rodded basis, may be used in each ft^3 of concrete. For each yd^3, therefore, the coarse aggregate will be 27 x 0.71 = 19.17 ft^3. Since it weighs 100 lb per ft^3, the dry weight of coarse aggregate is 1917 lb.

7.2.7 *Step 7* -- With the quantities of water, cement, and coarse aggregate established, the remaining material comprising the yd^3 of concrete must consist of fine aggregate and whatever air will be entrapped. The required fine aggregate may be determined on the basis of either weight or absolute volume as shown:

7.2.7.1 *Weight basis* -- From Table 6.3.7.1, the weight of a yd^3 of non-air-entrained concrete made with aggregate having a nominal maximum size of $1\frac{1}{2}$ in. is estimated to be 4070 lb. (For a first trial batch, exact adjustments of this value for usual differences in slump, cement factor, and aggregate specific gravity are not critical.) Weights already known are:

Water, net mixing	300 lb
Cement	484 lb
Coarse aggregate	1917 lb (dry)‡
Total	2701 lb

The weight of fine aggregate, therefore, is estimated to be

4070 - 2701 = 1369 lb (dry)‡

7.2.7.2 *Absolute volume basis* -- With the quantities of cement, water, and coarse aggregate established, and the approximate entrapped air content (as opposed to purposely entrained air) taken from Table 6.3.3, the fine aggregate content can be calculated as follows:

$$\text{Volume of water} = \frac{300}{62.4} = 4.81\ ft^3$$

$$\text{Solid volume of cement} = \frac{484}{3.15 \times 62.4} = 2.46\ ft^3$$

$$\text{Solid volume of coarse aggregate} = \frac{1917}{2.68 \times 62.4} = 11.46\ ft^3$$

$$\text{Volume of entrapped air} = 0.01 \times 27 = 0.27\ ft^3$$

$$\text{Total solid volume of ingredients except fine aggregate} = 19.00\ ft^3$$

$$\text{Solid volume of fine aggregate required} = 27 - 19.00 = 8.00\ ft^3$$

$$\text{Required weight of dry aggregate} = 8.00 \times 2.64 \times 62.4 = 1318\ \text{lb}$$

7.2.7.3 Batch weights per yd^3 of concrete calculated on the two bases are compared as follows:

	Based on estimated concrete weight, lb	Based on absolute volume of ingredients, lb
Water, net mixing	300	300
Cement	484	484
Coarse aggregate, dry	1917	1917
Fine aggregate, dry	1369	1318

* The specific gravity values are not used if proportions are selected to provide a weight of concrete assumed to occupy 1 yd^3.

† This is not the specified strength used for structunl design but a higher figure expected to be produced on the average. For the method of determining the amount by which average strength should exceed design strength, see ACI 214.

‡ Aggregate absorption of 0.5 percent is disregarded since its magnitude is inconsequential in relocation to other approximations.

7.2.8 *Step 8* -- Tests indicate total moisture of 2 percent in the coarse aggregate and 6 percent in the fine aggregate. If the trial batch proportions based on assumed concrete weight are used, the adjusted aggregate weights become:

Coarse aggregate, wet	1917 (1.02) = 1955 lb
Fine aggregate, wet	1369 (1.06) = 1451 lb

Absorbed water does not become part of the mixing water and must be excluded from the adjustment in added water. Thus, surface water contributed by the coarse aggregate amounts to 2 - 0.5 = 1.5 percent; that contributed by the fine aggregate to 6 - 0.7 = 5.3 percent. The estimated requirement for added water, therefore, becomes

$$300 - 1917(0.015) - 1369(0.053) = 199 \text{ lb}$$

The estimated batch weights for a **yd³** of concrete are:

Water, to be added	199 lb
Cement	484 lb
Coarse aggregate, wet	1955 lb
Fine aggregate, wet	1451 lb

7.2.9 *Step 9* -- For the laboratory trial batch, it was found convenient to scale the weights down to produce 0.03 **yd³** or 0.81 **ft³** of concrete. Although the calculated quantity of water to be added was 5.97 lb, the amount actually used in an effort to obtain the desired 3 to 4 in. slump is 7.00 lb. The batch as mixed therefore consists of:

Water, to be added	7.00 lb
Cement	14.52 lb
Coarse aggregate, wet	58.65 lb
Fine aggregate, wet	43.53 lb
Total	123.70 lb

The concrete has a measured slump of 2 in. and unit weight of 149.0 lb per **ft³.** It is judged to be satisfactory from the standpoint of workability and finishing properties. To provide proper yield and other characteristics for future batches, the following adjustments are made:

7.2.9.1 Since the yield of the trial batch was

$$123.70/149.0 = 0.830 \text{ ft}^3$$

and the mixing water content was 7.00 (added) + 0.86 on coarse aggregate + 2.18 on fine aggregate = 10.04 lb, the mixing water required for a **yd³** of concrete with the same slump as the trial batch should be

$$10.04 \times 27/0.830 = 327 \text{ lb}$$

As indicated in Paragraph 6.3.9.1, this amount must be increased another 15 lb to raise the slump from the measured 2 in. to the desired 3 to 4 in. range, bringing the net mixing water to 342 lb.

7.2.9.2 With the increased mixing water, additional cement will be required to provide the desired water-cement ratio of 0.62. The new cement content becomes

$$342/0.62 = 552 \text{ lb}$$

7.2.9.3 Since workability was found to be satisfactory, the quantity of coarse aggregate per unit volume of concrete will be maintained the same as in the trial batch. The amount of coarse aggregate per **yd³** becomes

$$\frac{58.65}{0.83} \times 27 = 1908 \ \textit{lb wet}$$

which is

$$\frac{1908}{1.02} = 1871 \ \textit{lb dry}$$

and

$$1871\ (1.005) = 1880 \text{ SSD*}$$

7.2.9.4 The new estimate for the weight of a **yd³** of concrete is 149.0 x 27 = 4023 lb. The amount of fine aggregate required is therefore

$$4023 - (342 + 552 + 1880) = 1249 \text{ lb SSD}$$

or

$$1249/1.007 = 1240 \text{ lb dry}$$

The adjusted basic batch weights per **yd³** of concrete are:

Water, net mixing	342 lb
Cement	522 lb
Coarse aggregate, dry	1871 lb
Fine aggregate, dry	1240 lb

7.2.10 Adjustments of proportions determined on an absolute volume basis follow a procedure similar to that just outlined. The steps will be given without detailed explanation:

7.2.10.1 Quantities used in nominal 0.81 **ft³** batch are:

Water, added	7.00 lb
Cement	14.52 lb
Coarse aggregate, wet	58.65 lb
Fine aggregate, wet	41.91 lb
Total	122.08 lb

Measured slump 2 in.; unit weight 149.0 **lb/ft³;** yield 122.08/149.0 = 0.819 **ft³,** workability o.k.

7.2.10.2 Re-estimated water for same slump as

* Saturated-surface-dry

trial batch

$$\frac{27(7.00 + 0.86 + 2.09)}{0.8\ 19} = 328 \text{ lb}$$

Mixing water required for slump of 3 to 4 in.

328 + 15 = 343 lb

7.2.10.3 Adjusted cement content for increased water

34310.62 = 553 lb

7.2.10.4 Adjusted coarse aggregate requirement

$$\frac{58.65}{0.819} \times 27 = 1934 \textit{ lb wet}$$

or

1934/1.02 = 1896 lb dry

7.2.10.5 The volume of ingredients other than air in the original trial batch was

Water	$\frac{9.95}{62.4}$	=	0.159 **ft³**
Cement	$\frac{14.52}{3.15 \times 62.4}$	=	0.074 **ft³**
Coarse aggregate	$\frac{57.50}{2.68 \times 62.4}$	=	0.344 **ft³**
Fine aggregate	$\frac{39.54}{2.64 \times 62.4}$	=	0.240 **ft³**
Total		=	0.817 **ft³**

Since the yield was 0.819 **ft³**, the air content was

$$\frac{0.819 - 0.817}{0.819} = 0.2 \textit{ percent}$$

With the proportions of all components except fine aggregate established, the determination of adjusted **yd³** batch quantities can be completed as follows:

Volume of water	=	$\frac{343}{62.4}$	=	5.50 **ft³**
Volume of cement	=	$\frac{553}{3.15 \times 62.4}$	=	2.81 **ft³**
Volume of air	=	0.002 x 27	=	0.05 **ft³**
Volume of coarse aggregate	=	$\frac{1896}{2.68 \times 62.4}$	=	11.34 **ft³**
Total volume exclusive of fine aggregate			=	19.70 **ft³**
Volume of fime aggregate required	=	27 - 19.70	=	7.30 **ft³**
Weight of fine aggregate (dry basis)	=	7.30 x 2.64 x 62.4	=	1203 lb

The adjusted basic batch weights per **yd³** of concrete are then:

Water, net mixing	343 lb
Cement	553 lb
Coarse aggregate, dry	1896 lb
Fine aggregate, dry	1203 lb

These differ only slightly from those given in Paragraph 7.2.9.4 for the method of assumed concrete weight. Further trials or experience might indicate small additional adjustments for either method.

7.3 *Example 2* -- Concrete is required for a heavy bridge pier that will be exposed to fresh water in a severe climate. An average 28-day compressive strength of 3000 psi will be required. Placement conditions permit a slump of 1 to 2 in. and the use of large aggregate, but the only economically available coarse aggregate of satisfactory quality is graded from No. 4 to 1 in. and this will be used. Its dry-rodded weight is found to be 95 **lb/ft³**. Other characteristics are as indicated in Section 7.1.

The calculations will be shown in skeleton form only. Note that confusion is avoided if all steps of Section 6 are followed even when they appear repetitive of specified requirements.

7.3.1 *Step 1* -- The desired slump is 1 to 2 in.

7.3.2 *Step 2* -- The locally available aggregate, graded from No. 4 to 1 in., will be used.

7.3.3 *Step 3* -- Since the structure will be exposed to severe weathering, air-entrained concrete will be used. The approximate amount of mixing water to produce a 1 to 2-in. slump in air-entrained concrete with l-in. aggregate is found from Table 6.3.3 to be 270 **lb/yd³**. The recommended air content is 6 percent.

7.3.4 *Step 4* -- From Table 6.3.4(a), the water-cement ratio needed to produce a strength of 3000 psi in air-entrained concrete is estimated to be about 0.59. However, reference to Table 6.3.4(b), reveals that, for the severe weathering exposure anticipated, the water-cement ratio should not exceed 0.50. This lower figure must govern and will be used in the calculations.

7.3.5 *Step 5* -- From the information derived in Steps 3 and 4, the required cement content is found to be 270/0.50

= 540 lb/yd³.

7.3.6 *Step 6* -- The quantity of coarse aggregate is estimated from Table 6.3.6. With a fine aggregate having a fineness modulus of 2.8 and a 1 in. nominal maximum size of coarse aggregate, the table indicates that 0.67 ft³ of coarse aggregate, on a dry-rodded basis, may be used in each ft³ of concrete. For a ft³, therefore, the coarse aggregate will be 27 x 0.67 = 18.09 ft³. Since it weighs 95 lb/ft³, the dry weight of coarse aggregate is 18.09 x 95 = 1719 lb.

7.3.7 *Step 7* -- With the quantities of water, cement, and coarse aggregate established, the remaining material comprising the yd³ of concrete must consist of fine aggregate and air. The required fine aggregate may be determined on the basis of either weight or absolute volume as shown below.

7.3.7.1 *Weight basis* -- From Table 6.3.7.1 the weight of a yd³ of air-entrained concrete made with aggregate of 1 in. maximum size is estimated to be 3850 lb. (For a first trial batch, exact adjustments of this value for differences in slump, cement factor, and aggregate specific gravity are not critical.) Weights already known are:

Water, net mixing	270 lb
Cement	540 lb
Coarse aggregate, dry	1719 lb
Total	2529 lb

The weight of fiie aggregate, therefore, is estimated to be

3850 - 2529 = 1321 lb (dry)

7.3.7.2 *Absolute volume basis* -- With the quantities of cement, water, air, and coarse aggregate established, the fine aggregate content can be calculated as follows:

Volume of water $= \frac{270}{62.4}$ 4.33 ft³

Solid volume of cement $= \frac{540}{3.15 \times 62.4} =$ 2.75 ft³

Solid volume of coarse aggregate $= \frac{1719}{2.68 \times 62.4} =$ 10.28 ft³

Volume of air = 0.06 x 27 = 1.62 ft³

Total volume of ingredients except fine aggregate = 18.98 ft³

Solid volume of fine aggregate required = 27-18.98 = 8.02 ft³

Required weight of dry fine aggregate = 8.02 x 2.64 x 62.4 = 1321 lb

7.3.7.3 Batch weights per yd³ of concrete calculated on the two bases are compared as follows:

	Based on estimated concrete weight, lb	Based on absolute volume of ingredients, lb
Water, net mixing	270	270
Cement	540	540
Coarse aggregate, dry	1719	1719
Fine aggregate, dry	1321	1321

7.3.8 *Step 8* -- Tests indicate total moisture of 3 percent in the coarse aggregate and 5 percent in the fine aggregate. If the trial batch proportions based on assumed concrete weight are used, the adjusted aggregate weights become:

Coarse aggregate, wet	1719(1.03) = 1771 lb
Fine aggregate, wet	1321(1.05) = 1387 lb

Absorbed water does not become part of the mixing water and must be excluded from the adjustment in added water. Thus, surface water contributed by the coarse aggregate amounts to 3 - 0.5 = 2.5 percent; by the fine aggregate 5 - 0.7 = 4.3 percent. The estimated requirement for added water, therefore, becomes

270 - 1719(0.025) - 1321(0.043) = 170 lb

The estimated batch weights for a yd³ of concrete are:

Water, to be added	170 lb
Cement	540 lb
Coarse aggregate, wet	1771 lb
Fine aggregate, wet	1387 lb
Total	3868 lb

7.3.9 *Step 9* -- For the laboratory trial batch, the weights are scaled down to produce 0.03 yd³ or 0.81 ft³ of concrete. Although the calculated quantity of water to be added was 5.10 lb, the amount actually used in an effort to obtain the desired 1 to 2-in. slump is 4.60 lb. The batch as mixed, therefore, consists of:

Water, added	4.60 lb
Cement	16.20 lb
Coarse aggregate, wet	53.13 lb
Fine aggregate, wet	41.61 lb
Total	115.54 lb

The concrete has a measured slump of 2 in., unit weight of 141.8 lb/ft^3 and air content of 6.5 percent. It is judged to be slightly oversanded for the easy placement condition involved. To provide proper yield and other characteristics for future batches, the following adjustments are made.

7.3.9.1 Since the yield of the trial batch was

$$115.543/141.8 = 0.815\ ft^3$$

and the mixing water content was 4.60 (added) + 1.29 on coarse aggregate + 1.77 on fine aggregate = 7.59 lb, the mixing water required for a yd^3 of concrete with the same slump as the trial batch should be

$$\frac{7.59 \times 27}{0.815} = 251\ lb$$

The slump was satisfactory, but since the air content was too high by 0.5 percent, more water will be needed for proper slump when the air content is corrected. As indicated in Paragraph 6.3.9.2, the mixing water should be increased roughly 5 x 0.5 or about 3 lb, bringing the new estimate to 254 lb/yd^3.

7.3.9.2 With the decreased mixing water, less cement will be required to provide the desired water-cement ratio of 0.5. The new cement content becomes

$$254/0.5 = 508\ lb$$

7.3.9.3 Since the concrete was found to be oversanded, the quantity of coarse aggregate per unit volume will be increased 10 percent to 0.74, in an effort to correct the condition. The amount of coarse aggregate per yd^3 becomes

$$0.74 \times 27 \times 95 = 1898\ lb\ dry$$

or

$$1898 \times 1.03 = 1955\ wet$$

and

$$1898 \times 1.005 = 1907\ lb\ SSD$$

7.3.9.4 The new estimate for the weight of the concrete with 0.5 percent less air is 141.8/0.995 = 142.50 lb/ft^3 or 142.50 x 27 = 3848 lb/yd^3. The weight of sand, therefore, is

$$3848 - (254 + 508 + 1907) = 1179\ lb\ SSD$$

or

$$1179/1.007 = 1170\ lb\ dry$$

The adjusted basic batch weights per yd^3 of concrete are:

Water, net mixing	254 lb
Cement	508 lb
Coarse aggregate, dry	1898 lb
Fine aggregate, dry	1170 lb

Admixture dosage must be reduced to provide the desired air content.

7.3.10 Adjustments of proportions determined on an absolute volume basis would follow the procedure outlined in Paragraph 7.2.10, which will not be repeated for this example.

CHAPTER 8 -- REFERENCES

8.1 -- *Recommended references*

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation, including year of adoption or revision. The documents listed were the latest effort at the time this document was revised. Since some of these documents are revised frequently, generally in minor detail only, the user of this document should check directly with the sponsoring group if it is desired to refer to the latest revision.

American Concrete Institute

116R-90	Cement and Concrete Terminology, SP-19(90)
201.2R-77 (Reapproved 1982)	Guide to Durable Concrete
207.1R-87	Mass Concrete
207.2R-90	Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete
207.4R-80(86)	Cooling and Insulating Systems for Mass Concrete
212.3R-89	Chemical Admixtures for Concrete
214-77 (Reapproved 1989)	Recommended Practice for Evaluation of Strength Test Results of Concrete
224R-90	Control of Cracking in Concrete Structures
225 R-85	Guide to the Selection and Use of Hydraulic Cements
226.1 R-87	Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete
226.3R-87	Use of Fly Ash in Concrete
301-89	Specifications for Structural Concrete for Buildings
302.1R-89	Guide for Concrete Floor and Slab Construction
304R-89	Guide for Measuring, Mixing, Transporting, and Placing Concrete
304.3R-89	Heavyweight Concrete: Measuring, Mixing, Transporting, and Placing
318-83	Building Code Requirements for Reinforced Concrete

345-82	Standard Practice for Concrete Highway Bridge Deck Construction

ASTM

C 29-78	Standard Test Method for Unit Weight and Voids in Aggregate
31-87a	Standard Method of Making and Curing Concrete Test Specimens in the Field
C 33-86	Standard Specification for Concrete Aggregates
C 39-86	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
C 70-79(1985)	Standard Test Method for Surface Moisture in Fine Aggregate
C 78-84	Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
C 94-86b	Standard Specification for Ready-Mixed Concrete
C 125-86	Standard Definitions of Terms Relating to Concrete and Concrete Aggregates
C 127-84	Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate
C 128-84	Standard Test Method for Specific Gravity and Absorption of Fine Aggregate
C 136-84a	Standard Method for Sieve Analysis of Fine and Coarse Aggregates
C 138-81	Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete
C 143-78	Standard Test Method for Slump of Portland Cement Concrete
C 150-86	Standard Specification for Portland Cement
C 172-82	Standard Method of Sampling Freshly Mixed Concrete
C 173-78	Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
C 192-81	Standard Method of Making and Curing Concrete Test Specimens in the Laboratory
C 231-82	Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
C 260-86	Standard Specification for Air-Entraining Admixtures for Concrete
C 293-79	Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)
C 494-86	Standard Specification for Chemical Admixtures for Concrete
C 496-86	Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
C 566-84	Standard Test Method for Total Moisture Content of Aggregate by Drying
C 595-86	Standard Specification for Blended Hydraulic Cements
C 618-85	Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete
C 637-84	Standard Specification for Aggregates for Radiation-Shielding Concrete
C 638-84	Standard Descriptive Nomenclature of Constituents of Aggregates for Radiation-Shielding Concrete
C 989-87a	Standard Specification for Granulated Blast-Furnace Slag for Use in Concrete and Mortars
C 1017-85	Standard Specification for Chemical Admixtures for Use in Producing Flowing Concrete
C 1064-86	Standard Test Method for Temperature of Freshly Mixed Portland-Cement Concrete
D 75-82	Standard Practice for Sampling Aggregates
D 3665-82	Standard Practice for Random Sampling of Construction Materials
E 380-84	Standard for Metric Practice

The above publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 19150
Detroit, MI 48219-0150

ASTM
1916 Race Street
Philadelphia, PA 19103

8.2 -- *Cited references*

1. "Silica Fume in Concrete," ACI Committee 226 Preliminary Report, ACI Materials Journal, *Proceedings* V. 84, Mar.-Apr. 1987, pp. 158-166.

8.3 -- *Additional references*

1. "Standard Practice for Concrete," *Engineer Manual* No. EM 1110-2-2000, Office, Chief of Engineers, U.S. Army Corps of Engineers, Washington, D.C., June 1974.
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4. Townsend, Charles L., "Control of Temperature Cracking in Mass Concrete," *Causes, Mechanism, and Control of Cracking in Concrete*, SP-20, American Concrete Institute, Detroit, 1968, pp. 119-139.

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6. Fuller, William B., and Thompson, Sanford E., "The Laws of Proportioning Concrete," *Transactions,* ASCE, V. 59, Dec. 1907, pp. 67-143.

7. Powers, Treval C., *The Properties of Fresh Concrete,* John Wiley & Sons, New York, 1968, pp. 246-256.

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9. Abrams, Duff A, "Design of Concrete Mixtures," *Bulletin* No. 1, Structural Materials Research Laboratory, Lewis Institute, Chicago, 1918, 20 pp.

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11. Young, R. B., "Some Theoretical Studies on Proportioning Concrete by the Method of Surface Area Aggregate," *Proceedings,* ASTM, V. 19, Part 2, p. 1919.

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APPENDIX 1 -- METRIC (SI) SYSTEM ADAPTATION

A1.1 Procedures outlined in this standard practice have been presented using inch-pound units of measurement. The principles are equally applicable in SI system with proper adaptation of units. This Appendix provides all of the information necessary to apply the proportioning procedure using SI measurements. Table A1.1 gives relevant conversion factors. A numerical example is presented in Appendix 2.

TABLE A1.1-CONVERSION FACTORS, in.-lb TO SI UNITS*

Quantity	in-lb unit	SI† unit	Conversion factor (Ratio: in.-lb/SI)
Length	inch (in.)	millimeter (mm)	25.40
Volume	cubic foot (ft^3) cubic yard (yd^3)	cubic meter (m^3) cubic meter (m^3)	0.02832 0.7646
Mass	pound (lb)	kilogram (kg)	0.4536
Stress	pounds per square inch (psi)	megapascal (MPa)	6.895×10^{-2}
Density	pounds per cubic foot (lb/ft^3) pounds per cubic yard (lb/yd^3)	kilograms per cubic meter (kg/m^3) kilograms per cubic meter (kg/m^3)	16.02 0.5933
Temperature	degrees Fahrenheit (F)	degrees Celsius (C)	‡

*Gives names (and abbreviations) of measurement units in the inch-pound system as used in the body of this report and in the SI (metric) system, along with multipliers for converting the former to the latter. From ASTM E 380.
†Systéme International d'Unites
‡C = (F − 32)/1.8

Al.2 For convenience of reference, numbering of subsequent paragraphs in this Appendix corresponds to the body of the report except that the designation "Al" is prefixed. All tables have been converted and reproduced. Descriptive portions are included only where use of the SI system requires a change in procedure or formula. To the extent practicable, conversions to metric units have been made in such a way that values are realistic in terms of usual practice and significance of numbers. For example, aggregate and sieve sixes in the metric tables are ones commonly used in Europe. Thus, there is not always a precise mathematical correspondence between inch-pound and SI values in corresponding tables.

A1.5.3 *Steps in calculating proportions* -- Except as discussed below, the methods for arriving at quantities of ingredients for a unit volume of concrete are essentially the same when SI units are employed as when inch-pound units are employed. The main difference is that the unit volume of concrete becomes the cubic meter and numerical values must be taken from the proper "A1" table instead of the one referred to in the text.

A1.5.3.1 *Step 1. Choice of slump* -- *See* Table A1.5.3.1.

TABLE A1.5.3.1 — RECOMMENDED SLUMPS FOR VARIOUS TYPES OF CONSTRUCTION (SI)

Types of construction	Slump, mm Maximum*	Slump, mm Minimum
Reinforced foundation walls and footings	75	25
Plain footings, caissons, and substructure walls	75	25
Beams and reinforced walls	100	25
Building columns	100	25
Pavements and slabs	75	25
Mass concrete	75	25

*May be increased 25 mm for methods of consolidation other than vibration

A1.5.3.2 *Step 2. Choice of nominal maximum size of aggregate.*

A1.5.3.3 *Step 3. Estimation of mixing water and air content* -- See Table A1.5.3.3.

A1.5.3.4 *Step 4. Selection of water-cement ratio* -- See Table A1.5.3.4.

A1.5.3.5 *Step 5. Calculation of cement content.*

A1.5.3.6 *Step 6. Estimation of coarse aggregate content* -- The dry mass of coarse aggregate required for a cubic meter of concrete is equal to the value from Table A1.5.3.6 multiplied by the dry-rodded unit mass of the aggregate in kilograms per cubic meter.

A1.5.3.7 *Step 7. Estimation of fine aggregate content* -- In the SI, the formula for calculation of fresh concrete mass per cubic meter is:

$$U_M = 10G_a(100 - A) + C_M(1 - G_a/G_c) - W_M(G_a - 1)$$

where

U_M = unit mass of fresh concrete, kg/m^3
G_a = weighted average specific gravity of combined fine and coarse aggregate, bulk, SSD
G_c = specific gravity of cement (generally 3.15)
A = air content, percent
W_M = mixing water requirement, kg/m^3
C_M = cement requirement, kg/m^3

A1.5.3.9 *Step 9. Trial batch adjustments* -- The following "rules of thumb" may be used to arrive at closer approximations of unit batch quantities based on results for a trial batch:

A1.5.3.9.1 The estimated mixing water to produce the same slump as the trial batch will be equal to the net amount of mixing water used divided by the yield of the trial batch in m^3. If slump of the trial batch was not correct, increase or decrease the re-estimated water content by 2 kg/m^3 of concrete for each increase or decrease of 10 mm in slump desired.

A1.5.3.9.2 To adjust for the effect of

TABLE A1.5.3.3 — APPROXIMATE MIXING WATER AND AIR CONTENT REQUIREMENTS FOR DIFFERENT SLUMPS AND NOMINAL MAXIMUM SIZES OF AGGREGATES (SI)

Slump, mm	Water, Kg/m^3 of concrete for indicated nominal maximum sizes of aggregate 9.5*	12.5*	19*	25*	37.5*	50†*	75†‡	150†‡
Non-air-entrained concrete								
25 to 50	207	199	190	179	166	154	130	113
75 to 100	228	216	205	193	181	169	145	124
150 to 175	243	228	216	202	190	178	160	—
Approximate amount of entrapped air in non-air-entrained concrete, percent	3	2.5	2	1.5	1	0.5	0.3	0.2
Air-entrained concrete								
25 to 50	181	175	168	160	150	142	122	107
75 to 100	202	193	184	175	165	157	133	119
150 to 175	216	205	197	184	174	166	154	—
Recommended average§ total air content, percent for level of exposure:								
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5**††	1.0**††
Moderate exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5**††	3.0**††
Extreme exposure‡‡	7.5	7.0	6.0	6.0	5.5	5.0	4.5**††	4.0**††

*The quantities of mixing water given for air-entrained concrete are based on typical total air content requirements as shown for "moderate exposure" in the Table above. These quantities of mixing water are for use in computing cement contents for trial batches at 20 to 25 C. They are maximum for reasonably well-shaped angular aggregates graded within limits of accepted specifications. Rounded coarse aggregate will generally require 18 kg less water for non-air-entrained and 15 kg less for air-entrained concretes. The use of water-reducing chemcial admixtures. ASTM C 494, may also reduce mixing water by 5 percent or more. The volume of the liquid admixtures is included as part of the total volume of the mixing water.

†The slump values for concrete containing aggregate larger than 40 mm are based on slump tests made after removal of particles larger than 40 mm by wet-screenmg.

‡These quantities of mixing water are for use in computing cement factors for trial batches when 75 mm or 150 mm normal maximum size aggregate is used. They are average for reasonably well-shaped coarse aggregates, well-graded from coarse to fine.

§Additional recommendations for air-content and necessary tolerances on air content for control in the field are given in a number of ACI documents, including ACI 201, 345, 318, 301, and 302. ASTM C 94 for ready-mixed concrete also gives air content limits. The requirements in other documents may not always agree exactly so in proportioning concrete consideration must be given to selecting an air content that will meet the needs of the job and also meet the applicable specifications.

**For concrete containing large aggregates which will be wet-screened over the 40 mm sieve prior to testing for air content, the percentage of air expected in the 40 mm minus material should be as tabulated in the 40 mm column. However, initial proportioning calculations should include the air content as a percent of the whole.

††When using large aggregate in low cement factor concrete, air entrainment need not be detrimental to strength. In most cases mixing water requirement is reduced sufficiently to improve the water-cement ratio and to thus compensate for the strength reducing effect of entrained air concrete. Generally, therefore, for these large nominal maximum sizes of aggregate. air contents recommended for extreme exposure should be considered even though there may be little or no exposure to moisture and freezing.

‡‡These values are based on the criteria that 9 percent air is needed in the mortar phase of the concrete. If the mortar volume will be substantially different from that determined in this recommended practice, it may be desirable to calculate the needed air content by taking 9 percent of the actual mortar volume.

TABLE A1.5.3.4(a) — RELATIONSHIPS BETWEEN WATER-CEMENT RATIO AND COMPRESSIVE STRENGTH OF CONCRETE (SI)

Compressive strength at 28 days, MPa*	Water-cement ratio, by mass: Non-air-entrained concrete	Air-entrained concrete
40	0.42	—
35	0.47	0.39
30	0.54	0.45
25	0.61	0.52
20	0.69	0.60
15	0.79	0.70

*Values are estimated average strengths for concrete containing not more than 2 percent air for non-air-entrained concrete and 6 percent total air content for air-entrained concrete. For a constant water-cement ratio, the strength of concrete is reduced as the air content is increased.

Strength is based on 152 X 305 mm cylinders moist-cured for 28 days in accordance with the sections on "Initial Curing" and "Curing of Cylinders for Checking the Adequacy of Laboratory Mixture Proportions for Strength or as the Basis for Acceptance or for Quality Control" of ASTM Method C 31 for Making and Curmg Concrete Specimens in the Field. These are cylinders cured moist at 23 ± 1.7 C prior to testing.

The relationship in this Table assumes a nominal maximum aggregate size of about 19 to 25 mm. For a given source of aggregate, strength produced at a given water-cement ratio will increase as nominal maximum size of aggregate decreases; see Sections 3.4 and 5.3.2.

incorrect air content in a trial batch of air-entrained concrete on slump, reduce or increase the mixing water content of A1.5.3.9.1 by 3 kg/m^3 of concrete for each 1 percent by which the air content is to be increased or decreased from that of the trial batch.

A1.5.3.9.3 The re-estimated unit mass of the fresh concrete for adjustment of trial batch proportions is equal to the unit mass in kg/m^3 measured on the trial batch, reduced or increased by the percentage increase or decrease in air content of the adjusted batch from the first trial batch.

TABLE A1.5.3.4(b) — MAXIMUM PERMISSIBLE WATER-CEMENT RATIOS FOR CONCRETE IN SEVERE EXPOSURES (SI)*

Type of structure	Structure wet continuously or frequently and exposed to freezing and thawing†	Structure exposed to sea water or sulfates
Thin sections (railings, curbs, sills, ledges, ornamental work) and sections with less than 5 mm cover over stee	0.45	0.40‡
All other structures	0.50	0.45‡

*Based on ACI 201.2R.

†Concrete should also be air-entrained.

‡If sulfate resisting cement (Type II or Type V of ASTM C 150) is used, permissible water-cement ratio may be Increased by 0.05.

TABLE A1.5.3.6 — VOLUME OF COARSE AGGREGATE PER UNIT OF VOLUME OF CONCRETE (SI)

Nominal maximum size of aggregate, mm	Volume of dry-rodded coarse aggregate* per unit volume of concrete for different fineness moduli† of fine aggregate			
	2.40	2.60	2.80	3.00
9.5	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
37.5	0.75	0.73	0.71	0.69
50	0.78	0.76	0.74	0.72
75	0.82	0.80	0.78	0.76
150	0.87	0.85	0.83	0.81

*Volumes are based on aggregates in dry-rodded condition as described in ASTM C 29.

These volumes are selected from empirical relationships to produce concrete with a degree of workability suitable for usual reinforced construction. For less workable concrete such as required for concrete pavement construction they may be increased about 10 percent. For more workable concrete. such as may sometimes be required when placement is to be by pumping, they may be reduced up to 10 percent.

†See ASTM Method 136 for calculation of fineness modulus.

TABLE A1.5.3.7.1 — FIRST ESTIMATE OF MASS OF FRESH CONCRETE (SI)

Nominal maximum size of aggregate, mm	First estimate of concrete unit mass, kg/m³*	
	Non-air-entrained concrete	Air-entrained concrete
9.5	2280	2200
12.5	2310	2230
19	2345	2275
25	2380	2290
37.5	2410	2350
50	2445	2345
75	2490	2405
150	2530	2435

*Values calculated by Eq. (A1.5.3.7) for concrete of medium richness (330 kg of cement per m3) and medium slump with aggregate specific gravity of 2.7. Water requirements based on values for 75 to 100 mm slump in Table A1.5.3.3. If desired, the estimate of unit mass may be refined as follows if necessary information is available: for each 5 kg difference in mixing water from the Table A1.5. 3.3 values for 75 to 100 mm slump, correct the mass per m³ 8 kg in the opposite direction; for each 20 kg difference in cement content from 330 kg, correct the mass per m³ 3 kg in the same direction; for each 0.1 by which aggregate specific gravity deviates from 2.7, correct the concrete mass 60 kg in the same direction. For air-entrained concrete the air content for severe exposure from Table A.1.5.3.3 was used. The mass can be increased 1 percent for each percent reduction in air content from that amount.

APPENDIX 2 -- EXAMPLE PROBLEM IN METRIC (SI) SYSTEM

A2.1 *Example 1* -- Example 1 presented in Section 6.2 will be solved here using metric units of measure. Required average strength will be 24 MPa with slump of 75 to 100 mm. The coarse aggregate has a nominal maximum size of 37.5 mm and dry-rodded mass of 1600 kg/m³. As stated in Section 6.1, other properties of the ingredients are: cement -- Type I with specific gravity of 3.15; coarse aggregate -- bulk specific gravity 2.68 and absorption 0.5 percent; fine aggregate -- bulk specific gravity 2.64, absorption 0.7 percent, and fineness modulus 2.8.

A2.2 All steps of Section 5.3 should be followed in sequence to avoid confusion, even though they sometimes merely restate information already given.

A2.2.1 *Step 1* -- The slump is required to be 75 to 100 mm.

A2.2.2 *Step* 2 -- The aggregate to be used has a nominal maximum size of 37.5 mm.

A2.2.3 *Step* 3 -- The concrete will be non-air-entrained since the structure is not exposed to severe weathering. From Table A1.5.3.3, the estimated mixing water for a slump of 75 to 100 mm in non-air-entrained concrete made with 37.5 mm aggregate is found to be 181 kg/m³.

A2.2.4 *Step 4* -- The water-cement ratio for non-air-entrained concrete with a strength of 24 MPa is found from Table Al.5.3.4(a) to be 0.62.

A2.2.5 *Step 5* -- From the information developed in Steps 3 and 4, the required cement content is found to be 181/0.62 = 292 kg/m³.

A2.2.6 *Step 6* -- The quantity of coarse aggregate is estimated from Table A 1.5.3.6. For a fine aggregate having a fineness modulus of 2.8 and a 37.5 mm nominal maximum size of coarse aggregate, the table indicates that 0.71 m³ of coarse aggregate, on a dry-rodded basis, may be used in each cubic meter of concrete. The required dry mass is, therefore, 0.71 x 1600 = 1136 kg.

A2.2.7 *Step* 7 -- With the quantities of water, cement and coarse aggregate established, the remaining material comprising the cubic meter of concrete must consist of fine aggregate and whatever air will be entrapped. The required fine aggregate may be determined on the basis of either mass or absolute volume as shown below:

A2.2.7.1 *Mass basis* -- From Table A1.5.3.7.1, the mass of a cubic meter of non-air-entrained concrete made with aggregate having a nominal maximum size of 37.5 mm is estimated to be 2410 kg. (For a first trial batch, exact adjustments of this value for usual differences in slump, cement factor, and aggregate specific gravity are not critical.) Masses already known are:

Water (net mixing)	181 kg
Cement	292 kg
Coarse aggregate	1136 kg
Total	1609 kg

The mass of fine aggregate, therefore, is estimated to be

$$2410 - 1609 = 801 \text{ kg}$$

A2.2.7.2 *Absolute volume basis* -- With the quantities of cement, water, and coarse aggregate established, and the approximate entrapped air content (as opposed to purposely entrained air) of 1 percent determined from Table Al.5.3.3, the sand content can be calculated as follows:

$$\text{Volume of water} = \frac{181}{1000} \qquad 0.181 \text{ m}^3$$

$$\text{Solid volume of cement} = \frac{292}{3.15 \times 1000} \qquad 0.093 \text{ m}^3$$

Solid volume of coarse aggregate	=	$\frac{1136}{2.68 \times 1000}$	0.424 m^3
Volume of entrapped air	=	0.01 x 1.000	0.010 m^3
Total solid volume of ingredients except fine aggregate			0.708 m^3
Solid volume of fine aggregate required	=	1.000 - 0.705	0.292 m^3
Required weight of dry fiie aggregate	=	0.292 x 2.64 x 1000	771 kg

A2.2.7.3 Batch masses per cubic meter of concrete calculated on the two bases are compared below:

	Based on estimated concrete mass, kg	Based on absolute volume of ingredients, kg
Water (net mixing)	181	181
Cement	292	292
Coarse aggregate (dry)	1136	1136
Sand (dry)	801	771

A2.2.8 *Step 8* -- Tests indicate total moisture of 2 percent in the coarse aggregate and 6 percent in the fine aggregate. If the trial batch proportions based on assumed concrete mass are used, the adjusted aggregate masses become

Coarse aggregate (wet) = 1136(1.02) = 1159 kg
Fine aggregates (wet) = 801(1.06) = 849kg

Absorbed water does not become part of the mixing water and must be excluded from the adjustment in added water. Thus, surface water contributed by the coarse aggregate amounts to 2 - 0.5 = 1.5 percent; by the fine aggregate 6 - 0.7 = 5.3 percent. The estimated requirement for added water, therefore, becomes

$$181 - 1136(0.015) - 801(0.053) = 122 \text{ kg}$$

The estimated batch masses for a cubic meter of concrete are:

Water (to be added)	122 kg
Cement	292 kg
Coarse aggregate (wet)	1159 kg
Fine aggregate (wet)	849 kg
Total	2422 kg

A2.2.9 *Step 9* -- For the laboratory trial batch, it is found convenient to scale the masses down to produce 0.02 m3 of concrete. Although the calculated quantity of water to be added was 2.44 kg, the amount actually used in an effort to obtain the desired 75 to 100 mm slump is 2.70 kg. The batch as mixed, therefore, consists of

Water (added)	2.70 kg
Cement	5.84 kg
Coarse aggregate (wet)	23.18 kg
Fine aggregate (wet)	16.98 kg
Total	48.70 kg

The concrete has a measured slump of 50 mm and unit mass of 2390 kg/m? It is judged to be satisfactory from the standpoint of workability and finishing properties. To provide proper yield and other characteristics for future batches, the following adjustments are made:

A2.2.9.1 Since the yield of the trial batch was

$$48.70/2390 = 0.0204 \text{ m}^3$$

and the mixing water content was 2.70 (added) + 0.34 (on coarse aggregate) + 0.84 (on fine aggregate) = 3.88 kg, the mixing water required for a cubic meter of concrete with the same slump as the trial batch should be

$$3.88/0.0204 = 190 \text{ kg}$$

As indicated in A1.5.3.9.1, this amount must be increased another 8 kg to raise the slump from the measured 50 mm to the desired 75 to 100 mm range, bringing the total mixing water to 198 kg.

A2.2.9.2 With the increased mixing water, additional cement will be required to provide the desired water-cement ratio of 0.62. The new cement content becomes

$$198/0.62 = 319 \text{ kg}$$

A2.2.9.3 Since workability was found to be satisfactory, the quantity of coarse aggregate per unit volume of concrete will be maintained the same as in the trial batch. The amount of coarse aggregate per cubic meter becomes

$$\frac{23.18}{0.0204} = 1136 \text{ kg wet}$$

which is

$$\frac{1136}{1.02} = 1114 \text{ kg dry}$$

and

$$1114 \times 1.005 = 1120 \text{ kg SSD*}$$

A2.2.9.4 The new estimate for the mass of a cubic meter of concrete is the measured unit mass of 2390 kg/m³. The amount of fine aggregate required is, therefore

$$2390 - (198 + 319 + 1120) = 753 \text{ kg SSD*}$$

or

$$753/1.007 = 748 \text{ kg dry}$$

The adjusted basic batch masses per cubic meter of concrete are

Water (net mixing)	198 kg
Cement	319 kg
Coarse aggregate (dry)	1114 kg
Fine aggregate (dry)	748 kg

A2.2.10 Adjustments of proportions determined on an absolute volume basis follow a procedure similar to that just outlined. The steps will be given without detailed explanation:

A2.2.10.1 Quantities used in the nominal 0.02 m³ batch are

Water (added)	2.70 kg
Cement	5.84 kg
Coarse aggregate (wet)	23.18 kg
Fine aggregate (wet)	16.34 kg
Total	48.08 kg

Measured slump 50 mm; unit mass 2390 kg/m³; yield 48.08/2390 = 0.0201 m³; workability o.k.

A2.2.10.2 Re-estimated water for same slump as trial batch:

$$\frac{2.70 + 0.34 + 0.81}{0.0201} = 192 \text{ kg}$$

Mixing water required for slump of 75 to 100 mm:

$$192 + 8 = 200 \text{ kg}$$

A2.2.10.3 Adjusted cement content for increased water:

$$200/0.62 = 323 \text{ kg}$$

A2.2.10.4 Adjusted coarse aggregate requirement:

$$\frac{23.18}{0.0202} = 1153 \text{ kg wet}$$

or

$$1163/1.02 = 1130 \text{ kg dry}$$

A2.2.10.5 The volume of ingredients other than air in the original trial batch was

Water	$\frac{3.85}{1000}$	= 0.0039 m3
Cement	$\frac{5.84}{3.15 \times 1000}$	= 0.0019 m3
Coarse aggregate	$\frac{22.72}{2.68 \times 1000}$	= 0.0085 m3
Fine aggregate	$\frac{15.42}{2.64 \times 1000}$	= 0.0058 m3
Total		0.0201 m3

Since the yield was also 0.0201 m³, there was no air in the concrete detectable within the precision of the unit mass test and significant figures of the calculations. With the proportions of all components except fine aggregate established, the determination of adjusted cubic meter batch quantities can be completed as follows:

Volume of water	$= \frac{200}{1000}$	= 0.200 m³
Volume of cement	$= \frac{323}{3.15 \times 1000}$	= 0.103 m³
Allowance for volume of cement		= 0.000 m³
Volume of coarse aggregate	$= \frac{1130}{2.68 \times 1000}$	= 0.422 m³
Total volume exclusive of fine aggregate		= 0.725 m³
Volume of fine aggregate required	= 1.000 - 0.725	= 0.275 m³
Mass of fine aggregate (dry basis)	= 0.275 x 2.64 x 1000	= 726 kg

The adjusted basic batch weights per cubic meter of concrete, then, are:

Water (net mixing)	200 kg

[1] Saturated-surface-dry.

Cement	323 kg
Coarse aggregate (dry)	1130 kg
Fine aggregate (dry)	726 kg

These differ only slightly from those given in Paragraph A2.2.9.4 for the method of assumed concrete weight. Further trials or experience might indicate small additional adjustments for either method.

APPENDIX 3 -- LABORATORY TESTS

A.3.1 Selection of concrete mix proportions can be accomplished effectively from results of laboratory tests which determine basic physical properties of materials to be used, establish relationships between water-cement ratio or water to cement and pozzolan ratio, air content, cement content, and strength, and which furnish information on the workability characteristics of various combinations of ingredient materials. The extent of investigation desirable for any given job will depend on its size and importance and on the service conditions involved. Details of the laboratory program will also vary, depending on facilities available and on individual preferences.

A3.2 *Properties of cement*

A3.2.1 Physical and chemical characteristics of cement influence the properties of hardened concrete. However, the only property of cement used directly in computation of concrete mix proportions is specific gravity. The specific gravity of portland cements of the types covered by ASTM C 150 and C 175 may usually be assumed to be 3.15 without introducing appreciable error in mix computations. For other types such as the blended hydraulic cements of ASTM C 595, slag cement in C 989 or pozzolan covered in C 618**,** the specific gravity for use in volume calculations should be determined by test.

A3.2.2 A sample of cement should be obtained from the mill which will supply the job, or preferably from the concrete supplier. The sample should be ample for tests contemplated with a liberal margin for additional tests that might later be considered desirable. Cement samples should be shipped in airtight containers, or at least in moisture-proof packages. Pozzolans should also be carefully sampled.

A3.3 *Properties of aggregate*

A3.3.1 Sieve analysis, specific gravity, absorption, and moisture content of both fine and coarse aggregate and dry-rodded unit weight of coarse aggregate are physical properties useful for mix computations. Other tests which may be desirable for large or special types of work include petrographic examination and tests for chemical reactivity, soundness, durability, resistance to abrasion, and various deleterious substances. Such tests yield information of value in judging the long-range serviceability of concrete.

A3.3.2 Aggregate gradation as measured by the sieve analysis is a major factor in determining unit water requirement, proportions of coarse aggregate and sand, and cement content for satisfactory workability. Numerous "ideal" aggregate grading curves have been proposed, and these, tempered by practical considerations, have formed the basis for typical sieve analysis requirements in concrete standards. ASTM C 33 provides a selection of sizes and gradings suitable for most concrete. Additional workability realized by use of air-entrainment permits, to some extent, the use of less restrictive aggregate gradations.

A3.3.3 Samples for concrete mix tests should be representative of aggregate available for use in the work. For laboratory tests, the coarse aggregates should be separated into required size fractions and reconstituted at the time of mixing to assure representative grading for the small test batches. Under some conditions, for work of important magnitude, laboratory investigation may involve efforts to overcome grading deficiencies of the available aggregates. Undesirable sand grading may be corrected by (1) separation of the sand into two or more size fractions and recombining in suitable proportions; (2) increasing or decreasing the quantity of certain sizes to balance the grading; or (3) reducing excess coarse material by grinding or crushing. Undesirable coarse-aggregate gradings may be corrected by: (1) crushing excess coarser fractions; (2) wasting sizes that occur in excess; (3) supplementing deficient sizes from other sources; or (4) a combination of these methods. Whatever grading adjustments are made in the laboratory should be practical and economically justified from the standpoint of job operation. Usually, required aggregate grading should be consistent with that of economically available materials.

A3.4 *Trial batch series*

A3.4.1 The tabulated relationships in the body of this report may be used to make rough estimates of batch quantities for a trial mix. However, they are too generalized to apply with a high degree of accuracy to a specific set of materials. If facilities are available, therefore, it is advisable to make a series of concrete tests to establish quantitative relationships for the materials to be used. An illustration of such a test program is shown in Table A3.4.1.

A3.4.2 First, a batch of medium cement content and usable consistency is proportioned by the described methods. In preparing Mix No. 1, an amount of water is used which will produce the desired slump even if this differs from the estimated requirement. The fresh concrete is tested for slump and unit weight and observed closely for workability and finishing characteristics. In the example, the yield is too high and the concrete is judged to contain an excess of fine aggregate.

A3.4.3 Mix No. 2 is prepared, adjusted to correct the errors in Mix No. 1, and the testing and evaluation repeated. In this case, the desired properties are achieved within close tolerances and cylinders are molded to check the compressive strength. The information derived so far can now be used to select proportions for a series of additional mixes, No. 3 to 6, with cement contents above and below that of Mix No. 2, encompassing the range likely to be needed. Reasonable

TABLE A3.4.1 — TYPICAL TEST PROGRAM TO ESTABLISH CONCRETE-MAKING PROPERTIES OF LOCAL MATERIALS

(Cubic yard batch quantities, lb)								Concrete characteristics			
Mix No.	Cement	Sand	Coarse Aggregate	Water Estimated	Water Used	Total used	Slump in.	Unit wt., lb per cu ft	Yield cu ft	28-day Compressive strength, psi	Work-ability
1	500	1375	1810	325	350	4035	4	147.0	27.45	—	Oversanded
2	500	1250	1875	345	340	3965	3	147.0	26.97	3350	o.k.
3	400	1335	1875	345	345	3955	4.5	145.5	27.18	2130	o.k.
4	450	1290	1875	345	345	3960	4	146.2	27.09	2610	o.k.
5	550	1210	1875	345	345	3980	3	147.5	26.98	3800	o.k.
6	600	1165	1875	345	345	3985	3.5	148.3	26.87	4360	o.k.

refinement in these batch weights can be achieved with the help of corrections given in the notes to Table 6.3.7.1.

A3.4.4 Mix No. 2 to 6 provide the background, including the relationship of strength to water-cement ratio for theparticular combination of ingredients, needed to select proportions for a range of specified requirements.

A3.4.5 In laboratory tests, it seldom will be found, even by experienced operators, that desired adjustments will develop as smoothly as indicated in Table A3.4.1. Furthermore, it should not be expected that field results will check exactly with laboratory results. An adjustment of the selected trial mix on the job is usually necessary. Closer agreement between laboratory and field will be assured if machine mixing is employed in the laboratory. This is especially desirable if air-entraining agents are used since the type of mixer influences the amount of air entrained. Before mixing the first batch, the laboratory mixer should be "buttered" or the mix "overmortared" as described in ASTM C 192. Similarly, any processing of materials in the laboratory should simulate as closely as practicable corresponding treatment in the field.

A3.4.6 The series of tests illustrated in Table A3.4.1 may be expanded as the size and special requirements of the work warrant. Variables that may require investigation include: alterative aggregate sources; maximum sizes and gradings; different types and brands of cement; pozzolans; admixtures; and considerations of concrete durability, volume change, temperature rise, and thermal properties.

A3.5 *Test methods*

A3.5.1 In conducting laboratory tests to provide information for selecting concrete proportions, the latest revisions of the following methods should be used:

A3.5.1.1 For tests of ingredients:

Sampling hydraulic cement--ASTM C 183

Specific gravity of hydraulic cement--ASTM C 188

Sampling stone, slag, gravel, sand, and stone block for use as highway materials--ASTM D 75

Sieve or screen analysis of fine and coarse aggregates--ASTM C 136

Specific gravity and absorption of coarse aggregates--ASTM C 127

Specific gravity and absorption of fine aggregates--ASTM C 128

Surface moisture in fine aggregate--ASTM C 70

Total moisture content of aggregate by drying--ASTM C 566

Unit weight of aggregate--ASTM C 29

Voids in aggregate for concrete--ASTM C 29

Fineness modulus--Terms relating to concrete and concrete aggregates, ASTM C 125

A3.5.1.2 For tests of concrete:

Sampling fresh concrete--ASTM C 172

Air content of freshly mixed concrete by the volumetric method--ASTM C 173

Air content of freshly mixed concrete by the pressure method--ASTM C 231

Slump of portland cement concrete--ASTM C 143

Weight per cubic foot, yield, and air content (gravimetric) of concrete--ASTM C 138

Concrete compression and flexure test specimens, making and curing in the laboratory--ASTM C 192

Compressive strength of molded concrete cylinders--ASTM C 39

TABLE A3.6.1 — CONCRETE MIXES FOR SMALL JOBS

Procedure: Select the proper nominal maximum size of aggregate (see Section 5.3.2). Use Mix B, adding just enough water to produce a workable consistency. If the concrete appears to be undersanded, change to Mix A and, if it appears oversanded. change to Mix C.

Nominal maximum size of aggregate, in.	Mix designation	Approximate weights of solid ingredients per cu ft of concrete, lb				
			Sand*		Coarse aggregate	
		Cement	Air-entrained concrete†	Concrete without air	Gravel or crushed stone	Iron blast furnace slag
1/2	A	25	48	51	54	47
	B	25	46	49	56	49
	C	25	44	47	58	51
¼	A	23	45	49	62	54
	B	23	43	47	64	56
	C	23	41	45	66	58
1	A	22	41	45	70	61
	B	22	39	43	72	63
	C	22	37	41	74	65
1½	A	20	41	45	75	65
	B	20	39	43	77	67
	C	20	37	41	79	69
2	A	19	40	45	79	69
	B	19	38	43	81	71
	C	19	36	41	83	72

*Weights are for dry sand If damp sand is used, increase tabulated weight of sand 2 lb and. if very wet sand is used, 4 lb

†Air-entrained concrete should be used mall structures which will be exposed to alternate cycle\ of freezing ad thawing Air-entrainment can be obtained by the use of an air-entraining cement or by adding an air-entraining admixture If an admixture is used, the amount recommended by the manufacturer will, in most cases, produce the desired air content

Flexural strength of concrete (using simple beam with third-point loading)--ASTM C 78

Flexural strength of concrete (using simple beam with center point loading--ASTM C 293

splitting tensile strength of molded concrete cylinders--ASTM C 496

A3.6 *Mixes for small jobs*

A3.6.1 For small jobs where time and personnel are not available to determine proportions in accordance with the recommended procedure, mixes in Table A3.6.1 will usually provide concrete that is amply strong and durable if the amount of water added at the mixer is never large enough to make the concrete overwet These mixes have been predetermined in conformity with the recommended procedure by assuming conditions applicable to the average small job, and for aggregate of medium specific gravity. Three mixes are given for each nominal maximum size of coarse aggregate. For the selected size of coarse aggregate, Mix B is intended for initial use. If this mix proves to be oversanded, change to Mix C; if it is undersanded, change to Mix A It should be noted that the mixes listed in the table are based on dry or surface-dry sand. If the fine aggregate is moist or wet, make the corrections in batch weight prescribed in the footnote.

A3.6.2 The approximate cement content per cubic foot of concrete listed in the table will be helpful in estimating cement requirements for the job. These requirements are based on concrete that has just enough water in it to permit ready working into forms without objectionable segregation. Concrete should slide, not run, off a shovel.

APPENDIX 4 -- HEAVYWEIGHT CONCRETE MIX PROPORTIONING

A4.1 Concrete of normal placeability can be proportioned for densities as high as 350 lb per cu ft by using heavy aggregates such as iron ore, iron or steel shot, barite, and iron or steel punchings. Although each of the materials has its own special characteristics, they can be processed to meet the standard requirements for grading, soundness cleanliness, etc. The selection of the aggregate should depend on its intended use. In the case of radiation shielding, determination should be made of trace elements within the material which may become reactive when subjected to radiation. In the selection of materials and proportioning of heavyweight concrete, the data needed and procedures used are similar to those required for normal weight concrete.

Aggregate density and composition for heavyweight concrete should meet requirements of ASTM C 637 and C 638. The following items should be considered.

A4.1.1 Typical materials used as heavy aggregates are listed in Table A4.1.1.

A4.1.2 If the concrete in service is to be exposed to a hot, dry environment resulting in loss of weight, it should be proportioned so that the fresh unit weight is higher than the required dry unit weight by the amount of the anticipated loss determined by performing an oven dry unit weight on concrete cylinders as follows. Three cylinders are cast and the wet unit weight determined in accordance with ASTM C 138. After 72 hours of standard curing, the cylinders are oven dried to a constant weight at 211 to 230 F and the average unit weight determined. The amount of water lost is determined by subtracting the oven dry unit weight from the wet unit weight. This difference is added to the required dry unit weight when calculating mixture proportions to allow for this loss. Normally, a freshly mixed unit weight is 8 to 10 lb per cu ft higher than the oven dry unit weight[2].

A4.1.3 If entrained air is required to resist conditions of exposure, allowance must be made for the loss in weight due to the space occupied by the air. To compensate for the loss of entrained air as a result of vibration, the concrete mixture should be proportioned with a higher air content to anticipate this loss.

A4.2 Handling of heavyweight aggregates should be in accordance with ACI 304.3R. (See also ASTM C 637 and C 638.) Proportioning of heavyweight concrete to be placed by conventional means can be accomplished in accordance with ACI 211.1 Sections 5.2 through 5.3.7 and the absolute volume method in Section 5.3.7.2. Typical proportions are shown in Table 2 of ACI 304.3R.

A4.3 *Preplaced heavyweight concrete* -- Heavyweight preplaced-aggregate concrete should be proportioned in the same manner as normal weight preplaced-aggregate concrete. (Refer to ACI 304, Table 7.3.2 -- Gradation limits for fine and coarse aggregate for preplaced aggregate concrete.) Example mixture proportions for the preplaced-aggregate method are shown in ACI 304.3R, Table 2 -- Typical proportions for high density concrete, and typical grout proportions can be found in ACI 304.3R, Table 3 -- Typical grout proportions.

A4.4 *Example* -- Concrete is required for counterweights on a lift bridge that will not be subjected to freezing and

TABLE A4.1.1 -TYPICAL HEAVYWEIGHT AGGREGATES

Material	Description	Specific gravity	Concrete, unit wt (lb/cu ft)
Limonite Goethite	Hydrous iron ores	3.4-3.8	180-195
Barite	Barium sulfate	4.0-4.4	205-225
Ilmenite Hematite Magnetite	Iron ores	4.2-5.0	215-240
Steel/iron	Shot, pellets, punchings, etc.	6.5-7.5	310-350

Note: Ferrophosphorous and ferrosilicon (heavyweight slags) materials should be used only after thorough investigation Hydrogen gas evolution in heavyweight concrete containing these aggregates has been known to result from a reaction with the cement.

thawing conditions. An average 28 day compressive strength of 4500 psi will be required. Placement conditions permit a slump of 2 to 3 in. at point of placement and a nominal maximum size aggregate of 1 in. The design of the counterweight requires* an oven dry unit weight of 225 lb per cu ft. An investigation of economically available materials has indicated the following:

Cement	ASTM C 150 Type I (non-air-entraining)
Fine aggregate	Specular hematite
Coarse aggregate	Ilmenite

Table A4.1.1 indicates that this combination of materials may result in an oven dry unit weight of 215 to 240 lb per cu ft. The following properties of the aggregates have been obtained from laboratory tests.

	Fine aggregate	Coarse aggregate
Fineness modulus	2.30	--
Specific gravity (Bulk SSD)	4.95	4.61
Absorption (percent)	0.05	0.08
Dry rodded weight	--	165 lb per cu ft
Nominal maximum size	-	1 in.

Employing the sequence outlined in Section 5 of this standard practice, the quantities of ingredients per cubic yard of concrete are calculated as follows:

A4.4.1 *Step 1 -- As* indicated, the desired slump is 2 to 3 in. at point of placement.

A4.4.2 *Step* 2 -- The available aggregate sources have been indicated as suitable, and the course aggregate will be a well-graded and well-shaped crushed ilmenite with a nominal maximum size of 1 in. The fine aggregate will be hematite.

A4.4.3 *Step* 3 -- By interpolation in Table 6.3.3, non-air-entrained concrete with a 2 to 3 in. slump and a 1 in. nominal maximum size aggregate requires a water content of approximately 310 lb per cu yd. The estimated entrapped air is 1.5 percent. (Non-air-entrained concrete will be used because (1) the concrete is not to be exposed to severe weather, and (2) a high air content could reduce the dry unit weight of the concrete.)

Note: Values given in Table 6.3.3 for water requirement are based on the use of well-shaped crushed coarse aggregates. Void content of compacted dry fine or coarse aggregate can be used as an indicator of angularity. Void contents of compacted 1 in. coarse aggregate of significantly more than 40 percent indicate angular material that will probably require more water than that listed in Table A1.5.3.3. Conversely, rounded aggregates with voids below 35 percent will probably need less water.

* Oven dry is specified and is considered a more consewative value than that of the air dry.

A4.4.4 *Step* 4 -- From Table 6.3.4(a) the water-cement ratio needed to produce a strength of 4500 psi in non-air-entrained concrete is found to be approximately 0.52.

A4.4.5 *Step 5* -- From the information derived in Steps 3 and 4, the required cement content is calculated to be 310/0.52 = 596 lb per cu yd.

A4.4.6 *Step 6 -- The* quantity of coarse aggregate is estimated by extrapolation from Table 6.3.6. For a fine aggregate having a fineness modulus of 2.30 and a 1 in. nominal maximum size aggregate, the table indicates that 0.72 cu ft of coarse aggregate, on a dry-rodded basis, may be used in each cubic foot of concrete. For a cubic yard, therefore, the coarse aggregate will be 27 x 0.72 = 19.44 cu ft, and since the dry-rodded unit weight of coarse aggregate is 165 lb per cu ft, the dry weight of coarse aggregate to be used in a cubic yard of concrete will be 19.44 x 165 = 3208 lb. The angularity of the coarse aggregate is compensated for in the ACI proportioning method through the use of the dry-rodded unit weight; however, the use of an extremely angular fine aggregate may require a higher proportion of fine aggregate, an increased cement content, or the use of air entrainment to produce the required workability. The use of entrained air reduces the unit weight of the concrete, but in some instances is necessary for durability.

A4.4.7 *Step* 7 -- For heavyweight concrete, the required fine aggregate should be determined on the absolute volume basis. With the quantities of cement, water, air, and coarse aggregate established, the fine aggregate content can be calculated as follows:

$$\text{Volume of water} = \frac{310 \text{ lb}}{62.4 \text{ lb per cu ft}} = 4.97 \text{ cu ft}$$

$$\text{Volume of air} = 0.015 \times 27 \text{ cu ft} = 0.40 \text{ cu ft}$$

$$\text{Solid volume of cement} = \frac{596 \text{ lb}}{3.15 \times 62.4 \text{ lb per cu ft}} = 3.03 \text{ cu ft}$$

$$\text{Solid volume of coarse aggregate} = \frac{3208 \text{ lb}}{4.61 \times 62.4 \text{ lb per cu ft}} = 11.15 \text{ cu ft}$$

Total volume of all ingredients except fine aggregate = 19.55 cu ft

$$\text{Solid volume of fine aggregate} = 27 \text{ cu ft} - 19.55 \text{ cu ft} = 7.45 \text{ cu ft}$$

$$\text{Required weight of fine aggregate} = 7.45 \text{ cu ft} \times 4.95 \times 62.4 \text{ lb per cu ft} = 2301 \text{ lb}$$

The actual test results indicated the concrete possessed the following properties:

Unit weight (freshly mixed)	235.7 lb per cu ft
Oven dry unit weight	228.2 lb per cu ft
Air content	2.8 percent
Slump	$2^1/_2$ in.
Strength	5000 psi at 28 days

Note: Oven dry unit weight of the concrete having a combination of hematite and ihnenite aggregates was 7.5 lb per cu ft less than the freshly mixed unit weight.

APPENDIX 5 -- MASS CONCRETE MIX PROPORTIONING

A5.1 *Introduction* -- Mass concrete is defined as "any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat of hydration from the cement and attendant volume change to minimize cracking."[A5] The purpose of the mass concrete proportioning procedure is to combine the available cementitious materials, water, fine and coarse aggregate, and admixtures such that the resulting mixture will not exceed some established allowable temperature rise, and yet meet requirements for strength and durability. In some instances, two mixtures may be required -- an interior mass concrete and an exterior concrete for resistance to the various conditions of exposure. Accordingly, concrete technologists and designers during the design stage should consider the effects of temperature on the properties of concrete. A 6-in. wall, for example, will dissipate the generated heat quite readily, but as the thickness and size of the placement increase, a point is reached, whereby, the rate of heat generated far exceeds the rate of heat dissipated. This phenomenon produces a temperature rise within the concrete and may cause sufficient temperature differential between the interior and exterior of the mass or between peak and ultimate stable temperature to induce tensile stresses. The temperature differential between interior and exterior of the concrete generated by decreases in ambient air temperature conditions may cause cracking at exposed surfaces. Furthermore, as the concrete reaches its peak temperature and subsequent cooling takes place, tensile stresses are induced by the cooling if the change in volume is restrained by the foundation or connections to other parts of the structure.

The tensile stress developed by these conditions can be expressed by the equation S = REeT; where R is the restraint factor, *E* is the modulus of elasticity, e is the thermal coefficient of expansion, and T is the temperature difference between the interior and exterior of the concrete or between the concrete at maximum temperature and at ambient air temperature. Detailed discussions on this subject of mass concrete can be found in References A5.l, A5.2, A5.3, A5.5 and A5.14.

Thermal cracking of bridge piers, foundations, floor slabs, beams, columns, and other massive structures (locks and dams) can or may reduce the service life of a structure by promoting early deterioration or excessive maintenance. Furthermore, it should be recognized that the selection of proper mixture proportions is only one means of controlling temperature rise, and that other aspects of the concrete work should be studied and incorporated into the design and construction requirements. For additional information on heat problems and solutions, consult References A5.2 and A5.14.

A5.2 *Mass concrete properties* -- During the design stage of a proposed project, desired specified compressive strength with adequate safety factors for various portions of the structure are normally first established. The engineer will then expand on the other desired properties required of the concrete.

The proportioning of ingredients such that a mass concrete mixture will have the desired properties requires an evaluation of the materials to be used. If adequate data are not available from recent construction projects using the proposed materials, representative samples of all materials proposed for use in the concrete must be tested to determine their properties and conformance with applicable specifications.

A5.3 *Properties of material related to heat generation* --

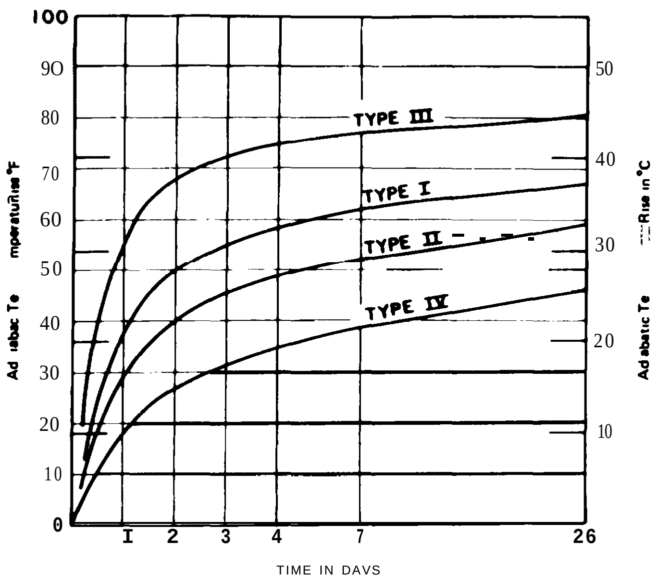
A5.3.1 *Cementitious materials* -- Cementitious material for mass concrete work may consist of portland cement or blended hydraulic cements as specified in ASTM C 150 and ASTM C 595, respectively, or a combination of portland cement and pozzolan. Pozzolans are specified in ASTM C 618.

A5.3.1.1 *Portland cement* -- The hydration of portland cement is exothermic; that is, heat is generated during the reaction of cement and water. The quantity of heat produced is a function of the chemical composition of the cement as shown in Fig. A5.3 and the initial temperature.

Type II cement is most commonly used in mass concrete, since it is a moderate heat cement and generally has favorable properties for most types of construction. When used with a pozzolanic admixture, which will be discussed later, the heat generated by a combination of Type II and pozzolan is comparative with that of Type IV. In addition, Type II is more readily available than Type IV. Optional heat of hydration requirements may be specified for Type II cement by limitations on the chemical compounds or actual heat of hydration at 7 days.

Low initial concrete placing temperature, commonly used in mass concrete work, will generally decrease the rate of cement hydration and initial heat generated. Correspondingly, strength development in the first few days may also be reduced.

The fineness of the cement also affects the rate of heat of hydration; however, it has little effect on the initial heat



Cement Type	Fineness ASTM C 115 cm^2/gm	28 Day Heat of Hydration Calories per gm
I	1790	87
II	1890	76
III	2030	105
IV	1910	60

Fig. A5.3-Temperuture rise of mass concrete containing 376 pcy (223 kg/m^3) of cement.

generated. Fine-ground cements will produce heat more rapidly during the early ages than a coarse-ground cement, all other cement properties being equal.

A5.3.1.2 *Blended hydraulic cements* -- Blended hydraulic cements conforming to the requirements of ASTM C 595, if available and economical, may be used effectively in mass concrete. These cements are composed of a blend of portland cement and blast-furnace slag or pozzolan. The suffix (MH) or (LH) may be used with the designated type of blended cement to specify moderate heat or low heat requirements where applicable.

A5.3.13 *Pozzolans* -- Major economic and temperature rise benefits have been derived from the use of pozzolans. Pozzolan is defined as “a siliceous or siliceous and aluminous material which in itself possesses 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 possessing cementitious properties.”[A5.9] Pozzolans include some diatomaceous earths, opaline cherts and shales, tuffs and volcanic ashes or pumicites, any of which may or may not be processed by calcination, and other various materials requiring calcination to induce satisfactory properties, such as some clays and shales. Fly ash, the finely divided residue that results from the combustion of ground or powdered coal and is transported from the combustion chamber by exhaust gases is also a pozzolan.

Utilization of pozzolans in mass concrete provides a partial replacement of cement with a material which generates considerably less heat at early ages. The early age heat contribution of a pozzolan may conservatively be estimated to range between 15 to 50 percent of that of an equivalent weight of cement.

The effects of pozzolan on the properties of freshly mixed concrete vary with the type and fineness; the chemical, mineralogical and physical characteristics of the pozzolan; the fineness and composition of the cement; the ratio of cement to pozzolan; and the weight of cement plus pozzolan used per unit volume of concrete. For example, it has been reported that some pozzolans may reduce water requirements by as much as 7 percent with a reduction of air-entraining admixture needs by up to about 20 percent. Since certain other pozzolans may require as much as 15 percent additional water and over 60 percent more air-entraining admixture, it is important to evaluate the pozzolan intended for use prior to the start of proportioning.

The proportion of cement to pozzolan depends upon the strength desired at a given age, heat considerations, the chemical and physical characteristics of both cement and pozzolan and the cost of the respective materials. Typical quantities of various types of pozzolan and other materials blended with portland cement to reduce heat generation are shown in Table A5.1.

A5.3.2 *Aggregates* -- The nominal maximum size aggregates recommended for use under various placing conditions are shown in Table A5.2. A nominal maximum size aggregate up to 6 in. (150 mm) should be considered, if large size aggregate is available, economical, and placing conditions permit. Because the larger aggregate provides less surface area to be coated by cement paste, a reduction in the quantity of cement and water can be realized for the same water-cement ratio. This relationship is reflected in Table 6.3.3. Typical gradations for individual size fractions of coarse aggregate are shown in Table A5.3. Gradings and other physical properties of fine aggregate should comply with the requirements of ASTM C 33.

A5.3.2.1 *Coarse aggregate combination* -- Upon determining the nominal maximum size, the individual aggregate size groups available should be combined to produce a gradation approaching maximum density and minimum voids. This results in the maximum amount of mortar available for placeability, workability, and finishability. The dry rodded unit weight method is generally applicable for combining size groups up to a nominal maximum size of 1½ in. (37.5 mm); however, this method is impractical for combining size groups of 3 in. (75 mm) or 6 in. (150 mm) nominal maximum size. Eq. (A5.3) gives an approximate percentage of material passing each sieve size required for a given aggregate type. This equation was developed from work by Fuller and Thompson (Reference A5.13) on the packing characteristics of particulate material. The parabolic curve generated from the equation approximates the ideal gradation for maximum density and minimum voids according to the particle shape of the aggregate. Combining the individual coarse aggregate size groups to approximate the ideal curve is the recommended procedure for use with 6 in. (150 mm) and 3 in. (75 mm) nominal maximum size aggregate mixtures in place of the dry rodded unit weight method.

$$P = \frac{d^x - 0.1875^x}{D^x - 0.1875^x}(100)$$

where

- P = cumulative percent passing the d-size sieve
- d = sieve opening, in. (mm)
- D = nominal maximum size aggregate, in. (mm)
- x = exponent (0.5 for rounded and 0.8 for crushed aggregate)

Based on the above equation, the ideal combined gradings for 6 in. and 3 in. (150 and 75 mm) crushed and rounded aggregates are shown in Table A5.4. An acceptable grading for an aggregate that is partially crushed or partially rounded may be interpolated from the gradations in Table A5.4. Using the individual gradation of each size group, 6 in. to 3 in. (150 mm to 75 mm), 3 in. to 1½ in. (75 mm to 37.5 mm) 1½ in. to ¾ in. (37.5 mm to 19 mm), and ¾ in. to No. 4 (19 mm to 4.75 mm), a trial and error method of selecting the percentage of each size group will be necessary to produce a combined grading of the total coarse aggregate approximating the idealized gradation. Selection of the percentage of each size group can usually be done such that the combined grading is generally within 2 or 3 percent of the ideal grading if the individual size group gradings are within the limits of Table A5.3. Where grading limits other than those of Table A5.3 may be used, more tolerance may be required on certain sieve sixes. Furthermore, natural aggregates in some areas may be deficient of certain sizes and, in such cases, modification of the idealized grading to permit use of this aggregate is recommended.

A5.3.2.2 *Coarse aggregate content* -- The proportion of fine aggregate for mass concrete depends on the final combined grading of coarse aggregate, particle shape, fineness modulus of the fine aggregate, and the quantity of cementitious material. Coarse aggregate amount can be found using the b/b, method, Table 5.3.6 of ACI 211.1, if the ASTM C 29 bulk unit weight has been determined. For large 3 in. (75 mm) and 6 in. (150 mm) nominal maximum size aggregate Table A5.5 approximates the amount of coarse aggregate as a percent of the total aggregate volume for different moduli of fine aggregate and nominal maximum

TABLE A5.1 — TYPICAL QUANTITIES OF POZZOLANS AND OTHER MATERIALS*

Material or class of material	Percent of total cementing material by absolute volume: Unexposed concrete†	Exposed concrete‡
Pozzolans (ASTM C 618):		
Class F	35	25
Class N, all types except uncalcined diatomite	30	20
Class N. uncalcined diatomite	20	20
Other materials:		
Slag or natural cement	35	25

*Other quantities of pozzolan or other materials may be used if verified to be acceptable by laboratory evaluations or previous expenence. No typical quantitites have been established for Class C pozzolan

†Unexposed concrete for massive structures (i.e. . gravity dams. spillways, lock walls. and similar massive structures)

‡Exposed concrete for massive structures (see previous note). and exposed structural concrete tie floodwalls, building foundations pavements, and similar moderate-size structures)

TABLE A5.2 — NOMINAL MAXIMUM SIZE OF AGGREGATE RECOMMENDED FOR VARIOUS TYPES OF CONSTRUCTION

Features	Nominal maximum size, in. (mm)
Sections over 7½ in. (190mm) wide. and in which the clear distance between reinforcement bars is at least 2¼ in. (57 mm)	1½(37.5)
Unreinforced sections over 12 in. (300 mm) wide and reinforced sections over 18 in (457 mm) wide, in which the clear distance between reinforcement bars is over 6 in (150 mm) and under 10 in (250 mm)	3(75)
Massive sections in which the cleardistance between reinforcement bars is at least 10 in. (250 mm) and for which suitable provision is made for placing concrete containing the larger sizes of aggregate without producing rock pockets or other undesirable conditions.	6(150)

TABLE A5.3 — TYPICAL COARSE AGGREGATE GRADATION LIMITS

	Size separation			
	Percent by weight passing individual sieves			
Sieve size in. (mm)	No.4 to ¾ in. (4.75 mm to 19 mm)	¾ in. to 1½ in. (19 mm to 37.5 mm)	1½ in. to 3 in. (37.5 mm to 75 mm)	3 in. to 6in. (75 mm to 150 mm)
7(177)				100
6(150)				90-100
4(100)			100	20-55
3(75)			90-100	0-15
2(50)		100	20-55	0-5
1-1/2(37.5)		90-100	0-10	
1(25)	100	20-55	0-5	
3/4(19)	90-100	0-15		
3/8(9.5)	20-55	0-5		
No. 4(4.75)	0-10			
No. 8(2.36)	0-5			

TABLE A5.4-IDEALIZED COMBINED GRADING FOR 6 IN. (150 mm) and 3 IN. (75 mm) NOMINAL MAXIMUM SIZE AGGREGATE FROM EQ. (A5.3)

	6 in. (150 mm)		3 in. (75 mm)	
	Percent passing		Percent passing	
Sievesize — in. (mm)	Crushed	Rounded	Crushed	Rounded
6(150)	100	100	—	—
5(125)	85	89		—
4(100)	70	78		—
3(75)	54	64	100	100
2(50)	38	49	69	75
1-1/2(37.5)	28	39	52	61
1(25)	19	28	34	44
3/4(19)	13	21	25	33
3/8(9.5)	5	9	9	14

sizes of coarse aggregate. The table is only applicable for 3 in. (75 mm) and 6 in. (150 mm) nominal maximum size aggregate.

A5.3.3 *Admixtures* -- When proportioning mass concrete use of admixtures should always be considered. The two most commonly used admixtures in mass concrete are air-entraining and water-reducing admixtures.

A5.3.3.1 *Air entrainment* -- Air entrainment in mass concrete is necessary if for no other reason than to increase workability of lean concrete mixtures. The use of air entrainment in mass concrete, as in other concrete, permits a marked improvement in durability, improvement in plasticity and workability, and reduction in segregation and bleeding. The effect of air entrainment on the strength of mass concrete is minimized due to the reduction in the quantity of paste in concrete which contains 3 in. (75 mm) and 6 in. (150 mm) nominal maximum size aggregate. However, such effects should be considered in the design of mass concrete having 1½ in. (37.5 mm) or ¾ in. (19 mm) nominal maximum size aggregate. In lean mixtures strengths are not reduced as much when air entrainment is used; in some cases strengths may increase due to the reduction in mixing water requirements with air entrainment. Air contents should be in accordance with those recommended in Table A5.6.

A5.3.3.2 *Water-reducing admixture* -- Water-reducing admixtures meeting the requirements of ASTM C 494 have been found effective in mass concrete mixtures. The water reduction permits a corresponding reduction in the cement content while maintaining a constant water-cement ratio. The amount of water reduction will vary with different concretes; however, 5 to 8 percent is normal. In addition, certain types of water-reducing admixture tend to improve the mobility of concrete and its response to vibration, particularly in large aggregate mixtures.

A5.4 *Strength and durability* -- The procedure for proportioning mass concrete is used primarily for controlling the generation of heat and temperature rise, while satisfying the requirements for strength and durability. The strength and durability properties are primarily governed by the water-cement ratio. The water-cement ratio is the ratio, by

TABLE A5.5 — APPROXIMATE COARSE AGGREGATE CONTENT WHEN USING NATURAL (N) OR MANUFACTURE (M) FINE AGGREGATE (Percent of total aggregate by absolute volume)

Nominal maximum size and type coarse aggregate	Sand type:	Fineness modulus 2.40		2.60		2.80		3.00	
		N	M	N	M	N	M	N	M
6 in. (150 mm) crushed		80	78	79	77	78	76	77	75
6 in. (150 mm) rounded		82	80	81	79	80	78	79	77
3 in. (75 mm) crushed		75	73	74	72	73	71	72	70
3 in. (75 mm) rounded		77	75	76	74	75	73	74	72

Note: For concrete containing 5½ percent air content and a slump of 2 in. (50 mm), both measured on the minus 1½ in. (37.5 mm) portion. The coarse aggregate contents given above may be increased approximately 1 or 2 percent if good control procedures are followed. The coarse aggregate content in the table pertains primarily to the particle shape in the minus 1½ in. (37.5 mm) portion.

TABLE A5.6–APPROXIMATE MORTAR AND AIR CONTENT FOR VARIOUS NOMINAL MAXIMUM SIZE AGGREGATES [1½ in. (37.5 mm) slump and air content of 5 to 6 percent in minus 1½ in. (37.5 mm) portion]

Nominal maximum size and type coarse aggregate	Mortar content cu ft/cu yd ± 0.2 (m3/m3 + 0.01)	Air content Total mixture, percent
6 in. (150 mm) crushed	10.5 (0.39)	3.0-4.0
6 in. (150 mm) rounded	10.0 (0.37)	3.0-4.0
3 in. (75 mm) crushed	12.0(0.44)	3.5-4.5
3 in. (75 mm) rounded	11.5 (0.43)	3.5-4.5

TABLE A5.7 — APPROXIMATE COMPRESSIVE STRENGTHS OF AIR-ENTRAINED CONCRETE FOR VARIOUS WATER-CEMENT RATIOS [Based on the use of 6 x 12-in. (152 x 305-mm) cylinders.]

Water-cement ratio by weight*	Approximate 28-day compressive strength, psi (MPa) (f_c')† Natural aggregate	Crushed aggregate
0.40	4500 (31.0)	5000(34.5)
0.50	3400(23.4)	3800(26.2)
0.60	2700(18.6)	3100(21.4)
0.70	2100(14.5)	2500(17.2)
0.80	1600(11.0)	1900(13.l)

*These W/C ratios may be converted to w/(c + p) ratios by the use 01 the equation in Section 5.3 4
†90 days when using pozzolan

TABLE A5.8 — MAXIMUM PERMISSIBLE WATER-CEMENT RATIOS FOR MASSIVE SECTIONS

Location of structure	Water-cement ratios, by weight Severe or moderate climate	Mild climate. little snow or frost
At the waterline in hydraulic or waterfront structures where intermittent saturation is possible	0.50	0.55
Unexposed portions of massive structure	No limit*	No limit
Ordinary exposed structures	0.50	0.55
Complete continuous submergence in water	0.58	0.58
Concrete deposited in water	0.45	0.45
Exposure to strong sulfate groundwater or other corrosive liquid, salt or sea water	0.45	0.45
Concrete subjected to high velocity flow of water (>40 f/s) (> l2 m/s)	0.45	0.45

Note I These w/c ratios may be converted to w/(c + P) ratios by use of equation in Section 5.3.4
*Limit Should be based on the minimum required for workability or Table A57 for strength

TABLE A5.9 — QUANTITIES OF MATERIALS SUGGESTED FOR CONCRETE PROPORTIONING TRIAL MIXTURES

Nominal maximum size aggregate in mixture in. (mm)	Quantities of aggregates, lb (kg)					Cement, lb. (kg)
		Coarse aggregates				
	Fine aggregate	No. 4 to ¾ in. (4.75 mm to 19 mm)	¾ in. to 1½ in. (19 mm to 37.5 mm)	1½ in. to 3 in. (37.5 to 75 mm)	3 in. to 6 in. (75 mm to 150 mm)	
¾ (19)	1200 (544)	1200 (544)	—	—	—	400 (181)
1½ (37.5)	1000 (454)	1000 (454)	1000 (454)	—	—	400 (181)
3 (75)	2000 (907)	1500 (680)	1000 (454)	2000 (907)	—	500 (227)
6 (150)	3000 (1361)	2000 (907)	1500 (680)	2500 (1134)	3000 (1361)	700 (318)

Note 1 The actual quantity of materials required depends upon the laboratory equipment availability of materials, and extent of the testing program
Note 2 If a pozzolan or fly ash is to be used in the concrete, the quantity furnished should be 35 percent of the weight of the cement
Note 3 One pal (3 8) of a proposed air-entraining admixture or chemical admixture will be sufficient

weight, of amount of water, exclusive of that absorbed by theaggregates, to the amount of cement in a concrete or mortar mixture. Unless previous water-cement ratio-compressive strength data are available, the approximate compressive strength of concrete tested in 6 x 12-in. (152 x 305-mm) cylinders for various water-cement ratios can be estimated from Table A5.7. The recommended maximum permissiblewater-cement ratio for concrete subject to various conditions of exposure are shown in Table A5.8. The water-cement ratio determined by calculation should be verified by trial batches to ensure that the specified properties of the concrete are met. Results may show that strength or durability rather than heat generation govern the propor-tions. When this situation occurs alterative measures to control heat will be necessary. For example, in gravity dam construction an exterior-facing mix may be used which con-tains additional cement to provide the required durability. Other measures may include a reduction in the initial temp-erature of concrete at placement or a limitation on the size of the placement. If compressive strengths are given for full mass mixture containing aggregate larger than 1½ in. (75 mm), approximate relationships between strength of the full mass mixture and wet screened 6 x 12-in. (152 x 305-mm) cylinder are available from sources such as Reference A5.6.

A5.5 *Placement and workability* -- Experience has demonstrated that large aggregate mixtures, 3 in. (75 mm) and 6 in. (150 mm) nominal maximum size aggregate, require a minimum mortar content for suitable placing and workability properties. Table A5.6 reflects the total absolute volume of mortar (cement, pozzolan, water, air, and fine aggregate) which is suggested for use in mixtures containing large aggregate sixes. These values should be compared with those determined during the proportioning procedure and appropriate adjustments made by either increasing or decreasing the trial mixture mortar contents for improved workability.

A5.6 *Procedure* -- Upon determining the properties of the materials and knowing the properties of the concrete, the proportioning procedure follows a series of straight-forward steps outlined in A5.6.1 to A5.6.12. Proportions should be determined for the anticipated maximum placing temperature due to the influence on the rate of cement hydration and heat generated. With the use of 3 in. (75 mm) or 6 in. (150 mm) nominal maximum size aggregate, the pro-cedure may be somewhat different from ACI 211. 1, mainly because of the difficulty in determining the density of the large aggregate by the dry rodded unit weight method. For nominal maximum size aggregate **1½** in. (37.5 mm) or less, proportioning in accordance with ACI 211.1 may be used.

A5.6.1 *Step 1* -- Determine all requirements relating to the properties of the concrete including:

1. Nominal maximum size of aggregates that can be used.
2. Slump range.
3. Water-cement ratio limitations.
4. Expected maximum placing temperature.
5. Air content range.
6. Specified strengths and test ages.
7. Expected exposure conditions.
8. Expected water velocities, when concrete is to be subjected to flowing water.
9. Aggregate quality requirements.
10. Cement and/or pozzolan properties.

A5.6.2 *Step 2* -- Determine the essential properties of materials if sufficient information is not available. Representative samples of all materials to be incorporated in the concrete should be obtained in sufficient quantities to provide verification tests by trial batching. The suggested quantities of materials necessary to complete the required tests are shown in Table A5.9. If pozzolan is economically available, or required by the specification, the percentage as suggested in Table A5.1 should be used as a starting point in the trial mixes.

From the material submitted for the test program, determine the following properties:

1. Sieve analysis of all aggregates.
2. Bulk specific gravity of aggregates.
3. Absorption of aggregates.
4. Particle shape of coarse aggregates.
5. Fineness modulus of fine aggregate.
6. Specificgravity of portland cement, and/or pozzolans and blended cement.
7. Physical and chemical properties of portland cement and/or pozzolans and blended cement including heat of hydration at 7 days.

A complete record of the above properties should be made available for field use; this information will assist in adjusting the mixture should any of the properties of the materials used in the field change from the properties of the materials used in the laboratory trial mix program.

A5.6.3 *Step 3* -- Selection of *W/C* ratio. If the water-cement ratio is not given in the project document, select from Table A5.8 the maximum permissible water-cement (*W/C*) ratio for the particular exposure conditions. Compare this *W/C* ratio with the maximum permissible *W/C* ratio required in Table A5.7 to obtain the average strength which includes the specified strength plus an allowance for anticipated variation and use the lowest *W/C* ratio. The *W/C* ratio should be reduced 0.02 to assure that the maximum permissible *W/C* ratio is not exceeded during field adjustments. This *W/C* ratio, if required, can be converted to a water-cement plus pozzolan ratio by the use of Eq. (6.3.4.1).

A5.6.4 *Step 4* -- Estimate of mixing water requirement. Estimate the water requirement from Table 6.3.3 for the specified slump and nominal maximum size aggregate. Initial placing temperature may affect this water requirement; for additional information consult Reference A5.6.

A5.6.5 *Step 5* -- Selection of air content. Select a total air content of the mixture as recommended in Table A5.6. An accurate measure of air content can be made during future adjustment of the mixture by use of Eq. (A5.6).

$$A = \frac{a}{1 + r\left(1 - \frac{a}{100}\right)} \qquad \text{(A5.6)}$$

where

A = air content of total mixture, expressed as a percent
a = air content of minus 1½ in. (37.5 mm) fraction of mixture, expressed as a percent
r = ratio of the absolute volume of plus 1½ in. (37.5 mm) aggregate to the absolute volume of all other materials in the mixture except air. If 100 percent of the aggregate passes the 1½ in. (37.5 mm) sieve, r =O, and A=a

A5.6.6 *Step 6* -- Compute the required weight of cement from the selected *W/C* (A5.6.3) and water requirement (A5.6.4).

A5.6.7 *Step 7* -- Determine the absolute volume for the cementitious materials, water content, and air content from information obtained in Steps 4, 5, and 6. Compute individual absolute volumes of cement and pozzolan.

$$V_{c+p} = \frac{C_w}{G_c(62.4)} \text{ cu ft or } \frac{C_w}{G_c(1000)} \text{ m}^3 \qquad \text{(A5.6A)}$$

$$V_c = V_{c+p}(1 - F_v) \qquad \text{(A5.6B)}$$

$$V_p = V_{c+p}(F_v) \qquad \text{(A5.6C)}$$

where

C_w = weight of the equivalent portland cement as determined from Step 6

G_c = specific gravity of portland cement

V_c = volume of cement (cu ft) (m^3)

V_p = volume of pozzolan (cu ft) (m^3)

V_{c+p} = volume of cement and pozzolan (cu ft) (m^3)

F_v = percent pozzolan by absolute volume of the total absolute volume of cement plus pozzolan expressed as a decimal factor

A5.6.8 *Step 8* -- Select percent of coarse aggregate. From Table A5.5, and based on the fineness modulus of the fine aggregate as well as the nominal maximum size and type of coarse aggregate, determine the coarse aggregate percentage of the total volume of aggregate.

A5.6.9 *Step 9* -- Determine the absolute volume of the total aggregate by subtracting from the unit volume the absolute volumes of each material as computed in Step 7. Based on the amount of coarse aggregate selected in Step 8, determine the absolute volume of the coarse aggregate. The remainder of the absolute volume represents the quantity of fine aggregate in the mix.

A5.6.10 *Step 10* -- Establish the desired combination of the separate coarse aggregates size groups. Using the individual coarse aggregates gradings, combine all coarse aggregate to a uniform grading approximating the gradings shown in Table A5.4 for 6 in. (150 mm) nominal maximum size aggregate (NMSA) or 3 in. (75 mm) NMSA. The percentage of each size group should be rounded to the nearest whole percent.

A5.6.11 *Step 11* -- Convert all absolute volumes to weight per unit volume of all ingredients in the mixture.

A5.6.12 *Step 12* -- Check the mortar content. From the absolute volumes computed earlier, compute the mortar content and compare the results with values given in Table A5.6. Values in Table A5.6 will provide an indication of the workability of the mixture as determined by past field performance. Table A5.6 can be used as an aid in making laboratory adjustments of the mixture.

A5.7 *Example problem* -- Concrete is required for a heavy bridge pier that will be exposed to fresh water in a severe climate, The design compressive strength is 3000 psi (20.7 MPa) at 28 days. Placement conditions permit the use of a large nominal maximum size aggregate, and 6 in. (150 mm) nominal maximum size crushed stone is available. Laboratory tests indicate that 6,3, 1½, and ¾ in. (150,75,37.5, and 19 mm) size groups of crushed stone have bulk specific gravities (saturated-surface-dry, S.S.D. basis) of 2.72, 2.70, 2.70, and 2.68, respectively; the natural fine aggregate available has a bulk specific gravity of 2.64 with a fineness modulus of 2.80. A Class F (fly ash) pozzolan is available and should be used to reduce the generation of heat in the concrete. The pozzolan has a specific gravity of 2.45, and Type II portland cement is available.

A5.7.1 *Step 1* -- Determine desired properties. The following properties have been specified upon review of the project documents and consultation with the engineer:

1. A 6 in. (150 mm) nominal maximum size crushed stone aggregate is available and economically feasible to use.
2. Slump range of the concrete will be 1 to 2 in. (25 to 50 mm) as measured in the minus 1½ in. (37.5 mm) portion.
3. Maximum permissible *W/C* ratio by weight required to be 0.50 for durability purposes.
4. Project documents require the concrete to be placed at 65 F (18 C) or below.
5. The concrete is required to be air entrained within a range of 1½ percent of 5 percent when tested on the minus 1½ in. (37.5 mm) material.
6. Assuming a standard deviation of 500 psi (3.45 MPa), considered good overall general construction control, and 80 percent of the tests above design strength, an average compressive strength of no less than 3400 psi (23.4 MPa) at 28 days (90 days with pozzolan) is required in accordance with ACI 214-77.
7. The concrete will be subjected to severe exposure conditions.
8. Water velocities around the concrete will not exceed 40 ft/sec (12 m/s).
9. Aggregates meeting the requirements of the project specifications are available.
10. The project specifications require the use of portland cement Type II and permit the use of pozzolan.

A5.7.2 *Step 2* -- Determine properties of the materials.

1. The coarse aggregates have the following sieve analyses:

Sieve size in. (mm)	Percent by weight passing individual sieves: No. 4 to ¾ in. (4.75 mm to 19 mm)	¾ in. to 1½ in. (19 mm to 37.5 mm)	1½ in. to 3 in. (37.5 mm to 75 mm)	3 in. to 6 in. (75 mm to 150 mm)
7 (175)				100
6 (150)				98
5 (125)				60
4 (100)			100	30
3 (75)			92	10
2 (50)		100	30	2
1½ (37.5)		94	6	
1 (25)	100	36	4	
¾ (19)	92	4		
⅜ (9.5)	30	2		
No. 4 (4.75)	2			

2. The bulk specific gravities (saturated-surface-dry, S.S.D. basis) of the coarse and fine (sand) aggregates are determined to be:

Size group	Specific gravity
6 in. to 3 in. (150 to 75 mm)	2.72
3 in. to 1½ in. (75 to 37.5 mm)	2.70
1½ in. to ¾ in. (37.5 to 19 mm)	2.70
¾ in. to No. 4 (19 to 4.75 mm)	2.68
Fine aggregate	2.64

3. The absorptions of the coarse and fine aggregates are as follows:

Size group	Absorption (percent)
6 in. to 3 in. (150 to 75 mm)	0.5
3 in. to 1½ in. (75 to 37.5 mm)	0.75
1½ in. to ¾ in. (37.5 to 19 mm)	1.0
¾ in. to No. 4 (19 to 4.75 mm)	2.0
Fine aggregate	3.2

4. The coarse and fine aggregate are totally crushed and natural, respectively.
5. The fineness modulus of the fine aggregate is 2.80.
6. Specific gravities of the portland cement and pozzolan are 3.15 and 2.45, respectively.
7. Physical and chemical tests of the portland cement and pozzolan verify compliance with the requirements of the project specifications.

A5.7.3 *Step 3* -- Selection of *W/C* ratio. From Table A5.8, the exposure conditions permit a maximum permissible *W/C* ratio of 0.50 and Table A5.7 recommends a maximum *W/C* ratio of 0.57 to obtain the desired average strength of 3400 psi (23.44 MPa). Since the exposure conditions require the lower *W/C* ratio, the designed *W/C* ratio will be 0.48 or 0.02 less than that permitted to allow for field adjustments.

Since a fly ash pozzolan is available and the quantity of concrete in the project justifies its use economically, 25 percent by volume will be used according to Table A5.1.

A5.7.4 *Step 4* -- Estimate of mixing water requirement. From Table 6.3.3 the estimated water content is 180 lb/cu yd (107 kg/m^3) based on the use of a 6 in. (150 mm) crushed stone (NMSA) and a slump of 1 to 2 in. (25 to 50 mm).

A5.7.5 *Step 5* -- Selection of air content. A total air content of 3.2 percent is selected which is within the range recommended in Table A5.6. During later adjustments, after all ingredients are determined, a more accurate total air content can be derived by the use of Eq. (A5.6).

A5.7.6 *Step 6* -- Determine weight of cement from selected *W/C* ratio and water demand.

from Step 3 $W/C = 0.48$

therefore: weight of cement in a total portland cement mixture equals

Combined grading computations

Sieve size in. (mm)	Grading of individual size groups percent passing				Trial and error selection Size group percentages and gradings 45 percent	25 percent	15 percent	15 percent	Combined grading percent passing	Idealize* grading percent passing
	6 in. to 3 in. (150 mm to 75 mm)	3 in. to 1½ in. (75 mm to 37.5 mm)	1½ in. to ¾ in. (37.5 mm to 19 mm)	¾ in. to No. 4 (19 mm to 4.75 mm)	6 in. to 3 in. (150 mm to 75 mm)	3 in. to 1½ in. (75 mm to 37.5 mm)	1½ in. to ¾ in. (37.5 mm to 19 mm)	¼ in. to No. 4 (19 mm to 4.75 mm)		
7 (175)	100				45	25	15	15	100	
6 (150)	98				44	25	15	15	99	100
4 (100)	30	100			14	25	15	15	69	70
3 (751	IO	92			4	23	15	15	57	54
2 (50)	2	30	100		1	8	15	15	39	38
1½ (37.5)		6	94			2	14	15	31	28
1 (25)		4	36	100		l	5	15	21	21
¾ (19)			4	92			1	14	15	15
⅜ (9.5)			2	30			0	5	5	5
No.4(4.75)				2				0	0	0

*From Table A5.4 for 6 in. (150 mm) nominal maximum size crushed material.

$$\frac{180}{0.48} = 375\ lb/cu\ yd\ or\ (222\ kg/m^3)$$

A5.7.7 *Step 7* -- Determine absolute volume per cubic yard (cubic meter) for the cementitious materials, water content and air content. As recommended in Table A5.1, 25 percent pozzolan by volume will be used. Using Eq. (A5.6.7A), (B), and (C), the absolute volume of cementitious material can be determined.

$$V_{c+p} = \frac{C_w}{G_c(62.4)} = \frac{375}{3.15(62.4)} = \underline{1.91\ cu\ ft/cu\ yd}\ or$$

$$\left(\frac{222}{3.15(1000)}\ \underline{0.070\ m^3/m^3}\right)$$

$$V_c = V_{c+p}(1 - F_v) = 1.91(1-0.25) = \underline{1.43\ cu\ ft/cu\ yd}$$

$$or\ (0.070\ (1 - 0.25) = \underline{0.052\ m^3/m^3})$$

$$V_p = V_{c+p}(F_v) = 1.91(0.25)\ \underline{0.48\ cu\ ft/cu\ yd}\ or$$

$$(0.070(0.25) = \underline{0.018\ m^3/m^3})$$

$$V_w = \frac{180}{62.4} = \underline{2.88\ cu\ ft}\ or\left(\frac{107}{1000} = \underline{0.107\ m^3/m^3}\right)$$

$$V_A = 0.032\ (27)\ yd\ or = \underline{0.86\ cu\ ft/cu\ yd}\ or$$

$$(0.032(1.0) = \underline{0.032\ m^3/m^3})$$

A5.7.8 *Step 8* -- For a natural fine aggregate with an F.M. of 2.80 and a 6-m (152 mm) (NMSA) crushed stone, the volume of coarse aggregate to be used in the trial batch is 78 percent--see Table A5.5.

A5.7.9 *Step 9* -- Determine the absolute volume of fine and coarse aggregates.

$27 - V_W - V_A - V_{c+p}$ = Vol of aggregate/cu yd or
$(1.0 - V_W - V_A - V_{c+p}$ = Vol of aggregate/m^3)
27 - 2.88 - 0.86 - 1.91 = 21.35 cu ft/cu yd or (0.79m^3/m^3)

Vol of coarse aggregate	= 21.35 (0.78) cu ft/cu yd
	or [0.79(0.78) m^3/m^3]
	= 16.65 cu ft/cu yd
	or (0.62 m3/m3)
Vol of fine aggregate	= 21.35(0.22) cu ft/cu yd
	or [0.79(0.22) m^3/m^3]
	= 4.70 cu ft/cu yd
	or (0. 17m^3/m^3)

A5.7.10 *Step 10* -- Combine the various size groups of coarse aggregate. The existing coarse aggregate gradings were combined by trial-and-error computations, resulting in the following percentages of each size group:

No. 4 to ¾ in.	(4.75 to 19 mm)	15 percent
¾ in. to 1½ in.	(19 to 75 mm)	15 percent
1½ in. to 3 in.	(75 to 150 mm)	25 percent
3 in. to 6 in.	(150 to 300 mm)	45 percent

A5.7.11 *Step 11* -- Convert all absolute volumes to weight per unit volume.

Material	Absolute volume x specific gravity x 62.4	lb/cu yd (kg/m³)
Portland cement	1.43(3.15)62.4	281(167)
Pozzolan	0.48(2.45)62.4	73 (43)
Water	2.88(1.00)62.4	180(107)
Air	0.86	
Fine aggregate	4.70(2.64)62.4	774(459)S.S.D.*
Coarse aggregate		
No. 4-¾ in. (4.75 -19 mm)	16.65(0.15)(2.68)62.4	418(248)S.S.D.*
¾–1½ in. (19mm-75 mm)	16.65(0.15)(2.70)62.4	421(250)S.S.D.*
1½–3 in. (75mm-150 mm)	16.65(0.25)(2.70)62.4	701(416)S.S.D.*
3-6 in. (150-300 mm)	16.65(0.45)(2.72)62.4	1272(755)S.S.D.*

*Weights based on aggregates in a saturated-surface-dry condition.

A5.7.12 *Step 12* -- Check mortar content and compare with Table A5.6

$$\text{Mortar content} = V_c + V_p + V_W + V_s + V_A$$
$$= 1.43 + 0.48 + 2.88 + 4.70 + 0.86$$
$$= 10.35 \text{ cu ft/cu yd } (0.383 \text{ m}^3/\text{m}^3)$$

From Table A5.6 the mortar content is estimated to be 10.5 cu ft/cu yd (0.39 m³/m³) which is within the ± 0.2 cu ft (2 0.01 m³) of the actual value.

A5.7.13 *Trial batch* -- From the above information the absolute volume and weight per cubic yard of each ingredient computes as follows:

Material	Absolute volume ft³/yd³(m³/m³)	Weight lb/yd³(kg/m³)
Portland cement	1.43(0.052)	281 (167)
Pozzolan	0.48(0.018)	73 (43)
Water	2.88(0.107)	180(107)
Air	0.86(0.032)	—
Fine aggregate	4.70(0.174)	774 (459)S.S.D.*
No. 4-¾ in. (4.75 -19 mm)	2.50(0.093)	418 (248)S.S.D.*
¾–1½ in. (19mm-75 mm)	2.50(0.093)	421 (250)S.S.D.*
1½–3 in. (75mm-150 mm)	4.16(0.154)	701 (416)S.S.D.*
3-6 in. (150-300 mm)	7.49(0.277)	1272 (755)S.S.D.*
Total	27.00(1.000)	4120 (2444)

*Weights are based on aggregate in a saturated-surface-dty condition.

The weights above should be reduced proportionately to facilitate the preparation of trial batches which in turn should be evaluated for proper moisture correction, slump, air content, and general workability. After the necessary adjustments, trial mixtures for strength verification and other desired properties of concrete should be made. Reference 2 will provide guidance in estimating the heat generated by the trial mixture and in determining whether or not other temperature control measures are needed.

A5.8 *References*

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A5.10 *Handbook for Concrete and Cement,* CRD-C 3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, 1949 (with quarterly supplements).

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