ACI 211.1-91
(Reapproved 2009)

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

An ACI Standard

Reported by ACI Committee 211

American Concrete Institute®

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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 consideration the requirements for placeability, consistency, strength, and durability. Example calculations are shown for both methods, including adjustments based on the characteristics 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 or 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 7½ 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 fine 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.).

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

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

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,