| | |
|---|---|
| IN-LB | Inch-Pound Units |
| SI | International System of Units |

# Selecting Proportions for Normal-Density and High-Density Concrete—Guide

Reported by ACI Committee 211

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American Concrete Institute
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# Selecting Proportions for Normal-Density and High-Density Concrete—Guide

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*This guide to concrete proportioning provides background information on, and a procedure for, selecting and adjusting concrete mixture proportions. It applies to normal-density concrete, both with and without chemical admixtures, supplementary cementitious materials, or both. The procedure uses calculations based on the absolute volumes occupied by the mixture constituents. The procedure incorporates consideration of requirements for aggregate gradation, workability, strength, and durability. Example calculations are provided, including adjustments based on the results of the first trial batch. Appendixes cover laboratory tests and proportioning of high-density concretes.*

**Keywords:** absolute volume; admixtures; air content; durability; mixture proportioning; supplementary cementitious materials; trial batching; water-cementitious materials ratio (*w*/*cm*); workability; yield.

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# CHAPTER 1—INTRODUCTION AND SCOPE

## 1.1—Historical background

The ability to tailor concrete properties in accordance with project requirements reflects technological developments that have taken place, for the most part, since the early 1900s. The use of the water-cement ratio (*w/c*)—one of the key parameters of mixture proportioning—as a tool for estimating strength was recognized in approximately 1918. In the early 1940s, improvements in durability were achieved with the use of air entrainment. These major developments in concrete technology were augmented by the development of chemical admixtures to achieve special properties, counteract possible deficiencies, and improve cost effectiveness (ACI 212.3R). The first water-reducing admixture was developed in the 1920s and was patented in Europe in 1932, and then in the United States in 1939. Slowly, water-reducing admixtures came into widespread use in the 1970s and played a major role in improving workability, thereby adjusting mixture proportions. Around this time, it was also found that some concrete characteristics could be improved with the addition of certain industrial by-products, now called supplementary cementitious materials (SCMs). The use of these materials has not only improved various concrete properties, but also played a major role in contributing to environmental sustainability. With the implementation of these technological developments, in current practice, most commercially produced concrete contains some type of chemical admixtures, SCM, or both, and their presence needs to be considered while mixture proportioning.

## 1.2—Introduction

Concrete is composed principally of aggregates, a portland or blended cement, and water, and may contain SCMs, chemical admixtures, or both. It will contain some amount of entrapped air and may also contain purposely entrained air created with the use of an admixture or air-entraining cement. Chemical admixtures are frequently used to accelerate or retard the time of setting, improve workability, or reduce water requirements (ACI 212.3R). Their use may affect strength and other concrete properties. Depending on the type and amount, certain SCMs such as fly ash (ACI 232.2R), natural pozzolans, slag cement (ACI 233R), and silica fume (ACI 234R) may be used in conjunction with portland or blended cement. They are added to provide specific properties such as higher strength, decreased permeability, resistance to the intrusion of aggressive solutions, increased resistance to alkali-aggregate reaction and sulfate attack (ACI 225R and ACI 233R), reduced heat of hydration, reduced shrinkage, improved late-age strength development, and for economic reasons.

The selection of mixture proportions involves a balance between economy and requirements for durability, strength, workability, density, and appearance. The required characteristics are determined by the intended application of concrete, and by the conditions expected to be encountered at the time of placement and beyond. These characteristics should be detailed in the job specifications. Some characteristics are governed by the concrete building code. A broad range of characteristics ranging from high strength to self-consolidation and flowable fills, from low-permeability bridge decks to pervious concrete parking lots, and many other characteristics and applications have been made possible with the use of admixtures and SCMs.

The best concrete proportions are based on previous experience with the materials that will be used on similar projects. Lacking that, numerous methods have been developed for proportioning concrete mixtures. Methods have been developed ranging from arbitrary cement:sand:rock:water proportions (that is, 1:2:3:0.5), empirical methods such as workability factors (Shilstone 1990), and methods developed from first principles such as packing models (de Larrard and Sedran 2002) and suspension methods (ACI 211.6T). It is beyond the scope of this discussion to review the background and theory behind these methods or those of the relatively simple procedures of this guide. Computer programs for concrete mixture design incorporating many of these theories are commercially available.

Frequently, existing concrete proportions are reproportioned to include chemical admixtures, SCMs, or a different material source. The performance of the reproportioned concrete should again be verified by trial batches in the laboratory or field.

Proportions calculated by any method should always be considered provisional, subject to revision based on trial batch results. Depending on circumstance, trial batches may be prepared in a laboratory. With success in the lab, the trials should move on to full-size field batches with the materials, means, and methods expected for the project. This procedure, when feasible, avoids 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 mixtures of the size and type to be used during construction. Trial batch procedures are discussed in Chapter 8, with additional background and details provided in the appendixes.

### 1.3—Scope

This guide describes a method for selecting proportions for concrete made with hydraulic cement meeting ASTM C150/C150M, C595/C595M, or C1157/C1157M with or without other cementitious materials, chemical admixtures, or both. This concrete consists of normal-density aggregates, high-density aggregates, or both (as distinguished from lightweight aggregates), with a workability suitable for normal cast-in-place construction (as distinguished from specialty concrete mixtures such as pervious or self-consolidating concretes). Proportioning with lightweight aggregates and recycled aggregates are other common options; however, they are beyond the scope of this document. Please refer to ASTM C330/C330M and ACI 213R for lightweight aggregates, and ACI 555R for recycled aggregates.

Also included are several design examples applying the procedure to a variety of situations. For proportioning with ground limestone or other aggregate mineral filler, refer to ACI 211.7R.

Information is provided on terms and concepts used in the proportioning procedure that may be unfamiliar to a novice user.

The procedure produces a first approximation for proportions of a concrete mixture. It is intended that the proportions be checked by trial batches in the laboratory, field, or both, and adjusted as necessary to produce a concrete with all the desired characteristics.

## CHAPTER 2—NOTATION AND DEFINITIONS

### 2.1—Notation

$\%free$ = percentage of free moisture on an aggregate, %
$\%SCM$ = percentage of supplementary cementitious material to total cementitious by weight, %
$\%total$ = percentage of total evaporable moisture content, %
$A\%$ = percentage of moisture absorption of an aggregate, %
$Air\%$ = percentage of concrete volume occupied by air, %
$c$ = cement weight, lb
$cm$ = cementitious weight, lb
$f_c'$ = specified compressive strength, psi
$f_{cr}'$ = required average compressive strength, psi
$MC\%$ = percentage of moisture content of an aggregate, %
$MC\%_{free}$ = percentage of free moisture content of an aggregate, %
$m_i$ = initial weight of sample being tested for moisture content, lb
$m_{OD}$ = oven-dry weight of sample, lb
$m_{SSD}$ = saturated surface-dry weight of sample, lb
$mw_{free}$ = free water weight, lb
$PV$ = paste volume, ft$^3$
$R_Y$ = relative yield, %
$w$ = water weight, lb
$w_{batched}$ = batch-ready moisture-adjusted water weight, lb
$w_{free}$ = total free water, lb
$w_{SSD}$ = weight of aggregate in saturated surface-dry condition, lb
$Y$ = yield, %
$Y_d$ = design target volume, ft$^3$

## 2.2—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

**cement efficiency**—the strength gained from each pound of cement in a cubic yard. With units of psi/lb/yd$^3$, it is computed by dividing the strength by the weight of cement for a cubic yard of concrete mixture.

**dry-rodded unit weight**—weight per unit volume of oven-dry aggregate compacted by rodding. It is also known as "dry-rodded density." In this guide, dry-rodded density is used as the preferred term.

**finishability**—the ability to level, smooth, consolidate, and otherwise treat surfaces of fresh or recently placed concrete to produce a desired appearance and surface.

**specific gravity**—the ratio of weight of a volume of a material at a stated temperature to the weight of the same volume of distilled water at that stated temperature (refer to ASTM C125 for details). It is also known as "relative density." In this guide, specific gravity is used as the preferred term.

**unit weight**—the weight per unit volume of a material. It is also known as "density." In this guide, density is used as the preferred term.

**weight**—the amount or quantity of heaviness. It is also known as "mass." In this guide, weight is used as the preferred term.

# CHAPTER 3—CONCRETE PROPERTIES

The selection of concrete proportions involves matching the requirements of the project with the materials and methods available. In this chapter, some of the commonly encountered properties that go into specifying, designing, and proportioning concrete will be discussed. Concrete properties describe the way concrete behaves while being mixed, placed, cured, or in use.

Concrete proportions usually consider workability, strength, and durability needed for the specific application. Other properties may need to be considered to ensure meeting the expectations of the installed materials. These properties include pumpability, finishability, bleeding, density, heat generation, and permeability. For concrete slabs, mortar content and admixtures used can significantly affect finishing and set characteristics of the concrete materials. A project can impose the need for a particular property such as rapid strength gain, modulus of elasticity, filling of a steel-congested space, color, and architectural finish. For some of these properties, well-established relationships are known. For others, the relationship between the specific property and the mixture design can generally be described, with the details worked out through trial batches.

## 3.1—Water-cementitious materials ratio (*w/cm*)

It has long been known (Abrams 1918) that for a given set of materials and conditions, concrete strength and durability are directly related to the *w/cm*. This is the ratio of the weight of water, excluding that absorbed by the aggregate, divided by the weight of cementitious materials in a mixture, stated as a decimal. The abbreviation of "cm" represents cement and supplementary cementitious materials (SCMs) such as fly ash, silica fume, and slag cement, as discussed further in Chapter 7.

Differences in strength at a given *w/cm* may result from changes in placement or curing conditions; the maximum size, gradation, surface texture, particle shape, strength, and stiffness of aggregates; differences in cement types or sources; air content; and the use of chemical admixtures that affect the cement hydration process or that develop cementitious properties themselves. Because most of these factors are measurable, they are accounted for in the recommendations for quantity of water. Accurate predictions of strength and the meeting of strength targets should be based on trial batches, or experience with the project materials and requirements.

## 3.2—Workability

Workability is that property of freshly mixed concrete that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogeneous condition. It is affected by water quantity, aggregate grading, particle shape, and proportions of aggregate, as well as by the amounts and qualities of cement and other cementitious materials, chemical admixtures, amount of entrained air, and the consistency of the mixture.

## 3.3—Consistency

Consistency is the degree to which a freshly mixed concrete resists deformation—that is, its ability to flow. It is measured in terms of slump (ASTM C143/C143M); the higher the slump, the more mobile the mixture will be. This ability to flow affects the ease with which the concrete can be placed. In properly proportioned concrete, the unit water content required to produce a given slump will depend on several factors. The 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). The required mixing water decreases as the maximum size of well-graded aggregate is increased, or the level of air entrainment increases. Mixing-water requirements usually are reduced by water-reducing admixtures (ACI 212.3R). Slump characteristics are used for developing special concretes such as self-consolidating concrete (ACI 237R), or other applications needing close control of workability (ACI 238.1R).

## 3.4—Strength

Conventionally, the average of two 6 x 12 in. or three 4 x 8 in. cylinders fabricated, cured, and tested at the age of 28 days is the value accepted as concrete's compressive strength (ASTM C39/C39M). It is used as a controlling value for structural design, concrete proportioning, and evaluation of concrete. Concrete is commonly specified with compressive strengths from 2500 psi to greater than 10,000 psi. The variable nature of its constituents, the effects of the placement, and curing environment all affect concrete strength. Strength is affected by variations in mixture constituents,