



Concrete Craftsman Series

Concrete Fundamentals



CCS-0(16)



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Concrete Craftsman Series

Concrete Fundamentals

CCS-0 Concrete Fundamentals was originally written by ACI Committee E703, Concrete Construction Practices.

The 2016 edition of CCS-0 was reviewed and approved by an Education Task Group including: William Nash, William Palmer, Michael Pedraza, David Suchorski, and Scott Tarr. Thank you to the Task Group members for their thoughtful and thorough review of the fundamental material.

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Concrete Craftsman Series:
CCS-0 Concrete Fundamentals
ISBN 978-1-942727-63-7
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Art Program: Claire Hiltz
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Jerzy Zemajtis, Ph. D., P.E.
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Manager, Publishing Services: Barry M. Bergin
Production Editors: Carl Bischof, Kelli Slayden,
Kaitlyn Hinman, Tiesha Elam
Page Design & Composition: Ryan Jay
Manufacturing: Marie Fuller

First Printing: December 2015
Printed in Ann Arbor, Michigan.

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
USA
www.concrete.org
+1.248.848.3700

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PREFACE

This is one of six books in the Concrete Craftsman Series published by the American Concrete Institute. This book is intended for anyone who wants an introduction to concrete and concrete construction. Craftsmen in the concrete field may find it particularly useful as a guide for good practice.

Two other books in this series cover common concrete topics. “CCS-1 Slabs-on-Ground” covers good construction practices for slabs and is the basis for the ACI Flatwork Finisher Certification exam. “CCS-4 Shotcrete for the Craftsman” covers shotcrete construction practices and is the basis for the ACI Shotcrete Nozzleman Certification exam. CCS-4 is also available in a Spanish language edition.

Decorative concrete topics are covered in “CCS-5 Placing and Finishing Decorative Concrete Flatwork.” This book provides details about the materials, equipment, and techniques required to successfully install decorative concrete flatwork.

Two other books that are part of this series are no longer in publication. “CCS-2 Cast-in-Place Walls,” described formwork, reinforcement, placing of concrete, curing, and wall finishes. “CCS-3 Supported Beams and Slabs,” provided technical background on such subjects as shoring, reshoring, form removal, reinforcement placement, and concrete placing, finishing, and curing.

Because this book went back to cover the fundamentals, it is numbered accordingly. “CCS-0 Concrete Fundamentals,” starts with the most basic question of all, “What is concrete?” Other sections cover materials, basic construction practices, and testing. This book is a good starting point for someone in the concrete industry, whether they are an apprentice, a journeyman, a foreman, a material supplier, or even a young engineer without field experience. This book is not a design aid but rather a guide to good practice.

The design of concrete structures is the responsibility of a professional engineer. Designs are usually reviewed and approved by local building authorities and are governed by codes such as the International Building Code (IBC), or other local building codes that usually reference “Building Code Requirements for Structural Concrete (ACI 318) and Commentary.” This book is not a replacement for these documents. Plans and specifications for a specific project, and local building code requirements are required to be followed, even if they differ from the information in this book.



Fig. 0.1—Project plans and specifications should be followed. Practices described in this book are not a replacement for project plans

VOCABULARY

If you are using this book as an introduction to concrete, you will soon notice that a lot of ordinary words like accelerator, bleeding, blistering, honeycomb, slump, and many others have their own very special meaning when applied to concrete. To help with these meanings, listed are some of the terms that appear in this book, along with brief definitions. For longer definitions and for other words not included here, refer to “ACI Concrete Terminology (CT-13),” published by the American Concrete Institute.

Accelerator — an admixture that causes an increase in the rate of hydration of the hydraulic cement and thus shortens the time of setting, increases the rate of strength development, or both.

Admixture — a material other than water, aggregates, cementitious materials, and fiber reinforcement, used as an ingredient of a cementitious mixture to modify its freshly mixed, setting, or hardened properties and that is added to the batch before or during its mixing.

Aggregate — granular material, such as sand, gravel, crushed stone, crushed hydraulic cement concrete, or iron blast-furnace slag used with a cementing medium to produce either concrete or mortar.

Air-entraining agent — an admixture for concrete that develops a system of microscopic bubbles of air in cement paste, mortar, or concrete during mixing.

Air entrainment — the incorporation of air in the form of microscopic bubbles (typically smaller than 0.04 in. [1 mm]) during the mixing of either concrete or mortar.

Bleeding — the autogenous flow of mixing water within, or its emergence from, a newly placed cementitious mixture caused by the settlement of solid materials within the mass.

Blistering — the irregular raising of a thin layer at the surface of a placed cementitious mixture during or soon after the completion of the finishing operation (Fig. 0.2).

Bug holes — common term used to describe surface air voids. Small regular or irregular cavities, usually not exceeding 5/8 in. (15 mm) in diameter, resulting from entrapment of air bubbles in the surface of formed concrete during placement and consolidation.

Cement — any of a number of materials that are capable of binding aggregate particles together. (See also hydraulic cement.)

Cement paste — binder of concrete and mortar consisting essentially of cement, water, hydration products, and any



admixtures together with very finely divided materials included in the aggregates.

Cementitious materials — pozzolans and hydraulic cements. (See also fly ash, silica fume, and slag cement.)

Clinker — a partially fused product of a kiln that is ground to make cement.

Coarse aggregate — aggregate predominantly retained on the No. 4 (4.75 mm) sieve or that portion retained on the No. 4 (4.75 mm) sieve (Fig. 0.3).

Concrete compressive strength — measured maximum resistance of a concrete specimen to axial compressive loading and expressed as a force per unit cross-sectional area.

Consolidation — the process of reducing the volume of voids, air pockets, and entrapped air in a fresh cementitious mixture, usually accomplished by inputting mechanical energy.

Craze cracks — fine random cracks or fissures in a surface of plaster, cement paste, mortar, or concrete.

Crazing — the development of craze cracks; the pattern of craze cracks existing in a surface.

Curing — action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic cement hydration and, if applicable, pozzo-



Fig. 0.2—Example of concrete surface blistering (photo courtesy of Portland Cement Association (PCA))

lanic reactions to occur so that the potential properties of the mixture may develop.

Dropchute — a device used to confine or direct the flow of a falling stream of fresh concrete. (1) *articulated dropchute* — a device consisting of a succession of tapered metal cylinders so designed that the lower end of each cylinder fits into the upper end of the one below; (2) *flexible dropchute* — a device consisting of a heavy rubberized canvas or plastic collapsible tube.

Dusting — development of a powdered material at the surface of hardened concrete.

Final setting — a degree of stiffening of a cementitious mixture greater than initial setting, generally stated as an empirical value indicating the time required for the cementitious mixture to stiffen sufficiently to resist, to an established degree, the penetration of a weighted test device. (See also initial setting.)

Fine aggregate — (1) aggregate passing the 3/8 in. (9.5 mm) sieve, almost entirely passing the No. 4 (4.75 mm) sieve, and predominantly retained on the No. 200 (75 mm) sieve; (2) that portion of aggregate passing the No. 4 (4.75 mm) sieve and predominantly retained on the No. 200 (75 mm) sieve. (See also aggregate.)



Fig. 0.3—Coarse aggregates (photo courtesy of CTLGroup)

Fineness modulus — a factor obtained by adding the total percentages of material in the sample that are coarser than each of the following sieves (cumulative percentages retained), and dividing the sum by 100: No. 100 (150 mm), No. 50 (300 mm), No. 30 (600 mm), No. 16 (1.18 mm), No. 8 (2.36 mm), No. 4 (4.75 mm), 3/8 in. (9.5 mm), 3/4 in. (19.0 mm), 1-1/2 in. (37.5 mm), 3 in. (75 mm), and 6 in. (150 mm)

Fly ash — the finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gases from the combustion zone to the particle removal system.

Grout — mixture of cementitious materials and water, or other binding medium, with fine aggregate.

High-range water-reducing admixture — a water-reducing admixture capable of producing large water reduction or great flowability without causing undue set retardation or entrainment of air in mortar or concrete.

Honeycomb — voids left in concrete between coarse aggregates due to inadequate consolidation.

Hydration — the chemical reaction between hydraulic cement and water.

Hydraulic cement — a binding material that sets and hardens by chemical reaction with water and is capable of doing so underwater. For example, portland cement and slag cement are hydraulic cements.

Initial setting — a degree of stiffening of a cementitious mixture less than final set, generally stated as an empirical value indicating the time required for the cementitious mixture to stiffen sufficiently to resist, to an established degree, the penetration of a weighted test device. (See also final setting.)

Mortar — a mixture of cement paste and fine aggregate; in fresh concrete, the material occupying the interstices among particles of coarse aggregate; in masonry construction, joint mortar may contain masonry cement, or may contain hydraulic cement with lime (and possibly other admixtures) to afford greater plasticity and workability than are attainable with standard portland cement mortar.

Paste — see **Cement paste**.

Plastic shrinkage cracking — surface cracking that occurs in concrete before initial set.

Plasticity — property of freshly mixed cement paste, concrete, or mortar that determines its resistance to deformation or ease of molding.

Portland cement — a hydraulic cement made by pulverizing portland-cement clinker and usually with addition of calcium sulfate to control setting.

Pozzolans — a siliceous or silico-aluminous material that will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds having cementitious properties (there are both natural and artificial pozzolans).

Prestressed concrete — structural concrete in which internal stresses have been introduced to reduce potential tensile stresses in concrete resulting from loads.



Fig. 0.4—Rodding is performed using a tamping rod, the length and diameter of the rod may vary based on the size of the sample being consolidated (photo courtesy of PCA)

Retarder — an admixture that delays the setting of a cementitious mixture.

Rock pocket — a porous, mortar-deficient portion of hardened concrete consisting of coarse aggregate and voids. (See also honeycomb.)

Rodding — consolidation of concrete by means of a tamping rod (Fig. 0.4). (See also tamping.)

Scaling — local flaking or peeling away of the near-surface portion of hardened concrete or mortar (Fig. 0.5).

Segregation — the separation of coarse aggregate from the sand-cement mortar portion of the concrete mixture.

Setting — a chemical process that results in a gradual development of rigidity of a cementitious mixture, adhesive, or resin.



Fig. 0.5—Scaling removes the top layer of paste from the concrete (photo courtesy of PCA)

Sieve — a metallic plate or sheet, woven-wire cloth, or other similar device with regularly spaced apertures of uniform size mounted in a suitable frame or holder for use in separating granular material according to size.

Silica fume — very fine noncrystalline silica produced in electric arc furnaces as a byproduct of the production of elemental silicon or alloys containing silicon.

Slag cement — granulated blast-furnace slag that has been finely ground and that is hydraulic cement.

Slump — a measure of the consistency of freshly mixed concrete, equal to the subsidence of a molded specimen immediately after removal of the slump cone.

Specified compressive strength — compressive strength of concrete used in design.

Superplasticizer — See **High-range water-reducing admixture**.

Supplementary cementitious material — inorganic material such as fly ash, silica fume, metakaolin, or slag cement that reacts pozzolanically or hydraulically.

Tamping — the operation of consolidating freshly placed concrete by repeated blows or penetrations with a tamper. (See also consolidation and rodding.)

Tensile strength — maximum stress that a material is capable of resisting under axial tensile loading based on the cross-sectional area of the specimen before loading.

Tremie — a pipe or tube through which concrete is deposited under water, having at its upper end a hopper for filling and a bail for moving the assemblage.

Vibration — energetic agitation of freshly mixed concrete during placement by mechanical devices, either pneumatic or electric, that create vibratory impulses of moderately high frequency to assist in consolidating the concrete in the form or mold.

1. *External vibration* — employs vibrating devices attached at strategic positions on the forms and is particularly applicable to manufacture of precast items and for vibration of tunnel-lining forms; in manufacture of concrete products, external vibration or impact may be applied to a casting table.

2. *Internal vibration* — employs one or more vibrating elements that can be inserted into the fresh concrete at selected locations, and is more generally applicable to in-place construction.

3. *Surface vibration* — employs a portable horizontal platform on which a vibrating element is mounted.

Water-cement ratio (w/c) — the ratio of the mass of water, exclusive only of that absorbed by the aggregates, to the mass of portland cement in a cementitious mixture, stated as a decimal and abbreviated as w/c .

Water-cementitious materials ratio (w/cm) — the ratio of the mass of water, excluding that absorbed by the aggregate, to the mass of cementitious material in a mixture, stated as a decimal and abbreviated w/cm . (See also water-cement ratio.)

Workability — the property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogenous condition.

Yield — (1) the volume of freshly mixed concrete produced from a known quantity of ingredients; (2) the total mass of ingredients divided by the density mass of the freshly mixed concrete; (3) the number of units produced per bag of cement or per batch of concrete.

CHAPTER 1—INTRODUCTION

Those who work with concrete should know what concrete is made of and how it behaves. They should know the basic properties of concrete, and they should also recognize safety precautions needed to protect themselves and other workers when they are placing and finishing concrete.

Unlike other building materials that are delivered ready-to-use, most concrete has to be manufactured at or near the jobsite just before it is used. This makes the work of the concrete craftsman important to the success of the construction project (Fig. 1.1). An alternative is to use precast concrete that is manufactured offsite into the desired shape(s), (typically wall panels) and then transported to the jobsite (Fig. 1.2).

Understanding the basics should help workers to produce better concrete. To learn more, study the references shown in Appendix A. Three important sources, frequently referenced in this book by their initials, are:

- **American Concrete Institute (ACI):** prepares codes, specifications, guides and state-of-the-art reports for design and construction in concrete. www.concrete.org
- **ASTM International (ASTM):** prepares specifications and test methods for concrete materials and ready mixed concrete. www.astm.org
- **Portland Cement Association (PCA):** has many publications explaining how to get good quality concrete and how to build with it. www.cement.org

What is concrete?

Concrete is a mixture of cement, water, and aggregates (stone or sand) with or without admixtures, fibers, or other cementitious materials. Normalweight concrete, the concrete most commonly used for structural purposes, has a density of about 135 to 160 lb/ft³ (2160 to 2560 kg/m³). Lightweight structural concrete may have an equilibrium density of 90 to 115 lb/ft³ (1440 to 1840 kg/m³) or less, whereas special high-density (heavy-weight) concrete has a



Fig. 1.1—Concrete is not delivered in its final form. The fresh concrete should be placed, consolidated, finished, and cured



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Fig. 1.2—Precast panel construction



Fig. 1.3—Polished section sawed from hardened concrete. The cement-and-water paste coats each piece of aggregate and fills all spaces between the aggregate particles (photo courtesy CTLGroup)

density up to about 400 lb/ft³ (6400 kg/m³).

Most concrete today is made with portland cement and supplementary cementitious materials (SCMs). Concrete is sometimes described as a mixture of two major components: aggregates and paste. The paste, made of cement, SCMs, and water, binds the aggregates into a rock-like mass as the paste hardens (Fig. 1.3). The hardening is a chemical process called hydration, not a drying process, and it can take place under water as well as when exposed to air. Concrete does not harden or cure by drying, because the cement needs moisture to hydrate and harden. When the concrete dries fully it no longer gains strength.

People will often refer to the hardened mixture of cement, water, and aggregates as cement, but this is technically wrong. Concrete is the combination of these materials; only the binding powder is properly called cement (Fig. 1.4).

The paste part of the concrete also contains air, called entrapped air, which occurs when air is trapped during mixing, and is usually less than 2 percent by volume. Entrained air voids are usually scattered, comparable in size to the larger grains of sand. Often, the paste also contains very small spherical air voids, referred to as entrained air, intentionally introduced into



(a)

the mixture by means of an air-entraining admixture to improve certain properties in both the fresh and hardened concrete. As Fig. 1.5 shows, the greatest part of concrete is the aggregate.

Importance of concrete

Concrete is the most widely used construction material today. Worldwide, almost 5 tons (4.5 tonnes) of concrete is produced every year for every living human being. This happens because concrete is the cheapest, most readily available material. Fortunately, it is also strong, resistant to water and fire, and readily formable to an infinite variety of sizes and shapes.

Concrete has been used to build some of the largest and tallest of all manmade structures. For example, completed in 2009, the Trump International Hotel and Tower in Chicago, IL, stands at 1389 ft (423 m). The primary structure of this building is reinforced concrete (Fig. 1.6).

Although the bulk of conventional concrete has compressive strengths in the



(b)



(c)

Fig. 1.4 — Often incorrectly used, people will refer to concrete as cement. Cement is only one ingredient in a concrete mixture. Shown in (a) is cement (powder) (photo courtesy of PCA); (b) fresh concrete (plastic state); and (c) hardened concrete (finished product).

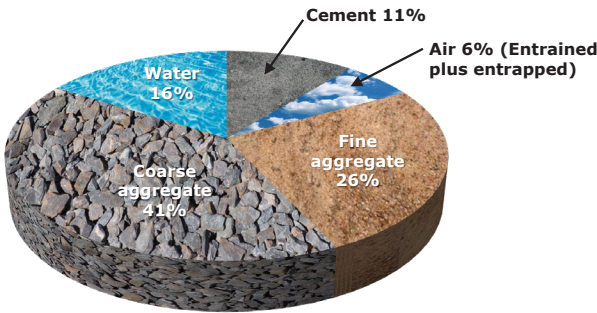


Fig. 1.5—Proportions by absolute volume of materials in a typical air-entrained concrete, freshly mixed. In other mixtures, total aggregate may range from 60 to 75 percent and cement from 7 to 15 percent



Fig. 1.6—Construction of the Trump International Hotel and Tower; Chicago, IL (photo courtesy of Lawrence Novak (PCA))

range of 3000 to 6000 psi (20 to 40 MPa), continuing advances in concrete technology are making ever-higher strengths available. Concrete for high-rise buildings frequently is designed for 9000 to 12,000 psi (60 to 80 MPa) strengths, and one building in Seattle has columns made of 19,000 psi (130 MPa) concrete. Ultra-high performance concrete (UHPC) can attain compressive strengths up to 29,000 psi (200 MPa). It is important to recognize that stronger concrete is not always better. Stronger concrete typically has a greater cement content and corresponding shrinkage potential; therefore, for thin, flat concrete structures like slabs-on-ground, stronger concrete can result in performance issues such as curling/warping and cracking. At the other end of the scale, low-strength concrete used for fill or insulation may have a compressive strength as low as 70 to 100 psi (0.5 to 0.7 MPa). One type of low strength concrete is auto-claved aerated concrete (AAC). AAC is made with fine aggregates, cement, and an expansion agent. The concrete can contain up to 80 percent air and typical compressive strengths are between 300 to 900 psi (2 to 6 MPa). AAC can be used to manufacture components that can be cut and shaped with conventional tools.

Importance of the craftsman

The concrete craftsman is a very important part of a successful concrete construction project. A successful project depends on the concrete developing the strength and other properties that the designer specified when the work was planned. The concrete quality depends directly on the concrete craftsman in the field or in a precast plant, and they should understand some of the important factors affecting how concrete develops and gains strength such as:

1. *Temperature and humidity*: This includes the temperature of the concrete as mixed and the humidity and temperature of the air it is exposed to as it sets. Warm concrete hardens faster than cool concrete but will not get as strong (lower ultimate or final strength). When humidity is low and temperature high or the wind is strong, the concrete surface can dry out causing cracks to appear before it hardens (refer to CCS-1). These cracks are commonly called plastic shrinkage cracks.
2. *Water content in relation to the amount of cementitious materials in the mixture*: Too much water causes concrete to be weaker and to shrink more.
3. *Type and fineness of cementitious materials*: The specifier usually selects one of the five standard types of portland cement described later in this book. Additionally, it is common for concrete mixtures to include SCMs such as pozzolans, slag cement, and silica fume. The choice of cement and SCMs often affects work at the jobsite because the materials can influence workability, setting time, and finishability of the concrete. Materials selection, however, is usually beyond the craftsman's control.
4. *Admixtures*: There are many types of admixtures available that are discussed in Chapter 2. Admixtures may change the setting and hardening time of the mixture. When properly selected for a particular site and weather conditions, they often make it easier for the craftsmen to do a good job. The craftsman should be aware of how admixtures may affect setting time to properly finish the concrete.

Adding water to concrete

Some concrete workers prefer the concrete mixture to be as wet as possible because this reduces the labor of placing (but not necessarily the overall labor requirement). This is not a good idea because adding water usually results in a lower strength that may not maintain compliance with specifications.

Engineers and specifiers use a term called water-cement ratio (w/c) to show how much water should go into the mixture. This is simply a fraction or proportion arrived at by dividing the mass of water in a batch of concrete by the mass of portland cement. A 1 yd³ (1 m³) batch of concrete containing 255 lb (150 kg) of water and 564 lb (335 kg) of cement would have

$$w/c = \frac{255 \text{ lb water}}{564 \text{ lb cement}} = 0.45 \text{ (in.-lb units)}$$

$$w/c = \frac{150 \text{ kg water}}{335 \text{ kg cement}} = 0.45 \text{ (SI units)}$$

Note: Water-cement or water-cementitious materials ratio is a dimensionless value.



Fig. 1.7—Construction of a commercial skyscraper hotel in Dallas, TX



Fig. 1.8—Concrete discharging from a ready mixed concrete truck chute; each aggregate particle is coated with paste

When concrete contains SCMs, the proper term to use is the w/cm , which is similar to the w/c except that the mass of the water is divided by the total mass of all portland cement and SCMs.

In properly made concrete, each aggregate particle is completely coated with paste (Fig. 1.8). Also, all of the spaces between aggregate particles are filled with paste. So, if the aggregates are of satisfactory quality, the quality of the concrete depends mostly on the quality of the paste. In turn, the quality of the paste depends on the proportion of water in the paste to cementitious materials. For concrete mixtures that are workable (can be placed with a reasonable amount of effort), those with low w/cm (small amount of water in the paste) are stronger and more durable than those with high w/cm (Fig. 1.9).

Most concretes have w/cm between about 0.4 and 0.7.

w/cm lower than 0.4 are used in low-permeability concrete and in very-high-strength concrete such as that in columns of tall buildings or dewatered specialty floor toppings. w/cm higher than 0.7 may be used in concretes where strength, durability, watertightness, and wear resistance are not critical.

While the ratio of the amount of water to the amount of cement is an important aspect in concrete mixture design, it is also important to consider the total amount of water and cement. Often, when lower w/cm are required, additional cementitious material is used as opposed to reducing the water content as intended. In these cases, even when the w/cm may be low, the mixture can have excess water.

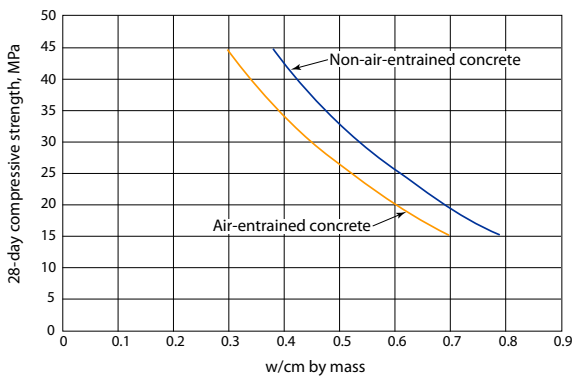
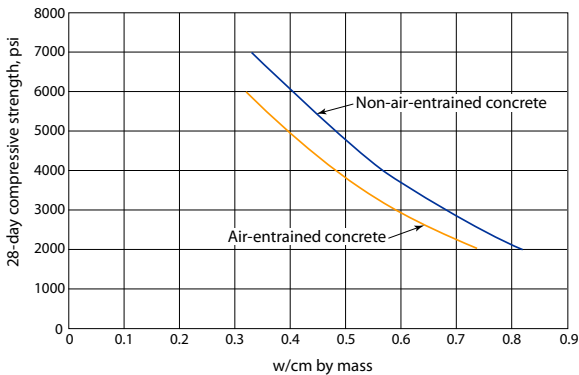


Fig. 1.9—Strength of concrete is greater when the w/cm is low. Low w/cm values also give more durable concrete. For a given w/cm , air-entrainment causes lower strength (Values from *Design and Control of Concrete Mixtures*¹)



Fig. 1.10—Concrete cracking can be unsightly and depending on the location can reduce the service life of the structure

Avoiding the use of excess water will produce stronger, more durable concrete. There are other reasons to resist adding water. Concrete shrinks as it dries, and this can lead to unsightly cracking (Fig. 1.10). The more water that is used, the greater the shrinkage potential. Excess water in the concrete also increases bleeding, which is the appearance of water on the fresh concrete surface as cement grains and aggregate particles start to settle. Increased bleed water may delay finishing or cause weakness in the upper layer of the concrete. Admixtures can be used to increase workability without adding excess water. For more information, see the chemical admixture discussion in Chapter 2.

Handling concrete safely

In addition to safeguarding the concrete by avoiding too much water, workers should consider their own safety when handling concrete (Fig. 1.11). Fresh portland cement

concrete is highly alkaline (caustic) and can cause skin irritation and burns. Take these simple precautions to avoid needless injury:

1. *Keep cement products off skin* — Experienced concrete craftsmen protect their skin with boots, gloves, clothing, and knee pads (Fig. 1.12). Skin injury may result from clothing that is wet from cement mixtures.
2. *Don't let skin rub against cement products* — Many cement products are abrasive. Rubbing increases the chances of serious injury. Keep concrete out of cuffs and boots.



Fig. 1.11—Hard hat, eye protection, safety vest, long-sleeved shirt, long pants, boots, and ear protection are minimum safety equipment for concrete work. Dust masks should be worn when necessary



Fig. 1.12—Worker wearing knee pads to protect his skin from fresh concrete

3. *Wash skin promptly after contact with cement products*
4. *Keep cement and cement products out of eyes* — Concrete workers should wear safety glasses or goggles. If any cement or cement mixtures get into the eye, flush immediately and repeatedly with water and consult a physician promptly.
5. *Keep products out of the reach of children* — Keep children away from cement powder and all freshly mixed cement products.

CHAPTER 2—CONCRETE MATERIALS

Freshly mixed concrete is made of cement, water, and aggregates such as sand and gravel. Frequently, it also contains one or more admixtures and supplementary cementitious materials (SCMs). The quality of these ingredients, their proportions, and the way they are mixed all affect the strength of the concrete. Typically a fresh concrete mixture should be plastic or semi-fluid, and capable of being shaped like modeling clay in the hand.

This chapter describes the following principal ingredients that make up the concrete mixture:

- Cement
- Fine aggregate
- Coarse aggregate
- Water
- Chemical admixtures
- Supplementary cementitious materials (SCMs)

Concrete as used in construction may also contain reinforcement in the form of steel or fiber-reinforced polymer (FRP) reinforcing bars (Fig. 2.1), welded wire reinforcement (sometimes called welded wire fabric or wire mesh [Fig. 2.2]), and various reinforcing fibers. Other reinforcement may be prestressed, either pretensioned or post-tensioned. Reinforcement is needed to give the concrete elements strength in tension (tensile strength). Concrete reinforcement is described in ACI document E2-00.

Portland cements

Portland cements are hydraulic cements, which means they set and harden by reacting chemically with water, and they are able to do so under water. During the reaction, which is called



Fig. 2.1—Concrete workers placing concrete through reinforcement



Fig. 2.2—Welded wire reinforcement

hydration, they give off heat as they form a stone-like mass that binds the aggregate particles together. Most of the concrete's hydration and strength gain take place in the first month (typically referred to as 28 days). After that there may be slow gains in strength over long periods, sometimes 50 years or more. In massive structures such as dams and large piers, and in hot weather, the heat that is generated can cause cracking and strength loss at times. However, in most concrete work, particularly in cold weather, the heat helps concrete to harden and gain strength faster.

Origins: Portland cement was patented in 1824 by Joseph Aspdin, a mason in England. He named it "portland" because concrete made with it was similar in color to natural limestone from the Isle of Portland. Although Aspdin was the first to patent a formula for cement, natural cements produced by heating natural minerals had been used for centuries. The Greeks and Romans used lime mortars that were given hydraulic properties by the addition of volcanic ash and other natural pozzolans. The first recorded shipments of portland cement to the U.S. came from Europe in 1868, and it was first manufactured in the U.S. in 1871 (*Design and Control of Concrete Mixtures*¹).

Manufacture: To make portland cement, finely ground raw materials such as limestone, clay, cement rock, and iron ore are blended by either a wet or dry process to produce a mixture with desired chemical composition. The raw mix is heated in a kiln to 2600 to 3000°F (1400 to 1650 °C). In the kiln it changes chemically into pellets of cement clinker. The clinker is cooled and ground to the fineness of face powder with a small amount of gypsum added to regulate the setting time. The resulting cement is not a single chemical, but is a complex mix of chemical compounds that participate in the hydration process.

Types of portland cement

ASTM C150/C150M, "Standard Specification for Portland Cement," defines the principal types of portland cement used in the U. S.:

Type I, normal cement—A general-purpose cement used where special properties of the other types are not required. Widely used in slabs-on-ground, reinforced concrete buildings, bridges, and elsewhere that concrete is not exposed to aggressive environments or to objectionable temperature rise due to heat of hydration.

Type II, moderate sulfate resistance—Used where moderate sulfate exposure is required to be resisted, as in drainage structures where sulfate in groundwater is not unusually severe. Usually generates heat of hydration more slowly than Type I. Gains strength more slowly than Types I and III, but eventually catches up (about 56 days) when concrete is properly cured.

Type III, high early strength cement—Develops strength much sooner than Type I would have at 28 days, usually in a week or less. Similar to Type I, but more finely ground so that it develops strength faster. Useful when forms need to be removed early, as for example, in precast plants or when a structure will be put into service quickly.

Type IV, low heat of hydration—Develops strength at slower rate than other types and releases less heat as it hydrates. Used in massive structures such as gravity dams and mat foundations where the rate and amount of heat generated during hardening is required to be minimized. Type IV cement is no longer manufactured in the U. S. because SCMs offer a less expensive way to control temperature rise.

Type V, high sulfate resistance—Used only in concrete exposed to severe sulfate action, principally where soils or ground waters have a high sulfate content. Sulfate attacks on concrete can cause the concrete to crack and break up unless the concrete is made sulfate-resistant.

ASTM C150/C150M also provides for three types of air-entraining cements — Types IA, IIA, and IIIA — which are similar to Types I, II, and III described previously, except that they are manufactured with small amounts of air-entraining materials that improve the resistance of concrete to freezing-and-thawing cycles. Most concrete producers believe it is more effective to add air-entraining admixtures during the concrete mixing process rather than to use special cements so there is limited demand for air-entraining cements.

Two cements that produce a moderate heat of hydration, Type II(MH) and Type II(MH)A, are also described in ASTM C150/C150M.

Type I portland cement is usually carried in stock and is supplied when the cement type is not specified. Type II is also widely available, particularly in areas with saltwater exposure or high sulfate content in the soil. Together Types I and II make up 90 percent of the cement shipped from U.S. plants. Type III and white cement are available in the larger cities, and they represent about 4 percent of cement shipments.

White and colored portland cement

The gray or tan color of ordinary portland cement depends mostly on the amount of iron in the cement. White cement, which differs from ordinary cements chiefly in color, is made to conform to ASTM C150/150M, usually Type I or Type III. White portland cement is made with selected raw materials containing very little iron or manganese oxides, which are the substances that give cement the typical gray color. White portland cement is used primarily for architectural purposes in both precast and cast-in-place concrete (Fig. 2.3). It is necessary for white concrete, and gives brighter, more intense colors for colored concrete in which pigments are added during the mixing. Colored cements are produced by intergrinding pigments with white clinker.

Special types of cement

Only 6 percent of U. S. cement production goes into special hydraulic cements. Several of the more important types of special cement are briefly described.

Blended cements: Either ASTM C595/C595M, “Standard Specification for Blended Hydraulic Cements,” or ASTM C1157/C1157M, “Standard Performance Specification for Hydraulic Cement,” is used to specify blended cements. Blended cements are produced by combining two or more fine materials from the following:

- a.) Portland cement
- b.) Slag cement
- c.) Fly ash and other pozzolans
- d.) Hydrated lime
- e.) Ground limestone
- f.) Preblended combinations of (a) through (e)



Fig. 2.3—White portland cement (photo courtesy of Lehig White Cement Company)



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The cement types produced in this way are classified by ASTM standards. The cement types in ASTM C595/C595M include:

- Type IS – Portland blast-furnace slag cement
- Type IP – Portland-pozzolan cement
- Type IL – Portland-limestone cement
- Type IT – Ternary blended cement

These cements may have optional special properties designated by the additional notation, for example, MS for moderate sulfate resistance, HS for high sulfate resistance, MH for moderate heat of hydration, LH for low heat of hydration, and more.

The cement types in ASTM C1157/C1157M include:

- Type GU – Hydraulic cement for general construction
- Type HE – High early-strength
- Type MS – Moderate sulfate resistance
- Type HS – High sulfate resistance

Blended cements can be used in construction when specific properties of these types of cements are required. However, the concrete may not gain strength as fast as with ASTM C150/C150M cements.

Masonry cements: Masonry cements are hydraulic cements manufactured to meet ASTM C91/C91M, “Standard Specification for Masonry Cement,” requirements designed for use in mortar for masonry construction. They contain a variation of cement or hydraulic lime, usually in combination with other materials such as hydrated lime, limestone, chalk, slag, or clay. There are three types—M, N, and S—that are used with or without other cements to obtain workable, plastic masonry mortars. Masonry cements can be used for parging and plaster (stucco), but never for making concrete.

Expansive cements: These hydraulic cements expand rather than shrink during early hydration after setting. Manufactured to meet ASTM C845/C845M, “Standard Specification for Expansive Hydraulic Cement,” they are used most commonly to produce shrinkage-compensating concrete. There are three classifications—K, M and S. When the expansion is properly restrained, they are effective in making crack-free pavements and slabs, as well as plugging leaks in concrete and masonry walls. Expansive cements are not commonly manufactured; most concrete producers believe it is more economical to add an expansive admixture during the concrete mixing process rather than use a special expansive cement.

In addition, there are also oil-well, refractory, plastic, waterproof, and regulated-set cements, as well as others still

under development. Refer to *Design and Control of Concrete Mixtures*¹ for more information about blended cements.

Aggregates

The sand, gravel, crushed stone, and similar materials that are mixed with cement and water to make concrete are called



Fig. 2.4—Principal use of white portland cement is in architectural concrete, both precast and cast-in-place. The Advocate Condell Medical Center was renovated with architectural precast using white portland cement (photos courtesy of Condell Medical Center)  **Documents**
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aggregates. These materials make up 60 to 75 percent of the absolute (solid) volume of concrete and represent 70 to 80 percent of its mass. A 1 yd³ (1 m³) batch of normalweight concrete can contain 2600 to 3200 lb (1500 to 1900 kg) of aggregates.

Fine aggregate: If all of the particles are smaller than 3/8 in. (9.5 mm), the aggregate is defined as fine. Although most fine aggregates are natural sand, some are produced by crushing rock.

Coarse aggregate: If most of the particles are larger than about 1/4 in. (6.4 mm) the aggregate is defined as coarse. It can be either gravel or crushed material. Gravel usually has smoothly rounded particles, while crushed stone has rough, angular surfaces. The largest pieces of coarse aggregate can measure 6 in. (150 mm) or more.

Concrete that is made without coarse aggregate is usually called mortar or grout. Most concrete used in building construction has a maximum aggregate size from 3/4 to 1-1/2 in. (19 to 37.5 mm). In massive structures like dams and mat foundations, larger aggregate sizes are often used.

Natural gravel and sand are usually taken from a pit, river, lake, or seabed. Aggregates from saltwater areas should be used with caution because of problems with seashell and salt content. Crushed aggregate can be made from natural gravel, quarry rock, cobbles, or boulders. Air-cooled blast-furnace slag is also crushed to make both fine and coarse aggregate. Recycled or waste concrete can also be crushed to make satisfactory aggregate. Whether the aggregate is crushed or natural, the mix of particle sizes is not always ideal for making concrete. The aggregate producer may pass aggregate over screens that sort out particles of various sizes, then recombine them in proportions given in standard specifications.

The most common aggregates such as sand, gravel, crushed stone, or crushed slag, make concretes with densities from 135 to 160 lb/ft³ (2160 to 2560 kg/m³) when freshly mixed. Structural lightweight concrete with density from about 90 to 120 lb/ft³ (1440 to 1920 kg/m³) is made with aggregates of expanded shale, fired clay, slate, or slag. Even



Fig. 2.5—Technician grading coarse aggregate (photo courtesy of PCA)

lighter aggregates such as pumice, perlite, and vermiculite can be used to produce concretes with densities from 15 to 90 lb/ft³ (240 to 1440 kg/m³). At the other extreme, heavy materials such as barite, limonite, and iron and steel punchings are used in radiation-shielding concretes weighing up to 380 lb/ft³ (6100 kg/m³). Only the normalweight concrete and aggregates are reviewed here. Refer to *Design and Control of Concrete Mixtures*¹ for more information about other concretes.

Normalweight aggregates should meet the requirements of ASTM C33/C33M, “Standard Specification for Concrete Aggregates.” A number of tests can be made to determine if an aggregate can be used to make strong durable concrete. Important factors that affect the quality of the concrete are:

1. Nominal maximum size
2. Grading
3. Particle shape
4. Organic impurities
5. Silt and clay content
6. Amount of coarse and fine aggregate in the mix

Nominal maximum size of aggregate

The largest aggregate that can be used depends on the size and shape of the member being made from the concrete, and on the spacing and location of reinforcing steel in it. Size of the largest pieces of aggregate are not allowed to be more than:

1. One-fifth of the narrowest dimension of the concrete member
2. Three-fourths of the smallest clear distance between reinforcing bars or bar bundles and the space between bars and form
3. One-third the depth, if concrete is going into a slab

Aggregate grading

Aggregates are made up of particles of many different sizes. To keep on making concrete batches that are essentially the same, the aggregate amount and distribution of particle sizes need to be essentially the same. To measure the particle sizes, a dry sample of the aggregate is passed through a number of standardized sieves (Fig. 2.6) starting with the largest openings and using smaller and smaller openings in successive sieves. The grading can then be defined precisely by the percentage of the total mass passing each sieve. Called a sieve analysis, refer to ASTM C136/C136M, “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates,” for this process.



Fig. 2.6—Sieves are available in different size diameters; larger sieves (Fig. 2.5) are available for larger quantities of aggregate. Many sieves are available for use in a mechanical shaker

There are several reasons why ASTM C33/C33M specifies grading limits and maximum aggregate sizes. The amount of cement and water needed for a mixture depends on the aggregate size. For example, with 1 in. (25 mm) maximum size aggregate, less cement and water are needed to produce concrete with a given strength than with 1/2 in. (12.5 mm) aggregate. Workability, porosity, resistance to freezing-and-thawing, pumpability, and other properties can also be affected by the grading and aggregate size. Variations in grading can also seriously affect the uniformity of concrete from one batch to the next. In general, aggregates that do not have a large deficiency or excess of aggregate passing each of the sieves will produce the best results. These aggregates are said to have a smooth grading curve. The specific grading selected is less critical than the need to prevent variation from batch to batch. The grading limits in ASTM C33/C33M are very wide to accommodate the variation found throughout the country. However, the variation within a specific source should be much smaller. The higher the tolerance in the finish, such as with superflat floors, requires more specific gradation and less variability. The gradation

of the aggregates can also be optimized to result in a minimized amount of cement paste and corresponding minimal shrinkage for that specific aggregate source. However, the aggregate source has one of the greatest influences on concrete shrinkage

Harmful materials in aggregate

Most specifications limit the amount of potentially harmful substances in aggregates (Table 2.1). ASTM C33/C33M

Table 2.1—Harmful Substances in Aggregates

Substances	Effect on concrete
Organic impurities	Affects setting and hardening, may cause deterioration
Materials finer than the No. 200 (75 mm) sieve	Affects bond, increases water requirement
Coal, lignite, or other lightweight materials	Affects durability, may cause stains and popouts
Soft particles	Affects durability
Clay lumps and friable particles	Affects workability and durability, may cause popouts
Chert of less than 2.40 relative density	Affects durability, may cause popouts
Alkali-reactive aggregates	Causes abnormal expansion, map cracking, and popouts

Note: Information is from *Design and Control of Concrete Mixtures*¹ Table 5-6.



Fig. 2.7—A popout occurs when internal pressure causes a small part of the concrete surface to break away, usually leaving a cone-shaped hole. Popouts range in size from 1/4 in. (6 mm) or less in diameter to 2 in. (50 mm) or more, depending on aggregate size (photo courtesy of Frances Griffith)

places maximum allowable percent limits on deleterious materials, such as clay lumps and friable particles, in fine and coarse aggregates. A primary concern is that poor aggregates will harm the concrete durability. Additionally, organic impurities such as peat and humus may delay setting and hardening of concrete and reduce its strength gain. Many impurities can cause popouts, which are the breaking away of small parts of a concrete surface due to localized internal pressure. Typically, they are caused by freezing of moisture in unsound aggregates, and leave cone-shaped fractures in the concrete surface (Fig. 2.7). In other examples, impurities are expansive without freezing, such as lignite; this can result in numerous flakes in the surface.

Handling aggregates

All handling and stockpiling operations cause some segregation and breakage of coarse aggregates. Crushed aggregates segregate less than rounded ones, and larger aggregates segregate more than smaller ones. Sometimes the different size fractions of



Fig. 2.8—Aggregate stockpiles should be kept clean and separate. Handling to minimize segregation is important (photo courtesy of PCA)

coarse aggregates are stockpiled and batched separately. Proper stockpiling procedures, however, can at times eliminate the need for this (Fig. 2.8).

When aggregates are delivered by truck, the most economical and acceptable method is the truck-dump method, which discharges the loads in a way that keeps them tightly joined; particles that roll down the sides of the pile cause segregation. The aggregate is later moved with a front-end loader that should slice off the edges of the pile from top to bottom so that every slice contains a portion of each horizontal layer. *Design and Control of Concrete Mixtures*¹ gives detailed information on handling and storage of aggregates. Where ready mixed concrete is used, the producer routinely handles aggregate storage methods.

Mixing water

Water quality is a concern because chemicals in it, even in very small amounts, sometimes change the setting time of the mixture or the long-term properties of the concrete. Almost any natural water that is drinkable can be used to make concrete. Treated city water, or tap water, from most U.S. and Canadian cities with a populations of 20,000 or more are also suitable for making concrete. Some water that

is not drinkable, including recycled waters from mining and other industrial operations, may also be used, but tests should be made of such water before using it. Non-drinkable water should be tested in accordance with ASTM C1602/C1602M, “Standard Specification for the Mixing Water Used in the Production of Hydraulic Cement Concrete.”

Seawater containing up to 35,000 parts per million (ppm) of dissolved solids, is not harmful to the strength of plain (unreinforced) concrete, but it may cause reinforcement to rust in reinforced concrete. Waters containing appreciable amounts of oil, salt, algae, or sugar should be checked before using in concrete. Mortar cubes made with questionable water should have at least 90 percent of the reference strength of specimens made with clean water. Follow ASTM C191, “Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle,” to assure that the water does not affect the setting time of the cement to an unacceptable degree. Where specifications place severe limitations on chloride content of concrete, it might be necessary to consider the chloride content of mixing water when selecting concrete proportions.

Admixtures

Any material deliberately added to change the fresh or hardened characteristics of concrete, before or during mixing (Fig. 2.9) other than cementitious materials, water, aggregates and fiber reinforcement is called an admixture. There are many kinds of admixtures, including:

- Air-entraining admixtures
- Accelerating admixtures
- Retarding admixtures
- Water-reducing admixtures
- High-range water-reducing admixtures (superplasticizers)
- Miscellaneous special purpose admixtures, such as colors, corrosion inhibitors, and pumping aids

ASTM C260/C260M, “Standard Specification for Air-Entraining Admixtures for Concrete,” is a standard specification specifically for air-entraining admixtures. ASTM C494/C494M, “Standard Specification for Chemical Admixtures for Concrete,” defines requirements for accelerating admixtures, retarding admixtures, water-reducing admixtures, and high-range water-reducing admixtures (superplasticizers). It also provides for dual-function admixtures that combine water reduction with either acceleration or retardation of the mixture. Finely divided SCMs such as fly ash and natural pozzolans are covered by ASTM C141/C141M, “Standard