SECOND EDITION

ENGINEERED CONCRETE

MIX DESIGN AND TEST METHODS

IRVING KETT

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Dedication

With appreciation and love I dedicate this textbook to my darling wife, Ethel.

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Acknowledgment

Over the years of teaching I have encountered many fine engineering students. Probably one of the most gifted graduate students I have had the pleasure of having in my class was Michael M. Kamegawa. He deserves recognition for his contribution to this book by virtue of his artistic enhancement of the original text.

About the Author
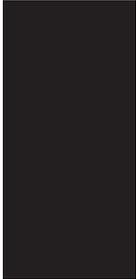
Irving Kett, Ph.D., has been a professor of civil engineering at California State University, Los Angeles, for the past thirty-eight years. Prior to his academic appointment, he spent over twenty-five years in the practice of engineering, principally in the design and construction of highways and bridges. In addition to his work in the United States, including Alaska, Dr. Kett also practiced as a civil engineer in Asia and Europe.

As a faculty member in the Civil Engineering Department, Dr. Kett's area of specialization has been transportation engineering. He has, however, been responsible for the concrete laboratory for many years. It was while teaching this course for undergraduate civil engineering students and conducting research projects in concrete technology with graduate students that he gradually developed the textbook on concrete laboratory procedures that is now also used in industry not only in the United States, but also in Canada, Europe, and elsewhere.

During his long career as a civil engineer, Dr. Kett published over twenty professional articles, based primarily upon his professional experience, and four textbooks. He has been a Fellow in the American Society of Civil Engineers since 1966 and a member of eight professional and honorary engineering societies. He holds four university degrees.

During World War II, Dr. Kett saw combat with the U.S. Army as an enlisted soldier in the Pacific Theater. He later served in a similar capacity in Korea. Dr. Kett received a direct commission in the Army Corps of Engineers in 1955. In Dr. Kett's last assignment for the U.S. Army, he was recalled to active duty for three years and sent to the Middle East to help supervise the construction of two multibillion-dollar, high-performance airbases. For almost four decades Dr. Kett served in the United States military as an active reservist or on active duty in the U.S. Army while building his civilian career. He retired in 1982 as a colonel, a rank that he held during the last seven years of his Army career.

Part 1

Introduction

Introduction

The purpose of this book is to familiarize civil engineering and construction technology students with two of the most important materials of construction, Portland cement (PC) and Portland cement concrete (PCC). People frequently make the error of using these terms interchangeably. It is important to keep in mind that PC is a powder, while PCC is initially a plastic material and for the remainder of its life, a solid. A valid analogy is to compare PC to flour and PCC to bread. The book aims to assist students to gain an understanding of PC and PCC through the physical handling and testing of these materials in the laboratory environment. While the book was primarily written for use at the college level, it may also serve as a practical guide for the graduate engineer and laboratory technician.

The body of this book is divided into four sections. Section 1 explains how concrete batches are designed, mixed, and measured for various consistencies, which is explained in a special chapter titled "Mix Design Procedures." Section 2 details the tests of the primary component materials of concrete other than water—namely Portland cement, aggregates, and mortar. Section 3 includes some of the fundamental testing procedures in conformity with the standards of the American Society for Testing Materials (ASTM). Section 4 includes the various appendices, followed by an index of additional data sheets. There probably will never be enough laboratory time to complete all of the test procedures, even in a 15-week university semester.

The testing procedures included herein are intended to accurately reflect the specific ASTM designation, sometimes with modifications dictated by the inherent time constraints of an academic laboratory. In certain cases, therefore, such as in securing the specific gravities and absorption of aggregates, modifications were introduced to fit the usual 3-hour laboratory module. Where the particular ASTM method permits alternate procedures, only the one more applicable to the teaching situation was chosen.

The unique property of all products utilizing hydraulic cements is the interval required to obtain test specimens and its time sensitivity. For this reason, considerable time must elapse between specimen preparation and testing. This complicates the scheduling process when planning a course in Portland cement concrete and makes this laboratory unique. Sample course outlines for both a ten-week academic quarter and a fifteen-week semester are included in Appendix F. It is recommended that the five additional weeks in the semester be utilized for additional testing on aggregates, cement, and mortar. The same number of periods is shown to be devoted to PCC testing in both schedules.

The United States has been for many years, and remains in transition from the U.S. Standard System of Measurements to the SI (Système International d'Unités, commonly referred to as the metric system). Only two small nonindustrialized nations, Liberia in Africa and Myanmar (formerly known as Burma) in southwestern Asia, still have not converted to the SI system. Since both systems of measurements are still currently being used, in this book the SI system was chosen to be the primary measurement system shown, with the equivalent U.S. Standard in parentheses as a "soft" conversion between the two systems. The values of the two measurements are, therefore, not identical.

Brief Overview of Portland Cement and Concrete Technology

Portland cement concrete (PCC) is composed of three basic components: Portland cement, aggregates, and water. In addition, there may be a host of other materials, called additives, which may be added to the basic mix in order for the concrete to develop special properties. These include air entraining agents, accelerators, decelerators, coloring agents such as carbon black, fly ash, pozzolons, silica fume, water-reducing agents, super-plasticizers, among others. The use of admixtures is a specialized subject for experienced engineers, and therefore was not deemed suitable for inclusion in the body of this book. A brief description, however, of the properties and use of PCC additives is included in Appendix D.

Cementing Materials

Any material that can be made plastic and that gradually hardens to form an artificial stonelike substance is called a *cementitious* material. Hydraulic cements, namely portland and natural, along with limes, fly ash, and silica fume, are currently the principal cementing materials used in structures. They become plastic by the addition of water; the mix then sets and hardens. The other principal type of cementing agents are asphalts, which are made plastic either by heating, emulsifying, or by the addition of a cutback agent. Asphalt concretes are vastly different from hydraulic concretes. The hardening process of the latter requires a hydration mechanism. This book is only concerned with one type of hydraulic, namely Portland, although natural cements will be mentioned briefly because of their historic significance and continued, although limited, use.

The earliest cement known was *puzzalon* cement, which was first used by the Romans over 2000 years ago. There are examples of puzzalonic cement structures still in existence and in good condition. Those cements were produced by mixing lime with volcanic ash, called *pozzolana,* which is found near the town of Pozzuola, Italy. Natural cements in more recent years were produced by burning a limestone high in clay minerals and magnesia to drive off the carbonic acid and then grinding the resultant clinker into a fine powder. In comparison to Portland cement, natural cement possesses lower tensile strength, gains strength more slowly, and its properties are less uniform.

Portland cement was first made in Portland, England, from which it derived its name, by Joseph Aspdin in 1824. It can be produced either by a wet or a dry process. In the wet method (Figure 1) the raw materials are blended and ground in a slurry condition. In the dry process (Figure 2) operations are carried out with the materials in a dry state. Adjustments to the constituents are made by the addition of clay or stone of known characteristics. Portland cement is obtained from finely pulverized clinker produced by calcining to incipient fusion properly proportioned argillaceous and calcareous materials. The final constituents and properties of Portland cement are very carefully controlled during manufacturing.

Portland cement comes in five basic types and a number of specialty varieties to fulfill different physical and chemical requirements. The most frequently used cements are as follows:

Drilling rig
Overburden

Shale

To crusher

Each raw material
is stored separately

Limestone

Raw materials consist of
combinations of limestone,
cement rock, marl or oyster shells,
and shale, clay, sand, or iron ore

To vibrating screen

Primary crusher

Secondary crusher

Raw materials conveyed
to grinding mills

1. Stone is first reduced to 125 mm size, then to 20 mm, and stored.

Dry process

To air separator

Limestone Sand Clay Iron ore

Oversize

Dust
collector

Hot air
furnace

Raw mix

To kiln

Fines

Raw materials
are proportioned

Grinding mill

To pneumatic pump

Dry mixing and
blending silos

Ground raw
material storage

Air

or

2. Raw materials are ground to powder and blended.

Wet process

Limestone Sand Clay Iron ore

Water
added
here

Oversize

Vibrating
screen

Slurry

Fines

Grinding mill

Slurry
pumps

Slurry is mixed and
blended

Slurry
pump

Storage basins

To kiln

Raw materials
are proportioned

2. Raw materials are ground, mixed with water to form slurry, and blended.

To
kiln

Dust
collector

Raw mix is kiln burned to
partial fusion at 1450°C–1650°C

Materials are
stored separately

Clinker

Coal, oil, gas,
or other fuel

Gypsum

Fan   Dustbin   Rotating kiln   Clinker cooler

Air

Clinker and gypsum conveyed
to grinding mills

3. Burning changes raw mix chemically into cement clinker.

Air
separator

Dust
collector

Clinker Gypsum

Oversize

Fines

Materials
are proportioned

Grinding mill

Cement
pump

Bulk storage

Bulk
truck

Bulk
car

Box
car

Packaging
machine

Truck

4. Clinker with gypsum is ground into cement and shipped.

FIGURE 1
Wet-process manufacture of Portland cement. (Reprinted with permission of the Portland Cement Association.)

1. Stone is first reduced to 125 mm size, then to 20 mm, and stored.

2. Raw materials are ground to powder and blended.

3. Burning changes raw mix chemically into cement clinker. Note four-stage preheater, flash furnaces, and shorter kiln.

4. Clinker with gypsum is ground into portland cement and shipped.
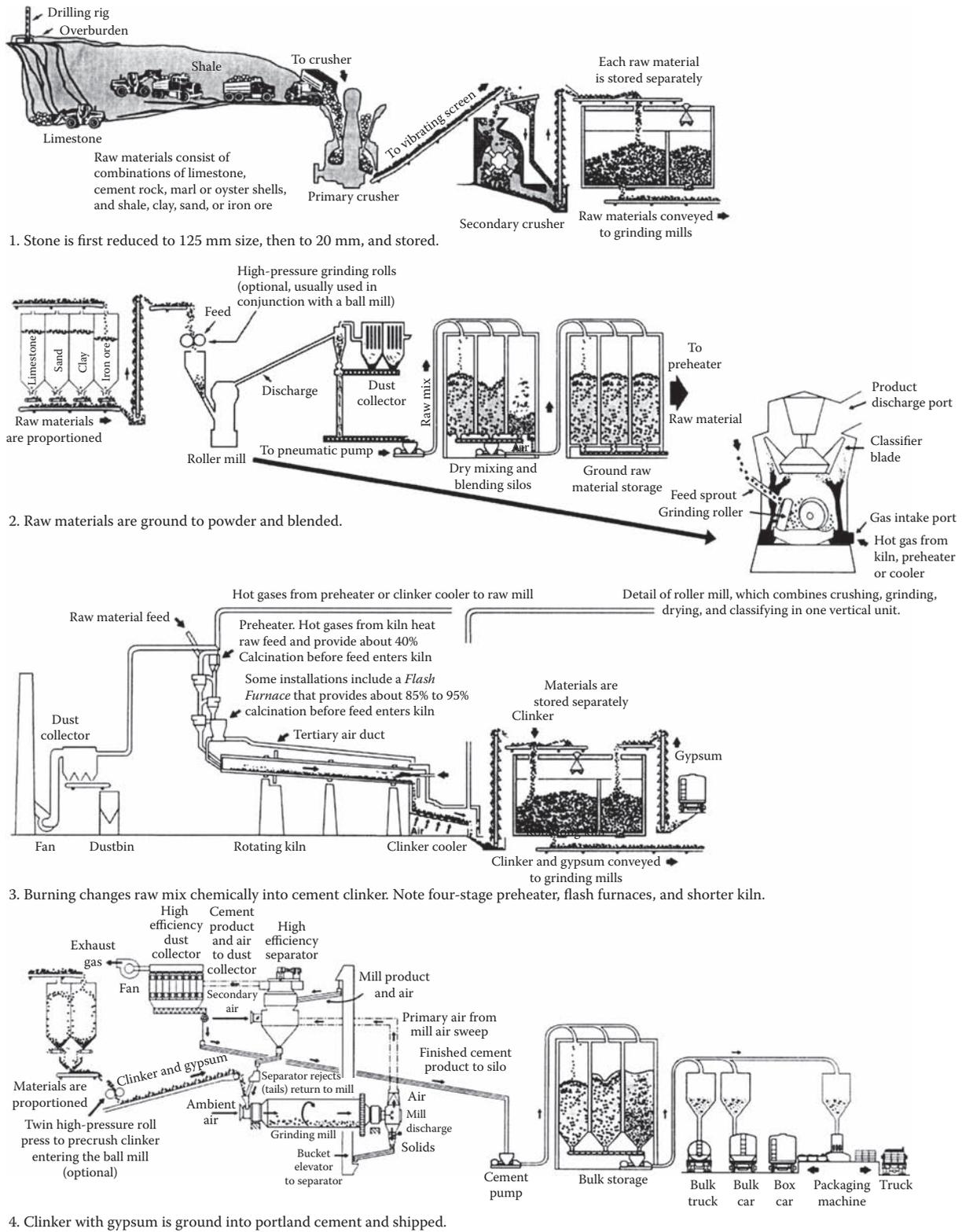
FIGURE 2

Dry-preprocess manufacture of Portland cement. (Reprinted with permission of the Portland Cement Association.)

Type I: normal or general purpose
Type II: moderately sulfate resistant
Type III: high early strength
Type IV: low heat of hydration
Type V: sulfate resistant

For Types I, II, and III, designations with an A after the number indicate that the cement contains an air-entraining agent. There is also a white Portland cement in Types I and III for special purposes. This does not exhaust the list of hydraulic cements that are available, but it will suffice for the purpose of this book.

Aggregates

Aggregates are the inert particles that are bound together by the cementing agent (such as Portland cement) to form a mortar or a concrete. Mortar is a mixture of fine aggregate, a cementing material, and water. A mixture of only cement and water is referred to as *neat cement*. Concrete is composed of the ingredients of mortar plus coarse aggregates. The boundary size definition of fine aggregates is one that passes a 5-mm (No. 4) sieve. Coarse aggregate particle sizes are those that are retained on a 5-mm (No. 4) sieve opening. There is no real maximum aggregate size, but in most concretes for pavements and structures the upper limit is usually 5 cm (2 in), but it may be larger.

Coarse aggregates are obtained from gravel or crushed stone, blast furnace slag, or recycled concrete. Trap rocks, granite, limestones, and sandstones are satisfactory for crushed stone. Fine aggregates are derived from the same sources except that in the place of gravel, naturally occurring sand is used. All aggregates should be composed of hard particles and free of injurious amounts of clay, loam, and vegetable matter. The principal characteristics of aggregates that affect the strength, durability, and workability of a concrete are cleanness, grading, hardness, and shape. Usually the aggregates are stronger than the concrete from which they are made. A coating of dirt or dust on the aggregate will reduce the strength of concrete because it prevents the particles from properly bonding to the mortar. A well-graded aggregate mix is essential to obtaining an economical concrete of good quality. If poorly graded, even clean, sound aggregate will require excessive water for workability, resulting in lower strength, or the mix will require an excessive amount of cement to develop a given strength.

The American Society for Testing Materials (ASTM) specification for the grading and quality of aggregates for normal weight concrete is defined by Designation: C 33. There are seven standard sieve openings for fine aggregate and up to thirteen sieve sizes for coarse aggregates. The grading requirements are shown in Tables 1 and 2.

TABLE 1
Grading Requirement for Fine Aggregates from ASTM Designation: C 33

Sieve Size (Specification E 11)	Percent Passing
9.5 mm (⅜ in.)	100
4.75 mm (No. 4)	95–100
2.36 mm (No. 8)	80–100
1.16 mm (No. 16)	50–85
600 μm (No. 30)	25–60
300 μm (No. 50)	10–30
150 μm (No. 100)	2–10

TABLE 2
Grading Requirements for Coarse Aggregates from ASTM Designation: C 33

Nominal Sieve Size	Amounts Finer than for Sieve Size, Weight Percent												
	100 mm (4 in.)	90 mm (3.5 in.)	75 mm (3 in.)	63 mm (2.5 in.)	50 mm (2 in.)	37.5 mm (1.5 in.)	25 mm (1 in.)	19 mm (0.75 in.)	12.5 mm (0.5 in.)	9.5 mm (.375 in.)	4.75 mm (No. 4)	2.36 mm (No. 8)	1.16 mm (No. 16)
37.5–90 mm (1.5–3.5 in.)	100	90–100		25–60		0–15		0–5					
37.5–63 mm (1.5–2.5 in.)			100	90–100	35–70	0–15		0–5					
25–50 mm (1–2 in.)				100	90–100	35–70	0–15		0–5				
4.75–50 mm (No. 4–2 in.)				100	95–100		35–70		10–30		0–5		
19–37.5 mm (0.75–1.5 in.)					100	90–100	20–55	0–15		0–5			
4.75–37.5 mm (No. 4–1.5 in.)					100	95–100		35–70		10–30	0–5		
12.5–25 mm (0.5–1 in.)						100	90–100	20–55	0–10	0–5			
9.5–25 mm (0.375–1 in.)						100	90–100	40–85	10–40	0–15	0–5		
4.75–25 mm (No. 4–1 in.)						100	95–100		25–60		0–10	0–5	
9.5–19 mm (.375–.75 in.)							100	90–100	20–55	0–15	0–5		
4.75–19 mm (No. 4–.75 in)							100	90–100		20–55	0–10	0–5	
4.75–12.5 mm (No. 4–0.5 in)								100	90–100	40–70	0–15	0–5	

Water

The water used for concrete should be clean and free from dirt or organic matter. Water containing even small quantities of acid can have a serious deleterious effect on concrete. The presence of oil will result in slowing the set and reducing the strength. Generally speaking, if water is potable, it is satisfactory for the production of a good concrete.

Objectives in Designing a Concrete Mixture

Concrete may be considered as being composed of four basic separate ingredients: cement, coarse aggregates, fine aggregates, and water. Another way of looking at concrete is as a graded mixture of fine and coarse aggregates held together by wetted cement. Still another way of viewing concrete is that the coarse aggregates are held together by a mortar that is composed of cement, fine aggregates, and water. The requirements of concrete are complex, but the ultimate aim is to produce the most economical combinations of concrete materials that will satisfy the performance requirements and specifications. A properly designed concrete mixture should possess the following physical properties:

1. When still in the plastic state, it must be adequately *workable*.
2. It must fulfill the required *strength* parameters.
3. *Durability* to be able to withstand imposed forces and elements such as traffic abration for a concrete pavement.
4. Other properties that may vary in importance with the location of the concrete in a structure are *permeability* and *appearance*.

In the next chapter, the mechanics of proportioning normal concrete will be explained.

Mix Design Procedures
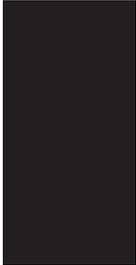
A concrete mix design can be proportioned from existing statistical data using the same materials, proportions, and concreting conditions. When there are no existing records or they are insufficient, the concrete mixture must be determined by trial mixtures. In a laboratory class situation, no body of field experience with the materials is assumed to exist.

In concrete proportioning by the method of trial mixtures, certain design objectives must be established beforehand. These are as follows:

1. Required 28-day compressive strength, f'_c, or some other strength parameter such as the modulus of rupture.
2. Portland cement content based upon a water-to-cement (w/c) ratio, and under certain conditions, the minimum specified cement content.
3. Maximum allowable w/c ratio.
4. Maximum size of the large aggregates.
5. Acceptable range of slumps and the percent of air for an air-entrained concrete.

Once these parameters have been established, trial mixes can then be formulated and the specimens prepared. In practice, three mixtures would be prepared with three specimens each. A w/c ratio would be determined from reference tables for one mix design. Other mix designs would then be computed somewhat above and somewhat below the first w/c. However, as you will note, the highest w/c must never exceed a certain limiting value that is obtained from an appropriate table for the particular structure and environmental conditions. The three mixes should produce a range of strengths (f'_{cr}), be within the specified slump ±20 mm (¾ in.), and at an air content ±0.5% of the maximum permitted. f'_{cr} will be defined twice later in this chapter, once when discussing the U.S. Standard System of Measurements and also under the SI System. Because of time constraints it is hardly likely that you will have the opportunity to conduct three different tests to establish the one that will result in the desired f'_{cr}. Each test consists of three specimens. In practice, the w/c as the abscissa is plotted against the strength as the ordinate. From the resulting curve, a w/c is taken off at the desired f'_{cr}. The difference between f'_c and f'_{cr} is explained later in this chapter.

Several proportioning methods are available. The one that will be described in this handbook is based upon the absolute volume method from the American Concrete Institute's Committee 211, "Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete." In order to use this method, certain physical properties of the materials need to be determined in the laboratory before designing the mixtures. These are as follows:

1. Apparent specific gravity of the Portland cement.
2. Bulk specific gravities and percent of moisture present in the saturated surface dry (SSD) condition for both the coarse and fine aggregates.
3. Rodded unit weight of the coarse aggregates.
4. Fineness modulus of the fine aggregates.
5. Free moisture present in both the coarse and the fine aggregates.

TABLE 3
Example of a Fineness Modulus Computation

Sieve Size	Percentage of Individual Fraction Retained, by Weight	Cumulative Percentage Passing, by Weight	Cumulative Percentage Retained, by Weight
9.5 mm (⅜ in.)	0	100	0
4.74 mm (No. 4)	2	98	2
2.36 mm (No. 8)	13	85	15
1.18 mm (No. 16)	20	65	35
600 μm (No. 30)	20	45	55
300 μm (No. 50)	24	21	79
150 μm (No. 100)	18	3	97–283
Pan total	3–100	0	

Fineness modulus = 283/100 = 2.83.

The term *fineness modulus* (FM) may be used to define either a coarse or a fine aggregate in accordance with ASTM Designation: C 125. However, in this book, reference will only be made to the FM for the fine aggregate. The FM is a factor obtained by adding the percentage of material in the sample that is coarser than each of the following sieves (cumulative percentage retained) and dividing the sum by 100. The computation is illustrated in Table 3.

In describing the mix design procedure, it will be necessary to consider the same absolute volume method separately for both systems of measurements. The size of the design batch for the SI System will be the cubic meter while for the U.S. Standard System of Measurements it will be the cubic yard. Two other values that need to be considered in trial mix proportioning are the unit weight and the yield. Both of these are determined in accordance with ASTM Designation: C 138, which is included in this book. The unit weight of freshly mixed concrete is expressed in a weight per volume while the yield is calculated by dividing the total weight of all the materials batched by the unit weight of the freshly mixed concrete.

The term *batch* is not unique to concrete works. It is simply the quantity of materials required for a single operation. To produce concrete of uniform quality, the materials must be accurately introduced into the mixer by mass or weight, depending upon the system of measurement used. However, a one-cubic-meter batch or a one-cubic-yard batch does not mean that the resultant quantity produced is exactly one cubic meter or one cubic yard. The reason for that is the variability in yield. Concrete should be thoroughly mixed until a uniform appearance is obtained. All concrete specimens in the laboratory should be prepared in accordance with ASTM Designation: C 192, which is included in this book. Concrete mixers, whether stationary or mobile, have a rated maximum capacity and rotational speed. These provisions from the equipment manufacturer should be followed. Generally the maximum recommended mixing quantity is about 57.5% of the volume of the drum. Shrink mixing, a method of overloading the drum, is poor practice and should not be permitted.

The various tables that are introduced for the mix design computations were taken from the PCA Engineering Bulletin, *Design and Control of Concrete Mixtures* (1995, 2002), from both the United States and Canadian editions. In some instances the tables were modified to facilitate their use in the handbook for application to concrete mix designs in either the SI or U.S. Standard Systems of measurements. Where it was not deemed practical to use the same table for both systems of measurements, the tables were introduced separately under the respective mix design methods for each system. Tables 4, 5, 6, and 7 were modified to be applicable to both measurement systems. The other necessary tables are included under the discussion for each of the two measurement systems.

Tables 4, 5, and 6 are self-explanatory and their use furthermore will be illustrated in the design examples shown under each of the two measurement systems. However, Table 7 requires a little explanation.

TABLE 4
Maximum Water/Cement Ratio for Various Exposure Conditions

Exposure Condition	Maximum W/C Ratio by Weight for Normal Weight Concrete
Concrete protected from exposure to freezing and thawing or the application of deicer chemicals	Select the W/C ratio on the basis of strength, workability, and finishing needs
Concrete intended to be watertight:	
a. Concrete exposed to fresh water	0.50
b. Concrete exposed to brackish water or seawater	0.45
Concrete exposed to freezing and thawing in a moist condition:[a]	
a. Curbs, gutters, guardrails, or other thin sections	0.45
b. Other elements	0.50
c. In the presence of deicing chemicals	0.45
For corrosion protection for reinforced concrete exposed to deicing salts, brackish water, seawater, or spray from these sources	0.40

[a]   Air-entrained concrete.
Adapted from the ACI 318 Committee Report, "Building Code Requirements for Reinforced Concrete."

TABLE 5
Volume of Coarse Aggregate per Unit Volume of Concrete as per ASTM Designation: C 29

Maximum Size of Aggregate, mm (inches)	Volume of Rodded Coarse Aggregates per Unit Volume of Concrete for Different Fineness Moduli of Fine Aggregates as per ASTM Designation: C 29[a]			
	2.40	2.60	2.80	3.00
9.5 mm (⅜ in.)	0.50	0.48	0.46	0.44
12.5 mm (½ in.)	0.59	0.57	0.55	0.53
19 mm (¾ in.)	0.66	0.64	0.62	0.60
25 mm (1 in.)	0.71	0.69	0.67	0.65
37.5 mm (1.5 in.)	0.75	0.73	0.71	0.69
50 mm (2 in.)	0.78	0.76	0.74	0.72
76 mm (3 in.)	0.82	0.80	0.78	0.76

[a]   Volume of either Dry- or SSD-Rodded. It is important to differentiate in computing the adjusted moisture content for the concrete mix.
Adapted from the ACI 211 Report, "Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete."

When a body of data exists for the particular materials and mix design, a standard deviation is computed. This standard deviation is introduced into two equations, which in turn yields a modification factor. In effect, the design objective then becomes the preparation of a concrete with a compressive strength of f'_{cr}, which is greater than the specified design concrete strength, f'_c. Since there are variations in the results obtained in any concrete, the objective is to design the most economical mix that will still result in a high degree of assurance that the concrete will not be less than f'_c. Since in a teaching laboratory each group starts off at time zero, there is no assumed existing body of data and, therefore, Table 7 will be used. There are other refinements in developing the ultimate f'_{cr} that will not be introduced in this manual because a classroom environment does not permit the amount of time required for the more detailed procedure. For further information, the reader is referred to the appropriate chapter in the applicable Portland Cement Association (PCA) *Design and Control of Concrete Mixtures* (1995, 2002) and the *Recommended Practice for Evaluation of Strength Test Results of Concrete* (1983) by the American Concrete Institute (ACI) Committee 214 Report. Both are referenced in the Bibliography (Appendix H).

TABLE 6
Recommended Slumps for Various Types of Construction[a]

Concrete Construction	Slump in mm (inches)	
	Maximum	Minimum
Reinforced foundation and footings	75 mm (3 in.)	25 mm (1 in.)
Plain footings, caissons, and substructure walls	75 mm (3 in.)	25 mm (1 in.)
Beams and reinforced walls	100 mm (4 in.)	25 mm (1 in.)
Building columns	75 mm (3 in.)	25 mm (1 in.)
Pavements and slabs	75 mm (3 in.)	25 mm (1 in.)
Mass concrete	50 mm (2 in.)	25 mm (1 in.)

[a] In designing for slump, try to aim for the middle of the range.

Adapted from the ACI 211 Report, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete."

TABLE 7
Required Average Compressive Strength When Data to Establish a Standard Deviation Is Not Available

Specified Compressive Strength, f'_c, MPa (psi)	Required Average Compressive Strength, f'_{cr}, MPa (psi)
Less than 20 MPa (3000 psi)	f'_c + 6.9 MPa (1000 psi)
20 to 35 MPa (3000–5000 psi)	f'_c + 8.3 MPa (1200 psi)
Over 35 MPa (5000 psi)	f'_c + 9.6 MPa (1400 psi)

Adapted from the ACI Committee Report, "Building Code Requirements for Reinforced Concrete."

TABLE 8
Minimum Portland Cement Requirements for Normal-Density Concrete Placed in Slabs and Pavements

Maximum Size of Aggregates, mm	Portland Cement,[a] kg/m^3
40	282
20	324
14	354
10	366

[a] Cement quantities need to be increased in cases of severe environmental conditions; for tremie concrete (that is, concrete placed under water) quantities should be ≥390 kg/m^3, or for a very cold climate, where the concrete is subject to freezing and thawing cycles, the cement content should be ≥335 kg/m^3.

Adapted from the ACI Committee 302 Report, "Guide for Concrete Floor and Slab Construction."

What follows is an explanation of the proportioning of normal weight and strength concrete mixtures by the absolute volume method for both the SI and the U.S. Standard systems of measurement. Several of the mix design tables that could not be accommodated for both of the systems of measurements simultaneously are shown separately in Tables 8 through 14.

With regard to Table 5, "Volume of Coarse Aggregate per Unit Volume of Concrete," a modification is sometimes used. In structures where there is less demand for workability, such as in concrete flatwork (pavements being a prime example), the quantity of coarse aggregates may be increased by about 10%.

Conversely when more workability is required, such as in a pumpcrete, the quantity of coarse aggregates is generally decreased by a similar amount. This factor will be used in the illustrative example for concrete mix design.

A relationship exists between the compressive strength of a concrete and its flexural strength, both taken at 28 days. While the connection between the two values is far from precise, it is sufficiently valid for initial mix design purposes. However, before the design is used, its flexural strength adequacy should be tested. The w/c ratio should be adjusted, up or down, in order to obtain the most economical concrete mix that satisfies the other requirements. The approximate corresponding compressive strength for a given flexural strength can be derived from the following equations:

$$f'_c = (MR/K)^2 \text{ --- in MPa for the SI System} \tag{1}$$

$$K = 0.7 \text{ to } 0.8$$

$$f'_c = (MR/K)^2 \text{ --- in psi for the Standard U.S. System} \tag{2}$$

$$K = 7.5 \text{ to } 10$$

MR stands for Modulus of Rupture, which is the flexural strength based on ASTM Designation: C 78. The higher K-values are applicable for the stronger concretes. These equations will be used in the illustrative examples, with K = 0.8 and 10.

The International System of Measurements

Illustrative Problem for Concrete Mix Design by the Absolute Volume Method

Design Parameters—design the concrete for an unreinforced, air-entrained pavement, in a very cold climate where there is no statistical data available for the proposed mix design; 25 cm thick; specified 28-day concrete flexural strength of 4.7 MPa; the coarse aggregates have a bulk specific gravity of 2.70; a rodded density of 1650 kg/m^3 at the saturated surface dry (SSD) condition and a moisture content of 1.5% above the SSD condition; the fine aggregates have a bulk specific gravity of 2.65 with a fineness modulus of 2.75 and a moisture of 5% above the (SSD) condition. The apparent specific gravity of the Portland cement = 3.15.

Design Solution—For structural concrete, the required compressive strength is specified. Only in the case of pavements is the flexural strength criterion used instead. However, since the mix design tables are predicated on compressive strength, Equation (1) above is used to determine the approximate equivalent compressive strength, f'_c.

$$f'_c = (MR/0.8)^2 = (4.7/0.8)^2 = 34.5 \text{ MPa}$$

Step 1
Determine the required mix design strength, f'_{cr}, from Table 7 = 34.5 + 8.3 = 42.8 MPa.

Step 2
This is the estimated water/cement ratio from Table 9. Since the table does not show the w/c ratio beyond a strength of 35 MPa, a quesstimate was made to specify a 0.35 w/c ratio, which is very low. In practice, a

TABLE 9
Approximate Relationship between W/C Ratio and the Concrete Compressive Strength

Compressive Strength at 28 Days, MPa (See Table 9 for Percent Air Allowed)	Water/Portland Cement Ratio by Mass	
	Non-Air-Entrained Concrete	Air-Entrained Concrete
40	0.42	—
35	0.47	0.39
30	0.54	0.45
25	0.61	0.52
20	0.69	0.60
15	0.79	0.70

Adapted from the ACI Committee 211 Report, "Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete."

water-reducing or superplastizer additive would very likely have to be added in order that the concrete mix be sufficiently workable at the 0.35 w/c ratio. Check Table 4 to assure that the maximum w/c ratio is not exceeded. However, because of the fairly high percent of entrained air, the mix may still prove to be sufficiently workable. Only after the trial batch is prepared and the slump measured will the engineer (or the student) know what modification needs to be made to the mix for workability. Actually, admixtures, except for air-entraining agents, are not considered in this book. It is simply too complex and time consuming a subject to cover in an undergraduate laboratory course. The student does not have the time to go back and adjust the mix because of the 28-day strength. In the case of an air-entrained concrete, the student will only be able to adjust the slump by changing the w/c ratio and the percent of entrained air. Check whether the cement content equals or exceeds the recommended quantity shown in Table 8, if applicable to the design structure.

Step 3

In selecting the maximum size of coarse aggregate, there are a number of criteria that need to be met. They will all be enumerated here even though not all are applicable in this illustrative design problem. The criteria for the maximum permissible size of aggregate are as follows:

1. Not to exceed one-fifth the narrowest dimension between the insides of a form.
2. Three-quarters of the clear space between reinforcing bars, ducts, or any other appurtenances embedded in the concrete.
3. Three-quarters of the clear space between the reinforcing bars and the inside face of the forms.
4. In the case of an unreinforced concrete slab, one-third the minimum slab thickness, where the concrete is not a uniform depth.

There are several less frequently encountered criteria, which will not be enumerated here. It is generally most economical to specify the largest coarse aggregate size practical for the design conditions. In the case of the 25-cm pavement thickness, this would translate to a 75-mm aggregate, which is on the high side, but if available and economical, should be used. Generally speaking, a 50-mm aggregate is the largest size that is commonly encountered. For this design exercise, the 75-mm maximum size stone will be specified. Furthermore, in the case of a paving concrete, it is desirable to specify a crushed gravel because of the need for maximum traction between the pavement surface and the vehicles.

Step 4

The air content depends principally upon the environment under which the structure will be functioning. Refer to Table 10. The structure in this problem would qualify as a Category 1, exposed to freezing and thawing, for an air content of 4 to 7%. Table 11 indicates a target percent of entrained air at 4.5, which is in the 4 to 7% range shown in Table 10. For any number of reasons it is not possible to specify and expect to

TABLE 10
Air Content Requirements According to Category

Air[a] Content Category	Range of Air Content in % at Indicated Nominal Maximum Sizes of Coarse Aggregates		
	10 mm	14–20 mm	28–40 mm
1	6–9	5–8	4–7
2	5–8	4–7	3–6

[a] Category 1 is for concrete exposed to freezing and thawing. Category 2 is for concrete not exposed to freezing and thawing.

TABLE 11
Approximate Water and Air Content Requirements for Various Slumps and Maximum Size Aggregates in the Concrete Mix

Slump, mm	Water per kg/m³ of Concrete for Indicated Maximum Size of Aggregate in mm[a]			
	10	20	40	80
Non-air-entrained concrete				
25–50	207	190	166	130
75–100	228	205	181	145
150–175	243	216	190	160
Approximate % entrained air	3	2	1	0.3
Air-entrained concrete				
25–50	181	168	150	122
75–100	202	184	165	133
150–175	216	197	174	154
Recommended % air for level of exposure	Slumps for Concrete with Aggregates Larger Than 40 mm Are Made after the Removal of the +40-mm Particles by Wet Screening.			
Mild exposure	4.5	3.5	2.5	1.5
Moderate exposure	6.0	5.0	4.5	3.5
Severe exposure	7.5	6.0	5.5	4.5

Adapted from the ACI Committee 211 Report, "Standard Practice for Normal, Heavyweight and Mass Concrete."

repeatedly obtain an exact % of air. Furthermore, the author is of the opinion that slightly more air is preferable to less air. Therefore, a target percent air will be chosen of −1% to +2%. In the case of this illustrative design example, a target percent of air of 5% (−1% to +2%) for a range of 4 to 7% was chosen.

Step 5
The desired concrete slump must be specified. For this purpose, refer to Table 6, which shows 2.5 to 7.5 cm.

Step 6
Compute the quantities for the 1-cubic meter trial batch and then an adjustment will be made, taking into consideration the yield of the resultant concrete mix. First, the amount of air-entraining agent, which is usually a liquid made from wood resin, sulfonated hydrocarbons, fatty and resinous acids, or synthetic materials, is determined from the manufacturer's specifications. Usually it is in terms of an amount per 100 kg of Portland cement in the mix for each additional percentage of entrained air desired. The total quantity is never enough to significantly affect the overall volume of mixing materials.

Coarse aggregate quantity is estimated from Table 5, bearing in mind the maximum size of coarse aggregates and the fineness modulus of the fine aggregates. In the case of this illustrative problem, they are 7.5 cm and 2.75, respectively. This results in an interpolated volume of dry rodded coarse aggregates of 0.78.

Slump from Table 6 shows 2.5 to 7.5 cm. Water content from Table 11 = 122 kg/m^3, using the lower slump of 2.5 to 5.0 cm and the more desirable range from the author's experience in slipform paving operations.

Cement content is based upon a w/c ratio of 0.35 = 122/0.35 = 349 kg/m^3. Referring to Table 8, the minimum recommended Portland cement content for this mix is 335 kilograms. Table 4 permits a w/c ratio of 0.45 for this concrete. Therefore, the design w/c ratio and design cement quantity is satisfactory for the trial mix.

Coarse aggregates were found to have a rodded SSD condition density of 1650 kg/m^3. For a cubic meter batch of concrete, the required C.A. weight = $0.78 \times 1650 = 1287 + 10\%$ (as explained on page 13) = 1416 kg.

At this point the quantity of all the materials in the mix has been accounted for except for the fine aggregates. The latter is found by subtracting the volume of the air, cement, coarse aggregates, and water from a cubic meter to estimate the fine aggregate quantity in the batch.

Air = 0.05 = 0.050 m^3
Cement = $349/(3.15 \times 1000)$ = 0.111 m^3
Coarse aggregates = $1416/(2.70 \times 1000)$ = 0.524 m^3
Water = $122/(1 \times 1000$ = 0.122 m^3

Total volume of the above materials = 0.807 m^3
Computed volume of fine aggregates = 1.000 − 0.807 = 0.193 m^3
Weight of fine aggregates in the concrete batch = $0.193 \times 2.65 \times 1000$ = 511 kg

Total weight of all the ingredients in the 1-cubic-meter concrete batch = 349 kg (cement) + 1416 kg (coarse aggregates) + 511 kg (fine aggregates) + 122 kg (water) = 2398 kg.

A moisture correction at this point is needed to compensate for the moisture in the aggregates above that present for the SSD condition. The new trial batch weights are as follows:

Coarse aggregates = 1416×1.015 = 1437 kg
Fine aggregates = 511×1.05 = 537 kg
Water = $122 − 1416 \times 0.015 − 511 \times 0.05$ = 75 kg
Cement = 349 kg

Total materials after water adjustment remains the same: 2398 kg

Assume that all the allotted water was used in the mixing process and that the slump and the air were within specified limits. Therefore, there need be no adjustment made in the ingredients. Otherwise, changes would have to be made in total water, air-entraining agent, and possibly the need to introduce a water-reducing additive.

In the laboratory, mixes will normally be based on batches made from 5, 10, or at the most 15 kg of Portland cement. For example, consider a 10-kg batch. The quantities would be as follows:

Cement = 10 kg
Coarse aggregates = $10/349 \times 1437$ = 41.2 kg
Fine aggregates = $10/349 \times 537$ = 15.4 kg
Water = $10/349 \times 75$ = 2.1 kg

Total weight of the batch = 68.7 kg

Two additional computations need to be made in order to adjust the batch to result in a 1-cubic-meter volume. The procedure for carrying out these computations is detailed in ASTM Designation: C 138. These are the *unit weight* and the *yield*. From the 10-kg trial batch, a bucket of 0.025 m^3 was filled and weighed. The result was 61.1 kg or 2444 kg/m^3. The latter value is designated as W. The actual weight of the materials computed for the 1-cubic-yard batch is designated as W_1. The yield is as follows:

$$Y = W_1/W = 2398 \text{ kg}/2444 \text{ kg/m}^3 = 0.981 \text{ cubic meters}$$

Therefore, all of the quantities in the final mix need to be increased because the yield is less than one. If the yield were greater than one, the weight of the ingredients would have had to be decreased. The following is the final mix design adjustment, although in the field, measurements need to continuously be made in order to check the aggregates, unit weight of the freshly mixed concrete, and the yield:

    Cement = 349.0/0.981 = 356 kg
    Coarse aggregates = 1437/0.981 = 1465 kg
    Fine aggregate = 537/0.981 = 565 kg
    Water = 75/0.981 = 76 kg

    Total weight of final adjusted materials/m^3 = 2462 kg

In the above computations, the specific gravity of water is always assumed to be one and the density at 1 gm/cm^3. The variation in this value because of temperature differentials is too insignificant for this type of work. The actual specific gravities of the Portland cement should be determined in the laboratory, using ASTM Designation: C 188. However, if the specific gravity for the Portland cement has not been determined, a value of 3.15 may be used, probably without appreciable error. This was the approach that was taken in the computations for the illustrative concrete mix design problem. The specific gravities of other cementitious materials such as fly ash, silica fume, or other pozzolans must be determined in the laboratory or obtained from the producer. Their values will vary substantially from 3.15.

The U.S. Standard System of Measurements

Illustrative Problem for Concrete Mix Design by the Absolute Volume Method

Design Parameters—Design the concrete for an unreinforced, air-entrained pavement in a mild climate. Assume that there is no available statistical data for the proposed mix design, and use the following parameters: 10 inches thick; specified 28-day concrete flexural strength of 700 psi; the coarse aggregates have a bulk specific gravity of 2.70, with a rodded density of 110 lb/ft^3 at the saturated surface dry (SSD) condition, and a moisture content of 1.5% above the SSD condition; the fine aggregates have a bulk specific gravity of 2.65 with a fineness modulus of 2.75 and a moisture of 5% above the (SSD) condition.

Design Solution—For structural concrete the required compressive strength is specified. Only in the case of pavements is the flexural strength criterion used instead. However, since the mix design tables are predicated on compressive strength, Equation (2) is used to determine the approximate equivalent compressive strength, f'_c.

$$f'_c = (MR/10)^2 = (700/10)^2 = 4900 \text{ psi}$$

TABLE 12
Approximate Relationship between W/C and the Concrete Compressive Strength

	Water/Cement Ratio by Weight	
Compressive Strength at 28 Days, psi[a]	Non-Air-Entrained Concrete	Air-Entrained Concrete
6000	0.41	0.35
5000	0.48	0.40
4000	0.57	0.48
3000	0.68	0.59
2000	0.82	0.74

[a] Values are the estimated average strengths for concrete containing not more than the percentage of entrained air shown in Table 14 for a maximum size aggregate of 1 inch.
Adapted from the ACI Committee 211 Report, "Standard Practice for Normal, Heavyweight, and Mass Concrete."

Step 1

Determine the required mix design strength, f'_{cr}, from Table 7 = 4900 + 1200 = 6100 psi.

Step 2

Use an estimated water/cement ratio from Table 12. It is possible that a water-reducing or superplastizer additive will have to be added in order that the concrete mix be sufficiently workable at the 0.40 w/c ratio. Check Table 4 to assure that the maximum w/c ratio is not exceeded. Only after the trial batch is prepared and the slump measured will the engineer (or the student) know what modification needs to be made to the mix for workability. In practice this may require adjusting the w/c ratio. Actually, additives, except for air-entraining agents, are not considered in this handbook. It is simply too complex and time consuming a subject to cover in an undergraduate laboratory course. The student does not have the time to go back and adjust the mix because of the 28-day strength. In the case of a non-air-entraining concrete, the student will only be able to adjust the slump by changing the w/c ratio. The entrained air in the mix is accepted and used in the design computations.

Step 3

Select the maximum size of coarse aggregate. There are a number of criteria that need to be met. They will all be enumerated here, even though not all are applicable in this illustrative design problem. The criteria for the maximum permissible size of aggregate are as follows:

1. Not to exceed one-fifth the narrowest dimension between the insides of a form.
2. Three-quarters of the clear space between reinforcing bars, ducts, or any other appurtenances embedded in the concrete.
3. Three-quarters of the clear space between the reinforcing bars and the inside face of the forms.
4. Or in the case of an unreinforced concrete slab, one-third the minimum slab thickness, where the concrete is not a uniform depth.

There are several less frequently encountered criteria, which will not be enumerated here. It is generally most economical to specify the largest coarse aggregate size practical for the design conditions. In the case of the 10-inch pavement thickness, this would translate to a 3-inch aggregate, which is on the high side, but if available and economical, should be used. Generally speaking, a 2-inch aggregate is the largest size that is commonly encountered. For this design exercise, the 3-inch maximum size stone will be specified. Furthermore, in the case of a paving concrete, it is hardly likely that an uncrushed gravel would be used because of the need for maximum traction between the pavement surface and the vehicles.

TABLE 13
Minimum Portland Cement Requirements for Normal-Density Concrete

Maximum Size of Aggregate, inches	Portland Cement,[a] lb/yd³
1½	470
1	520
¾	540
½	590
⅜	610

[a] Cement quantities need to be increased in cases of severe environmental conditions such as for tremie concrete (that is, concrete placed under water), where quantities should be ≥650 lb/ft³, or for a very cold climate, where the concrete is subject to freezing and thawing cycles, the cement content should be 540 lb/ft³.

Adapted from the ACI Committee 302 Report, "Guide for Concrete Floor and Slab Construction."

Step 4

The air content depends principally upon the environment under which the structure will be functioning. There is no need to specify an air entrainment for the concrete in this illustrative design problem. Many engineers would recommend some entrained air for all pavement concrete to improve workability. However, the author elected not to specify any entrained air because of the mild climate. Some air is present in all concrete mixes, derived principally from the fine aggregates. In all concrete mixes it is necessary to determine the actual percentage of air present, even when it is not specifically called for and cannot be controlled. The actual percentage of entrained air present is information that is required in designing the mix, as will soon become evident. Table 14 indicates that an estimated 0.3% of entrapped air will be present in the mix.

Step 5

The desired concrete slump must be specified. For this purpose refer to Table 6, which shows 1 to 3 inches.

Step 6

Compute the quantities for the 1-cubic-yard trial batch and then an adjustment will be made to take into consideration the yield of the resultant concrete.

Coarse aggregate quantity is estimated from Table 5, bearing in mind the maximum size of coarse aggregates and the fineness modulus of the fine aggregates. In the case of this illustrative problem, they are 3 and 2.75 inches, respectively. This results in an interpolated volume of dry rodded coarse aggregates of 0.78.

Slump from Table 6 shows a 1 to 3 in size. Water content from Table 14 = 180 lb/yd³, using the lower slump of 1 to 2 in., which is the more desirable range from the author's experience in slipform paving operations. Furthermore it will result in a somewhat stronger concrete, with the lower w/c ratio, which this design calls for. Of course the mix must have the necessary workability as well as strength.

Cement content is based upon a w/c ratio of 0.40 = 180/0.40 = 450 lb/yd³. Referring to Table 13, the minimum recommended Portland cement content for this mix of 470 lb is based only upon aggregate size, since there are no adverse environmental factors to consider. The maximum size aggregate shown in Table 13 is only 1½ inches and a 3-inch maximum size aggregate is specified in this design. Since larger aggregates require less mortar paste and, therefore, less Portland cement, as can be seen in Table 13, it was decided that the 450 lb/ft³ or even a somewhat smaller cement quantity would be satisfactory for this mix. Table 4 defines various maximum w/c ratios based upon exposure conditions. Since this concrete is being designed for a

TABLE 14
Approximate Mixing Water and Air Content for Different Slumps and Aggregate Sizes

Slump in Inches	Water in Pounds per Cubic Yard of Concrete for the Indicated Slumps and Maximum Sizes of Aggregates[a]						
	⅜ in.	½ in.	¾ in.	1 in.	1½ in.	2 in.	3 in.
Non-air-entrained concrete							
1–2	350	335	315	300	275	260	220
3–4	385	365	340	325	300	285	245
6–7	410	385	360	340	315	300	270
Approximate % of entrapped air in non-air-entrained concrete	3	2.5	2	1.5	1	0.5	0.3
Air-entrained concrete							
1–2	305	295	280	270	240	205	180
3–4	340	325	305	295	275	265	225
6–7	365	345	325	310	290	280	260
Average % air content for level of exposure	Slump for Concrete with Aggregates >40 mm Are Made after Removal of the +40-mm Particles by Wet Screening.						
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5
Moderate exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5
Severe exposure	7.5	7.0	6.0	6.0	5.5	5.0	4.5

[a] The water estimates in this table are for angular crushed stone. The quantities may be reduced by about 10 lb for subangular coarse aggregates, 35 lb for gravel with some crushed particles, and 45 lb for rounded gravel to produce the slumps shown. A change in water content of 10 lb/yd³ will affect the slump by about 1 inch. Of course an increase in water will raise the slump and conversely. A decrease in air content of 1% will increase water demand for the same slump by about 5 lb/yd³.

Adapted from ACI Committee 211, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete" and from ACI Committee Report 318-83, "Building Code Requirements for Reinforced Concrete."

mild climate with no other special exposure conditions, the limitations in Table 4 do not apply. Therefore, the design w/c ratio and the computed cement quantity are satisfactory for the trial mix.

Coarse aggregates were found to have an SSD condition density of 110 lb/ft³. For a cubic-yard batch of concrete, the required weight of coarse aggregates = $0.78 \times 110 \times 27 = 2317$ lb + 10% (as explained on page 13) = 2549 lb.

At this point the quantity of all the materials in the mix has been accounted for except for the fine aggregates. The latter is found by subtracting the volume of the air, cement, coarse aggregates, and water from a cubic meter to estimate the fine aggregate quantity in the batch.

Air = $0.015 \times 27 = 0.40$ ft³
Cement = $450/(3.15 \times 62.4) = 2.29$ ft³
Coarse aggregates = $2549/(2.70 \times 62.4) = 15.13$ ft³
Water = $180/(1 \times 62.4) = 2.88$ ft³
Total volume of the above materials = 20.70 ft³
Computed volume of fine aggregates = $27.00 - 20.70 = 6.30$ ft³
Weight of fine aggregates in the concrete batch = $6.30 \times 2.65 \times 62.4 = 1042$ lb

Total weight of all the ingredients in the 1-cubic-yard concrete batch = 450 lb (cement) + 2549 lb (coarse aggregates) + 1042 lb (fine aggregates) + 180 lb (water) = 4221 lb

A moisture correction at this point is needed to compensate for the moisture in the aggregates above that present for the SSD condition. The new trial batch weights are as follows:

Coarse aggregates = 2549 × 1.015 = 2587 lb
Fine aggregates = 1042 × 1.05 = 1094 lb
Water = 180 − 2549 × 0.015 − 1042 × 0.05 = 90 lb
Cement = 450 lb

Total materials after water adjustment remains the same: 4221 lb

Assume that all the allotted water was used in the mixing process and that the slump was within specified limits. Therefore, there need be no adjustment made in the ingredients. Otherwise changes would have to be made in total water and possibly the need to introduce a water reducing additive.

In the laboratory, mixes will normally be based on batches made from 10, 20, or at most 40 lb of Portland cement. For example, consider a 30-lb batch. The quantities would be as follows:

Cement = 30 lb
Coarse aggregates = 30/450 × 2587 = 172 lb
Fine aggregates = 30/450 × 1094 = 73 lb
Water = 30/450 × 87 = 6 lb

Total weight of the batch = 281 lb

Two additional computations need to be made in order to adjust the batch to result in a 1-cubic-yard volume. The procedure for carrying out these computations is detailed in ASTM Designation: C 138. These are the *unit weight* and the *yield*. From the 30-lb trial batch, a bucket of 1.02 ft³ was filled and weighed. The result was 159 lb/1.02 ft³ or 4209 lb/yd³. The latter value is designated as W. The actual weight of the materials computed for the 1-cubic-yard batch of 4221 lb is designated as W_1. The yield is as follows:

$$Y = W_1/W = 4221 \text{ lb}/4209 \text{ lb/yd}^3 = 1.003 \text{ yd}^3$$

Therefore, all of the quantities in the final mix need to be decreased because the yield is greater than one. If the yield were less than one, the weight of the ingredients would have had to be increased. The following is the final mix design adjustment, although in the field, measurements need to be continuously made to the check the aggregates, the unit weight of the freshly mixed concrete, and the yield:

Cement = 450/1.003 = 449 lb
Coarse aggregates = 2587/1.003 = 2579 lb
Fine aggregate = 1094/1.003 = 1091 lb
Water = 90/1.003 = 90 lb

Total weight of final adjusted materials/yd³ = 4209 lb

In the above computations the specific gravity of water is always assumed to be one and the density at 62.4 lb/ft³. The variation in this value because of temperature differentials is too insignificant for this type of work. The actual specific gravities of the Portland cement should be determined in the laboratory, using ASTM Designation: C 188. However, if the specific gravity for the Portland cement has not been determined, a value of 3.15 may be used, probably without appreciable error. This was the approach that was taken in the computations for the illustrative concrete mix design problem. The specific gravities of other cementitious materials such as fly ash, silica fume, or other pozzolans, if included in the concrete mixture, must always be determined in the laboratory or obtained from the producer. Their values will vary substantially from 3.15.

Tests for Aggregates, Portland Cement, and Mortar

Rodded Unit Weight
of Coarse Aggregates
(ASTM Designation: C 29)

Purpose

Determination of the unit weight of coarse aggregates in a compacted condition. This test method is applicable to aggregates not exceeding 15 cm (6 inches) in nominal size. The unit weight so determined is necessary for the design of a concrete mixture by the absolute value method as explained beginning on pages 14 and 23, depending on the system of measurement.

Equipment and Materials

- Balance accurate to 0.05 kg (0.1 lb) with a range to at least 25 kg (64 lb)
- Straight steel tamping rod 16 mm (⅝ inch) in diameter and about 60 cm (24 inches) in length with one end rounded in a hemispherical tip
- Watertight metal bucket having approximately equal height-to-diameter ratio, but the height should always be between 80 to 150% of the diameter
- Quantity of oven dry aggregate sample should be at least 125% of the quantity required to fill the metal pail

Test Procedure

1. Calibrate the metal bucket to determine its volume by determining the net weight of water required to fill it and dividing it by the density of water. For this test procedure it is sufficiently accurate to accept the density of water at room temperature to be 998 kg/m^3 (62.3 lb/ft^3).

2. Rodding the aggregates. Fill the bucket one-third full and rod the aggregate layer with 25 strokes of the tamping rod, evenly distributed over the surface. Add another layer of aggregates so that the bucket is approximately two-thirds full and repeat the rodding procedure. The third layer of aggregates should fill the pail to overflowing. Again repeat the tamping procedure and strike off the excess with the tamping rod. Manually try to balance the depressions below the top of the bucket with slight projections above the top. When tamping the first lift, do not permit the rod to penetrate to the bottom of the bucket. However, the subsequent lifts should penetrate to the top of the previous lift.

3. The rodded unit weight is computed in kg/m^3 (lb/ft^3) from the net weight of the rodded aggregates in the bucket divided by its volume.

Explanation of Computations and Data Sheet

1. Computations: Calculate the rodded unit weight as follows:

$$M_{SSD} = (G - T)(1 + A/100)/V$$

M_{SSD} = the rodded unit weight of the saturated surface dry aggregate, kg/m³ (lb/ft³)

   G = combined mass of the oven-dry aggregate and the bucket, kg (lb)

   T = mass of the bucket alone, kg (lb/f)

   V = volume of the bucket, m³ (ft³)

   A = % absorption, determined by ASTM Method C 127

Calculate the rodded unit weight to the nearest 10 kg/m³ (1 lb/ft³). Conduct three tests. Average any two that do not differ by more than 40 kg/m³ (2.5 lb/ft³).

2. Data Sheet: There are no special data sheets for this test. Follow the instructions included in the Test Procedure.

Compressive Strength of Hydraulic Cement Mortars
(ASTM Designation: C 109)

Purpose

The following covers only that portion of ASTM Designation: C 109 that is required to determine the compressive strength of 50 mm (2 inches) of Portland cement mortar cubes.

Equipment and Materials

- A 2-kg scale accurate to 0.1 gram
- Six 50-mm (2-inch) cube molds
- Hard rubber tampers 13×25 mm ($\frac{1}{2} \times 1$ inch) cross section and 12 to 15 cm (5 to 6 inches) in height
- Rubber gloves
- Small steel trowels
- Large spoons
- Electrically driven mechanical mixer equipped with a paddle and mixing bowl as shown in Figure 3
- 500 grams of Portland cement
- 1375 grams of Ottawa Sand
- 242 cc of water

Test Procedure

1. Place the 242 cc of water in the mixing bowl, add the 500 grams of cement, and mix at a slow speed (140 ± 5 rpm) for 30 seconds.

2. Add the 1375 grams of Ottawa Sand over a 30-second period while continuing to mix at a slow speed.

3. Stop the mixing, change the mixer setting to medium speed (285 ± 5 rpm), and mix for 30 seconds.

4. Stop the mixer and let the mortar stand for 90 seconds. During the first 15 seconds, scrape down into the batch any mortar that may have collected on the sides of the bowl. Cover the bowl for the remainder of the interval.

5. Finish preparing the mortar by mixing for 60 seconds at medium speed.

6. Immediately upon completion of mixing, start molding the specimens by placing a 25± mm (1± inch) layer of mortar in all of the six cube compartments. Tamp the mortar layer in each cube compartment, with the hard rubber tamper, 32 times within about 10 seconds in accordance with Figure 4 in four rounds. Each round should be at right angles to the other and consist of eight adjacent strokes over the surface of the specimen. Use sufficient tamping pressure to ensure uniform filling of the molds. Complete the lift in each mold in turn before moving on to the next one.
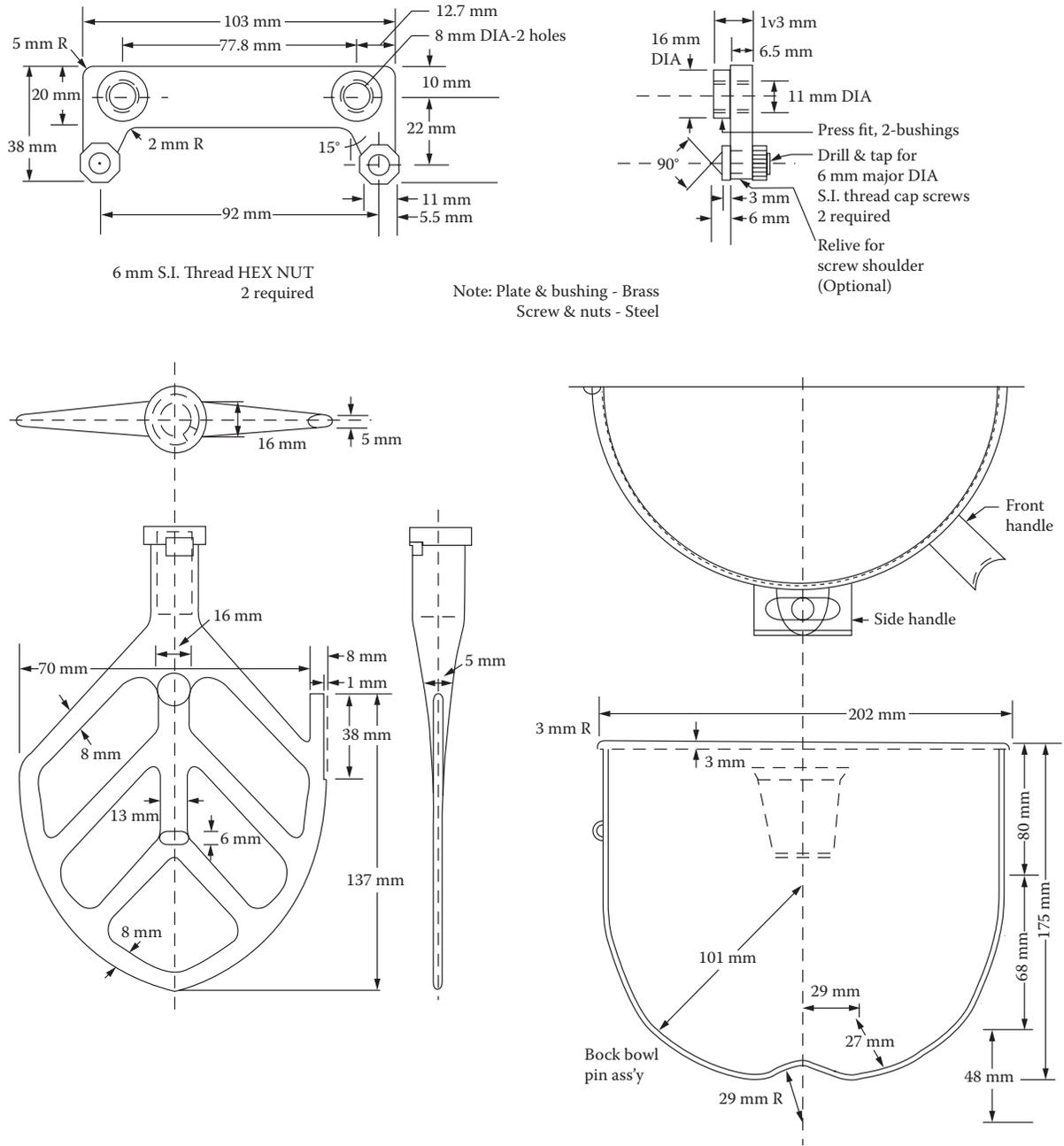
Figure 3
Mixing bowl and paddle from ASTM Designation: C 305. Copyright ASTM. Reprinted with permission.

7. Complete the filling of the molds by adding another layer and duplicate the tamping procedure. At this point the mortar should be slightly above the top of the molds. Carefully cut the excess mortar flush with the edge of a steel trowel.

8. Place the completed mortar cubes in a moist closet, protected from dripping water, for between 20 and 24 hours, after which the cubes are to be stripped from the molds.

9. Insert the mortar cubes in a saturated lime water bath until ready for testing. Periodically the lime water should be changed to keep the water clean.

10. All specimens should be tested within a specified time period.

Rounds 1 and 3   Rounds 2 and 4
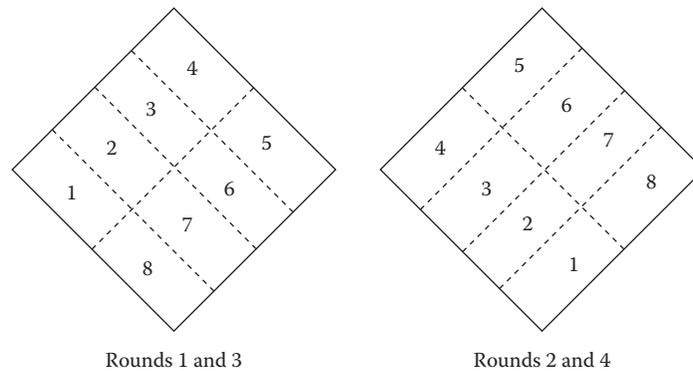
Figure 4
Order of tamping the mortar specimens. Copyright ASTM. Reprinted with Permission.

Test Age	Permissible Time Tolerance
24 hours	± ½ hour
3 days	± 1 hour
7 days	± 3 hours
28 days	± 12 hours

Prior to testing, the specimens should be wiped clean. Apply the loads only to the true surfaces of the cubes. Use a straight edge to check the cube surfaces. Any loose grains of sand or other extraneous material should be removed from the surfaces in contact with the testing machine. The specimen should be placed under the center of the upper bearing block of the testing machine. A light coating of oil should be applied to the upper platen. The rate of load application should produce failure of the specimens during a time interval of 20 to 80 seconds.

Explanation of Computations and Data Sheet: C 109

1. Computations: Record the maximum compressive load and compute the compressive strength in pascals or pounds/square inch.
2. Data Sheet: The following data sheet should be used to record findings.

Data Sheet (ASTM Designation: C 109)

Specimen No.	Time of Loading in Seconds	Total Load in kg or Pounds	Specimen Cross Section in Meters^2 or Inches^2	Specimen Strength in Pascals or psi
1				
2				
3				
4				
5				
6				

Specific Gravity and Absorption Tests of Coarse and Fine Aggregates for Use in the Design of Portland Cement Concrete Mixtures
(ASTM Designations: C 127 and C 128)

Purpose

Determine the bulk and apparent specific gravities, and absorption of coarse and fine aggregates. Absorption is the process by which water is drawn into and tends to fill the permeable pores in a porous solid body.

Equipment and Materials

- Balance with a capacity of at least 2 kg, with an accuracy to 0.1 grams
- Wire basket of 3.35-mm (No. 6) or finer mesh with about a 1-liter capacity
- Six 500-ml pycnometers
- A conical sheet metal brass mold, 40 mm (1½ in.) in diameter at the top, 90 mm (3½ in.) in diameter at the bottom, and 75 mm (3 in.) in height
- Metal tamping rod with a flat circular tamping face 25 mm (1 in.) in diameter, weighing 340 grams (12 ounces)
- Suitable balance and apparatus for suspending sample in water
- Large splitter for coarse aggregate and a small splitter for fine aggregate
- 5 kg of coarse aggregate, where the nominal maximum size is 37.5 mm (1½ in.) or less and all material is retained on the 4.75-mm (No. 4) sieve
- 3 kg of fine aggregate, all particles passing the 4.75-mm (No. 4) sieve

Test Procedure

1. Coarse Aggregate: ASTM Designation: C 127

   a. Select by quartering or use of a sample splitter approximately 5 kg of aggregate. Reject all material passing a No. 4 sieve.

   b. Thoroughly wash the sample to remove all dust or other coatings from the particles.

   c. Dry the sample to a constant weight at a temperature of 100° to 110°C (212° to 230°F). Cool at room temperature for about 15 minutes and then immerse in water at room temperature for approximately ½ hour.

   d. Remove sample from water and wipe the particles until all surface films are removed. Weigh the sample in this saturated surface dry condition to the nearest 0.5 grams.

e. Immediately after weighing, place the sample in a wire basket, suspend in water, and obtain the buoyant weight.

f. Dry the sample to a constant weight at a temperature of 100° to 110°C (212° to 230°F) and cool in room temperature for at least ½ hour and weigh.

g. Computations:

$$\text{Bulk Specific Gravity (Oven Dry)} = \frac{A}{B-C}$$

$$\text{Bulk Specific Gravity (Saturated Surface Dry)} = \frac{B}{B-C}$$

$$\text{Apparent Specific Gravity} = \frac{A}{A-C}$$

$$\text{Absorption in Percent} = \frac{(B-A)\times100}{A}$$

A = weight of oven-dry sample in air, grams

B = weight of saturated surface dry sample in air, grams

C = weight of saturated sample in water, grams

2. Fine Aggregate: ASTM Designation: C 128

a. Obtain by sample splitting or quartering 3000 grams of aggregate, including equal quantities of all fractions.

b. Dry to a constant weight at a temperature of 100° to 110°C (212° to 230°F).

c. Allow to cool and cover with water for about ½ hour.

d. Remove excess water and spread on a flat surface. Expose to a gentle moving flame until test sample approaches a free-flowing condition.

e. Place a portion of the fine aggregate sample loosely into the mold. Tamp lightly 25 times and lift the mold vertically. If surface moisture is present, the fine aggregate will maintain its molded shape. Continue drying and testing until upon removal of the mold, the aggregate slumps slightly. This indicates that the saturated surface dry condition has been reached.

f. Immediately introduce into the pycnometer 500.0 grams of the fine aggregate. Fill the pycnometer almost to capacity and eliminate the air bubbles by agitation. Add water until the bottom of the meniscus is at the 500-cc line, etched on the pycnometer. Determine the total weight of the flask, including the sample and the water.

g. Carefully remove the fine aggregate and dry to a constant weight of 100° to 110°C (212° to 230°F) and cool for at least ½ hour and weigh.

h. Computations:

$$\text{Bulk Specific Gravity (Oven Dry)} = \frac{A}{B+500-C}$$

$$\text{Apparent Specific Gravity} = \frac{A}{B-C+A}$$

$$\text{Bulk Specific Gravity (SSD Condition)} = \frac{500}{B+500-C}$$

$$\text{Absorption in Percent} = \frac{(500-A)\times100}{A}$$

A = weight of oven-dry sample in air, grams

B = weight of pycnometer filled with water, grams

C = weight of pycnometer with sample and water, grams

3. Special Instructions
   a. Determine the specific gravities for three samples of both the coarse and fine aggregates. Test the fourth sample, if necessary, in order to obtain three sets of results that vary from each other by no more than 2%. If these precisions are not met, rerun the entire test.
   b. Using the correct specific gravity in the design of a Portland cement concrete mix is important. The particular specific gravity used must be consistent with the moisture condition of the aggregates being batched, whether on an oven dry or a saturated surface dry (SSD) condition. Either specific gravity may be used. In an oven dry condition the aggregates do not possess any absorbed or surface water. In an SSD condition, the water-permeable voids of the aggregates are filled with water, but no additional free water is present.

Explanation of Computations and Data Sheet

1. Computations were explained separately under Section C: Test Procedure, for both the coarse and fine aggregates.
2. Data Sheet: See the Specific Gravity Data Sheet (page 36). For both the fine and course aggregates, the last value obtained in the laboratory will be (A) the weight of the oven dry sample. Once the saturated surface dry condition is obtained and weighed, value (C) is determined, which is, in effect, a measure of buoyancy. In the case of the coarse aggregate, (C) is obtained directly. To get the value (A), the aggregates are placed in an oven and dried to a constant weight. The four values, bulk (dry and SSD), apparent, and absorption, are then computed for each sample. Based upon the results, a decision needs to be made as whether or not to test the fourth sample for either or both of the aggregates. The final step is to determine the accepted results by averaging the values of those samples that fall within the guideline criteria as explained in (C). These values will then be used in the various mix design computations. It is for this reason that obtaining accurate specific gravities is so important. Do not hesitate to redo the entire procedure if the results are questionable.

Coarse and Fine Aggregates Specific Gravity Data Sheet
(ASTM Designations: C 127 and C 128)

Coarse Aggregates: ASTM Designation: C 127				
Passing ____ Sieve & Retained on ____ Sieve	Sample 1	Sample 2	Sample 3	Sample 4
(A) Wt. oven-dry sample (g)				
(B) Wt. SSD sample (g)				
(C) Wt. saturated sample in water (g)				
Bulk specific gravity				
Apparent specific gravity				
Effective specific gravity				
Absorption, %				
Average Values: Bulk Sp. Gr. = ; Apparent Sp. Gr. = ; Effective Sp. Gr. = ; Absorption = .				
Fine Aggregates: ASTM Designation: C 128				
(A) Wt. oven-dry sample (g)				
(B) Wt. pycnometer + water to calibration mark (g)				
(C) Pycnometer + water + sample to calibration mark (g)				
Bulk specific gravity				
Apparent specific gravity				
Effective specific gravity				
Absorption, %				
Average Values: Bulk Sp. Gr. = ; Apparent Sp. Gr. = ; Effective Sp. Gr. = ; Absorption = .				

Resistance to Degradation of Small-Sized Coarse Aggregates by Abrasion and Impact in the Los Angeles Machine
(ASTM Designation: C 131)

Purpose

The test is to determine the ability of coarse aggregate smaller than 37.5 mm (1½ in.) to resist abrasion, using the Los Angeles Testing Machine.

Equipment and Materials

- Los Angeles Testing Machine (details shown later in this chapter)
- Sieves following specifications in ASTM Designation: E 11
- Abrasive charge in accordance with Table 15
- Sizes of the test samples in accordance with Table 16

Test Procedure

Select the proper amount of aggregate and abrasive charge in accordance with the following tables:

The abrasive charge consists of steel spheres approximately 47.6 mm (1⅞ in.) in diameter, each ball weighing between 390 and 445 grams.

Place the test sample and the abrasive charge in the Los Angeles Abrasion Machine. The machine should rotate at a speed of 30 to 33 rpm for 500 revolutions. After the prescribed number of revolutions, the material shall be discharged from the machine. Separate the aggregates on a 1.7-mm (No. 12) sieve. Carefully weigh the material retained on the 1.7-mm (No. 12) sieve to the nearest whole gram.

Explanation of Computations and Data Collection

1. Computations: Calculate the difference between the original sample weight and that retained on the 1.7-mm (No. 12) sieve. Express that value as a percentage of the original sample weight. This value is considered as the percentage of wear.

2. Data Sheet: There are no special data sheets. Simply follow the instructions in the Test Procedure, for data collection.
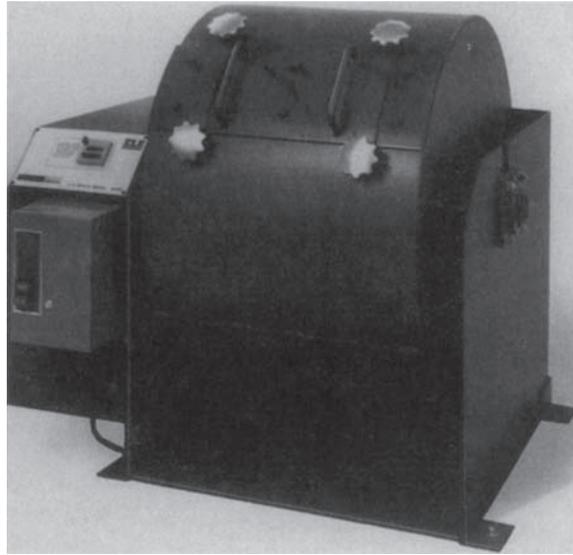
Figure 5
Los Angeles Abrasion Machine. Courtesy of ELE International, Inc., Soiltest Products Division, Lake Bluff, Illinois.

TABLE 15
Abrasive Charge

Grading	Number of Spheres	Weight of Charge in Grams
A	12	5000 ± 25
B	11	4584 ± 25
C	8	3330 ± 20
D	6	2500 ± 15

TABLE 16
Grading of Test Samples

Sieve Sizes from ASTM Designation: E 11		Weight of Indicated Size in Grams Aggregate Grading			
Passing	Retained On	A	B	C	D
37.5 mm (1.5 in.)	25.0 mm (1 in.)	1250 ± 25			
25.0 mm (1 in.)	19.0 mm (¾ in.)	1250 ± 25			
19.0 mm (¾ in.)	12.5 mm (.5 in.)	1250 ± 25	2500 ± 10		
12.5 mm (½ in.)	9.5 mm (⅜ in.)	1250 ± 25	2500 ± 10		
9.5 mm (⅜ in.)	6.3 mm (¼ in.)	2500 ± 10			
6.3 mm (¼ in.)	4.75 mm (#4)	2500 ± 10			
4.75 mm (#4)	2.36 mm (#8)	5000 ± 10			
Total		5000 ± 10	5000 ± 10	5000 ± 10	5000 ± 10

Dry Sieve Analysis of Fine and Coarse Aggregates
(ASTM Designation: C l36)
Material Finer than 75 μm (No. 200 Sieve) by Washing
(ASTM Designation: C 117)

Purpose

Determination of the particle size distribution of fine and coarse aggregates by sieving.

Equipment and Materials

- Balance, sensitive to within 0.1% of the weight of the sample to be tested
- Standard sieves for grading of fine aggregates—4.75 mm, 2.36 mm, 1.18 mm, 600 μm, 300 μm, 150 μm, 75 μm (Nos. 4, 8, 16, 30, 50, 100, and 200)
- Standard sieves for grading coarse aggregates 2 in., 1½ in., l in., ¾ in., ⅜ in., plus a 4.75-mm (No. 4) sieve
- Fine (0.5 kg) and coarse (2 to 20 kg, depending upon maximum size from 9.5 mm to 50 mm [⅜ to 2 in.]) aggregate samples

Test Procedure

1. Samples—use dry aggregates from the specific gravity and absorption tests of coarse and fine aggregates.

2. Continue the sieving until not more than 1% by weight of the residue passes any sieve during 1 minute.

3. For the wet analysis procedure (ASTM C 117), after weighing the dry aggregates, cover with water, agitate, and pour off the wash water containing suspended particles. Repeat until the wash water is clear. Dry the aggregates a second time at 230° ± 9° F (110° ± 5°C) and weigh.

TABLE 16a
Sieve Analysis for Fine and Coarse Aggregate (ASTM Designation: C 136)

Dry Sieve Analysis							
Sample Number				Sample Number			
Sieve Size	Weight Retained (g)	% Retained	% Passing	Sieve Size	Weight Retained (g)	% Retained	% Passing
2 in.				2 in.			
1½ in.				1½ in.			
1 in.				1 in.			
¾ in.				¾ in.			
½ in.				½ in.			
⅜ in.				⅜ in.			
#4				#4			
#8				#8			
#16				#16			
#30				#30			
#50				#50			
#100				#100			
#200				#200			
Pan				Pan			
Total				Total			

Explanation of Computations and Data Sheets

1. Computations: Using Table 16a (Dry Sieve Analysis for Fine and Coarse Aggregates), calculate percentages on the basis of the total weight of the sample. Compute the percent of material retained on each sieve and the percent of material that passes through each sieve size for both the coarse and the fine aggregates. Follow the procedure at the bottom of Table 16b for the determination of all minus No. 200 (pan) mineral aggregates by wet analysis. Plot the results on the gradation chart (Figure 5b), which is a semilog scale and/or on Figure 5c, which shows the sieve sizes raised to the 0.45 power. Both graphs are commonly used to help select the best aggregate blend. On both graphs the ordinate is the total percent by weight passing a given size on an arithmetic scale. *The nominal maximum size aggregate for a concrete mix is the smallest size through which at least 95% of the aggregates will pass.* Plot the midband gradation line on this graph. It is generally considered best when this gradation line is parallel to the maximum density line and a few percentages above or below it.

2. Data Sheets: For dry sieve analysis for fine and coarse aggregate, use the data sheet (Table 16a); for the wet sieve analysis, use the data sheet on page 41, Gradation Charts, pages 42 and 43, and Aggregate Blend Design for Portland cement concrete mixes, page 44.

TABLE 16b
Wash and Dry Sieve Analysis for Fine and Coarse Aggregate (ASTM Designation: C 117)

Wash and Dry Sieve Analysis							
Sample Number				Sample Number			
Sieve Size	Weight Retained (g)	% Retained	% Passing	Sieve Size	Weight Retained (g)	% Retained	% Passing
2 in.				2 in.			
1½ in.				1½ in.			
1 in.				1 in.			
¾ in.				¾ in.			
½ in.				½ in.			
⅜ in.				⅜ in.			
#4				#4			
#8				#8			
#16				#16			
#30				#30			
#50				#50			
#100				#100			
#200				#200			
Pan				Pan			
Total				Total			

a. Wt. of sample (g):	—	a. Wt. of sample (g): —
b. Wt. of sample after washing (g):	—	b. Wt. of sample after washing (g): —
c. Loss in washing, (a − b) (g):	—	c. Loss in washing, (a − b) (g): —
d. Pan from dry sieve (g):	—	d. Pan from dry sieve (g): —
Total—200, (c + d) (g):	—	Total—200, (c + d) (g): —

Figure 5b
Millimeter gradation chart.

United States Bureau of Public Roads 0.45 Power Gradation Chart

Sieve Sizes Raised to 0.45 Power

Percent Passing

Percent Passing

Sieve Sizes
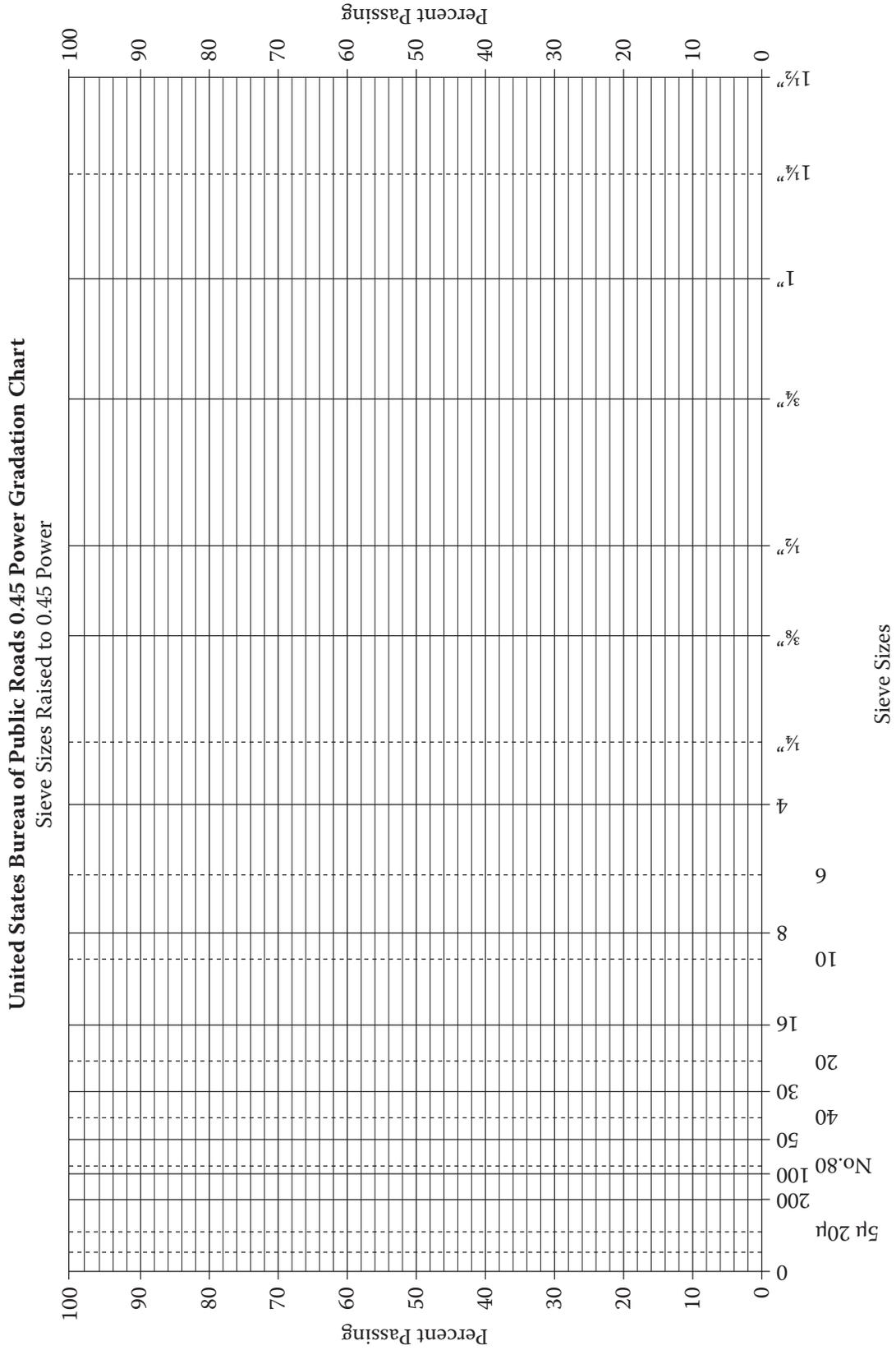
Figure 5c
U.S. Bureau of Public Roads 0.45 power gradation chart.

TABLE 16c
Combined Gradation Form

Material % in Mix									Target Value	Specification Limits
U.S. Sieves	No. 1		No. 2		No. 3		No. 4		Combined Gradation	
	% Passing	% in Batch	% Passing	% in Batch	% Passing	% in Batch	% Passing	% in Batch		
2 in.										
1½ in.										
1 in.										
¾ in.										
½ in.										
⅜ in.										
No. 4										
No. 8										
No. 16										
No. 30										
No. 50										
No. 100										
No. 200										

Note: Aggregate Blend Design Chart for a Portland Cement Concrete Mix.

Clay Lumps and Friable Particles in Aggregates
(ASTM Designation: C 142)

Purpose

Clay and friable particles may be present in the form of lumps in natural aggregates. If they are near the surface, these lumps can cause pitting under the influence of traffic. Specifications frequently limit these particles to a maximum of 1%.

Equipment and Materials

- Weighing device accurate to 0.1%
- Flat pans for spreading the test specimens in a thin layer
- Sieves as called for in the Testing Procedure
- Drying oven capable of maintaining a free circulating air temperature of 110° ± 5°C (230° ± 9°F)
- Test samples as called for

Test Procedure

1. Test samples shall be prepared in accordance with ASTM Designation: C 117, and after oven drying at 110° ± 5°C (230° ± 9°F), shall consist of the following quantities: Fine aggregates shall consist of particles retained on a 1.18-mm (No. 16) sieve and weigh at least 25 grams. Coarse aggregate sizes and minimum quantities per sample are as follows:

Size of Particles Making Up Test Sample	Minimum Weight of Test Sample in Grams
4.75 to 9.5 mm (No. 4 to ⅜-inch sieves)	1000
9.5 to 19.0 mm (⅜- to ¾-inch sieves)	2000
19.0 to 37.5 mm (¾- to 1½-inch sieves)	3000
Retained on 37.5 mm (1½-inch sieve)	5000

where the test sample consists of both fine and coarse aggregates, the material is separated on a 4.75-mm (No. 4) sieve. The fine and coarse fractions are then handled as above.

2. The weighed specimens are spread in a thin layer on the bottom of a container and covered with distilled water for about 24 hours.

3. Roll and squeeze the individual particles between the thumb and forefinger. Try to break down the particles but only with the thumb and forefinger. Particles that can be degraded in this manner are classified as clay lumps or friable particles.

4. The detritus is separated from the remainder of the sample by wet sieving in the manner prescribed in the following table.

Size of Particles Making Up Test Sample	Size of Sieve for Removing Residue Particles
Fine Aggregate	850 μm (No. 20)
4.75 to 9.5 mm (No. 4 to ⅜ inch)	2.36 mm (No. 8)
9.5 to 19.0 mm (⅜ to ¾ inch)	4.75 mm (No. 4)
19.0 to 37.5 mm (¾ to 1½ inches)	4.75 mm (No. 4)
Over 37.5 mm (1½ inches)	4.74 mm (No. 4)

Agitate the sieve during the wet sieving operation to assure removal of all undersized particles.

5. Remove the retained particles and dry to a constant weight in the oven at a temperature of 110° ± 5°C (230° ± 9°F). Allow the aggregates to cool and weigh to nearest 0.1%.

Explanation of Computations and Data Sheet

1. Computation:

$$P = [(W - R)/W] \times 100$$

P = % of clay lumps and friable particles

W = weight of the test sample

R = weight of particles retained on the designated sieve in wet sieving

For coarse aggregates, P shall be based upon the weighted average of the clay lumps and friable particles in each sieve size fraction. Any coarse aggregate fraction that is less than 5% of the total gradation shall not be tested separately. That coarse aggregate fraction shall be assumed to contain the same percent of clay lumps and friable particles as that found in the next larger or smaller coarse aggregate fraction.

2. Data Sheet: There is no prescribed format for data collection for this testing procedure. Simply follow the instructions for recording the data indicated in the Testing Procedure.

Density of Hydraulic Cement
(ASTM Designation: C 188)

Purpose

Determination of the density of a hydraulic cement in connection with the design of Portland cement concrete mixtures.

Equipment and Materials

- Standard Le Chatelier Flask shown in Figure 6
- Heavy rubber pad about 12 in. × 12 in. square
- Lead-ring weight to fit around stem of the flask
- Funnel
- Thermometer
- Portland cement or other mineral filler
- Kerosene

Test Procedure

1. Fill the flask with kerosene to a mark on the stem between the 0- and the 1-cm mark. Dry the inside of the flask if there are any drops above the liquid level.

2. Place the flask in a constant-temperature bath and record the initial height of the kerosene in the flask. The constant-temperature bath should be maintained at a temperature such that its temperature variation between the initial and final readings within the flask do not vary by more than 0.2°C.

3. Carefully introduce about 64 grams of cement, weighed to the nearest 0.1 grams. Try to avoid the cement adhering to the inside of the flask or sticking to the neck. The cement should be introduced slowly through a funnel. Place the stopper on the flask.

4. Remove the flask from the bath and place it on the rubber mat. Take off the lead weight and manipulate the flask on the mat so as to remove all air bubbles from the flask.

5. Return the flask to the bath and check the temperature within the flask. If it is within 0.2°C of the original temperature inside the flask, take the final reading.
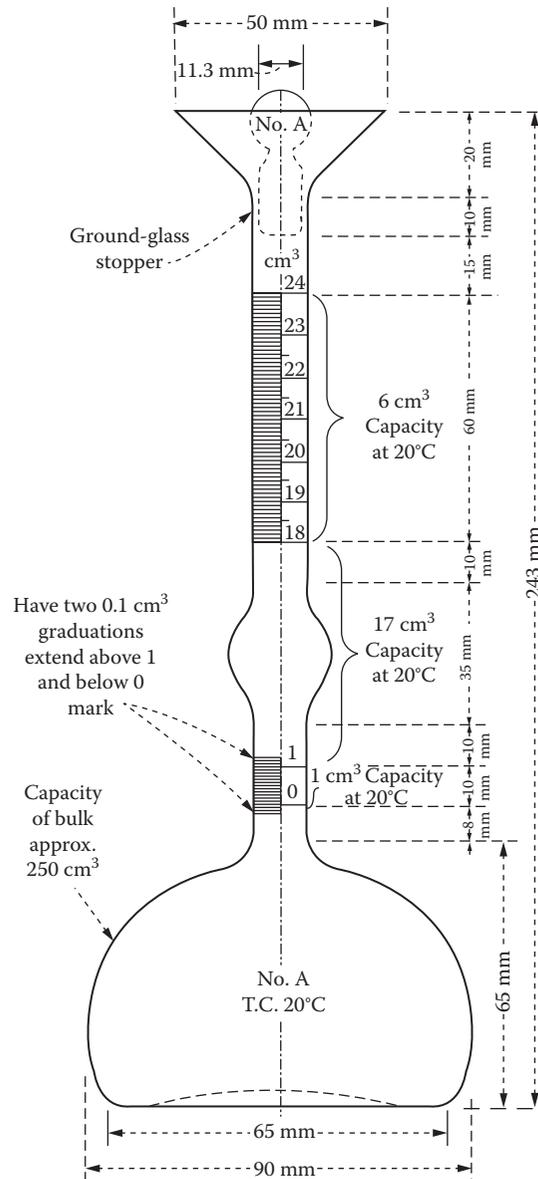
Figure 6
Le Chatelier flask for density determination of mineral filler. Copyright ASTM. Reprinted with permission.

Explanation of Computations and Data Sheet

1. Computations: Density, p = mass of cement/displaced volume

   Conduct the density determination on two samples of cement. If they do not differ by more than 0.03 g/cm, take the average. Otherwise, run three additional determinations until a pair of valves are obtained within 0.03 g/cm^3.

2. Data Sheet: Record the readings and complete the following data sheet.

Data Sheet for Determination of Portland Cement Specific Gravity (ASTM Designation: C 188)

	Specimen Numbers				
	1	2	3	4	5
Initial bath temp., °C					
Final height, cm					
Initial height, cm					
Displaced volume, cm^3					
Final bath temp., °C					
Specific gravity = 64 grams/ displacement, cm^3					

Average specific gravity of accepted specimen results =

Data Sheet for Determination of Portland Cement Specific Gravity (ASTM Designation: C 188)

	Specimen Numbers				
	1	2	3	4	5
Initial bath temp., °C					
Final height, cm					
Initial height, cm					
Displaced volume, cm^3					
Final bath temp., °C					
Specific gravity = 64 grams/ displacement, cm^3					

Average specific gravity of accepted specimen results =

Tensile Strength of Hydraulic Cement Mortars
(ASTM Designation: C 190)

Purpose

Determination of the tensile strength of hydraulic cement mortars using briquet specimens.

Equipment and Materials

- 2-kg scale accurate to 0.1 gram
- Briquet molds as shown in Figure 7
- Small steel trowels
- Clips for holding the test specimens in accordance with Figure 6
- Testing machine capable of applying the load at a rate of 2.67 ± 0.11 (600 ± 25 lb/ft^2)/minute
- Ottawa Sand with at least 85% passing the 850-μm (No. 20) sieve and not more than 5% passing the 600-μm (No. 30) sieve
- Portland cement

Test Procedure

Normal room temperature shall be assumed for the laboratory, curing facility, and the water used. The specimens will be prepared in briquet gang molds in multiples of three.

1. The proportions of the standard mortar shall be 1 part cement (300 grams Types I, IA, II, or III) to 3 parts of Ottawa Sand (900 grams) for 6 specimens or 400 grams of cement and 1200 grams of Ottawa Sand for 9 specimens. The amount of water required shall be determined by reference to the following table after the normal consistency of a neat cement is obtained in accordance with ASTM Designation C 187.

Percent Water Required for Neat Cement Paste of Normal Consistency	Percent Water Required for Standard Mortar, One Part Cement to Three Parts Sand
15	9.0
16	9.2
17	9.3

Percent Water Required for Neat Cement Paste of Normal Consistency	Percent Water Required for Standard Mortar, One Part Cement to Three Parts Sand
18	9.5
19	9.7
20	9.8
21	10.0
22	10.2
23	10.3
24	10.5
25	10.7
26	10.8
27	11.0
28	11.2
29	11.3
30	11.5

2. Weigh and thoroughly mix the dry materials on a smooth nonabsorbent surface and form a crater. Pour the proper amount of clean water into the crater and completely mix for 30 seconds with a steel trowel. Permit the materials to absorb the water for an additional 30 seconds, during which the drier materials on the edges are turned into the mortar mass in order to reduce evaporation and promote absorption. For the next 90 seconds, vigorously mix the mortar with the hands fitted with snug-fitting rubber gloves.

3. Coat the briquets with a thin film of mineral oil and place them on a piece of clean glass or metal.

4. The briquets should now be filled with the mortar. Fill the molds heaping full without compaction. Firmly press the mortar into the molds with the gloved hand, applying the thumb pressure twelve times for each mold. Again, heap additional mortar on each specimen and strike off the excess with a steel trowel. Cover the specimens with a similar piece of glass or metal and turn the assembly over, reversing top and bottom. Repeat the process of heaping, thumping, and troweling the excess mortar as performed on the opposite surface.

5. Place the specimens in a curing room with the upper surface exposed but not subject to dripping water for between 20 to 24 hours. Then strip the specimens from the molds and place in saturated lime water until ready for testing. The lime water should be changed periodically as required to be kept clean.

6. All specimens should be tested within a specified time period.

Test Age	Permissible Time Tolerance
24 hours	± ½ hour
3 days	± 1 hour
7 days	± 3 hours
28 days	± 12 hours

Prior to testing, the specimens should be wiped clean and surface dry. Any loose grains of sand or other extraneous material should be removed from the surfaces in contact with the testing machine. The specimen should be centered in the clips and the pressure applied at the rate of 2.67 ± 0.11 kN (600 ± 25 lb)/minute.

Explanation of Computations and Data Sheet

Computations: Record the breaking load for each specimen and compute the tensile stress in kilopascals or pounds/inch^2 in the following data sheet. The tensile stress of all acceptable specimens, made from the same mortar, should be computed to and averaged to the nearest 34.5 kPa (5 psi) strength.

Data Sheet for ASTM Designation: C 190

Specimen Number	Maximum Load, Newtons or Pounds	Cross Section, cm × cm or inch × inch	Tensile Stress in kPa or psi
1			
2			
3			
4			
5			
6			
7			
8			
9			
Date specimens prepared:			
Date specimens tested:			
Average tensile strength of the mortar:			

Note—1 in. = 25.4 mm

Figure 7
Briquet gang mold and specimen. Copyright ASTM. Reprinted with permission.

Figure 8
Clips for briquet testing machine. Copyright ASTM. Reprinted with permission.

Time of Set of Hydraulic Cement by Vicat Needle
(ASTM Designation: C 191)
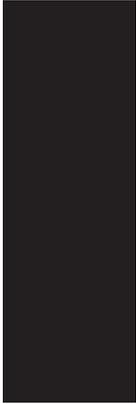
Purpose

Determination, via Vicat needle, of the time required to set hydraulic cement.

Equipment and Materials

- 2-kg scale accurate to 0.1 grams.
- Vicat Apparatus as shown in Figure 9, which consists of a movable rod, B, weighing 500 grams; one end, C, the plunger end, being 10 mm in diameter for a distance of at least 5 cm; and the other end having a movable steel needle, D, 1 mm in diameter and 5 cm in length. The rod, B, is reversible and can be raised or lowered by the set screw, E, which has an adjustable indicator, F. The latter moves over a graduated scale, attached to the frame, A. The cement paste is held in a conical ring, G, which has an inside diameter of 7 cm at the bottom and 6 cm at the top, and has a height of 4 cm. The truncated cone rests on a glass plate, H, which is 10 cm square.
- An electrically driven mixer with a 4.73-liter bowl and a removable stainless steel paddle that conforms to within 0.8 mm to the shape of the bowl.
- For a scraper, use a kitchen tool known as a plate and bowl scraper.
- At least 3 kg of Portland cement and a supply of water.

Test Procedure

There three parts to this procedure:

1. Preparation of the cement paste
2. Determination
3. Time of setting determination

Preparation of the Cement Paste

1. Place an estimated amount of water into the mixing bowl.
2. Add 650 grams of Portland cement and let it sit for 30 seconds.
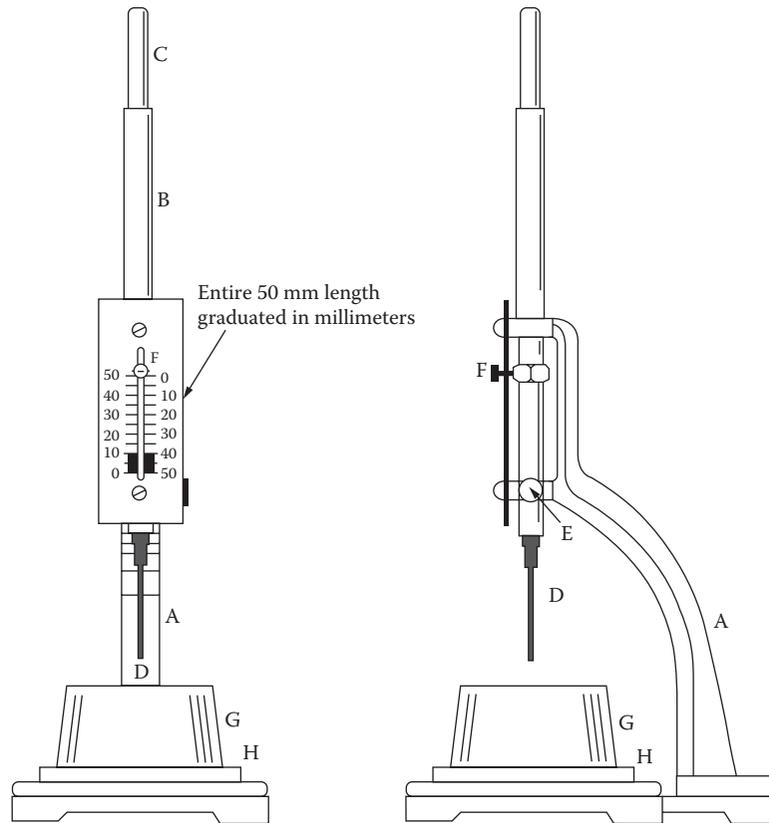
Figure 9
Vicat Apparatus. Copyright ASTM. Reprinted with permission.

3. Mix at a speed of about 140 rpm for 30 seconds, stopping the mixer for 15 seconds to allow for scraping down any paste that may have collected on the sides of the bowl.

4. Perform a final mix at about 285 rpm for 60 seconds.

5. Quickly form the cement paste into a ball with rubber-gloved hands, and then toss the ball six times through the air for about 15 cm.

6. Press the spherically shaped ball into the Vicat ring, G, with the palm of one hand until the paste completely fills the ring, holding the bottom of the ring in the other hand.

7. Remove any excess from the bottom of the ring with the gloved hand.

8. Place the ring and cement paste onto the glass plate, H, and remove the excess paste from the top of the ring with a small steel trowel, creating a reasonably smooth plane at the top.

Consistency Determination

1. Place the rod, C, at the bottom of the Vicat Apparatus with the needle, D, at the top.

2. The plunger end, C, should now be brought into contact with the top of the cement paste in the ring; tighten the set screw, E.

3. Set the movable indicator, F, to the zero mark on the scale and release the rod immediately

4. The paste will be considered to have normal consistency if C settles 10 ± 1 mm into the paste in 30 seconds.

5. Repeat the procedure with fresh cement batches, varying the amount of water until a paste of normal consistency is obtained.

6. The amount of water required to obtain a cement paste of normal consistency should be determined to the nearest gram.

Time of Setting Determination

1. Begin the time of setting determination immediately after the normal consistency specimen in the ring has been undisturbed in a moist cabinet for 30 minutes.

2. Determine the penetration of the 1-mm needle, D, in 30 seconds and every 15 (10 for Type III cement) minutes thereafter, until a penetration of 25 mm or less is obtained. For this test lower the needle, D, until it just touches the cement paste, tighten the set screw, E, and set the movable indicator, F, to the zero mark on the scale and release the rod. Allow the needle to settle for 30 seconds and take the reading to determine the penetration.

3. Record the results of all penetration readings on the table in the following section, "Explanation of Computations and Data Sheet."

4. Determine the time of initial set by interpolating the results to find the time for a penetration of 25 mm.

5. The final setting time is recorded when the needle, D, does not visibly sink into the paste.

Explanation of Computations and Data Sheet

1. Computations: The only computation required in the Test Procedure outlined previously is the interpolation of the time of set unless a test value of exactly 25 mm of penetration of needle, D, is obtained. Normally there will be a prior period value greater than 25 mm and a succeeding one of less than 25 mm, from which the time to the nearest minute will be determined for the time of setting determination. With each succeeding rest period of 10 or 15 minutes, depending upon the type of cement in the test specimen, the depth of penetration will decrease. Follow the steps shown in the following data table.

Data Sheet for ASTM Designation: C 191

Amount of Water Required, to the Nearest Gram, to Prepare a Normal Consistency Specimen of 650 grams of Portland Cement Paste by the Procedure Described in the Consistency Determination in the Test Procedure	
Time Periods	Penetration of Needle, D, mm
30 sec immediately after completion of 30-min cure	
First rest period[a]	
30 sec	
Second rest period[a]	
30 sec	
Third rest period[a]	
30 sec	
Fourth rest period[a]	
30 sec	
Fifth rest period[a]	
30 sec	
Time to reach 25 mm penetration to the nearest minute = _____. This value is obtained by interpolating between the last two test results obtained, one being above and the other below 25 mm.	

[a] The rest periods are 15 minutes for all types of Portland cement except for Type III, high early strength. The rest period for the Type III cement is 10 minutes.

Fineness of Portland Cement by Air Permeability Apparatus
(ASTM Designation: C 204)

Purpose

The procedure covered in this manual includes only that part of ASTM Method C 204 that deals with the fineness determination of Portland cement at normal room temperatures. The Blaine air permeability apparatus is used to express the fineness as a total surface area in square centimeters per gram.

Equipment and Materials

- Blaine air permeability apparatus as detailed in Figure 10
- Medium retentive filter paper having the same diameter as the inside of the cell and corresponding to Type 1, Grade B, as described in Federal Specification for Paper, Filter (UU-P-236)
- Light grade of mineral oil for the manometer
- Timer accurate to 0.5 seconds
- Sample of National Institute of Standards and Technology (NIST) Standard Reference Material No. 114
- Portland cement

Test Procedure

The procedure consists of two distinct methodologies: first to calibrate the apparatus and then to determine the specific surface of the standard sample.

1. Calibration of the apparatus is made by determining the bulk volume of the compacted bed of the NIST Standard Reference Material No. 114 powder.
    - Press down two filter paper disks in the permeability cell on the perforated metal disk with a slightly smaller-diameter rod.
    - Fill the cell with an ACS reagent-grade or better mercury.
    - Use tongs when handling the cell and remove any air bubbles adhering to the sides of the cell.
    - Level the mercury to the top of the cell with a glass plate.
    - Remove the mercury from the cell and weigh it, W_A.
    - Remove the top filter paper from the permeability cell.
    - Compress a trial quantity of 2.80 grams of the Portland cement into the space above the filter paper to the gauge line (height of 15 ± 1.0 mm) in the cell. The cement bed should be firm. If it cannot be compressed to the desired volume, adjust the quantity of cement.
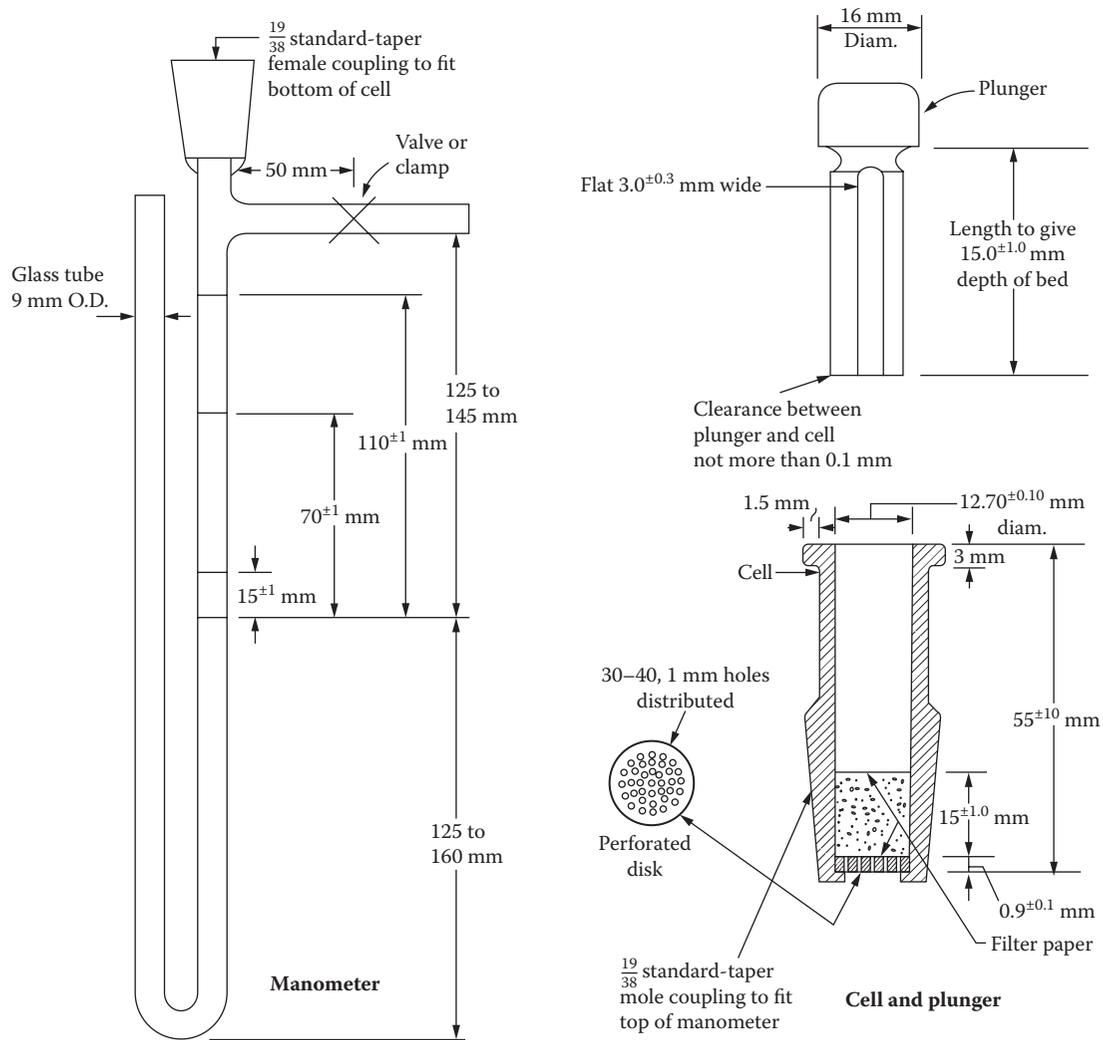
Figure 10
Blaine air permeability apparatus. Copyright ASTM. Reprinted with permission.

- Place the other filter paper above the cement bed, fill the remaining space in the cell above the filter paper with mercury, remove entrapped air in the mercury column, and again use tongs when handling the cell and remove any air bubbles adhering to the sides of the cell.
- Level the mercury to the top of the cell with a glass plate.
- Remove the mercury from the cell and weigh it, W_B.
- Compute the volume occupied by the cement bed in the cell using the following equation:

$$V = (W_A - W_B)/D$$

  D = the density of mercury, which can be assumed at 13.54 g/cm^3 at room temperatures of 18° to 28°C (64° to 82°F).
- Average at least two volume determinations that agree to within ±0.005 cm^3 and record this value.

2. The weight in grams of the NIST Standard Reference Material No. 114 required to produce a bed of cement having a porosity of 0.005 ± 0.005 is computed as follows:

$$W_C = 1.58V$$

3. Prepare a cement bed of the NIST Standard Reference Material No. 114 of weight W_C to the nearest 0.001 grams; tap the sides of the cell to level the cement, using filter papers top and bottom as previously; compress the cement with the plunger until the plunger collar is in contact with the top of the cell; slowly withdraw the plunger a short distance, rotate 90^0, repress the cement bed, and then slowly withdraw; attach the permeability cell to the manometer tube with an airtight connection; slowly evacuate the air in the manometer U-tube until the liquid reaches the top mark, then tightly close the valve; start the timer when the bottom of the meniscus reaches next to the top mark and stop the timer when the bottom of the meniscus reaches the bottom mark; note and record the time interval; repeat this procedure three times; the same cement bed may be used by refluffing the cement between each determination; the average of these determinations is designated as T_S. All of the tests in this procedure should be conducted at approximately the same room temperature. All of the cements tested should be at room temperature.

4. Repeat step 3 above, but this time use the Portland cement whose fineness is to be found, using the same weight, W_C, with the following exceptions: only one time-of-flow determination needs to be made, and for W_C for a Type III or other very fine ground Portland cement use a $W_C = 1.48V$. The resulting time is designated as T.

Explanation of Computations and Data Sheet

Computations: The specific surface of the Portland cement specimen, S, in cm^2/g is obtained using the following equation:

$$S = S_S(T)^{1/2}/(T_S)^{1/2}$$

Data Sheet for ASTM Designation: C 204

Weight in grams: $W_A =$; $W_B =$; $W_C =$
Determination of V in cm^3: $V_1 =$; $V_2 =$; $V_3 =$
Accepted value for V after at least 2 determinations =
Permeability tests to determine T_S in seconds:
Accepted value, T_S, after at least 3 determinations =
Penetration test to determine T in seconds =
$S = S_S(T)^{1/2}/(T_S)^{1/2} =$
S_S is obtained from the data on the vial containing the standard cement sample (NIST Standard Reference Material No. 114).

Sand Equivalent Value of Soils and Fine Aggregates
(ASTM Designation: D 2419)

Purpose

To determine the percent of undesirable particles in the fine aggregate fraction used in the design of Portland cement concrete mixtures. The method is also applicable for determining the relative proportions of detrimental fine dust or claylike material in soils.

Equipment and Materials

The Sand Equivalent test kit consists of the following:

- Graduated plastic cylinder
- Rubber stopper
- Irrigation tube
- Weighted foot assembly and a siphon assembly
- 3.78-liter (1 gallon) bottle
- Four measuring tins having a diameter of approximately 57 mm (2¼ inches) and a capacity of 85 ± 5 ml
- Funnel
- Stop watch
- Mechanical sand equivalent shaker
- Stock calcium chloride solution
- 4.75-mm (No. 4) sieve
- Fine aggregate

Test Procedure

1. Prepare fine aggregate passing a 4.75-mm (U.S. standard No. 4) sieve, oven dried and room temperature condition, before testing. Quarter by splitting approximately 1500 grams. Moisten each specimen slightly to prevent loss of fines, and mix each specimen thoroughly. Place each of the four specimens in a closed can.

2. Siphon 101.6 ± 2.54 mm (4 ± 0.1 inches) of working calcium chloride solution into the plastic cylinder. Pour one of the prepared specimens into the plastic cylinder using the funnel to avoid spillage. Tap the bottom of the cylinder sharply by hand to release any air bubbles. Allow the material to stand for about 10 minutes.

3. Place the stopper on the cylinder and vigorously shake it manually to loosen the material. Place the cylinder in the mechanical sand equivalent shaker, set the timer, and allow the machine to run for 45 seconds. Remove the cylinder from the mechanical shaker, remove the stopper, and set it upright on the table.

4. Insert the irrigator tube into the cylinder and rinse material from the inside surface as it is lowered. Force the irrigator through the material to the bottom of the cylinder by applying a gentle stabbing and twisting action, while the working solution flows from the irrigator tip. This action flushes the fine particles into the suspension above the coarser sand sizes. Continue this irrigation process until the cylinder is filled to the 381-mm (15-inch) mark.

5. Raise the irrigator slowly without shutting off the flow so that the liquid level is maintained at about 381 mm (15 inches) while the irrigator is being withdrawn. Regulate the flow just before the irrigation is entirely withdrawn and adjust the final level to 381 mm (15 inches).

6. The flow is supplied through the siphon assembly to a 3.78-liter (1-gallon) bottle of working calcium chloride solution placed on a shelf about 1 meter (3 feet ± 1 inch) above the work surface. Allow the cylinder to now stand undisturbed for 20 minutes. Start the timing immediately after withdrawing the irrigator tube. At the end of the 20-minute sedimentation, read and record the top of the clay suspension. This is referred to as the *clay reading*. If no clear line of demarcation has formed at the end of the 20-minute period, allow the cylinder to stand undisturbed until a clay reading can be obtained. Immediately read and record the level of the top of the clay suspension and the total suspension time. If the total sedimentation time exceeds 30 minutes, rerun the test on the other prepared samples of the same material. Read and record the clay column height of the specimen requiring the shortest sedimentation period only.

7. After the clay reading has been taken, place the weighted foot assembly into the cylinder and lower it gently until it comes to rest on the top of the sand. Be careful not to hit the mouth of the cylinder with the weighted foot assembly. Tip the assembly toward the graduations on the cylinder until the indicator touches the inside wall of the cylinder. Subtract 25.4 cm (10 in.) from the level indicated by the extreme top edge of the indicator and record this as the *sand reading*. Do not apply pressure to the assembly at any time.
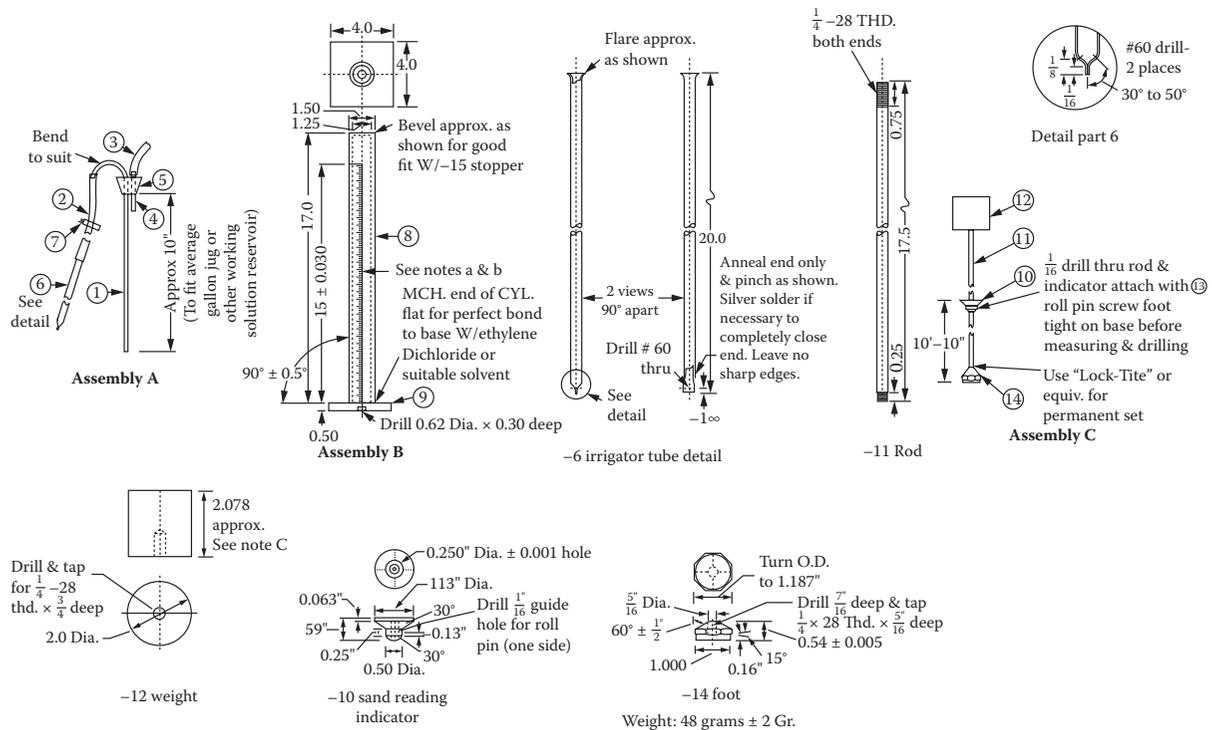
Figure 11
Sand equivalent test apparatus. Copyright ASTM. Reprinted with permission.

Explanation of Computations and Data Sheet

1. Computations: Report the result as a percent, always carrying the sand equivalent (SE) up to the next higher whole number (do not use any decimals). If more than one SE test is made, take the average of each whole number value for each test specimen to the next higher whole number. Use 2.5 mm (0.1 in.) as the smallest unit for the readings and always use the higher graduation if the readings fall between one-tenth inch marks. Calculate the sand equivalent to the nearest 0.1% using the following formula:

$$SE = \frac{\text{Sand Reading}}{\text{Clay Reading}} \times 100\%$$

Cleaner aggregates will have a higher SE value. Specifications generally call for a minimum SE on the order of 25 to 35%.

2. Data Sheet: It was not deemed necessary to develop a special data sheet for this test. Simply follow the instructions in the Test Procedure.
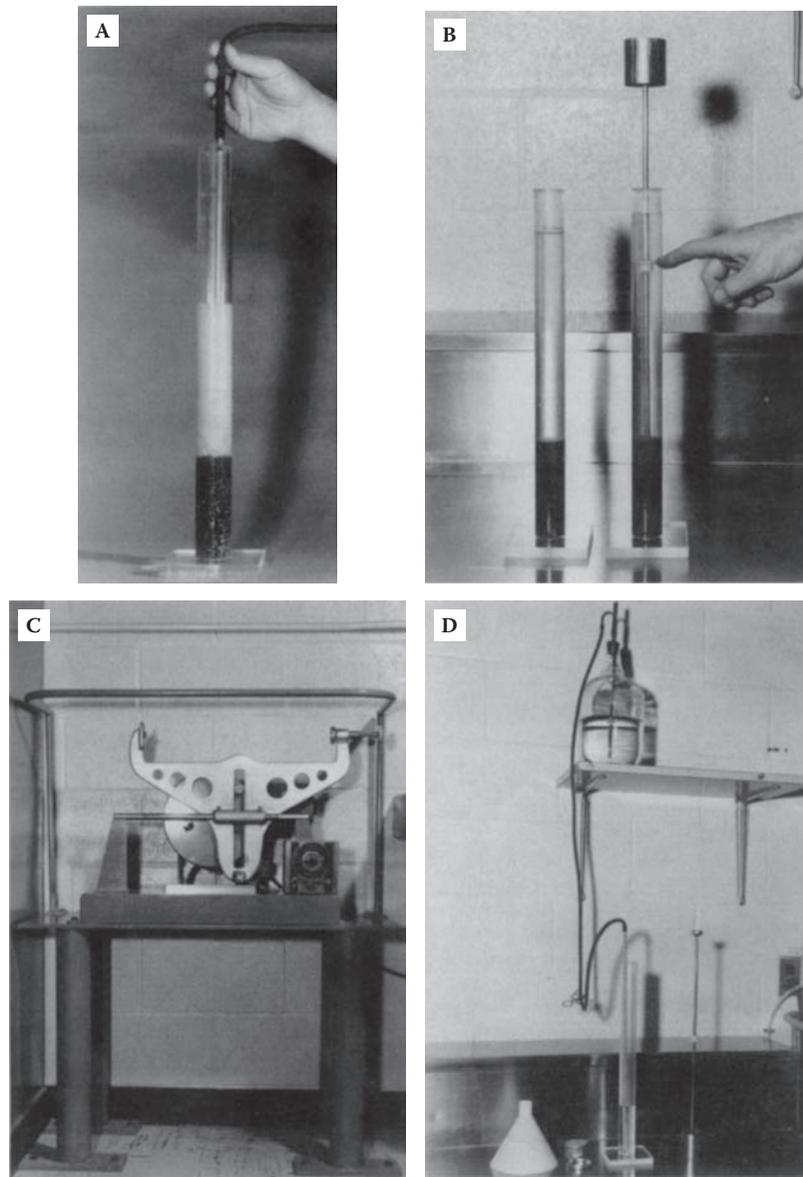
Figure 12
Sand equivalent test apparatus and procedures. Copyright ASTM. Reprinted with permission.

Index of Aggregate Particle Shape and Texture
(ASTM Designation: D 3398)

Purpose

This method covers the determination of the particle index of aggregate as an overall measure of particle shape and texture. The procedure, as described below, applies to aggregates with a maximum size of 19.0 mm (¾ in.). For larger particle sizes, bigger molds of approximately the same diameter to height ratios should be used. There should also be a proportional increase in the number of rodding strokes used so that the compaction energy per volume of material is approximately constant. For testing of fine aggregate, that is, material passing the 4.75-mm (No. 4) sieve, a smaller mold of proportional dimensions and rodding stokes per layer may be used.

Equipment and Materials

- Cylindrical mold, made of a sufficient steel thickness to withstand rough usage, with an inside diameter of 152 ± 0.13 mm (6.000 ± 0.005 inches) and an inside height of 177.80 ± .013 mm (7.000 ± 0.005 inches) as shown in Figure 13.
- Steel tamping rod of 16 mm (⅝ in.) in diameter and approximately 610 mm (24 in.) in length. The tamping end should be rounded to a hemispherical tip.
- Scale of at least 15 kg capacity, accurate to within 4 grams.

Test Procedure

1. Carefully determine the volume of the cylindrical mold by filling with water and weighing.

2. Obtain a quantity of aggregate sample such that at least 6 kg (13 lb) of each size as shown in the following table is available for testing. Aggregate sizes that are less than 10% of the total gradation need not be tested.

Passing	Retained
19.0 mm (¾ inch)	12.5 mm (½ inch)
12.5 mm (½ inch)	9.5 mm (⅜ inch)
9.5 mm (⅜ inch)	4.75 mm (No. 4)
4.75 mm (No. 4)	2.36 mm (No. 8)
2.36 mm (No. 8)	1.18 mm (No. 16)
1.18 mm (No. 16)	600 μm (No. 30)
600 μm (No. 30)	300 μm (No. 50)
300 μm (No. 50)	150 μm (No. 100)
150 μm (No. 100)	75 μm (No. 200)
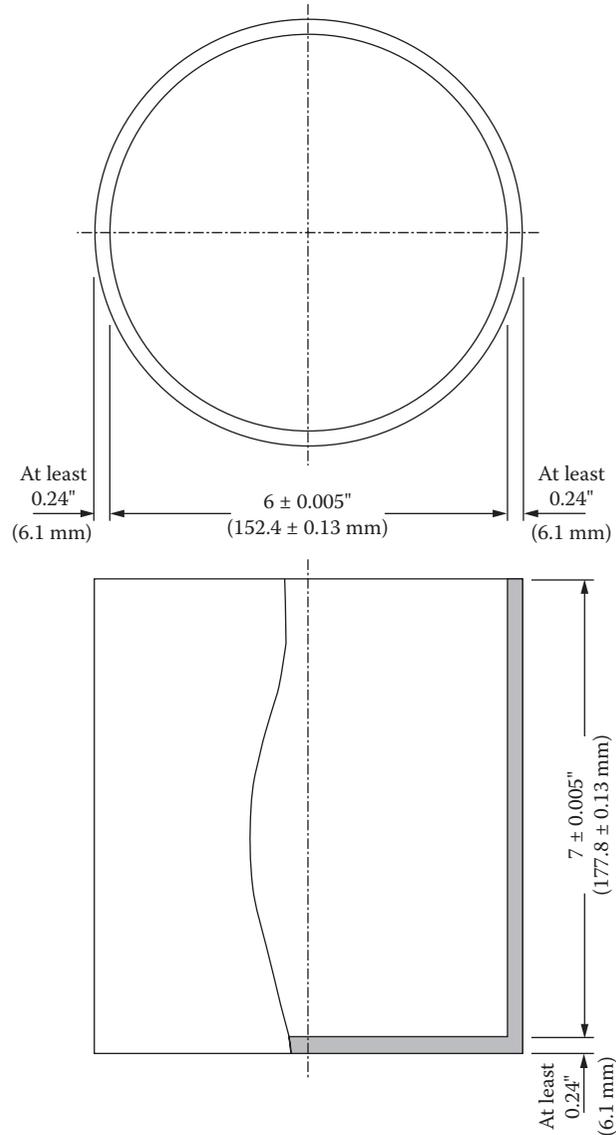
Figure 13
Cylindrical mold. Copyright ASTM. Reprinted with permission.

3. Determine the bulk specific gravity of each aggregate size to be tested in accordance with ASTM Methods C 127 and C 128. The determination of the saturated surface dry condition in ASTM C 128 is established by the use of hard-finished paper towels. This is a departure from the procedure in C 128 for fine aggregates.

4. Using oven-dry materials, determine the percent of voids for each aggregate size to be tested at two compaction levels. First, conduct two tests for each size, three layers, at 10 tamps per layer. Then rerun the test, using the same aggregates at 50 tamps per layer. The method of filling the mold and tamping is as follows:

   a. Fill the molds in three equal lifts, leveling each lift with the fingers.

   b. Compact each layer with the required number of tamps by holding the tamp about 50 mm (2 inches) above the surface of the aggregate, and releasing the tamp so that it falls freely with the rounded end of the tamp penetrating the aggregate layer. Repeat for each layer. After the final lift has been properly tamped, add individual pieces of aggregate so that the top surface is as even as possible with no projections above the rim of the mold.

5. Use the average weight of two compaction tests for each aggregate size for both compaction efforts. The two results should agree within approximately 0.5%. Otherwise rerun the tests.

Explanation of Computations and Data Collection

1. Computations: Calculate the percent of voids for each aggregate size as follows:

$$V_{10} = [1 - (W_{10}/sv)] \times 100$$

$$V_{50} = [1 - (W_{50}/sv)] \times 100$$

V_{10} = voids in aggregate compacted at 10 tamps per layer, %.

V_{50} = voids in aggregate compacted at 50 tamps per layer, %.

W_{10} = average net weight of aggregates in mold compacted at 10 tamps per layer.

W_{50} = average net weight of aggregates in mold compacted at 50 tamps per layer.

s = bulk specific gravity of the aggregate size fraction.

v = volume of the cylindrical mold, ml.

The particle index (I_o) is computed as follows:

$$I_o = 1.25V_{10} - 0.25V_{50} - 32.0$$

Calculate the weighted particle index for the mix of particle sizes tested based upon the percent of each size in the aggregate sample in accordance with the following equation:

$$\text{Weighted } I_o = \frac{I_1 \times T + I_2 \times \% + I_3 \times \% + \text{etc.}}{100\%}$$

2. Data Collection Form: The data collection form is shown at the end of this chapter. For those aggregate sizes that represent less than 10% of the total aggregate sample, use the average particle index of the next size higher and the next size lower, which were determined. This is shown in the following illustrative example.

Illustrative Example (ASTM Designation: D 3398)

Sieve Size		Aggregate Grading %	Particle Index of Each Size Group	Weighted Average of Aggregate Grading × Particle Index ÷ 100
Passing	Retained			
19.0 mm	12.5 mm	3	17.2[a]	0.5
12.5 mm	9.5 mm	42	17.2[b]	7.2
9.5 mm	4.75 mm	36	15.8[b]	5.7
4.75 mm	2.36 mm	7	15.2[c]	1.1
2.36 mm	1.18 mm	10	14.6[b]	1.5
1.18 mm	600 µm	2	14.6[a]	0.3
Totals		100		16.3

[a] Use particle index for the adjacent size since less than 10%.

[b] Particle index measured for these sizes since ≥10%

[c] Use average particle index for the 2.36-mm to 4.75-mm size of the particle indices above and below since less than 10%.

Data Sheet (ASTM Designation: D 3398)

Sieve Size		Aggregate Grading %	Particle Index of Each Size Group	Weighted Average of Aggregate Grading × Particle Index÷100
Passing	Retained			

Flat or Elongated Particles in Coarse Aggregate
(ASTM Designation: D 4791)

Purpose

Determination of the percentages of flat or elongated particles in coarse aggregates.

Equipment and Materials

- Proportional caliper device as shown in Figure 14
- Scales accurate to 0.5% of the mass to be weighed
- Suitable coarse aggregate sample splitters

Test Procedure

1. Samples: The size of the coarse samples should be in accordance with the following table:

Maximum Nominal Aggregate Size, mm (in.)	Approximate Minimum Mass of Samples from ASTM Designation: D 75 kg (lb/f)
9.5 (⅜)	10 (25)
12.5 (½)	15 (35)
19.0 (¾)	25 (55)
25.0 (1)	50 (110)
38.1 (1½)	75 (165)
50 (2)	100 (220)
63 (2½)	125 (275)
75 (3)	150 (330)
90 (3½)	175 (385)

Place the thoroughly mixed samples in appropriate size splitters (the individual chutes shall have a minimum individual width approximately 50% greater than the largest size of aggregate). Reintroduce the split sample into the splitter as many times as necessary to reduce the sample size either to that specified or until approximately 100 particles are obtained.

2. Sieve the sample in accordance with ASTM Designation: C 136.

(a) Test for elongation

(b) Test for flatness

Figure 14
Use of the proportional calipers in testing for particle shape.

3. Test the particles in each size fraction that is present in the amount of 10% or more into one of three categories: flat, elongated, or rhombic. When a particular sieve size represents less than 10% of the sample, use the same percentage of flat and/or elongated particles as the next smaller or the next larger size, or the average of the next smaller and next larger sizes, if both are present.

4. Use the proportional caliper device as shown in Figure 15 for determining the percentage of flat or elongated particles present in each significant size (representing >10% of the sample). Dimension ratios of less than 1:2 are considered rhombic, 1:2 is defined as slightly flat or elongated and is not considered in the evaluation, 1:3 is flat or elongated, and 1:5 or greater is defined as being very flat and elongated.

5. Method of testing for flat or elongated: The sketches in Figure 15 indicate the way the proportional caliper device is used to determine the elongation or flatness of a particle. To test for elongation, set the larger opening equal to the length of the particle. The particle is elongated if the width can be placed within the smaller opening. To test for flatness, a similar procedure is followed except that the particle width is used instead of the length. Consider the elongation or flatness ratio in identifying how the particle is to be rated. Therefore, a particle may be rated for both elongation and flatness. For example, if the measure of its elongation is 1:2, or rhombic, and the flatness ratio is 1:3, the overall shape of the particle should be considered in both categories in the table. Only particles with a ratio of 1:3 or greater will be considered elongated and/or flat, unless specifications require otherwise.

Explanation of Computations and Data Sheet

1. Computations: The weighted average of the combined elongated and flat particles is generally based upon dimension ratios of equal or greater than 3:1. In the illustrative example taken from the data sheet on page 71, the computation would be as follows:

$$\text{Weighted average percent of elongated and flat coarse particles} = \frac{(25.0+5.0)0.05+(25.0+5.0)0.10+(10.0+3.4)0.15+(20.0+6.7)0.15}{1.00}$$

$$= \frac{(15.4+0)0.13+(9.7+9.7)0.18+(9.5+11.9)0.11+(9.5+11.9)0.09}{1.00}$$

$$= 23.86\%$$

Report to the nearest percent = 24% elongated and flat particles for the sample in the illustrative example later in this chapter.

Figure 15
Details of the proportional caliper (drawings are not to scale).

Specifications may require a different criteria for evaluating elongated and flat particle shape. What is recommended here is to combine the ratios ≥ 3:1. However, other data is readily available from the illustrative example shown on the data sheet on the next page.

2. Data Sheet: An illustrative data sheet is provided at the end of this section. The data collection shown follows the procedures outlined in the Test Procedure. Take particular notice of the notes that are directly beneath the data sheet. For example, the shapes of particle sizes of 100 and 12.5 mm were not determined separately but taken from the average of the adjacent particle sizes. However, since the 100-mm size was the largest particle examined and the 12.5-mm size the smallest, only the percentages of the adjacent particle sizes could be considered.

Illustrative Example (ASTM Designation: D 4791)

| Sieve Sizes | | Sample Wt. Gm – % of Total | Rhombic | | Slightly Flat or Elongated, 1:2 | | Flat or Elongated, 1:3 | | Very Flat or Elongated, 1:5 | |
Pass mm (in.)	Retain mm (in.)		Wt. Gm	% Total	Wt. Gm	% Total	Wt. Gm	% Total	Wt. Gm	% Total
100 (4)[a]	90 (3½)	500–5.0		40.0		30.0		25.0		5.0
90 (3½)	75 (3)	1000–10	400	40.0	300	30.0	250	25.0	50	5.0
75 (3)	63 (2½)	1500–15	800	53.3	500	33.3	150	10.0	50	3.4
63 (2½)	50 (2)	1500–15	600	40.0	500	33.3	300	20.0	100	6.7
50 (2)	38 (1½)	1300–13	700	53.8	400	30.8	200	15.4	0	—
38 (1½)	25 (1)	1800–18	1000	55.6	450	25.0	175	9.7	175	9.7
25 (1)	12.5 (½)	1100–11	473	43.0	391	35.6	105	9.5	131	11.9
12.5 (½)[a]	9.5 (⅜)	900–9.0		43.0		35.6		9.5		11.9
9.5 (⅜)	Pan	400–4.0		—		—		—		—
Total		10,000								

[a] Since the percentage of these sizes is less than 10% of the total mass of the aggregate sample, the percentage of the various shape ratios are taken from the adjacent aggregate sizes. The percent of elongated and flat particles are computed to the nearest 0.1% for each size greater than 9.5 mm (⅜ in.), based upon the combined weight for each dimension ratio. Percent elongated and flat particles = 24%. See the previous section titled "Explanations of Computations and Data Sheet."

Data Sheet (ASTM Designation: D 4791)

Sieve Sizes		Sample		Rhombic		Slightly Flat or Elongated, 1:2		Flat or Elongated, 1:3		Very Flat or Elongated, 1:5	
Pass mm (in.)	Retain mm (in.)	Wt. Gm	% Total	Wt. Gm	% Total	Wt. Gm	% Total	Wt. Gm	% Total	Wt. Gm	% Total

Standard Specifications for Wire Cloth and Sieves for Testing Purposes
(ASTM Designation: E 11)

Purpose

ASTM Designation: E 11 covers the requirements for the design and construction of various types of testing sieves. However, the only purpose in introducing E 11 in this handbook is to present the specifications that govern the openings in testing sieves, used for aggregate size classification. These are covered in Table 17. If the details of the design and construction of these sieves are required, the reader is directed to ASTM Designation: E 11 in the applicable ASTM publication. The table covers all standard sieve sizes used by the U.S. Standard System of Measurements and their approximate equivalent SI dimensions (soft conversion). Please take notice of the six notes, A through F, directly under Table 17.

TABLE 17
Nominal Dimensions and Permissible Variations for Wire Cloth of Standard Test Sieves (U.S.) Standard Series

Sieve Designation		Nominal Sieve Opening, in.[b]	Permissible Variation of Average Opening from the Standard Sieve Designation	Opening Dimension Exceeded by Not More than 5% of the Openings	Maximum Individual Openings	Nominal Wire Diameter, mm[c]
Standard[a]	Alternative					
(1)	(2)	(3)	(4)	(5)	(6)	(7)
125 mm	5 in.	5	±3.70 mm	130.0 mm	130.9 mm	8.00
106 mm	4.24 in.	4.24	±3.20 mm	110.2 mm	111.1 mm	6.30
100 mm[d]	4 in.[d]	4	±3.00 mm	104.0 mm	104.8 mm	6.30
90 mm	3½ in.	3.5	±2.70 mm	93.6 mm	94.4 mm	6.30
75 mm	3 in.	3	±2.20 mm	78.1 mm	78.7 mm	6.30
63 mm	2½ in.	2.5	±1.90 mm	65.6 mm	66.2 mm	5.60
53 mm	2.12 in.	2.12	±1.60 mm	55.2 mm	55.7 mm	5.00
50 mm[d]	2 in.[d]	2	±1.50 mm	52.1 mm	52.6 mm	5.00
45 mm	1¾ in.	1.75	±1.40 mm	46.9 mm	47.4 mm	4.50
37.5 mm	1½ in.	1.5	±1.10 mm	39.1 mm	39.5 mm	4.50
31.5 mm	1¼ in.	1.25	±1.00 mm	32.9 mm	33.2 mm	4.00
26.5 mm	1.06 in.	1.06	±.800 mm	27.7 mm	28.0 mm	3.55
25.0 mm[d]	1.00 in.[d]	1	±.800 mm	26.1 mm	26.4 mm	3.55
22.4 mm	⅞ in.	0.875	±.700 mm	23.4 mm	23.7 mm	3.55
19.0 mm	¾ in.	0.750	±.600 mm	19.9 mm	20.1 mm	3.15
16.0 mm	⅝ in.	0.625	±.500 mm	16.7 mm	17.0 mm	3.15
13.2 mm	0.530 in.	0.530	±.410 mm	13.83 mm	14.05 mm	2.80
12.5 mm[d]	½ in.[d]	0.500	±.390 mm	13.10 mm	13.31 mm	2.50
11.2 mm	⁷⁄₁₆ in.	0.438	±.350 mm	11.75 mm	11.94 mm	2.50
9.5 mm	⅜ in.	0.375	±.300 mm	9.97 mm	10.16 mm	2.24
8.0 mm	⁵⁄₁₆ in.	0.312	±250 mm	8.41 mm	8.58 mm	2.00
6.7 mm	0.265 in.	0.265	±.210 mm	7.05 mm	7.20 mm	1.80
6.3 mm[d]	¼ in.[d]	0.250	±.200 mm	6.64 mm	6.78 mm	1.80
5.6 mm	No. 3½[e]	0.223	±.180 mm	5.90 mm	6.04 mm	1.60
4.75 mm	No. 4	0.187	±.150 mm	5.02 mm	5.14 mm	1.60
4.00 mm	No. 5	0.157	±.130 mm	4.23 mm	4.35 mm	1.40
3.35 mm	No. 6	0.132	±.110 mm	3.55 mm	3.66 mm	1.25
2.80 mm	No. 7	0.110	±.095 mm	2.975 mm	3.070 mm	1.12
2.36 mm	No. 8	0.0937	±0.80 mm	2.515 mm	2.600 mm	1.00
2.00 mm	No. 10	0.0787	±0.70 mm	2.135 mm	2.215 mm	0.900
1.7 mm	No. 12	0.0661	±0.60 mm	1.820 mm	1.890 mm	0.800
1.4 mm	No. 14	0.0555	±0.50 mm	1.505 mm	1.565 mm	0.710
1.18 mm	No. 16	0.0469	±0.45 mm	1.270 mm	1.330 mm	0.630
1.00 mm	No. 18	0.0394	±0.40 mm	1.080 mm	1.135 mm	0.560
850 μm[f]	No. 20	0.0331	±35 μm	925 μm	970 μm	0.500
710 μm	No. 25	0.0278	±30 μm	775 μm	815 μm	0.450
600 μm	No. 30	0.0234	±25 μm	660 μm	695 μm	0.400
500 μm	No. 35	0.0197	±20 μm	550 μm	585 μm	0.315
425 μm	No. 40	0.0165	±19 μm	471 μm	502 μm	0.280
355 μm	No. 45	0.0139	±16 μm	396 μm	426 μm	0.224
300 μm	No. 50	0.0117	±14 μm	337 μm	363 μm	0.200
250 μm	No. 60	0.0098	±12 μm	283 μm	306 μm	0.160

TABLE 17 (continued)
Nominal Dimensions and Permissible Variations for Wire Cloth of Standard Test Sieves (U.S.) Standard Series

| Sieve Designation | | Nominal Sieve Opening, in.[b] | Permissible Variation of Average Opening from the Standard Sieve Designation | Opening Dimension Exceeded by Not More than 5% of the Openings | Maximum Individual Openings | Nominal Wire Diameter, mm[c] |
Standard[a] (1)	Alternative (2)	(3)	(4)	(5)	(6)	(7)
212 μm	No. 70	0.0083	±10 μm	242 μm	263 μm	0.140
180 μm	No. 80	0.0070	±9 μm	207 μm	227 μm	0.125
150 μm	No. 100	0.0059	±8 μm	174 μm	192 μm	0.100
125 μm	No. 120	0.0049	±7 μm	147 μm	163 μm	0.090
106 μm	No. 140	0.0041	±6 μm	126 μm	141 μm	0.071
90 μm	No. 170	0.0035	±5 μm	108 μm	122 μm	0.063
75 μm	No. 200	0.0029	±5 μm	91 μm	103 μm	0.050
63 μm	No. 230	0.0025	±4 μm	77 μm	89 μm	0.045
53 μm	No. 270	0.0021	±4 μm	66 μm	76 μm	0.036
45 μm	No. 325	0.0017	±3 μm	57 μm	66 μm	0.032
38 μm	No. 400	0.0015	±3 μm	48 μm	57 μm	0.030
32 μm	No. 450	0.0012	±3 μm	42 μm	50 μm	0.028
25 μm[d]	No. 500	0.0010	±3 μm	34 μm	41 μm	0.025
20 μm[d]	No. 635	0.0008	±3 μm	29 μm	35 μm	0.020

[a] These standard designations correspond to the values for test sieve openings recommended by the International Standards Organization, Geneva, Switzerland, except where noted.

[b] Only approximately equivalent to the metric values in Column 1.

[c] The average diameter of the wires in the x and y direction, measured separately, of any wire cloth shall not deviate from the nominal values by more than ± 15%.

[d] These sieves are not in the standard series but they have been included because they are in common usage.

[e] These numbers (3½ to 635) are the approximate number of openings per linear inch, but it is preferred that the sieve be identified by the standard designation in millimeters or micrometers.

[f] 1000 μm–1mm.

Tests for Portland Cement Concrete

Compressive Strength of Cylindrical Concrete Specimens
(ASTM Designation: C 39)

Purpose

Determination of the compressive strength of cylindrical specimens; either molded or drilled cores. The method is limited to concrete having a density of at least 800 kg/m^3 (50 lb/ft^3). The 28-day compressive strength (f$'_c$) of molded cylinders is normally used in design.

Equipment and Materials

- Reusable steel or wax-coated cardboard disposable cylindrical molds, 15 cm (6 inches) diameter by 30 cm (12 inches) in height or 10 cm (4 inches) diameter by 20 cm (8 inches) in height
- Moist storage facility for curing the fresh concrete specimens
- Straight steel tamping rod 16 mm (⅝ inch) diameter and about 60 cm (24 inches) in length with one end rounded in a hemispherical tip
- Rubber mallet weighing about 0.6 kg (1.3 lb)
- A set of special steel caps of appropriate diameter with a neoprene pad contact with the concrete for capping the specimen
- Testing machine capable of applying load continuously at the rate of 0.14 to 0.34 MPa/s (20 to 50 psi/s) with a maximum load capacity of at least 150,000 kg (400,000 lb)

Test Procedure

Preparation of Cylindrical Specimens

1. Prepare and cure the specimens in accordance with ASTM Designation: C 192.
2. Perform air content, slump, and/or penetration tests on the fresh concrete, prior to casting the specimens in accordance with ASTM Designations: C 143, C 231, and C 360.
3. Fill the cylinders with three lifts of freshly mixed concrete, tamping each lift 25 times with the tamping rod. Also tap each lift lightly with a mallet 10 to 15 times.
4. Strike off the excess concrete with the tamping rod and finish to a smooth surface with a steel trowel.
5. It is recommended that specimens be prepared and tested in groups of three.

Curing of the Concrete Specimens

1. Allow the specimens to set for about 24 hours at normal room temperature, with the top surface covered to prevent loss of moisture.
2. Strip the mold from the specimens and place in the curing facility until ready for testing.

Compression Testing Procedure

1. Remove the specimen from the curing facility just prior to testing. Specimens shall be tested while still in a moist condition.
2. Measure the diameter of the specimen, determined at right angles to each other about mid-height of the specimen. Average the two values to the nearest 0.25 mm (0.01 inches).
3. Center the capped specimens in the testing machine and load at the prescribed rate of 0.14 to 0.34 PMa/min (20 to 50 psi/min). Another way to look at the loading rate in the U.S. System of measurements is 5000 lb/min until approximately ½ the estimated ultimate load, and then continue loading at 1000 lb/min until failure.
4. Load to failure.
5. Record the ultimate load, the angle of fracture, and any other pertinent aspects of failure such as voids.

Explanation of Computations and Data Sheet

1. Computations: Determine the compressive strength of each specimen by dividing the maximum load to failure by the average cross-sectional area as explained in the Compression Testing Procedure, item 2. The compressive strength of the mix should be based upon the average of the test results of the three specimens. The usual practice in industry is to prepare and test only two specimens. Based on the author's experience, three specimens are recommended in a learning laboratory. If any one of the three specimens is badly honeycombed or obviously deficient in some other aspect, it may be discarded and not included in the test result for that mix. The results of any one specimen whose value differs from the average of the other two by more than 10% should be carefully examined. They may indicate testing, handling, or mixing problems. The value of any set should be carried to the nearest to the nearest 100 kPa (10 psi) for the average of all specimen results used. The standard recognized cylinder size is 15 cm (6 inches) in diameter by 30 cm (12 inches) in height. However, an accepted alternative size is 10 cm (4 inches) in diameter by 20 cm (8 inches) in height. The smaller cylinders are becoming increasingly popular because they require less material, are easier to handle, and less storage space is needed. However, the latter tend to break at slightly higher strengths. Therefore, the values determined should be multiplied by 0.95 in order to better correlate with the standard of 15-cm or (6-inch) diameter specimens.
2. Data Sheet: A sample data sheet with computations is provided at the end of this chapter. A careful smooth full-page curve should be drawn through the average values for the strengths at 7, 14, 21, and 28 days, and the strength values for those time intervals should be obtained from the graph. The strength in Mpa or psi should be the ordinate of the graph and the time in days of curing from mixing to testing, or the abscissa. The %f$_c$′ should be obtained from the values taken from the curve drawn from the graph. Since concrete is a somewhat nonhomogeneous material, test values are sometimes obtained that are illogical and not in conformity with most of the results. Those values should be discarded and not permitted to influence the results.

Illustrative Example (ASTM Designation: C 39)

Date specimens were cast: 3/1/99						
Description of test specimens: 6 in. × 12 in. concrete cylinders						
Concrete mix design: C.A. 1682 lb; F.A. 1141 lb; P.C. 857 lb; Water 331 lb						
Additives: None; Maximum size: C.A. 1 in.; F.M. 3.00						
Specimen No.	Days Cured	Area cm^2/in.^{2}	Load kg/lb	Fract. Angle	Stress MPa/psi	% f$'_c$
1	7	28.31 in.^{2}	141,000 lb	72	4981 psi	
2	7	28.28 in.^{2}	140,000 lb	75	4950 psi	
3	7	28.35 in.^{2}	146,000 lb	45	5150 psi	
Average					**5030 psi**	**77%**
4	14	28.29 in.^{2}	164,000 lb	50	5,797 psi	
5	14	28.33 in.^{2}	167,000 lb	65	5,894 psi	
6	14	28.27 in.^{2}	169,000 lb	60	5,978 psi	
Average					**5890 psi**	**90%**
7	21	28.40 in.^{2}	138,000 lb	Badly honeycombed		
8	21	28.32 in.^{2}	174,000 lb	60	6144 psi	
9	21	28.33 in.^{2}	180,000 lb	50	6354 psi	
Average					**6250 psi**	**96%**
10	28	28.28 in.^{2}	180,000 lb	80	6365 psi	
11	28	28.36 in.^{2}	188,000 lb	60	6629 psi	
12	28	28.30 in.^{2}	185,000 lb	75	6537 psi	
Average					**6510 psi**	**100%**

Data Sheet (ASTM Designation: C 39)

Date specimens were cast:						
Description of test specimens:						
Concrete mix design: C.A. ; F.A. ; Water						
Additives: ; Maximum size C.A. ; F.M.						
Specimen No.	Days Cured	Area cm^2/in.^{2}	Load kg/lb	Fract. Angle	Stress MPa/psi	% f$'_c$

Note: f$'_c$ based upon average 28-day strength for the concrete mix.

Flexural Strength of Concrete Using Simple Beam with Third-Point Loading
(ASTM Designation: C 78)

Purpose

To determine the flexural strength of a concrete beam with loading at the third points.

Equipment and Materials

- Rigid steel forms 51 cm (20 inches) long by 15 cm (6 inches) in the other two dimensions
- Point loading apparatus capable of maintaining the specified span length and distance between load applying blocks and support blocks to within ±0.13 cm (±0.05 inches)
- A suitable loading machine capable of applying the loads at a uniform rate without interruption See Figures 16 and 17 for details of the test beam and the loading apparatus.

Test Procedure

1. Preparation: Make the specimens in accordance with the concrete batch procedure. Test the concrete for slump and air content. Fill the beam forms with three lifts of concrete, tamping each lift 25 times with the 16-mm (⅝-inch) tamping rod or fill the form in one lift and consolidate the concrete with a mechanical vibrating table. Be careful not to overvibrate since that would cause segregation.

2. Curing: Allow the specimens to remain in the steel forms with the top properly covered for about 24 hours at normal room temperature. Strip the forms and place the specimens in the curing facility until ready for testing.

3. Testing: Remove the specimens from the curing facility and mark the beam where it will be in contact with the supports and at the opposite side where it will be in contact with the third-point loading. Remember that none of these contact points should be on the top or hand-finished surface of the specimen. In other words the beam should be tested 90° to its casting position. This should assure proper contact at the load points. However, this should be checked. Use 6.4-mm (¼-inch) thick leather shims, 3 cm (1 inch) long, for the full width of the specimen, wherever a gap in excess of 0.10 mm (0.004 inches) exists between the loading and support points and the specimen.

   a. Begin the test as soon as possible, while the specimen is still moist from the curing room.

   b. Apply an initial load of 2300 kg (5000 lb) rapidly; continue loading at a rate of 450 kg (1000 lb) *per minute* until failure.

   c. Record the ultimate load, the exact location of fracture, and the type of failure.

   d. If the failure occurs more than 5% of the length, 2.25 cm (0.9 inches) outside the middle third of the beam in the tension surface, discard the results of that specimen.

   e. After the test, measure the cross section at each end and at the center. Compute the average height and depth.
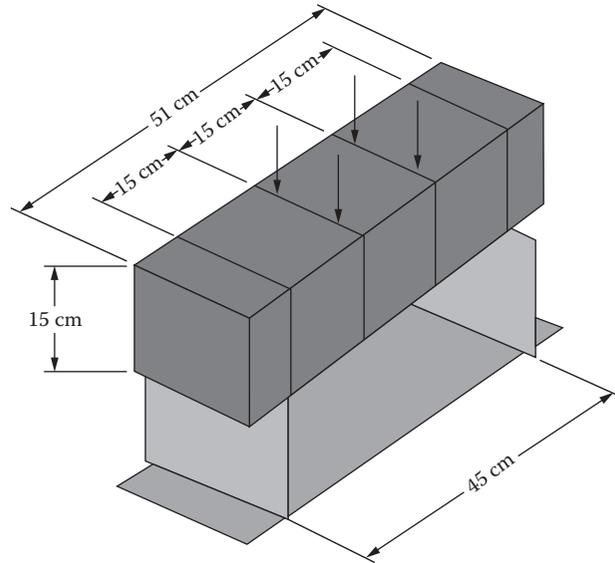
Figure 16
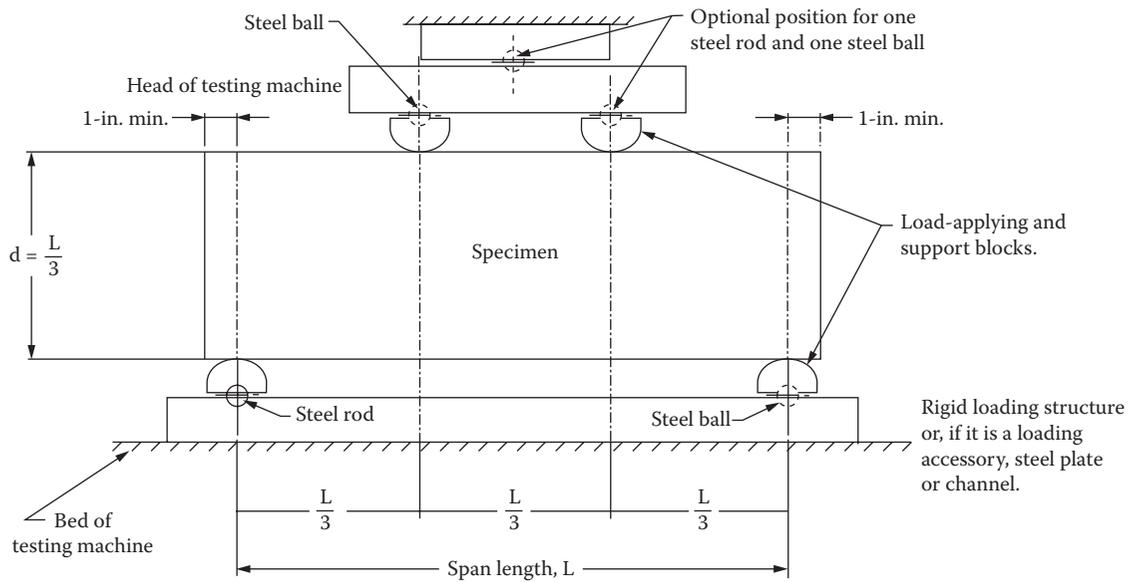Three-dimensional view of test beam in loading apparatus.

Figure 17
Diagrammatic view of third-point loading apparatus. Copyright ASTM. Reprinted with permission.

Explanation of Computations and Data Sheet

1. Computations: The flexure strength, or the modulus of rupture, as it is usually called, is computed from the following equation:

$$\text{M.R.} = Pl/bd^2$$

When the fracture occurs outside the middle third of the specimen but within 5% of the supported span length, compute the modulus of rupture from the following equation:

$$\text{M.R.} = 3Pa/bd^2$$

P = the applied load in newtons or pounds.

l = supported length of the beam in cm or in.

b = average width of the specimen in cm or in.

d = average depth of the specimen in cm or in.

a = average distance between the fracture line, measured on the tension surface, from the nearest support in cm or inches.

Compute the modulus of rupture to the nearest 0.05 MPa (5psi).

2. Data Sheet: A data sheet with sample computations appears at the end of this chapter. The third column with the average b × d refers to the depth and height dimensions, respectively. In the illustrative example, the U.S. Standard of Measurements are used. It should be noted that the results for specimens 5 and 9 were disregarded. Specimen 5 broke at 3.9 inches from the closest support. Where the specimen breaks outside of the middle third of the beam, it must fracture within 5% of the middle third. Since in this test the distance between supports was 18 inches, the minimum distance between the break and the nearest support must be 5.1 inches. The distance as measured from the top face of the beam, in the position as tested, was only 3.9 inches. In the case of beam specimen 9, the failure took place outside of the middle third. However, it was acceptable because the average distance of the fracture, again measured along the top surface, was within the 5% criterion. Nevertheless, the result of this specimen was rejected because its value of 623 psi differed by more than 16% from the values of the other two specimens, which were quite close.

Illustrative Example (ASTM Designation: C 78)

Date specimens were cast: 3/1/99; Comments:							
Description of test specimens: 6 in. × 6 in. × 21 in. beams; Distance between supports: 18 inches							
Specimen No.	Days Cured	Average b × d cm or in.	Load kg/lb	Location of Fracture	M.R. MPa/psi	% f′$_c$	Remarks
1	7	6.03 in. × 6.00 in.	7700 lb	Middle Third	638 psi		f′$_c$ = 6450 psi
2	7	5.98 in. × 6.02 in.	7600 lb	Middle Third	631 psi		
3	7	6.00 in. × 5.99 in.	8450 lb	Middle Third	707 psi		
Average	**7**				**660 psi**	**10.2**	
4	14	5.97 in. × 6.01 in.	8300 lb	Middle Third	687 psi		
5	14	6.03 in. × 6.00 in.	7800 lb	3.9 in. from support	—	—	Disregard
6	14	6.01 in. × 5.99 in.	8450 lb	Middle Third	705 psi		
Average					**695 psi**	**10.8**	
7	21	5.98 in. × 6.01 in.	10,500 lb	Middle Third	875 psi		
8	21	6.04 in. × 5.98 in.	10,000 lb	Middle Third	833 psi		
9	21	5.97 in. × 6.01 in.	8450 lb	5.3 in. from support	623 psi	—	Δ too great
Average					**855 psi**	**13.3**	
10	28	6.01 in. × 6.00 in.	10,600 lb	Middle Third	882 psi		
11	28	6.03 in. × 5.99 in.	11,750 lb	Middle Third	978 psi		
12	28	5.98 in. × 5.99 in.	9250 lb	Middle Third	775 psi		
Average					**880 psi**	**13.6**	

Data Sheet (ASTM Designation: C 78)

Date specimens were cast:	; Comments:						
Description of test specimens:			; Distance between supports:				
Specimen No.	Days Cured	Average b × d cm or in.	Load kg/lb	Location of Fracture	M.R. MPa/psi	% f′$_c$	Remarks
1							
2							
3							
Average							
4							
5							
6							
Average							
7							
8							
9							
Average							
10							
11							
12							
Average							

Unit Weight, Yield, and Air Content of Concrete
(ASTM Designation: C 138)

Purpose

To determine the unit weight and yield of freshly mixed concrete. From the data developed under this procedure it is also possible to determine the approximate percent of entrained air in the concrete. However, a more expeditious way is to use the Chace air indicator. It must be emphasized that neither of the two techniques is a substitute for the more accurate pressure and volumetric methods.

Equipment and Materials

- Balance or scale with a capacity of at least 25 kg (55 lb), with an accuracy of 0.3% of any test load
- Round steel tamping rod 16 mm (⅝ inch) in diameter, having the tamping end rounded to a hemispherical tip, approximately 60 cm (24 inches) long
- Cylindrical steel container with a capacity of 11 liters (0.4 ft³)
- Rectangular, flat, steel strike-off plate at least 6 mm (¼ inch) thick and measuring 40 cm by 40 cm (16 in. × 16 in.) square
- Rubber mallet weighing approximately 0.6 kg (1.4 lb)
- Chace air indicator (Figure 18) and a liter of rubbing alcohol

Test Procedure

1. Compact the freshly mixed concrete in three layers of approximately equal volume. Rod each layer with 25 strokes of the tamping rod, distributing the strokes equally over the surface of the concrete, beginning with the center and moving toward the rim of the container. When rodding the bottom (first) layer, do not strike the bottom of the container. For the other two layers, penetrate approximately 2.5 cm (1 inch) into the previous lift with each stroke of the tamping rod. After each layer is rodded, distribute 15 uniform taps around the container with the rubber mallet to release any trapped air pockets in the concrete. After the third lift has been rodded and tapped, there should be an excess of concrete about 3 mm (⅛ inch) above the rim of the container.

2. Carefully strike off the concrete projecting above the container with the strike-off plate. Press the latter on the top of the concrete, covering about ⅔ of the surface. Withdraw the plate with a sawing motion to finish only the area covered. Then place the strike-off plate over the original ⅔ of the surface covered. With a vertical pressure and a sawing motion, cover and finish the entire surface.

3. After strike-off, clean the outside of the container and carefully determine the net weight of concrete.
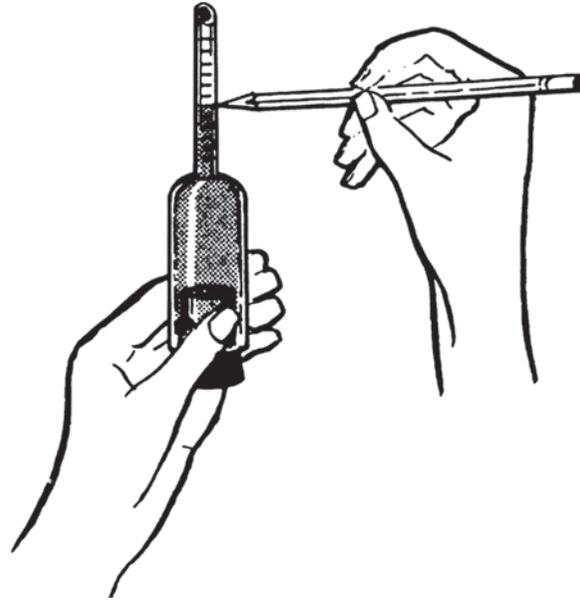
Figure 18
Chace air indicator shown being used to determine the approximate air content of fresh concrete. Reprinted with permission of the Canadian Portland Cement Association.

Explanation of Computations and Data Sheet

1. Computations: Compute the unit weight of the concrete in kg/m^3 or lb/ft^3 from an accurate determination of the volume of the container and the net weight of the concrete. Then calculate the yield from one of the following formulas as appropriate:

$$Y(m^3) = W_1/W \text{ or } Y(yd^3) = W_1/27W$$

The final computation involves the relative yield, which is determined as follows:

$$R_y = Y/Y_d$$

R_y = relative yield
W = unit weight of concrete in kg/m^3 or lb/ft^3
W_1 = total weight of materials in the batch, kg or lb
Y = volume of concrete produced per batch, m^3 or yd^3
Y_d = volume of concrete which the batch was designed to produce, usually 1 m^3 or 1 yd^3

The value R_y can used to determine the quantity in the mix design to obtain a yield of 1. For example if N_1 = the weight of the Portland cement in the design batch, by dividing N_1 by R_y one can obtain the quantity of cement required for a volume of either 1 m^3 or 1 yd^3. If N = the weight of cement in kg/m^3 or lb/yd^3, this value can be obtained from the equation $N = N_1/R_y$. The same holds true for all the other components of the concrete mix, such as aggregates, water, and admixtures.

2. Data Sheet: The data sheet below is in two parts, one below the other. There is space for results of six specimens. The first one was used as an illustrative example, which is demonstrated for the SI System. In the U.S. Standard System of Measurements, it is important to remember that the volume of concrete is normally considered in terms of a cubic-yard batch and that a cubic-foot weight must, therefore, be multiplied by the factor 27 for W to be in lb/yd^3.

Data Sheet (ASTM Designation: C 138)

Test No. and Date	Net Wt. of Container, kg or lb	Wt. of Container + H_2O, kg or lb	Net Wt. of Water, kg or lb	Vol. of Container, m^3 or ft^3
1 3/1/99	1.15 kg	27.43 kg	26.28 kg	0.0263 m^3
2				
3				
4				
5				
6				

Data Sheet (ASTM Designation: C 138)

Test No. and Date	Wt. of Container + Concrete	Net Wt. of Concrete	W, kg/m^3 or lb/ft^3	W_1, kg or lb	$Y = W_1/W$	Y_d	$R_y = Y/Y_d$
1 3/1/99	73.34 kg	72.19 kg	2745 kg/m^3	2698 kg	0.983 m^3	1 m^3	0.983
2							
3							
4							
5							
6							

Slump of Hydraulic Cement Concrete
(ASTM Designation: C 143)

Purpose

To determine the consistency of a freshly mixed concrete by measuring the slump.

Equipment and Materials

- Frustum of a cone made of noncorrosive sheet metal, not less than 1.14 mm (0.045 inch) thick, 30.5 cm (12 inches) in height, with a 20.8-cm (8-inch) base, having a diameter at the top of 10.2 cm (4 inches), with foot pieces and handles as shown in Figure 19. There should also be a metal base plate with clamps that engages the foot pieces while the concrete is being poured into the slump cone and tamped with the tamping rod.
- Round steel tamping rod 16 mm (⅝ inch) in diameter, having the tamping end rounded to a hemispherical tip, approximately 60 cm (24 inches) long
- Suitable, graduated metal scale approximately 25 cm (1 ft) in length

Test Procedure

1. Dampen the slump cone and the metal base plate; then engage the slump cone with the base plate clamps. The base plate should rest on a level surface.

2. Fill the slump cone in three lifts, tamping each lift 25 times with the tamping rod, starting from the center and working toward the perimeter. The bottom lift should be rodded the full depth down to the base plate. For the two other lifts, the strokes of the tamping rod should penetrate into the underlying concrete layer. The top lift should remain heaped above the top of the slump cone after completing the rodding. Each of the three lifts should contain approximately an equal volume of concrete. Therefore, the bottom layer should have a rodded depth of about 7 cm (2½ inches) and the second lift to about 15 cm (6 inches).

3. Strike off the excess concrete with a screeding and rolling motion of the tamping rod.

4. Remove the cone carefully with a slow vertical motion without any rotational or lateral motion. The entire procedure from the time the fresh concrete is ready for testing to this point should be no more than five minutes. The time from the filling of the slump cone to determining the slump should be within 2½ minutes.

5. Set the slump cone in an inverted position next to the concrete and measure the distance to the top of the original center of the specimen as shown in Figure 20.
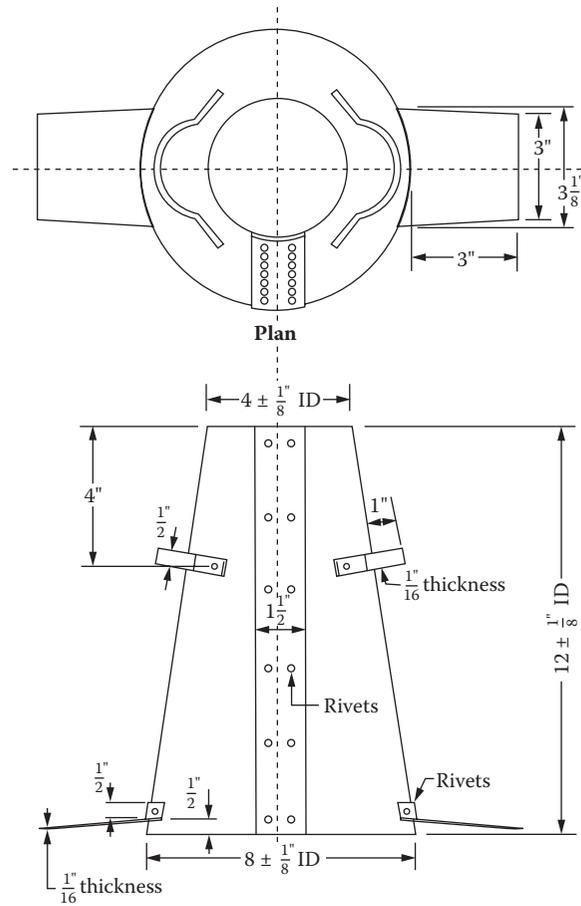
Figure 19
Mold for slump cone. Copyright ASTM. Reprinted with permission.

Explanation of Computations and Data Sheet

1. Computations: There are no computations. Simply record the measured slump of the concrete to the nearest 6 mm (¼ inch).

2. Data Sheet: For this test there is only one value to record and no special data sheet. Normally the percent of entrained air will be determined and recorded at the same time as the slump test is taken. This will be covered in the discussion of ASTM Designations: C 173 and C 231.

Figure 20
Demonstration of the use of a slump cone. The top photograph illustrates a low slump and the bottom a high slump. Reprinted with permission of the Canadian Portland Cement Association.
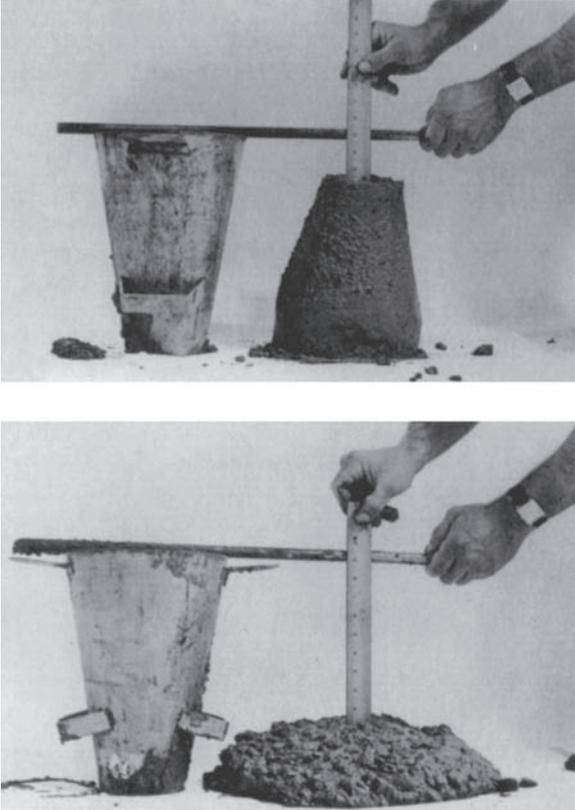
Air Content of Freshly Mixed Concrete by the Volumetric Method
(ASTM Designation: C 173)

Purpose

This method is applicable for the determination of the air content of fresh concrete composed of any type of aggregate. The test is not affected by atmospheric pressure and the relative density of the materials need not be known. The volumetric method requires the removal of air from a known volume of concrete by agitating the concrete in an excess of water. The procedure described in this manual is applicable for concrete mixtures with a maximum size aggregate passing the 37.5-mm (1½-inch) sieve.

Equipment and Materials

- Air meter consisting of a bowl and top as shown in Figure 21 and conforming to the following requirements: the bowl shall have a volume of at least 2.1 liters (0.075 ft³) and have a diameter 1 to 1.25 times the height and constructed with a flange at or near the top surface; the top section shall have a capacity at least 20% greater than the bowl and have a watertight connection; it shall also be equipped with a transparent scale, graduated in increments not greater than 0.5% from 0 to ≥9% of the volume of the bowl.
- Funnel with a spout that can extend to the bottom of the top section.
- Steel tamping rod 16 mm (⅝ inch) in diameter, rounded to a hemispherical shape at both ends.
- Flat, steel strike-off at least 3 mm × 20 mm × 300 mm (¼ in. × ¾ in. × 12 in.).
- Metal or plastic calibrated cup having a capacity at least equal to the volume of the bowl and graduated in approximately 1% increments.
- Small rubber bulb syringe having a capacity greater than or equal to that of the calibrated cup.
- Pouring container of about 1 liter or 1 quart capacity.
- Small metal scoop.
- 1 liter or 1 quart of rubbing alcohol.
- Rubber mallet about 0.60 kg (1.25 lb).

Test Procedure

1. Calibrate the air meter and the calibrated cup initially and annually or whenever the volume of either is suspect. The volume of the measuring bowl is determined by carefully weighing the amount of water and its temperature to fill the measuring bowl. Obtain the mass of water in the bowl from the following, interpolating as necessary. Then calculate the volume, V, by dividing the mass of water required to fill the measuring bowl by its density from the table. Determine the volume of the graduated measuring cup by the same method. Determine the accuracy of the graduations on the neck of the top of the air meter by filling the assembled bowl and top section with water to the level mark for the highest air content graduation. Then add water in
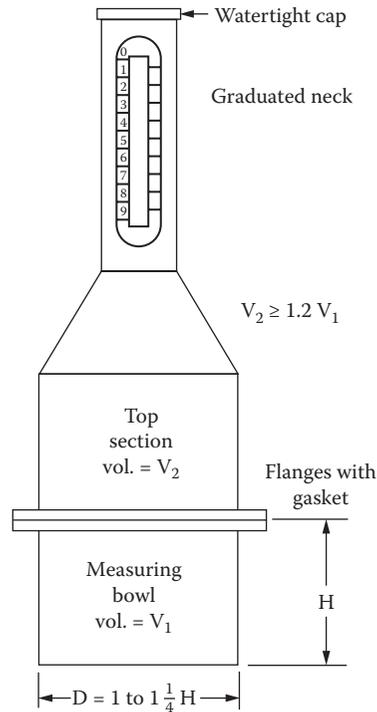
Figure 21
Volumetric apparatus for measuring the air content of fresh concrete.

increments of 1.0% of the volume of the bowl throughout the graduated range of air. The error at any point should not exceed 0.1% of air.

Test Procedure (ASTM Designation: C 173)

Temperature			
°C	°F	kg/m³	lb/ft³
15.6	60	999.01	62.366
18.3	65	998.54	62.336
21.1	70	997.97	62.301
23.0	73.4	997.54	62.274
23.9	75	997.32	62.261
26.7	80	996.59	62.216
29.4	85	995.83	62.166

2. Fill the measuring bowl with three layers of concrete, tamping each 25 times with the rod. After each lift is rodded, tap the sides of the bowl 15 times with the rubber mallet to remove any voids or trapped air bubbles.

3. Strike off the excess concrete from the top of the bowl and wipe the flange clean. Then attach the top section to the bowl and insert the funnel. With the rubber syringe and using a mixture of 50% water and 50% alcohol, pour enough liquid into the air meter assembly to raise the bottom of the meniscus to the zero mark. Attach and tighten the watertight cap.

4. Repeatedly invert and agitate the assembly for a minimum of 45 seconds. Do not keep the unit in the inverted position for more than five seconds at a time to prevent the concrete mass from lodging in the neck.

5. Tilt the assembly at about a 45° angle and roll it back and forth vigorously for approximately 1 minute. Then take a reading.

6. Repeat the previous procedure again and after 1 minute take a reading. Repeat the same procedure until two successive readings do not differ by more than 0.25% of air. Always read to the bottom of the meniscus.

7. If the liquid level is obscured by foam, use the syringe to add alcohol, in calibrated one-cup increments, to establish a readable meniscus. Keep a record of the number of calibrated cups of alcohol used.

8. Disassemble the apparatus and examine the contents. If any portion of the concrete mass has not been disturbed during the procedure, the test is considered invalid and must be repeated.

Explanation of Computations and Data Sheet

1. Computations: The air content, as a percent of the concrete in the measuring bowl, is obtained from Test Procedure item 6, to the nearest 0.25%. If it was necessary to utilize additional alcohol to clear the foam, as described in Test Procedure item 7, the quantity of additional alcohol must be added to the observed percent of air.

2. Data Sheet: No special form has been devised for this test.

Making and Curing Concrete Test Specimens in the Laboratory
(ASTM Designation: C 192)

Purpose

Procedures for making and curing concrete test specimens under conditions of laboratory control.

Equipment and Materials

- Molds, forms, and tamping rods as specified for the particular specimens being prepared
- Vibrating table
- Appropriate apparatus for determining the slump, percent air entrainment, and yield in accordance with the appropriate ASTM designations
- Scales
- Concrete mixer
- Necessary hand tools such as shovels, pails, trowels, scoops, pans; curing materials with which to cover the freshly made specimens; and rubber gloves
- Cement, aggregates, water, and additives (if required)

Test Procedure

1. The moisture content of the aggregates must be determined prior to any mixing operations in order to be able to calculate how much water needs to be added. An adjustment must also be made to the weight of aggregates required, based upon the amount of absorbed and free water present. The adjusted weights of water and aggregates should then meet the previously made computations as outlined in the Mix Design Procedures on pages 8 through 27.

2. Just prior to the start of mixing, the mixer must be "buttered" with a small quantity of a mortar mix, consisting of fine aggregates, cement, and water in the approximate proportions to closely simulate the test batch. The quantity should be just sufficient to coat the inside of the drum of the mixer. The purpose is to prevent the loss of mortar from the concrete to coat the drum.

3. When additives are called for in the concrete mix, disperse them in the initial three quarters of the estimated mixing water. The additives should be thoroughly dispersed in the mixing water. If more than one additive is called for, disperse each additive in separate mixing water containers.

4. Before starting the rotation of the drum, charge the mixer with the coarse aggregates and about ¼ of the mixing water. Start the mixer and add the fine aggregate, cement, and ½ of the estimated required mixing water in that order. Mix for 3 minutes after all of the ingredients have been added, followed by a 3-minute rest period. During this time, take a slump test to determine how much of the remaining mixing water should be added in order to obtain the required slump. Except

as necessary for conducting the slump test, keep the open end of the mixer covered during the rest period to prevent loss of moisture. This is followed by a final two minutes of mixing.

5. At the completion of mixing, deposit the concrete in a suitable, clean, damp pan. If necessary, remix the fresh concrete by shovel or trowel until it appears uniform. Then take whatever tests are called for, such as the final slump test, percent of entrained air, and yield; ASTM Designations: C 138, C 143, and C 173 or C 231. Based upon these tests, a further adjustment may need to be made to the mix design. The trial mixtures should have a slum and air content of ±20 mm (±0.75 inch) and ±0.5%, respectively, of the maximum permitted. A convenient rule of thumb to follow is as follows: increase the mixing water by 3 kg (5 lb) for each 1% decrease in air to achieve the same slump in a 1-m^3 (1-ft^3) batch and conversely if the air needs to be increased. Reduce the mixing water by 5 kg (10 lb) for each 25 mm (1 inch) in required slump reduction; and of course the converse is true to increase the slump. Once the mix has been redesigned, taking the above factors into account and the yield, a new trial batch needs to be made and tested for conformity with specifications. The American Concrete Institute recommends two methods for proportioning a concrete mix design. One is by mass, when using the SI System, or by weight when using the U.S. Standard System. The other is the volumetric method, which is the one chosen for illustration in pages 8 through 27 and use in this manual. It is considered the more accurate of the two. The size of the trial batch should be on the order of about 0.1 m^3 (or about 2 ft^3).

6. Once a satisfactory mix has been produced, prepare the specimens for the testing program. The quantity of each mix in the laboratory should be based upon the volume of concrete required to prepare the specimens or the maximum mixing capacity of the mixing drum, as specified by the manufacturer, whichever is smaller.

7. All specimens should be removed from their molds or forms and placed in the curing facility not less than 16 hours and not more than 32 hours after casting.

8. The specimens are to remain in the curing environment until just before they are ready for testing. All specimens should be tested while their surfaces are still thoroughly moist. Curing for all specimens may be carried out by continuous immersion in saturated lime water. However, for flexure, specimens must be in a saturated lime solution for at least 20 hours prior to testing at a temperature of 23 ± 1.7°C (73.4 ± 3°F).

Explanation of Computations and Data Sheets

1. Computations: The only computations necessary for ASTM Designation: C 192 involve the computations of the mix design and modifications as indicated by the results of the trial batches, as described herein.

2. Data Sheets: Those used in this procedure are according to the specimens prepared, such as for compression, flexure, tension, bond, Young's Modulus, Poissons's Ratio, etc., each of which has its own specially prepared data sheet. These tables are initially to be filled out when the specimens are prepared and completed at the time of testing. The mix design is based upon the initial computations and then as modified by the trial batches, described herein in ASTM Designation: C 192. The tables were designed both for the concrete mixture used as well as the test results of the specimens. No special data sheet was prepared for this test procedure.

Air Content of Freshly Mixed Concrete by the Pressure Method
(ASTM Designation: C 231)

Purpose

To determine the air content of freshly mixed concrete made with relatively dense aggregates, by observing the change in volume of the concrete with a change in pressure. For other than dense stone aggregates, use ASTM Designation: C 173.

Equipment and Materials

- Air meters, types A and B, as shown in Figures 22 and 23
- Steel trowel
- Funnel with a spout that can extend to the bottom of the top section
- Steel tamping rod 16 mm (⅝ inch) in diameter, rounded to a hemispherical shape at both ends
- Flat, steel strike-off at least 3 mm × 20 mm × 300 mm (¼ in. × ¾ in. × 12 in.)
- Metal or plastic calibrated cup having a capacity at least equal to the volume of the bowl
- Rubber mallet about 0.60 kg (1.25 lb)
- Vibrator
- 37.5-mm (1½-inch) sieve with a sieving area $\geq$0.19 m^2 (2 ft^2)

Test Procedure

1. An initial calibration should be performed on the meter used in accordance with the instructions included with the unit.

2. A determination needs to be made of the voids in the aggregates in order to deduct their volume from the measured air content of the concrete. This is called the *aggregate correction factor*. The steps are as follows:

   a. Prepare separate samples of fine and coarse aggregates in the quantities that will be used in a volume of concrete that will exactly fill the container. The necessary weights of aggregates are computed as follows:

$$F_s = S/B \times F_b; \; C_s = S/B \times C_b$$

   F_s = quantity of fine aggregate in concrete sample, kg or lb
   S = volume of the measuring bowl in m^3 or ft^3
   B = volume of concrete produced per batch, obtained in accordance with ASTM Designation: C 138 in m^3 or yd^3
   F_b = quantity of saturated surface dry fine aggregate used in the batch in kg or lb
   C_s = quantity of coarse aggregate required for concrete sample in kg or lb
   C_b = quantity of saturated surface dry coarse aggregate used in the batch in kg or lb
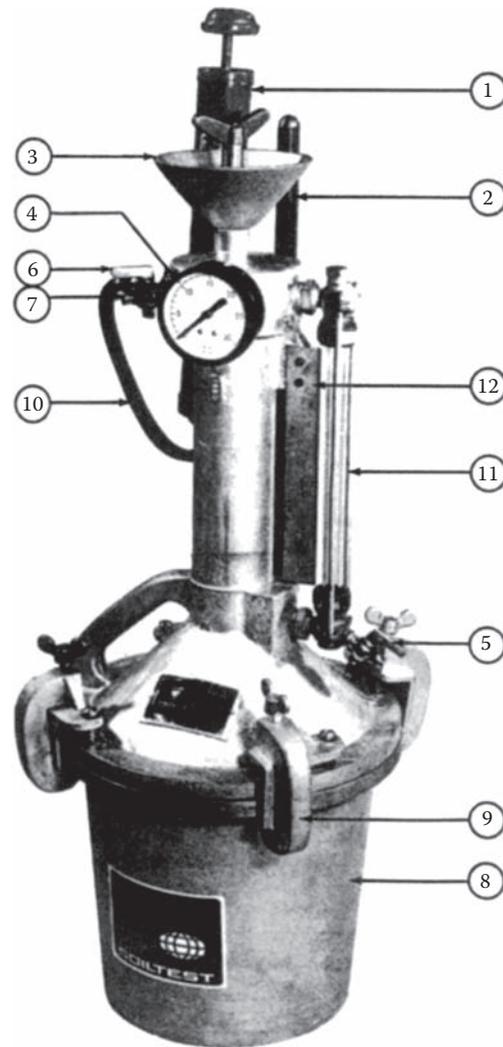
Figure 22

Diagram of a type A air meter: (1) hand pump, (2) tamping rod, (3) funnel and thumb valve, (4) pressure gauge, (5) petcock (drain), (6) petcock (air), (7) snifter valve, (8) container, (9) clamps and thumb screws, (10) hose attachment, (11) water glass, (12) graduated scale. Courtesy of ELE International, Inc., Soiltest Products Division, Lake Bluff, Illinois.

    b.   Fill the mixing bowl one-third full of water. Add the mix of fine and coarse aggregates, F_s and C_s, as computed above, a small amount at a time. Deposit the aggregates so as to trap as little air as possible. Tap the sides of the bowl and lightly rod the top 2.5 cm (1 inch) of the aggregates 10 times. Also stir after each addition of aggregates to eliminate entrapped air.

    c.   Proceed in accordance with the instructions for the particular air meter to determine the percent of air voids in the aggregates. This quantity is designated as G and it will be deducted from the percent of entrained air of the sample tested.

3. Determine the percent of entrained air in the concrete sample, A_1, by following the instructions accompanying the particular air meter in the laboratory. Of course this air meter must meet the specifications for ASTM Designation: C 231, and it must be so stipulated in the accompanying instructional material.

4. Representative type A and B air meters are shown in Figures 22 and 23, together with detailed instructions for their use. Other manufacturers produce similar units, all meeting the ASTM Designation: C 231 specifications. Their instructions may contain certain differences, which must be followed.

Operating Instructions for Determining Entrained Air for a Type Air Meter as Shown in Figure 22

A. Determination of air in the aggregates:

 1. Fill the container about half full of water. Pour the fine aggregate slowly into the container and stir vigorously by hand, so that the aggregate will be completely inundated with no air entrapped around or between the particles. Note: Much care should be taken in performing this operation or the air entrapped between the particles will not be completely removed and the test will show erroneous results.

 2. Fill the container with water. Wipe the contact surfaces clean and clamp the top section of the apparatus firmly in the container.

 3. Close the petcock at the bottom of the water glass and open the petcock and funnel valve at the top. Fill the apparatus with water to a level slightly above the arrow mark on the graduated scale. Close the funnel valve and adjust the water level to the arrow mark on the graduated scale by means of the lower petcock. (The distance between the arrow mark or initial water level and the zero mark corrects for the expansion of the apparatus under the applied pressure of 15 psi and does not represent air.)

 4. Close the top petcock and apply pressure with the pump until the gauge reads exactly 15 psi or the correct operating pressure.

 5. Read and record the subsidence of the water level. Repeat the test on other samples until it is apparent from the results obtained that all the air between the fine aggregate particles is being stirred out.

 6. Repeat the above procedure with the sample of coarse aggregate. The sum of the readings obtained for the two samples is the subsidence of the water level due to the air within the aggregate particles, and is the correction to be applied in determining the air content of the concrete. The test can be applied to the sample of fine and coarse aggregate combined, but more difficulty will be experienced in stirring out entrapped air.

B. Determination of air content in concrete: procedure

 1. Fill the container with concrete in three equal lifts, rodding each 25 times with ⅝ in. bullet-pointed rod. Strike off the surface. Small variations in the strike-off will have little effect on results.

 2. Wipe the contact surfaces clean and clamp the top section of the apparatus firmly to the container.

 3. Close the petcock at the bottom of the water glass and open the petcock and funnel valve at the top. Fill the apparatus with water to a level slightly above the arrow mark on the graduated scale. Close the funnel valve and adjust the water level to the arrow mark on the graduated scale by means of the lower petcock.

 4. Close the top petcock and apply pressure with the pump until the gauge reads exactly 15 psi or the correct operating pressure.

 5. Read the subsidence of the water level and subtract from this value the correction for air held within the pores of the aggregate particles. The resulting value is the percentage of air in the concrete.

 6. Release the pressure, opening the top petcock. Release the water by opening the C Clamps. Remove the top and clean the apparatus at once and permit it to dry. It may be necessary to clean the water glass occasionally by removing the nuts at the top and bottom of the water gauge assembly. The threads on the thumb screws and on the funnel valve should be oiled occasionally.

C. Corrective air pressure to be used for air contents exceeding limits of scale: Correction multiples to be used for the Acme air meter when the air content is so great that a reading is not obtainable using 15 lb pressure.

Try 10 lb pressure, multiplying reading by 1.25

5 lb = reading × 2.03
10 lb = reading × 1.25
15 lb = reading × 1.00

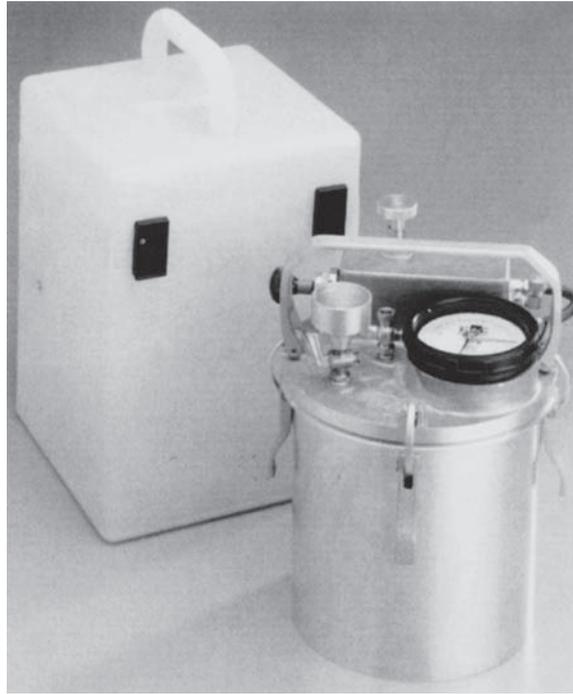Courtesy of ELE International, Inc., Soiltest Products Division, Lake Bluff, Illinois.

Figure 23
Photograph of a type B air meter, sheet 1 of 3. Courtesy of ELE International, Inc., Soiltest Products Division, Lake Bluff, Illinois.

Operating Instructions for Determining Entrained Air for a Type B Air Meter, as Shown in Figure 23

1. Place concrete to be tested in material container (1) in three equal layers. Rod each layer 25 times, as directed in making compressive test cylinder specimens. Excess concrete should be removed by sliding strike-over bar (3) across the top flange, using a sawing motion, until container is just level-full.
2. Wipe lip of container (1) clean of all sand and mortar.
3. Close main air valve (4 colored red) on top of air receiver. Open both petcocks (8 and 9) on top of lid.
4. Place lid (5) on material container and close the four toggle clamps (6).
5. Pour water into funnel (7) until water comes out petcock (8) in the center of lid. Jar meter gently until no air bubbles come out through center petcock. Close both petcocks (8 and 9).
6. Close air bleeder valve (10) in end of air receiver and gently pump air into receiver until gauge hand (12) comes to the vicinity of the red line. A little to one side or the other will make no difference as long as the hand has gone past the initial starting point.
7. Tap gauge (13) gently with one hand and at the same time crack bleeder valve (10) in end of air receiver until gauge hand (12) rests exactly on the initial starting point. Then quickly close bleeder valve (10).
8. Open main air valve (4 red) between air receiver and material container. Jar container (1) slightly when pressure is on to allow for possible rearrangement of particles. Tap gauge (13) gently until hand (12) comes to rest. This reading is percent of air entrained.
9. In cases where voids in the aggregate are appreciable and it is desired to deduct their volume from the measured air content, deduction can be determined by placing the amount of each size of aggregate used in the test in the material container, filling the container with water, and completing the regular detremination for air content. This reading is the aggregate correction factor.

Courtesy of ELE International, Inc., Soiltest Products Division, Lake Bluff, Illinois.

Explanation of Computations and Data Sheet

1. Computations: The only computations necessary for this procedure are those involved in determining the air voids in the aggregates, both coarse and fine. Calculate the amount of aggregates that are in the concrete volume equal to the volume of the air meter bowl. This is of course determined by carefully determining the net weight of water required to fill the bowl and then taking that proportional value of the batch to find the weights for the coarse and fine aggregates. Follow the instructions in Test Procedure item 2 to obtain G, the air voids in the aggregates. The computed air content of the concrete is obtained from the equation:

$$A_s = A_1 - G$$

A_s = percent entrained air in the concrete specimen.
A_1 = apparent percent air in the concrete specimen since it includes the permeable air voids in the aggregates.
G = the correction factor in percent for air voids in the aggregates.

2. Data Sheet: The steps required for the determination are shown below in each of the two copies of a convenient data sheet. Batches are generally in m^3 or yd^3 in accordance with the yield calculation made from ASTM Designation: C 138 in order to compute batch yields to a whole m^3 or yd^3. A first step, therefore, is to determine the yield of the batch, if this has not already been performed. The batch volume, B, should be to a whole, even m^3 or yd^3, with the quantities for each component of the mix adjusted to reflect a whole m^3 or yd^3, F_b, and C_b (see equations in Test Procedure item 2a).

Data Sheet (ASTM Designation: C 231)

Air Content of Fresh Mixed Concrete by the Pressure Method
Weight of measuring bowl and water in kg or lb =
Net weight of measuring bowl in kg or lb =
Volume of measuring bowl in m^3 or yd^3 =
Quantity of F.A. required for test, F_s =
Bowl volume/batch volume × F.A. in batch in kg or lb =
Quantity of C.A. required for test, C_s =
Bowl volume/batch volume × C.A. in batch in kg or lb =
G =
H_1
H_s

Data Sheet (ASTM Designation: C 231)

Air Content of Fresh Mixed Concrete by the Pressure Method
Weight of measuring bowl and water in kg or lb =
Net weight of measuring bowl in kg or lb =
Volume of measuring bowl in m^3 or yd^3 =
Quantity of F.A. required for test, F_s =
Bowl volume/batch volume × F.A. in batch in kg or lb =
Quantity of C.A. required for test, C_s =
Bowl volume/batch volume × C.A. in batch in kg or lb =
G =
H_1
H_s

Bond Strength of Concrete Developed with Reinforcing Steel
(ASTM Designation: C 234)
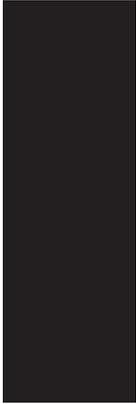
Purpose

To determine the bond strength between a concrete and deformed steel reinforcing bars due to the adhesion of the paste to the steel, the friction between the steel and the concrete, and the bearing of the concrete against the lugs of the deformed steel bars.

Equipment and Materials

- Two types of molds are required for the preparation of 15-cm (6-inch) molds for both vertical embedded bars and for top and bottom horizontally embedded bars. Molds for both types of specimens shall be constructed of watertight, easily assembled and disassembled steel forms at least 6 mm (¼ inch) thick, as shown in Figure 24.
- 2 dial gages graduated to 0.25 mm (0.001 inch) with a range up to at least 13 mm (0.5 inch) with appropriate brackets
- Suitable testing apparatus that can support the specimen on a machined steel bearing plate with dimensions no less than the cross section of the specimens and able to accommodate the reinforcing steel
- 15 cm × 15 cm (6 in. × 6 in.) pieces of plywood with a center hole to permit the reinforcing steel to pass through at least 6 mm (¼ in.) thick to act as a cushion between the concrete specimen and the steel bearing plate of the testing apparatus
- Three 15 cm (6 in.) diameter × 30 cm (12 in.) molds for determining the 28-day compressive strength of the concrete
- No. 6 (19 cm) deformed steel reinforcing bars (RE-bars) ≥ 60 cm (2 ft) in length
- All of the equipment and materials used in ASTM Designation: C 192, "Making and Curing Concrete Test Specimens"

Test Procedure

The testing apparatus described herein differs from the one shown in the ASTM Method, although it is not presented as the mandatory piece of equipment. Furthermore, in the ASTM Method, the measurement of the embedded steel slippage from the concrete block is based on the movement of the loaded steel end minus the elongation due to the tension that the affected length of bar is undergoing. In the procedure described below, the measurements of the movement of the steel bar during the test are with relation to the nonloaded end of the bar and only one measuring gauge can be used for this purpose. The other measuring gauge is used to record the elongation of the RE-bar to assure that it has not exceeded the yield point of the steel. This is based upon the experience of the author. There is then no need to deduct any elongation of the RE-bar to obtain the net slippage of the RE-bar in the concrete. The sketches and pictures on pages 120 and 121 show how the procedure is carried out.
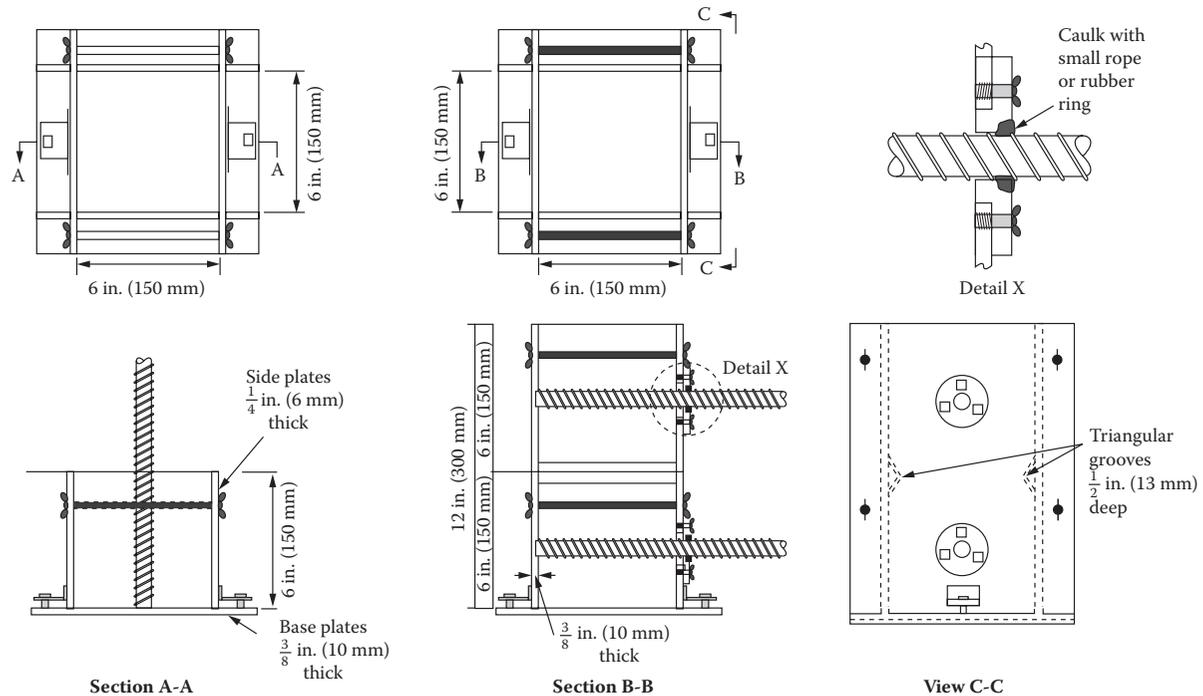
Figure 24
Molds for bond specimens. Copyright ASTM. Reprinted with permission.

1. Prior to casting the specimens, the insides of the steel molds should be coated with a thin film of mineral oil. Clean the RE-bars of rust and mill scale with a stiff wire brush. If there is any oil or grease on the RE-bars, carefully clean it off with a suitable solvent. A test set should consist of 3 vertical bar forms and 3 horizontal bar forms. Each of the latter will have a top horizontal and a bottom horizontal bar, for a total of nine test specimens for bond. Center and align the RE-bars in the forms. After the RE-bars are assembled in the forms, make the joints mortar tight by applying a suitable caulking compound on the outside of the forms, between the RE-bars and the forms. If the same concrete mixture has not previously been used for a compression test determination, a set of 3 specimens should also be prepared to find the 28-day compression strength, f'_c.

2. Using the same procedure as described in ASTM Procedure: C 192, mix the concrete and check and record the slump and the air content.

3. Fill the forms with two incremental layers of concrete for the vertically embedded RE-bars and in four layers for the horizontally embedded bars, tamping each lift with the tamping rod 25 times. If the concrete has a very low slump <2.5 cm (1 in.), it may also be necessary to place the filled mold on a vibrating table. After the concrete has been satisfactorily placed and consolidated, the bars should be twisted several times about a half turn in each direction, so as to assure that the ribs of the RE-bars are filled with the mortar from the concrete. At this point it may also be necessary to adjust the caulking compound.

4. Strike off any excess concrete from the top layer with a steel trowel and finish to a smooth surface. Place the whole assembly in a secured location and protect the exposed surface of the concrete from evaporation.

5. Strip the forms between 20 and 24 hours after curing at an ambient temperature of about 20° ± 3°C (68° ± 5°F). Immediately upon stripping, place the vertical bar specimens in the curing facility. Before the horizontal RE-bar specimens are placed in the curing facility, carefully separate the top horizontal from the bottom horizontal bar specimens by laying the joined specimens on a solid surface and strike it sharply with a cold chisel and hammer at the V-notch, which is between the two specimens. In doing so, be very careful not to touch or in any way disturb the RE-bars. Handle all the specimens only by the concrete, not the RE-bars. At this point, all the specimens should be in the curing facility.

6. At 28 days, and just prior to testing, remove the specimens one by one from the curing facility. They should be tested while the specimens are still moist from the curing facility. Place the previously prepared thin pieces of plywood with a center hole on the long end of the RE-bar, which will be gripped by the tension jaws of the testing machine. The plywood should be between the machine bearing plate and the bottom of the concrete cube. The function of the plywood is to distribute the

load, due to any imperfections in the concrete surface. The plywood pieces are for a single test specimen only and discarded. Conduct the test on all the vertical, all the top, and all the bottom horizontal bars together. It is not difficult to differentiate between the top and bottom horizontal RE-bar specimens. The bottom RE-bar specimens will have a much smoother surface since they were formed in contact with the steel form. The top RE-bar specimen has its top hand finished with a trowel. Set the deflection gauge on the nonmovable platform of the testing machine with the stem in contact with the top of the projecting RE-bar. Measure the distance from the bottom of the concrete to the center of the tension grip jaws. This distance will be designated as L in the formula to determine the elongation for yield. See Figure 2 for a picture of the setup.

7. Apply an initial load of 2.2 kN (500 lb) to secure the specimen in the jaws of the testing machine and then zero the gauge. Proceed to load the specimen at a rate of 4.4 kN/minute (1000 lb/minute) and take readings every 2.2 kN (500 lb) increments of load or about every 30 seconds.

8. Continue loading the specimen without interruption until one of the following occurs:

   a. The specimen (concrete) splits, at which time the load reduces to zero.

   b. The yield point of the steel has been approached, based upon the computed elongation. The modulus of elasticity for the RE-bar is assumed to be 200 GPa (29×10^6 psi) in computing the elongation at yield.

   c. A slippage of at least 2.5 mm (0.1 inch) has occurred between the concrete and the embedded RE-bar as measured from the unloaded end of the steel, which projects approximately 1 cm (⅜ inch) from the concrete block in all of the specimens.

Invariably the test will end with the splitting of the specimen. Only rarely will a slippage of 2.5 mm (0.1 inch) occur before the concrete splits. In the experience of the author, reaching the yield point of the RE-bar before the concrete fails (7a) or having experienced a slippage of 2.5 mm (0.1 inch) (7c) is even less probable. However, all three criteria must be considered and used at the time of the test and recorded in the notes along with the final readings.

Explanation of Computations and Data Sheets

1. Computations: A No. 6 deformed RE-bar is assumed as being used in this test, which results in a nominal cross-sectional area of 2.84 cm^2 (0.44 in.^{2}) for computational purposes. A deformed RE-bar of another diameter may also be used. The considered effective diameter of a No. 6 deformed RE-bar is approximately 1.9 cm (¾ in.). For a No. 6 RE-bar with an embedded length of 15 cm (6 in.), the surface area used in the calculation for bond stress is 90 cm^2 (14.14 in.^{2}). The yield point of RE-bars may be taken as 250 MPa (36 ksi). To compute the elongation for the yield point, use the equation:

$$\Delta = \frac{P \times L}{A \times E} = \frac{s \times L}{E}$$

P/A = s = the tensile stress in the bar. Taking s as the yield stress, the formula becomes the second expression for Δ, since L has been measured as explained in Test Procedure item 6.

Therefore, the value for Δ in either centimeters or inches can be computed.

The bond stress at any recorded point in the test can readily be computed by dividing the load by the embedded area of the RE-bar. The design bond stress is taken as the point where the slip equals 0.25 mm (0.01 in.). This value is taken from the plotted curves. The values of the three tests for each RE-bar orientation and position should be consolidated as shown in the sample summary computation table on page 116. The results should be plotted on a single sheet of graph with the slip between the RE-bar and the concrete as the abscissa and the RE-bar bond stress as the ordinate, as shown on Figure 25. Building specifications generally delineate different allowable bond stresses for vertical RE-bars and for the two horizontal RE-bar positions. Check your test results against that of a recognized building specification as to which RE-bar alignment results in the highest and which in the lowest accepted value for bond strength.

2. Data Sheets: Two data sheets have been designed for this ASTM Method. They are shown on at the end of this chapter, including illustrations for their use. Notice that these data sheets include the orientation of the RE-bar on the top line along with the date of the test. The concrete mix design is also called for on this data sheet since it is important to determine the bond strength as a percent of the 28-day compressive strength of the concrete, f$'_c$. Note also the place for the measured length of the RE-bar from the bottom of the concrete block as the specimen sits in the testing machine to the center of the gripping jaws. Special testing instructions are also included even though they are explained in the body of the procedure. The values for the summary data sheets on pages 116 and 117 are obtained by averaging the values from the previous data sheets, which includes three specimens for each RE-bar configuration—vertical, horizontal top, and bottom RE-bars. You will note that only the data for the horizontal top RE-bar configuration has been included, although the summary data sheet
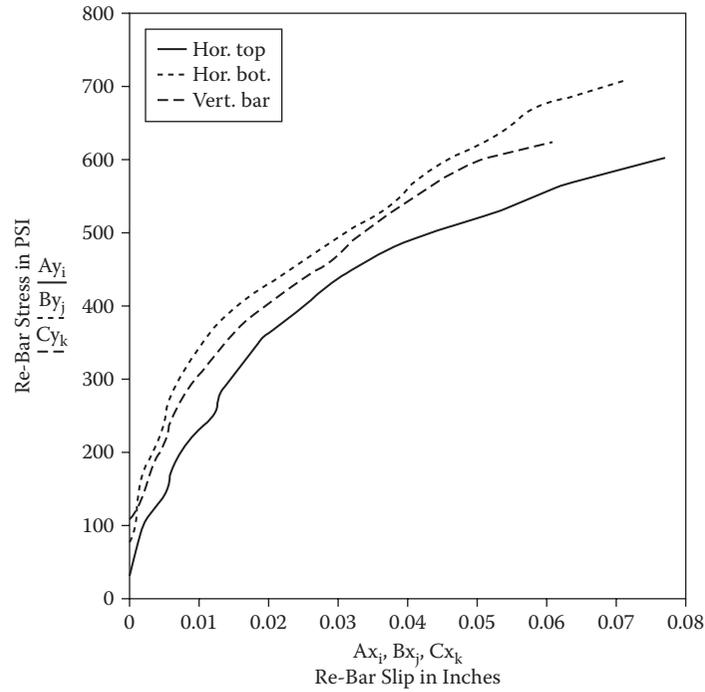
Figure 25
Graph of bond stress versus slip.

includes the values for all three RE-bar configurations. Only in this way could the graph in Figure 25 have been plotted. The graph is computer plotted, although a carefully drawn hand plot would also be acceptable. Note also that the accepted bond strength is obtained from the graph at a RE-bar slip of 0.25 mm (0.01 in.) although the data is generally taken well beyond this point. Figures 27 and 28 should help clarify the setup for this test procedure. Additional blank data sheets are included in the Appendix.
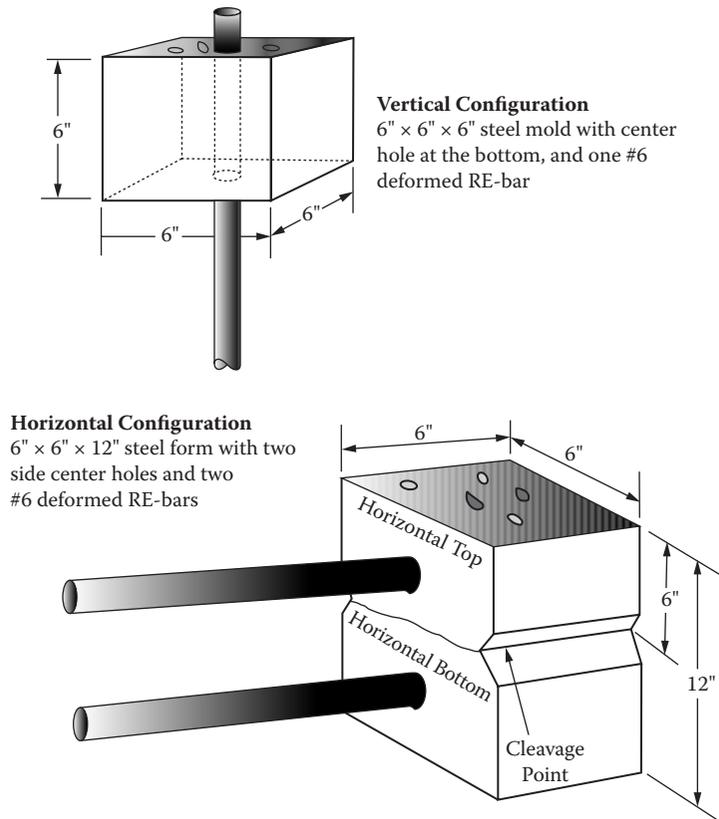
Figure 26
Schematic of bond specimens.
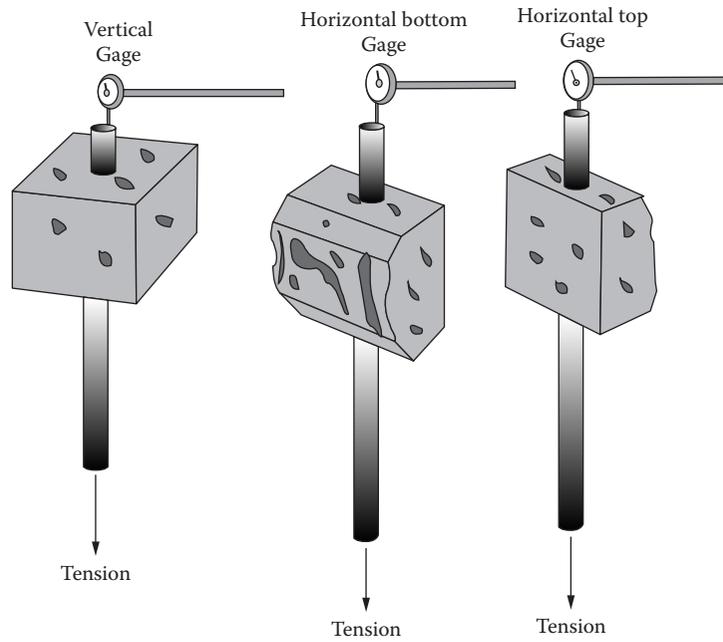
Figure 27
Schematic of bond Test Procedure, showing the differences in the concrete configuration for vertical, horizontal bottom, and horizontal top RE-bars due to the way the specimens are cast.
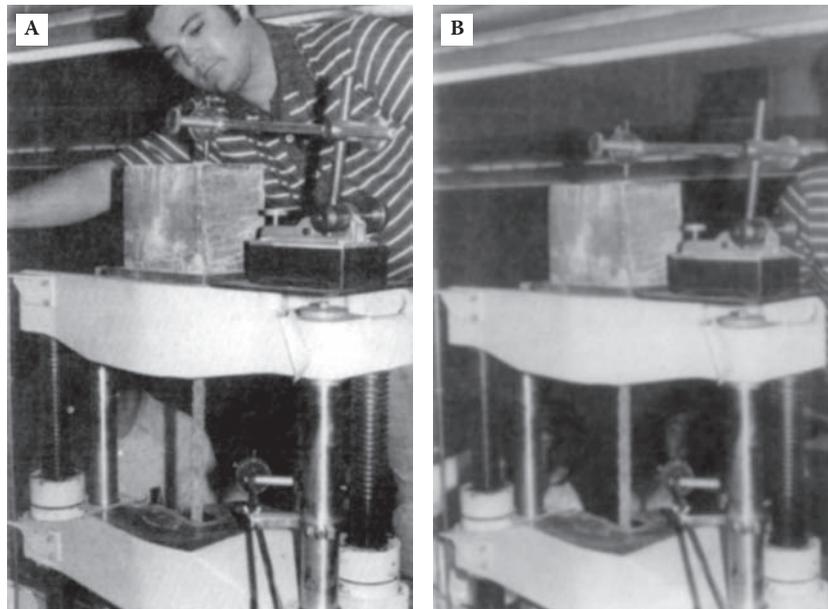
Figure 28
Bond specimens in the testing machine. (A) This view shows the split in the concrete cube at the time of failure, and (B) View showing the specimen, testing machine, dial indicators, and the bearing plate.

Data Sheet (ASTM Designation: C 234)

Date of test: RE-bar orientation:

Date specimens were cast:

Description of test specimens:

Measured length of RE-bar from bottom of concrete to the center of the jaws of the testing machine:

Maximum elongation to yield of the RE-bar in cm or in.:

Special instructions:

    1. Use a 2.2-kN (500-lb) seating load before zeroing the gages.

    2. Apply the load at a maximum rate of 4.4 kN (1000 lb) per/min.

    3. Use a value of E = 200 GPa (29 × 106 psi) and a Yield Point = 250 MPa (36,000 psi).

Scale Reading kg or lb	Dial Reading of RE-bar Slip, mm or in.			Remarks
	Specimen 1	Specimen 2	Specimen 3	

Data Sheet (ASTM Designation: C 234)

Date of test: RE-bar orientation:

Date specimens were cast:

Description of test specimens:

Measured length of RE-bar from bottom of concrete to the center of the jaws of the testing machine:

Maximum elongation to yield of the RE-bar in cm or in.:

Special instructions:

    1. Use a 2.2-kN (500-lb) seating load before zeroing the gages.

    2. Apply the load at a maximum rate of 4.4 kN (1000 lb) per/min.

    3. Use a value of E = 200 GPa (29×10^6 psi) and a Yield Point = 250 MPa (36,000 psi).

Scale Reading kg or lb	Dial Reading of RE-bar Slip, mm or in.			Remarks
	Specimen 1	Specimen 2	Specimen 3	

Data Sheet (ASTM Designation: C 234)

Date specimens were cast: RE-bar orientation:

Description of test specimens:

Measured length of RE-bar from bottom of concrete to the center of the jaws of the testing machine:

Maximum elongation to yield of the RE-bar in cm or in.:

Special instructions:

1. Use a 2.2-kN (500-lb) seating load before zeroing the gages.
2. Apply the load at a maximum rate of 4.4 kN (1000 lb) per/min.
3. Use a value of E = 200 GPa (29×10^6 psi) and a Yield Point = 250 MPa (36,000 psi).

Scale Reading kg or lb	Dial Reading of RE-bar, mm or in.			Remarks
	Specimen 1	Specimen 2	Specimen 3	

Illustrative Example (ASTM Designation: C 234)

Date of test: 3/1/99 RE-bar orientation: horizontal top

Date specimens were cast: 2/1/99

Description of test specimens: 6 in. × 6 in. × 6 in. concrete cube

Measured length of RE-bar from bottom of concrete to the center of the jaws of the testing machine: 22.7 inches

Maximum elongation to yield point of RE-bar in cm or in.: 0.028 in.

Special instructions:

    1. Use a 2.2-kN (500-lb) seating load before zeroing the gages.

    2. Apply the load at a maximum rate of 4.4 kN (1000 lb) per/min.

    3. Use a value of E = 200 GPa (29×10^6 psi) and a Yield Point = 250 MPa (36,000 psi).

Scale Reading kg or lb	Dial Reading of RE-bar Slip, mm or in.		
	Specimen 1	Specimen 2	Specimen 3
500 lb	0.000 in.	0.000 in.	0.000 in.
1000 lb	0.000 in.	0.002 in.	0.0001 in.
1500 lb	0.001 in.	0.003 in.	0.002 in.
2000 lb	0.002 in.	0.005 in.	0.007 in.
2500 lb	0.004 in.	0.007 in.	0.008 in.
3000 lb	0.007 in.	0.008 in.	0.009 in.
3500 lb	0.010 in.	0.010 in.	0.015 in.
4000 lb	0.012 in.	0.011 in.	0.016 in.
4500 lb	0.014 in.	0.014 in.	0.017 in.
5000 lb	0.017 in.	0.018 in.	0.021 in.
5500 lb	0.020 in.	0.023 in.	0.028 in.
6000 lb	0.023 in.	0.027 in.	0.033 in.
6500 lb	0.029 in.	0.031 in.	0.041 in.
7000 lb	0.037 in.	0.039 in.	0.049 in.
7500 lb	0.044 in.	0.049 in.	0.069 in.
8000 lb	0.058 in.	0.068 in.	Concrete
8500 lb	0.077 in.	Concrete	Failed
9000 lb	Concrete	Failed	
9500 lb	Failed		

Illustrative Example (ASTM Designation: C 234)

Length of RE-bar embedment (L) in cm or inches = 6 inches

Nominal diameter of RE-bar (d) in cm or inches = 0.75 inches

Bond area between the concrete and the RE-bar = πdL = 14.14 in.^{2}

Bond stress in MPa or psi = $\dfrac{\text{Load in newtons or lb}}{\text{Bond Area in m}^2\text{ or in.}^2}$

Load = kg × g = Newtons or Load in lb	RE-bar Slip, mm or in., and Orientation			Bond Stress in MPa or psi
	Horizontal Top	Horizontal Bottom	Vertical	
500 lb	0.000 in.	0.000 in.	0.000 in.	35 psi
1000 lb	0.001 in	0.000 in.	0.000 in.	71 psi
1500 lb	0.002 in.	0.001 in.	0.000 in.	106 psi
2000 lb	0.005 in.	0.001 in.	0.002 in.	141 psi
2500 lb	0.006 in.	0.002 in.	0.003 in.	177 psi
3000 lb	0.008 in.	0.004 in.	0.005 in.	212 psi
3500 lb	0.012 in.	0.005 in.	0.006 in.	248 psi
4000 lb	0.013 in.	0.006 in.	0.008 in.	283 psi
4500 lb	0.016 in.	0.008 in.	0.011 in.	318 psi
5000 lb	0.019 in.	0.011 in.	0.014 in.	354 psi
5500 lb	0.024 in.	0.014 in.	0.018 in.	389 psi
6000 lb	0.028 in.	0.019 in.	0.023 in.	424 psi
6500 lb	0.034 in.	0.025 in.	0.029 in.	460 psi
7000 lb	0.042 in.	0.030 in.	0.033 in.	495 psi
7500 lb	0.054 in.	0.037 in.	0.038 in.	530 psi
8000 lb	0.063 in.	0.041 in.	0.044 in.	566 psi
8500 lb	0.077 in.	0.046 in.	0.051 in.	601 psi
9000 lb		0.052 in.	0.062 in.	626 psi
9500 lb		0.059 in.		672 psi
10,000 lb		0.072 in.		707 psi
10,500 lb				742 psi
11,000 lb				778 psi

Data Sheet (ASTM Designation: C 234) Summary Sheet

Length of RE-bar embedment (L) in cm or inches =

Nominal diameter of RE-bar (d) in cm or inches =

Bond area between the concrete and the RE-bar = πdL =

Bond stress in MPa or psi = $\dfrac{\text{Load in newtons or lb}}{\text{Bond Area in m}^2 \text{ or in.}^2}$

Load = kg × g = Newtons or Load in lb	RE-bar Slip, mm or in., and Orientation			Bond Stress in MPa or psi
	Horizontal Top	Horizontal Bottom	Vertical	

Ball Penetration in Freshly Mixed Concrete
(ASTM Designation: C 360)

Purpose

Applicable for the determination of the depth of penetration of a metal weight into freshly mixed hydraulic cement concrete. The consistency of concrete is measured by the penetration of a cylinder into fresh concrete. The objective of this test procedure is similar to that of obtaining the slump of a freshly mixed concrete, ASTM Designation: C 143. The latter is the more frequently used method, although ASTM Designation: C 360 may afford a better guide to the workability of a concrete mix.

Equipment and Materials

- The ball penetration apparatus of a 14 ± 0.05 kg (30 ± 0.1 lb) cylinder with a hemispherical shaped bottom (the dimensions and the configuration of the apparatus is shown in Figure 29); watertight metal bucket having approximately equal height-to-diameter ratio so that the center of the stirrup of the ball penetration apparatus will be able to rest on the rim (approximately 25 cm [10 in.]) of the pail; round steel tamping rod 16 mm (⅝ in.) diameter, having the tamping end rounded to a hemispherical tip, approximately 60 cm (24 in.) long
- Necessary hand tools such as shovels, scoops, rubber gloves, and a small wood float

Test Procedure

Fill the metal pail to the top in three lifts, tamping each lift 25 times as specified in ASTM Designation: C 138, and then strike off the fresh concrete to a smooth surface at the same level as the top of the pail. The pail should be resting on a smooth surface and not subject to any vibrations during the course of the test. Set the base of the apparatus on the rim of the pail, lower the weight (sometimes referred to as the *Kelly Ball*) to the surface of the concrete, and then release it slowly. After the weight has come to rest, read the penetration to the nearest 6.4 mm (¼ in.). The scale for this test is calibrated in the U.S. Standard System of Measurements. The values may readily be converted the SI measurements by reference to the metric equivalents table shown under the diagram in Figure 30. Take a minimum of three readings. Empty and refill the pail for the same concrete batch for each reading. If the difference between the minimum and maximum reading exceeds 2.5 cm (1 in.), repeat the test. Take additional readings until three successive results are within 2.5 cm (1 in.).
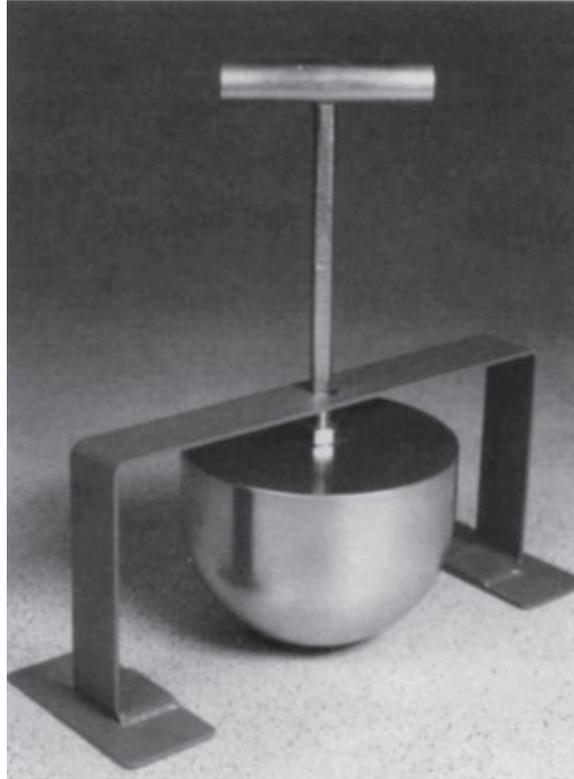
Figure 29
Ball penetration apparatus. Courtesy of ELE International, Inc., Soiltest Products Division, Lake Bluff, Illinois.

Explanation of Computations and Data Sheet

1. Computations: After three consecutive test results are within 1 in. (25 mm), take the average of the three as the value of the ball penetration to the nearest ¼ inch in the Standard U.S. System of Measurements. If SI measurements are used, convert to the nearest mm.

2. Data Sheet: Use the following suggested data sheet or devise any other suitable one. Note that in this test procedure the U.S. Standard System of Measurements is regarded as the standard. However, the result may readily be converted to the nearest mm.

    Three tables are shown below. The first one is for purposes of illustration. Note that six tests were made before three consecutive results were obtained with values within ¼ inch.
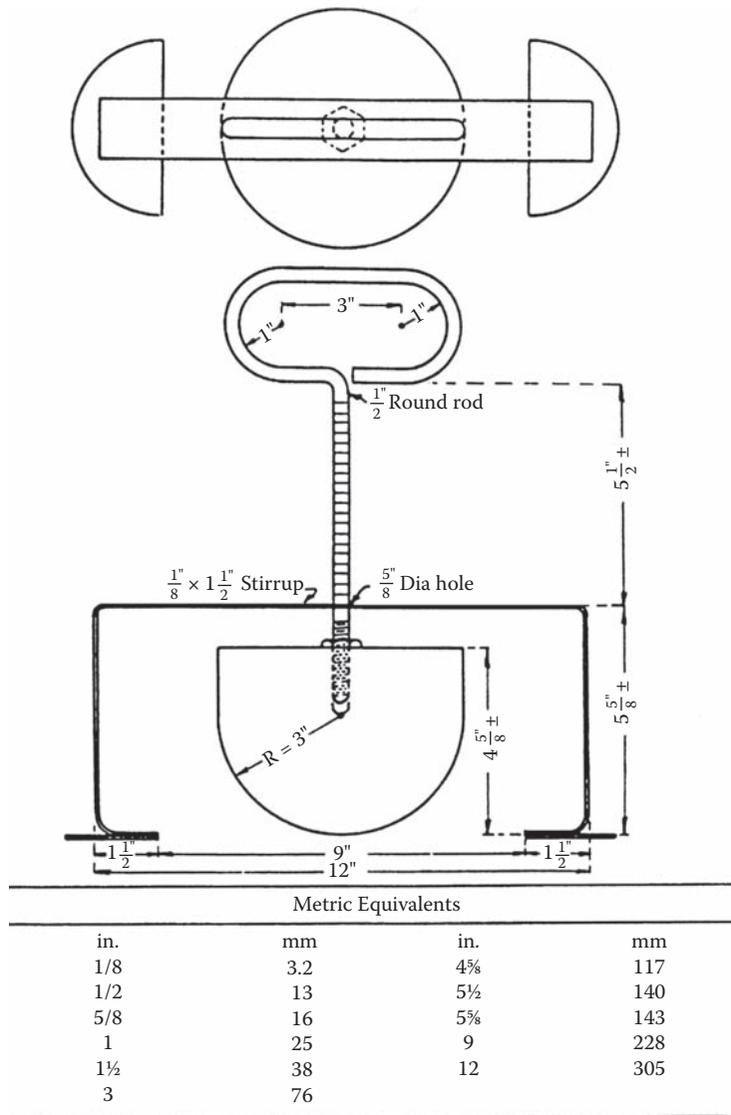
Figure 30
Ball penetration apparatus and metric equivalents. Copyright ASTM. Reprinted with permission.

Test No. and Ball Penetration to the Nearest ¼ in.								
1	2	3	4	5	6	7	8	9
1½ in.	1¼ in.	1 in.	1¾ in.	1½ in.	1½ in.			
Average of last three readings = 1½ in. (38 mm)								

Test No. and Ball Penetration to the Nearest ¼ in.								
Average of last three readings =								

Test No. and Ball Penetration to the Nearest ¼ in.								
1	2	3	4	5	6	7	8	9
Average of last three readings =								

Test No. and Ball Penetration to the Nearest ¼ in.								
Average of last three readings =								

Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
(ASTM Designation: C 469)

Purpose

To determine Young's Modulus and Poisson's Ratio of Portland Cement Concrete under longitudinal compression, using the chord modulus to define elasticity.

Equipment and Materials

- Compression testing machine
- Compressometer-extensometer, as shown in Figures 31, 32, and 33
- A set of steel caps of appropriate diameter with neoprene contact pads
- A small bubble level to assure that the yokes are parallel
- External calipers and a steel ruler, accurate to the nearest 0.25 mm (0.01 inch)

Test Procedure

Determine the diameter of the specimen at the mid-height by averaging two diametrical measurements to the nearest 0.25 mm (0.01 inch). Both ends of the specimen, top and bottom, should be capped with the contact pads. Use the small vial level to assure that all three yokes are level when they are secured to the specimen. After the specimen has been placed in the compressometer-extensometer, using a nominal 20-cm (8-inch) gauge length and carefully seated on the compression machine, measure the gauge length to the nearest 0.25 mm (0.01 inch). Apply the mass or force to the specimen at a rate of 450 kg (1000 lb)/minute. Each specimen will have at least three loading cycles. During the first loading procedure, no data will be recorded. The purpose of the initial loading is for seating the gages, observing the performance of the assembly, and to note any problems. Then proceed to take at least two subsequent cycles of loading and unloading. The number of loading cycles will depend upon the reproducibility of the test results. The values used will be the average of two consecutive cycles, when they are reasonably similar. Therefore, the number of loading cycles that are necessary will depend upon the test results. Prior to conducting ASTM Designation: C 469, it is necessary to have determined the compressive strength of the specimens, using ASTM Designation:

C 39, so that the ultimate compressive strength is fairly accurately known. Compute 25% and 40% of the estimated average ultimate load for comparable concrete specimens. The test procedure is as follows:

1. Take the first load and transverse strain reading when the longitudinal strain reaches 0.000050 inches/inch. Note that because of the way the yoke is hinged, the value of the transverse strain reading needs to be divided by 2 in order to obtain the correct value of the strain.

2. Take longitudinal and transverse strain readings at 25% and 40% of the estimated ultimate compressive load. Remember always to divide the transverse strain reading by 2.

3. After having taken the readings at the 40% point, unload the specimen and reset both gages.

4. Repeat steps 1 and 2.

5. If two consecutive cycles yield similar results, stop the test, remove the compressometer-extensometer, and load the specimen to failure. Record this value on the same data sheet. It should be comparable to that obtained from similar specimens tested under ASTM Designation: C 39. No two concrete specimens, even from the same concrete batch, will test identically.

6. Four individuals are required to conduct this test. One each to take notes, read the two gages, and to operate the compression machine.

Explanation of Computations and Data Sheet

1. Computations: The modulus of elasticity, E, which is also commonly referred to as Young's Modulus, is the ratio of the normal stress to the corresponding strain (s/ε) for compressive or tensile stresses below the proportional limit of the material.

   The English mathematician, Robert Hooke (1635–1703), derived Hooke's Law. From this the English scientist, Thomas Young (1773–1829), developed the modulus of elasticity, E. It is a measure of a material's stiffness or tendency to deform under load. Another direct result of Hooke's Law is Poisson's Ratio, μ, which was discovered by the French mathematician, Simeon Denis Poisson (1781–1840). It is the absolute value of the ratio of lateral strain to axial strain. It is the amount that a material will change in girth, or its tendency to change in volume, under load. The range of μ is between zero and 0.5. For ideal materials, if $\mu = 0$ then the axial strain would produce no lateral deformation, while if $\mu = 0.5$, the material would be perfectly incompressible.

   For normal weight concrete, E ranges from 14 to 41×10^3 MPa (2 to 6×10^6 psi). An approximate relationship also exists between E and the compressive strength of concrete cylinders. In the SI System a commonly used approximation is $5 \times 10^3 \times f_c'^{1/2}$. In the U.S. Standard System of Measurements it is $57 \times 10^3 \times f_c'^{1/2}$. Lightweight or very high-strength concrete exhibit other relationships between E and f_c'.

   There are a number of ways by which the Young's Modulus for concrete can be computed. Consider the generalized stress–strain curve for concrete above Figure 31, in which the longitudinal strain is the abscissa and the compressive stress is the ordinate in psi. The f_c' for the specimen was estimated at 3600 psi from previous tests of the same mix concrete at the same age and, therefore 40% = 1440 psi.

   a. The chord modulus method is derived from the slope between a strain of 50×10^{-6} and the stress at 40% of f_c'. On the graph it is defined as the line connecting the curve at C and at S. The resulting equation is SC = $(1440 - 200)/(400 - 50)10^{-6}$. Since this is the recommended mathematical relationship for obtaining E, the formula that forms the basis for the data sheet used in this test is

$$E = (s_2 - s_1)/(\varepsilon_2 - 0.000050)$$

$$E = (1440 - 200)/(400 - 50) \times 10^{-6} = 3.5 \times 10^6 \text{ psi}$$

E = the chord modulus of elasticity

s_2 = stress corresponding to 40% of the estimated ultimate load or ultimate stress, based upon previously tested specimens in accordance with ASTM Designation: C 39

s_1 = stress corresponding to a longitudinal strain of 0.000050

ε_2 = longitudinal strain corresponding to the s_2 stress

ε_1 = the strain 0.000050 and, therefore, does not appear in the formula for E
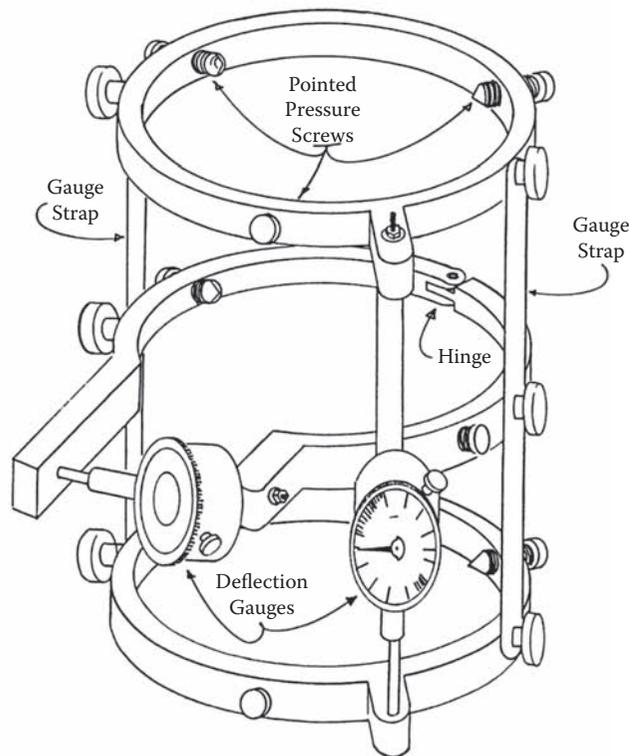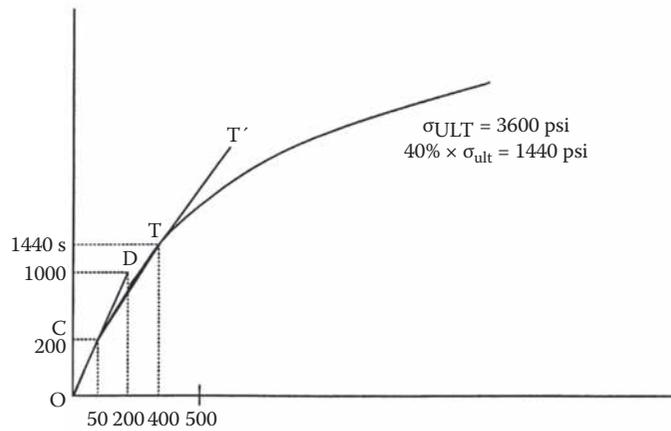
Figure 31

Three-dimensional drawing of the compressometer-extensomer. The compressometer-extensometer measures axial and diametrical deformation of concrete test specimens. The top and bottom metal rings and the yoke in the center move with the specimen under controlled loading. The deflection gages register changes in length and diameter as the vertical pressure is increased. This provides the data for a stress–strain diagram. The gauge straps are removed after the assembly with the specimen positioned in the compression machine and before any load is applied.

b. The dynamic modulus is derived from an approximation of the tangent to the curve at the origin, say the line OD. Therefore, the value of E would be $1000/200 \times 10^{-6} = 5 \times 10^6$ psi.

c. The secant modulus corresponds to the line SO, which is from the origin to the 40% point stress. The value of E would be $1440/400 \times 10^{-6} = 3.6 \times 10^6$ psi.

d. The tangent modulus corresponds to a line, drawn by eye, that is tangent to the curve at the 40% f'_c point, T – T′. The value for this modulus of elasticity would be about $(1440 - 940)/200 \times 10^{-6} = 2.5 \times 10^6$ psi.
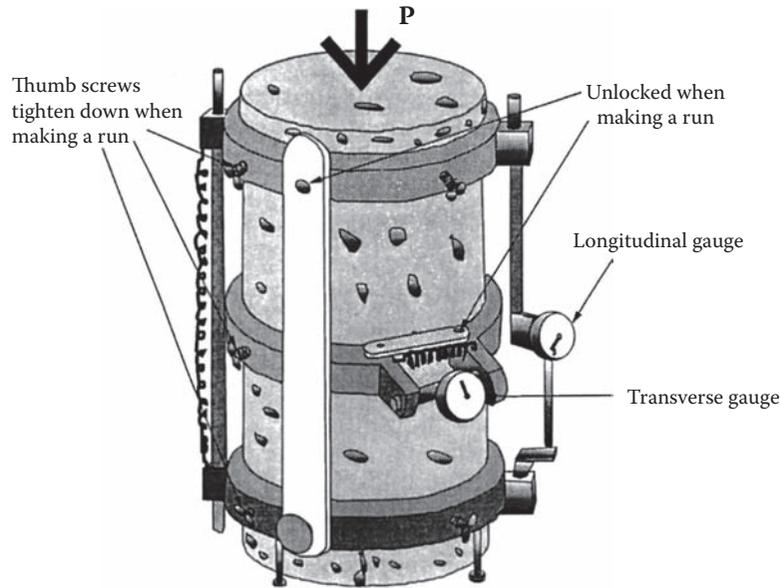
Figure 32

Assembly of the compressometer-extensometer and the specimen. After the data is obtained, the device is removed and the concrete cylinder is loaded to failure.

e. The chord modulus of elasticity, which is the one used by ASTM in this test procedure, generally computes somewhat of a mid-range of the other moduli. As a matter of fact, there is still another modulus of elasticity discussed in texts on mechanics of materials and that is the flexural modulus of elasticity for simply supported beams whose equation is

$$E = PL^3/48Iy$$

where

   P = the load

   L = the unsupported length

   I = the moment of inertia

   y = the mid-span deflection

f. The data required for Poisson's Ratio is obtained simultaneously while collecting the data for Young's Modulus in this testing procedure. When the concrete cylinder is loaded in uniaxial compression, as shown in Figure 33, it will experience a shortening in the longitudinal direction; that is, along the loaded axis, and an expansion in the plane at right angles. In other words, the diameter will increase in size, a lateral strain. The ratio of axial to lateral strain is referred to as *Poisson's Ratio*. The extreme range of values for Poisson's Ratio for concrete is about 0.15 to 0.25, with the aggregate, moisture content, age of the concrete, and compressive strength being contributing factors. The equation for Poisson's Ratio is

$$\mu = (\varepsilon_{t2} - \varepsilon_{t1})/(\varepsilon_2 - 0.000050)$$

where

$\varepsilon_{t2} - \varepsilon_{t1}$ = the transverse strain divided by 2 at stresses s_2 and s_1, respectively, and ε_2 = longitudinal strain corresponding to the s_2 stress, as previously defined in the section "Explanation of Computations and Data Sheet," item 1a. As an illustration, Poisson's Ratio is computed to the nearest 0.00 as follows:

$$\mu = (0.000088 - 0.000003)/(0.00049 - 0.000050) = 0.19$$

2. Data Sheet: The following data sheet illustrates, by example, the determination of E and μ using the U.S. Standard System of Measurements. There would have been no difference in using data from the SI System. Three points are determined in each loading cycle. The first one is longitudinal strain controlled at 0.000050. The other two are stress controlled at the estimated 25% and 40% of f'_c.
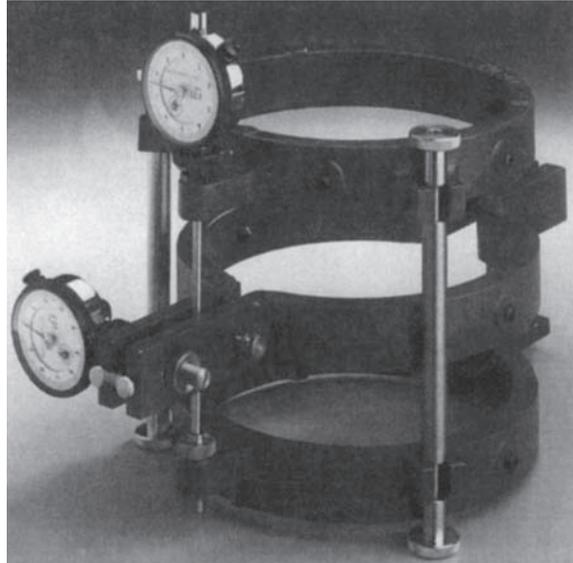
Figure 33

Photograph of a concrete cylinder compressometer-extensometer, designed in accordance with ASTM standards for the measurement of axial and diametrical deformation of specimens with dimensions 152 mm × 305 mm or 6 in. × 12 in. Courtesy of ELE International, Inc., Soiltest Products Division, Lake Bluff, Illinois. Note that the mechanism consists of three horizontal and parallel rings and two deflection gages. The rings have an inside diameter of 177 mm (7 in.) and are initially connected together by two gauge-length straps that set the distance between the rings. The overall gauge length is 203 mm (8 in.). A deflection gauge is positioned between the upper and lower rings to measure the change in longitudinal length under axial compression. The middle ring is hinged at the back side, has a spring at the front to keep it closed, and has a deflection gauge positioned between two points on the front of the ring. Since what is desired is the change in diameter, the reading of the deflection gauge connected to the middle ring needs to be divided by two, as previously explained. The two gages do not differ but move in opposite directions. Both deflection gages should read in increments of 0.00254 mm (0.0001 in.), with 100 increments per revolution of the dial. Notice that the two vertical gauge straps must be removed or better still remain connected only to the middle ring, after the unit is attached to the concrete cylinder but before any load is applied. While the test is being conducted, the top and bottom rings must be free to move in relation to one another, and the middle ring must be free to record changes in the girth of the cylinder.

If you look at the bottom of the blank data sheet at the end of this chapter, you will see a line marked "Dial Readings." For each testing cycle there are six bits of information that are read from the testing machine: the load for stress, S_1, and a total of five readings from the two gages. Two of the readings are from the longitudinal dial gauge and three from the transverse dial gauge. As mentioned previously, the transverse deformations need to be divided by 2 since the hinge is located 180° from the gauge. This is best done when the notes are reduced in computing the transverse strain. In other words, the transverse deformations indicated on the data sheet represent the expansion of the concrete at the center of the specimen.

The longitudinal deformation comparable to S_1 is computed by multiplying the longitudinal strain of 0.000050 by the gauge length. In the illustrative example, 0.000050 × the gauge length of 8.00 inches results in the value $4 × 10^{-4}$ inches, which is the same for each cycle. The five strain computations are obtained by dividing the longitudinal and transverse deformations by their respective length and diameter dimensions. For example, in the second cycle the longitudinal deformation at the stress, S, of 45 is divided by the measured gauge length of 8.00 to obtain 5.6. Similarly the comparable transverse deformation of 3.4/2 was divided by the average measured diameter of 6.00 to get the value of 0.28. You will notice that there is room on the data sheet for four loading cycles.

If more cycles are required, another data sheet would be needed for cycles 5 and more, which is not usually the case. In the illustrative example, cycles 3 and 4 were averaged for computing Young's Modulus and Poisson's Ratio. Cycle 4 was not really required since the values of 2 and 3 were reasonably close, although 3 and 4 are marginally closer. From the formulas previously stated in the section "Explanation of Computations and Data Sheet," item 1a for E and item 1f for μ, the values $2.57 × 10^6$ psi and 0.13, respectively, were computed. Once a sufficient number of loading cycles were performed, the compressometer-extensometer was removed and the specimen was loaded to failure, 153,000 lb, which compared quite favorably to the estimated 150,000 lb, from the specimens of the same concrete mix that were tested under conditions of ASTM Designation: C 39. Additional data sheets can be found in the Appendix.

Stress/Strain Data Sheet for the Determination of Young's Modulus and Poisson's Ratio for Concrete in Compression (ASTM Designation: C 469)

Stress MPa(psi)		Load kg (lb)	Deformation—mm(in. × 10⁻⁴) Longitudinal Transverse		Longitudinal Transverse Strain—mm/mm(in./in.) × 10⁻⁴	
S_1 – Comp	_____	Comp	_____	0.50	Comp	
$S = 0.25\ S_{ult}$	Comp	_____	_____	Comp	Comp	
$S = 0.40\ S_{ult}$	Comp	_____	_____	Comp	Comp	
S_1	191	5400	4	0	$0.50\varepsilon_1$	$0.0\varepsilon_{t1}$
S	1310	37,000	45	3.4	5.6	0.28
S_2	2120	60,000	63	11.5	$.9\varepsilon_2$	$0.96\varepsilon_{t2}$
S_1	212	6000	4	0	0.50	0
S	1310	37,000	39	5.1	4.	0.43
S_2	2120	60,000	57	10.	7.1	0.88
S_1	230	6400	4	0	0.50	0
S	1310	37,000	50	6.1	6.3	0.51
S_2	2120	60,000	65	12.5	8.1	1.00
S_1	210	5900	4	0	0.50	0
S	1310	37,000	45	4.9	5.6	0.41
S_2	2120	60,000	62	11.5	7.7	0.95

_____ = Dial readings   Comp = Computed from data

Age of specimen = 28 days

Longitudinal gauge distance = 8.00 inches

Diameter of specimen = 6.00 inches

Ultimate compressive load of test specimen = 153,000 lb

$E = 2.57 \times 10^6$ psi   ; $\mu = 0.13$

Remarks: all loads in pounds and dimensions in inches.

Stress/Strain Data Sheet for the determination of Young's Modulus and Poisson's Ratio for Concrete in Compression (ASTM Designation: C 469)

Stress MPa(psi)	Load kg (lb)	Deformation—mm(in. $\times 10^{-4}$) Longitudinal Transverse		Longitudinal Transverse Strain—mm/mm(in./in.) $\times 10^{-4}$	
S_1 – Comp	—	Comp	—	0.50	Comp
$S = 0.25\ S_{ult}$	Comp	—	—	Comp	Comp
$S = 0.40\ S_{ult}$	Comp	—	—	Comp	Comp
S_1				0.50	
S					
S_2					
S_1				0.50	
S					
S_2					
S_1				0.50	
S					
S_2					
S_1				0.50	
S					
S_2					

_____ = Dial readings   Comp = Computed from data

Age of specimen =

Longitudinal gauge distance =

Diameter of specimen =

Ultimate compressive load of test specimen =

E =   ; μ =

Remarks:

Splitting Tensile Strength of Cylindrical Concrete Specimens
(ASTM Designation: C 496)

Purpose

To determine the splitting tensile strength of cylindrical concrete specimens. This test procedure is also referred to as the *Brazil Test* because it was developed by a Brazilian engineer.

Equipment and Materials

- Testing machine used for ASTM Designation: C 39.
- If the diameter or the largest dimension of the upper bearing face is less than the length of the test cylinder, a supplementary bar is to be used with a length at least the length of the specimen, 5.1 cm (2 in.) wide, and a thickness not less than the overhang distance between the bearing face of the testing machine and the specimen; the bar must be machined to within 0.025 mm.
- Wood bearing strips of 3.2-mm (⅛-in.) thick plywood strips, 25 mm (1 in.) wide, slightly longer than the length of the specimen. These wood strips are to be placed between the steel bars and the specimen to take account of deviations in the surface of the specimen, and are to be used only once and then discarded.
- Suitable apparatus for aligning the specimen as shown in Figure 34.

Test Procedure

1. Draw diametral lines, cutting the axis of the cylinder at each end with the aid of a suitable alignment apparatus and then connect the diametral lines. See the sketch in Figure 35.

2. Determine the diameter of the concrete specimen by averaging diameter measurements to the nearest 0.25 mm (0.01 in.), one each at each end of the specimen and one at the center. Compute the length of the specimen by measuring the length at two locations, approximately 180° apart, to the nearest 2.5 mm (0.1 in.) and averaging them.

3. Center one of the plywood strips on the lower plate of the compression machine and center one of the diametral lines of the specimen over the middle of the wood strip.

4. Center another wood strip over the top diametral line of the specimen. Where necessary, carefully center the 5.1-cm (2-in.) wide steel bar over the wood strip (Figure 36).

5. Slowly lower the pressure head of the compression machine to the top of the steel bar or wood strip, as the case may be, until there is just enough pressure that the specimen is held in place.

6. Apply a steady load on a 15.2 cm (6 in.) diameter × 30.5 cm (12 in.) high concrete cylinder at an approximate rate of 4500 kg of mass per minute or 10,000 lb of force per minute. This translates to a stressing rate of 689 to 1380 kPa/min (100 to 200 psi/min). Record the load at failure, type of failure, and the appearance of the concrete at the plane of fracture.

A

$\frac{1"}{16}$

4"

Top

1"

Concrete
specimen

C

$8\frac{1"}{4}$

8"

B

$1\frac{1"}{4}$

16" min.

4"

Side

End

$\frac{1"}{16}$ aperture (cleft)

$\frac{1"}{2}$

$\frac{3"}{16}$

B

All faces machined and
precision fitted

Top

$\frac{1"}{2}$

Vertical $\frac{1"}{16}$
aperture in
center of bar

A
$\frac{1"}{16}$ aperture
(cleft)

C

$\frac{1"}{4}$

$\frac{1"}{4}$

$\frac{3"}{4}$

$\frac{1"}{2}$

$\frac{1"}{4}$

$\frac{1"}{4}$

Base plate
may be made of
4" channel

$\frac{3"}{16}$

$\frac{1"}{8}$

$\frac{3"}{16}$

End

Side
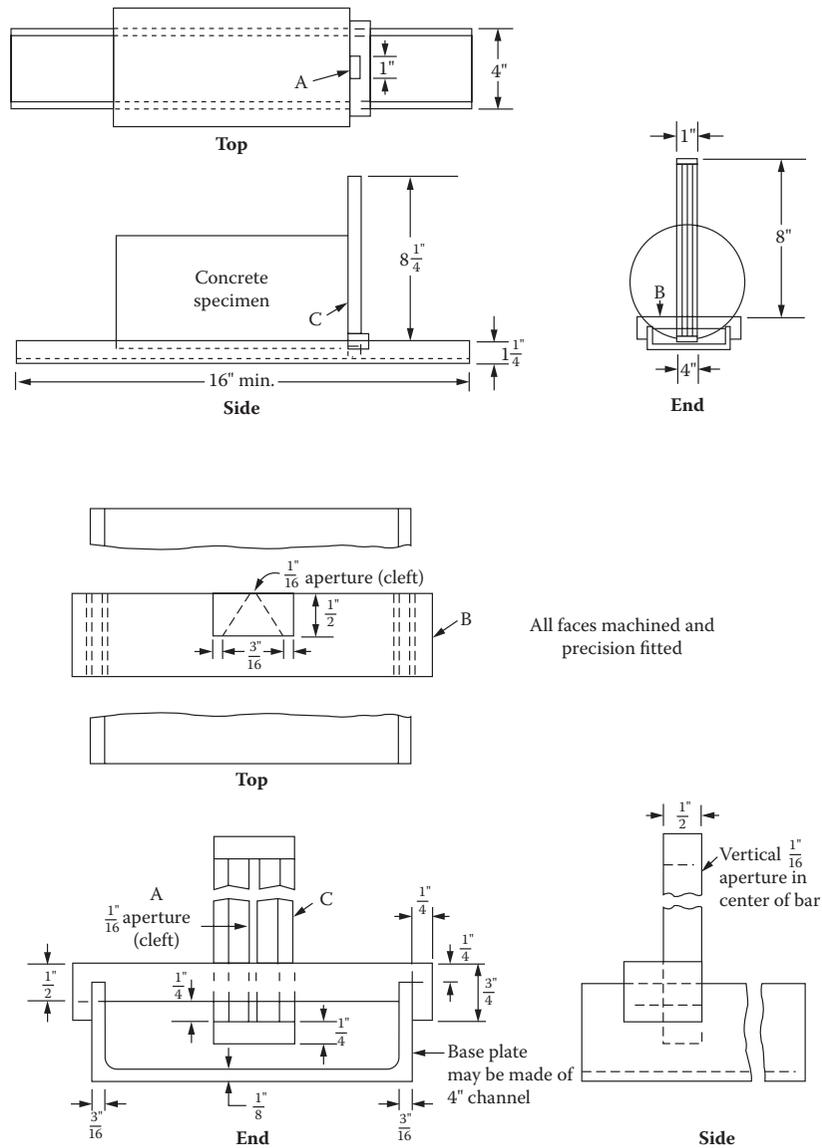
Metric Equivalents

in.	1/16	1/8	3/16	1/4	1/2	3/4	1	$1\frac{1}{4}$	2	$2\frac{1}{2}$	4	$7\frac{1}{2}$	8	$8\frac{1}{4}$	15	16
mm	1.6	3.2	4.8	6.4	13	19	25	32	50	65	100	190	200	205	375	400

Figure 34
Details of an apparatus for aligning a specimen. Copyright ASTM. Reprinted with permission.
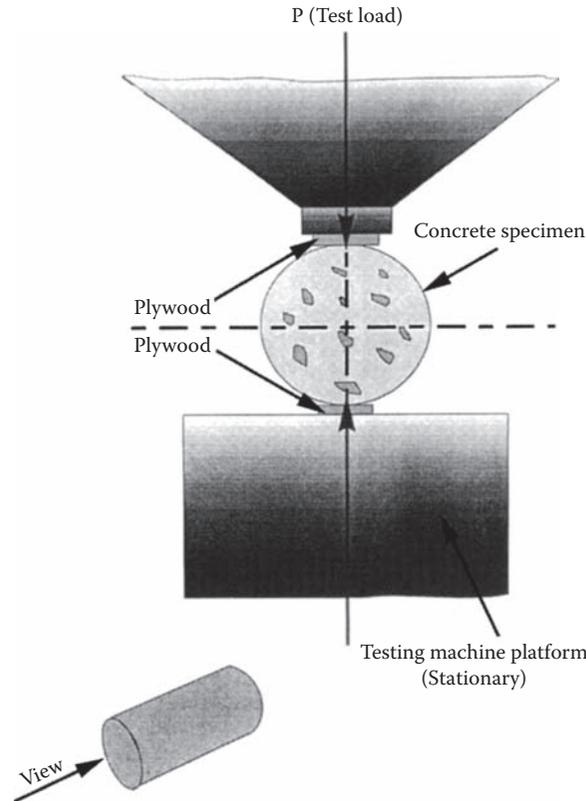
Figure 35
Diagram of a concrete cylinder in the testing machine, showing the front view of the diameter of the specimen and setup in profile.

Explanation of Computations and Data Sheet

1. Computations: The tensile splitting strength of a concrete cylinder is computed from the following formula:

$$T = (2 \times P)/(\pi \times l \times d)$$

T = the tensile splitting strength, kPa (psi)

P = the applied load at the time of failure of the specimen, lb (kN)

l = length of the cylindrical specimen in meters or inches

d = diameter of the specimen in meters or inches

The ASTM standard for this test is the value in inch-pound units. However, in conformity with the established procedure in this book, preference is still given to the SI System of Measurements. That is the accepted standard in most of the world and the United States is likewise moving in the direction of the SI System.

2. Data Sheet: Note the data and computed results on the following illustrative data sheet. Under the Remarks column for specimen number 1, it was noted that the failure took place because of coarse aggregate (C.A.) fracturing. In the other two specimens the failure took place in the mortar, that is, between the coarse aggregate particles. An important consideration in the testing of concrete mixes is the percent a particular strength parameter compares to the 28-day f'_c. The same consideration holds true for bond strength, tensile strength, etc. The standard by which all concrete strengths are compared is that of f'_c for the identical mix, cured under the identical conditions, and at the same age. Three parameters of measuring the tension strength of Portland cement concrete are included in this book. They are the modulus of rupture, M.R., of ASTM Designation: C 78; this test, ASTM Designation: C 496; and the direct tension test, which as yet has not been adopted by the ASTM but is included in the following testing procedure of this textbook. The first two are indirect evaluations of direct tensile strength, while the last is a direct evaluation. The latter method will be explained in the test procedure that follows.
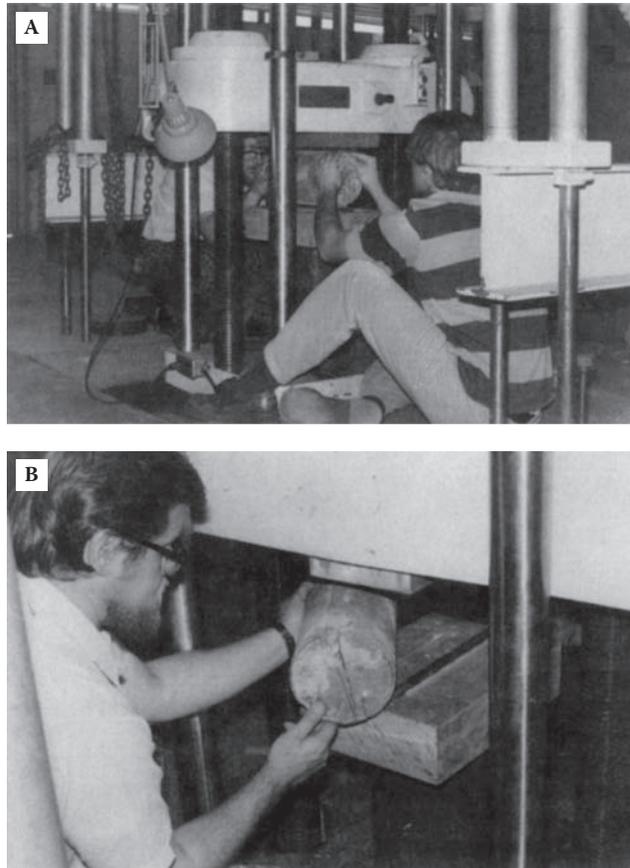
Figure 36
Top photograph showing the specimen being positioned in the testing machine. The bottom photograph was taken after the concrete specimen was loaded to failure and was being removed from the test apparatus with the fracture indicated.

Illustrative Example (ASTM Designations: C 496)

Date of test: 4/10/99

Date specimens were cast: 3/12/99

Description of specimen: moist cured for 28 days, the same mix design as used for compression specimens

Length of specimen, meters or inches = 12.0 inches

Diameter of specimen in meters or inches = 6.00 inches

f'_c concrete mix tested under ASTM Designation: C 39 = 5800 psi

Specimen Number	Max. Load, kg (mass) or lbf	Splitting Strength, kPa or psi	% f'_c	Remarks
1	50,000 lb/f	442 psi	7.7	C.A. fractures
2	55,000 lb/f	486 psi	8.4	mortar break
3	53,000 lb/f	469 psi	8.1	mortar break
Average		466 psi	8.0	

Note: $T = (2 \times P)/(\pi \times l \times d)$.

Data Sheet (ASTM Designation: C 496)

Date of test:

Date specimens were cast:

Description of specimen:

Length of specimen, meters or inches =

Diameter of specimen in meters or inches =

f'_c of concrete mix tested under ASTM Designation: C 39 =

Specimen Number	Max. Load, kg (mass) or lb/f	Splitting Strength, kPa or psi	% f'_c	Remarks

Note: $T = (2 \times P)/(\pi \times l \times d)$.

Rebound Number of Hardened Concrete
(ASTM Designation: C 805)

Purpose

To measure the rebound of a spring-loaded hardened steel l plunger after it has struck a smooth, solid, concrete surface. Only empirical relationships can be obtained between rebound hardness and the strength of the concrete. Unlike the standard test for the concrete strength, ASTM Designation: C 39, this is a nondestructive test. In 1948 a Swiss engineer, Dr. Ernst Schmidt, developed the first generally accepted impact hammer. It is sometimes referred to as the *Swiss Hammer.*

Equipment and Materials

- Spring-loaded steel rebound hammer, which when released strikes a steel plunger in contact with the concrete surface. The rebound distance of the steel hammer from the steel plunger is measured on a linear scale attached to the frame of the hammer (note the detail of the hammer and its method of use in Figures 37 and 38).
- Medium-grain textured silicon carbide abrasive stone for grinding smooth any loose mortar or other imperfections on the surface of the concrete to be tested.
- High-carbon tool steel test anvil, with dimensions of 15 cm diameter (6 in.) by 15 cm (6 in.) in height, with a fixture to center the rebound hammer over the impact area (hardened to a Rockwell 65-67 C) and designed to keep the device perpendicular to the concrete surface. The results of the test hammer should be verified twice a year by use of the test anvil (see photograph of the calibration anvil in Figure 39).

Test Procedure

1. The test hammer should be held perpendicular to the concrete surface. The plunger should be depressed by applying a gradual increase in pressure until it impacts. A reading is then taken from the scale on the side of the test hammer, while holding it firmly against the concrete. A button is provided to lock the pointer on the scale after impact in the event that it is not convenient to take the reading while holding the test hammer against the concrete. The latter case is particularly true when the hammer is held in an overhead position. Estimate the rebound on the scale to the nearest whole number.

2. Conversion graphs or tables are provided with the instrument to indicate a measure of compressive strength with the reading obtained from the test hammer scale. A typical set of such graphs is shown in Figure 37. Each instrument will come with its own set of graphs or tables, prepared by the manufacturer.

3. Take ten readings from each test area, with all the readings separated by at least 2.5 cm (1 in.). Disregard any reading where an impression is made on the surface of the concrete after the hammer impact, whether through crushing or breaking the surface or for any other visible surface imperfection.

4. If the rebound number on the anvil deviates from the nominal value shown on the manufacturer's instructions, the following formula applies:
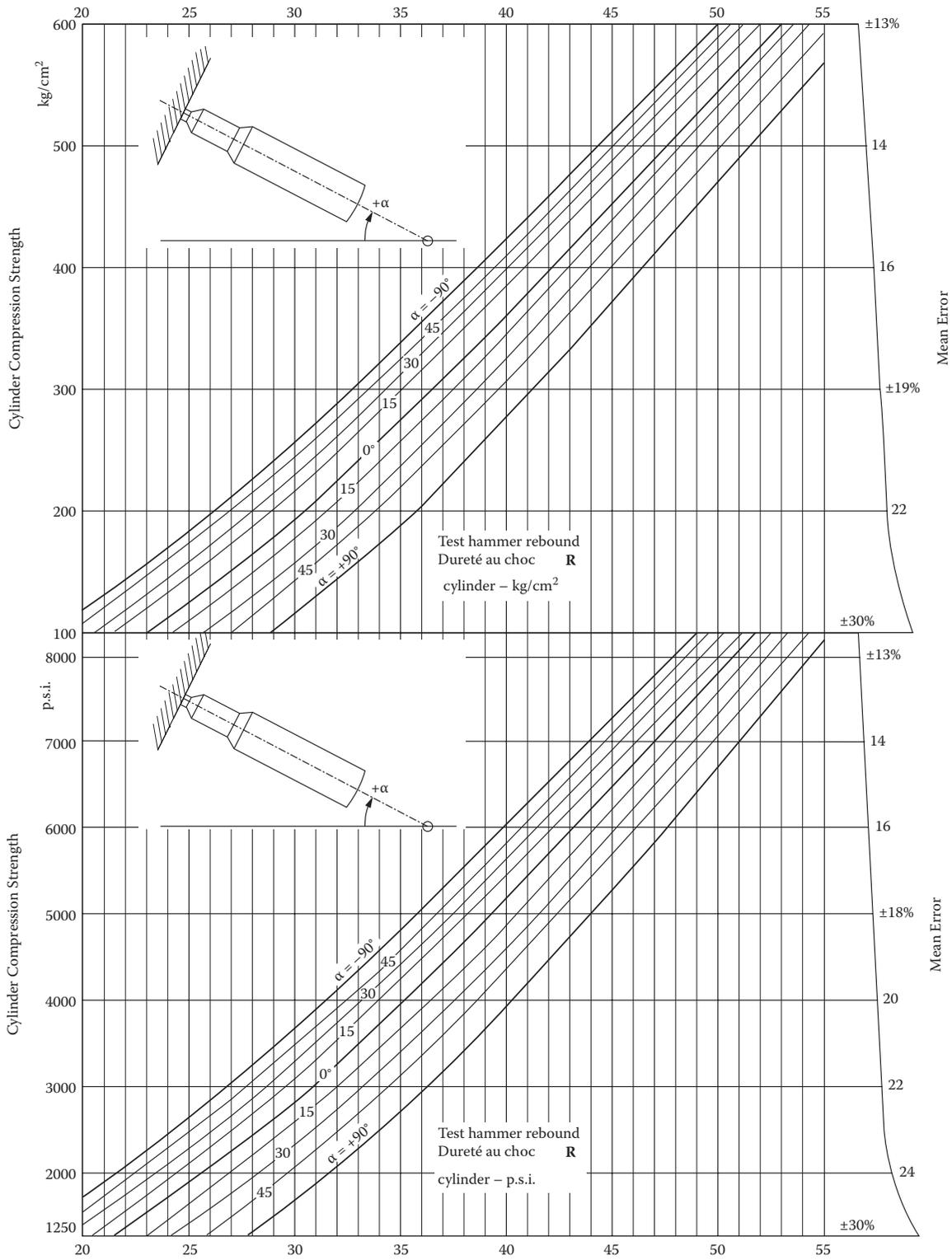
Figure 37
(a) Typical impact hammer calibration curves. Courtesy of ELE International, Inc., Soiltest Products Division, Lake Bluff, Illinois.
(b) Hammer in portable carrying case. Courtesy of Soiltest, Inc.
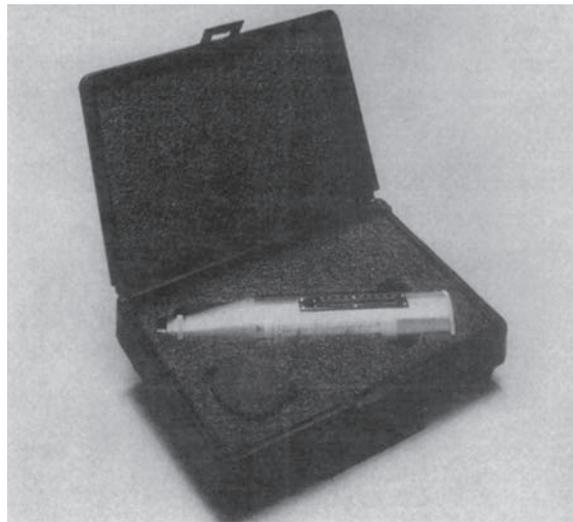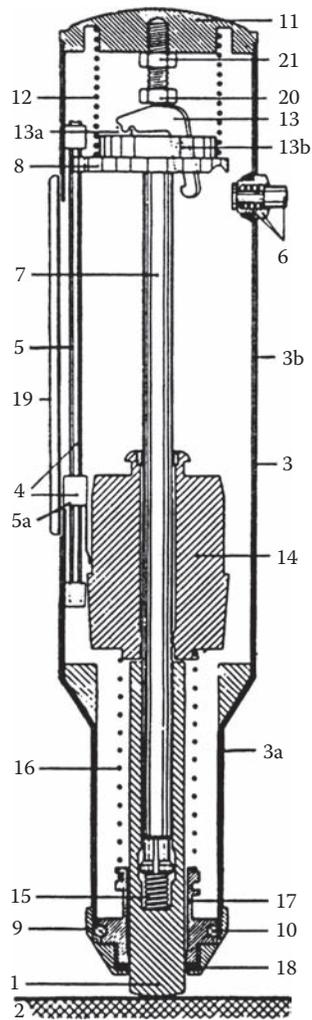
Figure 38
Details of the impact hammer. Courtesy of ELE International, Inc., Soiltest Products Division, Lake Bluff, Illinois.

$$R = \Sigma r/n \text{ (Specified Value on the Anvil}/R_a)$$

where

n = number of individual measurements, r, on the concrete, and R_a = rebound number of the test hammer on the anvil.

R = number measured on the concrete.

Explanation of Computations and Data Sheet

1. Computations: Take the average of the ten rebound readings. Discard those readings that differ from this average by 6 or more units. Compute the new average and determine the resultant compressive concrete strength. However, if more than two readings from the original set of ten differ by more than 6, the entire set should be discarded and ten new rebound readings taken at new locations within the test area.

2. Data Sheet: Ten readings are shown in the following Illustrative Example.. The average of the ten was found to be 49. However, two of the readings at 56 and 71 were 6 or more above the average of 49. Therefore, they were discarded and a new average for the remaining 8 values was computed to be 46. From the psi graph in Figure 37, the compressive strength of the
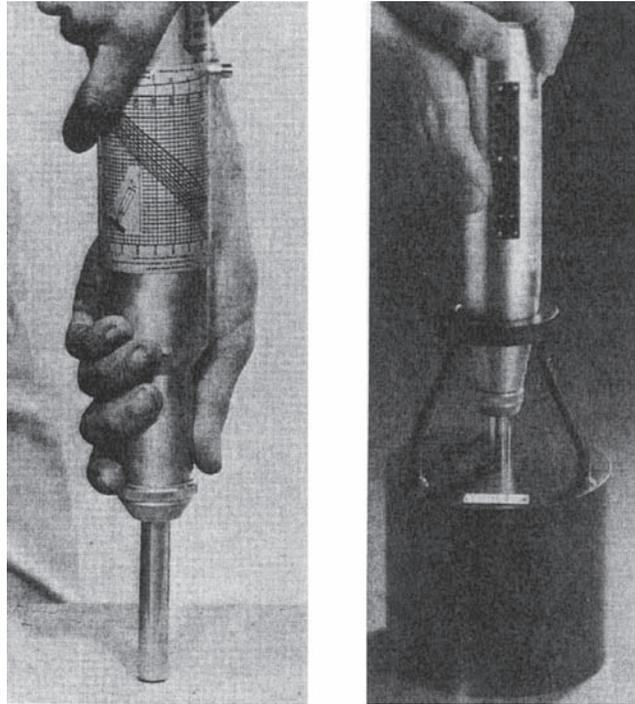
Figure 39
Photographs showing the impact hammer in operation in the vertical position, directed downward, and the calibration anvil for the impact hammer in the right photograph. Courtesy of ELE International, Inc., Soiltest Products Division, Lake Bluff, Illinois.

concrete was found to be 5400 psi for a vertically held hammer in a downward position. If a third value was 6 or more above the average of 49, the entire set would have been discarded. A blank data sheet is shown below the Illustrative Example and two additional ones are included in Appendix F. Again it must be emphasized that no theoretical relationship exists between the plunger rebound and the concrete strength. The rebound hammer should only be used in checking concrete uniformity and in comparing one concrete with another, not for any measure of absolute concrete strength.

Illustrative Example (ASTM Designation: C 805)

Test Number	Readings	Remarks
1	45	Test on 28-day concrete cylindrical test specimen, 6 in. × 12 in. height. Hammer held in a vertical position downward.
2	51	
3	37	
4	56	
5	39	
6	71	
7	47	
8	44	
9	50	
10	53	
Average of ten readings = 49		
Reading nos. discarded: 4 and 6		
New average = 46		
Concrete compressive strength, kPa or psi = 5400 psi		

Data Sheet (ASTM Designation: C 805)

Test Number	Readings	Remarks
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
Average of ten readings =		
Reading nos. discarded:		
New average =		
Concrete compressive strength, kPa or psi =		

Direct Tensile Test of Portland Cement Concrete
(Reference: None)
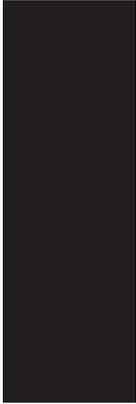
Purpose

To determine the tensile strength of a hydraulic concrete by a direct tension method. Because of the difficulty encountered in applying truly axial tensile loads to concrete specimens, direct tension testing of concrete specimens is rarely attempted. Both of the indirect indices of concrete tensile strength, namely the flexural and splitting tests, are known to yield results considerably higher than true tensile values. The method presented in this manual will be submitted to ASTM within the next year. In the meantime, I have decided to include the testing procedure herein.

Equipment and Materials

- All of the equipment and materials used in ASTM Designation: C 192, "Making and Curing Concrete Test Specimens," except that the molds should be a wax-coated cardboard disposable type
- Testing machine with jaw grips for holding the RE-bars of the test specimens
- Special fixtures to hold the specimen assemblies and align the RE-bar while they are being cast and allowed to develop the initial 24-hour strength before being placed in the curing facility; a photograph and details of the fixture are shown in Figure 40
- Machined No. 6 or 2-cm deformed RE-bars, 75 cm (30 in.) in length; see Figure 41, which shows the details of the RE-bar with a lubricated slip joint at the center

Test Procedure

1. Drill a hole at the bottom of the mold, just large enough to accommodate the RE-bar.

2. Lightly lubricate the RE-bar joint and assemble it into the fixture.

3. Prepare the specimens in accordance with ASTM Designation: C 192, including the filling of the mold in three lifts and tamping each 25 times, then striking off the excess concrete with a trowel to a smooth finish.

4. Follow the same curing and stripping instructions as for all laboratory prepared specimens, as indicated in ASTM Designation: C 192.

5. Just prior to testing, remove the specimens from the curing facility and measure the diameter of the cylinder at the center, by averaging two diameters at right angles to the nearest 0.25 mm (0.01 in.). Record the average diameter on the data sheet.

6. Place the specimen in the top and bottom jaws of the testing machine. The ends of each segment of RE-bar that is held by the jaws should be machined smooth with just the deformations removed for about 8 cm (3 in.).
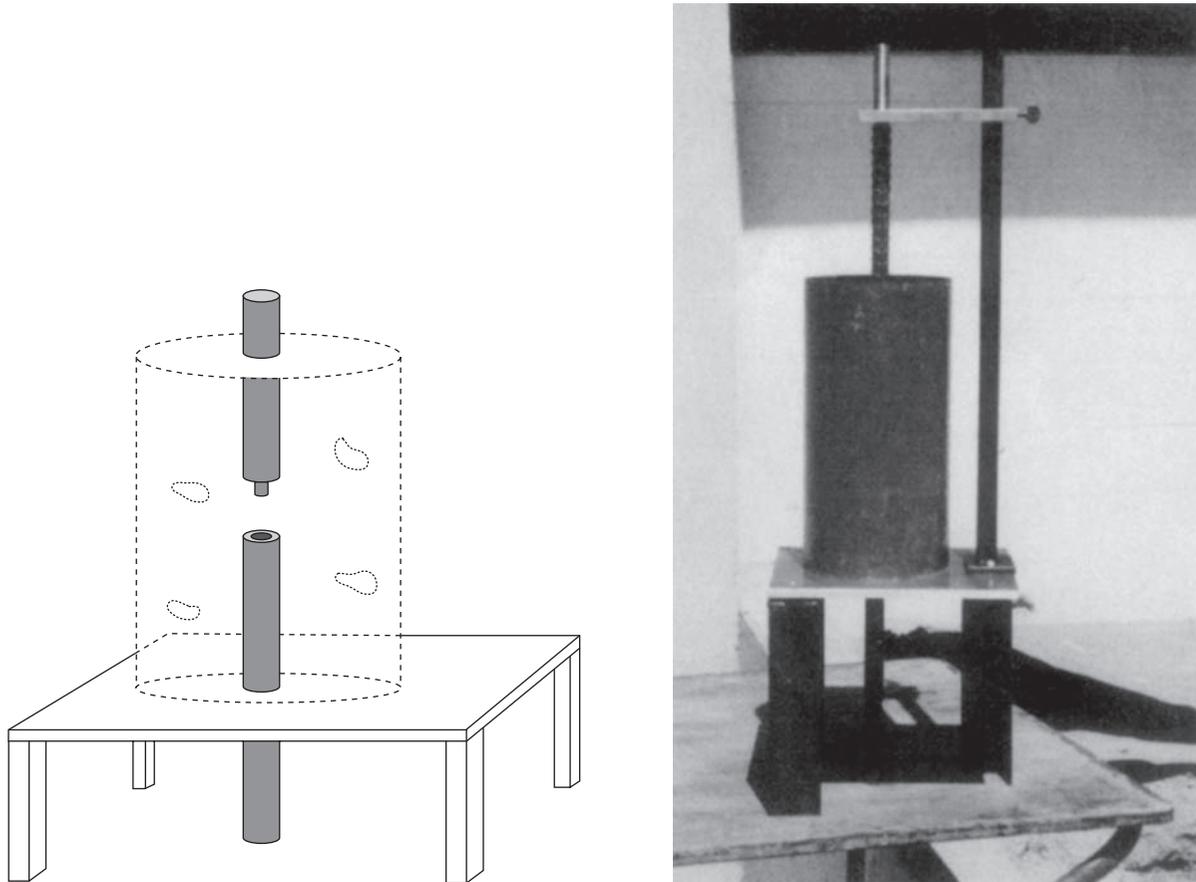
Figure 40
Photograph and sketch of fixture and RE-bar for concrete test specimens. Deformed RE-bar = 1 cm (⅜ in.) diameter. Drill to obtain close to a No. 6 bar or 2-cm diameter fit about 3 cm or 1⅛ in. in depth.

7. Once the specimen is properly gripped and seated in the jaws of the testing machine, apply load at the approximate rate of 4.4 kN/min or 1000 lb/min until failure. The rate of loading should be the same as for the Bond Strength Test (ASTM C 234).

8. Record the ultimate load, and the type and location of the failure.

9. See Figures 42, 43, and 44 for additional test details as well as the pictures of the specimens after failure.

Explanation of Computations and Data Sheet

1. Computations: In the sample computations and the illustrated data sheet, the U.S. Standard System of Measurements will be used. Therefore, a No. 6 deformed RE-bar will be assumed as well as a nominal 6-inch-diameter concrete cylinder. The cross-sectional area of the bar is taken as 0.44 square inches. The net cross-sectional area of the test specimen is, therefore,

$$28.27 \text{ in.}^2 - 0.44 \text{ in.}^2 = 27.83 \text{ in.}^2$$

The ultimate load is divided by the net cross-sectional area to determine the ultimate tensile stress at failure.

$$\sigma = P/A$$

The dimensions will depend upon the system of measurements used, whether kPa or psi.
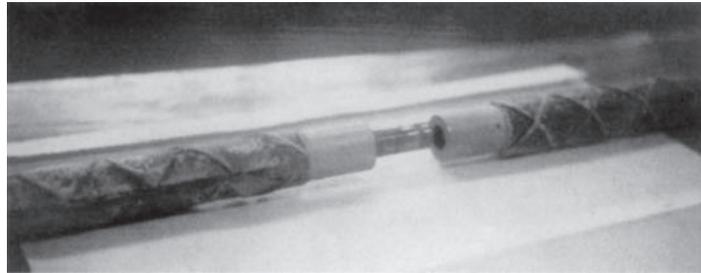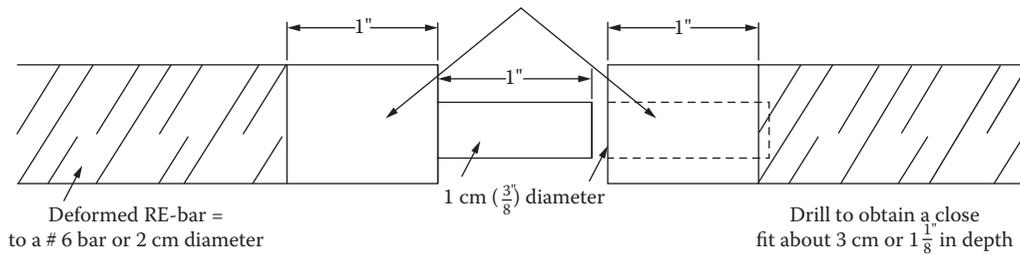
Figure 41
Photograph and details of the RE-bar at the joint assembly. Slip joint detail of the RE-bar for tension testing of concrete cylinders. The overall length of the finished RE-bar assembly = 75 cm or 30 in. The slip joint at the center is to be lightly lubricated. The ends of each RE-bar, at the joint, are to be machined to just remove the deformations for a length of about 2.5 cm or 1 in.

2. Data Sheet: An illustrated data sheet is shown below. It is common practice to prepare 12 test specimens and subject them to 7-day curing increments. The percent of the 28-day compressive strength, f'_c, is computed in this case for the average of the accepted values for each test group; that is, at 7, 14, 21, and 28 days. You will note that the results of several of the specimens were discarded, principally in this case because the values deviated so drastically from the other values in the group. You will notice also that in this particular test result, there was a relatively smaller percent increase in tensile strength over time than is usually the case with compression strengths within a 28-day period.
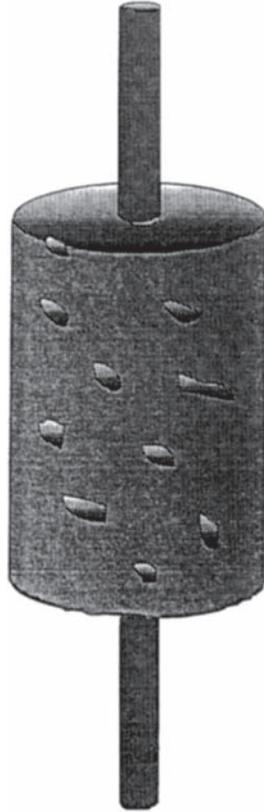
Figure 42
Sketch of a tension specimen ready for testing.
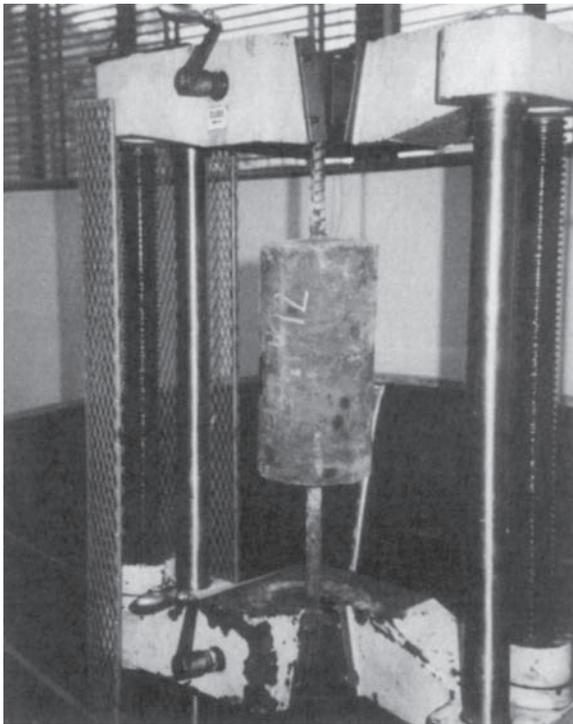
Figure 43
Cylindrical tension specimen in the testing machine.
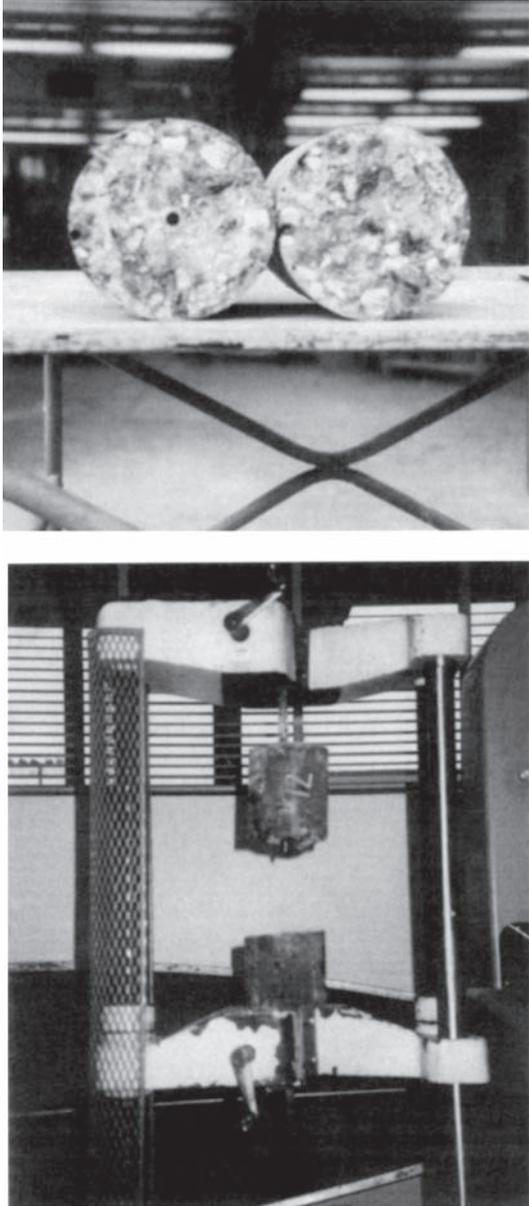
Figure 44
Photographs of a tension specimen after failure.

Illustrative Example for Direct Tensile Test

Date specimens were cast: 7/22/99

Description of test specimens: Same concrete mix design as for specimens tested in compression, ASTM Designation: C 39

Average diameter measured at the middle of specimen: 6.00 inches

f'_c from compression test specimens: 6450 psi

Specimen No.	Load, kg or lb	Tensile Stress, kPa or psi	Days Cured	% f'_c	Remarks
1	10,500 lb	377 psi	7		
2	10,000 lb	359 psi	7		
3	9800 lb	352 psi	7		
Average		363 psi	7	5.5	
4	10,500 lb	377 psi	14		
5	10,000 lb	359 psi	14		
6	10,000 lb	359 psi	14		
Average		365 psi	14	5.7	
7	11,700 lb	420 psi	21		
8	10,700 lb	384 psi	21		
9	10,500 lb	377 psi	21		
Average		394 psi	21	5.9	
10	10.700 lb	384 psi	28		
11	8000 lb	287 psi	28		Disregard
12	11,000 lb	395 psi	28		
Average		390 psi	28	6.0	

Data Sheet for Direct Tensile Test

Date specimens were cast:

Description of test specimens:

Average diameter measured at the middle of specimen:

f'_c from compression test specimens:

Specimen No.	Load, kg or lb	Tensile Stress, kPa or psi	Days Cured	% f'_c	Remarks

Part 4

Appendices

A: Measurement Conversion Factors between the S.I. System and the U.S. Standard Units

TABLE 18
Partial List of Factors to Convert the U.S. Standard Units of Measurements to the S.I. System[a]

Convert from	Multiply by	Dimension Obtained
cubic feet	0.028317	cubic meters
cubic yards	0.76456	cubic meters
feet	30.480	centimeters
feet	0.30480	meters
gallons (U.S.)	3.77853	liters
inches	2.5400	centimeters
miles (U.S.)	1.6093	kilometers
ounces	28.349	grams
pounds	453.59	grams
pounds	0.45359	kilograms
quarts	0.94633	liters
square feet	0.092903	square meters
square inches	6.4516	square centimeters
square yards	0.83613	square meters
stress (ksi)	6.8948	megapascals (MPa)
stress (psi)	6894.8	pascals (Pa)[b]
stress (psi)	0.0068948	megapascals (MPa)
temperature (°F)	$t_c = (t_f - 32)/1.8$	degree Celsius (°C)
temperature (°F)	$t_k = (t_f + 459.7)/1.8$	degree Kelvin (°K)
temperature (°K)	$t_c = t_k - 273.2$	degree Celsius (°C)
tons (short)	0.90718	metric tons
yards	0.91440	meters

[a] For a complete guide to the S.I. System refer to ASTM Designation: E 380.

[b] One pascal (Pa) = 1 newton per meter square, N/m^2. Since the pascal is a very small quantity, in practice, one uses multiples of this unit, namely, the kilopascal (kPa = 10^3 N/m^2), the megapascal (MPa = 10^6 N/m^2), and the gigapascal (GPa = $10^9 N/m^2$).

B: Laboratory Rules of Safety and Procedures

The following safety regulations apply to all individuals engaged in testing as well as to those who even casually enter the concrete laboratory area:

1. **SMOKING**—Strictly forbidden within any of the laboratory areas.
2. **CLOTHING**—Everyone should provide themselves with suitable work clothes, of substantial quality, in good repair, and clean, for use in the laboratory. Work shirts shall be long sleeved, rolled down, and buttoned at both the sleeves and the neck. Coveralls or a long-sleeved laboratory coat are suitable alternatives to other types of work clothes. Foot gear must include hard bottoms and uppers. Sandals, open-weave cloth shoes, tennis shoes, or other types with soft uppers or bottoms will not be permitted in the laboratory. Eye protection will be worn whenever materials are handled that could possibly shoot outward. Ordinary eyeglasses are defined as satisfactory, normal eye protection, and all students are encouraged to wear them when working in the laboratory. Goggles, when required, will be available in the laboratory.
3. **JOKES AND HORSEPLAY**—Tricks, practical jokes, and horseplay in any laboratory will result in severe disciplinary actions against the perpetrators. Every person has a responsibility to perform laboratory work with consideration for the safety of him- or herself as well as that of the safety of every other member of the group. A compressed air or gas hose is never to be used for cleaning a work area or clothing or pointed at another person. Never leave burners or fires of any kind going when not needed. Use only safety matches or laboratory flint lighters for igniting a flame.
4. **IN CASE OF FIRE**—Leave the vicinity and immediately inform the individual in charge and/or a laboratory technician. If it can be accomplished without incurring added risk, disconnect electrical connections in the area of the fire.
5. **VALVES AND CONTROLS**—Do not attempt to operate any valve or control on any piece of laboratory equipment before being instructed in its use by the instructor or the laboratory technician and prior to permission from the instructor.
6. **USE OF TOOLS**—Use only the proper tool as directed by the instructor or laboratory technician and be certain that it is in good condition. Keep all tools and equipment clean and free from oil or grease. Never carry tools in your pockets or throw them when finished using.
7. **LIFTING**—Never attempt to lift a heavier weight than you can comfortably handle. Get help when needed. In lifting, keep your back straight and as nearly upright as possible. Lift with the leg muscles and not with the more vulnerable muscles of the back and abdomen. Never attempt to lift when the body is in an awkward position, as when twisting, or when your footing is insecure.
8. **IN CASE OF ACCIDENT**—Report every injury, no matter how slight it may appear, immediately to the responsible individual. If possible, the injured person should immediately seek professional medical attention. The person in charge will make out an injury form and report the incident immediately to the proper authority in writing. In case of serious injury, no attempt will be made to move the injured. Medical assistance will immediately be requested, probably from the designated medical facility.
9. **CLEANUP AT THE END OF THE LABORATORY EXERCISE**—Every squad and each individual is responsible for cleaning all equipment used in that period. All equipment must be cleaned before it is returned to its proper place. Bench tops shall be clean and all equipment or samples cleaned and neatly arranged. All sample containers shall be wiped clean before storing. No one will be dismissed or excused from the laboratory until his or her particular squad has been checked out by the individual responsible for this important housekeeping operation.
10. **GENERAL PROVISION**—It is incumbent upon every individual to be thoroughly familiar with these safety rules, which will be distributed at the first class meeting. Strict attention to instructions by the instructor and/or the laboratory technician is an implied responsibility of every individual. One of the most important responsibilities of the instructor and the laboratory technician is that of safety. Do not hesitate to ask questions when in doubt about any procedure or proper use of apparatus.

C: Tables of Portland Cement Specifications from ASTM Designation: C 150

The tables that follow cover the eight types of Portland cement listed below:

Type I. Used when special cement properties are not required.

Type IA. Same as Type I where an air entrainment is required.

Type II. Used when a moderate sulfate resistance or moderate heat of hydration is required.

Type IIA. Same as Type II where an air entrainment is required.

Type III. Used when high early strength of the concrete is required.

Type IIIA. Same as Type III where an air entrainment is required.

Type IV. Used when a low heat of concrete hydration is required.

Type V. Used when a high-sulfate-resistant concrete is required.

TABLE 19
Standard Chemical Requirements for Portland Cements

Cement Type[a]	I and IA	II and IIA	III and IIIA	IV	V
Silicon dioxide (SiO_2), min, %	—	20.0	—	—	—
Aluminum oxide (Al_2O_3), max, %	—	6.0	—	_	—
Ferric oxide (Fe_2O_3), max, %	—	6.0	—	6.5	—
Magnesium oxide (MgO), max, %	6.0	6.0	6.0	6.0	6.0
Sulfur trioxide (SO_3),[b] max, % when (C_3A)[c] is 8% or less	3.0	3.0	3.5	2.3	2.3
When (C_3A)[c] is more than 8%	3.5	d	4.5	d	d
Loss on ignition, max, %	3.0	3.0	3.0	2.5	3.0
Insoluble residue, max, %	0.75	0.75	0.75	0.75	0.75
Tricalcium silicate (C_3S)[c], max, %	—	—	—	35[e]	—
Dicalcium silicate (C_2S)[c], min, %	—	—	—	40[e]	—
Tricalcium aluminate (C_3A)[c], max, %	—	8	15	7[e]	5[f]
Tetracalcium aluminoferrite plus twice the tricalcium aluminate[c] ($C_4AF + 2(C_3A)$), or solid solution ($C_4AF + C_2F$), as applicable, max, %	—	—	—	—	25[f]

[a] See Note.

[b] There are cases where optimum SO_3 (using Test Method C 563) for a particular cement is close to or in excess of the limit in this specification; in such cases where properties of a cement can be improved by exceeding the SO_3 limits stated in this table, it is permissible to exceed the values in the table, provided it has been demonstrated by Test Method C 1038 that the cement with the increased SO_3 will not develop expansion in water exceeding 0.020% at 14 days. When the manufacturer supplies cement under this provision, he shall, upon request, supply supporting data to the purchaser.

[c] The expressing of chemical limitations by means of calculated assumed compounds does not necessarily mean that the oxides are actually or entirely present as such compounds.

When expressing compounds, C = CaO, S = SiO_2, A = Al_2O_3, F = Fe_2O_3. For example, C_3A = 3CaO·Al_2O_3.

Titanium dioxide and phosphorus pentoxide (TiO_2 and P_2O_5) shall be included with the Al_2O_3 content. The value historically and traditionally used for Al_2O_3 in calculating potential compounds for specification purposes is the ammonium hydroxide group minus ferric oxide ($R_2O_3 - Fe_2O_3$) as obtained by classical wet chemical methods. This procedure includes as Al_2O_3 the TiO_2, P_2O_5, and other trace oxides which precipitate with the ammonium hydroxide group in the classical wet chemical methods. Many modern instrumental methods of cement analysis determine aluminum or aluminum oxide directly without the minor and trace oxides included by the classical method. Consequently, for consistency and to provide comparability with historic data and among various analytical methods, when calculating potential compounds for specification purposes, those using methods which determine Al or Al_2O_3 directly should add to the determined Al_2O_3 weight quantities of P_2O_5, TiO_5, and any other oxide except Fe_2O_3 which would precipitate with the ammonium hydroxide group when analyzed by the classical method and which is present in an amount of 0.05 weight % or greater. The weight percent of minor or trace oxides to be added to Al_2O_3 by those using direct methods may be obtained by actual analysis of those oxides in the sample being tested or estimated from historical data on those oxides on cements from the same source, provided that the estimated values are identified as such.

When the ratio of percentages of aluminum oxide to ferric oxide is 0.64 or more, the percentages of tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite shall be calculated from the chemical analysis as follows:

Tricalcium silicate = (4.071 × % CaO) − (7.600 × % SiO_2) − (6.718 × % Al_2O_3) − (1.430 × % Fe_2O_3) − (2.852 × % SO_3)
Dicalcium silicate = (2.867 × % SiO_2) − (0.7544 × % C_3S)
Tricalcium aluminate = (2.650 × % Al_2O_3) − (1.692 × % Fe_2O_3)
Tetracalcium aluminoferrite = 3.043 × % Fe_2O_3

When the alumina-ferric oxide ratio is less than 0.64, a calcium aluminoferrite solid solution (expressed as ss($C_4AF + C_2F$)) is formed. Contents of this solid solution and of tricalcium silicate shall be calculated by the following formulas:

ss($C_4AF + C_2F$) = (2.100 × % Al_2O_3) + (1.702 × % Fe_2O_3).

Tricalcium silicate = (4.071 × % CaO) − (7.600 × % SiO_2) − (4.479 × % Al_2O_3) − (2.859 × % Fe_2O_3) − (2.852 × % SO_3).

No tricalcium aluminate will be present in cements of this composition. Dicalcium silicate shall be calculated as previously shown.

TABLE 19 (continued)
Standard Chemical Requirements for Portland Cements

In the calculation of all compounds the oxides determined to the nearest 0.1% shall be used.

All values calculated as described in this note shall be reported to the nearest 1%.

[d] Not applicable.

[e] Does not apply when the heat of hydration limit in Table 4 is specified.

[f] Does not apply when the sulfate resistance limit in Table 4 is specified.

Source: ASTM. With permission.

TABLE 20
Optional Chemical Requirements for Portland Cements[a]

Cement Type	I and IA	II and IIA	III and IIIA	IV	V	Remarks
Tricalcium aluminate (C_3A)[b], max, %	—	—	8	—	—	For moderate sulfate resistance
Tricalcium aluminate (C_3A)[b], max, %	—	—	5	—	—	For high sulfate resistance
Sum of tricalcium silicate and tricalcium aluminate,[b] max, %	—	58[c]	—	—	—	For moderate heat of hydration
Equivalent alkalies ($Na_2O + 0.658K_2O$), max, %	0.60[d]	0.60[d]	0.60[d]	0.60[d]	0.60[d]	Low-alkali cement

[a] These optional requirements apply only if specifically requested. Availability should be verified. See Note in Section 4.

[b] The expressing of chemical limitations by means of calculated assumed compounds does not necessarily mean that the oxides are actually or entirely present as such compounds.

When expressing compounds, C = CaO, S = SiO_2, A = Al_2O_3, F = Fe_2O_3. For example, $C_3A = 3CaO \times Al_2O_3$.

Titanium dioxide and phosphorus pentoxide (TiO_2 and P_2O_5) shall be included with the Al_2O_3 content. The value historically and traditionally used for Al_2O_3 in calculating potential compounds for specification purposes is the ammonium hydroxide group minus ferric oxide ($R_2O_3 - Fe_2O_3$) as obtained by classical wet chemical methods. This procedure includes as Al_2O_3 the TiO_2, P_2O_5, and other trace oxides which precipitate with the ammonium hydroxide group in the classical wet chemical methods. Many modern instrumental methods of cement analysis determine aluminum or aluminum oxide directly without the minor and trace oxides included by the classical method. Consequently, for consistency and to provide comparability with historic data and among various analytical methods, when calculating potential compounds for specification purposes, those using methods which determine Al or Al_2O_3 directly should add to the determined Al_2O_3 weight quantities of P_2O_5, TiO_2, and any other oxide except Fe_2O_3 which would precipitate with the ammonium hydroxide group when analyzed by the classical method and which is present in an amount of 0.05 weight % or greater. The weight percent of minor or trace oxides to be added to Al_2O_3 by those using direct methods may be obtained by actual analysis of those oxides in the sample being tested or estimated from historical data on those oxides on cements from the same source, provided that the estimated values are identified as such.

When the ratio of percentages of aluminum oxide to ferric oxide is 0.64 or more, the percentages of tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite shall be calculated from the chemical analysis as follows:

Tricalcium silicate = $(4.071 \times \% \text{ CaO}) - (7.600 \times \% \text{ SiO}_2) - (6.718 \times \% \text{ Al}_2\text{O}_3) - (1.430 \times \% \text{ Fe}_2\text{O}_3) - (2.852 \times \% \text{ SO}_3)$
Dicalcium silicate = $(2.867 \times \% \text{ SiO}_2) - (0.7544 \times \% \text{ C}_3\text{S})$
Tricalcium aluminate = $(2.650 \times \% \text{ Al}_2\text{O}_3) - (1.692 \times \% \text{ Fe}_2\text{O}_3)$
Tetracalcium alumioferrite = $3.043 \times \% \text{ Fe}_2\text{O}_3$

When the alumina–ferric oxide ratio is less than 0.64, a calcium aluminoferrite solid solution (expressed as ss($C_4AF + C_2F$)) is formed. Contents of this solid solution and of tricalcium silicate shall be calculated by the following formulas:

ss($C_4AF + C_2F$) = $(2.100 \times \% \text{ Al}_2\text{O}_3) + (1.702 \times \% \text{ Fe}_2\text{O}_3)$.
Tricalcium silicate = $(4.071 \times \% \text{ CaO}) - (7.600 \times \% \text{ SiO}_2) - (4.479 \times \% \text{ Al}_2\text{O}_3) - (2.859 \times \% \text{ Fe}_2\text{O}_3) - (2.852 \times \% \text{ SO}_3)$.

No tricalcium aluminate will be present in cements of this composition. Dicalcium silicate shall be calculated as previously shown.

In the calculation of all compounds, the oxides determined to the nearest 0.1% shall be used.

All values calculated as described in this note shall be reported to the nearest 1%.

[c] The optional limit for heat of hydration in Table 4 shall not be requested when this optional limit is requested.

[d] This limit may be specified when the cement is to be used in concrete with aggregates that may be deleteriously reactive. Reference should be made to Specification C33 for suitable criteria or deleterious reactivity.

Source: ASTM. With permission.

TABLE 21
Standard Physical Requirements for Portland Cements

Cement Type[a]	I	IA	II	IIA	III	IIIA	IV	V
Air content of mortar,[b] volume %								
max	12	22	12	22	12	22	12	12
min	—	16	—	16	—	16	—	—
Fineness,[c] specific surface, m²/kg (alternative methods):								
Turbidimeter test, min	160	160	160	160	—	—	160	160
Air permeability test, min	280	280	280	280	—	—	280	280
Autoclave expansion, max, %	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Strength, not less than the values shown for the ages indicated below: [d]								
Comprehensive strength, MPa (psi):								
1 day	—	—	—	—	12.0	10.0	—	—
		(1740)	(1450)					
3 days	12.0	10.0	10.0	8.0	24.0	19.0	—	8.0
		(1740)	(1450)	(1450)	(1160)	(3480)	(2760)	(1160)
			7.0[f]	6.0[f]				
			(1020)[f]	(870)[f]				
7 days	19.0	16.0	17.0	14.0	—	—	7.0	15.
		(2760)	(2320)	(2470)	(2030)	(1020)	(2180)	
			12.0[f]	9.0[f]				
			(1740)[f]	(1310)[f]				
28 days	—	—	—	—	—	—	17.0	21.0
							(2470)	(3050)
Time of setting (alternative methods):[e]								
Gillmore test:								
Initial set, min, not less than	60	60	60	60	60	60	60	60
Final set, min, not more than	600	600	600	600	600	600	600	600
Vicat test:[g]								
Time of setting, min, not less than	45	45	45	45	45	45	45	45
Time of setting, min, not more than	375	375	375	375	375	375	375	375

[a] See Note.

[b] Compliance with the requirements of this specification does not necessarily ensure that the desired air content will be obtained in concrete.

[c] Either of the two alternative fineness methods may be used at the option of the testing laboratory. However, when the sample fails to meet the requirements of the air-permeability test, the turbidimeter test shall be used, and the requirements in this table for the turbidimetric method shall govern.

[d] The strength at any specified test age shall be not less than that attained at any previous specified test age.

[e] The purchaser should specify the type of setting-time test required. In case he does not so specify, the requirements of the Vicat test only shall govern.

[f] When the optional heat of hydration or the chemical limit on the sum of the tricalcium silicate and tricalcium aluminate is specified.

[g] The time of setting is that described as initial setting time in Test Method C 191.

Source: ASTM. With permission.

TABLE 22
Optional Physical Requirements for Portland Cements[a]

Cement Type	I	IA	II	IIA	III	IIIA	IV	V
False set, final penetration, min, %	50	50	50	50	50	50	50	50
Heat of hydration:								
7 days, max, kj/kg (cal/g)	—	—	290 (70)[b]	290 (70)[b]	—	—	250 (60)[c]	—
28 days, max, kj/kg (cal/g)	—	—	—	—	—	—	290 (70)[c]	—
Strength, not less than the values shown:								
Compressive strength, MPa (psi)								
28 days	28.0 (4060)	22.0 (3190)	28.0 (4060) 22.0[b] (3190)[b]	22.0 (3190) 18.0[b] (2610)[b]	—	—	—	—
Sulfate resistance,[d] 14 days, max, % expansion	—	—	—	—	—	—	—	0.040

[a] These optional requirements apply only if specifically requested. Availability should be verified. See Note in Section 4.

[b] The optional limit for the sum of the tricalcium silicate and tricalcium aluminate in Table 2 shall not be requested when this optional limit is requested. These strength requirements apply when either heat of hydration or the sum of tricalcium silicate and tricalcium aluminate requirements are requested.

[c] When the heat of hydration limit is specified, it shall be instead of the limits of C_3S, C_2S, and C_3A listed in Table 1.

[d] When the sulfate resistance is specified, it shall be instead of the limits of C_3A and $C_4AF + 2 C_3A$ listed in Table 1.

Source: ASTM. With permission.

D: Concrete Admixtures and Other Cementitious Materials

In ASTM Designation: C 125 a concrete admixture (sometimes called an *additive*) is referred to as "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 the mixing."

The number of admixtures on the market is very great and is increasing yearly. Almost every concrete property imaginable can be modified. However, it should be emphasized that admixtures are not a panacea to overcome deficiencies in the design of concrete mixes or inadequate practice in the handling, finishing, and curing of fresh concrete. There are times when unexpected results are derived from the use of additives. Sometimes it is due to unforeseen interaction between admixtures, if more than one is added to the mix, to unanticipated interaction between the cement and/or aggregates with the admixtures. Except for an air-entraining agent, a good rule of thumb to follow is to make trial batches, in the laboratory, with the admixtures before using them on the site of construction. Also, temperature and other weather conditions can influence the amount of admixture to use or even the results. Perhaps an even better principle to follow, except perhaps again in the case of an air-entraining agent, is that admixtures should only be used under the supervision of an experienced engineer.

The confusing subject of admixtures can be defined under the following categories:

1. Air-entraining agents, governed by ASTM Designation: C 260, are the oldest and probably the most valuable of all admixtures. While they have other advantages, such as improved workability, they are primarily utilized to improve the resistance of the concrete to frost action. All concrete and especially pavements, exposed to freezing temperatures, should include entrained air of about 4 to 8%, depending inversely upon the maximum size aggregate in the mix. All concrete contains some entrained air, principally from the fine aggregate, but less than that required to resist frost action. Honeycombing or other visible air pockets in the hardened concrete are not considered air voids. The latter are tiny, microscopic, uniform air bubbles distributed throughout the concrete mass. The usual method for producing air entrainment is to add a foaming agent prior to mixing. A number of organic compounds such as natural resins, tallows, and sulfonated soaps or oils are the commonly used agents, although the trend has been to use these products in proprietary form. The one significant drawback in the use of air entrainment is the reduction in concrete strength of about 3 to 4% for each increase in percent of air. The net loss in strength is ameliorated by the ability to reduce the water/cement ratio, which causes the strength of the concrete to rise. By taking the increased workability of the concrete mix because of the entrained air, the mix may be designed with less water. For each percent increase in the air content of the mix, the water may be reduced by about 3%. The result is a reduction in strength of the concrete after 28 days in the vicinity of about 15%. Therefore, for a structural member not exposed to adverse atmospheric conditions, air entraining would not be an option.

2. Chemical admixtures are governed by ASTM Designation: C 494, which recognizes seven types, A to G.
   - *Type A* is a water-reducing admixture which, as the name implies, requires a lower w/c ratio to obtain a desired concrete slump. To qualify as a Type A admixture, the water reduction should be at least 5%, with the usual range being 5 to 10%.
   - *Types B and C* are retarding and accelerating, respectively. As the designations imply, they either slow down or speed up the initial set and the final hardening of the fresh concrete. Depending upon atmospheric conditions and the demands of construction, these modifications to the normal behavior of concrete may be very important.

- *Types D and E* are combined water reducers as well as retarding and accelerating admixtures. In other words, Type D is a combination of Types A and B admixtures, while Type E combines the characteristics of Types A and C admixtures.
- *Type F* admixture is a high-range water-reducer, often referred to as a *superplasticizer,* which is required to lower the water requirement of the concrete by at least 12% but may in fact achieve a decrease in water requirement of between 15 and 30%.
- *Type G* is a combined superplasticizer and retarding admixture. Most water-reducing agents fall into one of three categories, salts and derivatives of lignosulfonates, salts and derivatives of hydroxy-carboxylic acids, and polymetric substances. The lignosulfonates, which are by-products of the paper industry, may be used in either normal range water-reducers or the high range. Salts of the derivatives of the hydroxy-caboxylic acids are used only in the former while the polymetric materials are suitable for superplasticizer admixtures. Most but not all of the admixtures used in concrete are the by-products of other industrial processes and formerly were treated as waste materials.

3. There are also any number of miscellaneous admixtures that do not fall under either of the above categories, which have been developed for special purposes. These include such diverse applications as grouting, bonding, damp-proofing, coloring agents, and expansion-producing admixtures, as well as corrosion inhibitors to reduce rust formation in reinforcing steel.

In summation, the engineer should be aware that a wide variety of concrete properties can be influenced by the judicious use of admixtures. The engineer should also realize, however, that in an admixture that has the desired effect, one property may prove harmful to the performance of another. Some admixture combinations are incompatible.

There is also another class of materials that goes back in history at least 3000 years. These are called in modern technology, *supplemental cementing materials.* Until relatively modern times they were used alone in combination with limes to produce concrete. In the past 100 years they have been used in combination with Portland cement. For that reason they are associated with additives. Fundamentally, these supplemental cementing materials are composed of fine solid particles that are added to the concrete mix to improve workability, durability, and to provide additional cementitious materials at a lower cost than Portland cement. Materials included in this category are fly ash, silica fume, and puzzolans. Finely ground slags are also included in this class of substances. These mineral additives are likewise, in many cases, the waste products of other industrial activities, often associated with coal burning. This is part of a process in which engineers are increasingly recycling existing structures and utilizing materials formerly considered suitable only for disposal. An important type of hydraulic cementitious material falls under the classification of pozzolans, which are siliceous or siliceous and aluminous compounds. In the presence of $Ca(OH)_2$ from the Portland cement and water it develops cementitious properties and thereby contributes to the strength of the concrete. The name is derived from a city near Naples, Italy, which is the site of a large deposit of volcanic ash. It is used today as an effective and inexpensive replacement for up to 20% of the Portland cement in the concrete. This volcanic puzzuolana earth was used by the Romans over two thousand years ago to make concrete. The types of cementing materials in general use are categorized as follows:

1. A hydraulic cement, such as portland, sets up and hardens by reacting chemically with water and is also capable of doing so also under water. Examples of these materials are Portland cement, slag cement, and Class C fly ash.

2. A pozzolanic (natural) cement is a siliceous or alumino-siliceous material in a finely divided form that in the presence of moisture, reacts chemically at normal temperatures with calcium hydroxide to form compounds that possess cementitious properties. This is true of all natural cements. Examples of these latter materials are silica fume, natural cements, and Class F fly ash.

3. The potential effects of supplemental cementing materials include the following:

   a. Water demand and workability

   b. Bleeding

   c. Time of initial and final set

   d. Entrained air

   e. Heat of hydration

   f. Physical properties such as strength parameters

      g.   Permeability

      h.   Resistance to chemical reaction such as sulfate resistance

      i.   Effect of freezing and thawing cycles

4. Portland cement concrete frequently includes 2 or 3 supplemental cementing materials.

5. The ASTM specifications for supplemental cementing materials are as follows:

   C 595: Blended Hydraulic Cements

   C 618: Fly Ash from Coal and Natural Cements

   C 989: Finely Ground Blast-Funace Slag

   C 1157: Performance Specifications for Blended Hydraulic Cement

   C 1240: Silica Fume

The subject of concrete admixtures is a very substantial and complex one. This is merely intended as a cursory overview of the subject. The student or engineer who wishes more information should consult the bibliography in Appendix G.

E: Development of ASTM Standards
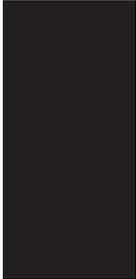
The American Society for Testing and Materials was organized in 1898 as a nonprofit organization to develop engineering standards for materials, products, systems, and services. Currently the work of the ASTM is performed by approximately 32,000 members worldwide. Something on the order of 10,000 standards are published each year. One of the unique features of the ASTM is that it of itself possesses no technical research or laboratory facilities. Possibly the best approach to develop an understanding of the functions and accomplishments of ASTM is to pose fundamental questions and then attempt to answer them.

1. *What is an ASTM standard?* It is a document that has been developed within the consensus principles of ASTM and meets the established procedures and regulations.

2. *What types of standards does ASTM produce?* There are six principle types: standard test methods, standard specifications, standard practice, standard terminology, standard guide, and standard classification.

3. *Why are ASTM standards so widely accepted?* Herein lies the key to the success of ASTM. Before an item becomes a standard it must undergo the scrutiny of a voluntary, full consensus approach that brings together diverse backgrounds and expertise, balanced representation of interests, intense round-robin testing, procedures to assure the latest, accurate information, and an atmosphere of objectivity.

4. *Who uses and writes the standards?* They are used and developed voluntarily by technical committees. They only become binding on the parties using them via contractual relationships.

5. *What are ASTM technical committees?* The 132 technical committees are subdivided into subcommittees and further into task groups. They are the instruments with the expertise and in which standards are developed. Standards development begins when a need is recognized and given to a task group to prepare a draft that then works its way through the approval process, if successful, which generally takes about 2 years. Any individual or commercial organization may initiate the process by submitting a request to the ASTM headquarters. The activities of the ASTM technical committees are governed by the ASTM Board of Directors, whose members are elected by the entire membership.

6. *What is the address and telephone number of the ASTM?* 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, Telephone: (610) 832-9500; FAX: (610) 832-9555.

F: Sample Course Outlines for 10-Week and 15-Week Laboratory Sessions

The class is assumed to be divided into two working squads. The Suggested Course Outlines that appear at the end of this chapter refer to the test procedures only by the ASTM Designation number. Therefore, in order to facilitate the references, the following page contains a summary of all the tests used in the Suggested Course Outlines. There are other test procedures in the handbook that were not included. Of course each instructor will use his or her own discretion in the development of the course outline for their class. Again I wish to emphasize that the laboratory test sequences in the outlines are only Suggested Course Outlines for a concrete laboratory course for undergraduate civil engineering students. The reason I included them in this handbook is the unique circumstances with regards to concrete testing wherein there are time constraints and time sequences that are quite unique to the testing of hydraulic cement concretes.

Summary of Testing Procedures in the Suggested Course Outlines

Title of Test Procedure	ASTM Designation
Coarse Aggregate Rodded Unit Weight	C 29
Compressive Strength of Cylindrical Concrete Specimens	C 39
Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)	C 78
Compressive Strength of Hydraulic Cement Mortars Using 5-cm (2-in.) Cube Specimens	C 109
Specific Gravity and Absorption Tests for Fine and Coarse Aggregates	C 127 and C 128
Sieve Analysis of Fine and Coarse Aggregates	C 136
Unit Weight, Yield, and Air Content of Concrete	C 138
Slump Test for Portland Cement Concrete	C 143
Density of Hydraulic Cement	C 188
Tensile Strength of Hydraulic Cement Mortars	C 190
Time of Setting of Hydraulic Cement by Vicat Needle	C 191
Fineness of Hydraulic Cement by Air Permeability Apparatus	C 204
Bond Strength of Portland Cement Concrete	C 234
Young's Modulus and Poisson's Ratio in Compression of Cylindrical Concrete Specimens	C 469
Splitting Tensile Strength of Cylindrical Concrete Specimens	C 496
Swiss Hammer Test	C 805
Direct Tensile Test of Portland Cement Concrete	None

Suggested Course Outline for 10-Week Quarter

Session	Laboratory Work
1	Introduction to the Course and to Portland cement and Portland cement concrete (PCC) Technology; organization of squads; Films on PCC Testing.
2	Lecture on PCC mix design using the Absolute Volume Method from the PCA Engineering Bulletin on the "Design and Control of Concrete Mixtures" from Chapter 8 of the Canadian Edition and Chapter 7 of the United States Edition.
3	Squad No. 1: C 29 (C.A. rodded unit weight), C 127, C 136, and C 188.
	Squad No. 2: C 128, C 136, and C 188.
	Both Squads: C 136 (from the results also determine the fineness modulus (F.M.) of the fine aggregates). See the appropriate pages in the respective *PCA Engineering Bulletin*. Squads will exchange data from C 127 and C 128.
4	Both Squads: Will perform C 138, C 143, and C 192 for the preparation of 18 specimens, 15 cm (6 in.) diameter by 30 cm (12 in.) in height. These specimens will be tested later in the course for compression, splitting, and for determination of Young's Modulus and Poisson's Ratio.
5	Both Squads: C 39 and C 805 7-day test.
	Squad No. 1: Preparation of 9 specimens for Bond Strength, C 234, and preparation of 12 specimens for Direct Tension Testing.
	Squad No. 2: Preparation of 9 specimens for Flexure Strength, C 78, 3 unreinforced, 3 with 30 kg, and 3 with 60 kg of steel fibers/m^3 or 3 with 50 lb and 3 with 100 lb of steel fibers/yd^3.
6	Both Squads: C 39 and C 805 14-day test.
	Squad No. 1: Preparation of 9 specimens for Flexure Strength, C 78, 3 unreinforced, 3 with 30 kg, and 3 with 60 kg of steel fibers/m^3 or 3 with 50 lb and 3 with 100 lb of steel fibers/yd^3; 7-day Direct Tension Test.
	Squad No. 2: Preparation of 12 specimens for Direct Tension Testing. Preparation of 9 specimens for Bond Strength, C 234.
7	Both Squads: C 39 and C 805 21-day test.
	Squad No. 1: 14-day Direct Tension Test.
	Squad No. 2: 7-day Direct Tension Test.
8	Both Squads: C 39 and C 805 28-day test. Tests on specimens for Young's Modulus and Poisson's Ratio, C 469, and for the Splitting Tensile Test, C 496.
	Squad No. 1: 21-day Direct Tension Test.
	Squad No. 2: 14-day Direct Tension Test.
9	Squad No. 1: Tests on all nine Bond Strength specimens, C 234, and the 28-day Direct Tension Test.
	Squad No. 2: Tests on all nine Flexure Strength specimens, C 78, and the 21-day Direct Tension Test.
10	Squad No. 1: Tests on all nine Flexure Strength specimens, C 78.
	Squad No. 2: Tests on all nine Bond Strength specimens, C 234, and the 28-day Direct Tension Test.

Note: Conduct the Rebound Hammer Test, ASTM Designation: C 805, on all specimens as the first step in the evaluation for other testing procedures. A particular effort should be made to correlate the Rebound (Swiss) Hammer results with the standard compression test, ASTM Designation: C 39. Unlike the Swiss Hammer Test, the latter is, of course, a destructive-type test. Try to do the same for the other standard, destructive tests, such as the modulus of rupture and the tension test.

Suggested Course Outline for 15-Week Semester

Session	Laboratory Work
1	Introduction to the Course and to Portland cement and Portland cement concrete (PCC) Technology; organization of squads; films on PCC Testing.
2	Lecture on PCC mix design using the Absolute Volume Method from the *PCA Engineering Bulletin* on the "Design and Control of Concrete Mixtures" from Chapter 8 of the Canadian Edition and Chapter 7 of the United States Edition. Lecture on PCC mix design using the Absolute Volume Method from the *PCA Engineering Bulletin* on the "Design and Control of Concrete Mixtures" from Chapter 8 of the Canadian Edition and Chapter 7 of the United States Edition.
3	Squad No. 1: C 29 (C.A. rodded unit weight), C 127, C 136, and C 188.
	Squad No. 2: C 128, C 136, and C 188.
	Both Squads: C 136 (from the results, also determine the fineness modulus (F.M.) of the fine aggregates). See the appropriate pages in the respective *PCA Engineering Bulletin*. Squads will exchange data from C 127 and C 128.
4	Squad No. 1: C 109
	Squad No. 2: C 190.
5	Squad No. 1: C 191.
	Squad No. 2: C 204.
6	Squad No. 1: C 190.
	Squad No. 2: C 109.
7	Squad No. 1: C 204.
	Squad No. 2: C 191.
8	Both Squads: Perform C 138, C 143, and C 192 for the preparation of 18 specimens 15 cm (6 in.) diameter by 30 cm (12 in.) in height. These specimens will be tested later in the course for compression, splitting, and for determination of Young's Modulus and Poisson's Ratio.
9	Both Squads: C 39 and C 805 7-day test.
	Squad No. 1: Preparation of 9 specimens for Bond Strength, C 234.
	Squad No. 2: Preparation of 9 specimens for Flexure Strength, C 78, 3 unreinforced, 3 with 30 kg, and 3 with 60 kg of steel fibers/m^3 or 3 with 50 lb and 3 with 100 lb of steel fibers/yd^3.
10	Both Squads: C 39 and C 805 14-day test.
	Squad No. 1: Preparation of 9 specimens for Flexure Strength, C 78, 3 unreinfoced, 3 with 30 kg, and 3 with 60 kg of steel fibers/m^3 or 3 with 50 lb and 3 with 100 lb of steel fibers/yd^3; 7-day Direct Tension Test.
	Squad No. 2: Preparation of 12 specimens for Direct Tension Testing.
11	Both Squads: C 39 and C 805 21-day test.
	Squad No. 1: Preparation of 12 specimens for Direct Tension Testing.
	Squad No. 2: Preparation of 9 specimens for Bond Strength, C 234, 7-day Direct Tension Test.
12	Both Squads: C 39 and C 805, 28-day test. Tests on specimens for C 469 and C 496.
	Squad No. 1: 7-day Direct Tension Test.
	Squad No. 2: 14-day Direct Tension Test.
13	Squad No. 1: Tests on all nine Bond Strength specimens, C 234, and 14-day Direct Tension Test.
	Squad No. 2: Tests on all nine Flexure Strength specimens, C 78, and the 21-day Direct Tension Test.
14	Squad No. 1: Tests on all nine Flexure Strength specimens, C 78, and the 21-day Direct Tension Test.
	Squad No. 2: 28-day Direct Tension Test.
15	Squad No. 1: 28-day Direct Tension Test.
	Squad No. 2: Tests on all nine Bond Strength specimens, C 234.

Note: Conduct the Rebound Hammer Test, ASTM Designation: C 805, on all specimens as the first step in the evaluation for other testing procedures. A particular effort should be made to correlate the Rebound (Swiss) Hammer results with the standard compression test, ASTM Designation: C 39. Unlike the Swiss Hammer Test, the latter is, of course, a destructive-type test. Try to do the same for the other standard, destructive tests, such as the modulus of rupture and the tension test.

G: New Developments in Portland Cement Concrete (PCC) Technology

Since the initial advance in PCC by Joseph Aspdin in 1824, the quality and uniformity of manufactured Portland cement made steady but slow progress. For many decades a fairly uniform PCC was produced and designers used a 28-day compressive strength of between 13.8 MPa (2000 psi) to 27.6 MPa (4000 psi). A convenient equation to use in converting a stress in psi to SI units is as follows:

$$\text{psi}(6.895 \times 10^3 \text{ Pa/psi}) = \text{MPa}$$

The specimens should be tested on 15 cm (6 in.) $\times$ 30 cm (12 in.) cylinders. As the compressive strength of normal concrete is gradually increasing, high-strength concrete (HSC) is now considered to be above 41 MPa (6000 psi). Most HSC compressive strengths are now designed for an f'_c of at least 70 Mpa (10,000 psi). High-strength concrete, or high-performance concrete (HPC), as it is sometimes called, has also been defined as high-strength, very high-strength, and ultra-high-strength concrete. The latter has reached strengths in the laboratory of 731 MPa (106,000 psi). The divisions between the different strengths of concrete are changing with time. Actually, while the terms HSC and HPC are at times used interchangeably, they really are not synonymous. High-performance concrete embodies many more properties other than strength such as the following:

- High early strength
- High abrasion resistance
- Resistance to freeze–thaw cycles and chemical attack
- Ease of placement and consolidation without segregation (which will be discussed under the rubric of self-consolidating concrete [SCC])

High-strength, lightweight concrete will also be considered later in this appendix. The testing methods for all types of concrete are generally similar. Civil engineers should have at least some passing familiarity with the various types of hydraulic concrete mixtures in current use. That is the purpose of this appendix.

In this appendix the four following recent developments in PCC technology will be discussed:

1. High-strength concrete
2. High-strength, lightweight concrete
3. Self-consolidating concrete
4. Mass concrete

High-Strength Concrete (HSC)

Although builders have been using various hydraulic cement concretes for thousands of years, it was not until early in the twentieth century that material technologists became involved in analyzing the chemical reactions involved and trying to optimize the strength of the concrete mix. As concrete strengths have advanced, there is no fixed point of separation between normal strength and high-strength concrete, although the American Concrete Institute established a tentative demarcation of 41 MPa (6000 psi) for HSC in 1984. Designers are increasingly calling for HSC in high-rise building construction and for bridges in order to be able to specify smaller members and thereby save weight and vertical clearances. This is particularly advantageous for the vertical members in buildings since it results in greater usable space.

The design of HSC requires much more attention to the details of testing than a normal concrete mix, even though the tests used in the mix design are similar. The production of HSC likewise requires a level of attention to detail beyond what is required for normal concrete. There are three aspects that require particularly close attention to details. These are the mortar paste, the quality of aggregates, and the cement–aggregate bond. In most aspects, all types of concrete are durable and forgiving materials of construction. In order to achieve optimum results, however, the use of appropriate materials and proper practice is mandated. Except for the greater attention to details, the laboratory tests and the procedures for all types of HPC vary little from ordinary Portland cement concrete.

High-Strength Lightweight Concrete

Lightweight concrete differs from ordinary concrete by the use of lightweight aggregates (both coarse and fine), which are usually made from expanded clays, shales, and slates. While this type of concrete can be made from both lightweight coarse and fine aggregates, optimal results are usually obtained by using a combination of lightweight coarse aggregates and natural sand or a mixture of both natural sand and lightweight fine aggregates. High-strength lightweight concrete is a special form of HSC. Lightweight aggregates have densities ranging from 560 to 1120 kg/m^3 (35 to 70 pcf) compared to 1200 to 1760 kg/m^3 (75 to 110 pcf) for normal weight aggregates. The usual range of lightweight concrete strengths ranges from 20 to 35 MPa (3000 to 5000 psi). High-strength lightweight concrete can also be made using the same addition of other cementitious materials and admixtures as for HSC, although the strengths will not be as significant as those for HSC because of the weakness of the expanded aggregates. Because of the high absorptive properties of the aggregates, it is difficult to design a mix on the basis of a water-to-cement (w/c) ratio. Since the aggregates may absorb 5 to 20% water by dry weight of the aggregates. It is therefore preferable to prewet but not to saturate the aggregates prior to batching the concrete.

A corollary to lightweight concrete is high-density concrete, which has a density of greater than 2900 kg/m^3 (180 pcf). Except for density, its physical properties are similar to those of normal weight concrete except for the aggregate densities as high as 6100 kg/m^3 (380 pcf). A typical location for high-density concrete would be for a containing dome for a nuclear reactor.

Self-Compacting Concrete (SCC)

In the 1980s the Japanese developed a unique form of concrete that is referred to as self-consolidating concrete. It is able to flow and consolidate under its own weight without the use of vibrators. The material can fill tight spaces without aggregate segregation or bleeding. This valuable property requires a significant increase of fines, such as fly ash (probably the best choice) and other mineral fillers such as limestone dust,

without increasing the water content in the mix. This changes the rheological behavior of the concrete to ensure high viscosity and flowability without coarse aggregate segregation. The content of particles finer than 150 μm (No. 100 sieve) needs to be between 520 to 560 kg/m³ (880 to 950 lb/yd³). High-range water reducers must also be incorporated to plasticize the mix. Since SCC is characterized by special liquid concrete properties, a number of new tests have been developed to measure properties such as its flowability, viscosity, and stability. If properly designed, SCC results in similar compressive strengths and durability to normal concrete, although it is more expensive.

SCC with high flowability is easy to place and facilitates the elimination of undesirable honeycombing in the hardened concrete. In fact, the SCC flows through heavy reinforcing steel and tight places. Well-consolidated concrete, which a well-designed SCC usually insures, is essential for achieving a low permeable, long-lasting structure.

Mass Concrete

There are no specific dimensions for defining this term and no accepted procedures for handling a situation of this type, but it can present an engineer with a serious problem. As a young engineer, the author faced this problem when pouring a massive highway arch in the heat of the summer. The ACI Committee 116 defines mass concrete as "Any large volume of cast-in-place concrete with dimensions large enough to require that measures be taken to cope with the generation of heat and attendant volume change to minimize cracking." Mass concrete temperature rise is caused by heat of hydration. As the interior temperature of the concrete rises, a differential develops with the surface concrete that may result in cracking. What the ACI code fails to mention is that if the temperature in the concrete rises high enough, it may result in burning of the cement.

There are a number of steps that can be taken to protect mass concrete pours from overheating. Many safeguards can be built into the structure during the design stage, such as limiting the amount of cement in the mix, specifying large aggregates, use of low-heat-of-hydration cement, use of a high percentage of pozzolans for the cementitious materials, placing embedded cooling pipes in the structure, and cooling the aggregates and the mixing water with ice. The latter was the option chosen by the designers of the arch on which the author worked. Another step taken on that project was scheduling the start of the pour of that arch beginning at midnight when the ambient temperature was cooler.

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Additional Copies of Laboratory Data Sheets

Compressive Strength of Concrete Cylinders (ASTM Designation: C 39)

Date specimens were cast:						
Description of test specimens:						
Concrete mix design: C.A. ; F.A. ; Water						
Additives ; Maximum size C.A. ; F.M.						
Specimen No.	Days Cured	Area cm²/in.²	Load kg/lb	Fract. Angle	Stress MPa/psi	% f'_c

Note: f'_c based upon average 28-day strength for the concrete mix.

Compressive Strength of Concrete Cylinders (ASTM Designation: C 39)

Date specimens were cast:						
Description of test specimens:						
Concrete mix design: C.A. ; F.A. ; Water						
Additives ; Maximum size C.A. ; F.M.						
Specimen No.	Days Cured	Area cm^2/in.^{2}	Load kg/lb	Fract. Angle	Stress MPa/psi	% f$'_c$

Note: f$'_c$ based upon average 28-day strength for the concrete mix.

Flexural Strength of Concrete Beams with Third-Point Loading (ASTM Designation: C 78)

Date specimens were cast: ; Comments:							
Description of test specimens: ; Distance between supports:							
Specimen No.	Days Cured	Average b × d cm or in.	Load kg/lb	Location of Fracture	M.R. MPa/psi	% f'$_c$	Remarks
1							
2							
3							
Average							
4							
5							
6							
Average							
7							
8							
9							
Average							
10							
11							
12							
Average							

Flexural Strength of Concrete Beams with Third-Point Loading (ASTM Designation: C 78)

Specimen No.	Days Cured	Average b × d cm or in.	Load kg/lb	Location of Fracture	M.R. MPa/psi	% f'$_c$	Remarks
1							
2							
3							
Average							
4							
5							
6							
Average							
7							
8							
9							
Average							
10							
11							
12							
Average							

Date specimens were cast: ; Comments:

Description of test specimens: ; Distance between supports:

Compressive Strength of Hydraulic Cement Mortars (ASTM Designation: C 109)

Specimen No.	Time of Loading in Seconds	Total Load in kg or Pounds	Specimen Cross Section in Meters^2 or Inches^2	Specimen Strength in Pascals or psi
1				
2				
3				
4				
5				
6				

Compressive Strength of Hydraulic Cement Mortars (ASTM Designation: C 109)

Specimen No.	Time of Loading in Seconds	Total Load in kg or Pounds	Specimen Cross Section in Meters^2 or Inches^2	Specimen Strength in Pascals or psi
1				
2				
3				
4				
5				
6				

Coarse and Fine Aggregates Specific Gravity Data Sheet
(ASTM Designations: C 127 and C 128)

Coarse Aggregates: ASTM Designation: C 127				
Passing ____ Sieve & Retained on ____ Sieve	Sample 1	Sample 2	Sample 3	Sample 4
(A) Wt. oven-dry sample (g)				
(B) Wt. SSD sample (g)				
(C) Wt. saturated sample in water (g)				
Bulk specific gravity				
Apparent specific gravity				
Effective specific gravity				
Absorption, %				
Average Values: Bulk Sp. Gr. = ; Apparent Sp. Gr. = ; Effective Sp. Gr. = ; Absorption = .				
Fine Aggregates: ASTM Designation: C 128				
(A) Wt. oven-dry sample (g)				
(B) Wt. pycnometer + water to calibration mark (g)				
(C) Pycnometer + water + sample to calibration mark (g)				
Bulk specific gravity				
Apparent specific gravity				
Effective specific gravity				
Absorption, %				
Average Values: Bulk Sp. Gr. = ; Apparent Sp. Gr. = ; Effective Sp. Gr. = ; Absorption = .				

Coarse and Fine Aggregates Specific Gravity Data Sheet
(ASTM Designations: C 127 and C 128)

Coarse Aggregates: ASTM Designation: C 127				
Passing ____ Sieve & Retained on ____ Sieve	Sample 1	Sample 2	Sample 3	Sample 4
(A) Wt. oven-dry sample (g)				
(B) Wt. SSD sample (g)				
(C) Wt. saturated sample in water (g)				
Bulk specific gravity				
Apparent specific gravity				
Effective specific gravity				
Absorption, %				
Average Values: Bulk Sp. Gr. = ; Apparent Sp. Gr. = ; Effective Sp. Gr. = ; Absorption = .				
Fine Aggregates: ASTM Designation: C 128				
(A) Wt. oven-dry sample (g)				
(B) Wt. pycnometer + water to calibration mark (g)				
(C) Pycnometer + water + sample to calibration mark (g)				
Bulk specific gravity				
Apparent specific gravity				
Effective specific gravity				
Absorption, %				
Average Values: Bulk Sp. Gr. = ; Apparent Sp. Gr. = ; Effective Sp. Gr. = ; Absorption = .				

Wash and Dry Sieve Analysis (ASTM Designation: C 117)

	Wash and Dry Sieve Analysis						
Sample Number				Sample Number			
Sieve Size	Weight Retained (g)	% Retained	% Passing	Sieve Size	Weight Retained (g)	% Retained	% Passing
2 in.				2 in.			
1½ in.				1½ in.			
1 in.				1 in.			
¾ in.				¾ in.			
½ in.				½ in.			
⅜ in.				⅜ in.			
#4				#4			
#8				#8			
#16				#16			
#30				#30			
#50				#50			
#100				#100			
#200				#200			
Pan				Pan			
Total				Total			

a. Wt. of sample (g):

b. Wt. of sample after washing (g):

c. Loss in washing, (a − b) (g):

d. Pan from dry sieve (g):

Total—200, (c + d) (g):

a. Wt. of sample (g):

b. Wt. of sample after washing (g):

c. Loss in washing, (a − b) (g):

d. Pan from dry sieve (g):

Total—200, (c + d) (g):

Wash and Dry Sieve Analysis (ASTM Designation: C 117)

Wash and Dry Sieve Analysis

Sample Number				Sample Number			
Sieve Size	Weight Retained (g)	% Retained	% Passing	Sieve Size	Weight Retained (g)	% Retained	% Passing
2 in.				2 in.			
1½ in.				1½ in.			
1 in.				1 in.			
¾ in.				¾ in.			
½ in.				½ in.			
⅜ in.				⅜ in.			
#4				#4			
#8				#8			
#16				#16			
#30				#30			
#50				#50			
#100				#100			
#200				#200			
Pan				Pan			
Total				Total			

a. Wt. of sample (g):

b. Wt. of sample after washing (g):

c. Loss in washing, (a − b) (g):

d. Pan from dry sieve (g):

Total—200, (c + d) (g):

a. Wt. of sample (g):

b. Wt. of sample after washing (g):

c. Loss in washing, (a − b) (g):

d. Pan from dry sieve (g):

Total—200, (c + d) (g):

Sieve Analysis for Fine and Coarse Aggregate (ASTM Designation: C 136)

Dry Sieve Analysis

Sample Number				Sample Number			
Sieve Size	Weight Retained (g)	% Retained	% Passing	Sieve Size	Weight Retained (g)	% Retained	% Passing
2 in.				2 in.			
1½ in.				1½ in.			
1 in.				1 in.			
¾ in.				¾ in.			
½ in.				½ in.			
⅜ in.				⅜ in.			
#4				#4			
#8				#8			
#16				#16			
#30				#30			
#50				#50			
#100				#100			
#200				#200			
Pan				Pan			
Total				Total			

Sieve Analysis for Fine and Coarse Aggregate (ASTM Designation: C 136)

Dry Sieve Analysis

Sample Number				Sample Number			
Sieve Size	Weight Retained (g)	% Retained	% Passing	Sieve Size	Weight Retained (g)	% Retained	% Passing
2 in.				2 in.			
1½ in.				1½ in.			
1 in.				1 in.			
¾ in.				¾ in.			
½ in.				½ in.			
⅜ in.				⅜ in.			
#4				#4			
#8				#8			
#16				#16			
#30				#30			
#50				#50			
#100				#100			
#200				#200			
Pan				Pan			
Total				Total			

TABLE 16c
Combined Gradation Form

Material % in Mix	No. 1		No. 2		No. 3		No. 4		Combined Gradation	Target Value	Specification Limits
U.S. Sieves	% Passing	% in Batch	% Passing	% in Batch	% Passing	% in Batch	% Passing	% in Batch			
2 in.											
1½ in.											
1 in.											
¾ in.											
½ in.											
⅜ in.											
No. 4											
No. 8											
No. 16											
No. 30											
No. 50											
No. 100											
No. 200											

Note: Aggregate blend design chart for a Portland Cement Concrete mix.

TABLE 16c
Combined Gradation Form

Material % in Mix	No. 1		No. 2		No. 3		No. 4		Combined Gradation	Target Value	Specification Limits
U.S. Sieves	% Passing	% in Batch	% Passing	% in Batch	% Passing	% in Batch	% Passing	% in Batch			
2 in.											
1½ in.											
1 in.											
¾ in.											
½ in.											
⅜ in.											
No. 4											
No. 8											
No. 16											
No. 30											
No. 50											
No. 100											
No. 200											

Note: Aggregate blend design chart for a Portland Cement Concrete mix.

Figure 5b
Millimeter gradation chart.

United States Bureau of Public Roads 0.45 Power Gradation Chart

Sieve Sizes Raised to 0.45 Power

Percent Passing

100 90 80 70 60 50 40 30 20 10 0

Percent Passing

100 90 80 70 60 50 40 30 20 10 0

Sieve Sizes: 1½" 1¼" 1" ¾" ½" ⅜" ¼" 4 6 8 10 16 20 30 40 50 No.80 100 200 5μ 20μ

Sieve Sizes
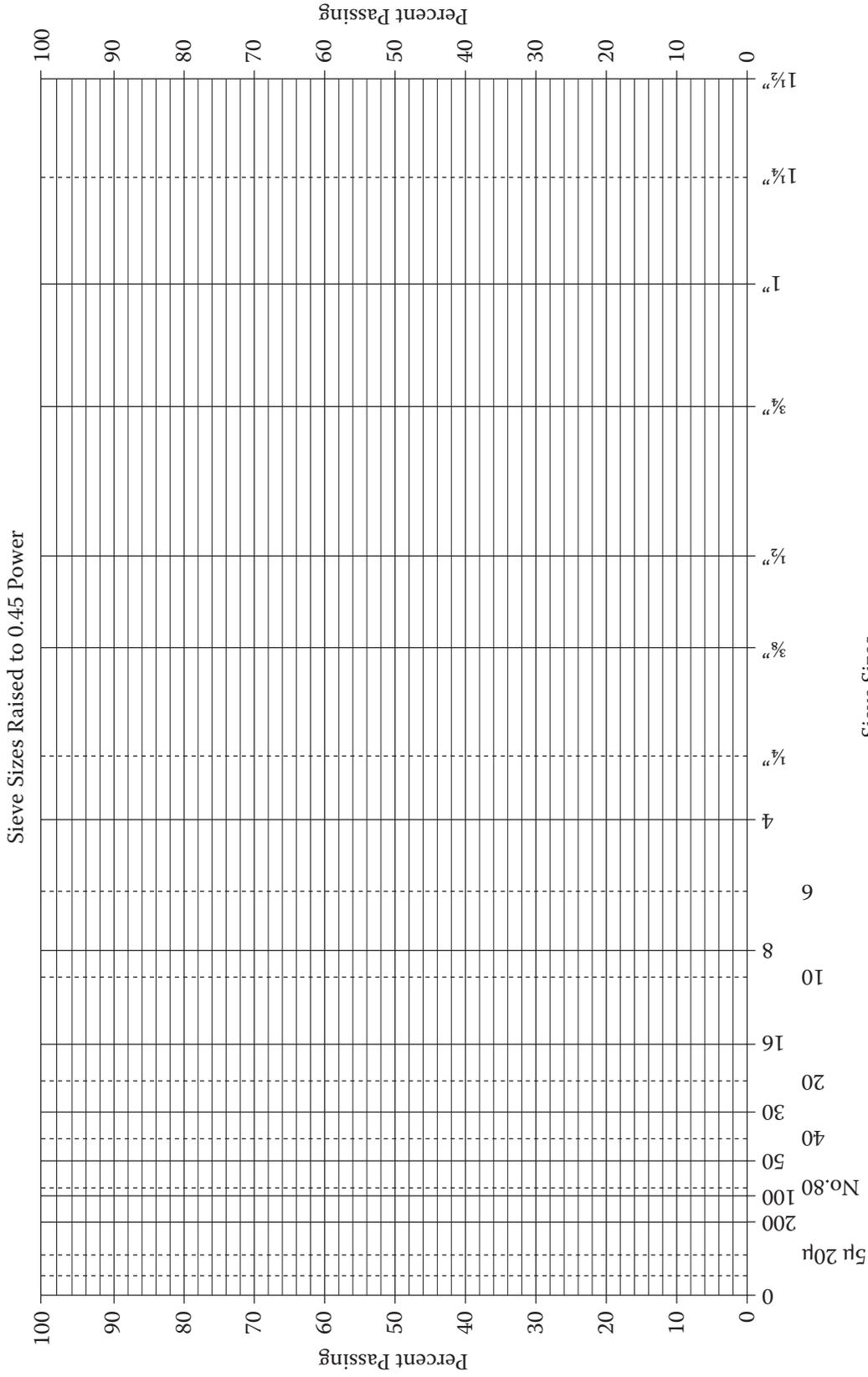
Figure 5c
U.S. Bureau of Public Roads 0.45 power gradation chart.

Wash and Dry Sieve Analysis (ASTM Designation: C 117)

Wash and Dry Sieve Analysis

Sieve Size	Weight Retained (g)	% Retained	% Passing	Sieve Size	Weight Retained (g)	% Retained	% Passing
2 in.				2 in.			
1½ in.				1½ in.			
1 in.				1 in.			
¾ in.				¾ in.			
½ in.				½ in.			
⅜ in.				⅜ in.			
#4				#4			
#8				#8			
#16				#16			
#30				#30			
#50				#50			
#100				#100			
#200				#200			
Pan				Pan			
Total				Total			

a. Wt. of sample (g):

b. Wt. of sample after washing (g):

c. Loss in washing, (a − b) (g):

d. Pan from dry sieve (g):

Total—200, (c + d) (g):

a. Wt. of sample (g):

b. Wt. of sample after washing (g):

c. Loss in washing, (a − b) (g):

d. Pan from dry sieve (g):

Total—200, (c + d) (g):

Wash and Dry Sieve Analysis (ASTM Designation: C 117)

Wash and Dry Sieve Analysis

Sieve Size	Weight Retained (g)	% Retained	% Passing	Sieve Size	Weight Retained (g)	% Retained	% Passing
2 in.				2 in.			
1½ in.				1½ in.			
1 in.				1 in.			
¾ in.				¾ in.			
½ in.				½ in.			
⅜ in.				⅜ in.			
#4				#4			
#8				#8			
#16				#16			
#30				#30			
#50				#50			
#100				#100			
#200				#200			
Pan				Pan			
Total				Total			

a. Wt. of sample (g):

b. Wt. of sample after washing (g):

c. Loss in washing, (a − b) (g):

d. Pan from dry sieve (g):

Total—200, (c + d) (g):

a. Wt. of sample (g):

b. Wt. of sample after washing (g):

c. Loss in washing, (a − b) (g):

d. Pan from dry sieve (g):

Total—200, (c + d) (g):

Data Sheet (ASTM Designation: C 138)

Test No. and Date	Net Wt. of Container, kg or lb	Wt. of Container + H_2O, kg or lb	Net Wt. of Water, kg or lb	Vol. of Container, m^3 or ft^3
1 3/1/99	1.15 kg	27.43 kg	26.28 kg	0.0263 m^3
2				
3				
4				
5				
6				

Data Sheet (ASTM Designation: C 138)

Test No. and Date	Wt. of Container + Concrete	Net Wt. of Concrete	W kg/m^3 or lb/ft^3	W_1 kg or lb	$Y = W_1/W$	Y_d	$R_y = Y/Y_d$
1 3/1/99	73.34 kg	72.19 kg	2745 kg/m^3	2698 kg	0.983 m^3	1 m^3	0.983
2							
3							
4							
5							
6							

Data Sheet for Determination of Portland Cement Specific Gravity (ASTM Designation: C 188)

Specimen Numbers					
	1	2	3	4	5
Initial bath temp., °C					
Final height, cm					
Initial height, cm					
Displaced volume, cm³					
Final bath temp., °C					
Specific gravity = 64 grams/ displacement, cm³					

Average specific gravity of accepted specimen results =

Data Sheet for Determination of Portland Cement Specific Gravity (ASTM Designation: C 188)

Specimen Numbers					
	1	2	3	4	5
Initial bath temp., °C					
Final height, cm					
Initial height, cm					
Displaced volume, cm³					
Final bath temp., °C					
Specific gravity = 64 grams/ displacement, cm³					

Average specific gravity of accepted specimen results =

Tensile Strength of Hydraulic Cement Mortars (ASTM Designation: C 190)

Specimen Number	Maximum Load, Newtons or Pounds	Cross Section, cm × cm or inch × inch	Tensile Stress in kPa or psi
1			
2			
3			
4			
5			
6			
7			
8			
9			
Date specimens prepared:			
Date specimens tested:			
Average tensile strength of the mortar:			

Tensile Strength of Hydraulic Cement Mortars (ASTM Designation: C 190)

Specimen Number	Maximum Load, Newtons or Pounds	Cross Section, cm × cm or inch × inch	Tensile Stress in kPa or psi
1			
2			
3			
4			
5			
6			
7			
8			
9			
Date specimens prepared:			
Date specimens tested:			
Average tensile strength of the mortar:			

Time of Set of Hydraulic Cement by Vicat Needle (ASTM Designation: C 191)

Amount of Water Required, to the Nearest Gram, to Prepare a Normal Consistency Specimen of 650 Grams of Portland Cement Paste by the Procedure Described in Test Procedure Item 2 =	
Time Periods	Penetration of Needle, D, mm
30 sec. immediately after completion of 30-minute cure	
First rest period[a]	
30 sec.	
Second rest period[a]	
30 sec.	
Third rest period[a]	
30 sec.	
Fourth rest period[a]	
30 sec.	
Fifth rest period[a]	
30 sec.	
Time to reach 25 mm penetration to the nearest minute = . This value is obtained by interpolating between the last two test results obtained, one being above and the other below 25 mm.	

[a] The rest periods are 15 minutes for all types of Portland cement except for Type III, high early strength. The rest period for the Type III cement is 10 min.

Time of Set of Hydraulic Cement by Vicat Needle (ASTM Designation: C 191)

Amount of Water Required, to the Nearest Gram, to Prepare a Normal Consistency Specimen of 650 Grams of Portland Cement Paste by the Procedure Described in Test Procedure Item 2 =	
Time Periods	Penetration of Needle, D, mm
30 sec. immediately after completion of 30-minute cure	
First rest period[a]	
30 sec.	
Second rest period[a]	
30 sec.	
Third rest period[a]	
30 sec.	
Fourth rest period[a]	
30 sec.	
Fifth rest period[a]	
30 sec.	
Time to reach 25 mm penetration to the nearest minute = . This value is obtained by interpolating between the last two test results obtained, one being above and the other below 25 mm.	

[a] The rest periods are 15 minutes for all types of Portland cement except for Type III, high early strength. The rest period for the Type III cement is 10 min.

Fineness of Portland Cement by Air Permeability Apparatus (ASTM Designation: C 204)

Weight in grams: W_A =   ; W_B =   ; W_C =
Determination of V in cm³: V_1 =   ; V_2 =   ; V_3 =
Accepted value for V after at least 2 determinations =
Permeability tests to determine T_S in seconds:
Accepted value, T_S, after at least 3 determinations =
Penetration test to determine T in seconds =
$S = S_S(T)^{1/2}/(T_S)^{1/2}$ =
S_S is obtained from the data on the vial containing the standard cement sample (NIST Standard Reference Material No. 114).

Fineness of Portland Cement by Air Permeability Apparatus (ASTM Designation: C 204)

Weight in grams: W_A =   ; W_B =   ; W_C =
Determination of V in cm³: V_1 =   ; V_2 =   ; V_3 =
Accepted value for V after at least 2 determinations =
Permeability tests to determine T_S in seconds:
Accepted value, T_S, after at least 3 determinations =
Penetration test to determine T in seconds =
$S = S_S(T)^{1/2}/(T_S)^{1/2}$ =
S_S is obtained from the data on the vial containing the standard cement sample (NIST Standard Reference Material No. 114).

Data Sheet for Determination of Index of Aggregate Particle Shape and Texture (ASTM Designation: D 3398)

Sieve Size		Aggregate Grading %	Particle Index of Each Size Group	Weighted Average of Aggregate Grading × Particle Index ÷100
Passing	Retained			

Data Sheet for Determination of Index of Aggregate Particle Shape and Texture (ASTM Designation: D 3398)

Sieve Size		Aggregate Grading %	Particle Index of Each Size Group	Weighted Average of Aggregate Grading × Particle Index ÷100
Passing	Retained			

Particle Shape Composition in Representative Coarse Aggregate Sample (ASTM Designation: D 4791)

Sieve Sizes		Sample		Rhombic		Slightly Flat or Elongated, 1:2		Flat or Elongated, 1:3		Very Flat or Elongated, 1:5	
Pass mm (in.)	Retain mm (in.)	Wt. Gm	% Total	Wt. Gm	% Total	Wt. Gm	% Total	Wt. Gm	% Total	Wt. Gm	% Total

Particle Shape Composition in Representative Coarse Aggregate Sample (ASTM Designation: D 4791)

Sieve Sizes		Sample		Rhombic		Slightly Flat or Elongated, 1:2		Flat or Elongated, 1:3		Very Flat or Elongated, 1:5	
Pass mm (in.)	Retain mm (in.)	Wt. Gm	% Total	Wt. Gm	% Total	Wt. Gm	% Total	Wt. Gm	% Total	Wt. Gm	% Total

Concrete Bond Strength Data Sheet (ASTM Designation: C 234)

Date of test:	RE-bar orientation:

Date specimens were cast:

Description of test specimens:

Measured length of RE-bar from bottom of concrete to the center of the jaws of the testing machine:

Maximum elongation to yield of the RE-bar in cm or in.:

Special instructions:

   1. Use a 2.2-kN (500-lb) seating load before zeroing the gages.
   2. Apply the load at a maximum rate of 4.4 kN (1000 lb) per/min.
   3. Use a value of E = 200 GPa (29×10^6 psi) and a Yield Point = 250 MPa (36,000 psi).

Scale Reading kg or lb	Dial Reading of RE-bar Slip, mm or in.			Remarks
	Specimen 1	Specimen 2	Specimen 3	

Concrete Bond Strength Data Sheet (ASTM Designation: C 234)

Date of test: RE-bar orientation:

Date specimens were cast:

Description of test specimens:

Measured length of RE-bar from bottom of concrete to the center of the jaws of the testing machine:

Maximum elongation to yield of the RE-bar in cm or in.:

Special instructions:

    1. Use a 2.2-kN (500-lb) seating load before zeroing the gages.

    2. Apply the load at a maximum rate of 4.4 kN (1000 lb) per/min.

    3. Use a value of E = 200 GPa (29×10^6 psi) and a Yield Point = 250 MPa (36,000 psi).

Scale Reading kg or lb	Dial Reading of RE-bar Slip, mm or in.			Remarks
	Specimen 1	Specimen 2	Specimen 3	

Stress/Strain Table for the Determination of Young's Modulus and Poisson's Ratio for Concrete in Compression (ASTM Designation: C 469)

Stress MPa(psi)	Load kg (lb)	Deformation—mm(in. $\times 10^{-4}$) Longitudinal Transverse		Longitudinal Transverse Strain—mm/mm(in./in.) $\times 10^{-4}$	
S_1 – Comp	—	Comp	—	0.50	Comp
$S = 0.25\ S_{ult}$	Comp	—	—	Comp	Comp
$S = 0.40\ S_{ult}$	Comp	—	—	Comp	Comp
S_1				0.50	
S					
S_2					
S_1				0.50	
S					
S_2					
S_1				0.50	
S					
S_2					
S_1				0.50	
S					
S_2					

_____ Dial readings   Comp = Computed from data

Age of specimen =

Longitudinal gauge distance =

Diameter of specimen =

Ultimate compressive load of test specimen =

E =   ; μ =

Remarks:

Stress/Strain Table for the Determination of Young's Modulus and Poisson's Ratio for Concrete in Compression (ASTM Designation: C 469)

Stress MPa(psi)	Load kg (lb)	Deformation—mm(in. $\times 10^{-4}$) Longitudinal Transverse		Longitudinal Transverse Strain—mm/mm(in./in.) $\times 10^{-4}$	
S_1 – Comp	—	Comp	—	0.50	Comp
$S = 0.25\ S_{ult}$	Comp	—	—	Comp	Comp
$S = 0.40\ S_{ult}$	Comp	—	—	Comp	Comp
S_1				0.50	
S					
S_2					
S_1				0.50	
S					
S_2					
S_1				0.50	
S					
S_2					
S_1				0.50	
S					
S_2					

_____ Dial readings   Comp = Computed from data

Age of specimen =

Longitudinal gauge distance =

Diameter of specimen =

Ultimate compressive load of test specimen =

E =   ; μ =

Remarks:

Splitting Tensile Strength of Cylindrical Concrete Specimens (ASTM Designation: C 496)

Date of test:				
Date specimens were cast:				
Description of specimen:				
Length of specimen, meters or inches =				
Diameter of specimen in meters or inches =				
f'_c of concrete mix tested under ASTM Designation: C 39 =				

Specimen Number	Max. Load, kg (mass) or lb/f	Splitting Strength, kPa or psi	% f'_c	Remarks

Note: $T = (2 \times P)/(\pi \times l \times d)$.

Splitting Tensile Strength of Cylindrical Concrete Specimens (ASTM Designation: C 496)

Date of test:				
Date specimens were cast:				
Description of specimen:				
Length of specimen, meters or inches =				
Diameter of specimen in meters or inches =				
f'_c of concrete mix tested under ASTM Designation: C 39 =				

Specimen Number	Max. Load, kg (mass) or lb/f	Splitting Strength, kPa or psi	% f'_c	Remarks

Note: $T = (2 \times P)/(\pi \times l \times d)$.

Data Sheet for Rebound Number for Hardened Concrete (ASTM Designation: C 805)

Test Number	Readings	Remarks
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		
Average of ten readings =		
Reading nos. discarded:		
New average =		
Concrete compressive strength, kPa or psi =		

Data Sheet for Rebound Number for Hardened Concrete (ASTM Designation: C 805)

Test Number	Readings	Remarks
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		
Average of ten readings =		
Reading nos. discarded:		
New average =		
Concrete compressive strength, kPa or psi =		

Direct Tensile Test of Portland Cement Concrete (Reference: None)

Date specimens were cast:

Description of test specimens:

Average diameter measured at the middle of specimen:

f'_c from compression test specimens:

Specimen No.	Load, kg or lb	Tensile Stress, kPa or psi	Days Cured	% f'_c	Remarks

Direct Tensile Test of Portland Cement Concrete (Reference: None)

Date specimens were cast:

Description of test specimens:

Average diameter measured at the middle of specimen:

f'_c from compression test specimens:

Specimen No.	Load, kg or lb	Tensile Stress, kPa or psi	Days Cured	% f'_c	Remarks

Index

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SECOND EDITION

"As every civil engineer knows, Portland Cement is the most versatile and important material of construction, and will probably remain so far into the future. Yet few books, if any, exist that offer an in-depth analysis of the mixing and testing methods of this vital hydraulic cement." This statement, written about the first edition of **Engineered Concrete: Mix Design and Test Methods**, remains as true today as it was ten years ago. Revised and updated, the second edition of this groundbreaking resource completely covers Portland Cement, Portland Cement Concrete, and their uses.

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- Several new tests and sample tearsheets

- Additional and updated data sheets

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