SECOND EDITION

ENGINEERED CONCRETE

MIX DESIGN AND TEST METHODS

IRVING KETT
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.
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 cut-back 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:
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.

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.

\[
\text{TABLE 1} \quad \text{Grading Requirement for Fine Aggregates from ASTM Designation: C 33}
\]

<table>
<thead>
<tr>
<th>Sieve Size (Specification E 11)</th>
<th>Percent Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5 mm (⅜ in.)</td>
<td>100</td>
</tr>
<tr>
<td>4.75 mm (No. 4)</td>
<td>95–100</td>
</tr>
<tr>
<td>2.36 mm (No. 8)</td>
<td>80–100</td>
</tr>
<tr>
<td>1.16 mm (No. 16)</td>
<td>50–85</td>
</tr>
<tr>
<td>600 μm (No. 30)</td>
<td>25–60</td>
</tr>
<tr>
<td>300 μm (No. 50)</td>
<td>10–30</td>
</tr>
<tr>
<td>150 μm (No. 100)</td>
<td>2–10</td>
</tr>
<tr>
<td>Nominal Sieve Size</td>
<td>100 mm (4 in.)</td>
</tr>
<tr>
<td>-------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>37.5–90 mm (1.5–3.5 in.)</td>
<td>100</td>
</tr>
<tr>
<td>37.5–63 mm (1.5–2.5 in.)</td>
<td></td>
</tr>
<tr>
<td>25–50 mm (1–2 in.)</td>
<td></td>
</tr>
<tr>
<td>4.75–50 mm (No. 4–2 in.)</td>
<td></td>
</tr>
<tr>
<td>19–37.5 mm (0.75–1.5 in.)</td>
<td></td>
</tr>
<tr>
<td>4.75–37.5 mm (No. 4–1.5 in.)</td>
<td></td>
</tr>
<tr>
<td>12.5–25 mm (0.5–1 in.)</td>
<td></td>
</tr>
<tr>
<td>9.5–25 mm (0.375–1 in.)</td>
<td></td>
</tr>
<tr>
<td>4.75–25 mm (No. 4–1 in.)</td>
<td></td>
</tr>
<tr>
<td>9.5–19 mm (.375–.75 in.)</td>
<td></td>
</tr>
<tr>
<td>4.75–19 mm (No. 4–.75 in)</td>
<td></td>
</tr>
<tr>
<td>4.75–12.5 mm (No. 4–.5 in)</td>
<td></td>
</tr>
</tbody>
</table>
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.
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.
Mix Design Procedures

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 $f'_c$, 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 $f'_c$ 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).

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### TABLE 4
Maximum Water/Cement Ratio for Various Exposure Conditions

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

* 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

<table>
<thead>
<tr>
<th>Maximum Size of Aggregate, mm (inches)</th>
<th>Volume of Rodded Coarse Aggregates per Unit Volume of Concrete for Different Fineness Moduli of Fine Aggregates as per ASTM Designation: C 29a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.40</td>
</tr>
<tr>
<td>9.5 mm (⅜ in.)</td>
<td>0.50</td>
</tr>
<tr>
<td>12.5 mm (½ in.)</td>
<td>0.59</td>
</tr>
<tr>
<td>19 mm (¾ in.)</td>
<td>0.66</td>
</tr>
<tr>
<td>25 mm (1 in.)</td>
<td>0.71</td>
</tr>
<tr>
<td>37.5 mm (1.5 in.)</td>
<td>0.75</td>
</tr>
<tr>
<td>50 mm (2 in.)</td>
<td>0.78</td>
</tr>
<tr>
<td>76 mm (3 in.)</td>
<td>0.82</td>
</tr>
</tbody>
</table>

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.”