CONCRETE

Microstructure, Properties, and Materials

THIRD EDITION

P. Kumar Mehta
Paulo J. M. Monteiro

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Concrete

Microstructure, Properties, and Materials

P. Kumar Mehta

Paulo J. M. Monteiro

Department of Civil and Environmental Engineering
University of California at Berkeley

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This book is dedicated to students, researchers, and practicing engineers in the concrete community who are faced with the challenges of extending the uses of the material to new frontiers of human civilization and to make it more durable, sustainable, and environment friendly.

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Contents

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Foreword

In recent years, a number of books on concrete technology have become available for use by students in civil engineering. Most of these books deal with the subject in a traditional manner, i.e., describing the characteristics of concrete-making materials and engineering properties of concrete without adequate reference to the material science controlling the properties. The previous editions of the text on concrete technology by Professors P. K. Mehta and Paulo Monteiro, both of the prestigious University of California at Berkeley, adopted the microstructure-property relationship approach commonly used in all materials science books to provide scientific explanations for strength, durability, and other engineering properties of concrete. This approach was widely appreciated, which is evident from the fact that the book has been translated and published in several foreign languages.

Now, the authors have brought out the third edition, which, while retaining the uniqueness and simplicity of earlier editions, extends the coverage to several topics of great importance for both students and professional engineers interested in concrete. The paramount importance of making durable concrete that is essential for sustainable development of the concrete industry is a hallmark of this unique book. The chapter on durability leads the reader in a systemic manner through the primary causes of deterioration of concrete and their control, and concludes with a holistic approach for building highly durable concrete structures. The authors are to be commended for successfully shifting the focus from strength to durability of concrete.

The third edition of the book also contains a comprehensive chapter on non-destructive testing methods and a thoroughly revised chapter on recent advancements in concrete technology including high-performance concrete, high-volume fly ash concrete, and self-consolidating concrete. Another unique feature of the text is the inclusion of approximately 250 line drawings and numerous photographs to illustrate the topics discussed. The book is splendidly designed so that it can be used equally by undergraduate and graduate students, and structural designers and engineers. My recommendation to those who may be searching for an outstanding book on modern concrete technology, either for classroom teaching or for professional use, is to search no more.

V. Mohan Malhotra
Scientist Emeritus
Canada Center for Mineral and Energy Technology
Ottawa, Canada

Preface

There is a direct relationship between population and urbanization. During the last 100 years, the world population has grown from 1.5 to 6 billion and nearly 3 billion people now live in and around the cities. Seventeen of the 20 megacities, each with a population of 10 million or more, happen to be situated in developing countries where enormous quantities of materials are required for the construction of housing, factories, commercial buildings, drinking water and sanitation facilities, dams and canals, roads, bridges, tunnels, and other infrastructure. And the principal material of construction is portland cement concrete. *By volume, the largest manufactures product in the world today is concrete.* Naturally, design and construction engineers need to know more about concrete than about other materials of construction.

This book is not intended to be an exhaustive treatise on concrete. Written primarily for the use of students in civil engineering, it covers *a wide spectrum of topics in modern concrete technology* that should be of considerable interest to practicing engineers. For instance, to reduce the environmental impact of concrete, roles of pozzolanic and cementitious by-products as well as superplasticizing admixtures in producing highly durable products are thoroughly covered.

One of the objectives of this book is to present the *art and science of concrete in a simple, clear, and scientific manner*. Properties of engineering materials are governed by their microstructure. Therefore, it is highly desirable that structural designers and engineers interested in the properties of concrete become familiar with the microstructure of the material. In spite of apparent simplicity of the technology of producing concrete, the *microstructure of the product is highly complex*. Concrete contains a heterogeneous distribution of many solid compounds as well as voids of varying shapes and sizes that may be completely or partially filled with alkaline solution.

Compared to other engineering materials like steel, plastics, and ceramics, the microstructure of concrete is not a static property of the material. This is because two of the three components of the microstructure, namely, the bulk cement paste and the interfacial transition zone between aggregate and cement paste change with time. In fact, the word *concrete* comes from the Latin term *concretus*, which means to grow. The strength of concrete depends on the volume of the cement hydration products that continue to form for several years, resulting in a gradual enhancement of strength. Depending on the exposure to environment, solutions penetrating from the surface into the interior of concrete sometimes dissolve the cement hydration products causing an increase in porosity which reduces the strength and durability of concrete; conversely, when the products of interaction recrystallize in the voids and microcracks, it may enhance the strength and durability of the material. This explains why analytical methods of material science that work well in modeling and predicting the behavior of microstructurally stable and homogeneous materials do not seem to be satisfactory in the case of concrete structures.

In regard to organization of the subject matter, the *first part* of this three-part book is devoted to hardened concrete microstructure and properties, such as strength, modulus of elasticity, drying shrinkage, thermal shrinkage, creep, tensile strain capacity, permeability, and durability to various processes of degradation. Definition of each property, its significance and origin, and factors controlling it are set forth in a clear manner. The *second part* of the book deals with concrete-making materials and concrete processing. Separate chapters contain state-of-the-art reviews on composition and properties of cements, aggregates, and admixtures. There are also separate chapters on proportioning of concrete mixtures, properties of concrete at early ages, and nondestructive test methods. The *third part* covers special topics in concrete technology. One chapter is devoted to composition, properties, and applications of special types of concrete, such as lightweight concrete, high-strength concrete, high-performance concrete, self-consolidating concrete, shrinkage-compensating concrete, fiber-reinforced concrete, concretes containing polymers, and mass concrete. A separate chapter deals with advances of concrete mechanics covering composite models, creep and shrinkage, thermal stresses, and fracture of concrete. The final chapter contains some reflections on current challenges to concrete as the most widely used building material, with special emphasis on ecological considerations.

A special feature of the book is the inclusion of numerous unique diagrams, photographs, and summary tables intended to serve as teaching aids. New terms are indicated in italics and are clearly defined. Each chapter begins with a preview of the contents, and ends with a self-test and a guide for further reading.

Acknowledgments

This thoroughly revised third edition of the book including the companion CD would not have been possible without the help and cooperation of many friends and professional colleagues. The authors thank all of them most sincerely.

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P. Kumar Mehta

Paulo J. M. Monteiro
University of California at Berkeley

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Part

I

Microstructure and Properties of Hardened Concrete

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Chapter

1

Introduction

Preview

This chapter describes important applications of concrete, and examines the reasons that made concrete the most widely used structural material in the world today. The principal components of modern concrete are identified and defined. A brief description of the major concrete types is given.

For the benefit of beginning students, an introduction to important properties of engineering materials, with special reference to concrete, is also included in this chapter. The properties discussed are strength, elastic modulus, toughness, dimensional stability, and durability.

1.1 Concrete as a Structural Material

In an article published by the *Scientific American* in April 1964, S. Brunauer and L.E. Copeland, two eminent scientists in the field of cement and concrete, wrote:

> The most widely used construction material is concrete, commonly made by mixing portland cement with sand, crushed rock, and water. Last year in the U.S. 63 million tons of portland cement were converted into 500 million tons of concrete, five times the consumption by weight of steel. In many countries the ratio of concrete consumption to steel consumption exceeds ten to one. The total world consumption of concrete last year is estimated at three billion tons, or one ton for every living human being. Man consumes no material except water in such tremendous quantities.

Today, the rate at which concrete is used is much higher than it was 40 years ago. It is estimated that the present consumption of concrete in the world is of the order of 11 billion metric tonnes every year.

Concrete is neither as strong nor as tough as steel, so why is it the most widely used engineering material? There are at least three primary reasons.

Figure 1-1 Itaipu Dam, Brazil. (Photograph courtesy of Itaipu Binacional, Brazil.)
This spectacular 12,600 MW hydroelectric project at Itaipu, estimated cost $18.5 billion, includes a 180-m high hollow-gravity concrete dam at the Paraná River on the Brazil-Paraguay border. By 1982 twelve types of concrete, totaling 12.5 million cubic meters, had been used in the construction of the dam, piers of diversion structure, and the precast beams, slabs, and other structural elements for the power plant.

The designed compressive strengths of concrete ranged from as low as 14 MPa at 1 year for mass concrete for the dam to as high as 35 MPa at 28 days for precast concrete members. All coarse aggregate and about 70 percent of the fine aggregate was obtained by crushing basalt rock available at the site. The coarse aggregates were separately stockpiled into gradations of 150, 75, 38, and 19 mm maximum size. A combination of several aggregates containing different size fractions was necessary to reduce the void content and, therefore, the cement content of the mass concrete mixtures. As a result, the cement content of the mass concrete was limited to as low as 108 kg/m^3, and the adiabatic temperature rise to 19°C at 28 days. Furthermore, to prevent thermal cracking, it was specified that the temperature of freshly cooled concrete would be limited to 7°C by precooling the constituent materials.

First, concrete* possesses excellent resistance to water. Unlike wood and ordinary steel, the ability of concrete to withstand the action of water without serious deterioration makes it an ideal material for building structures to control, store, and transport water. In fact, some of the earliest known applications of the material consisted of aqueducts and waterfront retaining walls constructed by the Romans. The use of *plain concrete* for dams, canal linings, and pavements is now a common sight almost everywhere in the world (Figs. 1-1 and 1-2).

*In this book, the term *concrete* refers to portland-cement concrete unless stated otherwise.

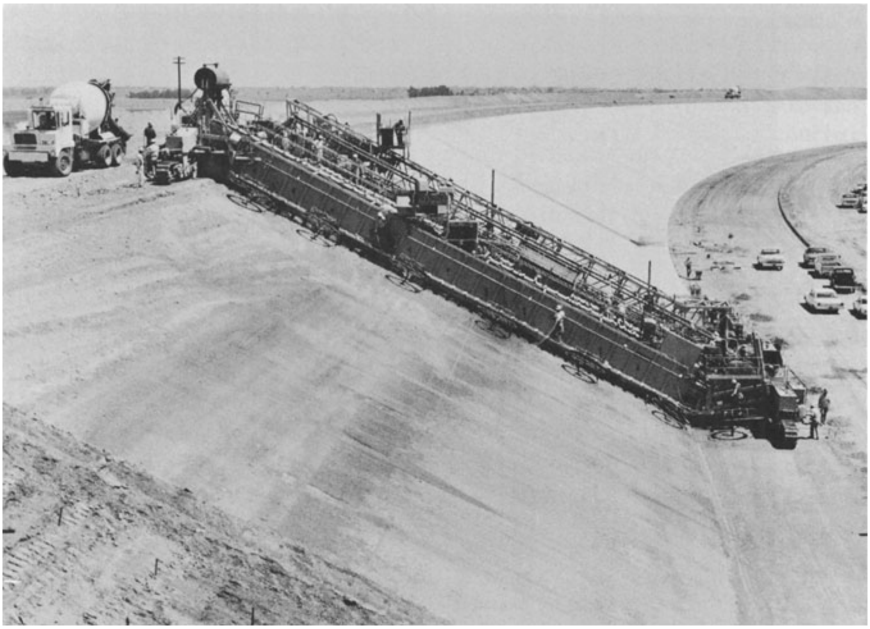

Figure 1-2 California aqueduct construction. (Photograph courtesy of the State of California, Department of Water Resources.)

In California, about three-fourths of the fresh water in the form of rain and snowfall is found in the northern one-third of the state; however, three-fourths of the total water is needed in the lower two-thirds, where major centers of population, industry, and agriculture are located. Therefore, in the 1960s, at an estimated cost of $4 billion, California undertook to build a water system capable of handling 4.23 million acre-feet (5.22 billion cubic meter) of water annually. Eventually extending more than 900 km from north to south to provide supplemental water, flood control, hydroelectric power, and recreational facilities, this project called for the construction of 23 dams and reservoirs, 22 pumping plants, 750 km of canals (California Aqueduct), 280 km of pipeline, and 30 km of tunnels.

An awesome task before the project was to transport water from an elevation near the sea floor in the San Joaquin Delta across the Tehachapi Mountains over to the Los Angeles metropolitan area. This is accomplished by pumping the large body of water in a single 587-m lift. At its full capacity, the pumping plant consumes nearly 6 billion kilowatt-hours a year.

Approximately 3 million cubic meters of concrete were used for the construction of tunnels, pipelines, pumping plants, and canal lining. One of the early design decisions for the California Aqueduct was to build a concrete canal rather than a compacted earth-lined canal, because concrete-lined canals have relatively lower head loss, pumping and maintenance costs, and seepage loss. Depending on the side slope of the canal section, 50- to 100-mm thick unreinforced concrete lining is provided. Concrete, containing 225 to 237 kg/m^3 *portland cement and 42 kg/m*^{3} *pozzolan, showed 14 , 24 , and 31 MPa compressive strength in test cylinders cured for 7, 28, and 91 days, respectively. Adequate speed of construction of concrete lining was assured by slip-forming operation.*

Structural elements exposed to moisture, such as piles, foundations, footings, floors, beams, columns, roofs, exterior walls, and pipes, are frequently built with reinforced and prestressed concrete (Fig. 1-3). *Reinforced concrete* is a concrete usually containing steel bars, which is designed on the assumption that the two materials act together in resisting tensile forces. With *prestressed concrete* by tensioning the steel tendons, a precompression is introduced such that the tensile stresses during service are counteracted to prevent cracking. Large amounts of concrete find their way into reinforced or prestressed structural elements. The durability of concrete to aggressive waters is responsible for the fact that its use has been extended to severe industrial and natural environments (Fig. 1-4).

The second reason for the widespread use of concrete is the ease with which structural concrete elements can be formed into a variety of shapes and sizes

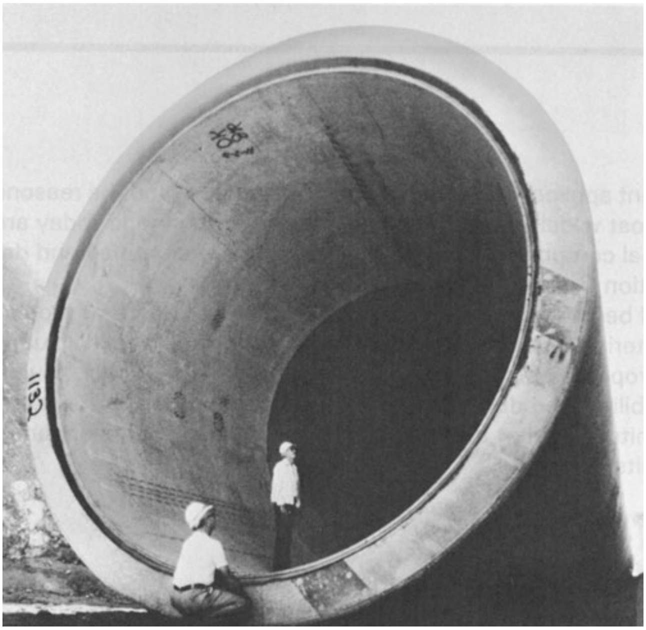

Figure 1-3 Central Arizona project pipeline. (Photograph courtesy of Ameron Pipe Division.)

The largest circular precast concrete structure ever built for the transportation of water is part of the Central Arizona Project—a $1.2 billion U.S. Bureau of Reclamation development, which provides water from the Colorado River for agricultural, industrial, and municipal use in Arizona, including the metropolitan areas of Phoenix and Tucson. The system contains 1560 pipe sections, each 6.7-m long, 7.5-m outside diameter (equivalent to the height of a two-story building), 6.4-m inside diameter, and weighing up to 225 tonnes.

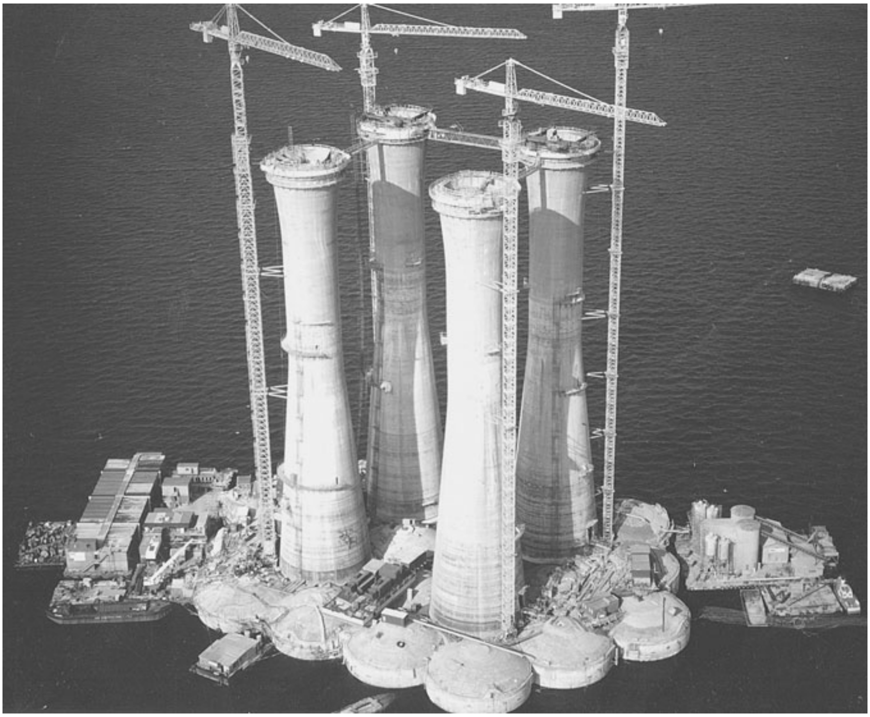

Figure 1-4 Statfjord B offshore concrete platform, Norway. (Photograph courtesy of Norwegian Contractors, Inc.)

Since 1971, twenty concrete platform requiring about 1.3 million cubic meters of concrete have been installed in the British and Norwegian sectors of the North Sea. Statfjord B, the largest concrete platform, built in 1981, has a base area of 18,000 m^2, 24 oil storage cells with about 2 million barrels of storage capacity, four prestressed concrete shafts between the storage cells and the deck frame, and 42 drilling slots on the deck. The structure was built and assembled at a dry dock in Stavanger; then the entire assembly, weighing about 40,000 tonnes, was towed to the site of the oil well, where it was submerged to a water depth of about 145 m. The prestressed and heavily reinforced concrete elements of the structure are exposed to the corrosive action of seawater and are designed to withstand 31-m high waves. Therefore, the selection and proportioning of materials for the concrete mixture was governed primarily by consideration of the speed of construction by slip-forming and durability of hardened concrete to the hostile environment. A free-flowing concrete mixture (220-mm slump), containing 380 kg/m^3 of finely ground portland cement, 20 mm of maximum-size coarse aggregate, a 0.42 water-cement ratio, and a superplasticizing admixture was found satisfactory for the job. The tapered shafts under slip-forming operation are shown in the figure.

(Figs. 1-5 to 1-10). This is because freshly made concrete is of a plastic consistency, which enables the material to flow into prefabricated formwork. After a number of hours when the concrete has solidified and hardened to a strong mass, the formwork can be removed for reuse.

Figure 1-5 Interior of the Sports Palace in Rome, Italy, designed by Pier Luigi Nervi, for Olympic games in 1960. (Photograph from Ediciones Dolmen.)

Nervi was a creative engineer with full appreciation of structural concept, practical constructability, and new materials. He was a pioneer of "ferro-cement" technology, which involves embedding a thin metallic mesh in a rich cement mortar to form structural elements with high ductility and crack-resistance. The above photograph shows the Palazzo dello Sport Dome built with a 100-m span, for a seating capacity of 16,000. Thin-walled precast elements with higher flexibility, elasticity, and strength capacity were created.

The third reason for the popularity of concrete with engineers is that it is usually the cheapest and most readily available material on the job. The principal components for making concrete, namely aggregate, water, and portland cement are relatively inexpensive and are commonly available in most parts of the world. Depending on the components' transportation cost, in certain geographical locations the price of concrete may be as high as U.S. \$75 to \$100 per cubic meter, at others it may be as low as U.S. \$60 to \$70 per cubic meter.

Some of the considerations that favor the use of concrete over steel as the construction material of choice are as follows:

Maintenance. Concrete does not corrode, needs no surface treatment, and its strength increases with time; therefore, concrete structures require much less maintenance. Steel structures, on the other hand, are susceptible to rather heavy corrosion in offshore environments, require costly surface treatment and other methods of protection, and entail considerable maintenance and repair costs.

Fire resistance. The fire resistance of concrete is perhaps the most important single aspect of offshore safety and, at the same time, the area in which

Figure 1-6 Fountain of Time: a sculpture in concrete. (Photograph courtesy of David Solzman.)
"Time goes, you say? Ah, no. Alas, time stays; we go." Concrete is an extraordinary material because it can be not only cast into a variety of complex shapes, but also given special surface effects. Aesthetically pleasing sculpture, murals, and architecture ornaments can be created by suitable choice of concrete-making materials, formwork, and texturing techniques. Fountain of Time is a massive 120 by 18 by 14 ft (36 by 5 by 4 m) work of art in concrete on the south side of the University of Chicago campus. The sculpture is a larger-than-life representation of 100 individual human figures, all cast in place in the exposed aggregate finish. In the words of Steiger, the central figure is Time the conqueror, seated on an armored horse and surrounded by young and old, soldiers, lovers, religious practitioners, and many more participants in the diversity of human life, finally embracing death with outstretched arms. Lorado Taft made the model for this sculpture in 1920 after 7 years of work. About the choice of concrete as a medium of art, the builder of the sculpture, John J. Earley, had this to say: "Concrete as an artistic medium becomes doubly interesting when we realize that in addition to its economy it possesses those properties which are the most desirable of both metal and stone. Metal is cast, it is an exact mechanical reproduction of the artist's work, as in concrete . . . Stone (sculpture) is an interpretation of an original work and more often than not is carried out by another artist. But stone has the advantage of color and texture which enable it to fit easily into varied surroundings, a capability lacking in metal. Concrete, treated as in the Foundation of Time, presents a surface almost entirely of stone with all its visual advantages while at the same time offering the precision of casting that would otherwise only be attained in metal."

the advantages of concrete are most evident. Since an adequate concrete cover on reinforcement or tendons is required for structural integrity in reinforced and prestressed concrete structures, the protection against failure due to excessive heat is provided at the same time.

Resistance to cyclic loading. The fatigue strength of steel structures is greatly influenced by local stress fields in welded joints, corrosion pitting, and sudden

Figure 1-7 Candlestick Park Stadium, San Francisco, California.

Cast-in-place and precast concrete elements can be assembled to produce large structures of different shapes. The photograph shows the sport stadium at Candlestick Park in San Francisco, California, which was constructed in 1958 with about 60,000 seating capacity. The roof canopy is supported by 24-ft (7.3-m) cantilevered precast concrete girders. Through a roof girder connection the cantilevered concrete member is supported by joining it to a cast-in-place concrete bleacher girder.

changes in geometry, such as from thin web to thick frame connections. In most codes of practice, the allowable concrete stresses are limited to about 50 percent of the ultimate strength; thus the fatigue strength of concrete is generally not a problem

1.2 Components of Modern Concrete

Although composition and properties of materials used for making concrete are discussed in Part II, here it is useful to define concrete and the principal concrete-making components. The following definitions are adapted from ASTM C 125* (*Standard Definition of Terms Relating to Concrete and Concrete Aggregates*), and ACI Committee 116 (A Glossary of Terms in the Field of Cement and Concrete Technology):

Concrete is a composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregate. In hydraulic-cement concrete, the binder is formed from a mixture of hydraulic cement and water.

*The ACI committee reports and the ASTM (American Society for Testing and Materials) standards are updated from time to time. The definitions given here are from the ASTM standard approved in the year 2004.

Figure 1-8 Baha'i Temple, Wilmette, Illinois. (Photograph courtesy from David Solzman.)
The Baha'i Temple is an example of the exceedingly beautiful, ornamental architecture that can be created in concrete. Describing the concrete materials and the temple, F. W. Cron (Concrete Construction, Vol. 28, No. 2, 1983) wrote: "The architect had wanted the building and specially the great dome, 27-m diameter, to be as white as possible, but not with a dull and chalky appearance. To achieve the desired effect Earley proposed an opaque white quartz found in South Carolina to reflect light from its broken face. This would be combined with a small amount of translucent quartz to provide brilliance and life. Puerto Rican sand and white portland cement were used to create a combination that reflected light and imparted a bright glow to the exposed-aggregate concrete surface. On a visit to the Temple of Light one can marvel at its brilliance in sunlight. If one returns at night, the lights from within and the floodlights that play on its surface turn the building into a shimmering jewel. The creativity of Louis Bourgeois and the superbly crafted concrete from Earley Studios have acted in concert to produce this great performance."

Aggregate is the granular material, such as sand, gravel, crushed stone, crushed blast-furnace slag, or construction and demolition waste that is used with a cementing medium to produce either concrete or mortar. The term *coarse aggregate* refers to the aggregate particles larger than 4.75 mm (No. 4 sieve), and the term *fine aggregate* refers to the aggregate particles smaller than 4.75 mm but larger than 75 μm (No. 200 sieve). *Gravel* is the coarse aggregate resulting from natural disintegration by weathering of rock. The term *sand* is commonly used for fine aggregate resulting from either natural weathering or crushing of stone. *Crushed stone* is the product resulting from industrial crushing of rocks, boulders, or large cobblestones. *Iron blast-furnace slag*, a by-product of the iron

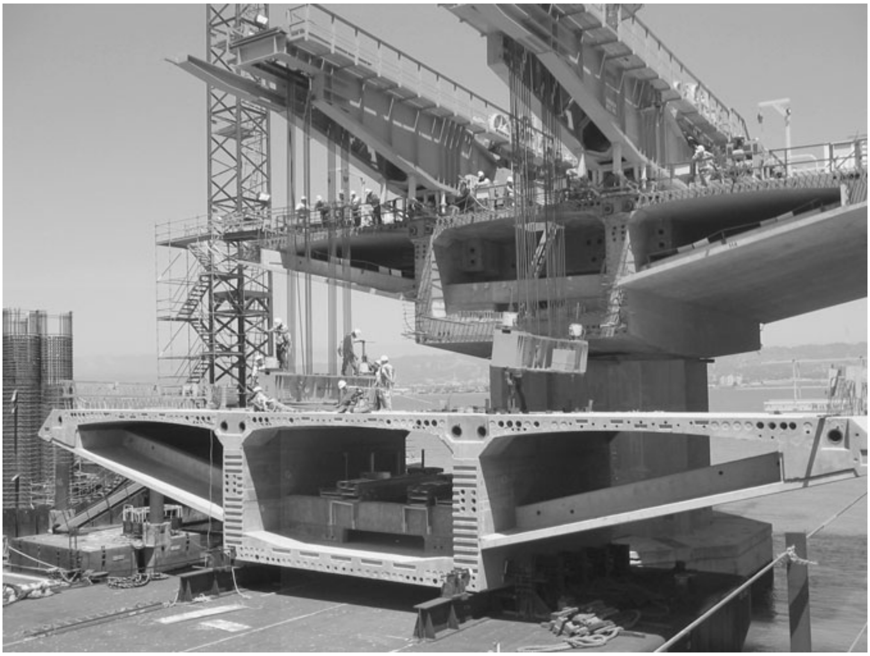

Figure 1-9 Precast concrete girders under installation for the Skyway Segment of the eastern span crossing the San Francisco Bay. (Photograph courtesy of Joseph A. Blum.)

The Loma Pietra earthquake caused damage in the eastern span of the San Francisco Bay Bridge. After years of studying the seismic performance of the bridge, the engineers decided that the best solution was to construct a new span connecting Oakland to the Yerba Buena Island. The two new twin precast segmental bridges will accommodate five lanes of traffic in each direction and a bike path on one side. The superstructure, constructed using the segmental cantilever method, will require 452 precast girders, each weighting as much as 750 tons.

industry, is the material obtained by crushing blast-furnace slag that solidified by slow cooling under atmospheric conditions. Aggregate from construction and demolition waste refers to the product obtained from recycling of concrete, brick, or stone rubble.

Mortar is a mixture of sand, cement, and water. It is like concrete without a coarse aggregate. *Grout* is a mixture of cementitious material and aggregate, usually fine aggregate, to which sufficient water is added to produce a pouring consistency without segregation of the constituents. *Shotcrete* refers to a mortar or concrete that is pneumatically transported through a hose and projected onto a surface at high velocity.

Cement is a finely pulverized, dry material that by itself is not a binder but develops the binding property as a result of hydration (i.e., from chemical reactions between cement minerals and water). A cement is called *hydraulic* when the hydration products are stable in an aqueous environment. The most commonly

(a) January 1994 (b) September 1994

(c) May 1995 (d) September 1995 (e) February 1996

Figure 1-10 Construction sequence of the Petronas Twin Towers. (Photographs courtesy of the Thornton Tomasetti Group.)

The Petronas Towers in Malaysia's capital city, Kuala Lumpur, is the tallest building in the world. The 452-m high structure composed of two, 88-story buildings and their pinnacles, optimized the use of steel and reinforced concrete. Steel was used primarily in the long-span floor beams, while reinforced concrete was used in the central core, in the perimeter columns, and in the tower perimeter ring beams. The strength of the concrete used in the building and foundation ranged from 35 to 80 MPa. The concrete mixture for the 80 MPa concrete, contained 260 kg/m^3 portland cement, 260 kg/m^3 of cementitious and pozzolanic blending material with 30 kg/m^3 silica fume, and 10 l/m^3 high-range water reducer to obtain a water-cement ratio of 0.27. The strength test was performed at 56 days to allow the slower reacting materials, such as fly ash, to contribute to the strength gain. High-strength mixtures were used in the lower level columns, core walls, and ring beams. Compared to a steel structure, an added benefit of using reinforced concrete was efficient damping of vibrations, which was an important consideration for the building's occupants in light of the structure's potential exposure to moderate and high winds.

used hydraulic cement for making concrete is *portland cement*, which consists essentially of reactive calcium silicates; the calcium silicate hydrates formed during the hydration of portland cement are primarily responsible for its adhesive characteristic, and are stable in aqueous environment.

The foregoing definition of concrete as a mixture of hydraulic cement, aggregates, and water does not include a fourth component, namely admixtures that are frequently used in modern concrete mixtures.

Admixtures are defined as materials other than aggregates, cement, and water, which are added to the concrete batch immediately before or during mixing. The use of admixtures in concrete is now widespread due to many benefits which are possible by their application. For instance, chemical admixtures can modify the setting and hardening characteristic of the cement paste by influencing the rate of cement hydration. Water-reducing admixtures can plasticize fresh concrete mixtures by reducing the surface tension of water; air-entraining admixtures can improve the durability of concrete exposed to cold weather; and mineral admixtures such as pozzolans (materials containing reactive silica) can reduce thermal cracking in mass concrete. Chapter 8 contains a detailed description of the types of admixtures, their composition, and mechanism of action.

1.3 Types of Concrete

Based on unit weight, concrete can be classified into three broad categories. Concrete containing natural sand and gravel or crushed-rock aggregates, generally weighing about 2400 kg/m^3 (4000 lb/yd^3), is called *normal-weight concrete*, and it is the most commonly used concrete for structural purposes. For applications where a higher strength-to-weight ratio is desired, it is possible to reduce the unit weight of concrete by using natural or pyro-processed aggregates with lower bulk density. The term *lightweight concrete* is used for concrete that weighs less than about 1800 kg/m^3 (3000 lb/yd^3). *Heavyweight concrete*, used for radiation shielding, is a concrete produced from high-density aggregates and generally weighs more than 3200 kg/m^3 (5300 lb/yd^3).

Strength grading of cements and concrete is prevalent in Europe and many other countries but is not practiced in the United States. However, from standpoint of distinct differences in the microstructure-property relationships, which will be discussed later, it is useful to divide concrete into three general categories based on compressive strength:

- *Low-strength concrete:* less than 20 MPa (3000 psi)
- *Moderate-strength concrete:* 20 to 40 MPa (3000 to 6000 psi)
- *High-strength concrete:* more than 40 MPa (6000 psi).

Moderate-strength concrete, also referred to as ordinary or normal concrete, is used for most structural work. High-strength concrete is used for special

TABLE 1-1 Typical Proportions of Materials in Concrete Mixtures of Different Strength

	Low-strength (kg/m^3)	Moderate-strength (kg/m^3)	High-strength (kg/m^3)
Cement	255	356	510
Water	178	178	178
Fine aggregate	801	848	890
Coarse aggregate	1169	1032	872
Cement paste proportion			
percent by mass	18	22.1	28.1
percent by volume	26	29.3	34.3
Water/cement by mass	0.70	0.50	0.35
Strength, MPa	18	30	60

applications. It is not possible here to list all concrete types. There are numerous modified concretes which are appropriately named: for example, fiber-reinforced concrete, expansive-cement concrete, and latex-modified concrete. The composition and properties of special concretes are described in Chap. 12.

Typical proportions of materials for producing low-strength, moderate-strength, and high-strength concrete mixtures with normal-weight aggregate are shown in Table 1-1. The influence of the cement paste content and water-cement ratio on the strength of concrete is obvious.

1.4 Properties of Hardened Concrete and Their Significance

The selection of an engineering material for a particular application has to take into account its ability to withstand the applied force. Traditionally, the deformation occurring as a result of applied load is expressed as *strain*, which is defined as the change in length per unit length; the load is expressed as *stress*, which is defined as the force per unit area. Depending on how the stress is acting on the material, the stresses are further distinguished from each other: for example, compression, tension, flexure, shear, and torsion. The stress-strain relationships in materials are generally expressed in terms of strength, elastic modulus, ductility, and toughness.

Strength is a measure of the amount of stress required to fail a material. The working stress theory for concrete design considers concrete as mostly suitable for bearing compressive load; this is why it is the compressive strength of the material that is generally specified. Since the strength of concrete is a function of the cement hydration process, which is relatively slow, traditionally the specifications and tests for concrete strength are based on specimens cured under standard temperature-humidity conditions for a period of 28 days. Typically, the tensile and flexural strengths of concrete are of the order of 10 and 15 percent, respectively, of the compressive strength. The reason for such a large difference between the tensile and compressive strength is attributed to the heterogeneous and complex microstructure of concrete.

With many engineering materials, such as steel, the observed stress-strain behavior when a specimen is subjected to incremental loads can be divided into two parts (Fig. 1-11). Initially, when the strain is proportional to the applied stress and is reversible on unloading the specimen, it is called the *elastic strain*. The *modulus of elasticity* is defined as the ratio between the stress and the reversible strain. In homogeneous materials, the elastic modulus is a measure of the interatomic bonding forces and is unaffected by microstructural changes. This is not true of the heterogeneous multiphase materials like concrete. The elastic modulus of concrete in compression varies from 14×10^3 to 40×10^3 MPa (2×10^6 to 6×10^6 psi). The significance of the elastic limit in structural design lies in the fact that it represents the maximum allowable stress before the material undergoes permanent deformation. Therefore, the engineer must know the elastic modulus of the material because it influences the rigidity of a design.

At a high stress level (Fig. 1-11), the strain no longer remains proportional to the applied stress, and also becomes permanent (i.e., it will not be reversed if the specimen is unloaded). This strain is called the *plastic* or *inelastic strain*. The amount of inelastic strain that can occur before failure is a measure of the *ductility* of the material. The energy required to break the material, the product of force times distance, is represented by the area under the stress-strain curve. The term *toughness* is used as a measure of this energy. The contrast

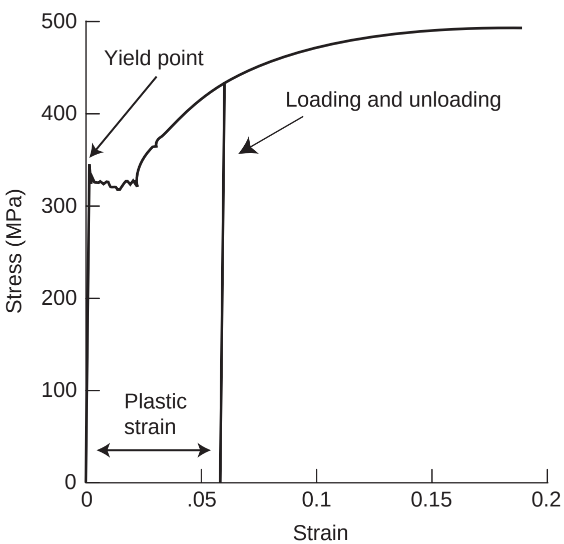

Figure 1-11 Stress-strain behavior of a steel specimen subjected to incremental loads.

between toughness and strength should be noted; the former is a measure of energy, whereas the latter is a measure of the stress required to fracture the material. Thus, two materials may have identical strength but different values of toughness. In general, however, when the strength of a material goes up, the ductility and the toughness go down; also, very high-strength materials usually fail in a brittle manner (i.e., without undergoing any significant plastic strain).

Although under compression concrete appears to show some inelastic strain before failure, typically the strain at fracture is of the order of 2000×10^{-6}, which is considerably lower than the failure strain in structural metals. For practical purposes, therefore, designers do not treat concrete as a ductile material and do not recommend it for structures that are subject to heavy impact loading unless reinforced with steel.

Concrete is a composite material, however, many of its characteristics do not follow the laws of mixtures. For instance, under compressive loading both the aggregate and the hydrated cement paste, if separately tested, would fail elastically, whereas concrete itself shows inelastic behavior before fracture. Also, the strength of concrete is usually much lower than the individual strength of the two components. Such anomalies in the behavior of concrete can be explained on the basis of its microstructure, specially the important role of the interfacial transition zone between coarse aggregate and cement paste.

The stress-strain behavior of the material shown in Fig. 1-11 is typical of specimens loaded to failure in a short time in the laboratory. For some materials the relationship between stress and strain is independent of the loading time; for others it is not. Concrete belongs to the latter category. If a concrete specimen is held for a long period under a constant stress, for instance 50 percent of the ultimate strength of the material, it will exhibit plastic strain. The phenomenon of gradual increase in strain with time under a sustained stress is called *creep*. When creep in concrete is restrained, it manifests itself as a progressive decrease of stress with time. The stress relief associated with creep has important implications for the behavior of plain, reinforced, and prestressed concrete structures.

Strains can arise even in unloaded concrete as a result of changes in the environmental humidity and temperature. Freshly formed concrete is moist; it undergoes *drying shrinkage* when exposed to the ambient humidity. Similarly, shrinkage strains result when, due to the heat generated by cement hydration, hot concrete is cooled to the ambient temperature. Massive concrete elements register considerable rise in temperature because of poor dissipation of heat, therefore significant *thermal shrinkage* occurs on cooling. Shrinkage strains can be detrimental to concrete because, when restrained, they manifest into tensile stress. As the tensile strength of concrete is low, concrete structures often crack as a result of restrained shrinkage caused by humidity and temperature changes. In fact, the cracking tendency of the material is one of the serious disadvantages in structures built with concrete.

Professional judgment in the selection of construction materials should take into consideration not only the strength, dimensional stability, and elastic properties of the material but also its durability, which has serious implications for the life-cycle cost of a structure. *Durability* is defined as the service life of a material under given environmental condition. Generally, watertight concrete structures endure for a long time. The excellent conditions of the 2700-year-old concrete lining of a water storage tank on the Rodos Island in Greece and several aqueducts built in Europe built by the Romans nearly 2000 years ago, are a living testimony to the long-term durability of concrete in moist environments. In general, there is a relationship between strength and durability when low strength is associated with high porosity and high permeability. Permeable concretes are, of course, less durable. The permeability of concrete depends not only on mix proportions, compaction, and curing, but also on microcracks caused by the ambient temperature and humidity cycles. Finally, as discussed in Chap. 14, ecological and sustainability considerations are beginning to play an important role in the choice of materials for construction.

1.5 Units of Measurement

The metric system of measurement, which is prevalent in most countries of the world, uses millimeters and meters for length; grams, kilograms, and tonnes for mass; liters for volume; kilogram force per unit area for stress; and degrees Celsius for temperature. The United States is the only country in the world that uses old English units of measurement such as inches, feet, and yards for length; pounds or tons for mass, gallons for volume, pounds per square inch (psi) for stress, and degree Fahrenheit for temperature. Multinational activity in the design and construction of large engineering projects is commonplace in the modern world. Therefore, it is becoming increasingly important that scientists and engineers throughout the world speak the same language of measurement.

The metric system is simpler than the old English system and has recently been modernized in an effort to make it universally acceptable. The modern version

TABLE 1-2 Multiple and Submultiple SI Units and Symbols

Multiplication factor	Prefix	SI symbol
$1\ 000\ 000\ 000 = 10^9$	giga	G
$1\ 000\ 000 = 10^6$	mega	M
$1\ 000 = 10^3$	kilo	k
$100 = 10^2$	hecto*	h
$10 = 10^1$	deka*	da
$0.1 = 10^{-1}$	deci*	d
$0.01 = 10^{-2}$	centi*	c
$0.001 = 10^{-3}$	milli	m
$0.000\ 001 = 10^{-6}$	micro	μ
$0.000\ 000\ 001 = 10^{-9}$	nano†	n

*Not recommended but occasionally used.
†0.1 nanometer (nm) = 1 angstrom (Å) is a non-SI unit which is commonly used.

TABLE 1-3 Conversion Factors from the U.S. to SI Units

To convert from:	To:	Multiply by:
yards (yd)	meters (m)	0.9144
feet (ft)	meters (m)	0.3048
inches (in.)	millimeter (mm)	25.4
cubic yards (yd^3)	cubic meters (m^3)	0.7646
U.S. gallons (gal)	cubic meters (m^3)	0.003785
U.S. gallons (gal)	liters	3.785
pounds, mass (lb)	kilograms (kg)	0.4536
U.S. tons (t)	tonnes (T)	0.9072
pounds/cubic yard (lb/yd^3)	kilograms/cubic meter (kg/m^3)	0.5933
kilogram force (kgf)	newtons (N)	9.807
pounds force (lbf)	newtons (N)	4.448
kips per square inch (ksi)	megapascal (MPa or N/mm^2)	6.895
Degrees Fahrenheit (°F)	degrees Celsius (°C)	(°F – 32)/1.8

of the metric system, called the *International System of Units* (Système International d'Unités), abbreviated SI, was approved in 1960 by many participating nations in the General Conference on Weights and Measures.

In SI measurements, meter and kilogram are the only units permitted for length and mass, respectively. A series of approved prefixes, shown in Table 1-2, are used for the formation of multiples and submultiples of various units. The force required to accelerate a mass of 1 kilogram (kg) at the rate of 1 meter per second per second (m/s^2) is expressed as 1 newton (N), and a stress of 1 newton per square meter (N/m^2) is expressed as 1 pascal (Pa). The ASTM Standard E 380-70 contains a comprehensive guide to the use of SI units.

In 1975, the U.S. Congress passed the Metric Conversion Act, which declares that it will be the policy of the United States to coordinate and plan the increasing use of the metric system of measurement (SI units). Meanwhile, a bilinguality in the units of measurement is being practiced so that engineers should become fully conversant with both systems. To aid quick conversion from the U.S. customary units to SI units, a list of the commonly needed multiplication factors is given in Table 1-3.

Test Your Knowledge

1.1 Why is concrete the most widely used engineering material?

1.2 Compared to steel, what are the engineering benefits of using concrete for structures?

1.3 Define the following terms: fine aggregate, coarse aggregate, gravel, grout, shotcrete, hydraulic cement.

1.4 What are the typical unit weights for normal-weight, lightweight, and heavyweight concretes? How would you define high-strength concrete?

1.5 What is the significance of elastic limit in structural design?

1.6 What is the difference between strength and toughness? Why is the 28-days compressive strength of concrete generally specified?

1.7 Discuss the significance of drying shrinkage, thermal shrinkage, and creep in concrete.

1.8 How would you define durability? In general, what concrete types are expected to show better long-time durability?

Suggestions for Further Study

ACI Committee Report 116R, Cement and Concrete Terminology, *ACI Manual of Concrete Practice*, Part 1, American Concrete Institute, Farmington Hills, MI, 2002.

American Society for Testing and Materials, *Annual Book of ASTM Standards*, Vol. 04.01 (Cement, Lime, and Gypsum), Philadelphia, PA, 2005.

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Mindess, S., R.J. Gray, and A. Bentur, *The Science and Technology of Civil Engineering Materials*, Prentice Hall, Upper Saddle River, NJ, p. 384, 1998.

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Chapter

2

Microstructure of Concrete

Preview

Microstructure-property relationships are at the heart of modern material science. Concrete has a highly heterogeneous and complex microstructure. Therefore, it is very difficult to constitute realistic models of its microstructure from which the behavior of the material can be reliably predicted. However, knowledge of the microstructure and properties of the individual components of concrete and their relationship to each other is useful for exercising control on the properties. This chapter describes the three components of the concrete microstructure, namely, hydrated cement paste, aggregate, and interfacial transition zone between the cement paste and aggregate. Finally, microstructure-property relationships are discussed with respect to their influence on strength, dimensional stability, and durability of concrete.

2.1 Definition

The type, amount, size, shape, and distribution of phases present in a solid constitute its *microstructure*. The gross elements of the microstructure of a material can readily be seen from a cross section of the material, whereas the finer elements are usually resolved with the help of a microscope. The term *macrostructure* is generally used for the gross microstructure visible to the human eye; the limit of resolution of the unaided human eye is approximately one-fifth of a millimeter (200 μm). The term *microstructure* is used for the microscopically magnified portion of a macrostructure. The magnification capability of modern electron microscopes is of the order of 10^5 times. Therefore, application of transmission and scanning electron microscopy techniques has made it possible to resolve the microstructure of materials to a fraction of one micrometer.

2.2 Significance

Progress in the field of materials has resulted primarily from recognition of the principle that the properties originate from the internal microstructure; in other words, properties can be modified by making suitable changes in the microstructure of a material. Although concrete is the most widely used structural material, its microstructure is heterogeneous and highly complex. The microstructure-property relationships in concrete are not yet fully developed; however, some understanding of the essential elements of the microstructure would be helpful before discussing the factors influencing the important engineering properties of concrete, such as strength (Chap. 3), elasticity, shrinkage, creep, and cracking (Chap. 4), and durability (Chap. 5).

2.3 Complexities

From examination of a cross section of concrete (Fig. 2-1), the two phases that can easily be distinguished are aggregate particles of varying size and shape, and the binding medium composed of an incoherent mass of the hydrated cement paste.

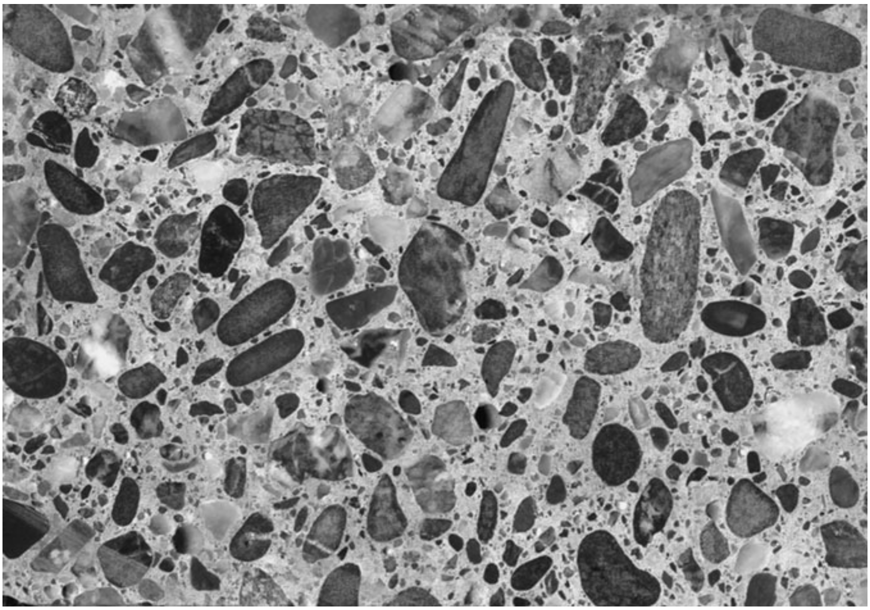

Figure 2-1 Polished section from a concrete specimen. (Photograph courtesy of Gordon Vrdoljak.)

Macrostructure is the gross structure of a material that is visible to the unaided human eye. In the macrostructure of concrete two phases are readily distinguished: aggregate of varying shapes and size, and the binding medium, which consists of an incoherent mass of the hydrated cement paste.

At the macroscopic level, therefore, concrete may be considered as a two-phase material, consisting of aggregate particles dispersed in a matrix of cement paste.

At the microscopic level, the complexities of the concrete microstructure are evident. It becomes obvious that the two phases of the microstructure are neither homogeneously distributed with respect to each other, nor are they themselves homogeneous. For instance, in some areas the *hydrated cement paste* mass appears to be as dense as the aggregate, while in others it is highly porous (Fig. 2-2). Also, if several specimens of concrete containing the same amount of cement but different amounts of water are examined at various time intervals, it

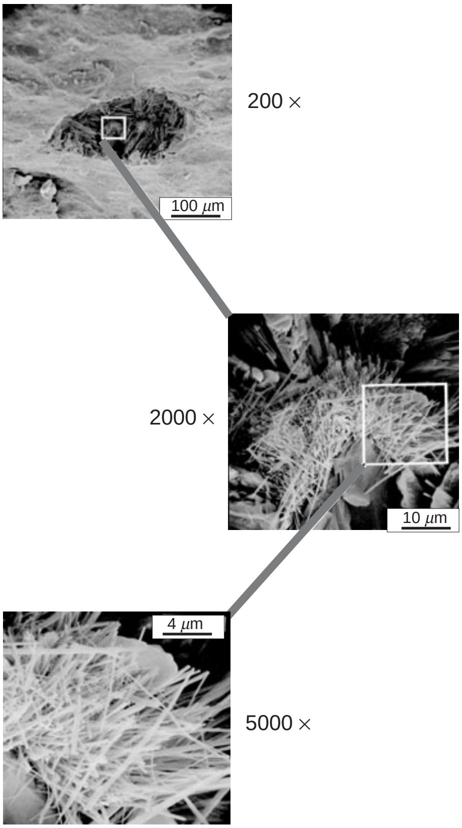

Figure 2-2 Microstructure of a hydrated cement paste.

Microstructure is the subtle structure of a material that is resolved with the help of a microscope. A low-magnification (200×) electron micrograph of a hydrated cement paste shows that the structure is not homogeneous; while some areas are dense, the others are highly porous. In the porous area, it is possible to resolve the individual hydrated phases by using higher magnifications. For example, massive crystals of calcium hydroxide, long and slender needles of ettringite, and aggregation of small fibrous crystals of calcium silicate hydrate can be seen at 2000 × and 5000 × magnifications.

will be seen that, in general, the volume of capillary voids in the *hydrated cement paste* decrease with decreasing water-cement ratio or with increasing age of hydration. For a well-hydrated cement paste, the inhomogeneous distribution of solids and voids alone can perhaps be ignored when modeling the behavior of the material. However, microstructural studies have shown that this cannot be done for the *hydrated cement paste* present in concrete. In the presence of aggregate, the microstructure of *hydrated cement paste* in the vicinity of large aggregate particles is usually very different from the microstructure of bulk paste or mortar in the system. In fact, many aspects of concrete behavior under stress can be explained only when the cement paste-aggregate interface is treated as a third phase of the concrete microstructure.

Thus the *unique features of the concrete microstructure* can be summarized as follows: First, there is the *interfacial transition zone*, which represents a small region next to the particles of coarse aggregate. Existing as a thin shell, typically 10 to 50 μm thick around large aggregate, the interfacial transition zone is generally weaker than either of the two main components of concrete, namely, the aggregate and the bulk hydrated cement paste; therefore, it exercises a far greater influence on the mechanical behavior of concrete than is reflected by its size. Second, each of the three phases is itself a multiphase in character. For instance, each aggregate particle may contain several minerals in addition to microcracks and voids. Similarly, both the bulk *hydrated cement paste* and the interfacial transition zone generally contain a heterogeneous distribution of different types and amounts of solid phases, pores, and microcracks, as will be described later. Third, unlike other engineering materials, the microstructure of concrete is not an intrinsic characteristic of the material because the two components of the microstructure, namely, the *hydrated cement paste* and the interfacial transition zone, are subject to change with time, environmental humidity, and temperature.

The highly heterogeneous and dynamic nature of the microstructure of concrete are the primary reasons why the theoretical microstructure-property relationship models, that are generally so helpful for predicting the behavior of engineering materials, are not of much practical use in the case of concrete. A broad knowledge of the important features of the microstructure of each of the three phases of concrete, as provided below, is nevertheless essential for understanding and control of properties of the composite material.

2.4 Microstructure of the Aggregate Phase

The composition and properties of different types of aggregates are described in detail in Chap. 7. Given here is only a brief description of the elements that exercise a major influence on properties of concrete.

The aggregate phase is predominantly responsible for the unit weight, elastic modulus, and dimensional stability of concrete. These properties of concrete depend to a large extent on the bulk density and strength of the aggregate, which in turn are determined by physical rather than chemical characteristics of the aggregate. In other words, the chemical or the mineralogical composition of the solid phases in aggregate is usually less important than the physical characteristics, such as volume, size, and distribution of pores.

In addition to porosity, the shape and texture of the coarse aggregate also affect the properties of concrete. Some aggregate particles are shown in Fig. 2-3. Generally, natural gravel has a rounded shape and a smooth surface texture. Crushed rocks have a rough texture; depending on the rock type and the choice of crushing equipment, the crushed aggregate may contain a considerable proportion of flat or elongated particles that adversely affect many properties of concrete. Lightweight aggregate particles from pumice, which is highly cellular, are also angular and have a rough texture, but those from expanded clay or shale are generally rounded and smooth.

Being stronger than the other two phases of concrete, the aggregate phase has usually no direct influence on the strength of normal concrete except in the case of some highly porous and weak aggregates, such as pumice. The size and the shape of coarse aggregate can, however, affect the strength of concrete in an indirect way. It is obvious from Fig. 2-4 that the larger the size of aggregate in

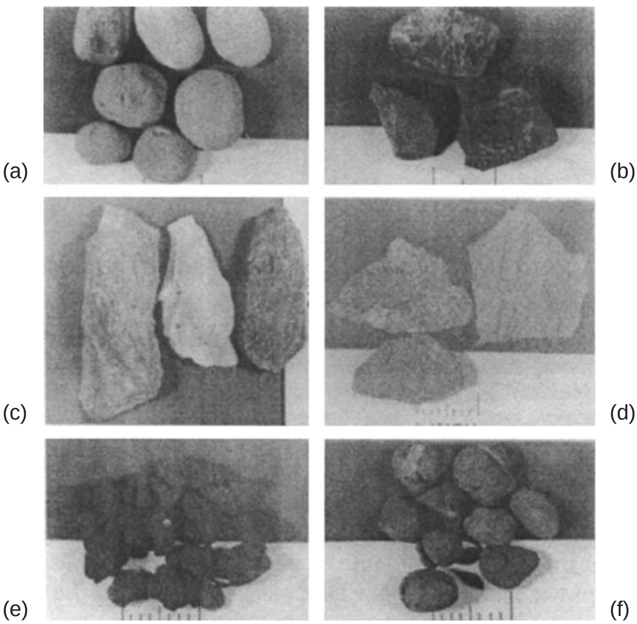

Figure 2-3 Shape and surface texture of a coarse aggregate particles: (*a*) gravel, rounded and smooth; (*b*) crushed rock, equidimensional; (*c*) crushed rock, elongated; (*d*) crushed rock, flat; (*e*) lightweight, angular and rough; (*f*) lightweight, rounded and smooth.

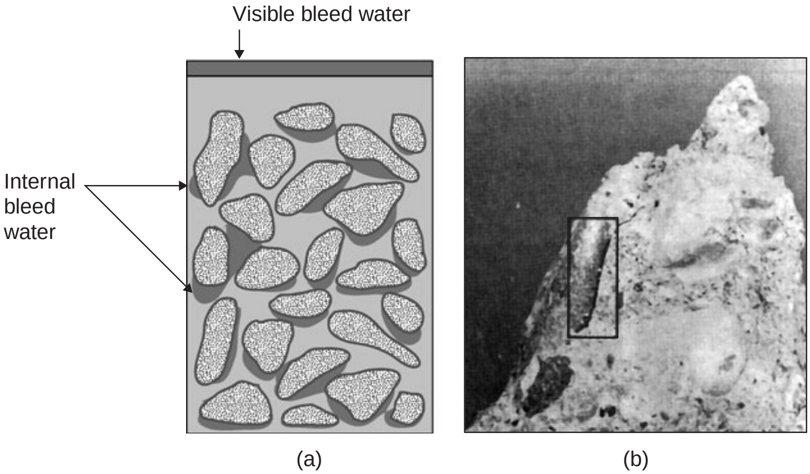

Figure 2-4 (*a*) Diagrammatic representation of bleeding in freshly deposited concrete; (*b*) shear-bond failure in a concrete specimen tested in uniaxial compression. *Internal bleed water tends to accumulate in the vicinity of elongated, flat, and large pieces of aggregate. In these locations, the aggregate-cement paste interfacial transition zone tends to be weak and easily prone to microcracking. This phenomenon is responsible for the shear-bond failure at the surface of the aggregate particle marked in the photograph.*

concrete and the higher the proportion of elongated and flat particles, the greater will be the tendency for water films to accumulate next to the aggregate surface, thus weakening the interfacial transition zone. This phenomenon, known as *bleeding*, is discussed in detail in Chap. 10.

2.5 Microstructure of the Hydrated Cement Paste

The term hydrated cement paste as used here refers to pastes made from portland cement. Although the composition and properties of portland cement are discussed in detail in Chap. 6, a summary of the composition will be helpful before discussing how the microstructure of the hydrated cement paste develops as a result of chemical reactions between portland-cement compounds and water.

Anhydrous portland cement is a gray powder composed of angular particles typically in the size range from 1 to 50 μm. It is produced by pulverizing a clinker with a small amount of calcium sulfate, the clinker being a heterogeneous mixture of several compounds produced by high-temperature reactions between calcium oxide and silica, alumina, and iron oxide. The chemical composition of the principal clinker compounds corresponds approximately to C_3S,* C_2S, C_3A,

*Cement chemists use the following abbreviations: C = CaO; S = SiO_2; A = Al_2O_3; F = Fe_2O_3; $\overline{S}$ = SO_3; H = H_2O.