Second Edition

Advanced Concrete Technology

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To students, teachers, researchers, and engineers in the field of concrete, who are the driving forces for the development of the science and technology of concrete, including the personnel working on the China 973 project, Basic Study on Environmentally Friendly Contemporary Concrete (2009CB623200).

CONTENTS

PREFACE

Portland cement concrete is the most widely used building material in the world. It plays an important role in infrastructure and private buildings construction. Due to the fast development of construction worldwide over the past decade, concrete technology has advanced significantly. To reflect the frontier development of concrete technology, the second edition of *Advanced Concrete Technology* now appears.

The second edition of *Advanced Concrete Technology* delivers a state-of-the-art exploration of contemporary and advanced concrete technologies developed over the last decade. It follows the principles and chapter division of the first edition, emphasizes the fundamental and scientific exploration of materials structures of concrete, and clarifies the essential concepts of concrete. The book combines the theories of concrete with practical examples of material design, explains the correlations among the composition, processing, characterization, properties, and performance of concrete and stresses the constraint of end-users on materials development.

The new book is divided into nine chapters, including new chapters on descriptions of the most recent advances in concrete technology. Chapter 1 gives a thorough introduction to concrete, including its definition and its historical evolution as a material used in engineering and construction. Chapter 2 provides in-depth explorations of the materials for making concrete with the addition of limestone and calcined clay cement, artificial sand, sea sand, and recycled aggregates. Chapter 3 discusses the concrete mix design methods and properties of fresh concrete, including its workability and rheology, as well as the methods for manufacturing, delivery, placing, compaction, finishing, and curing of concrete. Chapter 4 focuses on the material structure of concrete at different scales, in particular, the calcium silicate hydrate (C–S–H), the most important hydration product, at the atomic-to-nanometer scale. The structure of C–S–H is discussed with the results obtained by multi-scale simulation, including the quantum chemical method, the molecular potential-based method, and the coarse-grain Monte Carlo method over the past decade. Chapter 5 covers the properties of hardened concrete, including its strength, the stress-strain relationship, dimension stability, and durability. Chapter 6 provides updated knowledge on various advanced cement-based composites, including sea sand and seawater concrete and 3D-printed concrete, in addition to self-consolidation concrete, ultra-high strength concrete, engineered cementitious composites, etc. Chapter 7 introduces fulsome treatments of concrete fracture mechanics and explores the application of fracture mechanics in the design code of concrete structures, in addition to the double-K criterion. Chapter 8 covers essential knowledge of non-destructive testing in concrete engineering, including wave reflection and refraction theories, detecting principles and measurement methodologies for different non-destructive techniques. The new edition also includes an innovative magnetic corrosion detection transducer. Chapter 9 discusses the future and development trends of concrete technology. The new edition also introduces the carbon capture, utilization, and storage (CCUS) technologies, the application of nanotechnology, and data science and artificial intelligence in concrete technology.

This book perfectly fits the teaching needs of undergraduate and graduate students studying civil or materials engineering—especially those taking classes in the disciplines of *Properties of Concrete* or *Concrete Technologies*. It also provides the necessary knowledge and sufficient guidelines for practical engineers in the concrete industry.

During the process of writing the second edition of the book, the authors received enthusiastic help and invaluable assistance from many people, which is deeply appreciated. The authors would like to express their special thanks to Yunjian Li, Zhaoyang Sun, Qing Liu, Xing Ming, Guotao Qiu, Hongda Guo and Ms. Jianyu Xu.

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CHAPTER 1

INTRODUCTION TO CONCRETE

1.1 CONCRETE DEFINITION AND HISTORICAL DEVELOPMENT

Concrete is a man-made building material that looks like stone. The word "concrete" is derived from the Latin *concretus*, meaning "to grow together." Concrete is a composite material composed of coarse granular material (the aggregate or filler) embedded in a hard matrix (cement or binder) that fills the space among the aggregate particles and binds them together. Alternatively, we can say that concrete is a composite material that consists essentially of a binding medium in which are embedded particles or fragments of aggregates. The simplest definition of concrete can be written as

$$\text{concrete} = \text{filler} + \text{binder} \tag{1-1}$$

Depending on the types of binder used, concrete can be named in different ways. For instance, if concrete is made with nonhydraulic cement, it is called nonhydraulic cement concrete; if concrete is made of hydraulic cement, it is called hydraulic cement concrete; if concrete is made of asphalt, it is called asphalt concrete; if concrete is made of polymer, it is called polymer concrete. Both nonhydraulic and hydraulic cement need water to mix in and react. They differ here in the ability to gain strength in water. Nonhydraulic cement cannot gain strength in water, while hydraulic cement can.

Nonhydraulic cement concretes are the oldest concrete used in human history. As early as around 6500 BC, nonhydraulic cement concretes were used by the Syrians and spread through Egypt, the Middle East, Crete, Cyprus, and ancient Greece. However, it was the Romans who refined the mixture's use. The nonhydraulic cements used at that time were gypsum and lime. The Romans used a primal mix for their concrete. It consisted of small pieces of gravel and coarse sand mixed with hot lime and water, and sometimes even animal blood. The Romans were known to have made wide usage of concrete for building roads. It is interesting to learn that they built some 5300 miles of roads using concrete. Concrete is a very strong building material. Historical evidence also points out that the Romans used pozzolana, animal fat, milk, and blood as admixtures for making concrete. To trim down shrinkage, they were known to have used horsehair. Historical evidence also shows that the Assyrians and Babylonians used clay as the bonding material. Lime was obtained by calcining limestone with a reaction of

$$CaCO_3 \xrightarrow{1000^\circ C} CaO + CO_2 \tag{1-2}$$

When CaO is mixed with water, it can react with water to form:

$$CaO + H_2O \xrightarrow{\text{ambient temperature}} Ca(OH)_2 \tag{1-3}$$

and is then further reacted with CO_2 to form limestone again:

$$Ca(OH)_2 + CO_2 + H_2O \xrightarrow{\text{ambient temperature}} CaCO_3 + 2H_2O \tag{1-4}$$

The Egyptians used gypsum mortar in construction, and the half-water gypsum was obtained by calcining two-water gypsum with a reaction of:

$$2CaSO_4 \cdot 2H_2O \xrightarrow{107-130°C} 2CaSO_4 \cdot \frac{1}{2}H_2O + 3H_2O \tag{1-5}$$

When mixed with water, half-water gypsum could turn into two-water gypsum and gain strength:

$$2CaSO_4 \cdot \frac{1}{2}H_2O + 3H_2O \xrightarrow{\text{ambient temperature}} 2CaSO_4 \cdot 2H_2O \tag{1-6}$$

The Egyptians used gypsum instead of lime because it could be calcined at much lower temperatures. As early as about 3000 BC, the Egyptians used gypsum mortar in the construction of the Pyramid of Cheops. However, this pyramid was looted long before archeologists knew about the building materials used. Figure 1-1 shows a pyramid in Giza. The Chinese also used lime mortar to build the Great Wall in the Qin dynasty (220 BC) (see Figure 1-2).

A hydraulic lime was developed by the Greeks and Romans using limestone containing argillaceous (clayey) impurities. The Greeks even used volcanic ash from the island of Santorini, while the Romans used volcanic ash from the Bay of Naples to mix with lime to produce hydraulic lime. It was found that mortar made of such hydraulic lime could resist water. Thus, hydraulic lime mortars were used extensively for hydraulic structures from the second half of the first century BC to the second century AD. However, the quality of cementing materials declined throughout the Middle Ages. The art of burning lime was almost lost and siliceous impurities were not added. High-quality mortars disappeared for a long period. In 1756, John Smeaton was commissioned to rebuild the Eddystone Lighthouse off the coast of Cornwall, England. Realizing the function of siliceous impurities in resisting water, Smeaton conducted extensive experiments with different limes and pozzolans, and found that limestone with a high proportion of clayey materials produced the best hydraulic lime for the mortar to be used in water. Eventually, Smeaton used a mortar

Figure 1-1 Pyramid built with gypsum mortar, Giza, Egypt

Figure 1-2 The Great Wall built in the Qin dynasty (Photo provided by Tongbo Sui)

prepared from a hydraulic lime mixed with pozzolan imported from Italy. He made concrete by mixing coarse aggregate (pebbles) and powdered brick and mixed it with cement, very close to the proportions of modern concrete. The rebuilt Eddystone Lighthouse lasted for 126 years until it was replaced with a modern structure.

After Smeaton's work, hydraulic cement developed very fast. James Parker of England filed a patent in 1796 for a natural hydraulic cement made by calcining nodules of impure limestone containing clay. Vicat of France produced artificial hydraulic lime by calcining synthetic mixtures of limestone and clay. Portland cement was patented by Joseph Aspdin of England in 1824. The name Portland was coined by Aspdin because the color of the cement after hydration was similar to that of limestone quarried in Portland, a town in southern England. Portland cement was prepared by calcining finely ground limestone, mixing it with finely divided clay, and calcining the mixture again in a kiln until the CO_2 was driven off. This mixture was then finely ground and used as cement. However, the temperature claimed in Aspdin's invention was not high enough to produce true Portland cement. It was Isaac Johnson who first burned the raw materials to the clinkering temperature in 1845 to produce modern Portland cement. After that, the application of Portland cement spread quickly throughout Europe and North America. The main application of Portland cement is to make concrete. It was in Germany that the first systematic testing of concrete took place in 1836. The test measured the tensile and compressive strength of concrete. Aggregates are another main ingredient of concrete, which include sand, crushed stone, clay, gravel, slag, and shale. Plain concrete made of Portland cement and aggregate is usually called the first generation of concrete. The second generation of concrete refers to steel bar-reinforced concrete. François Coignet in France was a pioneer in the development of reinforced concrete. (Day and McNeil, 1996). Coignet started experimenting with iron-reinforced concrete in 1852 and was the first builder ever to use this technique as a building material (Encyclopaedia Britannica, 1991). He decided, as a publicity stunt and to promote his cement business, to build a house made of *béton armé*, a type of reinforced concrete. In 1853, he built the first iron reinforced concrete structure anywhere; a four-story house at 72 Rue Charles Michels in St. Denis (Sutherland et al., 2001). This location was near his family cement plant in St. Denis, a commune in the northern suburbs of Paris. The house was designed by local architect Theodore Lachez (Collins, 2004).

Coignet had an exhibit at the 1855 Paris Exposition to show his technique of reinforced concrete. At the exhibit, he forecast that the technique would replace stone as a means of construction. In 1856, he patented a technique of reinforced concrete using iron tirants. In 1861, he published his techniques of reinforced concrete.

Reinforced concrete was further developed by Hennebique at the end of the 19th century, and it was realized that performance could be improved if the bars could be placed in tension, thus keeping the concrete in compression. Early attempts worked, with the beams showing a reduced tendency to crack in tension, but after a few months, the cracks reopened. A good description of this early work is given in Leonhardt (1964). The first reinforced concrete bridge was built in 1889 in the Golden Gate Park in San Francisco, California.

To overcome the cracking problem in reinforced concrete, prestressed concrete was developed and was first patented by a San Francisco engineer named P.H. Jackson as early as 1886. Prestressed means that the stress is generated in a structural member before it carries the service load. Prestressed concrete was referred to as the third generation of concrete. Prestressing is usually generated by the stretched reinforcing steel in a structural member. According to the sequence of concrete casting, prestressing can be classified as pretensioning or post-tensioning. Pretensioning pulls the reinforcing steel before casting the concrete and prestress is added through the bond built up between the stretched reinforcing steel and the hardened concrete. In the post-tensioning technique, the reinforcing steel or tendon is stretched after concrete casting and the gaining of sufficient strength. In post-tensioning, steel tendons are positioned in the concrete specimen through prereserved holes. The prestress is added to the member through the end anchorage. Figure 1-3 shows the sequence of the pretensioning technique for prestressed concrete.

Prestressed concrete became an accepted building material in Europe after World War II, partly due to the shortage of steel. North America's first prestressed concrete structure, the Walnut Lane Memorial Bridge in Philadelphia, Pennsylvania, was completed in 1951. Nowadays, with the development of prestressed concrete, long-span bridges, tall buildings, and ocean structures have been constructed. The Barrios de Lura Bridge in Spain is currently the longest-span prestressed concrete, cable-stayed bridge in the world, with a main span of 440 m, while the Shibanpo Yangtze

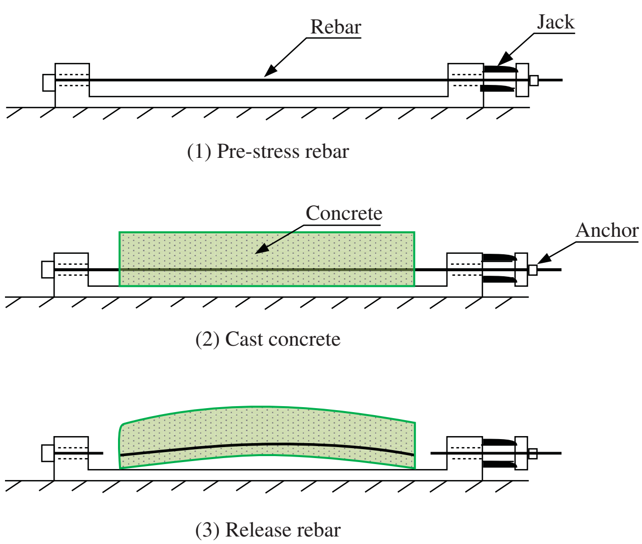

Figure 1-3 Pretensioning sequence for prestressed concrete

Bridge is the world's longest prestressed concrete girder bridge with the main span of 330 m. In Canada, the prestressed Toronto CN tower reaches a height of 553 m.

As a structural material, the compressive strength at an age of 28 days is the main design index for concrete. There are several reasons for choosing compressive strength as the representative index. First, concrete is used in a structure mainly to resist the compression load. Second, the measurement of compressive strength is relatively easier. Finally, it is thought that other properties of concrete can be related to its compressive strength. Pursuing high compressive strength has been an important direction of concrete development. As early as 1918, Duff Adams found that the compressive strength of concrete was inversely proportional to the water-to-cement (*w/c*) ratio. Hence, a high compressive strength could be achieved by reducing the *w/c* ratio. However, to keep concrete workable, there is a minimum requirement on the amount of water; hence, the *w/c* ratio reduction is limited, unless other measures are provided to improve concrete's workability. For this reason, progress in achieving high compressive strength was very slow before the 1960s. At that time, concrete with a compressive strength of 30 MPa was regarded as high-strength concrete. Since the 1960s, the development of high-strength concrete has made significant progress due to two main factors: the invention of water-reducing admixtures and the incorporation of mineral admixtures, such as silica fume, fly ash, and slag. Water-reducing admixture is a chemical admixture that can enable concrete with good workability under a very low *w/c* ratio; the latter are finer mineral particles that can react with a hydration product in concrete, calcium hydroxide, to make concrete's microstructure denser, hence improving concrete's properties. Silica fume also has a packing effect to further improve the matrix density. In 1972, the first 52-MPa concrete was produced in Chicago for the 52-story Mid-Continental Plaza. In 1972, a 62-MPa concrete was produced, also in Chicago, for Water Tower Place, a 74-story concrete building, the tallest in the world at that time (see Figure 1-4). In the 1980s, the industry was able to produce a 95-MPa concrete to supply to the 225 West Wacker Drive building project in Chicago, as shown in Figure 1-5. The highest compressive strength of 130 MPa was realized in the 220-m-high, 58-story building, the Union Plaza, constructed in Seattle, Washington (Caldarone, 2009).

Concrete produced after the 1980s usually contains a sufficient amount of fly ash, slag, or silica fume as well as many different chemical admixtures, so its hydration mechanism, hydration products, and other microstructure characteristics are very different from the concrete produced without these admixtures. Moreover, the mechanical properties are also different from the conventional concrete; hence, such concretes are referred to as contemporary concretes.

There have been two innovative developments in contemporary concrete: self-compacting concrete (SCC) and ultra-high-performance concrete (UHPC). SCC is a type of high-performance concrete (HPC). High-performance concrete is a concept developed in the 1980s. It is defined as a concrete that can meet special performance and uniformity requirements, which cannot always be achieved routinely by using only conventional materials and normal mixing, placing, and curing practices. The requirements may involve enhancement of the characteristics of concrete, such as placement and compaction without segregation, long-term mechanical properties, higher early-age strength, better toughness, higher volume stability, or longer service life in severe environments.

Self-compacting concrete is a typical example of high-performance concrete that can fill in formwork in a compacted manner without the need of mechanical vibration. SCC was initially developed by Professor Okamura and his research group in Japan in the late 1980s (Ozama et al., 1989). At that time, concrete construction was blooming everywhere in Japan. Since Japan is in an earthquake zone, concrete structures are usually heavily reinforced, especially at beam-column joints. Hence, due to low flowability, conventional concrete could hardly flow past the heavily reinforced rebars, leaving poor-quality cast concrete and leading to poor durability. Sometimes, the

Figure 1-4 Water Tower Place in Chicago, USA (Photo provided by Xiaojian Gao)

reinforcing steel was exposed to air immediately after demolding. To solve the problem, Professor Okamura and his research group developed concrete with very high flowability. With the help of the invention of the high-range water reducer or plasticizer, such highly flowable concrete was finally developed. They were so excited that they called this concrete "high-performance concrete" in the beginning. It was corrected later to SCC, as HPC covers broader meanings. Durability is a main requirement of HPC. It has been found that many concrete structures could not fulfill the service requirement, due not to lack of strength, but to lack of durability. For this reason, concrete with high performance to meet the requirement of prolonging concrete service life was greatly needed.

In the 1990s, a new type of "concrete" with a compressive strength higher than 200 MPa was developed in France. Due to the large amount of silica fume incorporated in such a material, it was initially called reactive powder concrete and later on the name changed to ultra-high-strength (performance) concrete (UHSC), due to its extremely high compressive strength (Richard and Cheyrezy, 1995). The ultra-high-strength concrete has reached a compressive strength of 800 MPa with heating treatment. However, it is very brittle, hence, incorporating fibers into UHSC is necessary. After incorporating fine steel fibers, a flexural strength of 50 MPa can be reached. The first trial application of UHSC was a footbridge built in Sherbrooke, Canada (Aitcin et al., 1998).

Figure 1-5 The 225 West Wacker building in Chicago, USA (Photo provided by Xiaojian Gao)

1.2 CONCRETE AS A STRUCTURAL MATERIAL

In this book, the term concrete usually refers to Portland cement concrete, if not otherwise specified. For this kind of concrete, the compositions can be listed as follows:

Portland **cement**
+ water (& admixtures) → cement **paste**
+ fine aggregate → **mortar**
+ coarse aggregate → **concrete**

Here it should be noted that admixtures are used in almost all modern practice and thus have become an essential component of contemporary concrete. Admixtures are defined as materials other than aggregate (fine and coarse), water, and cement that are added into a concrete batch immediately before or during mixing. The use of admixtures is widespread, mainly because many benefits can be achieved by their application. For instance, certain chemical admixtures can modify the setting and hardening characteristics of cement paste by influencing the rate of cement hydration. Water-reducing admixtures can plasticize fresh concrete mixtures by reducing the surface tension of the water. Air-entraining admixtures can improve the durability of concrete, and mineral admixtures such as pozzolans (materials containing reactive silica) can reduce thermal cracking. A detailed description of admixtures is given in Chapter 2.

Concrete is the most widely used construction material in the world, and its popularity can be attributed to two aspects. First, concrete can be used for many different structures, such as dams, pavements, building frames, or bridges, much more than any other construction material. Second, the amount of concrete used is much more than any other material. Its worldwide production exceeds that of steel by a factor of 10 in tonnage and by more than a factor of 30 in volume.

In a concrete structure, there are two commonly used structural materials: concrete and steel. A structural material is a material that carries not only its self-weight, but also the load passing from other members.

Steel is manufactured under carefully controlled conditions, always in a highly sophisticated plant; the properties of every type of steel are determined in a laboratory and described in a manufacturer's certificate. Thus, the designer of a steel structure need only specify the steel complying with a relevant standard, and the constructor needs only to ensure that the correct steel is used and that connections between the individual steel members are properly executed (Neville and Brooks, 1993).

On the other hand, concrete is produced in a cruder way and its quality varies considerably. Even though the quality of cement, the binder of concrete, is guaranteed by the manufacturer in a manner similar to that of steel, the quality of concrete is hardly guaranteed because of many other factors, such as aggregates, mixing procedures, and the skill of the operators of concrete production, placement, and consolidation.

It is possible to obtain concrete of specified quality from a ready-mix supplier, but, even in this case, it is only the raw materials that are bought for a construction job. Transporting, placing, and, above all, compacting greatly influence the quality of a cast concrete structure. Moreover, unlike the case of steel, the choice of concrete mixes is virtually infinite and therefore the selection has to be made with a sound knowledge of the properties and behavior of concrete. It is thus the competence of the designer and specifier that determines the potential qualities of concrete, and the competence of the supplier and the contractor that controls the actual quality of concrete in the finished structure. It follows that they must be thoroughly conversant with the properties of concrete and with concrete making and placing.

In a concrete structural element, concretes mainly carry the compressive stress and shear stress while the steel carries the tension stress. Moreover, concrete usually provides stiffness for structures to keep them stable.

As a type of structural material, concrete has been widely used to build various structures. High-strength concrete has been used in many tall building constructions. In Hong Kong, grade 90 concrete (i.e., compressive strength of 90 MPa) was used in the columns of the tallest building in the region, i.e., the 108-story International Commerce Centre (see Figure 1-6), which was built in 2010 and stands 484 m (1588 ft) tall.

Concrete has also been widely used in bridge construction. Figure 1-7 shows the Sutong Bridge that crosses the Yangtze River in China between Nantong and Changshu, a satellite city of Suzhou, in Jiangsu province, east China. It is a cable-stayed bridge with the third-longest main span, 1088 meters, in the world after the Russky bridge (1104 m) and the Hutong Yangtze River bridge (1092 m). Its two side spans are 300 m (984 ft) each, and there are also four small cable spans.

Figure 1-6 International Commerce Centre, Hong Kong. (Source: Wing1990hk / Wikimedia Commons / CC BY-SA 3.0)

Dam construction is another popular application for concrete. The first major concrete dams, the Hoover Dam and the Grand Coulee Dam, were built in the 1930s and they are still standing. The largest dam ever built is the Three Gorges Dam in Hubei province, China, as shown in Figure 1-8. The total concrete used for the dam was over 22 million m^3.

Concrete has also been used to build high-speed railways. Shinkansen, the world's first contemporary high-volume (initially 12-car maximum), "high-speed rail," was built in Japan in 1964. In Europe, high-speed rail was first introduced during the International Transport Fair in Munich in June 1965. Nowadays, high-speed rail construction is blooming in China. With 37,900 kilometers of lines by 2021, China has the world's largest network of high-speed railways. According to planning, 70,000 km of high-speed rail will be built in China by 2035. Figure 1-9 shows a high-speed rail system in China.

In addition, concrete has been widely applied in the construction of airport runways, tunnels, highways, pipelines, and oil platforms. Up to now, the annual world consumption of concrete has reached a value such that if the concrete were edible, every person on the Earth would have 2000 kg per year to "eat." You may wonder why concrete has become so popular.