

INTRODUCTION TO CONCRETE

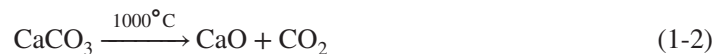
1.1 CONCRETE DEFINITION AND HISTORICAL DEVELOPMENT

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

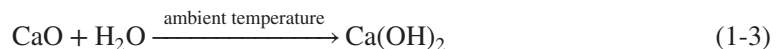
$$\text{concrete} = \text{filler} + \text{binder} \quad (1-1)$$

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.

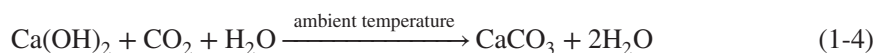
Nonhydraulic cement concretes are the oldest concrete used in human history. As early as around 6500 BC, nonhydraulic cement concretes were used by the Syrians and spread through Egypt, the Middle East, Crete, Cyprus, and ancient Greece. However, it was the Romans who refined the mixture’s use. The nonhydraulic 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



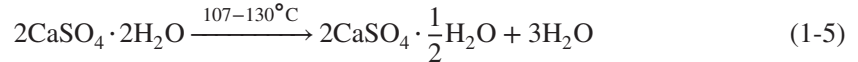
When CaO is mixed with water, it can react with water to form:



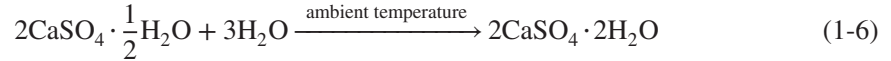
and is then further reacted with CO₂ to form limestone again:



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



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



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 preremoved 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 Shibampo Yangtze

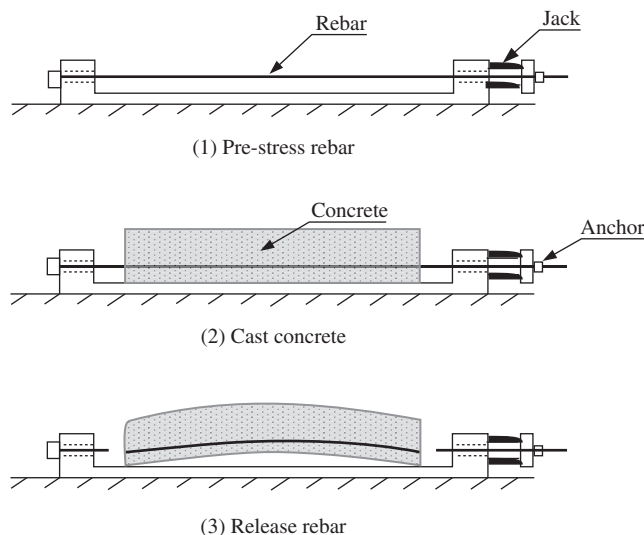


Figure 1-3 Pretensioning sequence for prestressed concrete

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.

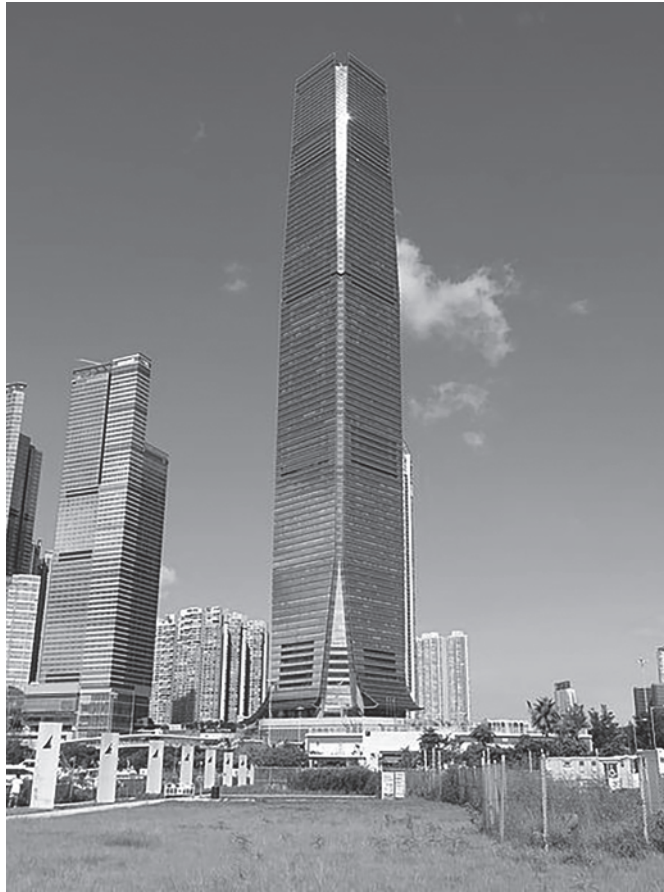


Figure 1-6 International Commerce Centre, Hong Kong. (Source: Wing1990hk / Wikimedia Commons / CC BY-SA 3.0)

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 m³.

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.



Figure 1-7 Sutong Bridge in Suzhou, Jiangsu, China (Photo provided by Xiaoyan Liu)



Figure 1-8 Three Gorges Dam, Hubei, China (Photo provided by Zhen He)



Figure 1-9 High speed rail in China (Photo provided by Guotang Zhao)

1.3 CHARACTERISTICS OF CONCRETE

1.3.1 Advantages of Concrete

- (a) *Economical*: Concrete is the most inexpensive and the most readily available material in the world. The cost of production of concrete is low compared with other engineered construction materials. The three major components in concrete are water, aggregate, and cement. Compared with steels, plastics, and polymers, these components are the most inexpensive, and are available in almost every corner of the globe. This enables concrete to be produced worldwide at a very low cost for local markets, thus avoiding the transport expenses and associated carbon emission for most other materials.
- (b) *Ambient temperature-hardened material*: Because cement is a low-temperature bonded inorganic material and its reaction occurs at room temperature, concrete can gain its strength at ambient temperature. Normally, no high temperature curing is needed.
- (c) *Ability to be cast*: Fresh concrete is flowable like a liquid and hence can be poured into various formworks to form different desired shapes and sizes right on a construction site or a precast plant. Hence, concrete can be cast into many different configurations. One good example to show concrete castability is the Baha'i Temple located in Wilmette, Illinois, USA, as shown in Figure 1-10. The very complex configurations of the different shapes of flowers in the wall and roof were all cast by concrete.
- (d) *Energy-efficient*: Compared to steel, the energy consumption of concrete production is low. The energy required to produce plain concrete is only 450–750 kWh/ton and that of reinforced concrete is 800–3200 kWh/ton, while structural steel requires 8000 kWh/ton or more to make.
- (e) *Excellent water resistance*: Unlike wood (timber) and steel, concrete can harden in water and can withstand the action of water without serious deterioration, which makes concrete an ideal material for building structures to control, store, and transport water, such as



Figure 1-10 Baha'i Temple in Wilmette, Illinois (Photo provided by Xiaojian Gao)



Figure 1-11 Pipeline under construction (Photo provided by Zhulin Zhang)

pipelines (Figure 1-11), dams, and submarine structures. A typical example of a pipeline application is the Central Arizona Project, which provides water from the Colorado River to central Arizona. The system contains 1560 pipe sections, each 6.7 m long, 7.5 m outside diameter, and 6.4 m inside diameter. Contrary to popular belief, water is not deleterious to concrete, even to reinforced concrete; it is the chemicals dissolved in water, such as chlorides, sulfates, and carbon dioxide, that cause deterioration of concrete structures.

- (f) *High-temperature resistance:* Concrete conducts heat slowly and can store considerable quantities of heat from the environment. Moreover, the main hydrate that provides binding to aggregates in concrete, calcium silicate hydrate (C–S–H), will not be completely dehydrated until 910°C. Thus, concrete can withstand high temperatures much better than wood and steel. Even in a fire, a concrete structure can withstand heat for 2–6 hours, leaving sufficient time for people to be rescued. This is why concrete is frequently used to build up protective layers for a steel structure.
- (g) *Ability to consume waste:* With the development of industry, civilization, and urbanization, more and more by-products or waste have been generated, which causes a serious environmental pollution problem. To solve the problem, people have to find a way to consume such wastes. It has been found that many industrial wastes can be recycled as a substitute (replacement) for cement or aggregate, such as fly ash, slag (GGBFS = ground granulated blast-furnaces slag), waste glass, and ground vehicle tires in concrete. Production of concrete with the incorporation of industrial waste not only provides an effective way to protect our environment, but also sometimes leads to the better performance of a concrete structure. Due to a large amount of concrete produced annually, it is possible to consume most of the industrial waste in the world in concrete production, provided that suitable techniques for individual waste incorporation are available.
- (h) *Ability to work with reinforcing steel:* Concrete has a similar value to steel for the coefficient of thermal expansion (steel 1.2×10^{-5} ; concrete $1.0\text{--}1.5 \times 10^{-5}$). Concrete produces good

protection to steel due to the existence of CH and other alkalis (this is for normal conditions). Therefore, while steel bars provide the necessary tensile strength, concrete provides a perfect environment for the steel, acting as a physical barrier to the ingress of aggressive species and giving chemical protection in a highly alkaline environment (pH value is about 13.5), in which black steel is readily passivated.

- (i) *Less maintenance required:* Under normal conditions, concrete structures do not need coating or painting as protection for weathering, while for a steel or wooden structure, it is necessary to have a protective layer. Moreover, the coatings and paintings have to be replaced every few years. Thus, the maintenance cost for concrete structures is much lower than that for steel or wooden structures.

1.3.2 Limitations

- (a) *Quasi-brittle failure mode:* The failure mode of materials can be classified into three categories: brittle failure, quasi-brittle failure, and ductile failure, as shown in Figure 1-12. Glass is a typical brittle material. It will break as soon as its tensile strength is reached. Materials exhibiting a strain-softening behavior (Figure 1-12b) are called quasi-brittle materials. Both brittle and quasi-brittle materials fail suddenly without giving a large deformation as a warning sign. Ductile failure is a failure with a large deformation that serves as a warning before the collapse, such as low-carbon steel. Concrete is a type of quasi-brittle material with low fracture toughness. Usually, concrete has to be used with steel bars to form so-called reinforced concrete, in which steel bars are used to carry tension and the concrete compression loads. Moreover, concrete can provide a structure with excellent stability. As elaborated previously, reinforced concrete is realized as the second generation of concrete.
- (b) *Low tensile strength:* Concrete has different values in compression and tension strength. Its tensile strength is only about 1/10 of its compressive strength for normal-strength concrete, even lower for high-strength concrete. To improve the tensile strength of concrete, fiber-reinforced concrete and polymer concrete have been developed.
- (c) *Low toughness (ductility):* Toughness is usually defined as the ability of a material to consume energy. Toughness can be evaluated by the area of a load–displacement curve. Compared to steel, concrete has very low toughness, with a value only about 1/50 to 1/100 of that of steel, as shown in Figure 1-13. Adding fibers is a good way to improve the toughness of concrete.
- (d) *Low specific strength (strength/density ratio):* For normal-strength concrete, the specific strength is less than 20, while for steel it is about 40. There are two ways to increase concrete specific strength: one is to reduce its density and the other is to increase its strength. Hence, lightweight concrete and high-strength concrete have been developed.
- (e) *Formwork is needed:* Conventional fresh concrete is in a liquid state and needs formwork to hold its shape and to support its weight. Formwork can be made of steel or wood, as shown

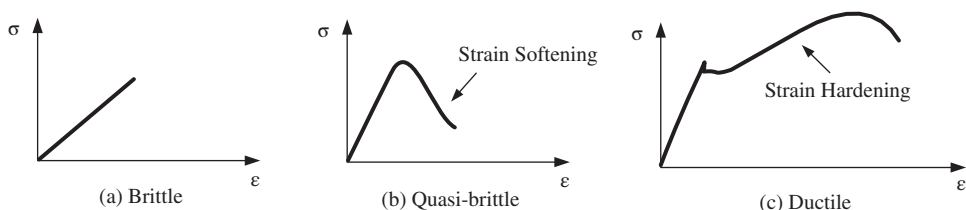


Figure 1-12 Three failure modes of materials

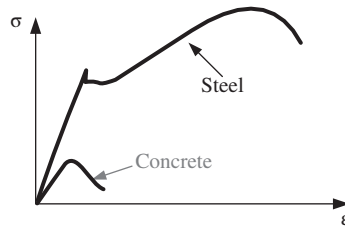


Figure 1-13 Stress-strain curves of steel and concrete

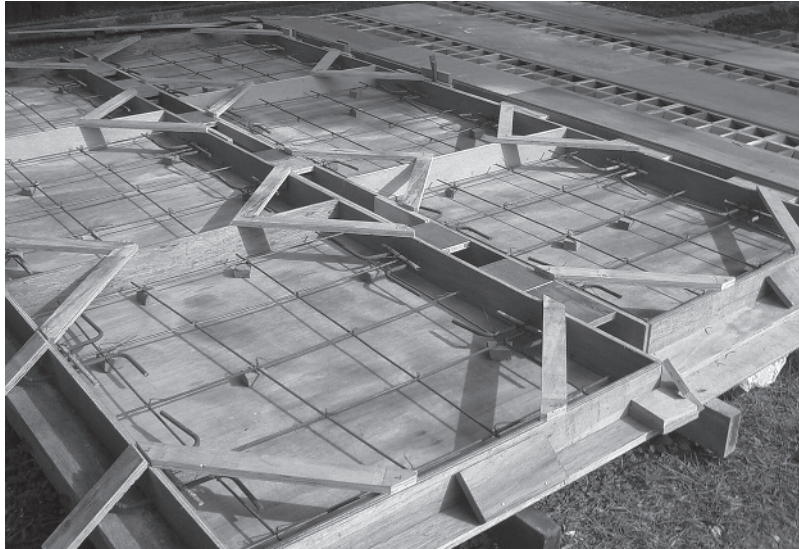


Figure 1-14 Formwork for concrete casting

in Figure 1-14. The formwork is expensive because it is labor-intensive and time-consuming to build and demold it. To improve efficiency, precast, extrusion, and 3D printing techniques have been developed.

- (f) *Long curing time:* The design index for concrete strength is the 28-day compression strength. Hence, full strength development needs a month at ambient temperature. The improvement measure that is able to reduce the curing period is steam curing or microwave curing.
- (g) *Working with cracks:* Even for reinforced concrete structure members, the tension side has a concrete cover to protect the steel bars. Due to the low tensile strength, the concrete cover cracks. To solve the crack problem, prestressed concrete is developed, and it is also realized as a third-generation concrete. Most reinforced concrete structures have existing cracks on their tension sides while carrying the service load.

1.4 TYPES OF CONCRETE

1.4.1 Classification in Accordance with Unit Weight

According to the unit weight of concretes, they can be classified into four categories, as shown in Table 1-1. Ultra-lightweight concrete can only be used to build up nonstructural members. Lightweight concrete can be used to build both nonstructural and structural members,

Table 1-1 Classification of concrete in accordance with unit weight

Classification	Unit weight (kg/m ³)
Ultra-lightweight concrete	< 1,200
Lightweight concrete	1,200 < UW < 1,800
Normal-weight concrete	≈ 2,400
Heavyweight concrete	> 3,200

Table 1-2 Concrete classified in accordance to compressive strength

Classification	Compressive strength (MPa)
Low-strength concrete	< 20
Moderate-strength concrete	20 ~ 50
High-strength concrete	50 ~ 150
Ultra high-strength concrete	> 150

depending on its specified composition. Normal-weight concretes are commonly used concretes in the construction of infrastructures and buildings. Heavyweight concrete is used to build some special structures, such as laboratories, hospital examination rooms, and nuclear plants, where radioactive protection is needed to minimize its influence on people's health.

The main component that makes a concrete unit weight (UW) difference is the aggregate. As discussed in Chapter 2, the four types of concrete differentiated by UW correspond to four different types of aggregates, i.e., ultra-lightweight aggregates for ultra-lightweight concretes, lightweight aggregates for lightweight concretes, normal-weight aggregates for normal-weight concretes while heavyweight aggregates for heavyweight concretes.

1.4.2 Classification in Accordance with Compressive Strength

According to its compressive strength, concrete can be classified into four categories, as listed in Table 1-2. Low-strength concrete is mainly used to construct mass concrete structures, subgrades of roads, and partitions. Moderate-strength concretes are the most commonly used concretes in buildings, bridges, and similar structures. High-strength concretes can be used to build tall building columns, bridge towers, and shear walls. Ultra-high-strength concretes have not yet been widely used in structural constructions. Only a few footbridges and some structural segments, such as girders, have been built using such concretes.

1.4.3 Classification in Accordance with Additives

According to the materials other than cement, aggregate, and water that are added into concrete mixtures as additives, concretes can be classified into different categories. Four examples are shown in Table 1-3. Fiber-reinforced concrete (FRC) is a type of concrete with fibers incorporated. Many different fibers have been used to produce fiber-reinforced concrete, including steel, glass, polymerics, and carbon. The purpose of incorporating fibers into concrete includes toughness enhancement, tension property improvement, shrinkage control, and decoration. Detailed information regarding FRC can be found in Chapter 6. Macro-defect-free (MDF) is a cement-based composite that incorporates a large amount of water-soluble polymer, produced in a twin-roll

Table 1-3 Concrete classifications in accordance to additives

Classification	Additives
MDF	Polymers
Fiber reinforced concrete	Different fibers
DSP concrete	Large amount silica fume
Polymer concrete	Polymers

**Figure 1-15** 3D printing technology (Photo provided by Zhendi Wang)

mixing process. It was developed to enhance the tensile and flexural properties of concrete. Concrete that has been densified with small particles is called DSP concrete which has incorporated a large amount of silica fume, a mineral admixture with very small particles. DSP concrete has excellent abrasion resistance and is mainly used to produce machine tools and industrial molds. Three methods have been developed to incorporate polymers into concrete: (1) using the polymer as a binder; (2) impregnating normal Portland cement concrete members with the polymer; and (3) using the polymer as an admixture in normal Portland concrete. MDF, DSP, and polymer in concrete are discussed in detail in Chapter 6.

1.4.4 Classification in Accordance with Construction Methods

Apart from the common casting method, there are some special types of concrete made by different construction methods. Associated with these different construction methods, these concretes possess specified properties and thus require special design. Some include 3D printable concrete, sprayable concrete, and roller-compacting concrete.

3D concrete printing (3DCP) (Figure 1-15) is a new construction technology developed in recent years. It adopts the layer-by-layer deposition method to construct the desired structure as per computer-aided design. Compared with the common casting method, 3D concrete printing

has various advantages, such as less waste generated (formwork-free characteristic), less labor required (automatic characteristic), and higher construction efficiency (automatic characteristic). In addition, it facilitates the construction of structures with complex geometry through customized design and automatic printing. 3DCP can largely reduce construction costs.

In the development of 3D printable concrete, the multi-level material design should be adopted, which considers requirements of the mixture design, rheology, the printing process, and the composite structure. A successful 3D printable concrete material cannot be “too stiff,” otherwise it cannot be delivered through the pump and hose; meanwhile, it cannot be “too soft,” otherwise it cannot support the weight of the printed structure. In other words, the fresh concrete needs to possess good pumpability for delivery and good buildability for deposition. Hence, the requirement for its fresh state mainly focuses on the careful tailoring of its flow characteristic. In other words, tailoring its rheological properties is the key focus. The details of 3D concrete printing are introduced in Chapter 3 of this book.

Spray concrete technology is a conventional construction method, which is also known as shotcrete. It refers to the pumping of sprayable concrete through a hose, and the concrete can be pneumatically projected at a high velocity onto the substrate to build the desired structure. The common practice of spraying is to construct structures on vertical and overhead surfaces, where it is difficult to apply casting in these applications. It is also applied to reinforce caves or tunnels as the support to surrounding rocks, and it is one of the key methods in the repair and retrofit of structures with defects. Compared to concrete that suits casting, the sprayable concrete has enhanced coherence to prevent pressure-induced bleeding in the pumping process. Meanwhile, it has enhanced adherence to guarantee the bond strength between the concrete-substrate interface. In addition, sprayable concrete is required to possess good pumpability for the delivery of the material.

Roller-compacting concrete is another conventional construction method that specifically is applicable to the construction of road pavements. Compared to the concrete that suits casting, roller-compacting concrete has enhanced anti-abrasion properties. Fresh roller-compacting concrete is very stiff and hard to flow. Hence, road rollers are applied to compact the fresh material for it to be uniformly distributed and leveled to the same height.

1.4.5 Classification in Accordance with Non-Structural Functionality

As a structural material, concrete has the primary function of load-bearing. Thus, mechanical properties, such as compressive strength, flexural strength, elastic modulus, are strongly emphasized during the development of concrete technology. Accordingly, new types of concrete, such as high-strength concrete, ultra-high-strength concrete, have been developed and utilized. Meanwhile, multi-functional concretes have been developed, in which, in some circumstances, the non-structural functionality attracts more attention.

- (a) *Decoration function*: Due to being in close contact with people in their daily lives, plain, gray, and boring concrete structures need to be turned into beautiful decorative elements. Concretes for decoration purposes have been developed, such as architectural concrete/colored concrete/polished concrete/stained concrete/stamped concrete.
- (b) *Abrasion-resistant function*: Abrasion-resistance is very important in dams, diversion channels, water channels, collecting pipes, floors, pavements, etc. A unique selection of the binder (i.e., high calcium aluminate ferrite phase), the stronger fine/coarse aggregates, and the particular mix proportion design ensure this functionality.
- (c) *Shielding function*: The ability to shield from micro-waves, radiation, acoustic noises, heat, etc., is an essential feature governing the safety of people’s daily environment. The unique designs of concrete density, pores, compositions, etc., have been explored to endow the shielding features of concrete structures.

With the development of nanotechnology, the multi-functionalities of concrete structures have been innovatively realized in recent years. By taking advantage of nanomaterials (such as nanoTiO₂, nanoSiO₂, nanoCaCO₃, nanoclay, carbon nanotubes, graphene, etc.), novel functionalities, such as photocatalysis, self-cleaning, rheology modifying, and heat conduction, have been developed to endow specific features and improved performances of traditional concrete.

1.5 FACTORS INFLUENCING CONCRETE PROPERTIES

1.5.1 *w/c* Ratio (or *w/b* or *w/p* Ratio)

One very important factor dictating the properties of concrete is the water/cement (*w/c*) ratio. In contemporary concrete, the *w/c* is frequently replaced with the *w/b* (water/binder) or the *w/p* (water/powder), since Portland cement is not the only binding material in concrete. The *w/c* or *w/b* ratio is one of the most important factors influencing concrete properties, such as compressive strength, permeability, and diffusivity. A lower *w/c* ratio will generally lead to stronger and more durable concrete. The influence of *w/c* on the concrete compressive strength has been known since the early 1900s (Abrams, 1927), leading to Abrams's law:

$$f_c = \frac{A}{B^{1.5(w/c)}} \quad (1-7)$$

where f_c is the compressive strength, A is an empirical constant (usually 97 MPa or 14,000 psi), and B is a constant that depends mostly on the cement properties (usually 4). It can be seen from the formula that the higher the *w/c* ratio, the lower the compressive strength. Another way to show the influence of the *w/c* ratio on the compressive strength of concrete can be written as

$$f_c = Af_{ce} \left(\frac{c}{w} - B \right) \quad (1-8)$$

where f_c is the compressive strength, A and B are empirical constants that depend on the aggregate, and f_{ce} is the compressive strength of a specified type of cement at 28 days. c/w is the reverse of *w/c*.

1.5.2 Cement Content

When water is added to a concrete mixture, cement paste will be formed. Cement paste has three functions in concrete: (1) binding; (2) coating; and (3) lubricating. Cement paste provides binding to individual aggregates, reinforcing bars, and fibers and glues them together to form a unique material. Cement paste also coats the surface of the aggregates and fibers during the fresh stage of concrete. The rest of the paste after coating can make the movement of the aggregates or fibers easier, rather like a lubrication agent. The cement content influences the concrete workability in the fresh stage, the heat release rate in the fast hydration stage, and the volume stabilities in the hardened stage. The range of the amount of cement content in mass concrete is usually 160–200 kg/m³, in normal strength concrete, it is less than 400 kg/m³, and in high strength concrete, it is 400–600 kg/m³.

1.5.3 Aggregate

- (a) *Maximum aggregate size*: The maximum coarse aggregate size mainly influences the cement paste requirement in the concrete. For the same volume of aggregates, those with a large aggregate size will lead to a small total surface area and a lower amount of cement paste coating. Hence, if the same amount of cement is used, concrete with a larger maximum

aggregate size will have more cement paste left as a lubricant and the fluidity of concrete can be enhanced, as compared to concrete with a smaller maximum aggregate size. For normal-strength concrete, at the same w/c ratio and with the same cement content, the larger the maximum sizes, the better the workability; at the same workability, the larger the maximum sizes, the higher the strength. However, a larger aggregate size has some drawbacks. First, a larger aggregate size may make the concrete appear nonhomogeneous. Second, a larger aggregate size may lead to a large interface that can influence the concrete transport properties and mechanical properties.

Generally, the maximum size of coarse aggregate should be the largest that is economically available and consistent with the dimensions of the structure. In choosing the maximum aggregate size, the structural member size and spacing of reinforcing steel in a member have to be taken into consideration. In no circumstances should the maximum size exceed one-fifth of the narrowest dimension in the sizes of the forms, one-third of the depth of slabs, or three-quarters of the minimum clear spacing between reinforcing bars.

- (b) *Aggregate grading*: Aggregate grading refers to the size distribution of the aggregates. The grading mainly influences the space-filling or particle packing. The classical idea of particle packing is based on the Apollonian concept, in which the smaller particles fit into the interstices left by the large particles. Well-defined grading with an ideal size distribution of aggregate will decrease the voids in the concrete and hence the cement content. As the price of the aggregate is usually only one-tenth that of cement, well-defined grading not only will lead to higher compressive strength and low permeability, but also is more economical at a lower cost.
- (c) *Aggregate shape and texture*: The aggregate shape and texture can influence the workability, bonding, and compressive strength of concrete. At the same w/c ratio and with the same cement content, aggregates with an angular shape and rough surface texture result in lower workability, but lead to a better bond and better mechanical properties. On the other hand, aggregates with spherical shape and smooth surface texture result in higher workability, but lead to a lower bond and lower mechanical properties.
- (d) *Sand/coarse aggregate ratio*: The sand/coarse aggregate ratio will influence the packing of the concrete. It also influences the workability of the concrete in the fresh stage. Increasing the sand to coarse aggregate ratio can lead to an increase in cohesiveness, but reduces the consistency. Of all the measures for improving the cohesiveness of concrete, increasing the sand/coarse aggregate ratio has been proven to be the most effective one.
- (e) *Aggregate/cement ratio*: The aggregate/cement ratio has an effect on the concrete cost, workability, mechanical properties, and volume stability. Due to the price difference between the aggregate and cement, increasing the aggregate/cement ratio will decrease the cost of concrete. From a workability point of view, an increase of the aggregate to cement ratio results in a lower consistency because of less cement paste for lubrication. As for mechanical properties, increasing the aggregate/cement ratio can lead to higher stiffness and compressive strength if proper compaction can be guaranteed. Increasing the aggregate/cement ratio will definitely improve the concrete's dimension stability due to the reduction in shrinkage and creep.

1.5.4 Admixtures

Admixtures (chemical admixtures and mineral admixtures) are important and necessary components for contemporary concrete technology. The concrete properties, both in fresh and hardened states, can be modified or improved by admixtures. For instance, concrete workability can be

affected by air-entraining agents, water reducers, and fly ash. Concrete strength can be improved by silica fume. More details regarding the effects of admixtures on concrete properties can be found in Chapter 2.

1.5.5 Mixing Procedures

Mixing procedures refer to the sequence of putting raw materials into a mixer and the mixing time required for each step. Mixing procedures directly influence the workability of fresh concrete and indirectly influence some mature properties of concrete.

Currently, ready-mixed concrete (RMC) is becoming popular. RMC can be manufactured in three ways:

- (a) *Central-mixing*: The concrete is mixed thoroughly in a stationary mixer and then discharged into transporting equipment such as a truck agitator, a truck mixer operating at agitation speed, or a no-agitating truck.
- (b) *Shrink-mixing*: The concrete is partially mixed in a stationary mixer and partially in a concrete truck mixer to complete mixing during its travel to the work site.
- (c) *Truck-mixing*: The concrete is mixed completely in a concrete truck mixer. The mixing constituents are batched at a plant, loaded into the transporting truck, and mixed as the truck travels to the work site.

The mixing time depends on the power of a mixer, the slump requirement, and the properties of the raw materials. It can range from 30 seconds to a few minutes.

The following special mixing procedure can be used to obtain very good workability with a good coating on the coarse aggregate to prevent alkali-aggregate reaction.

Step 1: Coarse aggregate + 50% water + 50% cement: mixing for 30 sec to 1 min.

Step 2: Adding 50% cement + 25% water + superplasticizer + fine aggregate: mixing for 2 min.

Step 3: Adding 25% water: mixing for 3 min.

1.5.6 Curing

Curing is defined as the measures for taking care of fresh concrete right after casting. The main principle of curing is to keep favorable moist conditions under a suitable temperature range during the fast hydration process for concrete. It is a very important stage for the development of concrete strength and in controlling early volume changes. Fresh concrete requires considerable care, just like a baby. Careful curing will ensure that the concrete is hydrated properly, with a good microstructure, proper strength, and good volume stability. On the other hand, careless curing always leads to improper hydration with defects in the microstructure, insufficient strength, and unstable dimensions. One of the common phenomena resulting from careless curing of concrete is plastic shrinkage, which usually leads to an early-age cracking that provides a path for harmful ions and agents to get into the concrete body easily and cause durability problems. Curing is a simple measure to achieve a good quality of concrete. However, it is often ignored on construction sites.

Some methods could be helpful in curing:

- (a) Moisten the subgrade and forms.
- (b) Moisten the aggregates.
- (c) Erect windbreaks and sunshades.
- (d) Cool the aggregates and mixing water.

- (e) Fog spray.
- (f) Cover.
- (g) High temperature (70–80°C) steam curing.
- (h) Use shrinkage compensating admixtures.

Recently, a new technique called internal curing has been developed, which uses the saturated porous aggregate to form a reservoir inside the concrete and provide water for concrete curing internally. Details of the relevant curing methods and the effects on the properties of concrete are explained in Chapter 3.

1.6 APPROACHES TO STUDY CONCRETE

The scope of materials, including concrete, research, design and development can be explained by the Chinese word, 材料, which is pronounced as *tsai liao* and means material. The first character, 材 (pronounced *tsai*), is composed of two parts, 木 (pronounced *mu*) and 才 (pronounced *tsai*). The first part, 木, means wood and is real, while the second part, 才, means properties or performance and is virtual. The two parts 木 and 才 represent the hardware and software of materials research, development and design. Similarly, the second character in the Chinese word for material, 料 (pronounced *liao*), is also composed of two parts, 米 (pronounced *mi*) and 斗 (pronounced *dou*). The first part 米 means rice and is real and the second part 斗 means container and is virtual. The two parts 米 and 斗 also represent the hardware and software of materials research, development and design. Materials research, design and development involve two aspects: hardware and software. The hardware includes material composition, microstructure, synthesis/processing. The software includes characterization, measurement, properties, and performance.

As a structural material, the fundamental approach in materials study also applies to concrete. About 25 years ago, a pyramid diagram was used to describe the philosophy in materials research, as shown in Figure 1-16. In this pyramid, the top is performance and the base is a triangle formed by three points: properties, microstructure, and processing. The philosophy behind this pyramid is that the processing, microstructure, and properties of material should be designed, developed, or investigated according to its performance requirement.

This concept was changed in 1999. The U.S. National Research Council has developed a new pyramid for materials research, as shown in Figure 1-17 (National Research Council, 1999). In this pyramid, the top is changed to end-use needs/constraints and the base is changed to a square with processing, properties, microstructure, and performance at each corner. The processing of concrete includes raw materials selection, mixing, placing, compacting, and curing. The properties of concrete include load-carrying capabilities, such as compressive strength, flexural strength, and fatigue

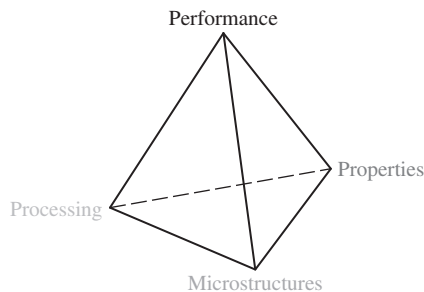


Figure 1-16 Fundamental approach of materials research – 1

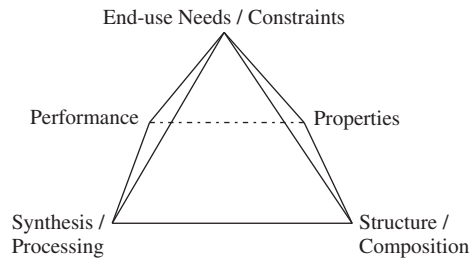


Figure 1-17 Fundamental approach of materials research – 2. (Source: U.S. National Research Council, 1999)

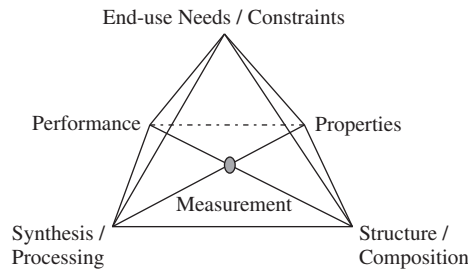


Figure 1-18 Measurement is an essential part of materials science and engineering

strength, dimensional stability, such as shrinkage and creep, and stress-strain or load-deformation relationship. The structure of concrete consists of different phases with different amounts, sizes, and special arrangements. It covers the nanoscale, microscale, and millimeter-scale, a typical multi-phase composite. The performance of concrete includes safety, durability, and serviceability.

The philosophy behind this pyramid is that the microstructure, processing, properties, and performance of material have to be designed, investigated, or developed comprehensively to meet the requirements of the end-use. In other words, it is the end-use that governs the design, research, or development of a material, not the material itself. The design and construction of the Eddystone Lighthouse by John Smeaton form a good example of an end-use constraint. Since the structure to be built was a lighthouse, which must be able to withstand watery conditions, Smeaton designed the building materials according to the constraints of such end needs, in their composition, processing, properties, and performance, which turned out to be hydraulic cement. The end requirements of a tall building are very different from those of a hydraulic dam. Hence, the materials' design and development must be very different for a tall building and a hydraulic dam.

By adding measurement and characterization at the center of the base of the pyramid shown in Figure 1-17, the essential portion of materials science and engineering, the scope of materials design and development is complete, as demonstrated in Figure 1-18. With measurement and characterization, the material's structure/composition can be quantified, the properties can be specified, and synthesis/processing can be identified. Moreover, with measurement, the four corners of the base can be connected.

A close look at the historic development of concrete shows that concrete has been applied in practice for more than 150 years without a systematic scientific background. Most practices followed empirical formulae and observations. Attention was paid mainly to the properties of concrete, especially compressive strength. Very limited understanding of the material structure of concrete emerged. Concrete is a typical multiscale material, and its material structure covers the nanometer scale, the micrometer scale, and the millimeter scale. The concrete phases in the

nanometer scale mainly constitute calcium silicate hydrate (C–S–H). It is believed that C–S–H contributes most to the binding strength, and understanding the nature of the C–S–H gel is key to revealing the behavior of concrete. The structure of C–S–H on the atomic level determines the nature of the mechanical properties, transport mechanism, and dimensional stability of hydrated cement paste. However, due to the limitations in experimental techniques and computer simulation in the past, studies on C–S–H structure are very limited. Nowadays, with the fast development of microstructure measurement technology and powerful computer simulation methods, it is possible to study and develop concrete technology more scientifically at the C–S–H level. The research activities aimed at understanding the nature of concrete hydrates at the nanometer-scale structure are developing very fast. A revolutionary breakthrough in concrete science is very likely. With such an understanding, it will be possible to design or develop concrete structures/compositions, properties, processing methods, and performance with solid knowledge to meet the need of every different end-use.

DISCUSSION TOPICS

Why is concrete so popular?

What are the weaknesses of concrete?

What are the factors influencing concrete properties?

Give some examples of concrete applications.

Can you list a few topics for concrete research?

When you do a structural design, which failure mode should be applied?

How would you like to improve concrete workability (fluidity or cohesiveness)?

How can you enhance concrete compressive strength?

Which principles are you going to follow if you are involved in concrete research?

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