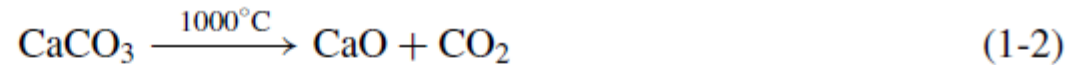


## 1.1 CONCRETE DEFINITION AND HISTORICAL DEVELOPMENT

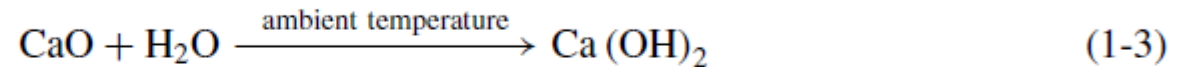
Concrete is a manmade building material that looks like stone. The word “concrete” is derived from the Latin *concretus*, meaning “to grow together.” Concrete is a composite material composed of coarse granular material (the aggregate or filler) embedded in a hard matrix of material (the cement or binder) that fills the space among the aggregate particles and glues 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 what kind of binder is used, concrete can be named in different ways. For instance, if a concrete is made with nonhydraulic cement, it is called nonhydraulic cement concrete; if a concrete made of hydraulic cement, it is called hydraulic cement concrete; if a concrete is made of asphalt, it is called asphalt concrete; if a 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 does.



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

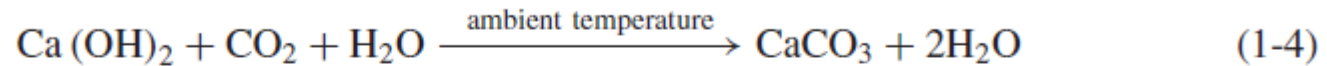


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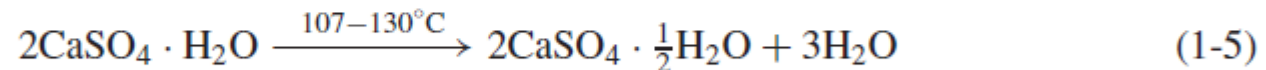
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## Chapter 1 Introduction to Concrete

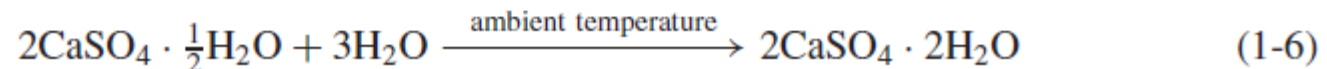
and is then further reacted with CO<sub>2</sub> to form limestone again:



The Egyptians used gypsum mortar in construction, and the gypsum was obtained by calcining impure gypsum with a reaction of



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





**Figure 1-1** Pyramid built with gypsum mortar in Gaza, Egypt

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

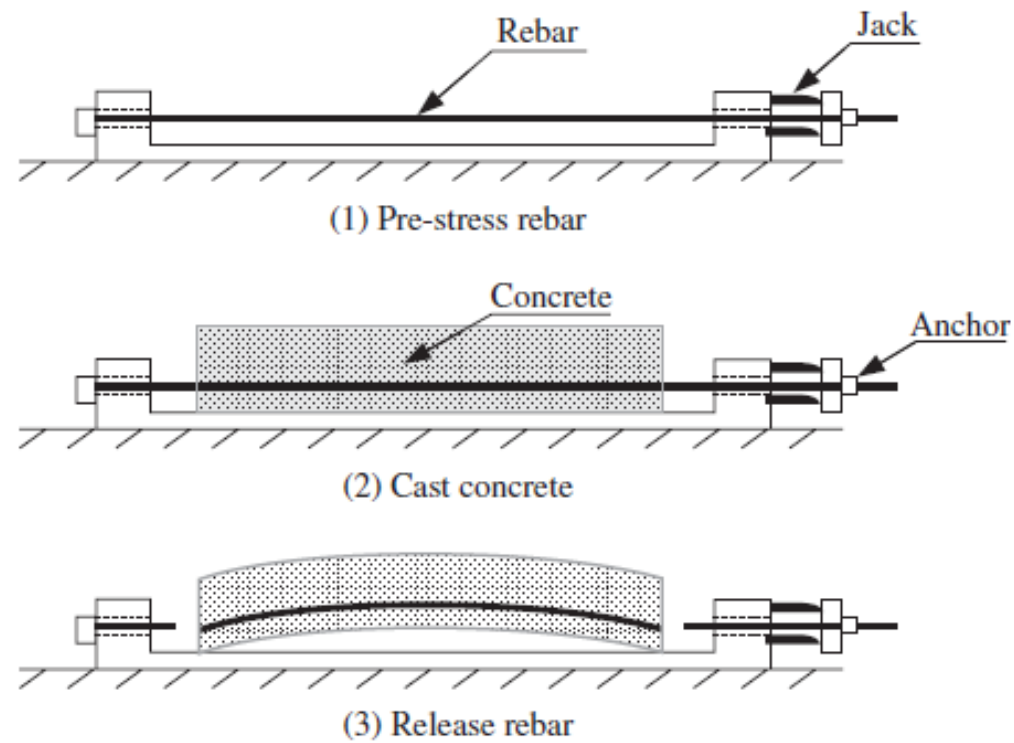


Figure 1-3 Pretensioning sequence for prestressing concrete

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. 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.



**Figure 1-4** Water Tower Place in Chicago, Illinois, 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**

Concretes have been widely used to build various structures. High-strength concrete has been used in many tall building constructions. In Hong Kong, grade 80 concrete (80 MPa) was utilized in the columns of the tallest building in the region. As shown in Figure 1-6, the 88-story International Finance Centre was built in 2003 and stands 415 m (1362 ft) tall.

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





Figure 1-6 International Finance Center, Hong Kong (Photo courtesy of user WING on





**Figure 1-7** The Sutong Bridge in Suzhou, Jiangsu, China

## 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 every corner of the world. This enables concrete to be produced worldwide at very low cost for local markets, thus avoiding the transport expenses necessary for most other materials.

Figure 1-9 High speed train

- (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. No high temperature 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. 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 are all cast by concrete.
- (d) *Energy efficient*: Compared with 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 resistance to water*: Unlike wood (timber) and steel, concrete can be hardened 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 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 is able to 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, more and more by-products or waste has been generated, causing 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 leads to better performance of a concrete structure. Due to the large amount of concrete produced annually, it is possible to completely consume most of industry waste in the world, 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  $1.2 \times 10^{-5}$ ; concrete  $1.0\text{--}1.5 \times 10^{-5}$ ). Concrete produces a good protection to steel due to 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. Moreover, the coatings and paintings have to be replaced 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 tension 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 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

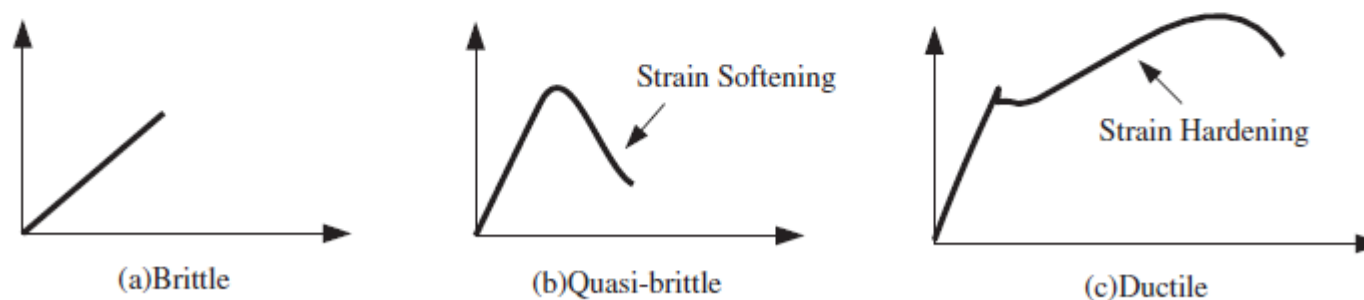
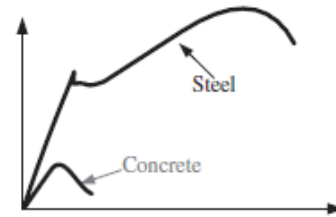


Figure 1-12 Three failure modes of materials





**Figure 1-13** Toughness of steel and concrete

- compression loads. Moreover, concrete can provide a structure with excellent stability. Reinforced concrete is realized as the second generation of concrete.
- (b) *Low tensile strength*: Concrete has different values in compression and tension strength. Its tension strength is only about 1/10 of its compressive strength for normal-strength concrete, or 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*: 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 in Figure 1-14. The formwork is expensive because it is labor intensive and time-consuming. To improve efficiency, precast 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 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.

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

<b>Classification</b>	<b>Unit Weight (Kg/m<sup>3</sup>)</b>
Ultra-lightweight concrete	<1200
Lightweight concrete	1200 < UW < 1800
Normal-weight concrete	~2400
Heavyweight concrete	>3200



**Table 1-2** Concrete classified in accordance with compressive strength

<b>Classification</b>	<b>Compressive Strength (MPa)</b>
Low-strength concrete	<20
Moderate-strength concrete	20–50
High-strength concrete	50–150
Ultra-high-strength concrete	>150

**Table 1-3** Concrete classifications in accordance with additives

<b>Classification</b>	<b>Additives</b>
MDF	Polymers
Fiber-reinforced concrete	Different fibers
DSP concrete	Large amount silica fume
Polymer concrete	Polymers

## 1.5 FACTORS INFLUENCING CONCRETE PROPERTIES

### 1.5.1 *w/c* ratio (or *w/b* or *w/p* ratio)

One property of concrete is the water/cement ratio. In contemporary concrete, *w/c* is frequently replaced with *w/b* (water/binder) or *w/p* (water/powder), since Portland cement is not the only binding material in such a 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 lead to a stronger and more durable concrete. The influence of *w/c* on the

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## 1.5 Factors Influencing Concrete Properties

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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 form to show the influence of the *w/c* ratio to compressive strength of a 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 cement at 28 days.  $c/w$  is the reverse of *w/c*.

### 1.5.2 Cement content

When water is added to a concrete mix, cement paste will be formed. Cement paste has three functions in concrete: binding, coating, and 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 concrete workabilities in the fresh stage, heat release rate in the fast hydration stage, and volume stabilities in the hardened stage. The range of the amount of cement content in mass concrete is 160–200 kg/m<sup>3</sup>, in normal strength concrete it is less than 400 kg/m<sup>3</sup>, and in high strength concrete it is 400–600 kg/m<sup>3</sup>.

### 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 aggregate, the ones 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 the 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 event 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 aggregate. The grading mainly influences the space filling or particle packing. The classical idea of
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## Chapter 1 Introduction to Concrete

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 a better compressive strength and low permeability, but also is more economical at 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 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 fine/coarse aggregate ratio will influence the packing of concrete. It also influences the workability of concrete in the fresh stage. Increase of the sand to coarse aggregate ratio can lead to an increase of 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, increase of the aggregate/cement ratio can lead to a high stiffness and compressive strength if proper compaction can be guaranteed. Increasing the aggregate/cement ratio will definitely improve concrete's dimension stability due to reduction of 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.

The following mixing procedure can be used to obtain a very good workability with a good coating on the coarse aggregate to protect 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 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 of careless curing is plastic shrinkage, which usually leads to an early age crack that provides a path for harmful ions and agents to get into the concrete body easily and causes durability problems. Curing is a simple measure to achieve a good quality of concrete. However, it is often ignored on construction sites.

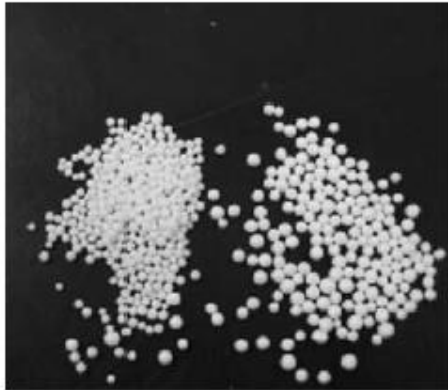
Some methods could be helpful in curing:

- (a) Moisten the subgrade and forms
- (b) Moisten the aggregate
- (c) Erect windbreaks and sunshades
- (d) Cool the aggregate and mixing water
- (e) Fog spray
- (f) Cover
- (g) High temperature (70–80°C) steam curing
- (h) Use shrinkage compensating concrete

Read CHAPTER 2  
**MATERIALS FOR MAKING CONCRETE**

2.1 Aggregates

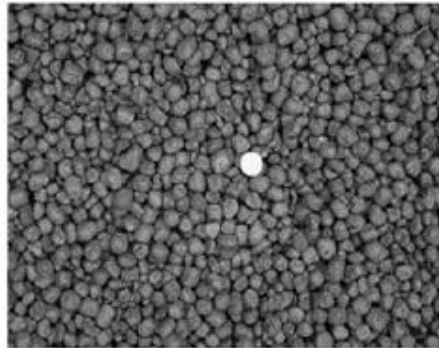
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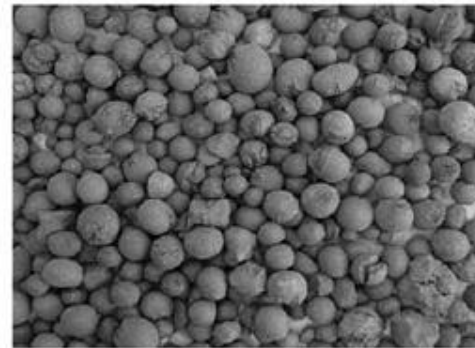
(a) Foam plastic



(b) Expanded volcano rock



(c) Expanded clay



(d) Expanded fly ash

Figure 2-3 Synthetic aggregates



## Aggregates

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(a) For the oven dry condition

$$MC (OD) = \frac{W_{stock} - W_{OD}}{W_{OD}} \times 100\% \quad (2-1)$$

where  $W_{stock}$  is the weight of aggregate in the stock condition, and  $W_{OD}$  the weight of oven-dried aggregates. It can be seen that  $MC_{OD}$  is a nonnegative value.

(b) For the saturated surface dry condition

$$MC (SSD) = \frac{W_{stock} - W_{SSD}}{W_{SSD}} \times 100\% \quad (2-2)$$

where  $W_{SSD}$  is the weight of aggregate in the SSD condition. As  $W_{stock}$  can be greater than, equal to, or less than  $W_{SSD}$ ;  $MC_{SSD}$  can be greater than, equal to, or less than zero.

(c) Absorption capacity

$$AC = \frac{W_{SSD} - W_{OD}}{W_{OD}} \times 100\% \quad (2-3)$$

Absorption capability of an aggregate is defined as the total amount of water that can be taken by an aggregate from the OD to the SSD condition.

### 2.1.3.3 Density and specific gravity

Since aggregates are porous materials, even a single piece of aggregate contains both solid material volume and pores volume. Hence, two types of aggregate density are defined.

Density ( $D$ ) is defined as the weight per unit volume of solid material only, excluding the pores volume inside a single aggregate:

$$D = \frac{\text{weight}}{V_{\text{solid}}} \quad (2-4)$$

Bulk density (BD) is defined as the weight per unit volume of both solid material and the pores volume inside a single aggregate:

$$\text{BD} = \frac{\text{weight}}{V_{\text{solid}} + V_{\text{pores}}} \quad (2-5)$$

where BD can be either  $\text{BD}_{\text{SSD}}$  or  $\text{BD}_{\text{AD}}$  according to the moisture condition of the aggregate when it is weighed.

Specific gravity (SG) is a ratio of density or bulk density of aggregate to density of water. Or SG is the mass of a given substance per unit mass of an equal volume of water. Depending

$$ASG = \frac{\frac{\text{weight of aggregate}}{V_{\text{solid}}}}{\text{density of water}} = \frac{D}{\rho_w} \quad (2-6)$$

$$\text{and } BSG = \frac{\frac{\text{weight of aggregate}}{V_{\text{solid}} + V_{\text{pores}}}}{\text{density of water}} = \frac{BD}{\rho_w} \quad (2-7)$$

In practice, the BSG value is the realistic one to use since the effective volume that an aggregate occupies in concrete includes its internal pores. The BSG of most rocks is in the range of 2.5 to 2.8. Similar to BD, BSG can be either  $BSG_{SSD}$  or  $BSG_{AD}$  according to the moisture condition of the aggregate. The BSG can be determined using the so-called displacement method. In this method, Archimedes' principle is utilized. The weight of aggregate is first measured in air, e.g., under the SSD condition, and is denoted as  $W_{SSD}$  in air. Then, the weight of the sample is measured in water, denoted as  $W_{SSD}$  in water. Thus, we have

$$BSG_{SSD} = \frac{W_{SSD \text{ in air}}}{W_{\text{displacement}}} = \frac{W_{SSD \text{ in air}}}{W_{SSD \text{ in air}} - W_{SSD \text{ in water}}} \quad (2-8)$$

where  $W_{\text{displacement}}$  is the weight of water displaced by the aggregates.

#### 2.1.3.4 Unit weight (UW)

The unit weight is defined as the weight per unit bulk volume for bulk aggregates. In addition to the pores inside each single aggregate, the bulk volume also includes the space among the particles. According to the weight measured at different conditions, the unit weight can be divided into UW(SSD) and UW(OD):

$$UW(SSD) = \frac{W_{SSD}}{V_{\text{solid}} + V_{\text{pores}} + V_{\text{spacing}}} \quad (2-9)$$

$$\text{and } UW(OD) = \frac{W_{OD}}{V_{\text{solid}} + V_{\text{pores}} + V_{\text{spacing}}} \quad (2-10)$$

The percentage of spacing (voids) among the aggregates can be calculated as

$$\text{Spacing (void)} = \frac{BD - UW}{BD} \times 100\% \quad (2-11)$$

### 2.1.3.5 Measurement of moisture content

Once the  $BSG_{SSD}$  is obtained for a type of aggregate, the moisture content of the aggregate under different moisture conditions can be conveniently determined using the following equation:

$$MC (SSD) = \frac{W_{stock} - \frac{W_{water} \times BSG_{SSD}}{BSG_{SSD} - 1}}{\frac{W_{water} \times BSG_{SSD}}{BSG_{SSD} - 1}} \quad (2-12)$$

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## 2.1 Aggregates

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where  $W_{stock}$  is the weight of the sample under the stockpile condition, and  $W_{water}$  is the short form of  $W_{SSD}$  in water.

If AC is known for the aggregate, MC(SSD) can also be calculated using the absorption capability of aggregates as

$$MC (SSD) = \frac{W_{stock} - W_{OD}(1 + AC)}{W_{OD}(1 + AC)} \quad (2-13)$$

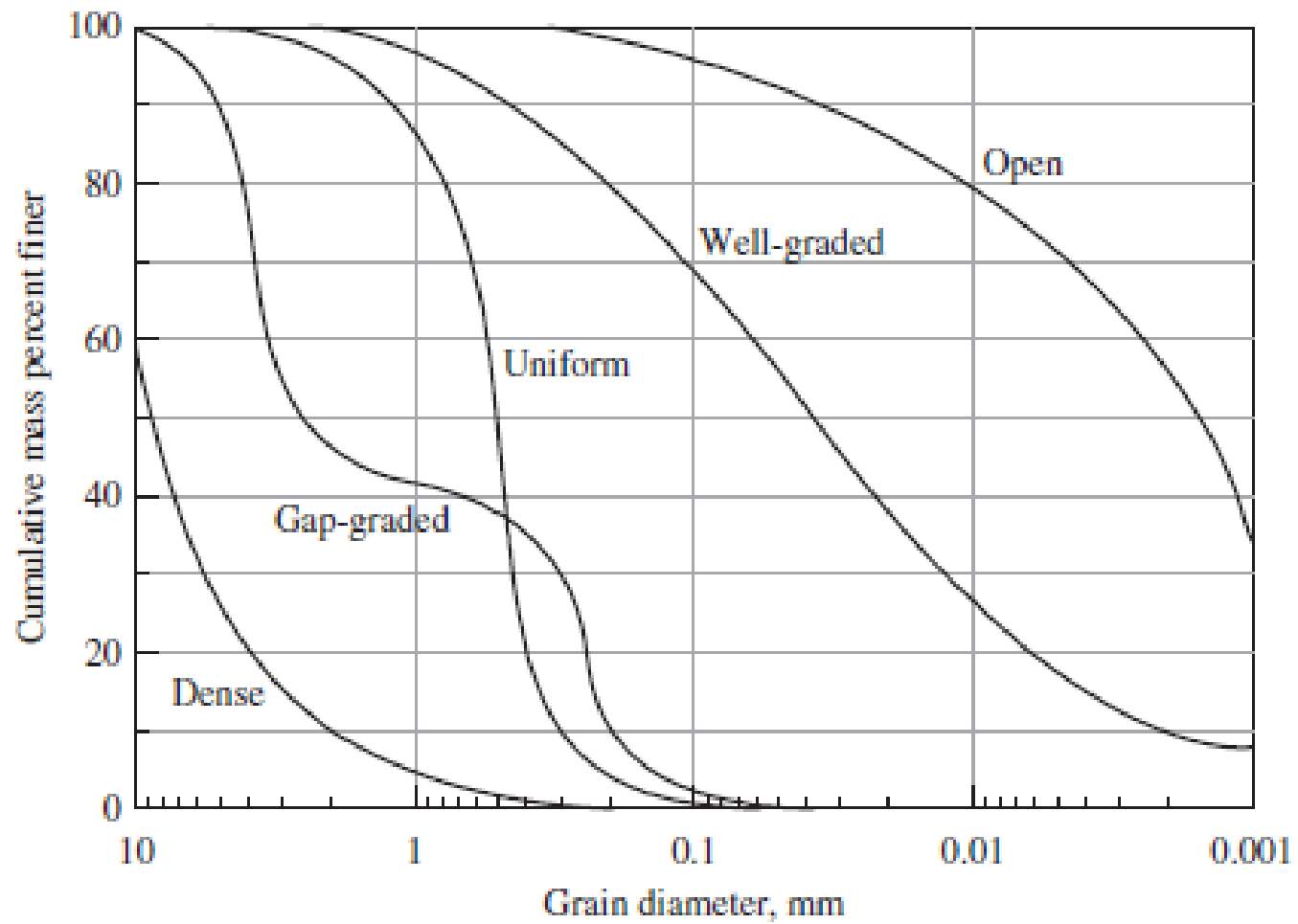


Figure 2-5 Five types of aggregate gradation

### 2.1.4.3 Fineness modulus for blending of aggregates

Blending of aggregates is undertaken for a variety of purposes, such as to remedy deficiencies in grading. A desired value of the fineness modulus can be calculated if the characteristics of the component aggregate are known. If two aggregates, designated A and B, are mixed together, having a fineness modulus of  $FM_A$  and  $FM_B$ , respectively, the resultant blend will have the following fineness modulus:

$$FM_{\text{blend}} = FM_A \times \frac{P_A}{100} + FM_B \times \frac{P_B}{100} \quad (2-15)$$

where  $P_A$  and  $P_B$  are the percentages, by weight, of aggregates A and B in the blend.

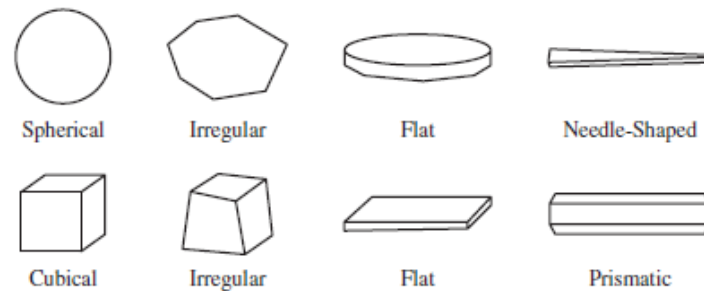
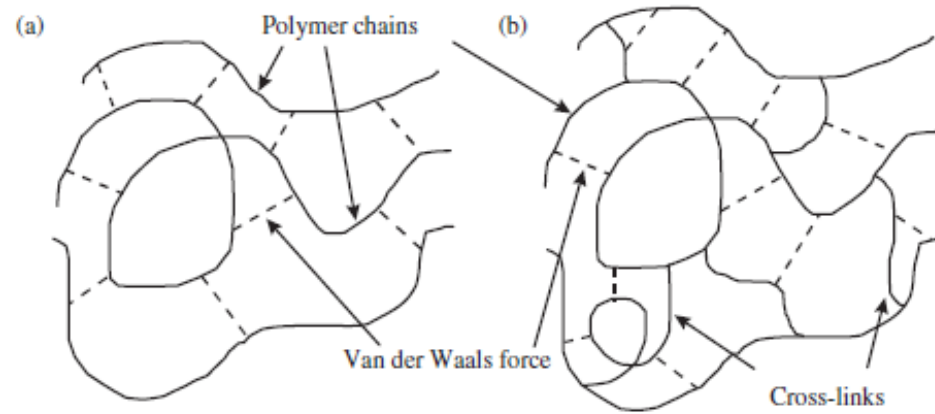


Figure 2-6 Different basic shapes of aggregates

Table 2-2 Effects of aggregate shape and surface texture on concrete strength

Affected Strength	Relative Effect (%) of	
	Shape	Surface Texture
Compressive	22	44
Flexural	31	26

## Read 2.2 CEMENTITIOUS BINDERS



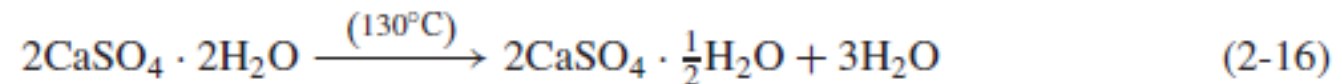
**Figure 2-7** Difference between (a) thermoplastics and (b) thermosets

**Table 2-3** Typical values of Young's modulus ( $E$  at room temperature), tensile strength, and glass transition temperature ( $T_g$ ) for various polymers

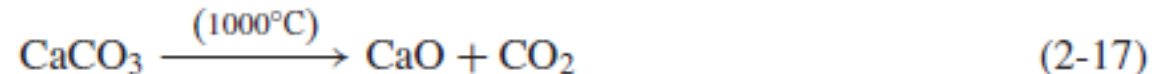
Category	Material	$E$ (GPa)	$\sigma_T$ (MPa)	$T_g$ (K)
Thermoplastic	Polyethylene (PE), low density	0.15–0.24	n/a	270
	Polyethylene, high density	0.55–1.0	20–37	300
	Polypropylene (PP)	1.2–1.7	50–70	253
	Polyvinyl chloride (PVC)	2.4–3.0	40–60	350
Thermosets	Polyesters	1.3–4.5	45–85	340
	Epoxies	2.1–5.5	40–85	380
Elastomers	Polyisoprene	0.002–0.1	~10	220
	Polybutadiene	0.004–0.1	n/a	171



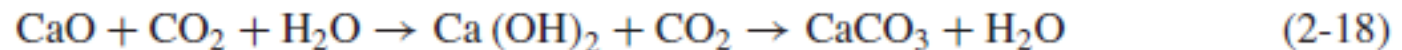
Inorganic binders are usually made of different natural minerals. The inorganic binder can be further classified into nonhydraulic cement and hydraulic cement. However, nonhydraulic here does not mean that it does not need water. In fact, all inorganic binders need water for mixing and reacting to form bonds. Nonhydraulic cement also needs water for mixing. Nonhydraulic means only that such cement cannot harden and thus gain strength in water. Typical examples of nonhydraulic cement are gypsum and lime. They have been used since 6000 BC, as mentioned in Chapter 1. Gypsum is a soft mineral composed of calcium sulfate dihydrate, called two-water gypsum. Under a temperature of  $130^{\circ}\text{C}$ , two-water gypsum can change to half-water gypsum and release some water:



When half-water gypsum is mixed with water, it can return to two water gypsum and form bonds. Lime is the product of calcination of limestone under  $1000^{\circ}\text{C}$ , and consists of the oxides of calcium:



When CaO is mixed with water again, the following reactions occur:

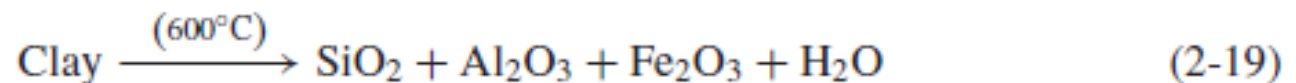


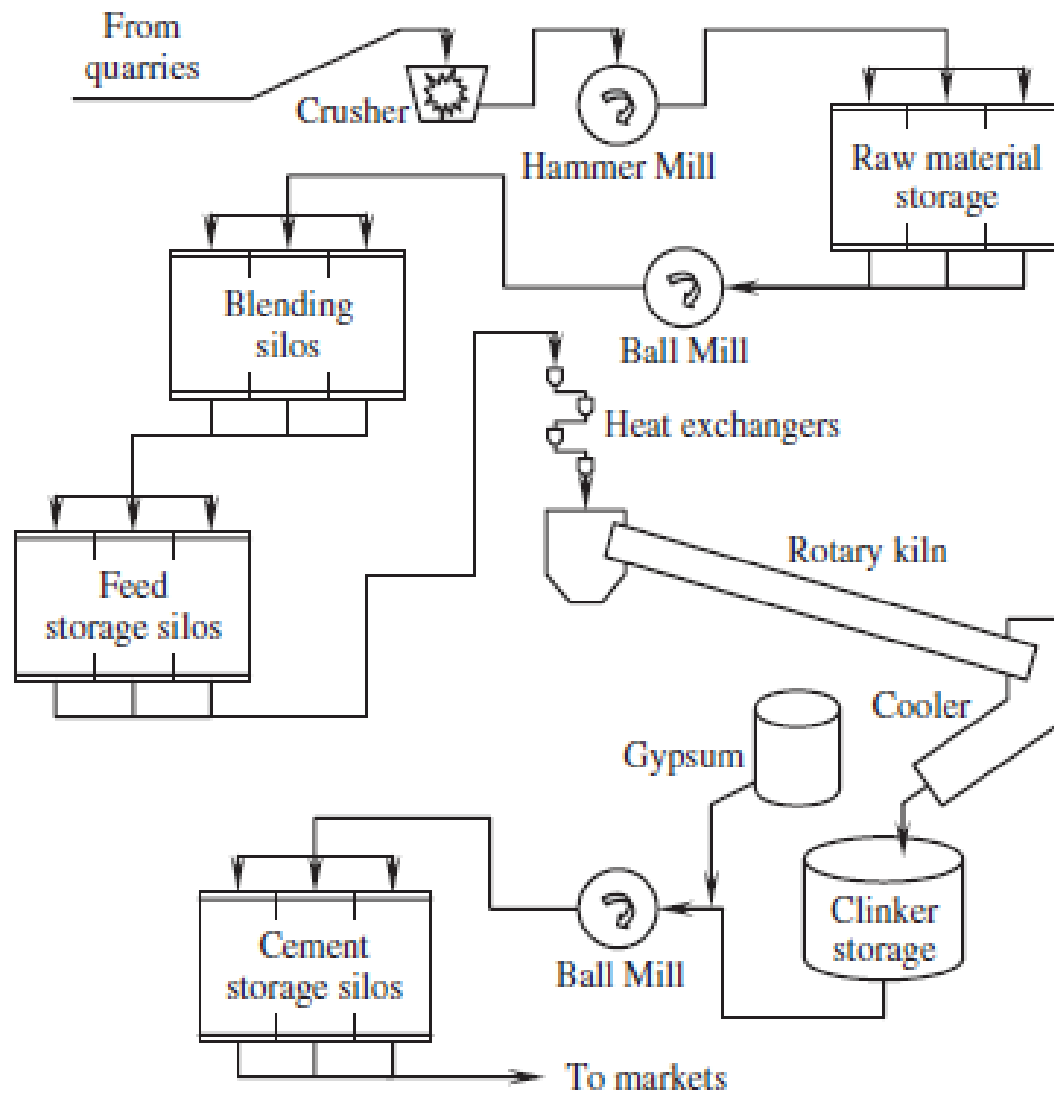
### 2.2.2.1 Manufacture of Portland cement

Portland cement is made by blending an appropriate mixture of limestone and clay or shale together, and by heating them to  $1450^{\circ}\text{C}$  in a rotary kiln. Currently, the capability of a rotary kiln can reach 10,000 metric tons daily. Figure 2-8 shows a model production line of the China Hailuo Cement Company.

The sequence of operations is shown in Figure 2-9, in which the preliminary steps are a variety of blending and crushing operations. The raw feed must have a uniform composition and be of fine enough size that reactions among the components can be completed in the kiln. Subsequently, the burned clinker is ground with gypsum to form the familiar gray powder known as Portland cement. The basic raw materials used for manufacturing Portland cement are limestone, clay, and iron ore. The primary reactions during the calcination process are listed as below.

- (a) Clay is mainly providing silicates ( $\text{SiO}_2$ ) together with small amount of  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$ . The decomposition of clay happens at a temperature around  $600^{\circ}\text{C}$ :



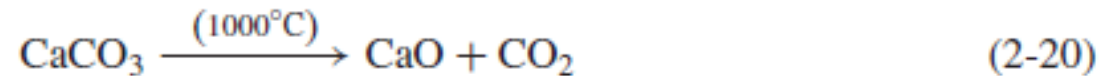


**Figure 2-9** Manufacturing process of Portland cement



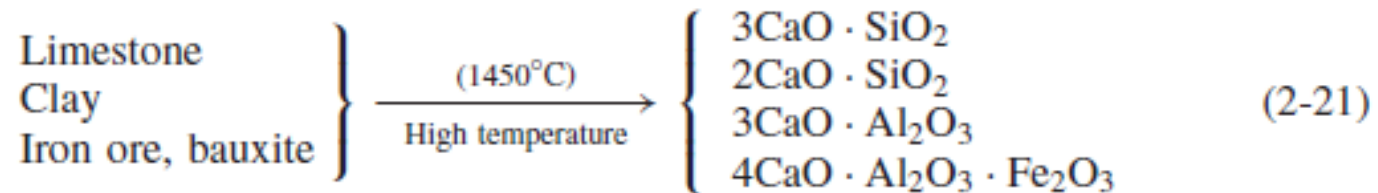
**Figure 2-8** A production line of 10,000 metric tons per day (Hai Luo Cement Company, China)

(b) Limestone ( $\text{CaCO}_3$ ) is mainly providing calcium ( $\text{CaO}$ ) and is decomposed at  $1000^\circ\text{C}$ :



(c) Iron ore and bauxite provide additional aluminum and iron oxide ( $\text{Fe}_2\text{O}_3$ ), which help the formation of calcium silicates at low temperature. They are incorporated into row mix.

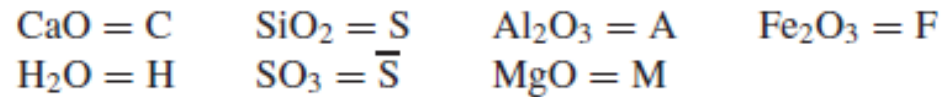
(d) There are different temperature zones in a rotary kiln. At various temperatures between  $1000$  and  $1450^\circ\text{C}$ , different chemical compounds are formed. The initial formation of  $\text{C}_2\text{S}$  occurs at a temperature of around  $1200^\circ\text{C}$ .  $\text{C}_3\text{S}$  is formed around  $1400^\circ\text{C}$ .



(e) The final product from the rotary kiln is called clinker. Pulverizing the clinker into small sizes ( $<75\ \mu\text{m}$ ) with addition of 3–5% gypsum or calcium sulf produces the Portland cement. Gypsum added is to control fast setting caused by  $3\text{CaO} \cdot \text{Al}_2\text{O}_3$ .

### 2.2.2.2 Chemical composition

(a) *Abbreviations:* In cement chemistry, the following abbreviations are adopted. Please note that they are not consistent with other types of chemistry, although these notations are also frequently used in ceramic chemistry.



Thus, we can write  $\text{Ca}(\text{OH})_2 = \text{CH}$ ,  $3\text{CaO} = \text{C}_3$ , and  $2\text{CaO} \cdot \text{SiO}_2 = \text{C}_2\text{S}$ .

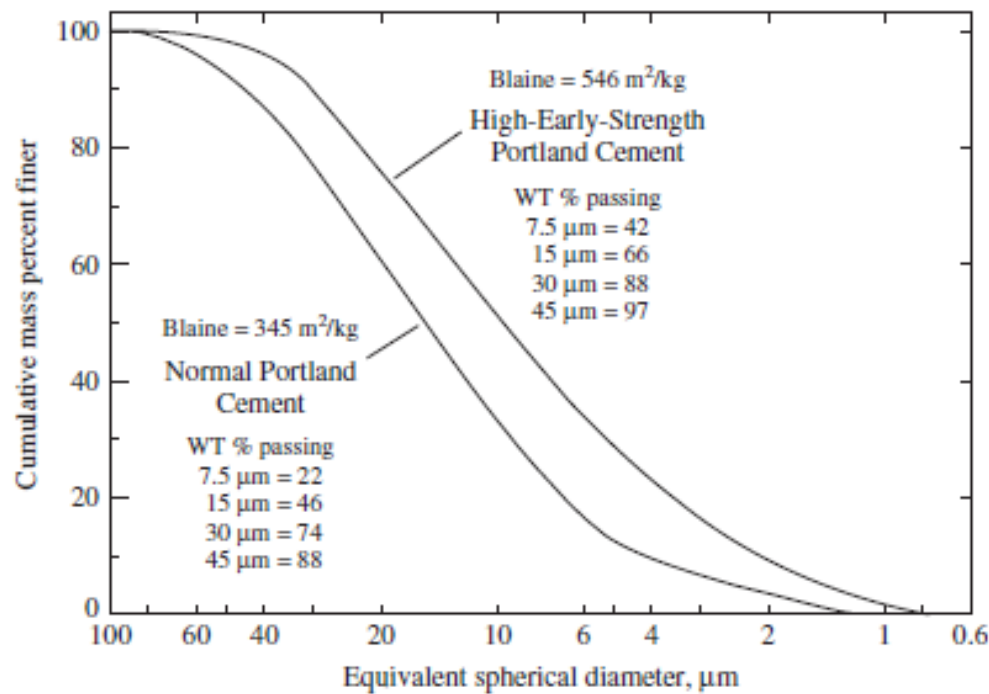


Figure 2-10 Typical particle size distributions of Portland cement



**Table 2-4** Major compounds of ordinary Portland cement

Compound	Oxide Composition	Color	Common Name	Weight Percentage
Tricalcium silicate	C <sub>3</sub> S	White	Alite	50
Dicalcium silicate	C <sub>2</sub> S	White	Belite	25
Tricalcium aluminate	C <sub>3</sub> A	white/grey	n/a	12
Tetracalcium aluminoferrite	C <sub>4</sub> AF	Black	Ferrite	8

- (b) *Major compounds*: The major compounds of ordinary Portland cement are listed in Table 2-4. They are C<sub>3</sub>S, C<sub>2</sub>S, C<sub>3</sub>A, and C<sub>4</sub>AF. C<sub>3</sub>S is called tricalcium silicate; C<sub>2</sub>S, dicalcium silicate; C<sub>3</sub>A, tricalcium aluminate; and C<sub>4</sub>AF, tetracalcium aluminoferrite. In addition, C<sub>3</sub>S the nickname alite; C<sub>2</sub>S, belite; and C<sub>4</sub>AF, ferrite. It should be indicated that C<sub>3</sub>S and C<sub>2</sub>S occupy 68 to 75% of Portland cement. Since the primary constituents of Portland cement are calcium silicates, we can define Portland cement as a material that combines CaO and SiO<sub>2</sub> in such a proportion that the resulting calcium silicate will react with water at room temperature and normal pressure.

The typical oxide composition of a general-purpose Portland cement can be found in Table 2-5. From the weight percentage of these oxides, the weight percentage of C<sub>3</sub>S, C<sub>2</sub>S, C<sub>3</sub>A, and C<sub>4</sub>AF in Portland cement can be calculated using an equation initially developed by Bogue and adopted by ASTM C150 as follows:

$$C_3S(\%) = 4.071C - 7.600S - 6.718A - 1.450F - 2.852\bar{S}$$

$$C_2S(\%) = 2.867S - 0.754C_3S$$

$$C_3A(\%) = 2.650A - 1.692F$$

$$C_4AF(\%) = 3.043F$$



**Table 2-5** Typical oxide composition of a general-purpose Portland cement

Oxide	Shorthand Notation	Common Name	Weight Percent
CaO	C	lime	64.67
SiO <sub>2</sub>	S	silica	21.03
Al <sub>2</sub> O <sub>3</sub>	A	alumina	6.16
Fe <sub>2</sub> O <sub>3</sub>	F	ferric oxide	2.58
MgO	M	magnesia	2.62
K <sub>2</sub> O	K	alkalis	0.61
Na <sub>2</sub> O	N	alkalis	0.34
SO <sub>3</sub>	$\overline{S}$	sulfur trioxide	2.03
CO <sub>2</sub>	$\overline{C}$	carbon dioxide	—
H <sub>2</sub> O	H	water	—

### 2.2.2.3 Hydration

Hydration of cement is the reaction between cement particles and water, including chemical and physical processes. The properties of fresh concrete, such as setting and hardening, are the direct results of hydration. The properties of hardened concrete are also influenced by the process of hydration. Hence, to understand the properties and behavior of cement and concrete, some knowledge of the chemistry of hydration is necessary.

(a) *Hydrations of pure cement compounds*: The mechanism of hydration of the cement as whole is very complex and has not been fully understood yet. So far, the only approach to studying the hydration of Portland cement is to investigate the reaction mechanism of individual compounds separately. This assumes that the hydration of each compound takes place independently and no interaction occurs. Although this assumption is not valid completely, it helps to understand the chemistry of hydration.

(b) *Calcium silicates*: The hydrations of two calcium silicates are stoichiometrically similar, differing only in the amount of calcium hydroxide formed, the heat released, and the reaction rate:



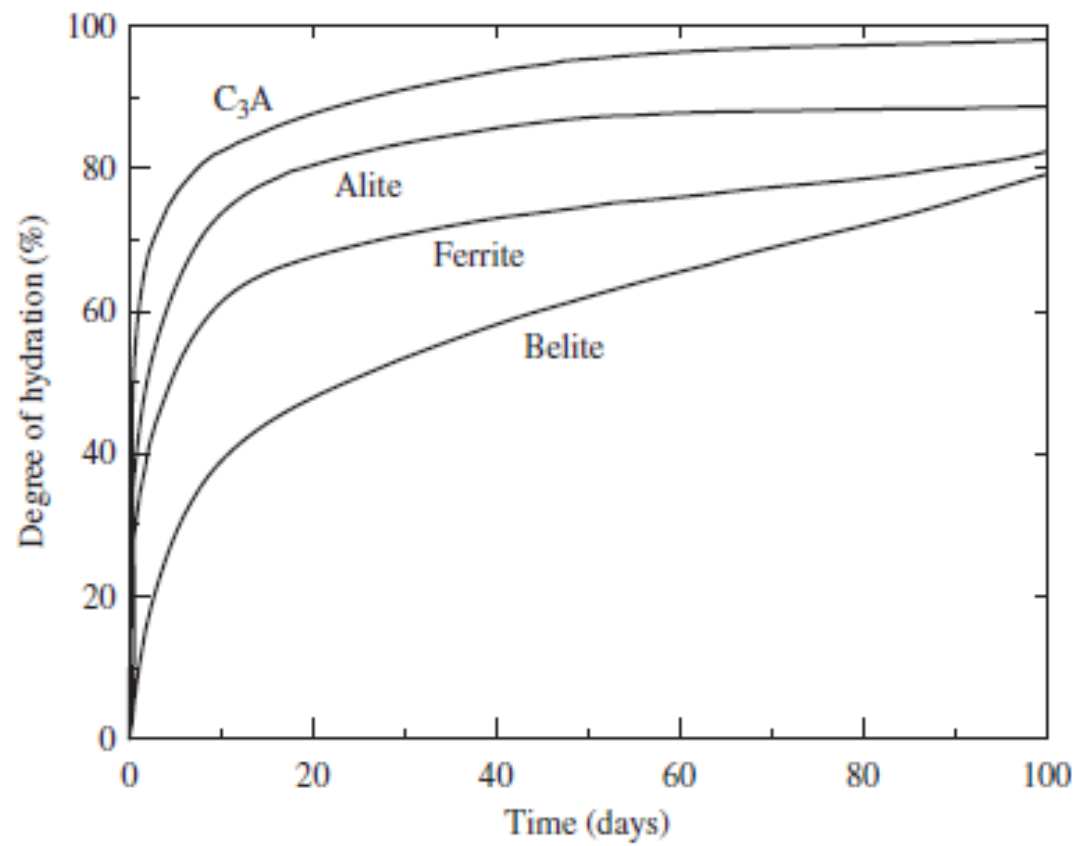


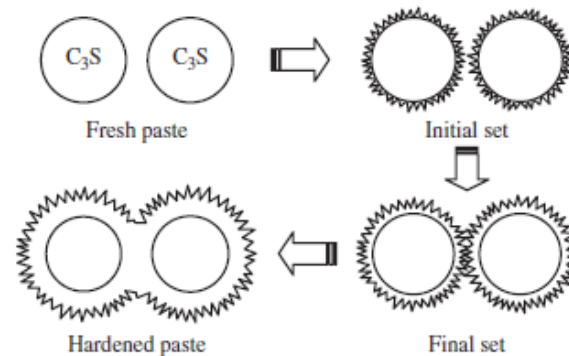
Figure 2-11 Hydration process of primary constituents of Portland cement

**Table 2-6** Kinetics of reaction, chemical processes, and relevance to concrete of the different reaction stages of cement

<b>Reaction Stage</b>	<b>Kinetics of Reaction</b>	<b>Chemical Processes</b>	<b>Relevance to Concrete</b>
1. Initial hydrolysis	Chemical control; rapid	Initial hydrolysis; dissolution of ions	n/a
2. Induction period	Nucleation control; slow	Continued dissolution of ions	Determines initial set
3. Acceleration	Chemical control; rapid	Initial formation of hydration products	Determines final set and rate of initial hardening
4. Deceleration	Chemical and diffusion control; slow	Continued formation of hydration products	Determines rate of early strength gain
5. Steady state	Diffusion control; slow	Slow formation of hydration products	Determines rate of later strength gain

#### 2.2.2.4 New understanding of the dynamics of cement hydration

Cement hydration is a complex physical–chemical process. During the process, a cement–water mixture is changed from a fluid state to a porous solid state. An adequate understanding of the mechanism of cement hydration is necessary for a full appreciation of cement concrete properties.



**Figure 2-14** Setting of fresh cement paste

The cement hydration process was traditionally studied using the calorimetric method. The hydration stages were identified by heat liberation measurement and the hydration mechanism was explained based on heat evolution. Some limitations (Gartner et al., 2002) were pointed out, such as that the liberated heat content was simply proportional neither to the degree of cement hydration nor to the development of the physical properties. This method provides only an approximation of the understanding of cement hydration and leaves space for cement scientists and engineers to explore more accurate ways.

Chemically, cement hydration involves ion dissolution and the formation of new chemical compounds. Physically, cement hydration involves microstructure formation and a porosity decrease process. When water is added into cement, the soluble ions in the cement dissolve into water. The ions in the pore solution are conductive and can form an electrical current under a certain electrical field. The conductivity of a cement mix depends mainly on the concentration of the ion solution and microstructure, especially the porosity and pore connectivity of the cement paste. Therefore, the electrical conductivity or resistivity of a cement mixture can be used to

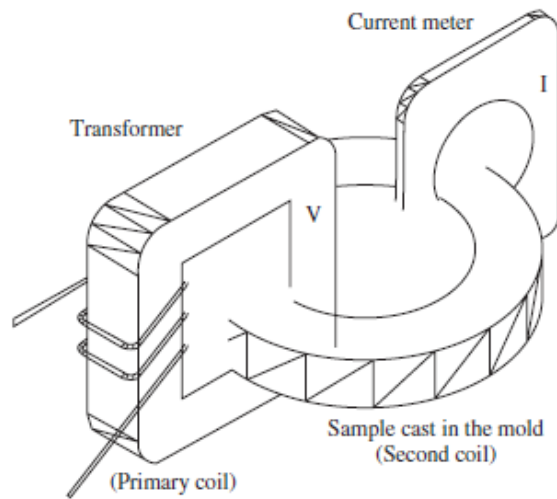
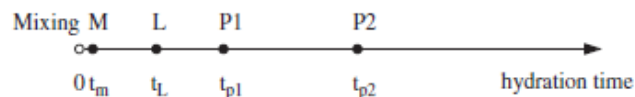
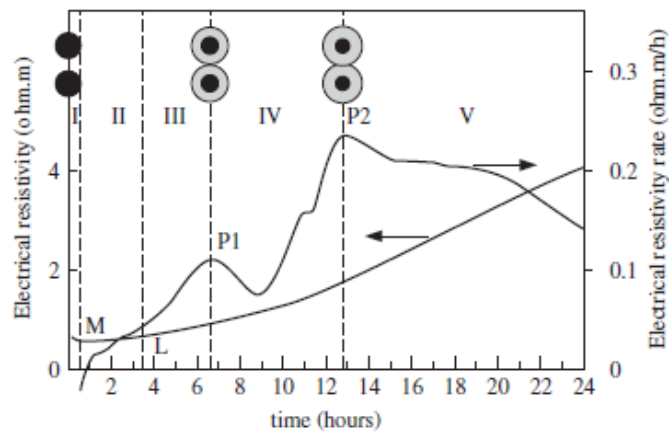
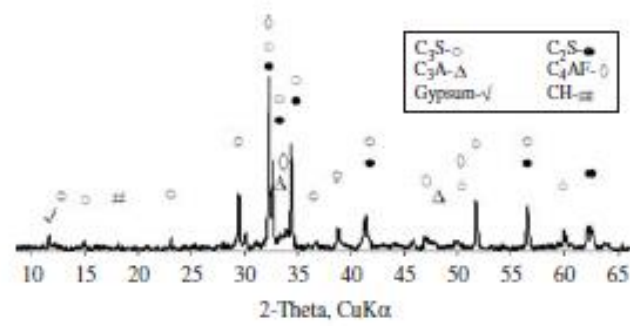
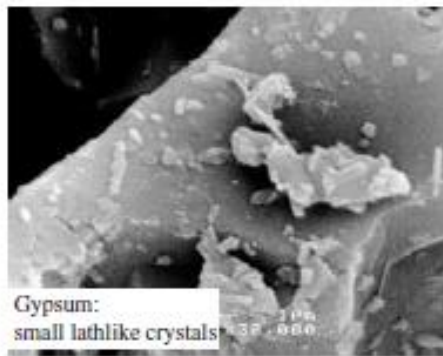


Figure 2-15 Electrical resistivity measurement setup

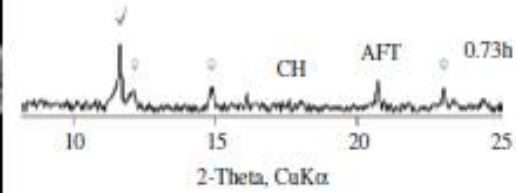
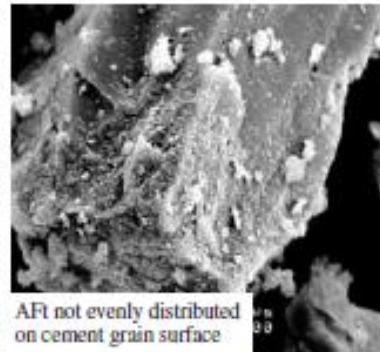
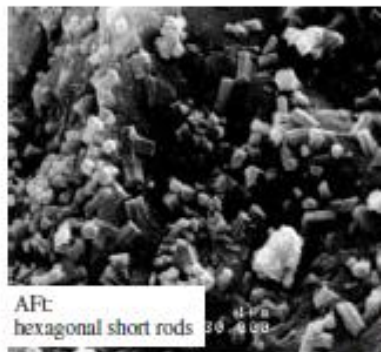


Electrical resistivity response				Setting time (ASTM C191)	
$t_m$	$t_L$	$t_{p1}$	$t_{p2}$	initial $t_{ini}$	final $t_{fin}$
0.73h	3.5h	6.7h	12.8h	3.75h	6.28h

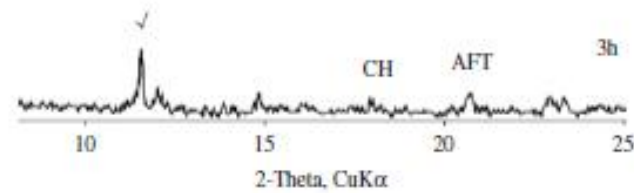
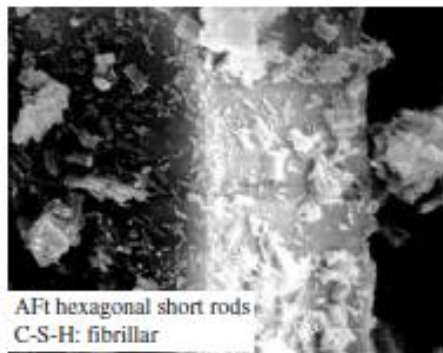




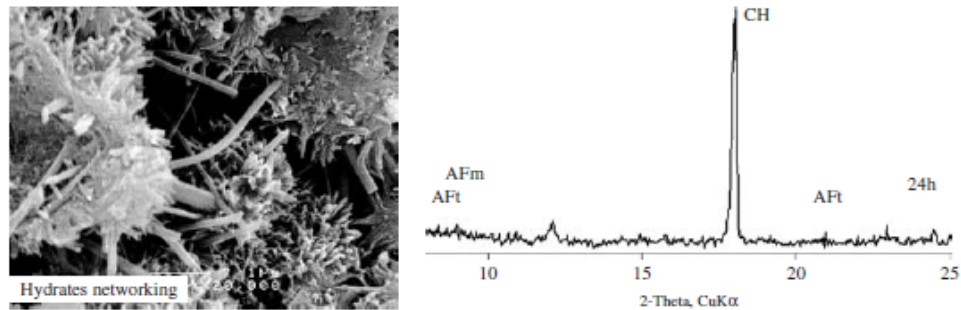
(a)  $t = 0$ , anhydrous cement



(b)  $t = 0.73h$  (at point M),  $C_3A$  rapid reaction



(c)  $t = 3h$  (close to point L)



(f) t = 24h

Figure 2-17 (continued)

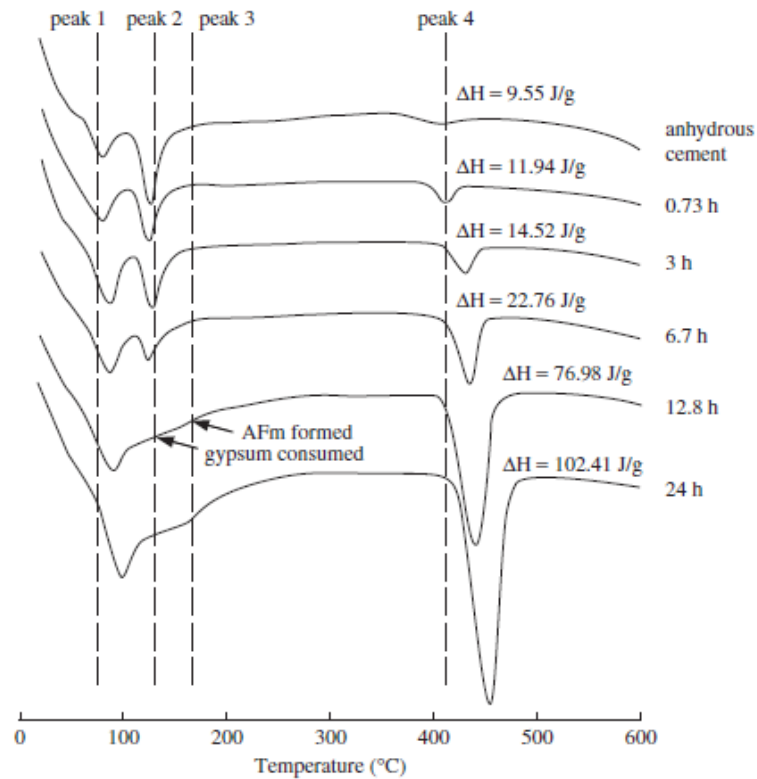
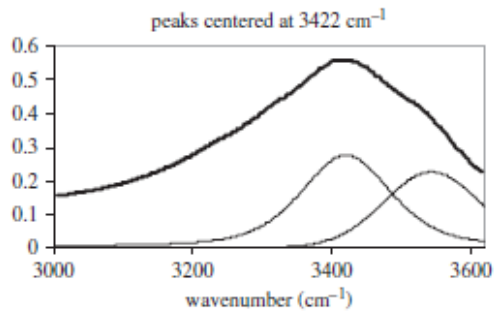
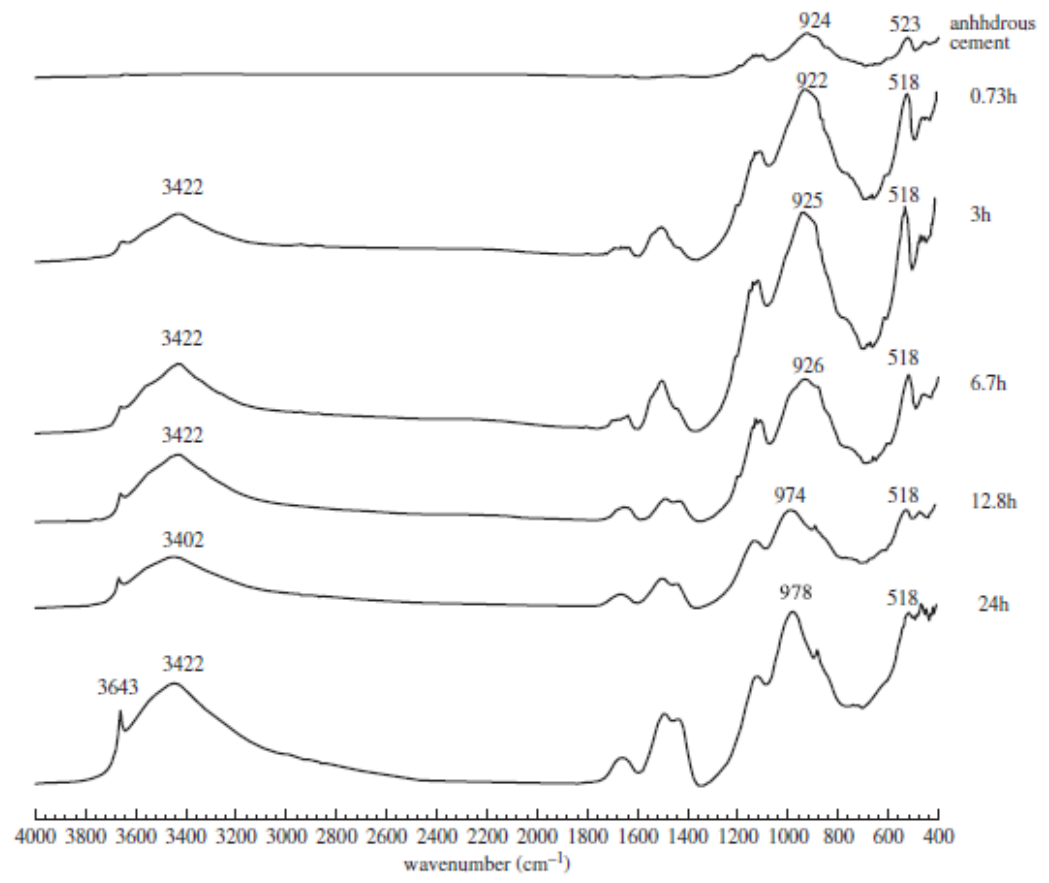
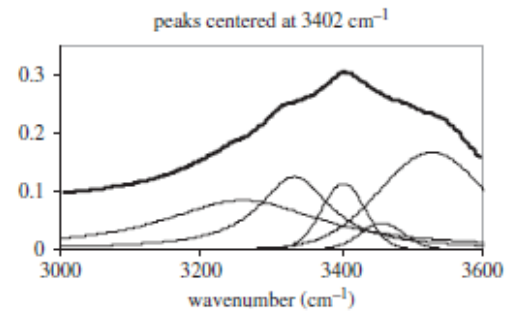


Figure 2-18 DTA results of cement and hydrated pastes at different ages



A - 6.7h

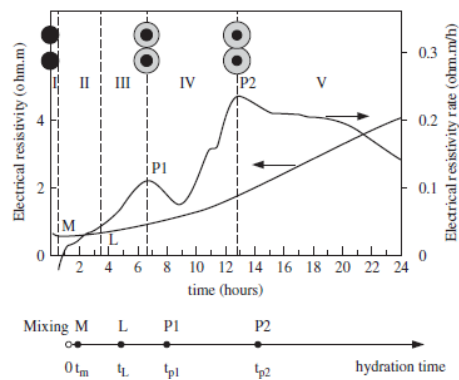


B - 12.8h

**Figure 2-19** FTIR spectra of anhydrous cement and hydrated samples at different ages

**Table 2-7** New understanding of the stages of hydration process

Hydration Stage	Kinetics of Hydration	Main Chemical Phenomena	Chemical Reaction
I. Dissolution (mixing to <i>M</i> )	Ion dissolution dominating	Initial rapid chemical reaction of $C_3A$	$C_3A + 3(C\bar{S}H_2) + 26H \rightarrow C_6A\bar{S}_3H_{32}$
II. Dynamic balance ( <i>M</i> to <i>L</i> )	A competition process of dissolution and precipitation	CH nucleation	$Ca^{2+} + OH^- \rightarrow Ca(OH)_2$
III. Setting ( <i>L</i> to <i>P1</i> )	The formation of hydration product C-S-H dominating	Chemical reaction control of $C_3S$	$C_3S + 11H \rightarrow C_3S_2H_8 + 3CH$
IV. Hardening ( <i>P1</i> to <i>P2</i> )	Continuous formation of hydration products	$C_3S$ hydration; phase transfer from Aft to AFm	$C_3S + 11H \rightarrow C_3S_2H_8 + 3CH$ $2C_2S + 9H \rightarrow C_3S_2H_8 + CH$ $C_6A\bar{S}_3H_{32} \rightarrow C_4A\bar{S}H_{12} + 2CaSO_4$ $C_6A\bar{S}_3H_{32} + 2C_3A + 4H \rightarrow 3C_4A\bar{S}H_{12}$
V. Hardening deceleration ( <i>P2</i> onward)	Chemical reaction slows down; diffusion control	The second reaction of $C_3A$ , $C_3S$ and other components	$C_3A + 3(C\bar{S}H_2) + 26H \rightarrow C_6A\bar{S}_3H_{32}$ $C_3S + 11H \rightarrow C_3S_2H_8 + 3CH$ $2C_2S + 9H \rightarrow C_3S_2H_8 + CH$



### 2.2.2.7 Basic tests of Portland cement

Portland cement concrete is the most widely used material in the world. The quality of Portland cement plays an important role in assuring the quality of construction and hence requires strict quality control. In this section, the basic tests for checking the quality of Portland cement are introduced.

(a) *Fineness (= surface area/weight)*: The fineness of Portland cement is an important quality index. It represents the average size of the cement grains. The fineness controls the rate and completeness of hydration due to the exposure surface of cement particles to the water. The finer the cement particles, the more rapid the reaction, the higher the rate of heat evolution, and the higher the early strength. However, finer cement particles can lead to high hydration heat, high possibility of early age cracking, and possible reduced durability. The fineness of Portland cement can be measured by different methods. One is the Blaine air permeation method defined in ASTM C204. In this method, cement particles are placed on a porous bed and then a given volume of fluid (air) is passed through the bed at a steady diminishing rate. After all the air is passed, the time ( $t$ ) for the process is recorded. The specific surface of the cement can be calculated using

$$S = K\sqrt{t} \quad (2-34)$$

where  $K$  is a constant. In practice,  $S$  (or  $K$ ) can be determined by comparing the sample to the known surface area issued by the U.S. National Institute of Standards and Technology. Examples of surface measurement are the surface area and pore size analyzer, which utilizes the adsorption of nitrogen on the particle surface. The ultimate sensitivity of the equipment is sufficient to detect less than  $0.001 \text{ cm}^3$  of desorbed nitrogen from 30%  $\text{N}_2/\text{He}$  mixture. Such equipment is shown in Figure 2-22.

Cementitious Binders



Figure 2-22 BET surface area analyzer



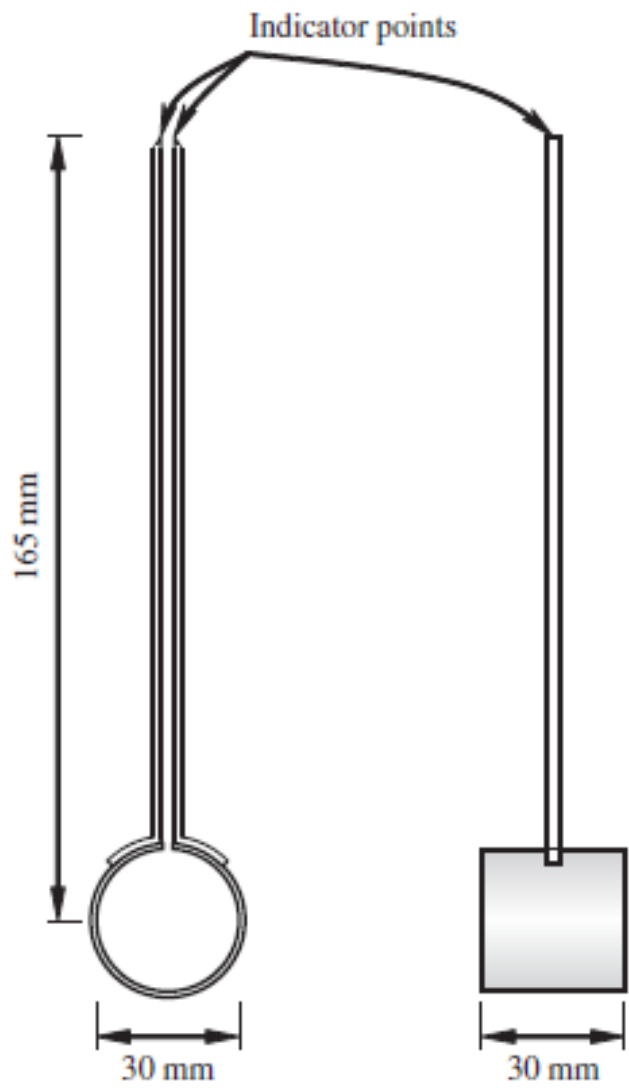
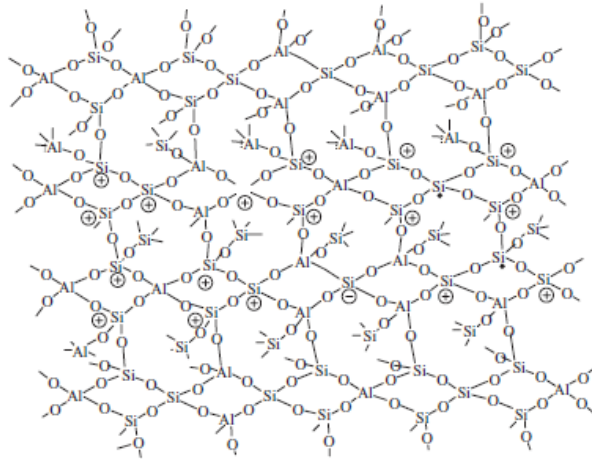


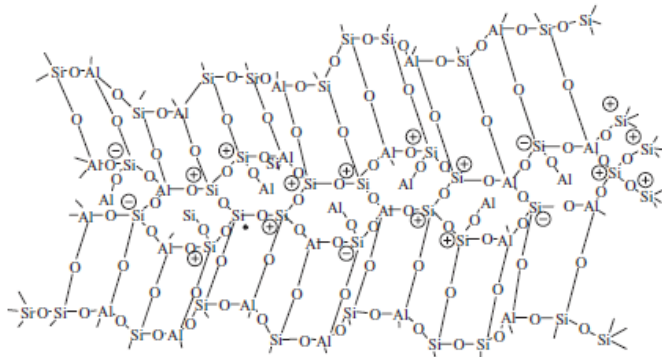
Figure 2-24 Le Chatelier test apparatus

## Read 2.2.3.2 Development of geopolymers

(a) Statistical structure model of K-PS geopolymer: the Si ions with a symbol of  $\oplus$  corresponding for  $\text{Si}^4(2\text{Al})$ ,  $\ominus$  for  $\text{Si}^4(4\text{Al})$ ,  $\bullet$  for  $\text{Si}^4(4\text{Si})$



(b) Statistical structure model of K-PSDS geopolymer



(c) Statistical structure model of K-PSS geopolymer

Figure 2-26 Statistical structure models of K-PSS geopolymer

## 2.3 Admixtures

**Table 2-10** Beneficial effects of different kinds of admixtures on concrete properties

<b>Concrete Property</b>	<b>Admixture Type</b>	<b>Category of Admixture</b>
<b>Workability</b>	Water reducers	Chemical
	Air-entraining agents	Air entraining
	Inert mineral powder	Mineral
	Pozzolans	Mineral
	Polymer latexes	Miscellaneous
<b>Set control</b>	Set accelerators	Chemical
	Set retarders	Chemical
<b>Strength</b>	Pozzolans	Mineral
	Polymer latexes	Miscellaneous
<b>Durability</b>	Air-entraining agents	Air entraining
	Pozzolans	Mineral
	Water reducers	Chemical
	Corrosion inhibitors	Miscellaneous
	Shrinkage reducer	Miscellaneous
<b>Special concrete</b>	Polymer latexes	Miscellaneous
	Silica fume	Mineral
	Expansive admixtures	Miscellaneous
	Color pigments	Miscellaneous
	Gas-forming admixtures	Miscellaneous

### 2.3.2.2 Shrinkage-reducing admixture

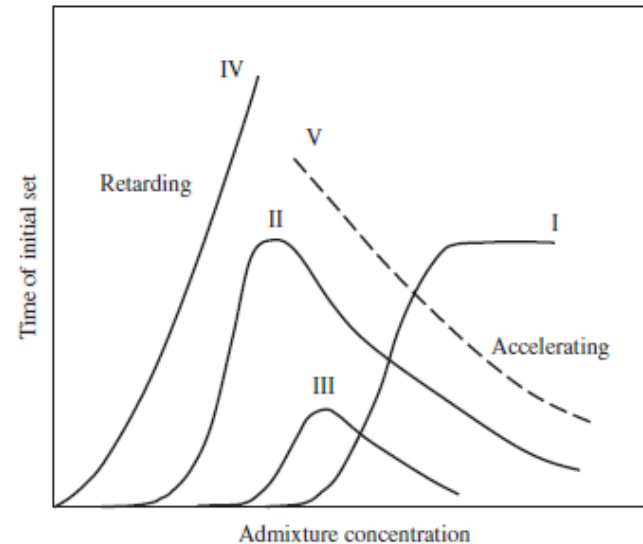
Shrinkage-reducing admixtures (SRA) provide a significant technical approach to reduce the drying shrinkage of concrete. SRA was invented in 1982, and Goto et al. (1985) applied for their patent in 1985. Subsequently, many researchers performed detailed studies on SRA. SRA is a liquid organic compound consisting of a blend of propylene glycol derivatives. Some literature has indicated that SRA can reduce long-term drying shrinkage by 50%, and there is a significant

---

improvement in restrained shrinkage performance. Even for concrete with proper curing at which the drying shrinkage would reduce to minimum, there is still a substantial reduction in drying shrinkage due to effect of SRA (Berke, et al., 1999). The main mechanism of SRA in reducing drying shrinkage of concrete is that the SRA lowers the surface tension of the pore solution and subsequently reduces the stresses in the pore solution that are directly proportional to the surface tension. With the reduction of the driving stress, the drying shrinkage can be reduced. However, in addition to reducing the surface tension, SRA also influences the dynamic process of cement hydration, as studied by He et al. (2006).

### 2.3.2.3 Setting-control admixture

Setting-control admixtures are used to either extend or shorten the plastic stage of concrete to meet the special requirements of the construction of concrete structures. If the admixture is used to extend the plastic period, it is called a retarder. If the admixture is used to shorten the plastic period, it is called an accelerator.



**Figure 2-33** Different types of setting-control admixtures

when it has a problem in traffic or operation. Figure 2-33 demonstrates the different types of setting control admixtures: monotonic retarding admixture, monotonic accelerating admixture, and dual-role setting control admixture. It can be seen from the figure that the function of a dual-role setting admixture largely depends on its concentration.

- (b) *Applications*: The major applications for setting-control admixtures are as follows.
- (i) *Retarding admixtures*: Mainly used (1) to offset fast setting caused by ambient temperature, particularly in hot weather; (2) as a setting control of large structural units to keep concrete workable throughout the entire placing period; (3) to meet the requirement of long transportation time from the concrete plant to the construction site. For example, for the construction of a pier for a bridge built up in the ocean, the concrete has to be transported by ferry from land to the site. In this case, 5 to 6 h or even longer may be required.
  - (ii) *Accelerators*: Accelerators have been widely used in civil engineering. The applications include plugging leaks in swimming pools, water tanks, and pipelines; emergency repairs for highways, bridges, airport runways, and tunnels; and winter construction in cold regions. Soluble inorganic salts, such as calcium chloride, are by far the best-known and most widely used accelerators. A side effect of using chloride, however, is that it induces corrosion of the reinforcement in concrete structures.

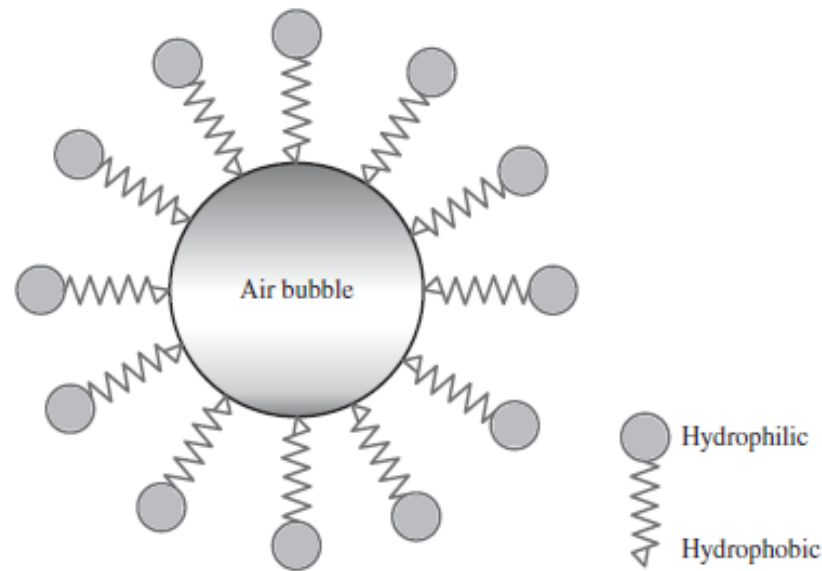


Figure 2-34 Mechanism of air entraining

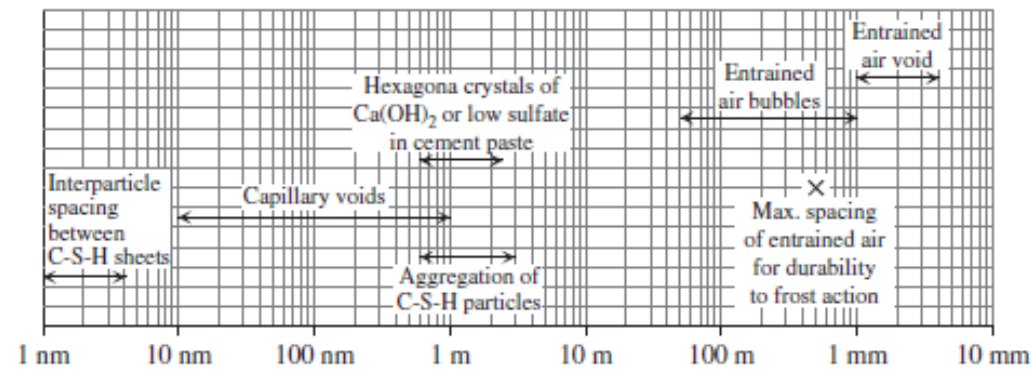


Figure 2-35 Size distribution of solids and pores in hydrated cement paste



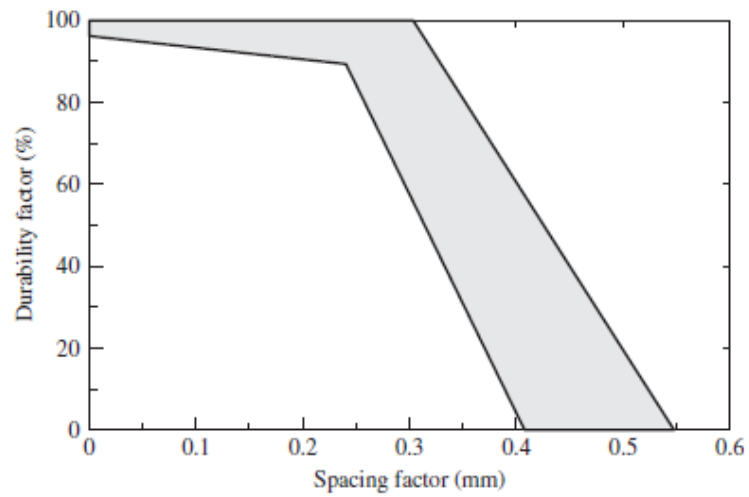


Figure 2-36 Effects of spacing factor on durability factor

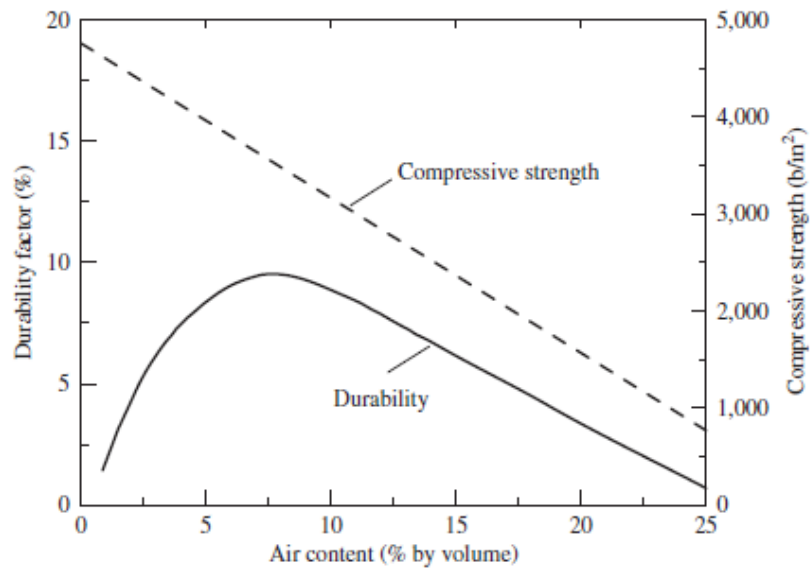


Figure 2-37 Effects of air content on durability factor and compressive strength

$$\begin{aligned}
 X &= \frac{\text{volume of gel (including gel pores)}}{\text{volume of gel} + \text{volume of capillary pores} + \text{entrained air}} \\
 &= \frac{0.68a}{0.32a + w/c + \text{entrained air}} \qquad (2-49)
 \end{aligned}$$

The percentage of the entrained air is based on the volume of concrete, and not the volume of cement paste.

Read 2.3.4 Mineral admixtures to 2.3.4.5 Benefits of using mineral admixtures in concrete

## 2.4 WATER

Water is an important ingredient of concrete, and a properly designed concrete mixture, typically with 15 to 25% water by volume, will possess the desired workability for fresh concrete and the required durability and strength for hardened concrete. The roles of water have been discussed

**Table 2-15** Benefits of using mineral admixtures in fresh concrete

Mineral Admixtures	Usual Dosage <sup>a</sup> (%)	Economic Benefits	Protecting Environment	Workability of Fresh Concrete		
				Increasing Fluidity	Increasing Cohesiveness	Decreasing Segregation
PFA or FA	10–40	✓	✓	✓	✓	✓
BFS or slag	20–60	✓	✓	✓	✓	✓
Silica fume	5–15		✓		✓	✓
Other pozzolans	10–30	✓	✓			✓

<sup>a</sup>Replacement of Portland cement

**Table 2-16** Benefits of using mineral admixtures in hardened concrete

Mineral Admixtures	Usual Dosage <sup>a</sup> (%)	Increasing Strengths	Decreasing Heat	Decreasing Cracking	Impermeability	Anti-chemical Attack <sup>d</sup>
PFA or FA	10–40	✓ <sup>b</sup>	✓	✓	✓	✓
BFS or slag	20–60	✓ <sup>c</sup>	✓		✓	✓
Silica fume	5–15	✓ <sup>c</sup>		✓	✓	✓
Other pozzolans	10–30	✓ <sup>b</sup>	✓	✓	✓	✓

<sup>a</sup>Replacement of Portland cement.

<sup>b</sup>Increasing strength at long term age.

<sup>c</sup>Increasing strength at early age and long term age, especially using silica fume.

<sup>d</sup>Anti-chemical attack may involve salt scaling, sulfates or seawater attack, resistance to alkali–aggregate reaction (AAR), resistance to corrosion of rebar, and so on.

earlier and are known as hydration and workability. The total amount of water in concrete and the water-to-cement ratio may be the most critical factors in the production of good-quality concrete. Too much water reduces concrete strength, while too little makes the concrete unworkable. Because concrete must be both strong and workable, a careful selection of the cement-to-water ratio and total amount of water are required when making concrete (Popovics, 1992).

#### 2.4.1 Mixing water

Water can exist in a solid form as ice, a liquid form as water, or a gaseous form as vapor. Mixing water is the free water encountered in freshly mixed concrete. It has three main functions: (1) it reacts with the cement powder, thus producing hydration products; (2) it acts as a lubricant, contributing to the workability of the fresh mixture; and (3) it secures the necessary space in the paste for the development of hydration products. The amount of water added for adequate workability is always greater than that needed for complete hydration of the cement in practice.

Read 2.4.2 Impurities in water to 2.4.3 Water for curing and washing

