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Constituents and Properties of Concrete

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40.1 Introduction

Concrete has been the most common building material for many years. It is expected to remain so in the coming decades. Much of the developed world has infrastructures built with various forms of concrete. Mass concrete dams, reinforced concrete buildings, prestressed concrete bridges, and precast concrete components are some typical examples. It is anticipated that the rest of the developing world will use these forms of construction in their future development of infrastructures.

In pre-historic times, some form of concrete using lime-based binder may have been used [Stanley, 1980], but modern concrete using Portland cement, which sets under water, dates back to mid-eighteenth century and more importantly, with the patent by Joseph Aspdin in 1824.

Traditionally, concrete is a composite consisting of the dispersed phase of aggregates (ranging from its maximum size coarse aggregates down to the fine sand particles) embedded in the matrix of cement paste. This is a Portland cement concrete with the four constituents of Portland cement, water, stone and sand. These basic components remain in current concrete but other constituents are now often added to modify its fresh and hardened properties. This has broadened the scope in the design and construction of concrete structures. It has also introduced factors that designers should recognize in order to realize the desired performance in terms of structural adequacy, constructability, and required service life. These are translated into strength, workability and durability in relation to properties of concrete. In addition, there is the need to satisfy these provisions at the most cost-effective price in practice.

The quality of concrete in a structure is determined not only by the proper selection of its constituents and their proportions, but also by appropriate techniques in the production, transportation, placing, compacting, finishing, and curing of the concrete of the actual structure, often at a job site. Although these processes have an impact on the actual quality of concrete achieved, they are not included under this chapter. Sources for such information include publications of concrete institutes in various countries, e.g., American Concrete Institute in the U.S. and the Concrete Society in the U.K.

The subject of concrete covers a very broad scope and a wealth of in-depth knowledge. This chapter is intended to provide a brief guide on the more important aspects for civil engineers rather than for concrete specialist in research or production of concrete. There are many textbooks and references besides those cited in this chapter from which more detailed information may be obtained. Some of these are listed under Further Information.

This chapter covers topics on the constituents and the properties of concrete. The engineer is concerned with both the properties of concrete in its fresh as well as its hardened state. The way fresh concrete is handled and the treatment of the hardened concrete at its early age have major influences on its as-built quality. These impact the resultant performance of the concrete structure as designed by the engineer.

Since the information provided in this chapter targets readers in English-speaking countries, it has selected information from two major practices, the American and the European (mainly British). This serves a wider range of users but also compares some common aspects of the two practices. An appreciation of the difference between the two practices is of importance in the coming years as more and more civil engineers practice on a global basis.

40.2 Constituents of Concrete

The constituents of modern concrete have increased from the basic four (Portland cement, water, stone, and sand) to include both chemical and mineral admixtures. These admixtures have been in use for decades, first in special circumstances, but have now been incorporated in more and more general applications for their technical, and at times economic benefits in either or both fresh and hardened properties of concrete.

Portland Cement

In the past, Portland cement is restricted to that used in ordinary concrete and is often called Ordinary Portland cement. There is a general movement towards grouping all types of Portland cement, included those blended with ground granulated slag or a pozzolan such as fly ash (also called pulverized fuel ash), and silica fume into cements of different sub-classes rather than special cements. This approach has been adopted in Europe (EN 197–1) but the American practice places them in two separate groups (American Society for Testing and Materials provides for Portland cement under ASTM C150 and blended cements under ASTM 595).

Raw materials for manufacturing Portland cement consist of basically calcareous and siliceous (generally argillaceous) material. The mixture is heated to a high temperature within a rotating kiln to produce a complex group of chemicals, collectively called cement clinker. Details of manufacturing process, the formation of these chemicals and their reactions with water are fully described in various textbooks (e.g., *Chemistry of Cement and Concrete*, 4th ed., Peter C. Hewlett, Ed). The name Portland originated from the similarity of Portland cement concrete to a well-known building stone in England found in the area called Portland. Portland cement is distinct from the ancient cement. It is termed hydraulic cement for its ability to set and harden under water.

Briefly, the chemicals present in clinker are nominally the four major potential compounds and several minor compounds (in small percentages, but not necessary of minor importance). The four major potential compounds are nominally (but actually impure varieties) termed as tricalcium silicate ($3CaO.SiO_2$), dicalcium silicate ($2CaO.SiO_2$), tricalcium aluminate ($3CaO.\ Al_2O_3$), and tetracalcium aluminoferrite ($4CaO.\ Al_2O_3.Fe_2O_3$). Cement chemists have abbreviated these chemical compounds to shorthand notations

TABLE 40.1 Listing of Cement Types (ASTM C150, ASTM 595 and EN 197–1)

European Designation		ASTM Designation	
Type	Description	Type	Description
I	Portland	I to V	Portland
II/A-S	Portland-slag	I(SM)	Slag-modified Portland
II/B-S			
II/A-P(Q)	Portland-pozzolana	I(PM)	Pozzolan-modified Portland
II/B-P(Q)			
II/A-D	Portland-silica fume	—	—
III/A	Blastfurnace	IS	Portland blast-furnace slag
III/B			
III/C			
IV/A	Pozzolanic	IP	Portland-pozzolan
IV/B			
V/A	Composite	—	—
V/B			

using C ≡ CaO; S ≡ SiO_2; A ≡ Al_2O_3; and F ≡ Fe_2O_3. Historically, because of their impure state, the compound C_3S is referred to as "Alite;" C_2S as "Belite;" C_3A as the "aluminate" phase and C_4AF as the "ferrite (or iron)" phase. In practice, two cements of the same potential compound composition may not necessarily behave in the same manner during the fresh and hardened states of concrete. The minor compounds of importance include the alkalis (sodium oxide and potassium oxide) and the amount of sulfate (mainly from added gypsum interground with clinker to prevent the violent reaction of tricalcium aluminate with the mixing water — flash set). The significance of these and other compounds in concrete is considered under the chapter on durability.

Cement may be marketed in bags (or sacks) but not necessarily of the same mass in different countries, (e.g., in U.S., a sack is of 94 lb, about 42 kg, but in U.K., a bag is of 50 kg). For ready-mixed concrete production, bulk delivery by cement tankers and pumped into plant silos is the most common practice. Hence, to avoid possible confusion, it is best to specify the amount of cement on the basis of mass, and not in number of bags, per unit volume.

Specifications for chemical and physical properties of cement are similar in most parts of the world. The approximate (not exactly equivalent) corresponding types of cement based on ASTM C150 and ASTM C595 to those based on EN 197–1 are shown in Table 40.1. For more information on the differences between the ASTM and EN standards, reference should be made to the specific standards. These include some differences in the percentages of components as well as physical and chemical properties of the cements and the details in the methods of determining these properties. Harmonizing of standards will be achieved through the development of ISO standards, a process that may take some time to be realized. The comparison provided is intended for guidance only.

The typical compositions in terms of Portland cement clinker and the other cementitious materials are shown in Tables 40.2(a) and (b). These cements are often called blended cements. The five types of Portland cement commonly used in the U.S. and their corresponding types in British standards are shown in Table 40.3.

Under ASTM, Type IA, IIA and IIIA in Table 40.2 are the corresponding cements with air entrainment capabilities. The role of entrained air is for resistance against freezing and thawing of concrete in cold climate. It is more common for air entrainment to be induced by a chemical admixture added at the time of mixing than by means of blended cements in shown in Table 40.2. By varying the dosage of air entraining agent added, the required air content in concrete is easily adjusted.

Among the five types of Portland cement, Type I is for general use with no special requirements. Type II is modified to provide moderate heat of hydration and moderate sulfate resistance. Type III has high early strength development, but currently most Type I cements have similar performance as Type III. Type IV has much lower heat of hydration but is not readily available, unless specially order where early

TABLE 40.2(a) Cement Types and Composition (% by mass) (European Designations)

Type	Clinker (K)	Ground Granulated Blastfurnace Slag (S)	Silica fume (D)	Pozzolona		Fly ash	
				Natural (P)	Industrial (Q)	Siliceous (V)	Calcareous (W)
I	95–100	—	—	—	—	—	—
II/A-S	80–94	6–20	—	—	—	—	—
II/B-S	65–79	21–35	—	—	—	—	—
II/A-P	80–94	—	—	6–20	—	—	—
II/B-P	65–79	—	—	21–35	—	—	—
II/A-Q	80–94	—	—	—	6–20	—	—
II/B-Q	65–79	—	—	—	21–35	—	—
II/A-V	80–94	—	—	—	—	6–20	—
II/B-V	65–79	—	—	—	—	21–35	—
II/A-W	80–94	—	—	—	—	—	6–20
II/B-W	65–79	—	—	—	—	—	21–35
II/A-D	90–94	—	6–10	—	—	—	—
II/A-M	80–94	—	6–20*				
II/B-M	65–79	—	21–35*				
III/A	35–64	36–65	—	—	—	—	—
III/B	20–34	66–80	—	—	—	—	—
III/C	5–19	81–95	—	—	—	—	—
IV/A	65–89	—	11–35				
IV/B	45–64	—	36–55				
V/A	40–64	18–30	—	18–30			—
V/B	20–38	31–50	—	31–50			—

Including the use of burnt shale or limestone.

TABLE 40.2(b) Cement Types and Composition (% by mass) (ASTM Designations)

Type	Clinker and Calcium Sulfate	Slag	Pozzolan
I, IA,II, IIA,III,IIIA,IV,V	100	0	0
I(SM)	>75	<25	0
I(PM)	>85	0	<15
IS	30–75	25–70	0
IP	60–85	0	15–40

TABLE 40.3 ASTM and BS Designations

ASTM Designations	BS Designations
Type I	Ordinary Portland
Type II	—
Type III	Rapid-Hardening Portland
Type IV	Low Heat Portland
Type V	Sulfate-Resisting Portland

thermal stress is a critical factor. Type V has much lower C_3A content for better sulfate resistance. Currently, blended cements are more readily available to meet these special requirements. Details of such applications are provided in the section on blended cement and mineral admixtures.

In the specifications for Portland cements (e.g., ASTM C 150) the requirements in chemical composition are for the purpose of cement manufacturing. Civil engineers are more interested in the physical requirements in terms of fineness, strength potential and setting times. Fineness is an indication of the average size of cement grains after grinding. It is expressed in surface area per unit mass, generally in the range of 300 to 400 m^2/kg. Fly ash is generally similar in fineness as ordinary Portland cement. Blast furnace slag may be ground finer or coarse than ordinary Portland cement. Silica fume is of very high fineness, often in the order of 20,000 m^2/kg. The higher fineness and better strength potential per unit mass of modern cements provide good early strength development and higher strength for the same water/cement ratio.

Strength potential of a cement is assessed by making mortar specimens with standard sand at a prescribed water/cement ratio and tested after curing under water at specified ages. ASTM and European standards specified different methods of making and testing of the mortar specimens. Each has it own specified grading for the standard sand, water/cement ratio, method of preparing test specimens and test methods. The specified 28-day strength of each type of cement depends on its composition. However, under EN 197–1, three different standard strength classes are specified with 28-day compressive strength of 32.5 MPa, 42.5 Mpa, and 52.5 MPa. Within each class, one with ordinary early strength (indicated by N) and another with higher early strength (indicated by R) are included. In relation to the specification requirements, strengths of modern cements are often found to be much higher than the specified values. To ensure uniformity for quality control in concrete production, some specifications have both a lower and upper limit for each strength class (e.g., EN 197–1 with a range of 20 MPa for 28-day strength).

The setting time of cement is determined using a paste of a prescribed initial stiffness. ASTM and European standards differ in the method of selecting the water/cement ratio for this stage. The subsequent testing using the "Vicat" needles is common to both. The difference between the values determined by these two approaches is not known, although the requirements on setting times are similar in cement specifications. The setting of cement as a constituent of concrete may be modified by the addition of chemical admixtures with either accelerating or retarding effects. Further information on this aspect is provided in the section of chemical admixtures below.

It is important to distinguish between the setting times determined for cement paste and those determined from wet-sieve mortar fraction of a concrete. The testing of both cement paste and for the mortar fraction of concrete is based on the principle of penetration resistance and for assessing the rate of stiffening of the respective composition, but their intended applications are very different. Cement paste testing is for production of cement; whereas in the case of concrete, it is associated with determining the change in stiffening rate of concrete due to the addition of a chemical admixture to control setting. To avoid confusion between the two cases, it may be useful to retain the term setting for cement and to refer to stiffening in the case of concrete.

Another physical property of Portland cement of interest to civil engineers is its density or specific gravity. This is determined by specified methods and does not vary much between batches from the same source of manufacture. Typical values for specific gravity of Portland cement lie within the range of 3.1 to 3.2. However, other cementitious materials, such as fly ash, slag or silica fume, generally have lower specific gravity values, in the range of 2.0 to 3.0. When blended cements are used in place of ordinary Portland cement, some minor adjustments are needed in computing the mass per cubic meter in the specified constituent proportions.

Supplementary Cementitious Materials

Supplementary cementitious materials commonly used in blended cement are fly ash, granulated blast furnace slag and silica fume besides natural pozzolans. They are also collectively called mineral admixtures, as distinct from chemical admixture (see later sections). Fly ash, also known as pulverized fuel ash (pfa), is fine particles in the flue gases after the burning of coal in power generation. There are spherical in shape and extracted by specially designed electrostatic precipitators, whereas the larger particles, which are not suitable for use as cement replacement materials, fall to the bottom of the furnace. The fineness of fly ash is of the same order as Portland cement (300 to 400 m^2/kg). Silica fume is also the fine particles collected the waste gases but is from the ferrosilicon industry. Due to its extreme fineness, (15,000 to 20,000 m^2/kg), it is densified (bulk density ranging from 130 to 430 kg/m^3) for ease of handling, hence it is often called condensed silica fume (csf). Ground granulated blastfurnace slag is a by-product of the

TABLE 40.4 Typical Composition of Cementing Materials

% by Mass	Portland Cement	Blast Furnace Slag	Low-lime Fly Ash	High-lime Fly Ash	Silica Fume
CaO	63	40	1	20	0
SiO_2	22	35	50	35	90
Al_2O_3	6	8	25	20	2
Fe_2O_3	3	0	10	5	2

production of iron in a blastfurnace. The molten slag from the furnace is rapidly cooled by water into glassy granulate form. The granulated slag is ground to fineness similar to that of normal cement, or finer for special applications. The grinding may be together with the cement clinker (intergrinding) or by separate grinding. Because slag is harder than clinker, intergrinding results in the clinker to be finer and that of slag coarser than the combined fineness. With separate grinding, both the slag and clinker may be ground to the same fineness. At times, slag is ground to a higher fineness to promote its rate of reactivity. The mineral admixtures may be blended for selected proportions in the plant as blended cement or added as an additional ingredient during batching of the materials into a mixer during concrete production. For the same combination of materials, either process produces similar resultant properties in both fresh and hardened concrete. Further details on the production of these mineral admixtures may be obtained from the publications listed under Further Information.

The specific gravity of fly ash, silica fume or slag is lower than that of Portland cement. Fly ash is normally in the range of 2.2 to 2.8 (ACI Committee 232), silica fume in the range of 2.2 to 2.3 (ACI Committee 234) and slag in the range of 2.9 to 3.0 (?) compared to 3.1 to 3.2 for Portland cement. Thus for the same mass of cementitious materials in a concrete mixture, the volume of these materials is slightly higher than for Portland cement.

The compounds found in mineral admixtures are similar to those in Portland cement but of different quantities. A comparison of typical chemical composition of the various cementing materials with Portland cement (Philleo, 1989) is shown in Table 40.4.

The hydration of the silicates in Portland cement produces calcium silicate hydrates and calcium hydroxide. When the concentration of calcium hydroxide is adequate to activate the silicates in the mineral admixtures, further calcium silicates are formed. This is known as pozzolanic reaction. In the case of blast furnace slag and high-lime fly ash there is sufficient calcium oxide in them for some degree of hydration to occur with the silicates. However, the strength developed by this self-activation process is generally too small for structural applications.

Calcium Aluminate Cement

Besides blended cements, there is another hydraulic cement used in construction. This is calcium aluminate cement, CAC (also called high alumina cement, HAC). The two major applications of CAC are as a refractory material and as a high resistance material for sewer pipe lining. In 1997, the Concrete Society reported on the study to re-assess the use of calcium aluminate cement in construction. Another recent source of information on the topic is the Proceedings of the International Conference on Calcium Aluminate Cements in 2001. Its resistance against biogenic sulfuric acid corrosion makes it most useful in sewer applications.

40.3 Aggregates

In general, aggregates in concrete have been grouped according to their sizes into fine and coarse aggregates. The separation is based on materials passing or retained on the nominally 5 mm (ASTM No. 4) sieve. It is common to refer to fine aggregate as sand and coarse aggregate as stone. Traditionally, aggregates are derived from natural sources in the form of river gravel or crushed rocks and river sand.

Fine aggregate produced by crushing rocks to sand sizes is referred as manufactured sand. Aggregates derived from special synthetic processes or as a by-product of other processes are also available. The use of such aggregates usually calls for special considerations not covered in this chapter. Similarly, lightweight or heavyweight aggregates for special applications are also not included. Some of these are listed in the "Further Information" section. This chapter considers only the ones classified as normal weight aggregates.

In most concrete mixtures, volume fraction of aggregates occupies more than double than that of the cement paste matrix. Hence, the physical properties of concrete are dependent on the corresponding properties of the aggregates. Civil engineers are more concerned with the physical, rather than the chemical or mineralogical, properties of aggregates. The only situation when mineralogical composition is of importance is treated under the chapter on durability in terms of alkali-aggregate reactions.

Although a full range of physical properties may be obtained, those of major interest to a civil engineer include specific gravity (or density), porosity and particle size distribution (or grading). Properties such as shape and surface texture of aggregates are usually stated in descriptive terms. They are not easily quantified and the semi-empirical test methods provide numerical values (e.g., elongation or flakiness index) that are limited to comparing different sources of supply in relative terms only. Others relate to thermal properties, e.g., specific heat and thermal coefficient of expansion are useful in specific applications such as mass concrete dams or thick sections. These topics are found in specialist literature. Some of these are listed in the "Further Information" section.

Each piece of aggregate may have a small amount of internal pores. These pores may be filled with water (saturated condition), partially or completely dry (oven-dry). Hence, bulk unit weight of aggregates may be expressed in the completely dry state (bulk specific gravity) or in the saturated state (bulk specific gravity, saturated-surface-dry basis). Specific test methods (e.g., ASTM C 127) are used to determine such values. They form the two extreme states of moisture in a particle of aggregate. In practice, the actual amount of moisture for aggregates stored under protection from the weather may be in between these two extremes.

When the pores of each piece of aggregate are filled with water, but without any water adhering on their surfaces, it is in its "saturated-surface-dry" (SSD) condition. The amount of water absorbed into the voids per unit mass of oven-dry aggregates is called the "absorption."

When the aggregates are placed together in bulk, there are voids between the particles. The packing of aggregates depends on their sizes and the amount of each size as well as the shape of the particles. The weight of a packing of aggregates in its dry state is called its dry-rodded unit weight when determined by ASTM C29 Method. It is an indication of the amount of cement paste needed to fill such voids. For a stockpile of sand, the particles are able to retain a significant amount of water within the voids. Thus the sand is above its saturated-surface-dry state. This additional amount of water held within the voids forms part of the water selected in mixture design. Together with the specific gravities of aggregates, they are factors of importance in mixture design.

The particle size distribution of an aggregate (often expressed as a percentage by mass of the total mass of aggregate) is called its grading. The separation into various sizes is based on a standard series of sieves of prescribed openings. In general, the successive sieve size has square openings with their sides based on the ratio of two, i.e., four times in the area of the openings.

The gradings of natural fine aggregates or sand depend on the source. The maximum size of particles is limited to those passing the 5 mm (4.75 mm in ASTM No. 4) sieve. Other than river gravels, coarse aggregates are produced in quarries by crushing of rocks. Standards usually provide overall limits on the grading of aggregates. The ideal grading is one that results in the least amount of voids when the total aggregates, both coarse and fine, are combined. The voids in the combined system have to be filled with cement paste in compacted concrete. Thus for a given set of requirements, such a combined grading leads to the most economic concrete as the cost of cement is much higher than that of aggregates. However, the best grading depends also on the shape of the particles. There is no standard approach to defining shape of aggregates although simple descriptive terms such as rounded, cubical, flaky or elongated are at times used.

The limits for fine and coarse aggregates (ASTM C33, BS 882) are shown in Table 40.5(a) and Table 40.5(b), respectively.

TABLE 40.5(a) Grading Limits of Fine Aggregate

Sieve Size		Percentage Passing		Cumulative Percentage Retained	
ASTM C33	BS 882	ASTM C33	BS 882	ASTM C33	BS 882
9.5 mm (3/8 in)	10.0 mm	100	100	0	0
4.75 mm (No. 4)	5.0 mm	95–100	89–100	5–0	11–0
2.36 mm (No. 8)	2.36 mm	80–100	60–100	20–0	40–0
1.18 mm (No. 16)	1.18 mm	50–85	30–100	50–15	70–0
600 µm (No. 30)	600 µm	25–60	15–100	75–40	85–0
300 µm (No. 50)	300 µm	10–30	5–70	90–70	95–30
150 µm (No. 100)	150 µm	2–10	0–15	98–90	100–85
			Total	338–215	401–115
			Fineness modulus	3.38–2.15	4.01–1.15

TABLE 40.5(b) Grading Limits of Coarse Aggregates

ASTM C33			BS 882		
Maximum Size	19.0 mm	12.5 mm	Maximum Size	20.0	14.0
Sieve Size	Percentage Passing		Sieve Size	Percentage Passing	
25.0 mm	100	—	37.5 mm	100	—
19.0 mm	90–100	100	20.0 mm	90–100	100
12.5 mm	—	90–100	14.0 mm	40–80	90–100
9.5 mm	20–55	40–70	10.0 mm	30–60	50–85
4.75 mm	0–10	0–15	5.0 mm	0–10	0–10
2.36 mm	0–5	0–5	2.36 mm	—	—

The maximum sizes of coarse aggregates commonly used are illustrated in Table 40.5(b). Other sizes up to 40 mm are used in mass concrete or concrete pavement.

Fineness modulus (FM) is the sum of the cumulative percentages retained on sieves (i.e., if each were the only sieve) starting from the size of 150 µm to the maximum size and divided by 100. It is often applied to fine aggregate as an indication of its fineness. It is to be noted that a fine grading has a lower value of fineness modulus. As shown in Table 40.5(a), for the upper (finest) and lower (coarsest) limits of fine aggregate, FM is 1.15 and 3.38, respectively. The same value of fineness modulus may be produced by two or more different gradings. However, a change in FM of 0.2 in fine aggregates may lead to a significant change is water demand for the same workability of a concrete mixture.

There are differences between the limits for ASTM and BS standards. In general, BS permits a wider range for grading of both fine and coarse aggregates. A grading in which one or more intermediate size fractions are missing is termed "gap graded." This is in contrast to the continuous grading commonly used. It has been found that satisfactory concrete mixtures can be obtained even for gradings that do not fall within the limits for one or more of the sieve sizes. A higher cement content and hence a higher cost is often incurred. However, this has to be compared to the cost of obtaining one of better grading from an alternate source.

Recycling of old concrete as aggregates has been much researched and some times applied. Information on such aggregates and their applications may be obtained from publications listed in the "Further Information" section.

40.4 Water

Water is needed for the hydration of cement but not all is used up for this purpose. Part of this added water is to provide workability during mixing and for placing. This latter usage can be reduced by the introduction of chemical admixtures, e.g., plasticisers. Where possible, potable water is used. Other sources may contain impurities that introduce undesirable effects on properties of fresh and hardened concrete. A good list is given in the PCA Manual (Kosmatka and Panarese, 1988). Neville (1995) provides additional information on quality of mixing water. ASTM C94 and BS 3148 both provide guidance on acceptance criteria for water of questionable quality in terms of strength and setting time. However, the two sets of recommendations have slightly different limits. Additional, optional chemical limits using wash water from mixer washout operations are also stated in ASTM C94. The use of recycled materials is often promoted for sustainable development. Seawater should not be used as mixing water for reinforced concrete due to the presence of chloride and its effect on corrosion of steel reinforcement.

40.5 Chemical Admixtures

Unlike mineral admixtures, which may be introduced as blended cements, chemical admixtures are typically added during the mixing process of concrete production. Chemical admixtures are manufactured to specified standards, e.g., air-entraining admixtures to ASTM C260 and other types to ASTM C494. To a civil engineer, description of admixtures according to their function is more useful than based on their chemical compositions.

Air-Entraining Admixtures

Chemical admixture was first used in 1930s for entraining air into concrete to increase its frost resistance. The fine air bubbles with a close spacing provide partial relief as the liquid phase in concrete progressively freezes. Dodson (1990) clarified that air-entraining admixtures (AEA) do not generate air in the concrete. Their function is to stabilize the air present within the void system of the mixture and water as well air infolded and mechanically enveloped during mixing. Even without an AEA, concrete contains some air, which is often referred to as “entrapped” air. These air voids are typically 1 mm or more in diameter and irregular in shape. They often collect at the paste-aggregate interface. Entrained air bubbles are mainly within the paste with diameters typically between 10 μm and 1 mm. They are spherical in shape at close spacing. The spacing factor (ASTM C457 method), which is the maximum distance in the cement paste from the periphery of an air void, is usually in the range of 0.10 to 0.20 mm. The commonly recommended air content is 5 to 6% in the compacted concrete. Air bubbles promote workability but their presence reduces the strength of concrete. These factors are taken into consideration in the design of concrete mixtures.

Accelerating Admixtures

The use of accelerating admixtures is common during cold-weather concreting, as the rate of hydration of cement is decreased by lower temperatures. Their function is to increase the rate of hydration, thereby speeding up the setting time and early strength development. In the past, calcium chloride has been the most commonly used for this purpose. However, in recent years, the effect of chloride on the corrosion resistance of embedded steel reinforcement and prestressed tendons has been recognized. This has resulted in limiting the total chloride content in concrete at levels that is exceeded by the normal addition of calcium chloride as accelerating admixture. Currently, non-chloride accelerating admixtures are available, e.g., calcium nitrite (also a corrosion inhibitor). The use of calcium nitrite leads to a better strength gain at later ages than calcium chloride. However, this may not be of importance in practice as moist curing on site is limited to early ages only.

Water Reducing and Retarding Admixtures

Although each of the two functions may be obtained separately as indicated in chemical admixture standards, it is more typical to use both at the same time. This is also due to the fact that the two functions are available in the typical materials used in their formulation, e.g., salts of lignosulfonic acids. In particular, both functions are useful in the case of hot-weather concreting.

The amount of mixing water in a typical concrete mixture is more than that needed for full hydration of the cement used. The excess water is intended to promote workability. However, when water is added to cement, there is a tendency for the cement particles to cluster together, forming into flocs. Some of the mixing water is trapped within the flocs and not available to contribute to the fluidity of the mixture.

Water reducing and retarding admixtures are surfactants and are adsorbed onto the surface of cement particles when added to the mixture. This induces a charge on to the cement particles thereby preventing their flocculation. The water so released improves the workability and the increase in surface of cement particles available for early hydration.

Water reducing admixtures provide the following potential applications:

(a) The simple addition of a dosage of the admixture to a plain concrete mixture increases its workability with only a small increase in the strength of the concrete — improving workability or plasticising action.
(b) By adding a dosage of the admixture, the mixture has the same degree of workability at lower water content and hence strength is increased if cement content remains the same — improving strength or water reducing.
(c) By adding a dosage of the admixture, the mixture may have the same degree of workability and strength by reducing both water content and cement content to retain its original water/cement ratio — saving cement. The cost of cement saved is generally more than the cost of admixture used — saving cost.

The effectiveness of a given dosage of water reducing and retarding admixture is reduced when the cement has a higher amount of alkalis or tricalcium aluminate. A higher fineness of the cement also has the same influence due to its larger surface area in adsorbing the admixture. Over a period of time, such variations in properties may occur even if it is supplied from the same cement manufacturer.

The requirements for admixtures are specified in terms of both water reducing and plasticising functions, e.g., ASTM C 494. The first generation of commercial water reducing admixtures, e.g., salts of lignosulfonic acids, provides about 10 to 15% reduction in water (minimum 5% in ASTM C 494). The second generation of water reducing admixtures enables about 15 to 20% in water reduction (minimum 12% in ASTM C494), e.g., sulfonated naphthalene formaldehyde, and is also called high range water reducing admixtures or superplasticisers. In recent years, the third generation of water reducing admixtures, e.g., carboxylate copolymers, has even higher water reducing capability as they enable the production of self-compacting concrete (no mechanical compaction required during concrete placing). The earlier types rely mainly of electrostatic repulsion of the same charge when the admixture is adsorbed on to the surfaces of cement particles. In the latest type, steric repulsion due to the long chain of the chemical plays a more important role in dispersing the cement particles. With the ability of progressive release of the chemicals by interacting with products of hydration, its high workability effect is prolonged (workability retention).

Retarding admixtures delay setting but not rate of strength development, except early strength when long retardation is provided. The effect of set retardation is assessed in terms of the time to develop a given degree of stiffness as indicated by the penetration resistance of the concrete. This is determined on the mortar fraction wet-sieved from a concrete mixture (ASTM C 403). The elapsed time after the initial contact of cement and water to reach a penetration resistance of 0.5 MPa (500 psi) is referred to as the initial setting time of concrete (not to be confused with initial set of cement by ASTM C 191). The time to reach a penetration resistance of 27.6 MPa (4000 psi) is referred to as the final setting time. A similar test method using the same principle but differing in some details in test method is specified in BS 5075 for chemical admixture tests. In addition to the 3.5 MPa penetration resistance, it includes the time to reach 0.5 MPa penetration resistance, but not for the 27.6 MPa. Although these are arbitrary limits selected for the purpose of testing chemical admixtures with specified mix proportions, they are approximately related to observed behavior in corresponding concretes as follows:

(a) Penetration resistance at 0.5 MPa (BS 5075 only) — limiting time for placing with initial workability.
(b) Penetration resistance at 3.5 MPa (BS 5075 and ASTM C 403) — limiting time for vibrating concrete without formation of cold joint (ASTM C 403 — initial set).
(c) Penetration resistance at 27.6 MPa (ASTM C 403 only) — final set or when compressive strength of standard 150mm diameter cylinder is about 0.7 MPa (100 psi).

When the above is applied to concrete mixtures in construction, their indicated significance should be taken as indicative only. The penetration resistance at an elapsed time after initial contact of water and cement is dependent on its initial stiffness (a physical factor involving mixture proportions of the mortar fraction, with or with chemical admixtures) and the change in stiffness due to cement hydration (chemical factor including the retarding effect of admixtures, if used). For example, a plain concrete with a higher water/cement ratio takes a longer time to reach the same penetration resistance than one at lower water/cement ratio even though the former tends to have a faster rate of reaction as the cement particles are more dispersed. Similarly, the test method (ASTM C 403) does not permit the use of a directly mixed mortar to simulate the mortar fraction of the concrete as this may lead to an increase in the setting times.

40.6 Hydration and Structure of Cement Paste

The chemical reactions of cement components and water are collectively called hydration. The two main types of components are the silicates and the aluminates. Under normal temperatures, the added gypsum is used up in reactions with the aluminates during the first one to two days. This can be delayed from taking place if the hydration process is subjected to high temperatures (exceeding about 70°C) during this stage (e.g., steam curing). The delayed reaction may take place at later ages causing undesirable expansion. The silicates react with water to form crystalline calcium hydroxide and a low crystalline calcium silicate hydrate called C-S-H gel. This structure has a typical gel porosity of about 26 to 28% with a very high specific surface (surface area per unit mass). The amount of water needed for full hydration of cement is about 20 to 25% by mass of cement. In addition, the gel pores also take up some of the mixing water. However, in practice, not all the mix water is used up in hydration and taken up by the gel pores. Depending on the amount of cement that has reacted, the balance of the water remains as much larger pores, often referred to as capillary pores. Gel pores, on the other hand, range from about 1 nm to about 0.1 μm. In well-hydrated cement paste, these fine pores results in extremely low permeability of the paste and a major factor for water tightness of properly cured concrete.

When water is added to cement, the first stage of reaction is very rapid but only for a short duration. The added gypsum prevents the reaction from becoming a "flash set." This is followed by a stage of very low reaction rate, called the "dormant period." This period can be extended by the used of chemical retarders (e.g., hot weather concreting) or reduced by chemical accelerators (e.g., cold weather concreting). The third stage begins with the renewed hydration of the silicates at an accelerating rate and is associated with initial set of cement (e.g., ASTM C 191). This is followed by the fourth stage during which the hydration rate slows down rapidly. The rate of hydration slows down further at the final stage which continues at a slow rate as long as the conditions enabling chemical reaction is maintained (over years with moist curing at normal temperatures).

The structure of the silicate hydrates consists of a family of silicates, called calcium silicate hydrates (C-S-H). The volume of cement, V_c and chemically combined water, V_{nw} is less than the volume of the C-S-H gel, V_g formed. However, the gel pores take up a volume of water, V_{gw}. It has been shown by Powers and Brownyard (1946/47) that the relative volume relationship is as follows:

$$V_c + V_{nw} < V_g < V_c + V_{nw} + V_g$$

For the paste to remain fully saturated, water from an external source has to fill up the difference in volume. In practice, moist curing provides this additional water to promote cement hydration at its maximum rate. If such water is not available, continuing hydration and loss of moisture to the environment reduce the internal moisture content. Hydration rate is severely reduced if the internal vapor pressure falls below about 0.8 (relative humidity of 80%) and extremely low below about 0.3. The rate of moisture loss depends on the initial moisture content in the concrete, the exposure temperature and relative humidity and the shape and size (surface/volume ratio) of the structural member.

The reaction of cement compounds with water may be separated into two main groups. The first stage is the aluminates with water contributing to the high heat of hydration. The added gypsum goes into solution to react with tricalcium aluminate forming a product known as ettringite.

$$\text{Tricalcium Aluminates} + \text{Calcium Sulfate} \rightarrow \text{Ettringite}$$

As sulfate is depleted, ettringite is converted into monosulfate.

$$\text{Ettringite} + \text{Tricalcium Aluminate} \rightarrow \text{Calcium Monosulfate}$$

The calcium silicates react with water to for calcium silicate hydrated (C-S-H) and calcium hydroxide. This is the primary reaction in blended cements. However, as the concentration of calcium hydroxide is built up, it reactions with the silicates present in fly ash, slag or silica fume (pozzolans) to form more C-S-H gel. This second reaction is known as the pozzolanic reaction. It takes place later than the primary reaction hence in the case of blended cement concrete, a longer duration of curing is needed to ensure adequate hydration is achieved.

Primary reaction

$$\text{Calcium silicates} + \text{Water} \rightarrow \text{Calcium Silicate Hydrates} + \text{Calcium Hydroxide}$$

Pozzolanic reaction

$$\text{Calcium Hydroxide} + \text{Pozzolans} \rightarrow \text{Calcium Silicate Hydrates}$$

Another important role of this second reaction is that it takes place in the liquid phase of the concrete, i.e., in capillary pores and in zones below coarse aggregates where voids are formed due to bleeding water trapped beneath them. The zone of cement paste around an aggregate is called the interfacial zone or transition zone. Its quality is generally slightly different from the bulk of the cement paste in the matrix of concrete. These voids contribute mainly to permeability of concrete. If these voids are filled with the C-S-H gels from pozzolanic reaction, the internal structure of concrete is improved. It is often noticed that its improvement against ingress of water and chemicals from external sources is more significant than the increase in strength.

40.7 Mixture Design

Mixture design does not carry the same degree of certainty as structural design. It is more appropriately defined as a process of selecting the type of mixture constituents and their proportions. The intended properties of the mixture are usually assessed by means of a trial batch, and the mixture proportions adjusted where necessary. This type of mixture is a designed mixture. On the other hand for minor projects or where past experience provides adequate information, mixture proportions may be specified. This type of mixture is a prescribed mixture. In small projects, constituents may even be batched by volume using predetermined sizes of volume boxes. However, in general, batching by mass is the common practice, particularly with ready-mixed concrete supply.

The method of mixture design is seldom of concern to civil engineers as proper selection of materials and mixture proportions relies on past experience with the constituents at hand and their performance in mixtures previously produced. However, it is useful to be familiar with the properties of fresh and hardened concrete commonly required and how the selected mixture proportions influence these properties.

The three main requirements are compressive strength, workability and durability. For the purpose of mixture design, simplified assumptions are used on the factors influencing these properties. Water/cement ratio is the main factor for compressive strength. However, for a specified strength used in structural design, the value is taken as the characteristic strength, i.e., the value below which a specified percentage of results is expected to fall, according to a Gaussian distribution of strength results. The mean strength for the mixture design includes a margin above this characteristic value, depending on the percentage selected. For example, for 5% defectives, the margin is 1.64 times the standard deviation. For ready-mixed concrete production, the range of standard deviation is usually between 3 to 5 MPa. For trial mix, a slightly higher margin is some times chosen. Workability is assumed to be dependent on water content (mass per cubic meter). The addition of water-reducing admixtures reduces the amount of water needed for the same workability. The likely amount of water to be reduced and the factors influencing the effectiveness of chemical admixtures have been described in earlier sections. Requirements for durability are commonly based on limiting the minimum cement content and the maximum water/cement ratio for various exposure conditions. This implicit approach is one of the most uncertain aspects in mixture design for service life prediction. Further information on durability considerations are described in later sections. Different approaches are used in the American (ACI Committee 211) and British (Department of the Environment) methods and they do not result in the same mixture proportions for the same set of requirements. It is preferred that users specify concrete by its performance requirements and for the producers of concrete to select the mixture proportions. Either from previous records or by testing, the requirements are demonstrated to be achievable before concrete is supplied to the project.

Hydrated cement paste (C-S-H gel) is the "glue" that holds the composite material together. Hence, its quality, dependent of its water/cement ratio and the degree of hydration (promoted by moist curing and indicated as strength gain) is the most important aspect of mixture design. The chemical resistance of concrete is also dependent on the type of chemical composition of cement. In particular, sulfate resistance and alkali aggregate reactions are influenced by the selection of appropriate cement type (see section on durability for more details). Another factor in the selection of cement composition relates to minimizing temperature rise in thick sections, particularly in hot weather concreting, where cement of low heat of hydration is specified. Further information on this topic is provided under hot weather concreting.

Aggregates are normally inert to chemicals in cement, except for the case of alkali-aggregate reaction. They play a significant role contributing not only to a lower cost of concrete but also to its properties. The aggregate/cement ratio is often a factor used in prescribed mixture proportions. The ease of placing and compacting concrete (part of workability requirements) is reduced by increasing amount of aggregates in the mixture. The amount of cement paste (aggregate/cement ratio) and its own fluidity (water/cement ratio) determine the workability of fresh concrete. The flow of concrete depends on the internal friction of the aggregate system and its reduction by the cement paste volume and its fluidity. The volumetric fraction of aggregates in concrete generally exceeds 60%. Hence, it is expected that to a large extent, physical properties of concrete depend on the corresponding physical properties of aggregates. These include thermal coefficient of expansion, specific heat and thermal conductivity. The deformation properties of concrete are similarly influenced, e.g., creep, shrinkage and modulus of elasticity. Further information on these topics may be obtained from the publications listed in Further Information.

The role of water in concrete is ambivalent. It is needed for chemical reaction of cement, for providing fluidity and in moisture curing. On the other hand, water not taken up for these purposes remains as capillary pores in hardened concrete. They contribute to drying shrinkage, and permeability for fluids and dissolved chemicals penetrating into concrete. These include detrimental materials such carbon dioxide and chlorides causing corrosion of embedded steel reinforcement. Sulfate attack, alkali-aggregate reactions, and delayed ettringite formation are discussed further in the section "Durability." Hence, in mixture design, the amount of water should be kept to the lowest, consistent with the mixing method. The degree of workability required is more cost-effectively provided by the addition of water-reducing admixtures.

40.8 Properties of Fresh Concrete

When concrete is freshly produced, it is plastic in behavior and is often called plastic concrete. The requirements for fresh concrete include the time available for placing it into formwork and workability. Before the advance of chemical admixtures, due to the setting of cement, the time available is often too short for transportation from the batching plant to the work site. The extension of this setting time by addition of chemical retarders has already been described under the section on chemical admixtures.

Workability

Workability is often referred to as the ease with which a concrete can be transported, placed and consolidated without excessive bleeding or segregation. It is obvious that no single test can evaluate all these factors. In fact, most of these cannot be easily assessed even though some standard tests have been established to evaluate them under specific conditions (not always similar to that occurring on site). Thus they are more useful in comparing mixtures than for acceptance testing on site. The rheology of fresh concrete has been approximated to that of a modified Bingham body (Tattersall, 1991). This defines a linear relationship between shear stress and shear strain rate, with the intercept at the shear stress axis defined as its yield stress. The slope of the line is called its plastic viscosity. The recent development of a new generation of water reducing admixture produces a self-compacting concrete with near zero yield stress and a low plastic viscosity. The concrete is self-leveling and self-compacting, i.e., no consolidation by vibration is needed to achieve full compaction. For various types of mixtures, different methods of determining workability have been established as standard tests. They cover the range of workability commonly used in construction.

Slump

In everyday practice, slump is the most common test for workability (e.g., ASTM C 143 or BS 1881:Part 102). Minor differences in testing procedures exist between different national standards even for this simple test. The main purpose of this test is intended to detect the change in water content as indicated by a change in slump. Before the age of chemical admixtures, a higher slump is deemed to indicate higher water content and may result in lower strength due to the likely higher water/cement ratio. However, change in water content is not the only variation in the mixture constituents that can lead to a change in slump. Changes in cement composition or cement fineness as well as changes in the grading and shape of aggregates are other common factors. A high slump can also be achieved with the addition of chemical admixtures at the same or lower water content. Changes in cement composition or cement fineness often lead to a change in the effectiveness of chemical admixture resulting in a change in slump. Although the slump test is still useful in indicating any change in consistency or fluidity between batches, however, the cause of the change is not easy to detect. In practice, a tolerance on the measured slump is permitted. This may be as high as one-third of the measured value.

Additional Properties of Fresh Concrete

The other properties of fresh concrete that are of interest to civil engineers include air content (freeze-thaw durability), temperature (hot or cold weather concreting) and density (lightweight or heavy weight concrete). Additional properties that may be assessed during trial mix stage may include bleeding, segregation and stiffening time. Another property that may be determined at this stage is the rate of slump loss or the retention time for good workability needed for construction purpose. Details of test methods are provided in standards.

40.9 Properties of Hardened Concrete

As a material for construction, the main function of concrete is to enable the structure to carry its self-weight and other imposed loads. Thus the most important properties of hardened concrete are its strength and rigidity (modulus of elasticity). Concrete is stronger in compression than in tension. Hence, it is often used in the form of a composite section with steel providing the tensile resistance. In the case of prestressed concrete, a compressive stress distribution is induced into the section to counteract the tensile stress due to loading. Hence, compressive strength of concrete is the most commonly specified property of hardened concrete. However, concrete is a brittle composite and its failure mode is dependent on its ultimate tensile strain. Even under axial compressive stress, tensile strain is generated by Poisson's effect in the lateral directions. This is evident from the failure mode when standard specimens (cubes or cylinders) are tested under an applied compressive load.

Compressive Strength

The compressive strength of hardened concrete is usually determined from standard specimens (cubes or cylinders) after they have been moist cured for 28 days. This is the historical practice, as many researchers have shown that there is no known technical basis for selecting this particular test age. Standard procedures for sampling, making, curing and testing of the test specimens are prescribed (e.g., ASTM C 39 for cylinders) so that the failure stress can be determined with better repeatability and reproducibility. The European practice (EN 206) uses cylinders or cubes as standard specimens. Standard cylinders have a length/diameter ratio of 2 but cubes have aspect ratio of unity. The ends of cylinders are capped to ensure smoothness and parallelism of the ends. Cubes are loaded against a pair of their molded sides to achieve the same requirements. Although the applied load is uniaxial compression, the friction between the test specimen and the metal bearing plates of the test machine introduces a set of biaxial state of stress at both ends of the specimen. Effectively, the end zones are under a triaxial state of stress. The influence of this end effect decreases with its distance from the contact surface. Neville (1995) suggests a distance of about 0.86d, where d is the lateral dimension of the specimen. Thus the zones of influence overlap in the case of cubes but in the case of standard cylinders (aspect ratio of 2), there is a middle zone free of the end effects. Hence, a standard cylinder fails at a lower applied load than a standard cube and reported as a lower stress when it is computed on simply load/area basis. Although the cylinder strength is closer to that due to unconfined uniaxial compression, testing of cubes do not required end preparation. The capping material for cylinders has to be stronger than that of the cylinder. This is critical for high strength concrete (80 to 100 MPa) and satisfactory end preparation is often by grinding of the ends held in special jigs. Hence, cubes are more convenient in this case. Since the main purpose of testing standard specimens is to verify the strength of concrete production, the choice of cylinders or cubes is equally satisfactory. Several researchers have reported on the relation between the strength determined from standard cylinders and standard cubes based on experimental results. EN 206 provides a table of corresponding strengths of cylinder to cube over a range of cylinder strength from 8 to 100 MPa. There is a general trend that the ratio of cube strength/cylinder strength decreases with increasing strength level (from 1.25 to 1.15 for the above range of cylinder strength).

Compressive strength of concrete is traditionally determined after 28 days of curing. This is also the concrete strength used in structural design codes. However, for the purpose of quality control in concrete production, this is no longer satisfactory for the current rate of construction. A large volume of concrete may have been built over the concrete for which the 28-day strength is just determined. The liability involved, if the test result is not in conformity with the specified value, is often unacceptable. Just as in modern manufacturing, the quality of a product should be assessed as soon as practical to provide feedback for adjustment if necessary. As designers, civil engineers are more concerned with the as-built structure even though satisfactory concrete is a pre-requisite. However, the current practice on site does not assess the concrete in the structure, but only the concrete as produced, sampled, cured and tested under standard conditions. There is a potential difference between such standard samples and the in-place concrete, which is likely to be of less compaction and much shorter period of curing than standard specimens. There is enough evidence from research and practice that in general, in-place strength of concrete is expected to be lower than that of the corresponding standard samples.

Assessment of in-place strength of concrete may be based on testing cored samples from structural members. ACI Committee 318 recommends that the concrete in the structure may be acceptable provided the strength determined from the average of three cores is at least 85% of the specified value and none of individual core is less than 75% of the specified value. BS 6089 recommends that the partial safety factor for concrete based on cores should not be less than 1.2 compared to the value of 1.5 used in design.

The designer is responsible to decide on the appropriate value for each case, taking into consideration the confidence on the estimated strength and the importance of the failure to conform. Since the standard samples in the British practice are cubes, there is a need to convert the strength determined from cylindrical cores (usually with length/diameter ratio about unity) into equivalent cube strength. The equation (BS 1881:Part 120) is based on assumed values for various factors used in the conversion (Concrete Society Technical Report No. 11).

The use of drilled cores for the purpose of assessing concrete strength in existing structures is usually limited to small number of cores. Besides the danger of cutting a reinforcement bar, the removal of concrete from critical locations is also not desirable. Hence, indirect means of assessment by non-destructive methods have been developed. Most of these do result in some degree of damage to the near surface zone of concrete. Many of these have reached the stage of standard methods and details are available in the respective testing standards. The more commonly used methods are listed below.

Method	American Practice	British Practice	Surface Damage
Rebound number	ASTM C 805	BS 1881:Part 202	Very minor
Pulse velocity	ASTM C 597	BS 1881:Part 203	Negligible
Penetration resistance	ASTM C 803	BS 1881:Part 207	Minor
Pullout strength	ASTM C 900	BS 1881:Part 207	Minor
Break-off number	ASTM C 1150	BS 1881:Part 207	Minor

None of the above methods provide a direct assessment of the compressive strength. Although the three methods with minor damage involve some aspects of strength, the volume of concrete assessed is small and only at the near surface zone. Rebound number is only a test of surface hardness. Pulse velocity measured directly through the thickness of a section provides better assessment than semi-direct or surface measurements. These two methods with minimal damage are based on the principle that compressive strength and the modulus of concrete are correlated. In all cases, a correlation curve is needed by testing companion standard specimens to provide the compressive strength. This approach is possible for new construction, where the same concrete mixture is available for preparing the specimens for both compressive strength and non-destructive measurement. For an existing structure, compressive strength is available only from testing cores taken from selected regions of the structure. The planning and interpretation of such assessment should be carried out by those who understand the principle behind the selected test method, the factors influencing the non-destructive measurement, the usefulness and limitations of the established correlation so as to provide meaningful conclusions.

Modulus of Elasticity

Modulus of elasticity is another important property in the design of concrete structures. It determines the deformation and deflection of structural members. Although the modulus of elasticity of normal weight concrete increases with concrete strength, its increase is much less, e.g., ACI 318 recommendation states that modulus of elasticity is proportional the square-root of cylinder strength of concrete. Hence, in the case of very high strength concrete, deflection limits may control the depth of section rather than concrete strength. High strength concrete is achieved with low water/cement ratio (aggregate/cement bond) and low water content (porosity arising from capillary pores). Since the conventional mixing process requires water content of at least about 150 kg/m,^{3} a high cement content is often needed leading to a lower aggregate content. The paste fraction has much lower modulus of elasticity than aggregates, hence in a composite, the relative volumetric composition of these two components determine the modulus of elasticity of concrete.

Determination of modulus of elastic of concrete (ASTM C 469 or BS 1881:Part 121) is by short-term loading within the stage where the stress-strain relationship is practically linear within the sensitivity of strain measurement system used. It is called the static modulus of elasticity and is in effect the secant modulus — slope between two defined points along the stress-strain curve. Even for this short duration of loading, some time-dependent strain (creep) occurs. There is also a dynamic modulus of elasticity, determined by means of vibration of a concrete specimen (ASTM C 215 or BS 1881:Part 209) with only a very low level of stress and short duration. With negligible creep, it is almost due to elastic effects. It is higher than static modulus and approximately equal to the initial tangent modulus of the stress-strain curve.

Volume Change

Two major types of volume change of interest to civil engineers are creep and shrinkage. Creep is the increase in strain due to sustained constant load. In most structures above ground, creep is taking place under drying conditions. Drying out of water from the interior of concrete leads to shrinkage. When creep and shrinkage occur simultaneously, it is known as drying creep. Creep without loss of moisture to the exterior is known as basic creep. Drying creep is higher than the sum of basic creep and shrinkage occurring separately. In prestressed concrete, both creep and shrinkage lead to a loss of prestressing force. Allowance for such losses have to be considered in the initial prestress applied.

Another form of shrinkage arises from the consumption of internal moisture due to continuing hydration of cement, drawing water from the capillary pores, without external supply of water (curing). This is known as autogenous shrinkage due to self-desiccation. For mixtures with water/cement ratio above 0.3, the amount of autogenous shrinkage is small compared to drying shrinkage. For low water/cement ratio mixtures, autogenous shrinkage may become the major contribution to total shrinkage.

Carbonation of concrete also induces shrinkage. This is known as carbonation shrinkage, which is accompanied by an increase in mass due to the reaction of carbon dioxide with calcium hydroxide (from hydration of silicates in cement) to form calcium carbonate.

Shrinkage is a three-dimensional change in volume, although it is generally reported as a linear strain. When shrinkage is restrained by boundary conditions, tensile stress is induced. If the magnitude of restrained shrinkage is higher than the ultimate tensile strain capacity of concrete, cracking occurs.

Permeation

Permeation relates to the ease with which fluids (liquids and gases) can penetrate into, or move through concrete. Durability of concrete is largely influenced by its permeation properties. These aspects are discussed in another chapter under "Durability of Concrete".

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